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Deliverable D12.3 (DJ1.1.1) Future Network Architectures

A possible scenario based on the findings of Joint Research Activity 1 (JRA1)

Deliverable D12.3 (DJ1.1.1)

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Abstract

This deliverable describes the process and results of the work carried out in GN3plus by JRA1 T1, as well as incorporating recommendations and lessons learnt from the other tasks in the JRA1 activity and the related Open Call Projects MOMOT, IRINA and REACTION. The document is meant to serve as an introduction for NRENs to possible new solutions and technologies and to provide guidelines as to how these could be implemented from an architectural point of view, and does not intend to propose or advocate for a single “fit-all” solution for the GÉANT/NREN network as a whole.

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Executive Summary

Today's users expect 24/7 access to their data, with an acceptable quality of service, wherever they are located. This means that in future NRENs will be facing increasing requirements in terms of new technologies, with the ensuing costs. The work of JRA1 Task 1 during GN3plus has focused on these requirements and on integrating the key findings of all other tasks, in this respect, including Open Call projects in JRA1, in an effort to devise viable solutions to meet these needs.
The boost in demand for fixed and mobile cloud services, in addition to the demands for cost reductions that NRENs are typically faced with, mean there are strict requirements to be met in terms of how the future NREN network will be equipped and managed, which call for a new network architecture that particularly considers the need to optimise the use of resources.

The main objective of this document is to capture and analyse some of the important trends and technology developments affecting the design of NREN networks. JRA1 takes the view that the pervasive use of mobile devices and cloud-based services will have a dramatic impact on the way NRENs will design networks in the future, and offers analyses and recommendations for technologies that it considers could prove especially useful for future NREN architectures. The document is meant to serve as an introduction for NRENs to possible new solutions and technologies and to provide guidelines as to how these could be implemented from an architectural point of view. It should be stressed, however, that it does not intend to propose or advocate for a single "fit-all" solution for the GÉANT/NREN network as a whole.

Requirements were collected from general literature, the work carried out by related GN3plus JRA1 tasks, and key results of the CONTENT, BonFIRE, and GEYSERS European projects. An analysis of these requirements reveals that the current network technologies and architecture cannot offer the fully dynamic and flexible transport services needed for orchestration of future services, which should include both IT and network infrastructure resources. In the area of cloud services, moreover, the need is foreseen to provide the infrastructure to support GÉANT Open Cloud Exchanges (gOCX) and implement Open Exchanges Points in different layers in order to potentially reduce costs.

The requirements of larger scientific projects that produce huge volumes of data, and which form an important part of the customer base of NRENs, have not been specifically validated in this document, which has focused on the analysis of certain new and upcoming trends. However, the requirements of these highly demanding users are implicitly reflected in some of the projects considered in this analysis, such as the European BonFIRE project mentioned above.

GN3plus JRA1 Task 1 collaborated closely with two Open Call projects, REACTION and MOMoT, which respectively address bandwidth improvement and alien waves with reference to the optical spectrum. This joint work has resulted in a better understanding of the spectral impact of different modulation

schemes and Alien Waves, which is fundamental towards optimising utilisation of the spectrum for ultra-high bandwidth and reuse by different entities. Common techniques for increasing bit rates, including sophisticated modulation schemes and super-channels, are also surveyed. Possible models to suit the set of technologies typically available at NRENs are investigated, and these models compared to vendor roadmaps, providing an overview of the basic handles and tools available to NRENs. Knowing these handles is key to identifying possibilities for cost savings through federations.

Alternative technologies to ensure time synchronisation between services in the NREN environment are explored, as, when traditional TDM technologies in the WAN are replaced with Ethernet, the intrinsic timing reference is no longer available. Technologies for providing synchronisation in the sub picosecond and nanosecond scales are also evaluated. Specifically, an experimental evaluation of PTP for providing synchronisation between Nuremberg and Munich over a packet-switched network given normal network conditions was conducted with successful results.

The knowledge gathered about emerging technologies and the tools available at the NRENs, made it possible to sketch a network architecture supporting the future need for cloud computing, mobile access and seamless provisioning of network resources and Zero Touch Connectivity. This architecture consists of a multi-domain Physical Infrastructure Layer comprising very heterogeneous technologies, with basic elements that can be manipulated including, among others, fibres, lambdas, spectrum, ODUs, Ethernet, exchanges points, and computational and storage resources. Specific technology sets vary for each NREN, and a key recommendation is to identify which of these resources are suitable for sharing or federated use.

A key challenge was to provide a unified description of the physical resources needed for scaled integrated provisioning. Physical Infrastructure Management is responsible for providing management of physical resources and enabling capabilities such as supporting the sharing of resources, while the Control and Service Orchestration layers are responsible for the service provisioning and orchestration of IT and network resources. A number of relevant technical solutions are investigated and proposed for a variety of scenarios, from multi-layer architectures to procedures, protocols and interfaces allowing integrated workflows to support delivery and operation of joint cloud and network services. It is recommended that unified management should be implemented in the network and that existing solutions should be integrated with available Open Source management platforms.

1 Introduction

End users, including students at universities or members of large research projects, nowadays expect to be able to access data wherever they are and wherever the data is located. Such mobility, combined with increased data volumes from emerging services such as high-demanding multimedia applications, has significant repercussions in terms of the ways data is stored and accessed. It also requires a rethinking of the transport infrastructure which supports data access and raises the need for an integrated view of the IT and network infrastructures, where these aspects are orchestrated using a single tool in the provision of services.

The massive use of the transport infrastructure caused by the growing demands from fixed and mobile cloud services, as well as emerging applications, requires that GÉANT and the NRENs upgrade their backbone and footprint accordingly. When the end users are mobile – including outside campus sites – how can the combined NREN and GÉANT community still satisfy the demand for "wherever-access" to cloud services? In addition, how will the integration of cloud services (educational and commercial) influence the typical NREN infrastructure?

Clearly, NRENs continuously need to upgrade their network with newer technologies in order to satisfy aggregated service demands, in particular from cloud and mobile users, in addition to the more prominent requirements of high-demanding scientific projects, such as the Large Hadron Collider [LHC], as discussed in the JRA1 T2 deliverable [D12-1_DJ1-2-1]. Hence, it is important to gain an overview of the current and potential transport technologies in the NREN domain, with an emphasis on their efficient use. This requires a knowledge of the available technologies currently deployed and of vendor roadmaps, as well as of potential technologies currently in the research labs. JRA1 Task 1 has investigated transport technologies beyond 100G bit rates, which are discussed here with reference to their applications in an NREN context. Obviously, new technologies also have drawbacks, which might influence application behaviour – e.g., while time distribution and synchronisation is inherent in legacy equipment, whereas there are certain challenges to be considered in this respect with newer technologies.

NRENs (and GÉANT) are therefore faced on the one hand with having to implement costly upgrades to their network infrastructures so as to meet the service requirements of cloud and mobile users, while at the same time most European NRENs are having to cut costs. Special focus should therefore be given to an efficient use and sharing of expensive resources for the mutual benefit of the NRENs and their stakeholders, including in terms of possible cost savings.

These are precisely the issues investigated by the JRA1 activity in GN3plus. Task 3 has addressed the possibilities of increasing the footprint of the NREN community and infrastructure and bringing mobility solutions closer to their users. The consequences for the network and the results of this research are documented in the JRA1 T3 deliverable [D12-2_DJ1-3-1]. The architectures for cloud services and their impact on the transport network, including proof-of-concept demonstrations, have been investigated by Task 2, as detailed in its deliverable [D12-1_DJ1-2-1]. In this report, Task 1 has utilised the findings from Task 2 and Task 3 to evaluate how NRENs can best upgrade and/or utilise their network infrastructures while taking into account the wide diversity of technologies and traditional approaches of the different NRENs.

In particular, the GÉANT Open Cloud eXchange (gOCX) concept developed by JRA1 Task 2 is applied to other Open Exchange points, for example Open Lightpath eXchange (OLX), which supports and facilitates the sharing of resources.

The main objective of JRA1 as a whole is to provide guidelines and recommendations to the NRENs to support emerging service demands as efficiently as possible. Figure 1.1, shows the three main areas of research which have contributed to the guidelines provided in this document.

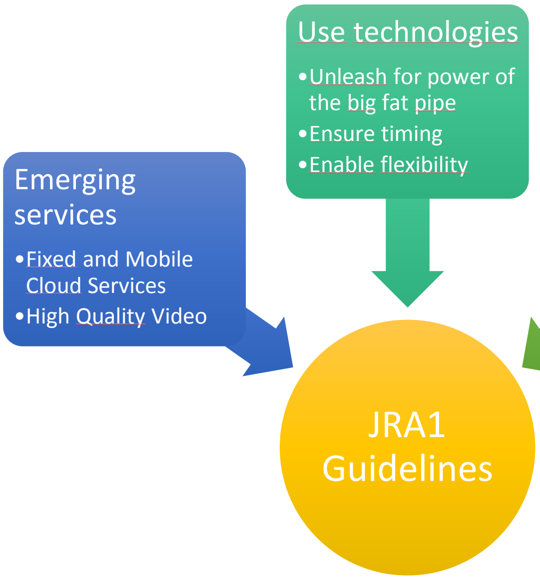


Figure 1.1: Motivators for the work

NREN users will in the future be requiring emerging services, which will have to be supported by the NRENs' network infrastructure. The use of new technologies beyond 100G for implementing "big fat pipes" provides the needed connectivity for high-demanding scientific projects capable of utilising such bandwidth. However, for smaller projects, it can give rise to several issues in terms of how these high-capacity connections can be used optimally with respect to bandwidth granularity, flexibility and other needed functionalities. Finally, it is of utmost importance to reduce costs, which could be achieved, for example, through resource sharing. The implementation of Open Light eXchanges is considered as one possible facilitator to enable this sharing of resources. The outcome of the work are a series of proposed network architecture components and a set of functional recommendations and guidelines to support the requirements outlined above. It is expected that these recommendations – or a subset of the same – can be used by NRENs to improve their utilisation of resources or to support a procurement process for new technologies on a functional level.

Section 2 of this report addresses the requirements for a new network architecture based on the needs for emerging services of the user communities. The growing mobility of users and use of cloud services are placing special demands on the NREN network infrastructure for requirements that it does not currently support. The NREN user base includes both individual users and highly demanding research projects.

In section 3, new technologies for increasing the capacity of the network infrastructure are described. The technological components for enabling resource sharing are also discussed, based on the results of close collaborations with the MOMoT, REACTION and IRINA GN3plus Open Call projects, which each address the issue of enabling flexibility on different layers. In addition, some typical scenarios in terms of the mix of technologies normally found at NRENs are described, along with a summary of how these technologies could be utilised to satisfy future needs.

Finally, in section 4, the necessary architectural functions and components for orchestrating services are discussed, and a set of recommendations and guidelines, which can be adapted to a given NREN infrastructure, are provided.

2 Requirement Analysis

Today's research networks offer a variety of services for NREN end users. Each NREN maintains its own repository of services made available to users from its wide range of research domains, including physics, chemistry, astronomy and others. However, users are increasingly interested in accessing resources located in different administrative domains, including in different countries, in addition to those offered by their local NREN. The GÉANT community has established several initiatives to address these needs, including proposing the multi-domain frameworks for monitoring (perfSONAR) and testing (GÉANT Testbeds Service (GTS)), dynamic bandwidth allocation (AutoBAHN) or a distributed management of identities (eduGAIN). All these efforts are focused on creating a European multi-domain platform with advanced services to satisfy the needs of NREN users.

Moreover, some NREN users need to access data wherever they are, and wherever such data is located, meaning there is a demand to accommodate increased mobility of data sources and data consumers in the network. Today's research networks are not yet ready to handle such requests, and these demands lead to new requirements in terms of how data is stored and accessed.

The requirements in this section are collected from different sources, including, among others, JRA1 Task 2 and Task 3, and further details can be found in the deliverables produced by these tasks [D12-1_DJ1-2-1] [D12-2_DJ1-3-1].

2.1 The Need for a New Architecture

As the availability of high-speed Internet access is increasing at a rapid pace and new demanding applications are emerging, distributed computing systems are also gaining popularity. Over the past decade, large-scale computer networks supporting both communication and computation were extensively employed in accordance with the cloud computing paradigm.

Cloud computing facilitates access to computing resources on an on-demand basis, enabling end users to retrieve 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 CO_2 footprint.

Cloud computing architectures comprise a variety of hardware and software components that communicate with each other through a high-performance network infrastructure. On the other hand, cloud computing services need to be supported by specific IT resources that may be remote and geographically distributed, and end-user connectivity requires high capacity with increased flexibility and dynamicity, whether on campuses or across NREN networks. A strong candidate to support these needs is optical networking, in view of its carrier-grade attributes, abundant capacity and energy efficiency, as well as of the recent technology advancements including dynamic control planes.

Recently, the concept of mobile computing is also gaining increased attention, as it aims to support the additional requirement for the 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 [DINH-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, [MUN-TECH]. Cisco's Global Mobile Data Traffic Forecast Update for 2012–2017 [CISCO-2013], predicted that by 2013 the number of mobile Internet users would exceed that of desktop Internet users, resulting in an enormous increase in mobile data, a big part of which would come from Cloud computing. While it is not the objective of the NRENs to provide commercial services, such trends are important to understand if NRENs want to consider the implementation of eduroam-like services in the mobile area.

At the same time, the current best-effort Internet architecture places significant constraints on the continuously increasing deployments of cloud-based services. New demanding applications that are distributed in nature clearly mark a need for the next generation networks to interconnect computing facilities (data centres) with end consumers and their home and mobile devices.

In conclusion, current networks cannot offer fully dynamic and flexible bandwidth transport services to end users, although initial steps, including demonstrations and proof-of-concept implementations, have been made in this direction by some NRENs. Additionally, the integration of diversified resources and services (mainly compute and network) is not sufficiently covered, and an overall combined strategy for GÉANT and the NRENs to undertake a full convergence of these kinds of resources and services would be beneficial.

Current networks cannot yet guarantee real end-to-end service provisioning between end user terminals via GÉANT, the NRENs and local campus networks.

However, the GÉANT community is aware of these needs and is identifying opportunities and challenges to be addressed in the near future to enable closer cooperation between the so far separate worlds of networking and cloud computing, .

2.2 Requirements of Cloud Services on Future Networking in the GÉANT and NREN Community

The "traditional" NREN network infrastructure is often implemented as an MPLS network over the DWDM infrastructure. Although this approach meets all the current demands and needs of NREN users, this technology, which is a decade old, cannot accommodate recent changes in network requirements, especially in the context of the exponential increase in demands for flexibility, network service availability and bandwidth granularity (some of which are addressed by technologies that are beyond the scope of this document and are not discussed here). In order to satisfy the needs of the research community for new services, the traditional model of the network should be examined and a set of new mechanisms built to complement the NRENs' current offer.

As explained in JRA1 T2's deliverable "Network Architectures for Cloud Services" [D12-1_DJ1-2-1], the service delivery infrastructure must guarantee resilience, security and SLAs, while maintaining a high-quality service performance. It is noted that service providers will consider moving their data centres physically closer to their customers, therefore network providers must provide scalable, seamless and unified solutions to interconnect resources located in these data centres with end customers. In the NREN community, this requirement may impose the need for the seamless migration of huge amounts of data from one data centre to another, very often located in a different administrative domain.

From the point of view of end users of cloud services, it is essential that they can access a highly-responsive platform, without any blocking elements put in place by their own network or by the network of the service provider. Currently, many commercial network operators are making the move towards the cloud business by setting up their own private data centres, which are usually geographically distributed and deploy significant computation power [TEL-2013].

The multi-domain, multi-administrative and multi-technology nature of European research networks creates unique opportunities to run a networked cloud facility for European researchers. The approach considered imposes several architectural and technological developments to be carried out as part of future GÉANT research activities:

- Integrated network and compute infrastructures.
- Network and compute resource federation across administrative boundaries.
- Open exchange points for different resources in a federated network environment, e.g. Open Cloud Exchange (OCX), Open Lightpath Exchange (OLX), etc.

As reported in the JRA1 T2 deliverable [D12-1_DJ1-2-1], a GÉANT Open Cloud eXchange initiative (gOCX) is underway within the GÉANT and NREN community which proposes a gOCX architecture, including a framework for QoS cloud services delivery from Cloud Service Providers to NREN customers (including universities and research institutes). 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. With this goal in mind, fruitful communication was initiated with a number of Content Service Providers (CSPs), which in the case of Amazon Web Services (AWS) resulted in the awarding of the Amazon Educational Grant, an important step in the promotion of cloud computing and cloud-ready networks in the GÉANT/NREN R&E community.

2.2.1 High-Speed Access Aggregation of High-Speed Mobile Data in the Core

JRA1 T3's deliverable [D12-2_DJ1-3-1] identifies some basic requirements for core network design for efficient aggregation of high-speed mobile data, taking into consideration the specifics of the R&E networking environment:

- Capacity dimensioning of the core network must take into consideration the fact that during peak periods the additive traffic load due to high-speed mobile data backhauling may scale to multi-Gbps speeds.
- The economics of sustaining peering with the commercial Internet close to the interconnection point of the aggregation network and the NREN network should be investigated, as in this way the NREN network could be offloaded from carrying large amounts of data, which requires serious investments (e.g. DWDM transponders, router line cards, etc.).
- It is unnecessary to maintain the extensive peering fabric where an established lightpath infrastructure is available, or may be obtained at a minimal cost, that can provide direct links to Internet exchange points. GÉANT and GÉANT Open, or GLIF, may serve as enablers of such lightpath services on an international scale. NREN networks provide this fabric in individual countries, and the feasibility of lightpath connection vs peering fabric has to be decided on a case-by-case basis (as shown in Figure 2.1).

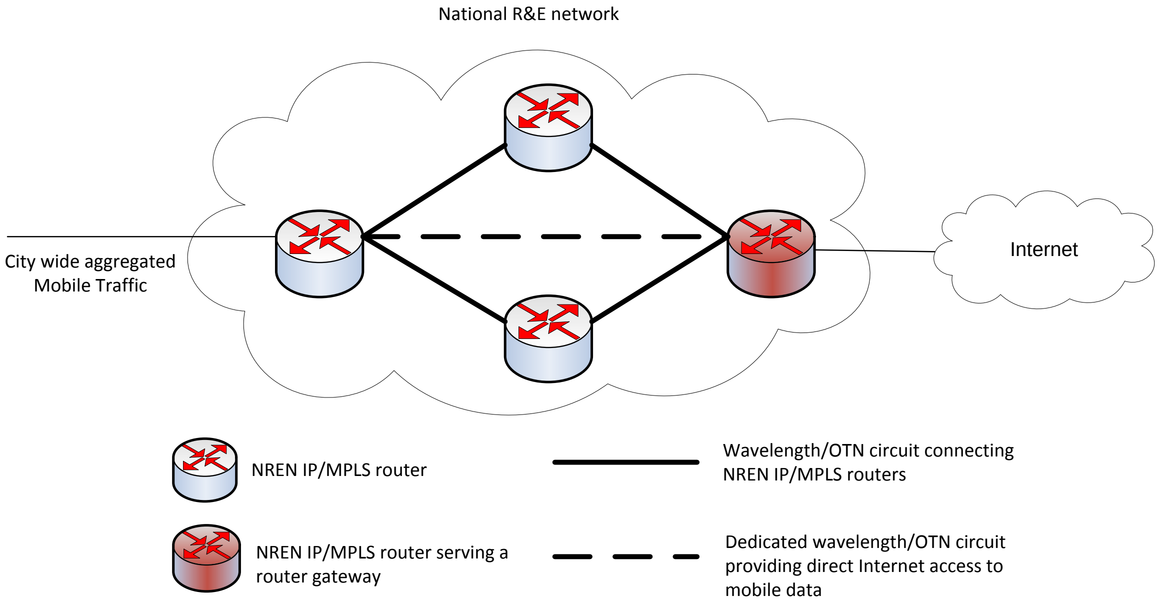


Figure 2.1 Providing dedicated wavelength/OTN circuits for Internet access

2.3 Requirements from GÉANT users

2.3.1 Expansion of eduroam

JRA1 T3’s deliverable [D12-2_DJ1-3-1] describes the eduroam model and its expansion worldwide. Figure 2.2 shows eduroam coverage around the world.

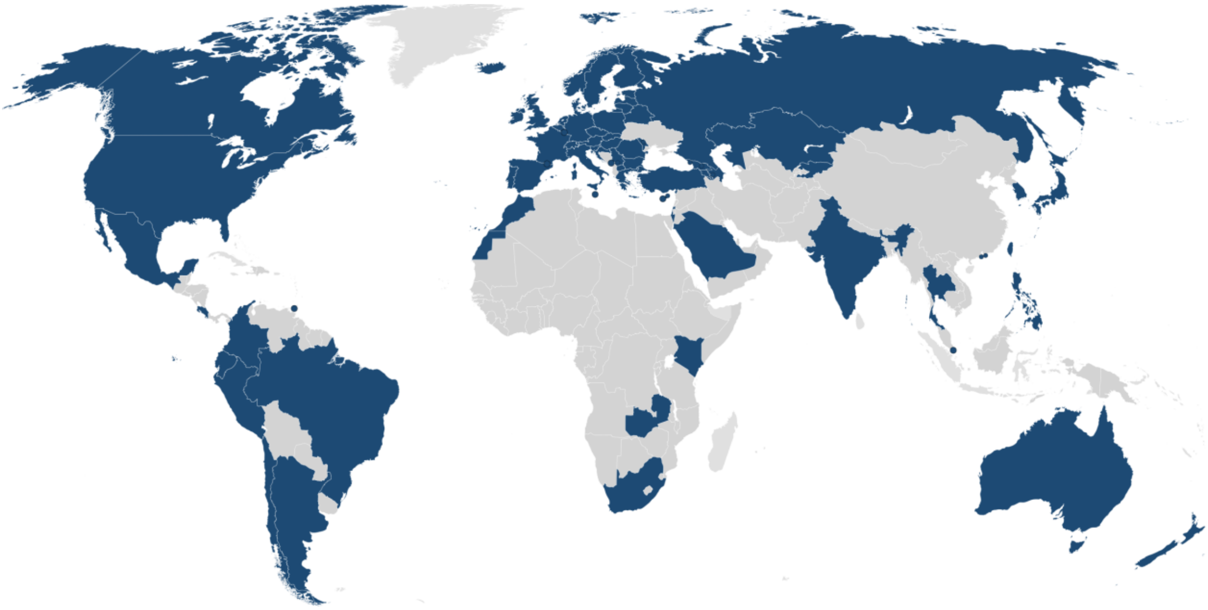


Figure 2.2: Countries with eduroam coverage (shown in dark blue) as of December 2014 [EDUROAM]

The JRA1 T3 deliverable concludes with a statement that eduroam access should not be limited to campuses, and can be provided in wider areas without any significant cost to the research community. Third-party WiFi infrastructure can be successfully used for eduroam access outside campuses with benefits for the research and education community, and National Research and Education Networks should consider promoting eduroam to WiFi providers and aggregating eduroam traffic from third-party WiFi infrastructures.

2.3.1.1 Authorisation-Only by NREN

In the simplest scenario, the NRENs only provide the authorisation of eduroam users and do not backhaul the traffic generated by eduroam users in the WiFi provider networks. The traffic is carried by the WiFi provider and transmitted to its upstream providers in the same way as all other traffic from the WiFi network.

2.3.1.2 Authorisation and Traffic Backhauling to NREN

In this scenario, traffic generated by eduroam users is transmitted from the WiFi provider's network directly to an NREN via a data link. This solution is especially useful for large WiFi providers with a great amount of traffic and metropolitan or regional WiFi infrastructures that can easily access an NREN PoP.

2.3.2 The Distribution of Time and Frequency Signals in Research Networks

Time is one of the base physical quantities, and as such its precise measurement is needed in many areas of life as well as science, such as radio astronomy, particle physics, laser optics, navigation, metrology, cellular networks or military systems [BOG-2014]. At the same time, the progress of science also depends on the accuracy of time and frequency measurements. Today's the atomic clocks achieve the highest levels of accuracy and would appear to be the perfect instrument, if it weren't for one major drawback – high cost. Satellite systems, on the other hand, may be prevented by environmental factors and constraints from achieving a high level of accuracy in transmitted signals and the resulting post-processing of measurement results.

Despite this lack of high-accuracy results, such satellite-based systems (e.g. GALILEO, GPS or GLONAS) remain those mostly used to obtain time and frequency synchronisations, as they represent an attractive compromise in terms of cost and accuracy. However, advanced technologies, such as time and frequency distribution systems over optical networks, are available for selected groups of users, e.g., meteorologists.

A few existing research projects are addressing the needs of end users for advanced time and frequency synchronisation. These projects promote the use of NREN infrastructures to transfer time and frequency signals over optical networks. A smooth and trouble-free operation of the time and distribution system depends on many factors [BOG-2015]:

- *Continuous and stable access to atomic time and frequency signals.*

  A system must make use of more than one clock reference signal. Therefore the architecture of the distribution system must be flexible enough to realise fibre-based connectivity to several locations, where atomic reference signals are distributed.

- *The continuous transmission of time and frequency signals at a distance, in order to synchronise and deliver them to local repositories.*

  These local repositories distribute time and frequency signals to end-users such as research institutions, centres of advanced technologies, and institutions related to navigation, military, or other units that need precise time and frequency.

- *The management of the time and frequency service.*

  Usually time and frequency signals are treated as alien transmissions in telecommunication networks, and therefore have to be managed and monitored properly to avoid any interference with the underlying network infrastructure.

2.3.3 Demand for Multi-Layer Connectivity

A typical EU-funded network research project usually deploys a set of local laboratories distributed in various EU countries. In order to validate a project's research concepts, scientists implement project findings in laboratories, which then must be interconnected with each other to create a distributed project-wide validation environment. GÉANT is a natural choice for researchers seeking connectivity. Examples of such research projects include (but are not limited to):

- XIFI, https://www.fi-xifi.eu
- Mantychore, http://www.mantychore.eu
- BonFIRE, http://www.bonfire-project.eu
- FEDERICA, http://www.fp7-federica.eu
- PHOSPHORUS, www.ist-phosphorus.eu

- GEYSERS, http://www.man.poznan.pl/online/en/projects/119/Geysers.html MUPBED, ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fire/mupbet-project-factsheet_en.pdf

All these projects r requested that GÉANT provide them with connectivity between research laboratories. Some required the creation of a complex, multi-domain network environment, implemented with the MD-VPN service in GÉANT (e.g. XIFI), while others only required static pipes between laboratories to realise their research goals. The nature of the needs of the end users (projects) varied, depending on the different goals and developments realised by the projects. Examples with details of the network setup for research projects can be found in several articles [BEL-2014, XIFI-D52, SEG-2012].

2.3.4 Lightpath Exchange

Open Lightpath Exchanges (OLX) perform a similar function for lightpaths to that performed by the Internet Exchanges that emerged 15+ years ago for the routed Internet [BOS-2012]. Open Lightpath Exchanges allow policy-free switching of end-to-end connections (lightpaths) delivered by multiple network service providers (connectors), using the facility for flexible hand-over for technology, operation and policy-neutral stitching. As described in [BOS-2012], OLX has the following features:

- Open Lightpath Exchanges are *technology-aware* and inclusive of technologies, transparently acting as inter-connector or connector-translator between two or more lightpath-segments.
- Open Lightpath Exchange operation is *lightweight*; supporting traditional network management processes as well as emerging capabilities such as dynamic provisioning.
- Open Lightpath Exchanges are *use-policy-free*; cross-connects are established solely on the basis of bi-lateral agreement between the connectors requesting the cross-connection.
- Open Lightpath Exchanges are located in *carrier-neutral* housing facilities, ensuring reasonable and non-discriminatory access into the facility.

According to [BOS-2012] the following European NRENs are currently investing their efforts in the OLX technology:

- NorthernLight (responsible organization: NORDUnet)
- NetherLight (responsible organization: SURFnet)
- CzechLight (responsible organization: CESNET)
- CERNLight (responsible organization: CERN)
- Marseille Optical Light Exchange Node (responsible organization: RENATER).

It is expected that OLX will emerge in the near future as the technology to provide interconnectivity for NRENs, and as complementary to the GÉANT offer rather than being in competition with it. OLXes may be used in the future to add resilience and richer connectivity, just as Internet Exchanges do for IP peerings. It is foreseen that OLX may comprise a substantial element of the future GÉANT architecture and roadmap.

2.4 Summary of New Requirements for NREN Architectures

Evidently, 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 making 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 unpredictability 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.
- Ability to distribute timing information throughout the network.

Based on these requirements, the new network architecture supporting cloud and mobile cloud services should provide the functions shown in Table 2.1 below.

Function	Description
Dynamic bandwidth allocation. Aggregated granularity	Dynamic on-demand setup of network connectivity between cloud sites with QoS guarantees. Bandwidth allocated based on a set of applications from a given site.
Dynamic bandwidth allocation. Application granularity	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.
Converged infrastructure supporting integrated wireless and wired high-capacity optical networks Integrated control and management of wired and wireless technologies	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 + compute infrastructures Integrated control and management of network and IT resources	The new architecture must support integration of network and computer technologies to provide unified services to end users.
QoS guaranteed service orchestration	Service orchestration across multiple technology domains (mobile, optical, compute) is necessary to enable provisioning of new services to users seamlessly and on-demand. (Basically this provides QoS to the previous two points.)
Cloud and photonic exchange points	New exchange points, extending the concept of Internet eXchange, should be designed to enable the establishment of, e.g., an ad-hoc InterCloud federation between cloud and network providers.
Sharing the spectrum	Sharing and exchange of resources are the critical features to be implemented in order to create a networking environment uniquely tailored to the needs of researchers. It is not necessary to keep the extensive peering fabric if established lightpath infrastructure is available or may be obtained at a minimal cost, thus providing direct links to Internet exchange points. GÉANT Open, GLIF or Open Lightpath eXchange may serve as enablers of such lightpath services on an international scale. Brokerage service should be provided by NRENs and GÉANT. Spectrum can be an asset for spectrum federations.
Capacity dimensioning	Capacity dimensioning of the core network must take into consideration the fact that during peak periods the additive traffic load due to high-speed mobile data backhauling may scale to multi-Gbps speeds.
Peering with the commercial Internet	The NRENs' network infrastructure should be offloaded from carrying large amounts of data – the economics of sustaining peering with the commercial Internet close to the interconnection point of the aggregation network and the NREN network should therefore be investigated.
eduroam expansion Backhauling eduroam traffic in research networks	eduroam access should not be limited to campuses and can be provided in wider areas without any significant cost to the research community. Third-party WiFi infrastructure can be successfully used for eduroam access outside campuses, with benefits for the research and education community, and National Research and Education Networks should consider promoting eduroam to WiFi providers and aggregating eduroam traffic from third-party WiFi infrastructures.

	In the simplest proposed scenario, the NREN is only responsible for the authorisation of users and does not participate in the data transmission. In the more complex scenarios, the NREN backhauls eduroam traffic itself.
(High-) Precision Timing functionality	The network architecture and technologies should allow distribution of exact time information originally based on atomic clocks. This includes transmission of time and synchronisation of local repositories.

Table 2.1: Summary of collected requirements for the new GÉANT architecture

3 Network Technology Enablers

This section discusses the emerging technologies and tools that NRENs will likely need to consider incorporating given short-, medium- and long-term outlooks. The previous section highlighted a number of requirements for the next-generation NREN infrastructure mainly from a user perspective; in this section, a subset of these future technologies are described and any challenges in terms of their utilisation with respect to the requirements are identified. This work focuses on network technologies and elements and does not address issues related to storage and computing resources, which are covered by other activities within GN3plus.

Section 3.1 outlines the different paths to achieving bit rates beyond 100G, and further how these technologies map to the roadmaps of different vendors. It provides an overview of current trends, and discusses how and when the needed technologies are expected to be available. Cost sharing for the most expensive parts of the infrastructure is highlighted as a possible way of reducing operational and capital costs.

Section 3.2 focuses on the optical spectrum and the results of the collaborations with the REACTION and MOMOT Open Call projects and discusses requirements for the sharing of resources, for example through Open Lightpath Exchange.

Section 3.3 continues this topic with a discussion of control tools and technologies for managing the spectrum, and specifically of how Software Defined Networking can apply to the lower layers in the network.

Section 3.4 focuses on the Open Call project IRINA, and how it relates to the NREN community. In the IRINA project the TCP/IP reference model is replaced by recursive Inter Process Communications (IPC). Precise timing distribution was inherent in SDH transport networks, but for future technologies this functionality will need further attention.

Section 3.5, evaluates the technologies (mainly PTP) for supplying time information distribution.

Section 3.6 describes the typical technology sets currently available at NRENS as well as those that will likely be available in future. It provides an overview of the possible handles and tools that are available to operators to integrate the recommendations provided in section 4.

3.1 Technologies to Enable High Capacity

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 current growth rates in capacity requirements of between 40% and 60% per year, given both a conservative and an aggressive estimate, this 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. Trends in the physical layer beyond 100G including research directions and vendor roadmaps are examined below to provide an overview of the high-bit rate architectures that are possible in the short-, medium- and long-term.

While some of technologies that will be used to make the next leap in optical transmission rate are enhancements of the technologies already used in 100G equipment (e.g. advanced modulation formats, coherent detection, FEC), others are innovative (e.g. the necessity for integration of flex-grid, super-channels, and new multiplexing schemes).

3.1.1 Enhanced Modulation Formats

The demand for new modulation formats for 100G+ transmission originates from the limitations of the modern electronic base. Making the next step in transmission speed to 1T using 100G modulation formats (for example, PM-QPSK) would require the use of 320 Gbaud systems with electronics capable of laser modulation with a 320 GHz frequency. This is very challenging and currently possible in practice only in experimental demonstrations, with the prospect of its being in production at the earliest in 10 years' time.

However, in order 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), and PM-64QAM (2 x 6 bits per symbol), in conjunction with coherent detection. Adding DSP and DAC (Digital Analog Convertor) to a transmitter allows these complex signals to be generated without problem.

This approach is very efficient, as it can keep baud rate low while the information rate is increasing, as more bits are transmitted in each time slot. However, two factors limit its efficiency: the need to achieve higher optical signal-to-noise ratio (OSNR) and non-linear impairments of fibre. In view of this, transmitters with the same power can be used for shorter reach when using modulation techniques with a higher bit-per-symbol value.

3.1.2 Coding and Forward Error Correction

Forward Error Correction is a coding technology (standardised for Optical Transport Networks in G.709) that improves error performance on noisy links, and is a key technology for extending optical reach by detecting and correcting bit failures which occur through transmission over optical fibre. With the increasing demand on channel capacity, FEC becomes a key tool to increase this capacity while at the same time maintaining optical reach.

FEC has evolved from classic hard-decision codes to concatenated codes and to soft-decision FEC. The FEC encoder at the transmitter side adds n-k redundant check bits to the information bits, constructing an n-bit codeword. After the codeword is transmitted to the receive end over a channel, the FEC decoder detects and corrects bit errors during decoding – if the errors are within the correction range [FECHua]

The ratio of the FEC over the payload decides the decoder's ability to correct bit-fails. A higher degree of overhead gives a higher degree of correction, but this is not linear. Soft-decision FEC is a new technique that provides a higher coding gain. Figure 3.1 shows the evolution of FEC for optical communication [FECHua]. More advanced FEC gives better BER performance, but will tend to increase the complexity of the system as well as the cost. Therefore, the right choice of FEC technique is crucial in order to reduce equipment cost while at the same time attaining the best possible performance.

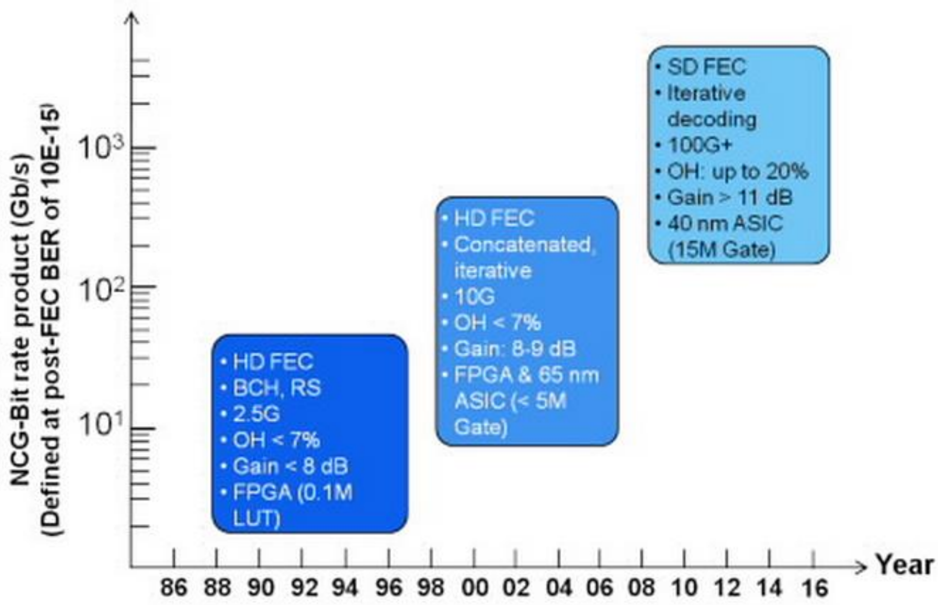


Figure 3.1: FEC evolution for optical communication [FECHua]

A good description of different FEC techniques can be found in these articles: [FECHua, BRINK2012, FEC-INFINERA].

3.1.3 Super Channel, "Subcarrier Multiplexing and Spacing" and Flexible Frequency Grid

One fundamental way of expanding network capacity is to improve the spectral efficiency of transmission systems that traditionally operate in the C band. Super-channel is an emerging technology that aggregates traffic into a wider channel with multiple closely-spaced subcarriers. Actual spacing of subcarriers is dependent on transmission modulation and technology design. For example, optical OFDM utilises optical subcarriers with spacing equal to multiples of the inverse of the symbol period [GAO2012], N-WDM has subcarriers spaced close or equal to the symbol rate with limited inter-subcarriers crosstalk [BOSCO2011], and Infinera 500GB/s super-channels work with 37.5 GHz subcarrier spacing []. Special subcarrier polarisation multiplexing is now widely used in 100G PM-QPSK, allowing transmission of two signals at orthogonal polarisations at the same frequency [IP2012]. The better spectral efficiency, and therefore network capacity, is achieved by aggregating subcarriers, utilising signal orthogonality and polarisation multiplexing.

The original fixed grid was constrained by technological limitations in terms of the central frequency stability of the laser and filters used. The main drawback of the fixed grid arrangement is that the intra-channel part of the spectrum is filtered out by all ROADMs or similar components on the transmission path. This unfortunately comprises a significant part of the available spectrum which is lost, for example almost 29% of 4.85 THz available in the extended C band (we consider 50 GHz grid and 0.28 nm channel bandwidth at FWHM). To limit this waste and support flexible allocation of super-channels (in terms of bandwidth and central frequency) the nodes need to be upgraded. The use of super-channels implies a need for improved flexibility of the network nodes. These network elements are grid-less, or support flexi-grid technology. A flexible approach to optical backbone networking was also defined by ITU-T Recommendation G.694.1 0 and extended with flexible grid support in G.872 [G.694.1]. The idea behind the ITU-T recommendation is an increase of granularity of the frequency grid. Granularity of channel width is reduced four times from 50 GHz to 12,5 GHz, and central frequency tuning from 50 GHz to 6,25 GHz. Central frequency is anchored to 193,1 THz and is defined by the following expression:

$$f[THz] = 193.1 + n \times 0.00625$$

While channel width around central frequency is given by:

$$b_f[GHz] = 2 \times m \times 6{,}25$$

Where n is the integer number including zero and m is the positive integer greater than zero. The main benefit of this is that it allows flexible usage of the spectrum, for example with some channels using 12,5 GHz and others using 50 GHz, thus allowing a mix of super-channels, 100G PM-QPSK and legacy 10G IMDD. The downside to this are higher requirements in terms of transceiver wavelength stability.

The dynamic assignment and decommissioning of various super-channels may lead to spectrum fragmentation similar to the fragmentation on an electronic hard drive. The small bits of spectra left work against the system's overall spectral efficiency, so spectrum defragmentation is needed. Several methods of spectrum defragmentation were proposed for either traffic interruption or transceiver tunability: the "Re-Optimisation" method interrupts traffic during spectrum defragmentation [PATEL2011]; the "Make-before-break" method prevents traffic interruption, but requires more hardware resources [TAKAGI2011]; the "Push-and-pull" method relies on tunability of system transceivers to aggregate the occupied spectrum [CUGINI2013]; and the "Hop-tuning" method makes use of the fast-tuning ability of transceivers to fit traffic spectrum at a suitable place with a maximum of a millisecond traffic interruption [WANG2013]. System defragmentation becomes a challenge with the scaling of the network and number of bypassing traffic through network nodes, as no efficient protocol and speed-agnostic way yet exists of signalling wavelength change.

3.1.4 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 subcarriers 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. subcarriers 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 minimal spectrum frequencies sufficient for signal reconstruction on the receiver side according to the Nyquist rate rule, and therefore reduces a wavelength spectrum width and potentially increases the number of waves in a given spectrum band [GAVIOLI-2010].
- OTDM (Optical Time Division Multiplexing). Sub-carriers in OTDM occupy different time-slots which should be synchronised by sharp impulses of ultra-short duration of about 5 ps and repetition in the 5 – 20 Ghz range [TUC-1988].
- SDM (Space-division multiplexing) is a new technology that uses multicore fibre (MCF) or few-mode fibre (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.
- TFP (Time-Frequency Packing). In TFN signalling, pulses can be packed closer than the Nyquist limit without performance degradation. This technology has been field-trialled by CNIT over the live GÉANT network within the framework of the GN3plus project [COFFEE].

3.1.5 Vendor Developments

The enhanced and emerging techniques described above are currently being researched at various telecom vendors' R&D departments and university research centres. The information gathered from different vendors gives the following outlook in terms of their planned steps in the move towards emerging 100G+ equipment:

- 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 fit into the existing 50GHz grid and hence will not need upgrading except for the transponders parts of network gear. This feature was expected to be in GA in 2014 so that NRENs could double the speed of their new 100G backbones as of 2015.
- Transmitters with DSP and DAC capable of shaping spectrum. Such transmitters are already available as part of the 100G equipment of some vendors and are expected to become a common feature soon. This functionality is required to support sophisticated modulation formats and shape spectrum for the creation of spectrum-efficient super-channels.
- Flex transponders – flexible in modulation format and bandwidth of signals.
- Flex-Grid Colourless/Directionless Multiplexors.
- Support of 400G, 500G, 800G and 1T super-channels with a space narrower than 50 GHz (38-40 GHz) between subcarriers, and therefore flex-grid ready. Nyquist WDM and OFDM are the first choice in multiplexing techniques.

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

3.1.6 Impact on NRENs

Many NRENs have just upgraded their optical backbones to 100G rates, which therefore do not need immediate upgrading to 100G+ speeds. However, some directions of backbones might experience shortages of bandwidth in the short-term, and a good solution for this could be 200 Gbps transponders working within the existing 50GHz grid. In this scenario it is likely that only the transponders would need replacing and not the mux and WSS modules, which could be achievable within a 1-year time frame.

Further increase of NREN optical infrastructure speed to 400 Gbps and 1 Tbps super-channels would involve more changes in the network equipment, as this upgrade requires flex-grid support not only in transponders but also in multiplexors and WSS cards. The availability of such equipment for production deployment is expected in 3-5 years' time that corresponds to the expected time of the need in such backbone speed for big providers.

3.2 Enablers for Spectrum Sharing

Today, optical networks are based on a set of optical components with fixed and predefined HW and SW that perform a specific task. The advantage of fixed optical networking is its simplicity. However, it is not efficient enough to make the most of the available optical spectrum resources.

Given the ever-increasing demand for capacity, and the fact that limited capacity is available on optical fibre and optical networks in general, it is important that optical resources are exploited to the best advantage. The emerging flexible optical networking and the technologies that enable it play with a set of optical variables in order to make the most of optical resources.

The benefits of optimising the use of the available spectrum are twofold: in the first place, it enables single entities to optimise capacity on their own infrastructure, and at the same it contributes to establishing a common framework based on an understanding of the impact of sharing the spectrum, which in turn helps promote Open Light Exchanges.

3.2.1 Building Blocks for Efficient Spectral Usage

Figure 3.2 shows the three building blocks required to enable flexible optical networking [TOM-2014]. The most basic building block comprises the physical layer technologies and subcomponents. These consist of flexible transceivers, a flexible frequency grid and flexible switches. The second important building block are the methodologies for the design and optimisation of the flexible optical network, while the third is a control plane mechanism that collects optical data from the physical layer and computes and adjusts the physical layer parameters for optimised usage.

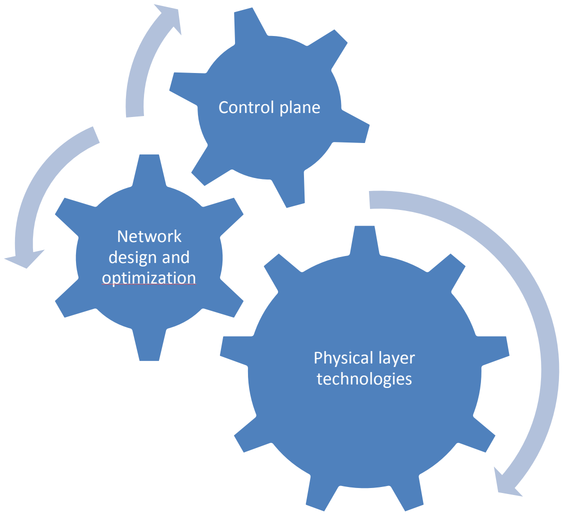


Figure 3.2: Three main building blocks of Optical Flexible Networking

The physical layer technology enablers are flexible transceivers (also called Bandwidth Variable Transceivers - BVTs), the flexible frequency grid and flexible optical switches.

Fixed and Flexible Transceivers

The components of fixed transceivers use a specific Symbol rate, a fixed number of subcarriers, fixed frequency spacing, fixed modulation format and fixed coding (FEC), and only work between specific source and destinations ports. Flexible transceivers, on the other hand, consist of components that can be switched between different Symbol rates, modulation formats, types of FEC and numbers of basic optical spectrum steps (12.5GHz), as discussed in section 3.1.3. Figure 3.3 shows the relevant components of a flexible transceiver.

In flexible transceivers, an even higher degree of flexibility can be achieved with the introduction of a sliceable transceiver. The subcarriers of these transceivers are grouped in a number of independent super-channels with different destinations. Sliceable BVT (SBVT) generates several optical flows routed on several specific portions of the optical spectrum, each directed to a different destination. Several techniques to achieve this functionality (SBVT) are discussed in [SAM-2015].

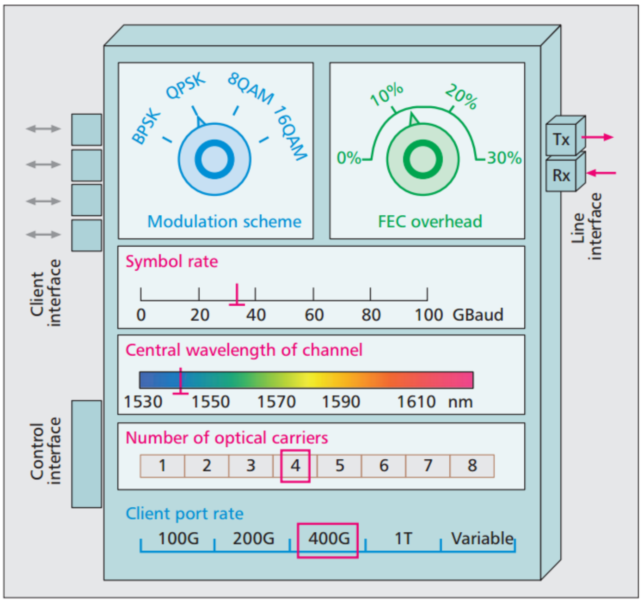


Figure 3.3: Flexible optical transceivers and tunability

Flexible frequency grid

A flexible frequency grid allows the allocation of a number of 12.5GHz slots of the spectrum as described in section 3.1.3.

Optical switching

A more flexible and scalable approach than handling total fibre capacity is optical channel switching. Traditional DWDM fixed grid systems utilise 50- or 100-GHz channels. For use in ring topologies of these fixed grid systems, a traditional two-degree ROADM (in the East and West direction) has been developed. These ROADMs offer two basic functions for fixed DWDM channels: they can simply be passed with equalisation or dropped and simultaneously added.

In order to create more complex topologies than point-to-point or ring topologies, a ROADM with a degree greater than two is necessary. The technology that supports advanced topologies utilises Wavelength Selective Switches (WSS). WSSs allow to route single or groups of lambdas from composite input to arbitrary composite output or vice versa.

A typical WSS comprises a diffraction grating-based free-space optics part and an arrayed switch engine [JDSU-WSS]. Signals pass through the front-end optic part of the WSS where they are magnified and collimated before entering a dispersive element. The dispersive element demultiplexes signals to separate wavelengths and the individual wavelengths are then directed into the switch engine.

Different technologies exist for implementing switch engines. These include, among others, Binary Liquid Crystal (LC), Liquid Crystal on Silicon (LCoS), and MEMS mirror arrays [].

As regards the second main building block of flexible optical networking (FON), i.e. the network design and optimisation aspect, in order to fully utilise the flexibility on the physical layer and optimise the network, a new network planning and design model should be developed. This is further discussed in sections 3.2.2 and 3.2.3.

The third main building block of FON, the control plane, enables efficient resource provisioning and the automation of the resource allocation and reallocation process. A possible solution using Software-Defined Networking (SDN), a concept that has gained much overall momentum, removes the control plane complexities from the HW and implements them in the in SW (in this document the terms control plane and SDN are used interchangeably). This functionality is further discussed in section 3.3.

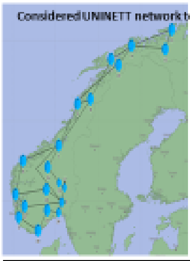
3.2.2 Joint Collaboration with the REACTION Open Call Project

The REACTION project [REACTION] focused on designing novel routing and spectrum allocation (RSA) algorithms in the context of flexible optical networks. On the data plane, the project developed an enhanced bandwidth variable transponder supporting 1 Tb/s multi-carrier transmission into a Sliceable BVT (SBVT) transponder, capable of creating multiple optical flow units that can be aggregated or independently routed according to traffic requirements. On the control plane, it developed a solution that relies on a GMPLS-based distributed control plane with a Path Computation Element (PCE) architecture.

JRA1 T1, in collaboration with the REACTION project, carried out a simulation based on UNINETT´s optical network in order to demonstrate the FON´s capacity to extend its lifetime by introducing some minor changes.

The current network includes point-to-point WDM links. Traffic is typically electronically terminated in the most relevant network nodes while nodes introducing a limited amount of traffic are equipped with fixed optical add-drop multiplexers (OADM). The current status of the network shows a network utilisation of up to 40 wavelengths, each operated at 10Gbps. In the last few years, a growth in traffic of around 30% per year has been recorded, which is expected to continue in the foreseeable future. Given this rate of increase, 10Gbps-based WDM technology will soon exhaust available spectrum resources. For this reason, 100Gbps line cards are considered for provisioning new traffic requests (the setup of the first 100Gbps lightpath was recently completed). In addition, the introduction of ROADM technologies, where optical bypass is implemented in intermediate nodes, is also considered. In the study, the UNINETT network is entirely re-designed taking into consideration the use of 100Gbps ROADM-based technologies. In particular, scalability performance is assessed by evaluating the fibre exhaustion time when either the fixed or the flexible grids are applied.

Figure 3.4 shows the network topology and the result of the upgraded network scenario based on 100Gbps ROADM-based technologies, both with and without the introduction of the flexi-grid functionality. The table on the left shows upgrade scenario 1, where ROADM and fixed 50GHz grid spacing is used and where the percentage of link utilisation at year 7 would be almost equal to 100%. The table on the right shows upgrade scenario 2 where ROADM and flexi-grid is used. The percentage of link utilisation at year 7 in this case would be reduced to 84%, giving an improvement of 15%.



The current status of the network shows a network utilization of up to 40 wavelengths, each operated at 10Gb/s.

LINK OCCUPATION PERCENTAGE																					
From \To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	From \To
1			0			90	65	18								98					1
2					33	90							50	25							2
3	0												45	30			98			15	3
4									60	23	13	13									4
5		33																15			5
6	90	90																			6
7	23							0		65											7
8	60						0		18												8
9				18				60													9
10				65			23														10
11				13								2.5									11
12				13							2.5										12
13		45	50																		13
14		30	25																		14
15																98	98				15
16	98														98						16
17			98												98						17
18					15														15		18
19																		15		15	19
20			15																15		20
From \To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	From \To

Upgrading scenario 1, ROADM and fixed 50GHz grid spacing: Percentage of link utilization at year 7, upon failure recovery (failed link node1-node3)

LINK OCCUPATION PERCENTAGE																					
FROM \ TO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	FROM \ TO
1			0			84	58	17								92					1
2					30	83							47	23							2
3	0												43	28			94			11	3
4									56	19	11	7.5									4
5		26																15			5
6	83	84																			6
7	19							0		58											7
8	56						0		17												8
9				17				56													9
10				58			19														10
11				9.4								3.8									11
12				9.4							1.9										12
13		43	47																		13
14		28	23																		14
15																94	92				15
16	94														92						16
17			92												94						17
18					11														15		18
19																		11		15	19
20			15																11		20
FROM \ TO	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	FROM \ TO

Upgrading scenario 2, ROADM and flexi-grid and 100G over 37.5GHz:
Percentage of link utilization at year 8, upon failure recovery (failed link node1-node3) in the case of flexible grid network

Figure 3.4: The simulation result from REACTION project

This shows that even introducing partial flexibility (only using flexi-grid functionality) would already result in an improvement in network utilisation.

3.2.3 Alien Wavelengths in NREN Networks

The Alien Wave (AW) concept was introduced already a decade ago in the context of optical transmission systems interoperability. AW was first deployed in subsea systems where the systems of two different vendors had to be combined in order to overcome the challenges posed by extreme distances. These were special cases that were rather rare in the telecommunications world. Nowadays, NRENs are interested in types of networks with very different parameters than those of most telecommunications operators or ISPs. NRENs connect several locations across a country, but users of their networks require state-of-the-art parameters and certain special features rather than huge capacity. Therefore NREN networks generally have considerable free spectrum that could be shared or even dedicated to AW. NRENs also provide international connections for their user community. Some connections and peering may be realised at higher layers through MPLS or VPNs, but there are new applications that require photonic services and end-to-end light paths without regeneration. NRENs can therefore be serious candidates or even pioneers for the use Alien Wave.

AWs play a very important role in flexible networks. AWs can give NRENs greater freedom in the selection of transport technologies for their networks, resulting in a reduction in their photonic transmission costs, which are often significant. Once the photonic layer supports Alien transmissions, many cost-effective third-party networking solutions may be implemented into existing transmission systems, as the NREN will not be locked in to using transponders and equipment from a single vendor. The greater selection of transport technologies offered by multiple vendors thus available to NRENs is likely to result in a considerable reduction in their CAPEX for new investments.

Moreover, AW allows unused capacity to be shared with other interested parties, which may significantly reduce overall network costs. With current 100G technology giving about 8.8 Tbps capacity per single fibre pair [VOJ-2014], much extra bandwidth remains available for sharing.

New technologies are also emerging that transfer accurate time and ultra-stable frequency transmitted over WDM systems as AWs. One such technology is WhiteRabbit [WHITE-RABBIT].

However, despite its many advantages, AW poses some engineering challenges in its planning and monitoring. Planning of AWs especially needs to consider guard bands to minimise interferences with existing traffic as well as the optical reach of projected AW. The proper monitoring of incoming light from alien channels is also crucial.

Some progress in this respect was made by a GN3plus Open Call project that designed a Multi-Domain Optical Modelling Tool (MOMoT) [MOMOT]. The MOMoT project was created to address both the planning and setup of AWs: first, by investigating the need and interest for AWs within the community, and then developing a modelling tool and user interface to assist NRENs in planning and setting up AWs across their networks.

AWs are a relatively new paradigm in the optical networking world. Not many references can be found on the topic, whether in academic or industry documents. The idea typically finds support among network operators, but attracts criticism from vendors of WDM equipment. Within the GÉANT community, the topic of deploying AWs has been under discussion for about half a decade, with tasks focused on experiments, field trials and evaluation of the practical perspectives of deploying AWs as a service.

The MOMoT project focused on designing and developing a tool for the basic evaluation of AW deployment scenarios. In particular, the tool takes a set of input parameters, such as those relating to the current state of the network, together with parameters related to existing channels deployed, and evaluates the impact an AW deployment will have on the existing wavelengths and the newly inserted AW. Such a tool serves to perform a “back-of-an-envelope” calculation and evaluation of the feasibility of deploying an AW in a given network scenario. The tool was developed with speed and effectiveness in mind, so that rather than having it perform fully detailed and time-consuming multi-channel simulations, a safe-zone approach was applied. The tool makes a quick assessment of multi-channel effects, without a deep simulation, and warns the user of any likely implications.

A survey carried out by CESNET, of NRENs that reported use of CBFs according to the 2014 GÉANT association Compendium, found that several of the interviewed NRENs from the GÉANT community had experience in the use of AWs. Seven of the 12 NRENs asked were using alien wavelength. Three had successfully tested or were set to deploy AWs in the near future. Two of the NRENs additionally reported bandwidth sharing. The results of this survey are shown in Table 3.1 below.

Country	NREN	Alien Wavelength Used	Alien Wavelength on CBF	Additional Info
Belgium	BELNET	NO	NO	
Czech Republic	CESNET	YES	YES	More technologies used: CzechLight and Cisco

Denmark	DEIC	NO	NO	Tested
Finland	FUNET	YES	NO	White rabbit for time-transfer services
France	RENATER	YES	NO	3rd party signal handled by OADMs
Hungary	NIIF	NO	NO	Ready for alien wavelength, but no real demand currently
Lithuania	LITNET	YES	NO	
Netherlands	SURFNET	YES	YES	
Poland	PIONIER	NO	PLANNED	Have tested before, plan to implement AW to SURFNET soon
Portugal	FCCN	NO	NO	Convert the lambdas to grey colour
Sweden	SUNET	YES	YES	Mixing several vendors equipment and are utilizing alien wavelengths
Switzerland	SWITCH	YES	YES	Specifically asked for alien wavelength support in public tender for the optical transmission system.

Table 3.1: Alien spectrum survey - Alien spectrum in NRENs, i.e. light in fibre from devices by different manufacturers without transponders

In the MOMoT project [MOMOT], the field trial between DANTE (now GEANT Limited) and SURFNET is used to validate the tool and serve as comparison with the commercially available VPItransmissionMaker. In the field trial, two Infinera channels are transmitted through the SURFNET Ciena equipment.

The MOMoT tool developed is compared with the field trial characterisations, and the curvature of the modelled BER with respect to receiver attenuation perfectly matches the results from the field trial. Also, the results from the analytical method used in MOMoT are in line with those from the "split-step" method used in the commercial VPItransmissionMaker. These results show that the MOMoT tool is suitable for performing assessments of the quality of Alien Waves channels for QPSK and coherent detection.

3.3 Tools for Controlling Wavelengths

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.

This section is in no way intended to provide solutions and developments for the existing work on SDN, but is included to illustrate how the transport network can adapt to SDN concepts and 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 an increasing need for convergence, from Data Centre to telecom operator networks. 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, 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, to support 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 the optical network for telecom network operators and Data Centre providers, software platforms and implementation, transition of existing network solutions, optimal exploitation of the 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), control protocol (e.g. OpenFlow – OF), or routing protocol (e.g. Border Gateway Protocol – BGP). In this context, SDN is becoming an established trend in the operation and management of today's Data Centres and local networks, which require a high degree of dynamicity. SDN has the potential to simplify network operation at the IP and Ethernet layers. Many layer 2/3 equipment providers support 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 SDN's features. Recent advancements achieved through Flexible Optical Networking and the introduction of flexibility in the optical domain are expected to provide the required functionalities to enable transport SDN.

Transport SDN is a subset of the SDN architecture functions, comprising the SDN architecture components – Data Plane, Control and Management Plane – and the part of the Orchestrator that are relevant to the TN.

In September 2013, OIF published a document describing the requirements on TN to support SDN features, services and applications based on the OIF SDN reference architecture [OIF-2013]. 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-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 as well as change their operational process, which may delay the deployment of Transport SDN solutions (3-year horizon). The initial cost will also be a challenge for operators making the next step towards an SDN-enabled transport network.

It is noted that the development of simple and effective control plane tools is crucial if the full benefits of flexibility on the physical layer described in section 3.2 are to be realised.

3.4 Flexibility Enabler for the Higher Layer

JRA1 Task 1 worked in close collaboration with the Open Call project IRINA [IRINA], which investigates the potential benefits of Recursive InterNetwork Architecture (RINA) specifically for the GÉANT and NREN environments. RINA is a clean-slate approach to network architecture design aimed at replacing the current Internet architecture, which is based on a TCP/IP stack of protocols.

Basically, RINA does away with the well-known TCP/IP reference model and leverages the inter-process communication (IPC) concept, where two applications on different end hosts communicate by utilising the services of a distributed IPC facility (DIF). A DIF is an organising structure – generally referred to as a "layer." The functions constituting this layer, however, are fundamentally different from those of the IP and TCP layers. A DIF can execute a full spectrum of network functions including routing, transport and management. A RINA network is a hierarchy of DIFs (layers) where each DIF represents the same set of IPC objects but performs different functions depending on its scope and configuration. The number of DIFs (layers) is not fixed and depends on a network's complexity and scale. RINA makes for a more homogeneous network structure as it uses of the same building blocks – DIFs – but which work differently depending on their specific functionality at each layer. Each DIF invokes RPC objects of the lower-layer DIF, so that RPC objects are invoked recursively through layers, hence the definition of "recursive" architecture.

Besides in its simplicity, the potential benefits of the RINA approach compared to current Internet architecture are to be found in the areas of QoS, policy-based routing, naming and addressing, efficient application development, application mobility, reliable and fast data transfer, native multi-homing, and security. In other words RINA addresses many of the most common Internet problems.

The IRINA Open Call project performedan analysis using SWOT and PEST techniques in order to assess and evaluate the impact of deploying a new network architecture such as RINA within the context of the NRENs and GÉANT.

IRINA drew up a brief summary of the estimated current and future NREN requirements, subdivided into two sections, namely service requirements and technical requirements. Some typical NREN service expectations include Network as a Service (NaaS), security, authentication, collaboration tools, multimedia content repositories and eLearning activities, while technical requirements include QoS, network virtualization, mobility, multi-homing, scalability, security and network management.

As a second step in the analysis phase, the project conducted a survey among NRENs in order to assess these requirements. The results of the survey were used to shape the project's use case, focusing on three aspects: the network topology comprising the NREN networks interconnected via the GÉANT backbone, the services currently deployed on these networks, and the estimated impact of future requirements on the selected services.

The use case considered three classes of NRENs (Large, Medium and Small) interconnected through GÉANT. These NRENs deploy three key services: video conferencing, VPN services, and cloud storage, with varying degrees of penetration. The key service that is analysed is the SeeVogh [SeeVogh] distributed video conferencing application. RINA was applied to this scenario, investigating various interconnections between NRENs and Regional Networks, User Networks, Commercial ISPs, IXPs, GÉANT and peering with neighbouring NRENs.

The project conducted a lab trial utilising the IRATI prototype software and a traffic generator, rina-tgen, which supports RPC API and mimics video traffic using the Poisson distribution [IRATI]. When performing maximum achievable bandwidth tests, the shim DIF for Hypervisors prototype outperformed an emulated e1000 NIC by more than an order of magnitude, and the virtio-net NIC by a factor of 3, showing that a simpler and cleaner architecture such as RINA also enables better performance.

3.5 Time Distribution and Inherent Challenges for Emerging Technologies

As explained in section 2, the distribution of time and frequency information is a requirement for a number of applications and therefore poses an inherent challenge for emerging technologies. While some applications, such as audio, video or mobile telecommunications applications, already benefit from a time accuracy in the micro-second range, special ultra-accuracy in the nanosecond range is necessary in other fields, for example sensing, metrology, navigation, geodesy, radio-astronomy, earth survey, seismology, fundamental physics, etc.

Originally, radio waves were used for time (and/or date) frequency dissemination, for example, DCF, TDF, and Time from NPL [DCF-77, TDF-2015, NPL-2015]. These systems have limited reach and are used for broadcasting national time, and their target accuracy is in the order of microseconds. GPS, GALILEO, or GLONASS continue to be used for time distribution despite the fact that now accurate time and frequency can be obtained from Global Navigation Satellite Systems (GNSS) [JIA-2014], and certain protocols for time distribution have been were already in place in the earliest days of the Internet. The oldest of these protocols was *datetime***,** where the server returned an ASCII string containing date and time in human-readable form. Another such protocol was *time*, which was machine readable, and where the server returned 4 bytes interpreted as a 32-bit unsigned binary number – the number of UTC seconds since 1 January, 1900. Both of these protocols are no longer used due to their low granularity of only 1 second.

Two time distribution protocols that are used widely today are:

- The ***Network Time Protocol (NTP)*** [NTP-2015] is the most widely used protocol for time distribution. It serves for general time settings and clock synchronisation in servers, workstations and network devices. The protocol is based on the exchange of two messages. The worst case uncertainty is one half of the round-trip time. Real achievable accuracy depends also on the stability of clocks in both server and client and on the one-way delay variation. In a standard case the NTP accuracy is in the order of milliseconds (in WAN) and hundreds of microseconds in LAN. However, it is possible to reach accuracy in the order of microseconds, assuming stable clock oscillators and hardware support.

- The ***Precision Time Protocol (PTP)*** specified in [IEEE-1588] is similar to NTP but can achieve a sub-microsecond accuracy. It is designed for accurate time synchronisation in LANs or limited range networks. The typical areas of usage are devices that require exact time, e.g. telecommunication devices, laboratory instruments or industrial systems. Although pure software implementations exist, the PTP system assumes hardware support for the best performance. The PTP time transfer system can operate on L2 (e.g. Ethernet frames) or L3 (UDP packets).

As the precision of the above-mentioned protocols depends on information granularity, varying propagation delay and level of hardware support, there is a huge range of accuracy of 9 orders of magnitude between 1 second and 1 nanosecond. As Galileo is currently not yet in service, only GPS can be used for high-accuracy time information. The non-military versions of GPS receivers currently available reproduce a GPS time scale that is metrologically bounded to the UTC time scale. When discussing GPS time accuracy, a distinction needs to be made between absolute accuracy and relative accuracy. Absolute accuracy suffers from a variation in radio signal delay in the troposphere that cannot be easily predicted, and the achievable accuracy is usually off by more than 10 nanoseconds. Relative accuracy (the difference between time signals in two localities) is significantly better and can achieve accuracy in the range of less than 1 nanosecond when using the Common View method (where both receivers observe the same satellite).

Similar or better accuracy can be delivered over networks by the White Rabbit (WR) [WHITE-RABBIT] time and frequency distribution system designed and implemented for CERN's scientific devices. This system enhances PTP to achieve sub-nanosecond accuracy in network connections up to 10 km in length. It utilises Synchronous Ethernet for frequency synchronisation and PTP for timing messages, and is implemented at the hardware level.

The stability of GPS-based PTP time synchronisation over networks has also been investigated in JRA1 over a 10GE Ethernet link between Erlangen and Munich, Germany (a distance of about 200 km). A

PTP grandmaster in Erlangen with GPS receiver delivered time and frequency information over the 10 GE link so that a PTP slave in Munich could synchronise to this reference signal. Various network impairments were then simulated in Munich to see how packet loss and jitter would affect time synchronisation. The results over this 200 km network connection showed that PTP synchronisation over such a distance is possible under normal network conditions and that only extensive delay variations above 80ms or packet loss over 10% would make PTP time synchronisation impossible [].

Most network vendors currently offer PTP support in their routers and switches. Fibre- or lambda-based transmissions can achieve an even better performance in the range of picosecond accuracy and have been the object of increased interest on the part of many laboratories in recent years. At least three NREN operators already transport time and/or frequency in the form of alien waves (CESNET, FUNET and RENATER), and two others (JANET and PSNC) are supporting transport on dedicated fibres.

3.6 Transport Network Architecture Models

In this section, the different sets of technologies typically available at the NRENs are discussed, identifying the various multi-technologies and how they are mapped or "layered". The term "Layering" is used here to intend 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, OTN switching (layer 1), Ethernet and carrier Ethernet switching (layer 2), and routing at layer 3 are considered to be candidate technologies.

The purpose of this investigation is to identify the handles, nuts and bolts that the different technologies offer the network administrator, and which have a direct impact on the implementation of the recommendations set out in section 4.1.

In order to investigate the different possible alternative transport network architecture scenarios, eight different transport network vendors were interviewed and asked their views on transport network architecture.

The common building blocks which all vendors agreed are needed are a packet and routing layer (L3) and 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.

Figure 3.5 illustrates three models for Transport network Architecture. The choice of model will depend on the size of network and the NREN´s (or service provider's) service portfolio

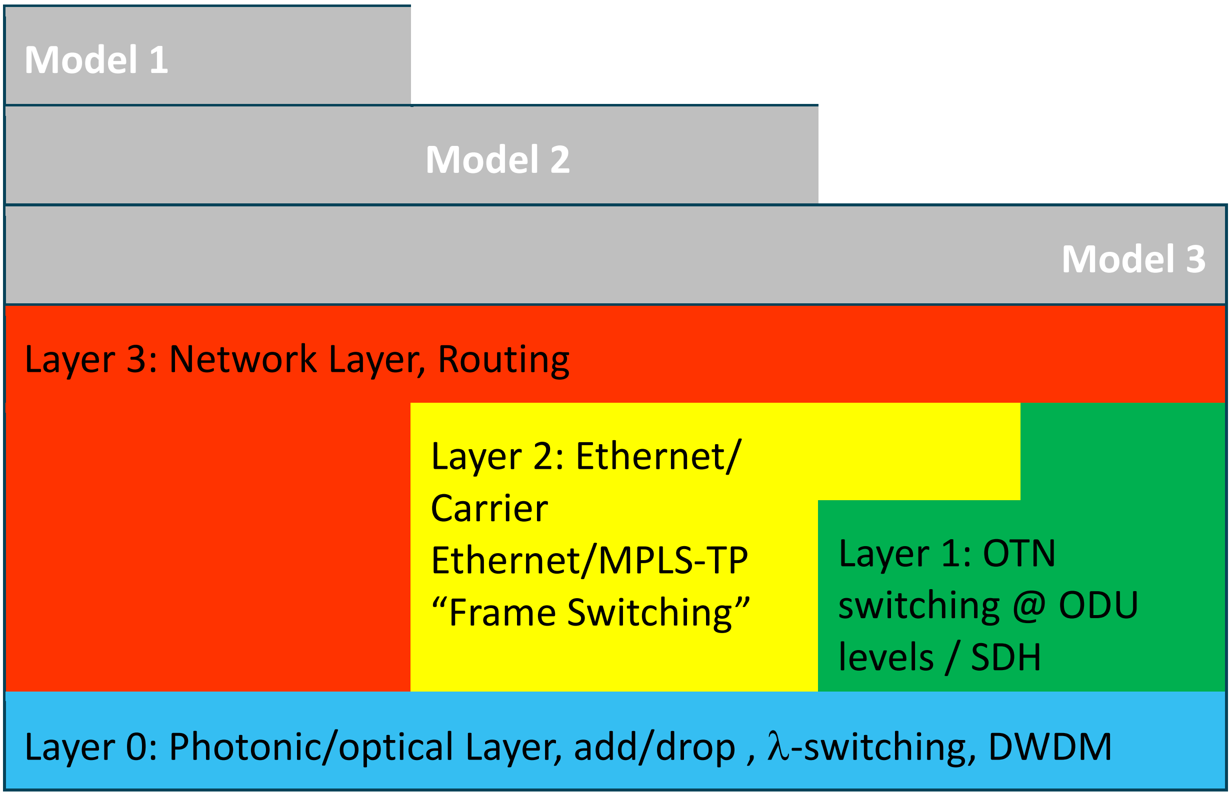


Figure 3.5: Transport Network Architecture Models

Depending on an NREN’s chosen technologies, different handles and configuration possibilities are given for the different layers. These handles include, among others, lambda switching using ROADM, spectrum, fibre, ODUs, Ethernet and IP. Any resource sharing possibilities are also identified. These three different possible transport network architecture models are discussed in detail below.

3.6.1 IP over Optical

The first model is the “IP over optical” approach. The concept is based on coloured[1] router interface implementation only over DWDM and photonic layer. In this model there is no need for an additional intermediate layer to support services, whether or not they are circuit-based. Packet-over-optics models have been under discussion by vendors and operators for a few years now, but it seems that their position is no stronger today than it was when such discussions began.

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 router level as at photonic level.

[1] Coloured interface refers to interfaces in a DWDM system between the router interface and the multiplexer

3.6.2 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 between 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 lower the 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 keeps incoming traffic as a packet and the grooming, aggregation and switching is performed at layer 2 either with native Ethernet or with MPLS-TP. [TRANSMODE]

3.6.3 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 utilisation of DWDM pipes, easy and fast deployments, diversity of paths, and restoration potential [ROY-2014]. With emerging super-channel 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 are 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, thus significantly reducing the forwarding services that the core routers perform.

4 Functional Network Architecture Layering

Based on what has been previously outlined, a functional architecture layering aimed at supporting the needs of the NRENs for a variety of services, including QoS-guaranteed, seamless and coordinated cloud and mobile cloud services across heterogeneous domains, is proposed. This architecture is based on the Infrastructure as a Service (IaaS) paradigm and includes the Physical Infrastructure, Physical Infrastructure Management, the Control Layer and the Service Orchestration Layer, as described below.

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: The infrastructure management layer is responsible for providing the management of physical resources and enabling capabilities such as supporting sharing of resources. It can therefore support converged management functions (e.g. monitoring, abstraction, discovery, or lifecycle management) for 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 a paradigm such as Software-Defined Networking (SDN). 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: 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 users' requirements as specified by the respective SLAs.

An overview of the proposed architecture is shown in Figure 4.1.

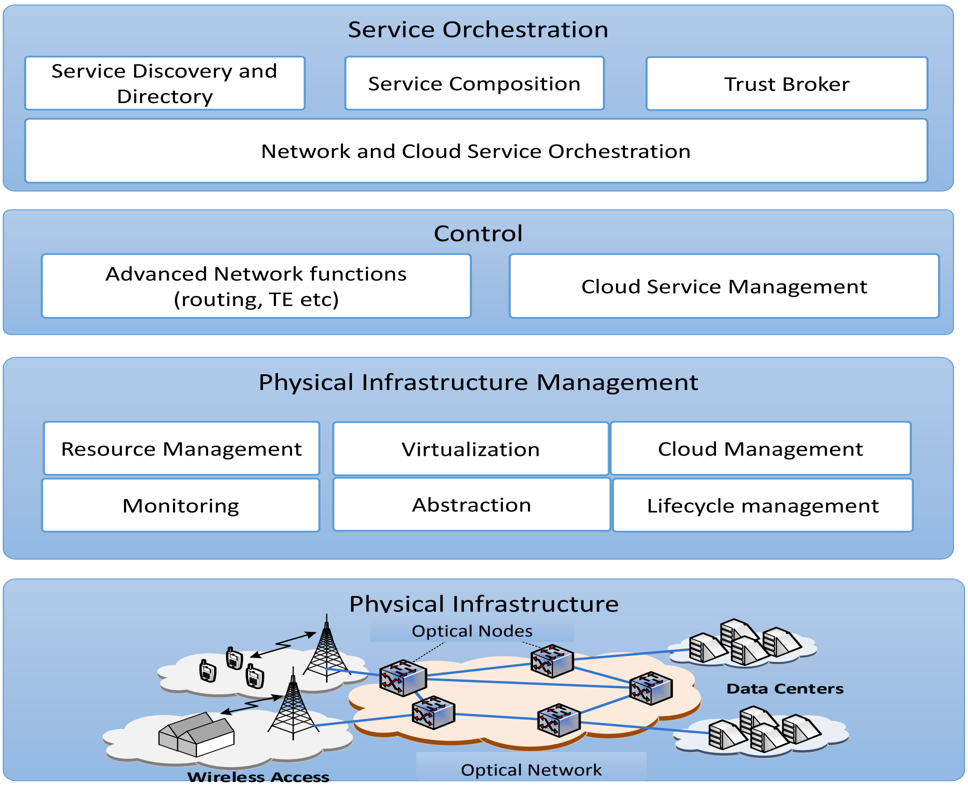


Figure 4.1: Proposed Architecture

The proposed functional architecture aims at overcoming the limitations of current architectures where control and data planes are tightly integrated, and support a set of predefined, proprietary network functionalities and protocols configured via vendor-specific interfaces. Instead it promotes a technology agnostic approach, where data, management and control layers are decoupled, facilitating interoperability, agility and adaptivity of the heterogeneous physical network infrastructure and its protocols, supporting fast delivery of novel services in a globally optimal manner. This will enable an evolving multi-vendor and multi-technology environment capable of accommodating challenging infrastructure scalability requirements. The proposed architecture also aims to guarantee compatibility with legacy technologies allowing co-existence and interoperation with currently available solutions in terms of technology, protocol and network management. In this context, cross-layer interfaces are key to ensure cooperation and interaction between the different architectural layers.

4.1 Physical Infrastructure Solutions Supporting Cloud and Mobile Cloud Services

In order to provide user access and connectivity to growing numbers of end devices and ensure that required services are supported, there is a clear need for an infrastructure integrating the heterogeneous optical, wireless, access, metro and core domains to seamlessly interconnect any users, any data sets and any end-devices (from data centres to sensors). The physical infrastructure described above involves a variety of heterogeneous technology domains that need to interact and interoperate in order to enable end-to-end service delivery.

As regards optical networks, recent technological advancements enable flexible, efficient, ultra-high data rate and ultra-low latency communications for Data Centres and cloud networks. Optical transmission solutions offering a high data rate and low latency have been demonstrated as field trial deployments of 400Gb/s channels [LAVI-2015], while research on more than 1 Tb/s per channel is already in progress [GER-2012], [IIEEE802.3]. However, beyond high capacity, optical networks need to address the requirement for high granularity to enable efficient utilisation of network resources both for service providers and end users. Optical Orthogonal Frequency Division Multiplexing (OFDM) [JIN-2009], optical packet switched networks [INTUNE], optical burst and optical frame switching technologies [ZER-2011] are examples of such solutions. These advanced, novel optical network technologies offer the flexibility and elasticity required by the diverse, dynamic and uncertain cloud and mobile cloud services market.

On the other hand, high-speed wireless access connectivity is provided by three prominent technologies: cellular LTE networks, WiMAX and WiFi. These technologies in turn vary across a number of specifications [], including: spectrum, antenna characteristics, encoding at the physical layer, and sharing of the available spectrum by multiple users, as well as maximum bit rate and reach. Femtocells appear to be a promising solution as they allow frequent spectrum re-use over smaller geographical regions with easy access to the network backbone. WiFi networks, however, are readily available and are easy to install and manage [RFIC-2013].

It is clear that the network technology domains involved, i.e. wireless and optical network domains, are very different in terms of a number of functional and performance characteristics as well as availability and maturity. In this type of environments, it is very important to define the resources that network operators can access and manipulate to effectively deploy the required services. These include a variety of diverse resources such as: optical fibres, wavelengths, optical and radio spectrum, ODUs, Ethernet switch ports and frames, exchange and access points, servers, storage, memory, Virtual Machines (VMs), etc. In the NREN environment, it is expected that further enhancement in terms of functionality and improved efficiency can be achieved through the federated use of resources.

To facilitate the potential adoption of the proposed functional architecture in the NRENs/GÉANT environment, a set of recommendations for the Physical Infrastructure have been identified which could be implemented by interested NRENs:

- Offer sharing of network resources, whether as stand-alone or federated: Identify the resources that can be shared between NRENs and implement all necessary technical solutions, to make these available and accessible to services as appropriate. Examples of such resources include optical fibres, wavelengths, optical and radio spectrum, and Ethernet switch ports. However, the final decision on resources offered in federation must be taken by each individual NREN.

- Investigate the economics of establishing peering with the commercial Internet close to the interconnection point of the aggregation network and the NREN network. In this way, the NREN network can be relieved from carrying large amounts of data, which requires substantial investment associated with network equipment (e.g. DWDM transponders, router linecards) purchasing (capital expenditure) and operation (operational expenditure).

- It will not be necessary to maintain an extensive peering fabric if the established lightpath infrastructure is available or can be obtained at a minimal cost, thus providing direct links to Internet exchange points. GÉANT and GÉANT Open, or GLIF, could serve as enablers of such lightpath services on an international scale.

4.2 Physical Infrastructure Management

The concept of heterogeneous infrastructure management, involving the functionalities illustrated in Figure 4.2, has already been addressed by several research projects and commercial systems. Traditionally, infrastructure management is vertically separated, i.e. each technology segment has its own management system, and the management of the various operational components (e.g. policies, processes, or equipment) is performed on a per-domain basis. Therefore, network management systems and cloud management systems are clearly differentiated.

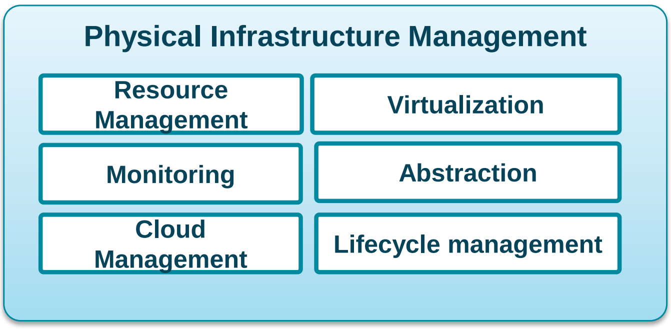


Figure 4.2: Physical infrastructure management

Network management has followed two approaches, depending on the context and the requirements of the network owners. On the one hand, centralised management assumes the existence of a single system that controls a whole network of elements, each of which runs a local management agent. Conversely, distributed management approaches introduce the concept of management hierarchies, where the central manager delegates part of the management load, distributed between different managers, each responsible for a segment of the network.

In order to support the multi-tenancy required by cloud infrastructures, which is also suitable for NREN environments, optical network virtualisation becomes a key technology that enables network operators to generate multiple, coexisting but isolated, virtual optical networks (VONs) running over the same physical infrastructure [PENG-2011]. Optical network virtualisation in general adopts the concepts of abstraction, partitioning, and aggregation over node and link resources to realise a logical representation of network(s) over the physical resources [JIN-2013]. Virtualisation of optical networks is one of the main enablers for deploying software-defined infrastructures and networks, enabling operators or NRENs to provide an array of innovative reduced-cost services and applications independently of the underlying technologies. Network management solutions focusing on optical network resources include the EU GEYSERS project [GEYSERS], which introduced the Logical Infrastructure Composition Layer (LICL) [GAR-2012]. LICL is a software middleware for the planning and allocation of virtual infrastructures composed of virtualised network and IT resources.

In wireless networks, significant management challenges exist because of the systems' complexity and a number of inter-dependent factors that affect wireless network behaviour. These include traffic flows, network topologies, network protocols, hardware, software and, most importantly, the interactions between these factors. In addition, due to high variability and dependency on environmental conditions, effectively obtaining and incorporating wireless interference into network management remains an open problem. Similarly to what occurs in the optical domain, multi-tenancy in wireless networks can be provided through virtualisation. Virtualisation and slicing in the wireless domain can take place in the physical layer, the data-link layer (with virtual Mac addressing schemes and open source driver manipulation) or the network layer (VLAN, VPN or label switching).

Overall, the Physical Infrastructure Management Layer should be responsible for providing access to and management of the physical resources, as well as enabling efficient resource provisioning. This can be achieved through sharing of resources, and solutions such as resource abstraction and virtualisation have been shown to be very effective for this purpose. Abstraction hides the complexity of the details of the physical layer, thereby facilitating resource management by providing simple infrastructure representations, for example as a graph view of the infrastructure exposing only the needed subset of properties to net and IT resources. On the other hand, virtualisation facilitates features such as slicing and aggregation of resources, and independency and isolation between virtual resources, but results in an additional cost in terms of a virtualisation overhead. It should be noted that these types of approaches will impose a requirement for a description and naming convention for legacy and future resources, and will introduce the need for new solutions as well as to modify existing tools, for example deploying conventions for alien waves. The tools for managing these changes were discussed in section 3.3.

Some general recommendations have been identified to guide NRENs and GÉANT towards an implementation of the proposed architecture:

- Implement unified management of the network. Integrate existing solutions (e.g. closed-box management platforms) with available Open Source management platforms through existing interfaces, capable of performing resource management actions over heterogeneous infrastructures. Use lessons learnt from on-going and finished projects (e.g. GEMBUS from GN3, LICL from GEYSERS, etc.).

- While implementing updates to the backbone network infrastructure, identify needs for an integrated network management. Have tender-winning vendors provide open, scalable and easy-to-extend management, with well-defined APIs to core functions and potential Open Source plug-ins, which could also contribute towards other de-facto standards in non-networking domains (e.g. clouds, storage, etc.).

- Resource virtualization is key. Implement necessary extensions to management platforms to allow easy slicing of network resources.

- Join the global NRENs' federation. Offer resources for sharing, implement Open *XXX* Exchange Points (where *XXX* stands for any technology that can be offered for federation, e.g. cloud resources – Open Cloud Exchange, light paths and/or optical spectrum – Open Lightpath Exchange, etc.).

4.3 Control and Service Orchestration Layers

The control and service orchestration layers (Figure 4.3) are responsible for service provisioning and orchestration of IT resources (computing and storage) located in geographically distributed DCs, seamlessly integrated with inter-DC networking. A number of relevant technical solutions have been investigated and proposed for a variety of scenarios, spanning from multi-layer architectures enabling the inter-cooperation between cloud and network domains, to procedures, protocols and interfaces allowing integrated workflows to support delivery and operation of joint cloud and network services.

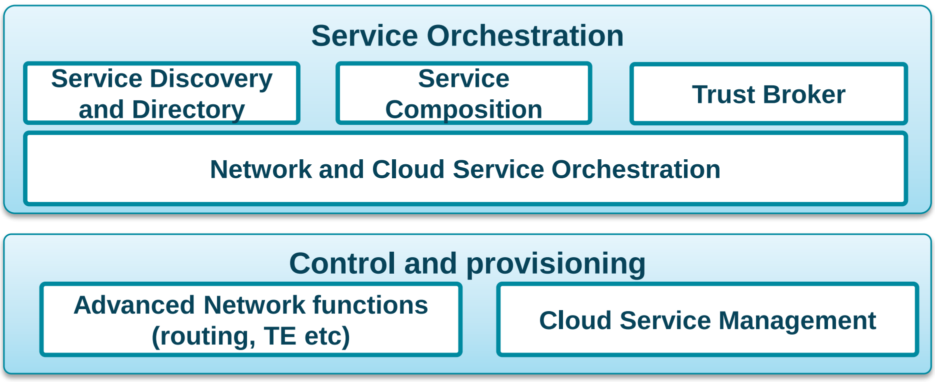


Figure 4.3: Control and service orchestration layers

The FP7 GEYSERS [GEYSERS] project developed a framework for on-demand provisioning of inter-DC connectivity services, specialised for cloud requirements, over virtual optical infrastructures [TZA-2014]. Following similar inter-layer approaches, some IETF drafts [DHO-2013] have proposed cross-stratum solutions for cooperation between application (service) and network layers in path computation for inter-DC network services, potentially combined with stateful Path Computation Element (PCE) mechanisms []. Other relevant research efforts include the FP7 projects SAIL [SAIL] and BonFIRE [BONFIRE].

Some of the control and orchestration challenges that need to be addressed include providing the tools and methodology for optimisation, to run services over multi-domain and, in some cases virtualised infrastructures that can support end-to-end QoS and security requirements.

Although Control and Service Orchestration layers are not being directly investigated by JRA1, due to overlaps with the areas of other GÉANT activities (e.g. JRA2 for network control and SA2-SA4 for multi-domain service orchestration), these layers have nonetheless been included in the overall architecture proposed by JRA1 for the sake of completeness. However, for specific details, future recommendations and technology choices, the outcomes of the JRA1, SA2 and SA4 activities on these topics should be referred to.

5 Conclusions

NRENs are facing ever-growing requirements from their users in terms of mobility, data access and resiliency, with increasing demands being placed on them to implement the technologies to meet these needs, along with the ensuing costs. The work of the GN3plus JRA1 Task 1 has focused on these requirements and on integrating the key findings from all other tasks in the activity, including Open Call projects on areas connected to JRA1, in the quest for a viable solution. The requirement analysis carried out reveals that the current network technologies and architecture cannot offer the fully dynamic and flexible transport services which it is foreseen will be needed for orchestration of future services, which should include both computing and network infrastructure resources. Additionally, in the area of cloud services, there are requirements to provide the infrastructure to support a possible GÉANT Open Cloud Exchanges (gOCX) and implement Open Exchange Points in different layers in order to reduce costs.

While the increased use of mobile end-user platforms may not directly affect transport infrastructures, owing to their wireless nature, the sheer number of devices itself may have a huge impact when traffic is backhauled in the network, which also places demands on the transport infrastructure. One of the main requirements that has emerged for the future network architecture is therefore that it should support sharing of resources for the purposes of both cost and energy savings. Future technologies for increasing bandwidth were surveyed, based on which different paths for increasing bit rates using super-channels, advanced modulation schemes and sophisticated forward error correction have been outlined. The short- and medium-term views of the future of the different vendors on the market have also been considered.

The needed building blocks for an efficient use of resources have been identified, and solutions proposed for the data plane, control plane and management/planning plane. As regards the data plane, the results of the joint work carried out with the REACTION project have shown how flexible optical networks can increase spectrum utilisation for a typical larger NREN. On the control and provisioning plane, the use of the transport SDN variant has shown to be a useful control mechanism.

The Open Call project MOMoT has developed a planning tool which analytically assesses the physical channel and indicates whether the use of one vendor's channel as alien wave in another vendor's network is viable to support the planning and management of the federated use of the spectrum. The results obtained by this tool are in line with similar results from a field trial carried out by GEANT Limited (formerly DANTE) and SURFNET. This planning tool, in combination with the findings of the REACTION Open Call project, will be essential to further progress towards a large-scale implementation of spectrum utilisation and sharing.

The efficient use of resources was also the focus of the IRINA Open Call project, which investigated how a clean-slate approach when replacing TCP/IP in the NREN context would fly: the studies not only reveal a much better performance than that of TCP/IP, but also a better performance than was initially expected. The concept is now being integrated with the SeeVogh application.

As current OTN-based transport networks do not provide exact time distribution and synchronisation, which was inherent in the SDH/SONET-based equipment, new ways of achieving synchronisation on a picosecond and nanosecond scale are needed. Alien waves have been validated for very high-precision atomic clock synchronisation, whereas Precision Time Protocol (PTP) has been evaluated for other, less expensive, purposes. In particular, results over a 200-km network connection showed that PTP synchronisation was possible under normal network conditions.

Different scenarios for multi-technologies at NRENs have been identified and categorised. In particular, three main models, based on the technology sets typically available at NRENs in the different layers, have been derived, and specific handles also identified for each model that can assist operators in implementing new services in their NRENs where requested, as well as enable sharing of resources with a view to reducing costs. A number of solutions for the physical infrastructure are suggested in this respect, including spectral sharing, radio spectrum sharing (where applicable), Ethernet switch ports etc. The functionalities to control and manage these physical resources, and the needed functions, such as resource management, virtualisation and abstraction, have been described.

Based on the service requirements, the technologies and the tools identified, a model for a new functional architecture layering has been proposed aimed at supporting the needs of the NRENs for a variety of services, including QoS-guaranteed, seamless and coordinated cloud and mobile cloud services across heterogeneous domains. The individual elements of this functional architecture, including the Physical Infrastructure, Physical Infrastructure Management, and the Control and Service Orchestration Layers, have been described, and a number of recommendations derived to facilitate its potential adoption in the NRENs/GÉANT environment.

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Glossary

API	application programming interface
AutoBAHN	Automated Bandwidth Allocation across Heterogeneous Networks
AW	Alien Wave
BVT	Bandwidth Variable Transponder
COFFEE	Coherent Optical system Field-trial For spectral Efficiency Enhancement
DC	Data Centre
DIF	distributed IPC facility
DWDM	Dense Wavelength Division Multiplexing
eduGAIN	A service that enables the trustworthy exchange of information related to identity, authentication and authorisation between the GÉANT Partners' federations
eduroam	A global service that provides secure roaming connectivity
FEC	Forward Error Correction
FMF	few-mode fiber
FON	flexible optical networking
FWHM	Full Width Half Maximum
GMPLS	Generalized Multi-Protocol Label Switching
GNSS	Global Navigation Satellite Systems
IMDD	Intensity Modulation Direct Detection
IP	Internet Protocol
IPC	inter-process communication
IRINA	Investigating Recursive InterNetwork Architecture
LAN	Local Area Network
LC	Liquid Crystal
LCoS	Liquid Crystal on Silicon
MCF	multicore fiber
MEMS	microelectromechanical systems
MOMoT	Multi-Domain Optical Modelling Tool
MPLS	Multi-Protocol Label Switching
MPLS-TP	Multiprotocol Label Switching - Transport Profile
NaaS	Network as a Service
NREN	National Research and Education Network
NTP	Network Time Protocol
N-WDM	Nyquist Wavelength Division Multiplexing
OAM	Orbital Angular Momentum Multiplexing
ODU	Optical channel Data Unit

OF	OpenFlow
OFDM	Orthogonal Frequency Division Multiplexing
OIF	Optical Internetworking Forum
OLX	Open Lightpath eXchange
OSNR	optical signal-to-noise ratio
OTDM	Optical Time Division Multiplexing
OTN	Optical Transport Network
PCE	Path Computation Element
perfSONAR	Performance Service Oriented Network Monitoring Architecture
PM-QPSK	Polarization Multiplexed Quadrature Phase Shift Keying
PTP	Precision Time Protocol
REACTION	Research and Experimental Assessment of Control plane archiTectures for In-Operation flexgrid Network re-optimization
RINA	Recursive InterNetwork Architecture
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RPC	Remote Procedure Call
RSA	routing and spectrum allocation
SBVT	Sliceable Bandwidth Variable Transponder
SDM	Space-division multiplexing
SDN	Software-Defined Networking
TCP	Transmission Control Protocol
TFP	Time-Frequency Packing
TN	Transport Network
UDP	User Datagram Protocol
VON	virtual optical network
WAN	Wide Area Network
WSS	Wavelength Selective Switches