29-04-2016

Deliverable D13.2
Blueprint of Services and Research Plan for Future Work

Deliverable D13.2

Contractual Date:	30-04-2016
Actual Date:	29-04-2016
Grant Agreement No.:	691567
Work Package/Activity:	13/JRA1
Task Item:	Task 2
Nature of Deliverable:	R (Report)
Dissemination Level:	PU (Public)
Lead Partner:	LITNET
Document Code:	GN4-1-16-553DE

Authors:	Alberto Colmenero (NORDUnet), Anna Manolova Fagertun (DTU), Daniel Camps Mur (i2Cat), David Schmitz (LRZ/DFN), Frans Panken (SURFnet), Hao Yu (DTU), Ilker Demirkol (i2Cat), Karim Boudjemaa (RENATER), Raimundas Tuminauskas (LITNET), Rob Smets (SURFnet), Zbigniew Ołtuszyk (PSNC)

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 691567 (GN4-1).

Abstract

This deliverable covers the intermediate stage of research within the scope of GN4-1 JRA1, and identifies architecture blueprints for making Zero Touch connectivity available to NREN/GÉANT users. The work reported in the deliverable focuses on two distinct areas, optical networking and radio access, and addresses the related technological challenges and transition to service process.

Table of Contents

Executive Summary 1

1 Introduction: Zero Touch in the NREN/GÉANT Environment 3

2 Alien Wave as a Service (AWS) Blueprint 5

2.1 Technology-Readiness of NREN/GÉANT Ecosystem 5

2.2 Alien Wave and Alien Wave Service: Definitions 8

2.2.1 Discussion 8

2.2.2 Alien Wave Definition and Types 8

2.2.3 Alien Wave Service 10

2.3 AWS Use Cases 11

2.3.1 Use Case 1: AW Type II Service (In Service) 11

2.3.2 Use Case 2: AW Type III Service (In Service) 12

2.3.3 Use Case 3: Photonic Exchange Prototype (In Service) 13

2.3.4 Use Case: 4: Carrying Infinera High-Capacity OCG (In Service) 14

2.3.5 Use Case 5: Transponderless network (SUNET – Deployment in 2016) 15

2.4 Industry Approach to Alien Waves 15

2.4.1 Standardisation: Black Link 15

2.4.2 Integrated IP over Photonics 16

2.4.3 Open Line System 17

2.4.4 Alien Wave Services 17

2.4.5 Current State of the Industry 18

2.5 Service Implementation 19

2.5.1 Operational Aspects (Network Dynamics) 19

2.5.2 Monitoring 20

2.5.3 Monitoring of Live AW Service 24

2.5.4 Distributed Wave Exchange Proposal*** 26

3 Integrated Mobility Service Blueprint 30

3.1 Implementations within the R&E Ecosystem 30

3.2 Integrated Mobility Use Cases 31

3.3 WaaS Implementation 32

3.3.1 WaaS Procurement 32

3.4 Inter-Domain Roaming Proposal 36

3.4.1 Inter-Domain Mobility Management at Layer 3 36

3.4.2 Inter-Domain Mobility Management at Layer 2 38
3.4.3 Integration with LTE 42
3.5 Prototyping and Modelling Results 44
3.6 Mapping the Service to the GÉANT/NREN Infrastructure 49

4 Further Work 51

5 Conclusions 54

Appendix A AWS Questionnaire and NREN Responses 57
A.1 AWS Questionnaire 57
A.2 Tables of NREN Responses 58

Appendix B Data Exchange Parameters for Alien Wave Provisioning 68

References 71

Glossary 73

Table of Figures

Figure 2.1: Use of alien waves and cross-border fibres among European NRENs, excluding GÉANT and NORDUnet 7
Figure 2.2 Diagram of Alien Wave type I 9
Figure 2.3: Diagram of Alien Wave type II 9
Figure 2.4: Diagram of Alien Wave type III 9
Figure 2.5: AW service provided by SURFnet to NORDUnet between Amsterdam and Hamburg 11
Figure 2.6: AW service provided by SURFnet to NORDUnet between Amsterdam and Hamburg and extended to Copenhagen by NORDUnet 12
Figure 2.7: Different AWs are exchanged at a photonic exchange in Brussels. 13
Figure 2.8: AW type II on an Infinera super structure. Payload is divided over 10 waves. 14
Figure 2.9: SUNET's concept network using AW Type I 15
Figure 2.10: Google Open Line System architecture for inter-data-centre connectivity 17
Figure 2.11: Alien Wavelength Service monitoring architecture 21
Figure 2.12: CMon architecture and workflow 24
Figure 2.13: CMon monitoring implementation topology diagram 25
Figure 2.14: Evolution of use case 3 into photonic exchange prototype 26

Figure 2.15: Layer structure of Open Photonic Exchange 27
Figure 2.16: Regional OPX illustration 29
Figure 3.1: Example scenario of users switching between different eduroam domains 32
Figure 3.2: Proposed PMIPv6 extension PBU and PBA formats 37
Figure 3.3: Inter-domain tunnel establishment in the proposed PMIPv6 extensions 37
Figure 3.4: PMIPv6 inter-domain tunnel configurations 38
Figure 3.5: User steering to the appropriate vAP 39
Figure 3.6: L2 tunnelling for inter-domain mobility, comprising direct tunnels and OMX routed tunnels 41
Figure 3.7: Static dedicated VLANs configuration for adjacent eduroam domains 42
Figure 3.8: vAP testbed set up 45
Figure 3.9: Software modules in UPC and UB RPi devices 46
Figure 3.10: Connection time when the device is not known to the system 48
Figure 3.11: Connection time when the device is known to the system (the MAC lists are configured) 48

Table of Tables

Table 1.1 Provider - User relationship for GÉANT services 4
Table 2.1: List of NRENs and organisations that responded to the questionnaire 5
Table 2.2: Black Link parameters 16
Table 2.3: AW monitoring data for demonstration 22
Table 2.4: Analysis of OPX deployment within the GÉANT ecosystem 28
Table 2.5: Distances between POPs for Baltics OPX case 29
Table 3.1: RASCI matrix for WaaS 35
Table 3.2: Integrated mobility architecture mapping to GÉANT/NREN ecosystem 50
Table 4.1: Further work directions 53
Table 5.1: Proposed architecture implementation checklist 56

Executive Summary

This deliverable covers the intermediate stage of research within the scope of GN4-1 JRA1 between pure technological research and actual service prototyping as carried out by Task 1 and Task 3 respectively. It identifies architecture blueprints for making Zero Touch connectivity available to users within the GEANT/NREN ecosystem. The work reported in this deliverable builds on previous research conducted by JRA1 in the GN3 and GN3Plus projects in the areas of optical exchanges, federated use of optical infrastructures and radio access networks. The work focuses on two distinct areas: optical networking and radio access. The deliverable serves three main purposes: a) to identify the requirements for developing services starting from the technologies analysed, b) to identify the applicability for these services within R&E networking, and c) to define the problematic areas that need to be addressed by future research.

Zero Touch connectivity as a concept involves providing the best possible end-user experience regardless of location and the type of user, be it a student with a smartphone or a research laboratory using advanced instrumentation. The underlying network technology is close to achieving this ambitious target. The portfolio of networking technologies differs across the R&E community depending on the user base. Seamless radio access including Wi-Fi and mobile technologies are essential to individual users within the community, while photonic spectrum sharing and alien wave services between the community member institutions (universities, NRENS, etc.) are essential to provide seamless reach to any part of the world. The deliverable addresses these two issues in detail.

Alien wave technology has already been around for a decade, but the industry and standards bodies have yet to embrace the concept and turn it into a business case. Section 2 opens with a summary of the current situation of alien wave services in the industry. The task produced a questionnaire specifically designed to advance the discussion on the definitions of alien waves and alien wave services, which it submitted to NRENs and organisations that were identified as having the capability to operate the photonic layer of their respective networks. The results show that there are differing opinions as to the exact definition of alien waves and how they may best be used across the community. Nonetheless, a number of use cases for alien wave services within NRENs and GÉANT are currently in operation. The proposed service blueprint addresses multi-domain monitoring as one of the main aspects involved in the provision of a reliable service. The Task evaluated multi-domain monitoring in a selected production scenario based on current agreements between R&E members for alien waves. In collaboration with SA3 Task 5, the multi-domain circuit monitoring tool CMon was adapted to monitor optical parameters. Finally, the concept of open photonic exchange included in the blueprint was derived from the task's further work on the aspects addressed during GN3 [GN3-11-074_DJ1.3.2] and GN3Plus [D12.1_DJ1.2.1].

Section 3 outlines an integrated wireless connectivity service blueprint, building on previous research carried out in JRA1 Task 3 during the GN3plus project, with a focus on the two main aspects of seamless inter-domain roaming in the eduroam environment and Wi-Fi expansion. The Wi-Fi as a service concept is mature enough and has been implemented by SURFnet in a production environment, while seamless inter-domain roaming needs further technology research to advance. The implementation of AP and VLAN switching technologies is of limited scope and not yet mature. The task set up a test environment using virtual AP to measure its performance and demonstrate that the mechanism operates as intended. The integrated wireless connectivity proposal will have to address the integration with mobile (3GPP, LTE, 5G and LTE-LAA), but the current campus-oriented scope of radio access networks limits the possibilities for GÉANT and the NRENs getting directly involved in its development. The issue is nevertheless important to the community and to the EC, therefore it is recommended that further development should take place in this area.

The effort in GN4-1 described in this deliverable also provides recommendations for future work that will be influenced mainly by Technology Readiness Level requirements. Alien optical transmission services are mature to the extent that GÉANT already uses alien wave services. Future effort should be directed at promoting the use of the NREN infrastructure for GÉANT connectivity. Radio access integration will continue as a part of the GÉANT community programme.

1 Introduction: Zero Touch in the NREN/GÉANT Environment

The current organisational setup of GÉANT, the NRENs and their constituencies forms an intricate structure comprising both users and providers of services. The same services may be provided by different entities to the same users depending on the availability of federated services, including network services, and user mobility. Table 1.1 below shows how a strict hierarchy from provider to user no longer exists: services are exchanged and shared amongst all GÉANT participants thus creating a pool of services for each entity to use. The Zero Touch Connectivity (ZTC) concept is applicable to the R&E community because the R&E networks are global and they combine networking infrastructures with services. JRA1 has examined ZTC from the perspective of network provision within the GÉANT/NREN ecosystem, as having the capacity to provide the ultimate user experience of being connected to the network anywhere, anytime, and irrespective of the underlying network technologies, topologies, protocols and architectures.

Service	User	Provider
Commodity Internet connectivity	University or Institute	NREN
		Commercial entities
	NREN	Commercial entities
		GÉANT WS
	GÉANT	Commercial entities
R&E and peering IP connectivity (non-commodity)	University or Institute	NREN
		Other University
	NREN	GÉANT
		Other NREN
	GÉANT	Other NREN
Dedicated connectivity services	University or Institute	NREN
		Commercial entities
	NREN	GÉANT
		NREN
		Commercial entity
	GÉANT	NREN
		Commercial entity
Wi-Fi and mobile access	Individual users	University/Institute
		NREN
		Federated (eduroam)

Service	User	Provider
		Commercial entities
	University or Institute	Commercial entities
		Federated (eduroam)
		Other University
		NREN (WaaS)

Table 1.1 Provider - User relationship for GÉANT services

Mapping network technologies into the GÉANT ecosystem extends them beyond the boundaries of single provider networks. Extending the technologies providers use to build their services (e.g. mobile offload or transponderless networks outside their boundaries means adding in the service level specification the interface to other providers. The GÉANT ecosystem is the ideal environment in which to implement such services, because while technically it is a multi-domain, multi-provider setup, it is also in its entirety part of the same R&E community it serves.

The work of mapping the service proposals onto the organisational structure of the GÉANT ecosystem has been carried out using two service blueprints that have the potential to bring Zero Touch Connectivity closer to the users:

1. **Alien Wave Service (AWS) blueprint**. Alien wave technology, as a transmission of optical signal from a vendor other than that of the established optical transmission platform, has been used in provider networks for more than a decade. Changes in the GÉANT network service landscape mandate a more efficient use of available resources and the shared use of NREN infrastructure also for GÉANT services. The Alien Wave Service addresses the multi-domain and multi-provider aspect of implementation of alien waves in the GÉANT ecosystem. It also proposes the concept of open photonic exchanges to be deployed within the GÉANT/NRENs environment to foster the federated use of infrastructure.

   The service itself, however, is not zero touch nor is likely to be in the foreseeable future. It is intended to make efficient network resources available where required thus facilitating the ultimate user experience from the ground level of physical infrastructure.
2. **Integrated mobility service blueprint**. Integrated mobility is also an old technology used in a single-provider environment. The service is also hugely impacted by the eduroam concept for inter-domain mobility, but the demands for seamless mobility and network resource allocation have changed profoundly with the current use of online content. Mobile operators are addressing this with the LAA/LTE-U (NTT DOCOMO, INC., 2014). The expansion of eduroam also results in scenarios where seamless multi-domain Wi-Fi mobility is required.

These services blueprints and their integration in the GÉANT ecosystem are outlined in sections 2 and 3 respectively. Section 4 sets out the further research and work needed to transition the services. The Conclusions in Section 5 provide a distillate of information to facilitate its use by readers wishing to deploy or evaluate the technologies and services outlined in the main body of the document.

2 Alien Wave as a Service (AWS) Blueprint

2.1 Technology-Readiness of NREN/GÉANT Ecosystem

There are certain prerequisites for a network to be able to deploy the alien wave service , in the first place the ability of the network operator to control their own (D)WDM infrastructure. Many NRENs in Europe do not have this ability (but rent connectivity from national transport providers, in the form of L2/L3 circuits) or they do not use WDM at the photonic layer, thus such a service is irrelevant to their portfolio. To evaluate the levels of technology-readiness for the deployment of AWS in the European NREN/GÉANT community, a thorough analysis of the TERENA Compendium 2014 [Compendium 2014] was carried out to identify those NRENs and organisations that have the capability to operate the photonic layer of their respective networks. A purpose-designed 12-question questionnaire was then submitted to these organisations, 20 of which responded, including GÉANT and NORDUnet (see Table 2.1 for the complete list of respondents).

Name of Organisation/NREN
PIONIER/PSNC
Agency ARNIEC/RoEduNet
GÉANT
SWITCH
SURFnet
EENet
CESNET
AMRES
NORDUnet
SUNET
NIIF Institute
Kaunas University of Technology / LITNET
Arnes
CARNet
GRNET SA
GARR
HEAnet
UNINET
DeiC
Renater

Table 2.1: List of NRENs and organisations that responded to the questionnaire

In terms of the use of AW in their organisations, the respondents' answers can be summarised as follows:

- 9 respondents provide an alternative definition of AW;
- 15 respondents have participated in AW trials;
- 8 respondents have received requests from clients for an AW service, 1 of these is confidential;
- 8 respondents have provided (limited) information on use cases with customers;
- 11 respondents have not had direct customer requests for AW services;
- 14 respondents plan to deploy AWs, 1 of these is confidential;
- 6 respondents do not plan to connect with neighbours over CBF via AW, 1 does not know and 1 response is confidential;
- 4 respondents do not have CBF deployed;
- 1 respondent does not operate its own WDM infrastructure and is thus not relevant to the discussion;
- 1 respondent does not see a need for AWs.

Based on the participants' answers regarding potential benefits and current deployments, it is evident that they consider the deployment of AWS to be mainly for internal purposes (i.e., not as a service to clients but for CAPEX savings). It is also clear that the availability of Cross Border Fibers (CBF) facilitates AW deployment. One of the most obvious deployment scenarios is for infrastructure sharing (thus achieving cost savings) – only 6 NRENs clearly state no plans to deploy AWs on CBFs (e.g. EENet does have CBF where AW could be deployed, but they do not plan to).

Due to the limited responses received to the questionnaire, an earlier version of an AW interest questionnaire (conducted during the MOMoT Open Call project [MOMoT]) was examined to obtain supplemental data for the survey. From this, three additional NRENs – RedIRIS, Belnet and Jisc (formerly JANET) – were identified as being interested in the technology or as having previously deployed it. However, these NRENs did not respond to the current questionnaire.

Based on the answers provided and the data from the TERENA Compendium [Compendium 2014], the Task drew up a technology-readiness map, shown in

Figure 2.1 below. It can be seen that AWs are widely deployed, and many organisations benefit from their cost-saving aspects. Spectrum sharing via cross-border fibres extends the (transparent) reach of network operators, which benefits their service portfolio.

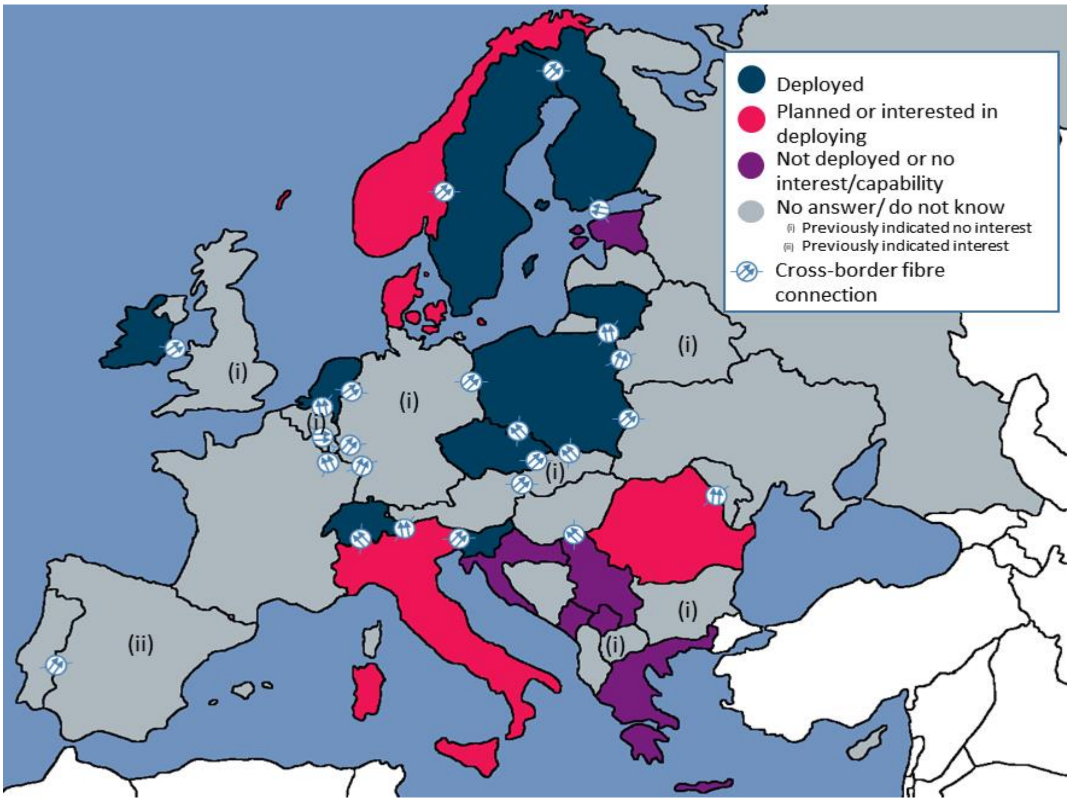

Figure 2.1: Use of alien waves and cross-border[1] fibres among European NRENs, excluding GÉANT and NORDUnet

Additionally, more and more NRENs have direct plans to deploy AWs, indicating that the potential benefits from the technology are well recognised among network operators. Furthermore, the expanding deployment of cross-border fibres between NRENs facilitates more intelligent traffic engineering across Europe, offloading heavy traffic between direct neighbours from the GÉANT core. This frees up resources resulting in improved quality of the services provided both via the NRENs and the GÉANT backbone.

The main take-home point from the analysis conducted is that there is great potential to deploy AWs more widely for the benefit of both NRENs and GÉANT as a whole. Infrastructure sharing is a promising solution for cost reduction. Furthermore, fast developments within the fields of SDN, infrastructure virtualization and orchestration platforms in the past couple of years indicate that the main challenge in AW deployment and operation (e.g., lack of end-to-end management) will soon be solved.

[1] "Cross-Border Fibre" in this section is understood as the definition given in the "Compendium" by the GÉANT Association. This definition cannot be applied straightforwardly to multi-national networks e.g. NORDUNET and GÉANT, which are not shown in the figure, though they span multiple countries.

2.2 Alien Wave and Alien Wave Service: Definitions

2.2.1 Discussion

An example Alien Wave definition was proposed in the questionnaire discussed above (see Appendix A):

> *An "Alien Wavelength" is a modulated channel (carrying digital user data) that travels transparently through multiple domains, which are running different vendor equipment compared to where it originates.*

Some of the respondents have provided corrections and suggestions to the proposed definition. These are summarised below:

- AW is a photonic DWDM signal (not a channel), i.e. it is considered in the context of optical transmission in the telecommunication networks using DWDM of some flavour.
- The AW signal has to be transferred from TX to RX on a purely optical path, without OEO conversion.
- At least some part of the AW signal path through the optical network goes through the equipment produced by a different vendor than that of end-point Rx/Tx.
- The modulation and digital/analogue data may be relevant to the particular alien wave, but not relevant in the definition.
- The underlying DWDM network infrastructure transporting AW may be just a single optical network but also may span different optical networks administered by different entities (domains).

2.2.2 Alien Wave Definition and Types

Based on the initial definition formulated, and taking into consideration the proposed changes, the following definition of alien wave was derived:

> *An Alien Wave is a photonic DWDM signal carrying user data that is transported transparently without OEO conversion through the DWDM network (networks) running the equipment of a different make than the signal ingress/egress end-points.*

This deliverable considers three types of alien wave services as outlined in [Peters, B.].

Alien Wave type I: "Own alien wave"

A type I alien wave is one where the optical signal is formed within the same network (administrative domain), but not within the optical network layer. Examples of such alien waves are tuneable pluggables as described in2.4.2. Figure 2.2 illustrates AW Type I.

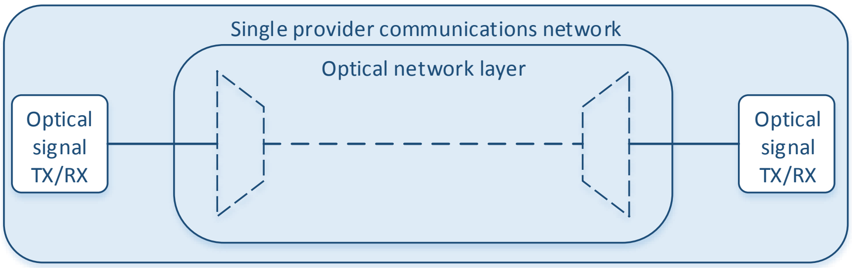

Figure 2.2 Diagram of Alien Wave type I

Alien Wave type II: "Customer's alien"

In a type II alien wave the optical signal originates and is passed out of scope of the provider's communications network (administrative domain). Typically, such alien waves are used to connect third parties directly over the optical network layer. Figure 2.3 illustrates AW Type II. This type of AW provides many advantages for NRENs in terms of cost reduction and fibre sharing with other NRENs

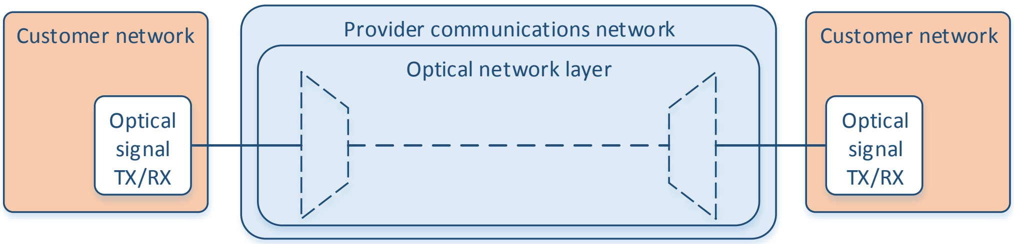

Figure 2.3: Diagram of Alien Wave type II

Alien Wave type III: "Multi-domain alien"

In type III alien waves the optical signal transits the provider network optical layer to another provider's optical network and not directly to the line interface. Typically, this means that the optical signal may have passed through one or more networks of different providers (without OEO transitions) before entering that particular communications network. Connectivity between domains can be achieved in various ways. The specifics of the design need to be agreed upon between the different domains and their network designers and others responsible for implementing and operating the network. Figure 2.4 illustrates AW Type III.

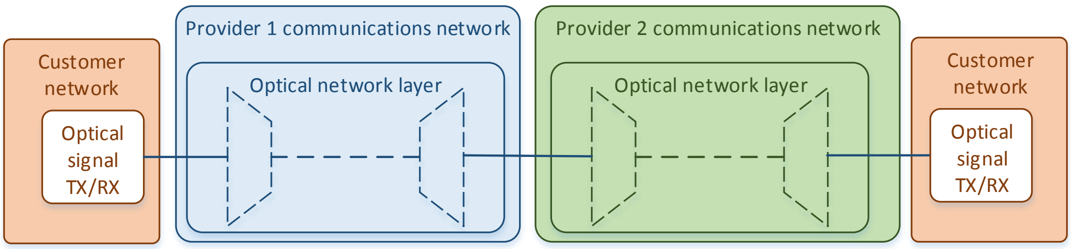

Figure 2.4: Diagram of Alien Wave type III

2.2.3 Alien Wave Service

An Alien Wave Service (AWS) is a network service defined by the service parameters (service level specification) based on the alien wave transport across the network. Alien wave types II and III are commonly understood to be alien wave services.

From the operational perspective, an Alien Wave Service involves two parties: the 'provider' and the 'user', and an agreed level of service referred to as a 'commitment' as described below. Details of sustainability, SLAs, and technical parameters for the service are set out in Appendix B.

AWS provider:

The provider stands for the entity (an NREN) that owns (or is able to provide) the DF infrastructure, the various in-line amplifiers and the housing of third-party equipment in one or both the terminal sites depending on the Alien Wave type.

The provider is responsible for delivering a service according to its specification and for maintaining the service throughout the duration of the contract.

GÉANT and other umbrella organisations such as GLIF should facilitate the multi-domain use of alien waves between the partners by implementing the information portal with the relevant data from partners and monitoring and modelling tools.

AWS user:

The user is willing to transmit data through a third-party entity domain network and owns the proper DWDM terminal equipment, in particular transponders interoperable with the DF infrastructure[2] of the other entity.

The user pays a fee to set-up the service and, on an annual basis, the maintenance price to the provider, or may reimburse service costs, subject to agreements on a case-by-case basis.

AWS commitment:

Both parties must agree on the specifications defined for the service and must continue to respect these specifications during the contract. As this is a new service (AWS), not much feedback has been received and no generic specification is available as yet. However, as a guideline, the following should be considered:

- **Service duration:** It is possible that public RFQ within the NRENs community could lead to change of ownership of the dark fibre infrastructure and thus jeopardise service delivery. The final duration of the service has to match whichever is the shortest between the duration of the DF, housing and DWDM maintenance contracts.

- **Basic service:** The service offered by the provider is a channel frequency spacing along its infrastructure between two end-points. User and provider have to reach an agreement

[2] Interoperability is determined by the respect of agreed parameters as outlined in Appendix B

suitable for both parties on each item of the service parameters to build a specification of service.

- **Service supervision & tooling:** As a standard network service, AWS must comply with a high availability rate. Based on the MTTR of the DF, DWDM equipment and housing maintenance contract, the provider should commit to a certain level of service availability. To run the service supervision 24h/7D, provider and user should use tools such as CMon [CMon] to provide a real-time view of the DWDM performance/alarms monitoring.

- **Service options:** Several service options are possible. One of these consists in proposing optical protection on the complete link if there are ROADMs on the end-points or partially if ROADMs exist on the AW path. The availability of these options depends on the NREN infrastructure.

2.3 AWS Use Cases

2.3.1 Use Case 1: AW Type II Service (In Service)

This setup describes a production scenario of an AW Type II service provided by SURFnet to NORDUnet:

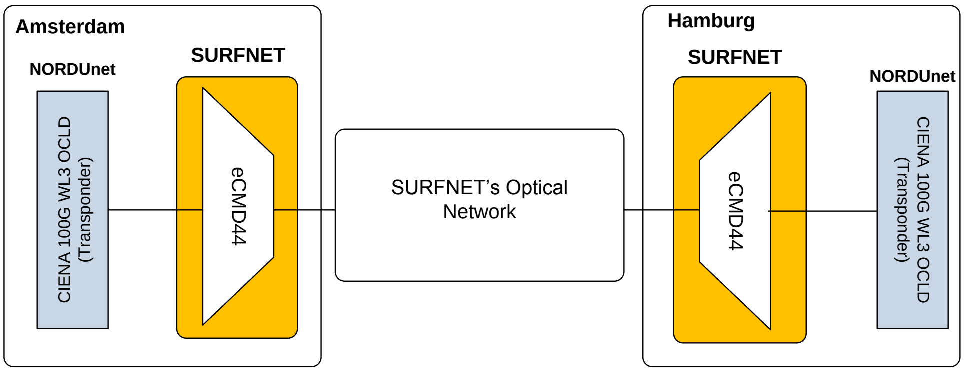

Figure 2.5: AW service provided by SURFnet to NORDUnet between Amsterdam and Hamburg

This 100G AW is used to provide connectivity from NORDUnet's OTN cross-connect in Amsterdam to the OTN cross-connect located in Hamburg. NORDUnet does not own fibre infrastructure between these locations and the use of AWs via SURFnet's optical network results in substantial cost savings for NORDUnet. The same setup is in use between Amsterdam and London.

The AW service's characteristics are as follows:

- 100G with DP-QPSK modulation.
- 50Ghz spacing.
- Tx power = 0.0 dBm (Both Amsterdam and Hamburg)
- Rx power = -9.6 dBm (Amsterdam) and -9.3 dBm (Hamburg)
- PRFBER (Pre-FEC Bit Error Rate) Amsterdam = 6.9E-06

- PRFBER (Pre-FEC Bit Error Rate) Hamburg = 2.5E-05

This is a good example of how NRENs can take advantage of each other's optical network and fibre infrastructure to provide connectivity. There is still an issue to be solved with regard to the efficient monitoring and operation of the AW and procedures to this effect need to be put into place at the NRENs.

2.3.2 Use Case 2: AW Type III Service (In Service)

The following scenario describes a production AW Type III service between SURFnet and NORDUnet.

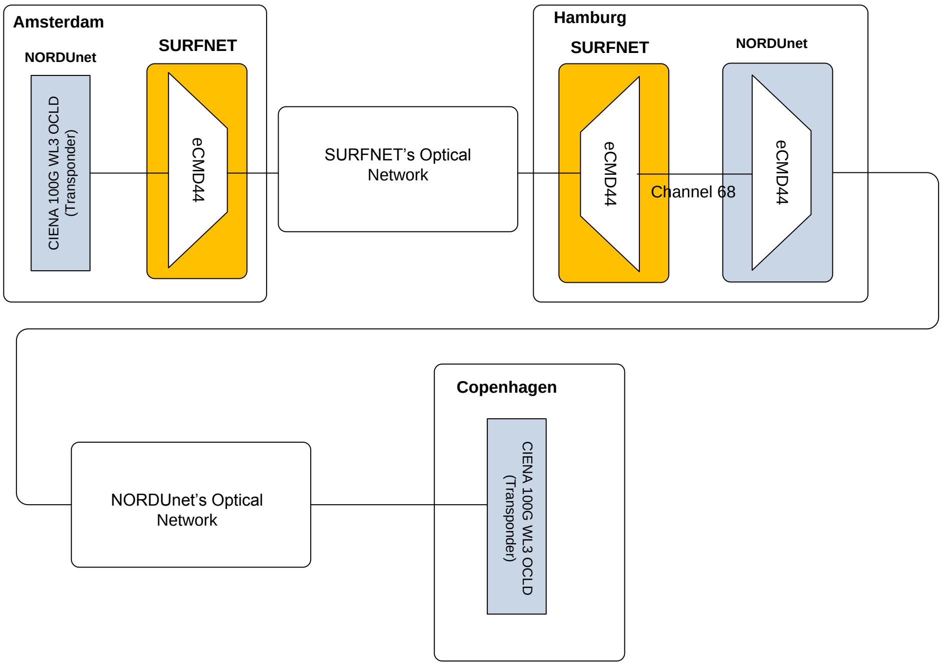

Figure 2.6: AW service provided by SURFnet to NORDUnet between Amsterdam and Hamburg and extended to Copenhagen by NORDUnet

This is a multi-domain AW scenario to provide 100G connectivity between the NORDUnet's routers in Copenhagen and Amsterdam for NORDUnet's 100G IP Core Network. The purpose of this AW is once again to make use of SURFnet's fibre availability between Hamburg and Amsterdam.

This AW service has the following characteristics:

- 100G DP-QPSK modulation.
- 50Ghz spacing.
- Tx power = 0.9 dBm (Both Amsterdam and Copenhagen)
- Rx power = -8.7 dBm (Amsterdam) and -12.3 dBm (Copenhagen)
- PRFBER (Pre-FEC Bit Error Rate) Amsterdam = 6.0E-05
- PRFBER (Pre-FEC Bit Error Rate) Copenhagen = 1.8E-04

Multi-domain AWs involve additional complexity since the interconnectivity between the two NRENs can be achieved in different ways. Defining a model template for interconnection of multi-domain AWs would require quite a broad knowledge, including of all optical networks available for AW connectivity. This means specific interconnectivity scenarios need to be designed on a case-by-case basis. In this case, NORDUnet and SURFnet connected their two domains via their filters, which involves special design considerations as it is not completely possible to control the power for an individual channel at the output of the filters.

Another particular aspect to consider when monitoring this type of AW is that each NREN only has visibility of their own portion of the AW. Different solutions are being considered to solve this issue. One possibility could be to send relevant performance monitoring data from all involved nodes to a central server where all data could be correlated and presented in an understandable way (see 2.5.2).

2.3.3 Use Case 3: Photonic Exchange Prototype (In Service)

The diagram below in Figure 2.7 shows a service where NORDUnet and SURFnet interconnect at Brussels. This is a particular version of the AW Type III service. The AW is no longer linear but is cross-connect. In this case NORDUnet had to redesign their node in Brussels to provide a third degree with a drop side (known as Direct Independent Access) to be connected to SURFnet's infrastructure. This allows any wavelength to be dropped towards SURFnet and vice versa. The wavelength can be carried and dropped anywhere in SURFnet's and NORDUnet's optical network extending both NRENs' infrastructure beyond their physical limits. The single fibre interconnecting the two locations can carry 88 waves. The purpose of this structure is to provide protection for normal and alien waves between London and Amsterdam (using the Zandvoort-Leiston subsea cable) by also routing them optically over Brussels as indicated by the red arrow. In Amsterdam and London, Optical Protection Switches are in place that switch to the secondary backup path (hot-standby) should the primary path fail.

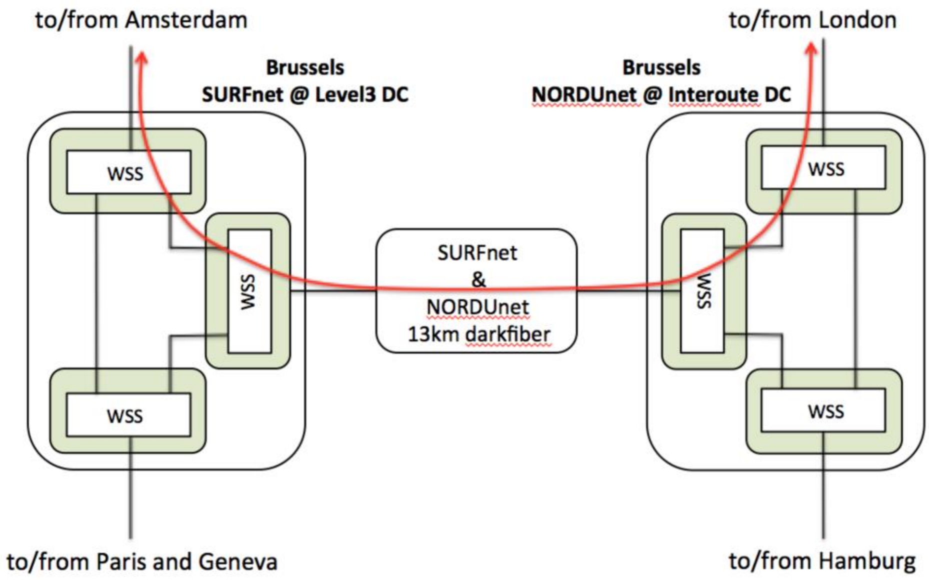

Figure 2.7: Different AWs are exchanged at a photonic exchange in Brussels.

The scalability of this exchange is mesh-like, however for improved scalability a hub-and-spoke architecture can be implemented, though this may affect signal fidelity.

The dark fibre connecting the two data centres can be seen as a long patch cord. Power levels on this fibre are the same as on a normal span. Padding is used to bring power levels to acceptable values as link engineering would prescribe to allow WSS-connected EDFAs (not shown here) to operate properly. This structure also allows waves to be routed from Geneva to London and from Hamburg to Geneva or Amsterdam. The only limitations on this service are in terms of wavelength contention and link design. Current technology dictates a 50GHz grid compliance. This infrastructure is currently carrying three AWs.

This service also has operational advantages compared to the previous example since it does not need cabling between the domains for every additional AW in the system, resulting in a considerable saving in terms of both time and resources.

This option could be considered to be CBF (Cross Border Fibre), where "Border" is understood as the limits of inter-domain connectivity between two NRENs.

2.3.4 Use Case: 4: Carrying Infinera High-Capacity OCG (In Service)

In this use case, SURFnet transports 10 waves from an Optical Carrier Group (OCG) of an Infinera system in GÉANT between Amsterdam and Hamburg. The potential payload of these waves is 500Gbps. The 10 waves are spaced 200GHz apart and map onto SURFnet's 50GHz light system.

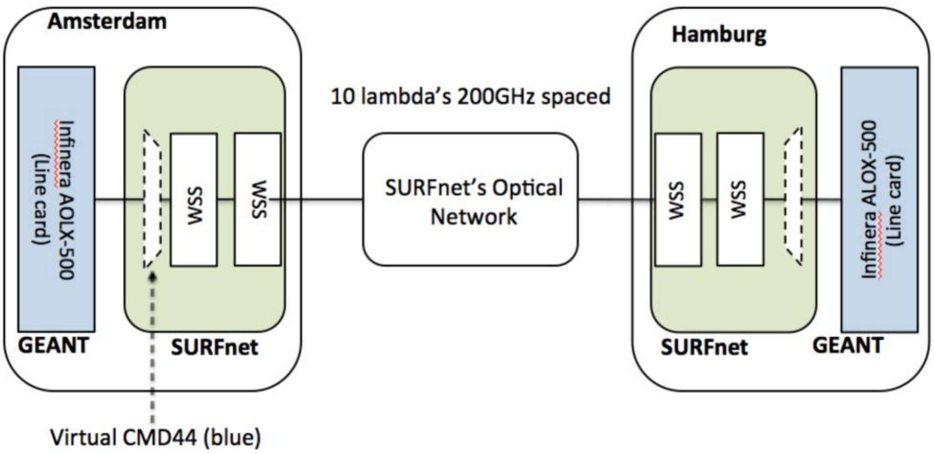

Figure 2.8: AW type II on an Infinera super structure. Payload is divided over 10 waves.

This Alien Wave is part of an OTN-switched network that uses ASON via GMPLS to trigger a reroute of traffic in case of failure. The system was demonstrated in tests before it was brought into service.

In all the above use cases SURFnet monitors its own performance of the DWDM transceivers to check for changes in FEC and PMD values.

2.3.5 Use Case 5: Transponderless network (SUNET – Deployment in 2016)

SUNET will rebuild their optical and IP backbone networks during 2016. Their new network will have to serve their high-capacity demands for connectivity to universities and research institutions in Sweden. This will be achieved by means of AWs using 100GE coherent interfaces in SUNET's routers connecting directly to the DWDM optical network, without the need for transponders. Considering the size of SUNET's network, this solution will provide considerable CAPEX reductions. The concept is depicted in Figure 2.9.

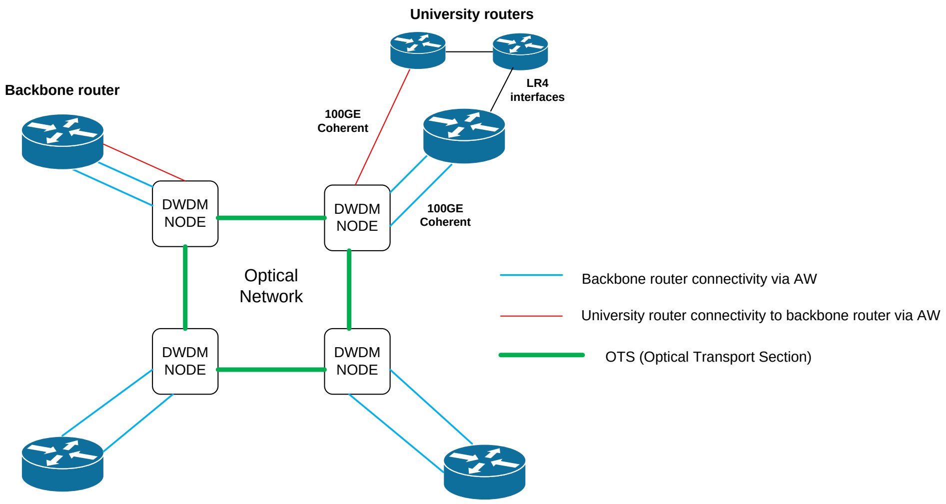

Figure 2.9: SUNET's concept network using AW Type I

The concept covers both AW types II and I because AWs connect SUNET's backbone routers and their customers' routers (universities in this case). To manage the AW services end-to-end this solution requires integrated network management of both router and network interfaces. Moreover SUNET's optical network will connect to NORDUnet's optical network using a similar solution to the one described in Use case 3, allowing both organisations to provide Type III Alien Waves (Multi-domain). SUNET expects its new optical network to become operational in 2016.

2.4 Industry Approach to Alien Waves

2.4.1 Standardisation: Black Link

ITU-T introduced the concept of "Black Link" describing DWDM application for single-channel and multi-channel transmission interfaces in specifications [G.698.2] and [G.698.3] respectively. The specifications also provide a naming convention and a set of parameters that describe the service. The current standard only covers 50 and 100GHz spacing for metro application speeds up to 10Gbps. Work by the standardisation committee is ongoing [T13SG15 Q6/15] to adopt specification to speeds up to 100Gbps. The indicated parameters, summarised in Table 2.2 below, must be agreed for the whole service or at the specific reference points.

No	Parameter
1.	Minimum channel spacing
2.	Bit rate / line coding
3.	Maximum BER
4.	Fibre type
5.	Maximum and minimum channel output power
6.	Minimum and maximum central frequency
7.	Maximum spectral excursion
8.	Minimum side mode suppression ratio
9.	Maximum channel extinction ratio
10.	Eye mask
11.	Maximum TX (residual) dispersion OSNR penalty
12.	Maximum ripple
13.	Max and min (residual) CHD
14.	Minimum optical return loss @ TX point
15.	Maximum discrete reflectance between RX and TX demarcation points
16.	Maximum differential group delay
17.	Maximum polarization dependent loss
18.	Maximum inter-channel crosstalk
19.	Maximum interferometric crosstalk
20.	Maximum optical path OSNR penalty
21.	Maximum and minimum mean input power
22.	Minimum OSNR
23.	Receiver OSNR tolerance
24.	Maximum reflectance of receiver

Table 2.2: Black Link parameters

Data of live use cases provisioning and operation (see 2.3) shows that not all parameters are critically necessary to establish an alien wave.

2.4.2 Integrated IP over Photonics

Juniper and Cisco adopted the above Black Link concept in the design of integrated optical routers. The DWDM interfaces available directly to such routers make the underlying DWDM network essentially a pure optical transport of the "black links" or "alien waves".

Both Cisco [Cisco nLight] and Juniper [Juniper ADVA] offer high levels of integration with the underlying black link transport, effectively making the DWDM interfaces on the routers manageable as "virtual" transponders with FEC from the DWDM side. Cisco has the advantage of a single-vendor solution, while Juniper uses as preferred manufacturer ADVA, for a fully converged portfolio. ACACIA has successfully produced a tuneable coherent 100G MSA module [Nelson et al.] with integrated SD-FEC pioneering the production of third-party 100G pluggables.

There is no reason to believe that other vendors' DWDM transport will not be capable of carrying the signals from such interfaces. The industry is reluctant to support third-party pluggables except in special cases where partnerships exist, as the deployment of this type of network leads to the break-up of proprietary management systems, and may lead to the breach and ultimate break-up of legacy maintenance contracts.

It is still mandatory for the DWDM line-side equipment on the same link to be from a single vendor, except in cases where no FEC is required. So far the only way to achieve real FEC interoperation between vendors on the line side [Wakim et al.] is using Reed Solomon (255,239) GFEC (ITU-T, 2012), which could theoretically expand the availability of alien waves and integration of DWDM in routers, but provides much less gain than proprietary algorithms (e.g. SD-FEC). Further advances in open FEC algorithms would provide an even greater range of open choices for connecting equipment from different vendors on the same alien wave link.

2.4.3 Open Line System

The Open Line System (OLS) concept originates from content/cloud providers such as Google [Vusirikala et al.] and Microsoft [Cox, J.]. At the base of their requirements are the bandwidth-hungry and cost-sensitive interconnections between data centres scattered around the world concentrating on the open WDM interface for transport through undersea cabling and DWDM systems. Both Google and Microsoft have publicly announced their interest and engagement in the development of an open WDM interface (called Open Line System), with simplified technical specifications and unified control (preferably based on Software Defined Networking (SDN)). The goal is to achieve true multi-vendor/multi-domain/multi-layer interoperability at the line side in order to avoid vendor lock-up and over-engineered transport solutions. Both parties are actively involved in the rapidly developing field of SDN and have contributed to the development of NETCONF [NETCONF] and YANG-based [YANG] models to facilitate the automation of network element configuration. Despite the fact that the focus of both operators is not on traditional telecom networking, their push for opening up the WDM layer proves that concepts such as OLS and Alien Waves are not only of academic interest but have real business potential. An example of Google's vision for an Open Line System architecture is shown in Figure 2.10 below [ECOC].

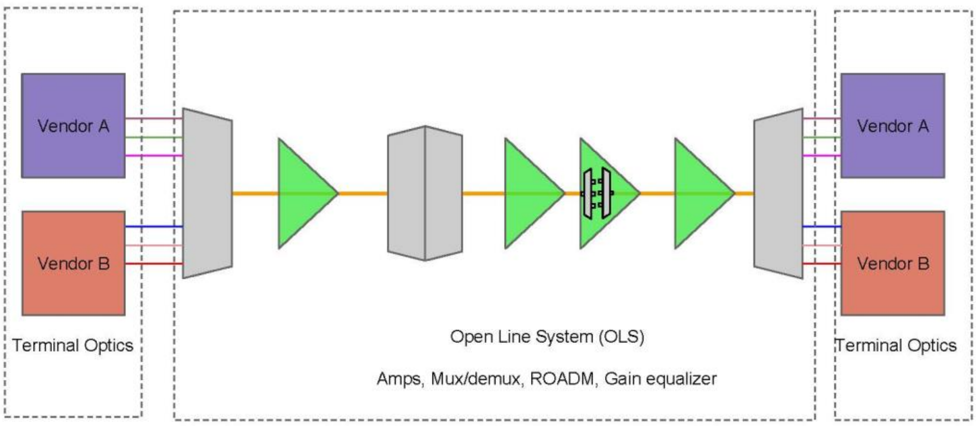

Figure 2.10: Google Open Line System architecture for inter-data-centre connectivity

2.4.4 Alien Wave Services

In 2014, a joint, non-proprietary white paper on IP and Optical Convergence was published [IP/OC WP], authored by network operators, and which outlined four essential use cases:

1. **Packet and optical data plane integration**. This use case outlines a purely optical transponder-less nation-wide infrastructure using pluggable optics directly to the routers.
2. **Packet and OTN integration in the core**. This use case takes advantage of a possible intermediate layer between the packet routing and the optical platform: OTN or Ethernet. A transponderless optical platform is also required for direct integration.
3. **Multilayer control and resilience**. This use case covers the operational aspects of the service: automated provisioning, dynamic readjustments, resilience mechanisms, and shared restoration scenarios.
4. **Multilayer planning and management**. This use case addresses management issues related to multilayer operations, including OSC integration and multi-vendor management support.

This would indicate that there is growing interest from the industry in using integrated multi-layer architectures to design their own networks. This is also confirmed by publicised use cases [McRae, N.] where telecom operators have tested and implemented alien waves within their domains.

Therefore, telecom operators do implement alien wave services provided there is a business opportunity for them. These services are not yet widely advertised [Dial Telecom], and each solution is tailored for the particular user/service, e.g. Google.

2.4.5 Current State of the Industry

In order to get a feel for the industry's stance with respect to the Alien Waves, the task attended the 2016 Optical Fibre Communication Conference in March 2016. At a glance, the conference programme reveals a great momentum within the industry with respect to discussing open optical systems and open transport platforms in general. The OFC conference is well-known for its versatile blending of industry and academia input and the topic of open transport networks (of which the Alien Waves concept is an integral part) was covered in several session of the technical programme as well as during the industry-driven sessions ('Market Watch' and 'Service Provider Summit').

On the exhibition floor, the major telecom players in the field (vendors and operators) gave their view on the latest trends in the fibre-optic telecommunications industry. Entire sessions were devoted to discussing open transport network infrastructures. The Open Line System and the latest developments within the Black Link standard were major discussion points in the renowned OFC Rump Session, entitled "Integrated (Black Box) vs. Disaggregated (White Box) networking". Another session during the Service Provider Summit entitled "Panel I: Vertically Integrated WDM Platforms vs. Open Line Systems" gave a clear indication that the field is driven by the major network operators (AT&T, NTT, Google, Microsoft and Verizon) and that equipment vendors are beginning to realise the benefits this paradigm shift can bring them. Accordingly, close collaborations between vendors and operators were demonstrated; NTT presented the first truly cross-vendor interconnection of components ("Black link"-style), and AT&T presented its initiative on providing open interfaces for all components within the WDM line system. The OpenROADM project was announced where specifications for these interfaces were proposed.

Beyond the purely technical aspects of the discussions, the topic of control of open transport interfaces was predominant. Linking open transport infrastructure with the SDN control plane architecture is inevitable and most operators (some in cooperation with their preferred vendors) are working on defining the proper abstractions and interfaces for a truly interoperable, multi-vendor, multi-technology control framework in support of open WDM systems (including Alien Waves). Transport SDN was a major focus point not only in the industry session but also in the academic field for several research projects presented at the conference. Even though none of the talks were specifically focused on providing Alien Waves (or in general open line systems) as a service to clients or end users, a clear trend was evident towards contributing to making Alien Waves more operational by using Transport SDN as an enabling technology.

In conclusion, the current trend within the industry in relation to open optical interfaces (including Alien Waves and Black Link) is clearly towards making the technology operational by increasing the flexibility of the control and management planes to handle such openness. The focus is on evaluating whether open interfaces are better (and if so, in which use-cases) compared to proprietary cutting-edge solutions by looking at deployment scenarios, business cases and CAPEX/OPEX perspectives. From the operational point of view, the focus is on integrating this emerging need for openness at the transport layer with the SDN control paradigm.

2.5 Service Implementation

2.5.1 Operational Aspects (Network Dynamics)

The Alien Wave service only covers availability of filtered optical spectrum, it is not a carrier or managed Ethernet service. The Alien Wave service is actually a filtered dark fibre service extended by one feature: optical amplification. By definition, the service is unprotected in the same way as a dark fibre service is unprotected. Resilience measures are possible in the single-domain scenarios (AW types I and II) if the layer 0 control plane is implemented. In terms of service design and implementation this means operators using Alien Wave services must only do so if there are sufficient backup paths that can provide bandwidth in the case of interruptions. This can be done using optical protection switch, OTN switching, Carrier Ethernet, or IP routing. The reason for this is that multiple layers of maintenance contracts define the service: dark fibre, provider optical systems, client optical transmission etc. As multiple stakeholders exist, and the cross-border service falls across multiple time zones, NRENs must comply with the service windows set by the NREN that provides them with the AW service.

An exchange of technical “supervisory” information needs to occur between the client and the provider beforehand to ensure the operation of the service:

- The customer should send the provider supervision data for control purposes, for example of compliance to the pre-defined parameters (optical format, frequency spacing and preFEC BER).
- The provider should send the customer supervision data for information purposes, for example on the operating status of the underpinned infrastructure (fibres, amplifiers).

The data shared, especially from the provider to the user, may be sensitive. It should therefore be kept to a minimum as relevant to the user and provider, and may be decided on a case-by-case basis.

Appendix B summarises the actual information exchange parameters based on the live use cases. This list is quite extensive and currently this exchange is specifically tailored and established on a case-by-case basis for each service.

For example, the addition and removal (e.g. by switching action of the service owner) of AWs over SURFnet's infrastructure frequently cause issues with NOC. Some systems allow easy masking of alarms, while others cannot perform this task. Because of the inherent heterogeneous shared infrastructure, a case-by-case implementation is necessary, which must consider:

- The need for implementing a test wave (yes or no).
- The need to exchange information on DWDM transceivers and amplifiers (This may not always be necessary if margins are high enough).
- Purpose of the AW: is this a wave that terminates on DWDM interfaces (type II) or continues in a different domain (type III), or is the wave switched and if so does this result in alarms and is this switching part of a NOC action or an automated protection action. In the latter case, more automation is required to screen alarms when alien waves are added or removed from the light system.

2.5.2 Monitoring

2.5.2.1 *Problem Description*

In an alien wave service, parts of the transmission path of the same optical signal are in different administrative domains. The provider (or providers) and users of the service must have visibility of the parameters of the signal through the optical path to ensure that the service levels are met. The optical service management and provision systems of operator networks are highly vendor-dependent and customised. An alien wave service requires only a small fraction of data from optical transmission management systems, therefore it must include a lightweight multi-domain platform to monitor service quality along the entire optical path.

2.5.2.2 *Architecture and Functional Requirements*

In order to monitor the AW services in a multi-domain environment, the following components should be included in the monitoring architecture, as shown in Figure 2.11.

- **Data Collector** – The Data Collector is responsible for collecting monitoring data. Each domain can install one or more Data Collectors in their network and configure them to collect different parameters. The Data Collector works in two modes, pushing and polling. In the polling mode, the Data Collector periodically queries the physical device for specific parameters and sends the data to the Central Manager. In the pushing mode, it listens on specific ports and lets the device push data to it. The polling mode is more suitable for non-critical parameters, e.g. bandwidth, while the pushing mode is normally used by time-sensitive parameters, e.g. interface 'up' and 'down' status. The current implementation of Data Collector uses SNMP query, which means the NRENs must allow the Data Collector to perform direct SNMP query on their equipment. This may not be possible for some NRENs due to operations policies, security concerns or equipment limitations. To monitor the AWS, Data Collector is therefore required to interface with the local network management system. An adaptation module should be implemented as shown in Figure 2.11. The adaptation module should be responsible for interfacing with various management systems, e.g. Incinga, Nagios, Cacti, etc. For the AWS, the provisioning team and monitoring team should collaborate on the adaptation to the local system.

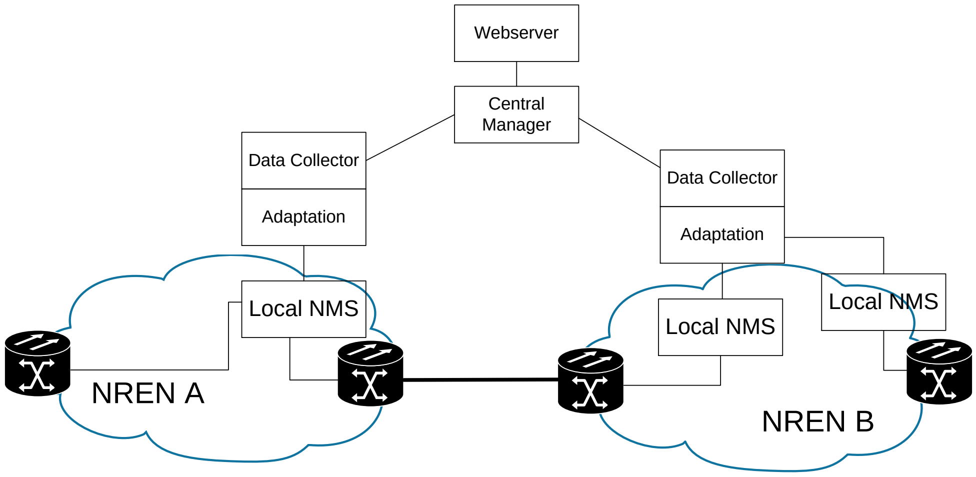

Figure 2.11: Alien Wavelength Service monitoring architecture

- **Central Manager** – Central Manager is the central component of the monitoring system. The circuit topology should be sent to the Central Manager by the provisioning system or administrator before the monitoring can begin. Topology information is stored in the central database for later circuit reconstruction. When the monitoring progress begins, the Central Manager processes the monitoring data from different Data Collectors and stores it in the database. The current implementation of the Central Manager requires little modification in order to provide a monitoring service to the AWS.
- **Webserver** – Webserver processes user requests and presents the monitoring results. And it should also allow users to manage links and users, search results, and see a graphical representation of the monitoring data.

2.5.2.3 *Alien Wave Service Monitoring Solution*

Circuit Monitoring [CMon] is a distributed multi-domain monitoring system. CMon fetches monitoring data from domains and splices different segment performances to show for the whole connection. CMon is able to provide end-to-end circuit monitoring services with great flexibility, extensibility, and vendor independency, regardless of the underlying circuit provisioning systems (CPSs). To offer AWS easy-to-use multi-domain optical link monitoring, the data collector, CMon Agent, should be installed and correctly configured by each domain. Each CMon Agent is managed by an NREN and will periodically collect metric data from the equipment and store it in the central database held by the CMon HQ. This allows the HQ to reconstruct the link topology and map the received monitoring data accordingly.

The architecture of CMon fits very well into the monitoring requirements mentioned above. Alien wave services, especially Type-III services, can take advantage of the monitoring service provided by CMon.

CMon Workflow

The CMon workflow is as follows (Figure 2.12):

1. **Topology construction**:

   The AWS administrator enters the circuit topology information via the CMon Webserver. The information is sent to CMon HQ and stored in the DB hosted on the same VM.
2. **Monitoring data collection**:

   The CMon Agent hosted by each participating NREN periodically fetches the monitoring data and sends it to CMon HQ.
3. **Data storage**:

   Upon receiving the data, CMon HQ stores it in the DB.
4. **Data presentation**:

   When requested by a user, CMon Webserver reads the monitoring data from the DB and matches it with the circuit topology, so that the user can see the metrics on the multi-domain circuit in seconds.

Monitoring Metrics

Monitoring metrics used in the live demonstration (see 2.5.3) are outlined in Table 2.3 below.

Parameter	Interface	Name	Options	OID/MIB
Interface status	PTP		Administration status	.1.3.6.1.2.1.2.2
Transmit power	PTP	OCH-OPR	Optical PM untimed	.1.3.6.1.4.1.562.68.10.1.1.2
			Optical 15 min	.1.3.6.1.4.1.562.68.10.1.1.4.1.1
			Optical 24h	.1.3.6.1.4.1.562.68.10.1.1.4.2.1
Receive power	PTP	OCH-OPT	Optical PM untimed	.1.3.6.1.4.1.562.68.10.1.1.2
			Optical 15 min	.1.3.6.1.4.1.562.68.10.1.1.4.1.1
			Optical 24h	.1.3.6.1.4.1.562.68.10.1.1.4.2.1
Errored seconds	OTUTTP	OTU-ES	Optical PM untimed	.1.3.6.1.4.1.562.68.10.1.1.2
			Optical 15 min	.1.3.6.1.4.1.562.68.10.1.1.4.1.1
			Optical 24h	.1.3.6.1.4.1.562.68.10.1.1.4.2.1
Severely errored seconds	OTUTTP	OTU-SES	Optical PM untimed	.1.3.6.1.4.1.562.68.10.1.1.2
			Optical 15 min	.1.3.6.1.4.1.562.68.10.1.1.4.1.1
			Optical 24h	.1.3.6.1.4.1.562.68.10.1.1.4.2.1
Pre-FEC Bit Error Rate	OTUTTP	OTU-PRFBER	Optical PM untimed	.1.3.6.1.4.1.562.68.10.1.1.2
			Optical 15 min	.1.3.6.1.4.1.562.68.10.1.1.4.1.1
			Optical 24h	.1.3.6.1.4.1.562.68.10.1.1.4.2.1
Alarm table				.1.3.6.1.2.1.118.1.1.2

Table 2.3: AW monitoring data for demonstration

CMON Adaptation for AWS Monitoring

The architecture topology of CMon is a star topology. NRENs can set up their Agent to monitor different metrics using various methods:

- **Solution A (SNMP Query)**

  Given the architecture described in Figure 2.12, CMon Agent should include the MIB OIDs of the aforementioned equipment metrics. The NREN can then install and configure the CMon Agent on a virtual machine in their domain following the CMon Installation Guide [CMon IG].

  Once it has been correctly configured, the CMon Agent installed in the NREN can periodically query the metrics from the device and send the monitoring data to the HQ.

  The administrator of the AWS should input the link topology into the database via the GUI so that monitoring data can be correctly mapped into the link skeleton.

- **Solution B (SNMP Traps)**

  As shown in Figure 2.12, where it is not possible to perform a direct SNMP query in the NREN domain, SNMP traps can be configured in the equipment and sent to the CMon Agent periodically.

  The NREN should install and configure the CMon Agent on a virtual machine in their domain following the CMon Installation Guide [CMon IG]. The NREN will have to configure the equipment to send SNMP traps to the Agent at a fixed interval so that data is pushed to the Agent periodically instead of being polled as in Solution A.

  This solution can ensure that the address of the provisioning equipment of the NREN is invisible to the CMon Agent in case of security policy concerns.

- **Solution C (Interfacing with NMS)**

  As depicted in Figure 2.12, for NRENs where neither an SNMP query nor an SNMP trap is possible, the CMon Agent is required to interface with the local NMS of the NREN. This integration is not supported in CMon Agent, thus requires additional development and customisation.

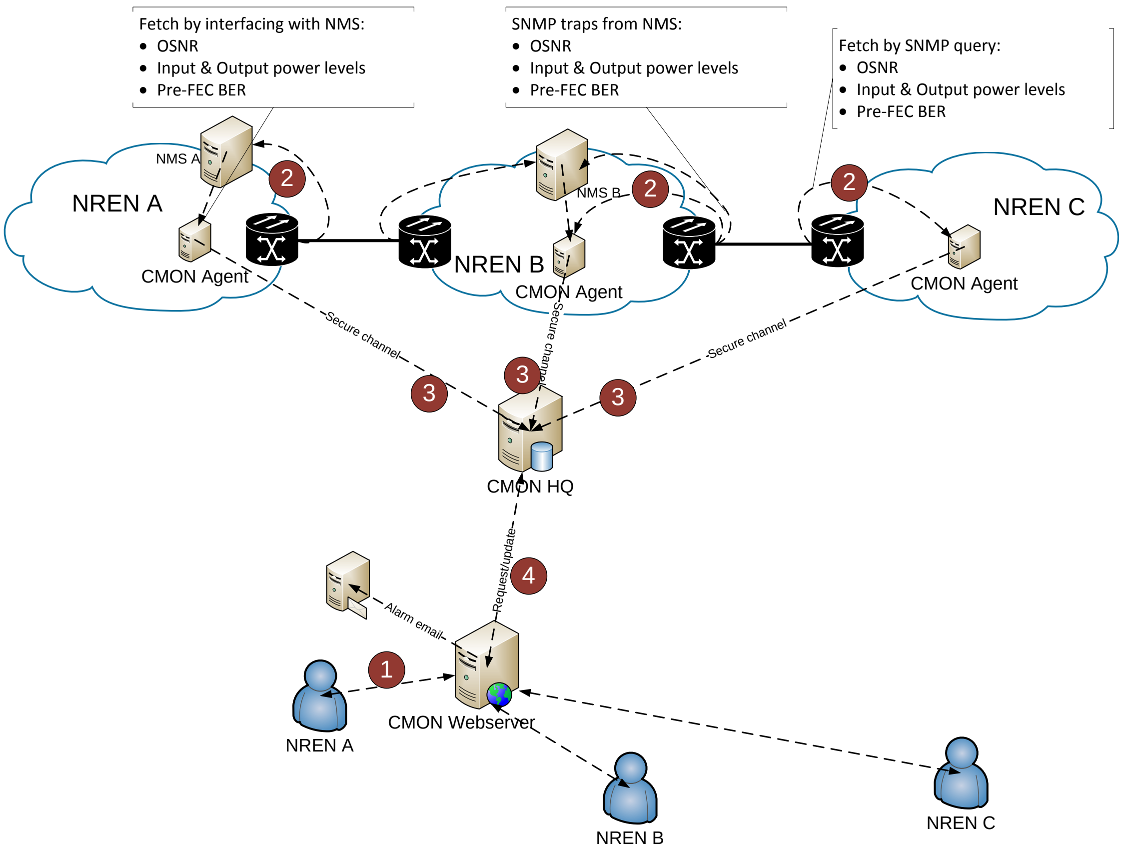

Figure 2.12: CMon architecture and workflow

2.5.3 Monitoring of Live AW Service

Currently a live AW service operates between SURFnet and NORDUnet through a PoP in Hamburg, as shown in Figure 2.6. In this situation, SURFNET is not able to monitor the performance of the wavelength running through its network since the transponders are not in their own domain. The CMon tool allows SURFNET to monitor performance data from NORDUnet's transponders.

A CMon Agent to collect metrics has been installed and operates in NORDUnet based on the monitoring architecture mentioned in the previous section. The implementation topology currently covers NORDUnet equipment in Amsterdam and Hamburg as shown in Figure 2.13.

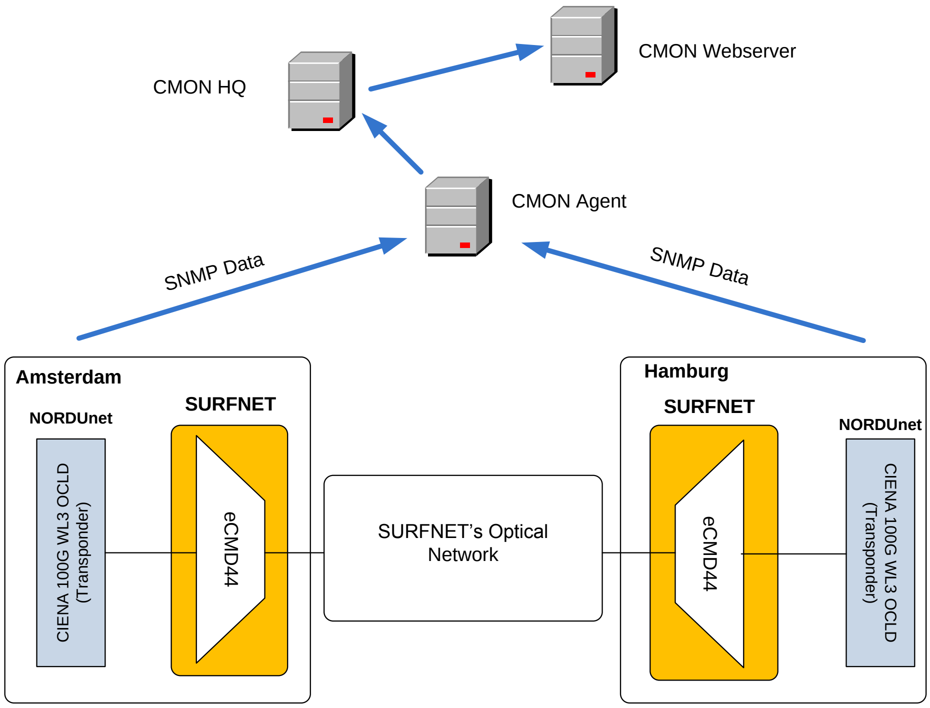

Figure 2.13: CMon monitoring implementation topology diagram

The administrator of the AW link can use the CMon console to monitor the following metrics:

- Operational and admin status;
- OCH-OPT (optical transmit power), real monitoring data;
- OCH-OPR (optical receiver power), real monitoring data;
- OTU-ES (errored seconds);
- OTU-SES (severily errored seconds);
- OTU-PREFBER (pre-FEC BER).

Main challenges:

- Security needs to be taken into consideration when enabling SNMP in the network. CMon Agent supports SNMP v.2. When using SNMP v.2 in the Ciena equipment [Ciena]some predefined users exist to communicate with the node. It is necessary to change the default communities in those users with SNMP write access. Moreover, it is recommended to restrict access of CMon Agent to only those nodes that are being monitored. The use of SNMP v3 would allow the definition of users with specific rights and individual access credentials.

- The management network of a photonic network is usually protected and resides behind a firewall to protect the network from undesired access. If the CMon agent is located outside the management network, it is necessary to design and plan access to the data according to company security policies, which is not always a straightforward task.

- CMon needs specific vendor MIBs to be able to retrieve performance data from the nodes.

2.5.4 Distributed Wave Exchange Proposal

The open lightpath exchange (OLE) concept is not new and is an established GÉANT service [GÉANT OSD], while further applications were researched by the JRA1 task in GN3plus [D12.1 (DJ1.2.1)]. The Global Lambda Integrated Facility [GLIF] also works towards the same multi-domain lightpaths scenario.

The concept of photonic open exchange is based on use case 3 (see 2.3.3). Extrapolating its further development, a hypothetical 3rd party coming from direction B and direction C to the hypothetical 3rd PoP in Brussels is added to the use case.

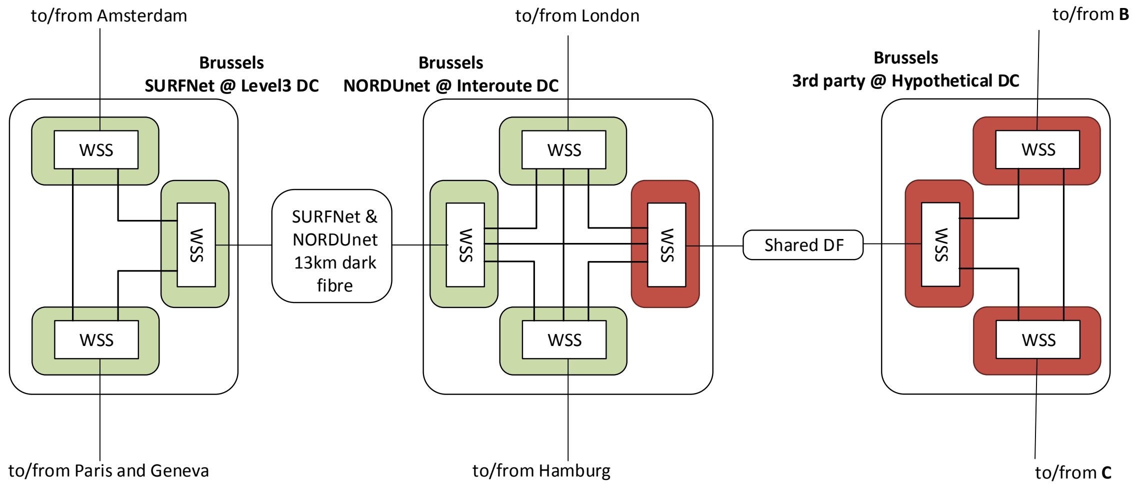

Figure 2.14: Evolution of use case 3 into photonic exchange prototype

This evolution requires a special setup specifically for the node where the new direction is added to enable the other parties to use the infrastructure without additional upgrades. The infrastructure can be used without regeneration as the new node is located in the same city. This however does not necessarily mean, that the infrastructure will not require regeneration at some point, for a long distance wave outside the city, but this is outside the scope of optical exchange.

The distributed OLE concept is applicable to the photonic layer with the restrictions outlined below:

1. **Spectrum**: The most popular and cost-effective systems have limitation of 80 waves per C-band. Thus, the number of actual lightpath connections that can be established is very limited even if a DF infrastructure could be dedicated to the photonic exchange. The federated use of infrastructure (e.g. NREN fibres) would mean that only a portion of optical spectrum would be available, further limiting the number of possible lightpaths.
2. **Distance:** The most popular line interfaces (transponders) support signal transfers up to 1000km without OEO regeneration. This is therefore the longest lightpath such an infrastructure can feasibly support. Longer lightpaths have to be regenerated using at least transponders of the same make as endpoints effectively splitting the lightpath in two or more photonic spans. This requirement to deploy additional physical infrastructures increases costs, time-to-service and decreases the flexibility of the OPX infrastructure.

3. **End-point handoff**:
    a. DWDM side: the current state (see 2.4.2) of DWDM line interfaces (transponders) mandates that the two connecting interfaces have to be compatible, which means in most cases they have to be produced by the same vendor. Users of either OPX or OPX services have to ensure handoff to the extent of compatibility of connecting equipment. Otherwise, the data flow will not be possible despite dedicated optical spectrum resource being made available.
    b. Client side: DWDM transponders and the underlying photonic layer do not decode client data. To establish end-to-end data flow across the exchange, equipment client-side interfaces must match, e.g. Ethernet, SDH, or OTN.

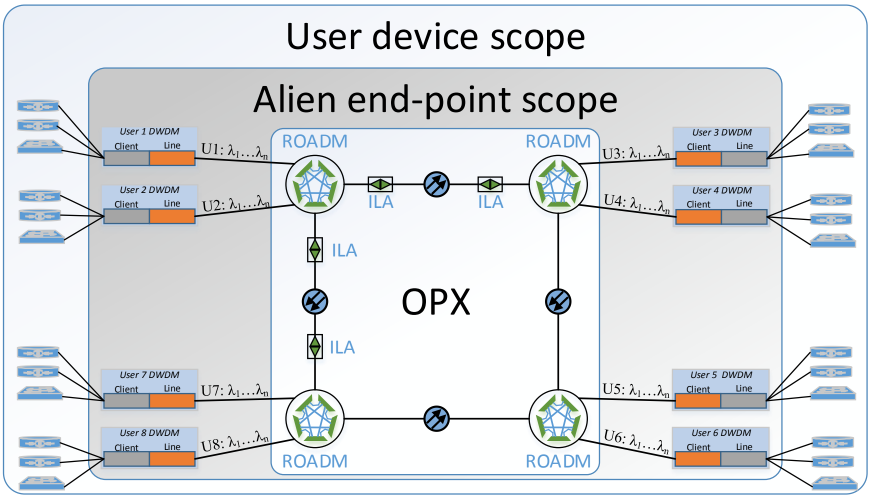

Figure 2.15: Layer structure of Open Photonic Exchange

The users are free to choose the make and type of their DWDM and routing/switching equipment, subject only to the availability of corresponding end-points for lightpath interconnection. The only limiting factor for scalability of such exchanges is the overall distance of optical signal transmission without OEO regeneration. Currently the estimated maximum optical transmission path does not exceed 2000km for long haul, and 1000km for short haul, using commodity terrestrial equipment for speeds up to 100G using QPSK modulation (e.g. DP-QPSK).

The OPX concept within the GÉANT/NRENs ecosystem (Table 2.4) is mapped by evaluating it against other possible networking contexts within the ecosystem. Cross-domain photonic exchanges spanning multiple contexts are also possible where metropolitan networks mix tightly with the national NREN infrastructure.

Scope	Analysis
Metro	Open photonic exchange on the metropolitan scale is the easiest implementation. It allows the shared use of DF and shared costs without any limiting factors such as dispersion and optical transmission distances. Potential users of such exchange are universities and other R&E centres in the same metropolitan area. Potential benefits are shared costs of DF and core DWDM components, independence of operation and flexibility.
National/ NREN	Technical implementation would be very different from country to country because of the greatly differing distances involved. As no standard solution is possible, each design has to be tailored to the specific NREN's needs. Potential users of such exchange are ISPs, big research instrumentation sites e.g. CERN, and possibly other governmental networks e.g. public administration. Potential benefit is the shared cost of DF and core DWDM infrastructure.
International/ regional	The collaboration between NORDUnet, SURFnet, PSNC, and GÉANT has shown that the international photonic exchanges provide most benefits in the cost savings and network extension capabilities. Potential users are connected NRENs, GÉANT, international research centres e.g. JIVE, and other partners. Other partners may include commercial entities e.g. cloud service providers. Potential benefits are cost savings, network extension, and independence of operation.
Pan-European/ GÉANT	The distances will be a limiting factor in deploying such exchange on the pan-European scale. Each connected NREN will have to consider the signal regeneration or will be limited in the reachability of the network. Potential users are NRENs and international research centres. Potential benefit is the reduced costs of operation.

Table 2.4: Analysis of OPX deployment within the GÉANT ecosystem

Based on the implementation and analysis of the use cases it is clear that the most efficient OPXs are on the metro level, regional, or between neighbouring countries. An illustration of a regional photonic exchange is provided based on a hypothetical setup around the Baltic Sea. Currently such a project is not possible because not all the DF routes are available to the R&E community. The illustration uses potential DF routes based on the results of the GÉANT regional studies conducted in the Baltics and Nordics during the GN3Plus project [D5.27_DS1.1.2].

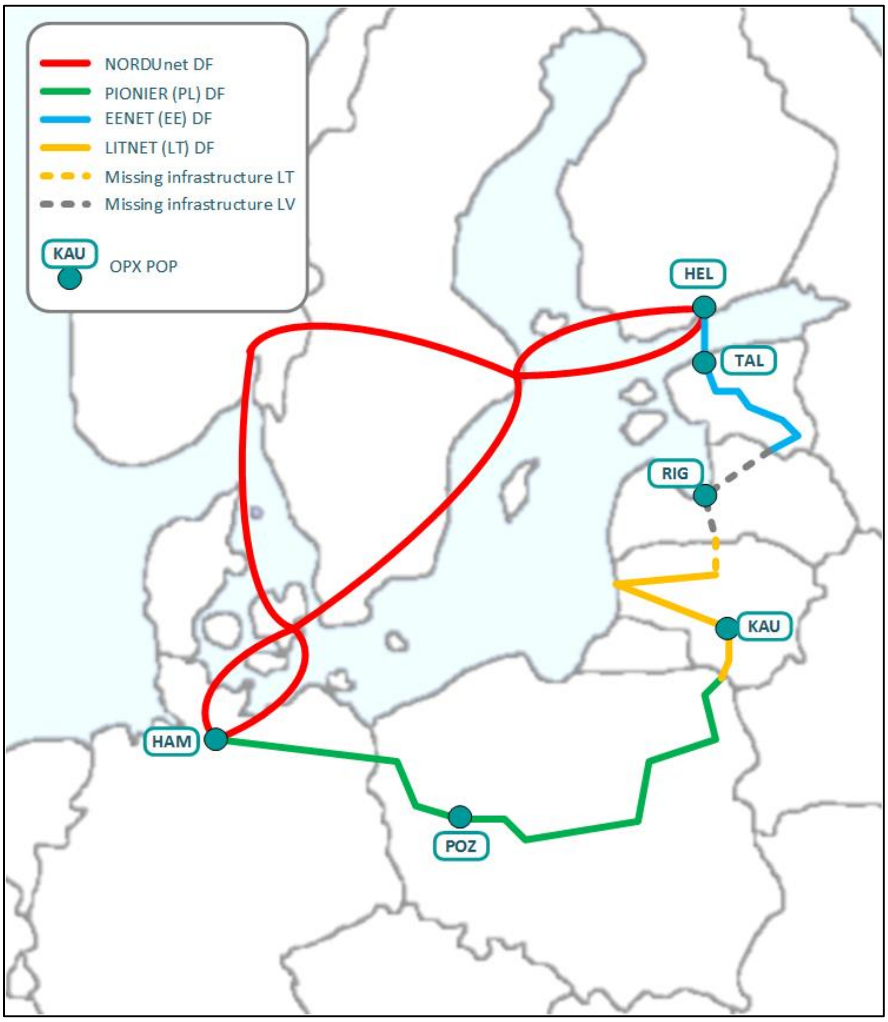

Figure 2.16: Regional OPX illustration

No.	DF span		DF route distance, km
	POP A	POP B	
1	Helsinki	Hamburg	1830
2	Hamburg	Poznan	725
3	Poznan	Kaunas	1300
4	Kaunas	Riga	530
5	Riga	Tallinn	510
6	Tallinn	Helsinki	105

Table 2.5: Distances between POPs for Baltics OPX case

From the distances shown in Table 2.5 above, it is clear that any alien wave service following a path from Hamburg to Helsinki would need to be regenerated. Even the regional photonic exchanges offer only partial paths to the connected parties. Service setup is not seamless across the entire OPX topology. Where connectivity services require regeneration, costs and provisioning times increase.

3 Integrated Mobility Service Blueprint

3.1 Implementations within the R&E Ecosystem

The literature defines various types and kinds of mobility: host mobility [Snoeren et al.], network mobility [Lach et al.], [Zhang, L.], etc. This deliverable addresses users' mobility needs within the network. For that purpose reference is made to the definition given in [Geihs et al.] briefly outlined in this section.

An integrated mobility proposal must consider several aspects:

- The capacity for users to use services and initiate new connections regardless of their location.
- Reduction of the response time for remote mobile users.
- The capacity to retain existing connections regardless of the users' movements (roaming).

When considering user mobility, three main scenarios are envisaged:

1. **Wandering:** The user is on the move within a particular area. The original literature referred to addresses the movement of the user within an office building during working hours. The R&E community user base (students & staff) are more likely to wander within the area of a campus or particular part of the town.
2. **Travelling:** This type of mobility addresses the issues involved when a user is on the move travelling from point A to point B, e.g. on a bus or train.
3. **Visiting:** This type of mobility occurs when the user visits another organisation.

The R&E community does not offer an integrated mobility platform to address all three kinds of mobility. However, several technical enablers have been implemented:

- **eduroam AAI confederation** originally, addresses mobility requirements of the "visiting" type. The expansion of eduroam to cover public areas and transport such as buses, airports and trains, partially addresses the mobility needs of the "travelling" R&E community. eduroam is implemented as a federation, with some areas serviced by organisations such as universities, colleges or schools, and others by NRENs, or even third parties. eduroam is not designed to provide full roaming, and does not enforce any data access policy.
- **L2 mobility** is implemented on most campuses and university premises. It addresses the "wandering" type of mobility requirements within the domain of a single entity (organisation) managing the network (operator). Users do not have to re-initiate connections as they

"wander" from one access-point to another. L2 mobility addresses the roaming part of the requirements.

Mobile network services for R&E community members. The mobile network service effort is not sufficiently coordinated but randomly implemented. The most popular type of implementation is a wholesale contract with mobile operators for their services. Usually these wholesale agreements happen within each university, some NRENs do provide mobile broadband and phone contracts to users [mobile_data].All the services implemented within the NREN community so far have addressed each type of mobility individually. Integration between all types is missing from the portfolio. An integrated mobility proposal:

- Should extend the boundaries of a particular R&E institution's network.
- Requires centralised technical (protocols, network equipment, etc.) and administrative (contracts) resources.

This means the NRENs are the best placed to implement an integrated mobility service.

3.2 Integrated Mobility Use Cases

Wi-Fi as a service (WaaS)

R&E institutions increasingly rely on Wi-Fi networks to enable users to access their ICT infrastructure. Wi-Fi nowadays is considered a given, and users (and especially freshmen) simply assume it will be available. The deployment and maintenance of a high-speed Wi-Fi network in an R&E institution, however, is a complex task that requires a wide variety of network architecture parameters to be taken into consideration. Not all institutions and still very few schools and vocational training centres have such expertise, which they are reluctant to gain as it is beyond their core activities.

ICT in general and Wi-Fi in particular has reached a level of maturity that allows institutes to use it as a common tool. The current solution, however, effectively means that the same Wi-Fi wheel is re-invented at each institution. It causes duplication of equipment and licenses, but also duplication of expertise and capacity needed to deploy and maintain the equipment at each institution. The Wi-Fi requirements of the R&E community differ significantly from those of private homes, small businesses or corporations in terms of number of simultaneously connected users, time-scale for the use of network resources, required features and density of areas where Wi-Fi signals are needed. However, requirements do not differ significantly between the various educational institutes within the R&E community. This motivated the task to consider expanding the NREN's fixed network services to locations inside the institutes and to offer Wi-Fi as an NREN service (WaaS).

Inter-domain roaming

The expansion of eduroam and mobile coverage has led to a situation where the "Wandering" type of mobility offered within the premises of single organisations is no longer sufficient. It is quite common to have a situation where the premises of two or more R&E institutions are in close geographical proximity thus resulting in overlapping eduroam islands. Current applications including online real-time communication require seamless connectivity. To meet these requirements, inter-domain roaming must be implemented. There are two scenarios for inter-domain roaming:

1. The first scenario occurs where there is more than one adjacent eduroam service area operated by different entities (e.g. Universities) so that their signals overlap (Figure 3.1). User roaming mandates switching the entire network context including IP addressing, access policies, etc. This causes a disruption of services dependent of network context, e.g. VPN tunnels, and TCP connections
2. User device roaming between Wi-Fi and mobile networks comprises the second case for inter-domain roaming. This scenario leads to an interdomain vertical handover in heterogeneous radio access networks. Interdomain vertical handover usually results in a change in the home IP address of the end device.

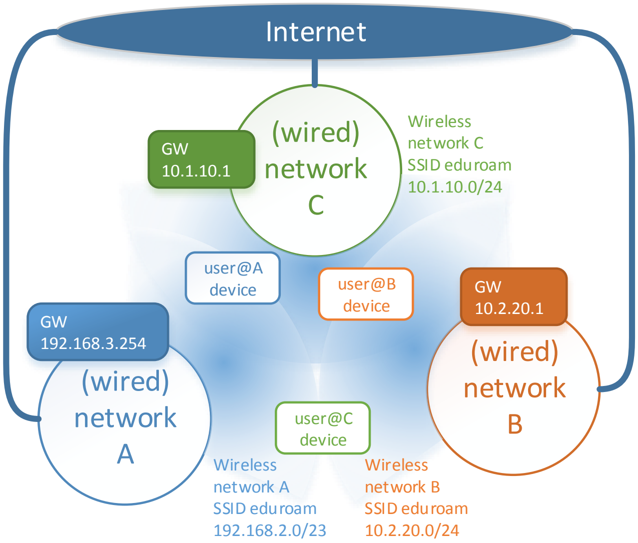

Figure 3.1: Example scenario of users switching between different eduroam domains

3.3 WaaS Implementation

The architectural considerations and proof-of-concept environment for WaaS implementation were set out by JRA1 T2 in GN3plus [D12.1 DJ1.2.1]. This section describes the lessons learned from procuring a WaaS solution and the operational steps taken.

3.3.1 WaaS Procurement

Various types of architectural designs are available on the Wi-Fi market, including the following scenarios:

- All traffic must pass a dedicated Wi-Fi controller.
- Only signalling traffic passes the controller.
- The controller functionality is divided among access points.
- One of the access points executes the controller functionality.

Each solution has its advantages and disadvantages and selecting the best option for WaaS requires considerable operational knowledge of each of the solutions. Since this operational knowledge is lacking at the NRENs, it was considered preferable to procure a third-party integrator who could both deliver and manage the WaaS. The procurement was conducted in two steps. Step 1 comprised an open call for all integrators to submit details of their experience both with Wi-Fi and with the R&E community. Experience with and certification of multiple Wi-Fi vendors was an important criterion in SURFnet's case, as it is considered indicative that the party has knowledge of the broad set of architectural solutions available on the market and that they can use this knowledge to select the best fit for Wi-Fi as an NREN service.

3.3.1.1 *Tenderer Selection*

Based on the above criteria, five companies were selected to proceed to Step 2. These five tenderers were invited to propose and offer a Waas solution for the R&E community. The procurement asked mainly for functional solutions. The companies were provided with a description of the required Wi-Fi as a service offering, as well as a proposed SLA between the NREN and the institutes. A few mandatory requirements were added on the basis of this WaaS service description and SLA, including:

- Support of 802.11ac
- IPv6.
- Ability for institutes to implement their own security policies, tools and equipment to gain insight in the reliability and the performance of WaaS as experienced by users of WaaS, support to first line support at institutions.
- Differentiation of client groups.
- Support of real-time applications.

3.3.1.2 *Award Criteria*

The five tenderers were awarded scores on their submissions based on five award criteria:

1. Proposed architecture and design.
2. Availability and reliability of their solution.
3. Evolution and (future) development of features.
4. Operational services capacity
5. Proposed SLA and price.

The price had to be calculated on a per-access point fee (accompanied by initial fees for installation and for adding a new R&E site). The overall awarding score was a weighted sum of these individual criteria.

3.3.1.3 *Responsibility Assignment Matrix (RASCI)*

The proper functioning of WaaS depends on various network components, including the ICT infrastructure of the institution, the connection to the NREN and the NREN's connections to other networks. Outsourcing of functions is common hence other parties may manage these connections or the associated switches/routers. In addition to network components, policies with respect to wall outlets, cabling and placement of access points often vary by institution. Clear descriptions are needed to ensure that every party knows its role and its responsibilities as part of the WaaS provision. A responsibility assignment matrix, also known as RASCI matrix, was used for this purpose. The letters are defined as follows:

- **Responsible (R)**: The party who does the work to achieve the task. There is at least one role which is assigned a responsible 'R' type.
- **Accountable (A)**: The one ultimately answerable for the correct and thorough completion of the deliverable or task, and the one who delegates the work to those responsible. In other words, an accountable (A) party must sign off (approve) work that the responsible party provides. There must be only one accountable party specified for each task or deliverable.
- **Support (S)**: Resources allocated to the responsible party. Unlike the consulted party, who may provide input to the task, support helps to complete the task.
- **Consulted (C)**: The party or person who provides information for the project or task and with whom there is two-way communication. These are usually several people, often subject matter experts.
- **Informed (I)**: The party or person who is kept informed about progress and with whom there is one-way communication.

Three interested parties in the provision of the WaaS are identified: a) the research/educational Institute (Institute), b) the WaaS Innovation Partner (WP), and c) the company that runs the national research network (NREN). The roles assigned to each party associated with the tasks in WaaS are shown in Table 3.1 below.

	Institute	WP	NREN
Design			
WaaS solution architecture		R	ASC
New WaaS customer or site			
Intake of new WaaS customer or site	C	I	RA
WaaS site roll-out management	SC	RA	I
Rollout-plan	SC	RA	I
WaaS network configuration	R	RA	R
WaaS initial configuration (staging)		RA	
WaaS preparation at Institute's premises	RA	I	
WaaS hardware delivery	I	RA	I
WaaS AP installation on site	RA	I	
WaaS initial commissioning (Testing)	CI	RA	
WaaS site completion (Acceptance)	S	R	A
Support			
Local client support	RA	CSI	
Incident management	CIS	R	A
Problem management	CIS	R	A
New features/ new opportunities		S	R
Security incident	IR	SR	AR

	Institute	WP	NREN
Design			
Operational			
Monitoring Institute LAN	RA	I	
Ensure availability SURFnet Network	I	I	RAC
Monitoring WaaS components	I	R	AI
Central AAA Radius Infrastructure	I	I	RAC
Network Services	RSCI	RASCI	
Change Management	I	R	A
Capacity Management	CI	R	A
Configuration management		RA	
Physical replacement of decentralized WaaS components	RA	SC	I
Reporting			
WaaS Management Reporting (SURFnet-Institute)	I	SI	RA
WaaS Management Reporting (partner-SURFnet)		RA	I

Table 3.1: RASCI matrix for WaaS

3.3.1.4 *Service Level Specification (SLS)*

The service contract describes the Wi-Fi service in terms of what is expected, and how issues should be reported, as well as how long it should take to resolve them. These expectations must be described in a SMART manner, so that both parties can determine objectively whether the service complies with the proposed offering. Service level commitments and related business agreements must be defined and apply to the designated area where Wi-Fi will be offered as a service. Since these commitments may vary by country and depend on the NREN's service offering, only general metrics can be given in the scope of this deliverable. Commitments are defined in Key Performance Indicators (KPIs). Besides the ability to verify the service commitments objectively, the institution can use the KPIs to determine whether the Wi-Fi infrastructure is suitable for specific ICT tasks or activities. Examples include: committed data rate of 2Mb/s at the application layer, mean date rate over 24 hours of 10Mb/s, minimal signal strength in the designated WI-Fi area of -62dbm, RTT < 15ms, jitter in RTT < 15ms, maximum number of clients per AP: 50, service availability: 99,5%, service reachability: 99,9%. Service reachability depends on the proper functioning of controllers and access points. Spare access points at the institution minimise the likelihood of WaaS failures due to a malfunctioning access point.

3.3.1.5 *Launching Customers*

The process to add new customers is described step by step below. An important criterion for WaaS is that it should eliminate the need for Wi-Fi expertise at the institutions:

1. The institution reads the WaaS service description which also includes the required conditions (e.g., support requirements of access switches: PoE+, 802.1p, trunk ports, etc.) and sends a request for more information including price. The request should include floor plans of the building showing the number of people in each area and an overview of the current Wi-Fi implementation.

2. Based on the floor plan, the NREN estimates the number of APs needed and provides an indicative quote.
3. Based on the price estimation, the institution decides to implement WaaS.
4. The NREN sends a list to the institution to collect network details (DHCP server, VLANs, user groups, QoS settings, Radius servers, etc.) and makes an appointment for a site survey (including RF-planning).
5. The site survey takes place and the list of details is discussed. Once the exact number of APs needed is established an offer is made and the contract signed.
6. Based on the site survey and the details provided in the exhaustive list produced during step 5, the institution locates where wall outlets for APs are needed and adapts the internal cables and switches accordingly. The NREN orders equipment and draws up a technical design of the WaaS site as well as a plan to verify the design.
7. The NREN verifies the technical design at the location and the WaaS service starts.

3.4 Inter-Domain Roaming Proposal

3.4.1 Inter-Domain Mobility Management at Layer 3

A network-based IP mobility management protocol Proxy Mobile IPv6 (PMIPv6) can do away with the need for TCP reestablishment by using the same home network prefix. However, the current version of PMIPv6 can only provide seamless handover within one domain. To resolve this issue, an extended PMIPv6 is proposed as shown in Figure 3.2.

The proposal also addresses the use of SDN together with PMIPv6 extensions to assist inter-domain mobility. On the signalling path, the PMIPv6 can be extended to enable inter-Local Mobility Anchor (LMA) binding update. Once the binding is completed, the two SDN controllers, one in the home domain and the other in the visiting domain, will jointly establish an inter-domain IP tunnel to route the downlink traffic to the moving device.

The proposal assumes the scenario where handover occurs between two adjacent domains, i.e. the home domain and the visiting domain. An extension to the message format of PMIPv6 is required in order to make inter-domain handover seamless. A new identifier digit, *I*, will be added to the Proxy Binding Update (PBU) and Proxy Binding Acknowledgement (PBA) message format in the Reserved section as shown in Figure 3.2. This is required to distinguish inter-LMA PBU or inter-LMA PBA messages from the normal PBU and PBA messages that are exchanged between LMA and the Mobility Access Gateways (MAG).

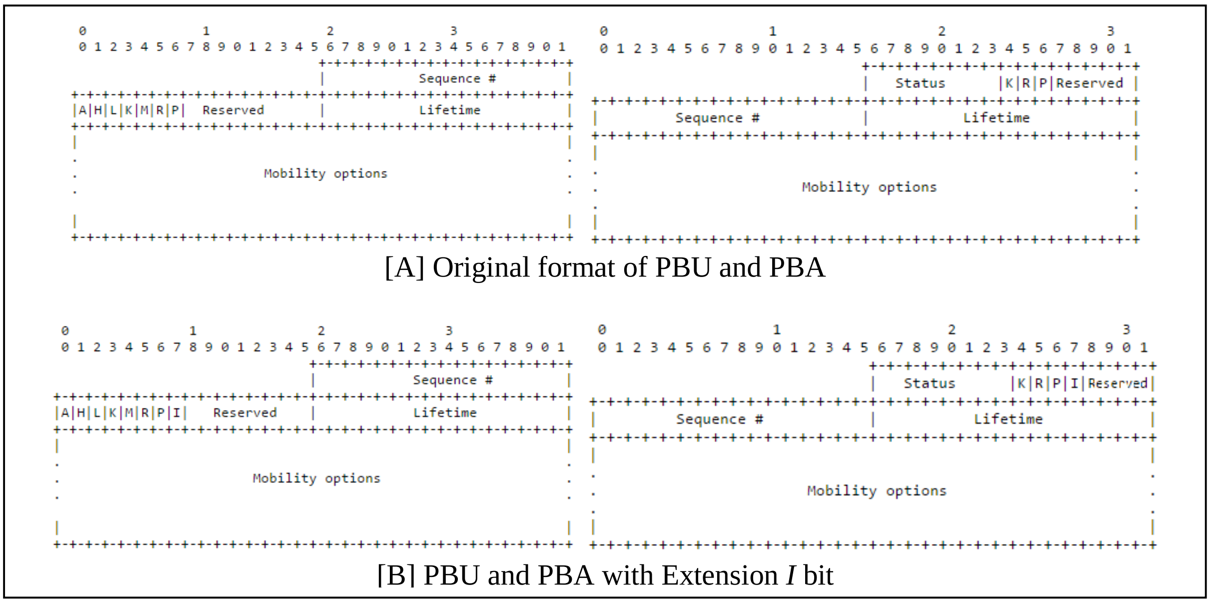

Figure 3.2: Proposed PMIPv6 extension PBU and PBA formats

However, the extension requires an inter-domain tunnel to be established when a handover is detected. As a result, the performance of such handover architecture can be limited due to the overhead latency generated by frequent establishment and tearing down of inter-domain tunnels when many devices are moving across domains. The handover starts when the MAG detects the visiting mobile device, and ends when the visiting mobile device has successfully received a Routing Advertisement (RA) message from the MAG, as shown in Figure 3.3.

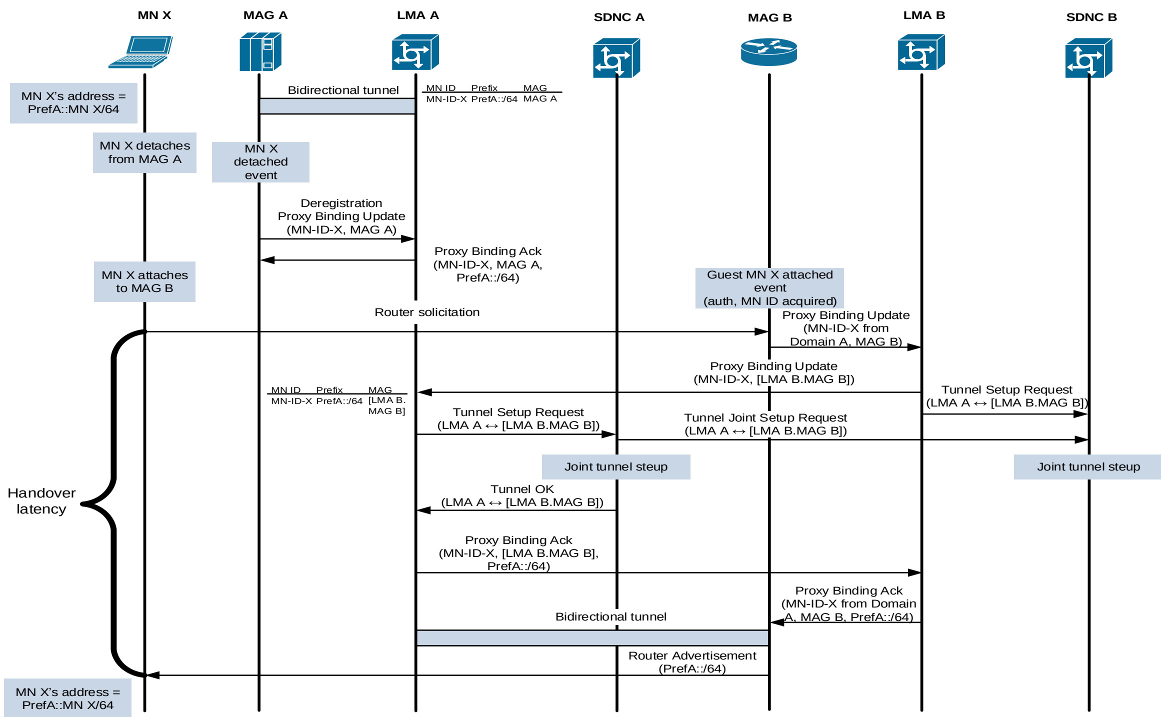

Figure 3.3: Inter-domain tunnel establishment in the proposed PMIPv6 extensions

The total handover latency will be heavily affected by the tunnel establishment delay. Since there is no delay guarantee from SDN-assisted inter-domain tunnel establishment, user traffic can be severely interrupted due to TCP retransmission or even TCP reestablishment. Thus a long-term static inter-domain tunnel between the adjacent LMAs is preferred in order to reduce the overall handover latency. The number of IP tunnels will increase exponentially in relation to the number of adjacent domains as shown below:

$$N = N_{LMA} \cdot (N_{LMA} - 1)/2$$

Where N is the number of interdomain IP tunnels and N_{LMA} is the number of domains based on the assumption that there is one LMA per domain. For example in Figure 3.4, $N = 3$ when there are 3 domains, and $N = 21$ when there are 7 domains. This also indicates that if the system needs to add one more domain, the number of new IP tunnels that need to be set up will be the number of existing domains:

$$\Delta N = N_{LMA}$$

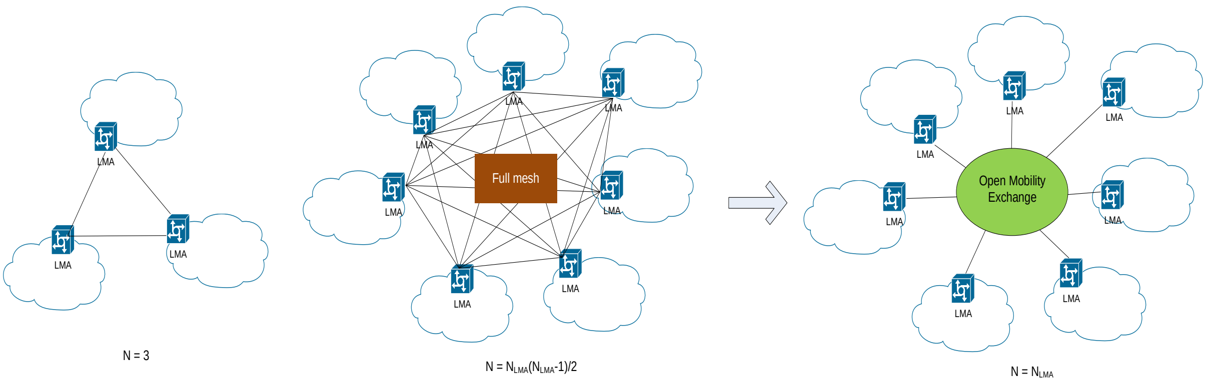

Figure 3.4: PMIPv6 inter-domain tunnel configurations

In order to increase scalability and guarantee Quality-of-Service (QoS) performances, the concept of Open Mobility Exchange (OMX) is proposed. Each LMA will maintain a long-term bi-directional link with the OMX in order to reduce the latency overhead of handover. The OMX is responsible for routing the received inter-domain PBU and PBA as well as the user traffic to the correct destination LMA.

3.4.2 Inter-Domain Mobility Management at Layer 2

3.4.2.1 *Virtual Access Point (vAP)*

Virtual Access Point (vAP) technology was studied with reference to its applications for the eduroam service. vAP technology is based on instantiating multiple Access Point instances over a single physical WLAN radio, without requiring support for any special feature on the mobile devices. In this context, vAPs are used for the purpose of enabling per-realm policies at the wireless segment, and facilitating inter-domain mobility.

Using vAPs for multi-vendor policy provisioning

Given the increasing demand for mobile data, situations where an eduroam Access Point can become congested at the radio level are more likely to occur. An eduroam service provider (SP) must therefore be able to define and enforce per-realm policies in the wireless segment, such as prioritising users from its home eduroam realm when congestion occurs. Several QoS mechanisms could be applied to enforce per-realm policies at the radio level [Cisco_ATF], but these mechanisms are not standardised across vendors. Hence, in this paper the usage of the vAP technology, supported across major WLAN vendors [Cisco], [Aruba], [Linux] is proposed as a mechanism to enforce per-realm QoS policies.

A WLAN Access Point controls the channel access priority of its associated users including the WMM Parameter Set in the Beacon frames it transmits, which contains the Contention Window (CW) settings used by the associated stations to access the wireless channel. Thus, if a (group of) eduroam realm(s) is represented by a vAP, the wireless access priority of the users attached to that vAP can be controlled by appropriately configuring the WMM Parameter Set broadcast by the vAP. Major WLAN vendors already provide tools to configure these parameters [Cisco_QoS].

This solution presents a challenge in terms of how to force users of a specific eduroam realm to attach to a particular vAP, since in eduroam all vAPs advertise “eduroam” as their SSID, regardless of the realm they represent. In order to steer users across vAPs, a black and white listing mechanisms is proposed based on the mobile device’s MAC address. The issue however is how to dynamically populate the access control lists of each vAP given that it is not possible to know a priori all the MAC addresses of the users of a given eduroam realm. Instead, any practical solution needs to identify the eduroam realm a given user belongs to first, and only afterwards configure the access control lists of the vAPs.

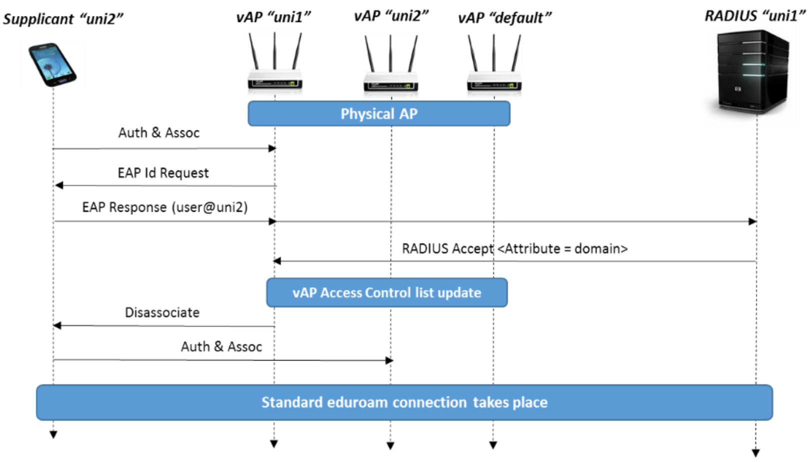

Figure 3.5: User steering to the appropriate vAP

Figure 3.5 illustrates a mechanism devised to steer a requesting user to the vAP representing its realm. A physical AP is shown where three vAPs have been pre-instantiated, two to represent the major universities offering eduroam services in a city, “uni1” and “uni2”, and another to represent any other eduroam realm (“default”). When a mobile device from a user belonging to the “uni2” realm connects to the AP for the first time, it will do so through any of the vAPs, e.g. the “uni1” vAP, since none of the vAPs are configured to blacklist the user. Consequently, the user will associate and proceed with the normal eduroam authentication process, whereby the home AAA server identifies the requesting user’s realm, which is then notified to the WLAN controller using a RADIUS AV pair in the RADIUS ACCEPT response. Hence, the WLAN controller pushes the user to the corresponding vAP by blacklisting its MAC address in the other vAPs. The experimental evidence gathered so far indicates that existing mobile devices on the market persistently try to connect to all vAPs advertising the same SSID, confirming the validity of the proposed vAP concept. Further testing is ongoing both on verifying the effectiveness of the user steering approach over a larger sample of smartphones, and on evaluating the delay introduced by the proposed mechanism in the standard eduroam association procedure.

Finally, it is worth noticing that in any practical deployment the number of vAPs instantiated in a given physical AP should be limited, e.g. below five, in order to reduce the overhead in terms of transmitted Beacon and Probe Request/Response frames.

Leveraging vAPs to enable L2 inter-domain mobility

Although not strictly necessary to achieve inter-domain mobility, the proposed vAP concept naturally extends to a layer 2 inter-domain mobility solution, whereby the WLAN controller binds traffic generated from a vAP corresponding to a home eduroam realm to a layer 2 tunnel between the visited and home eduroam realms. In order to limit the effect of remote broadcast traffic traversing the layer 2 tunnel over the radio channel, vAPs should implement Proxy ARP functionalities [Proxy_ARP]. A Candidates technology to implement the required layer 2 tunnelling is for example Ethernet over GRE (EoGRE), which is also supported by major networking vendors [EoGRE], and can be secured using IPSEC.

In a practical implementation both vAPs and the corresponding EoGRE tunnels for the target eduroam realms should be pre-instantiated, for example one for each realm coexisting in a given city. It should be noted though that pre-instantiated EoGRE tunnels do not scale if the number of tunnels is large. In this case, the introduction of a new entity implementing an Open Mobility Exchange (OMX) is proposed, which maintains EoGRE tunnels with all existing eduroam realms. The OMX routes the packets received from an EoGRE tunnel to their corresponding home domains by inspecting in-packet information, e.g. a VLAN tag, that indicates the target eduroam realm. A detailed implementation of the OMX may be the subject of future work.

Figure 3.6 illustrates the setup of the EoGRE tunnels to ensure inter-domain mobility by always routing user traffic through their corresponding home network.

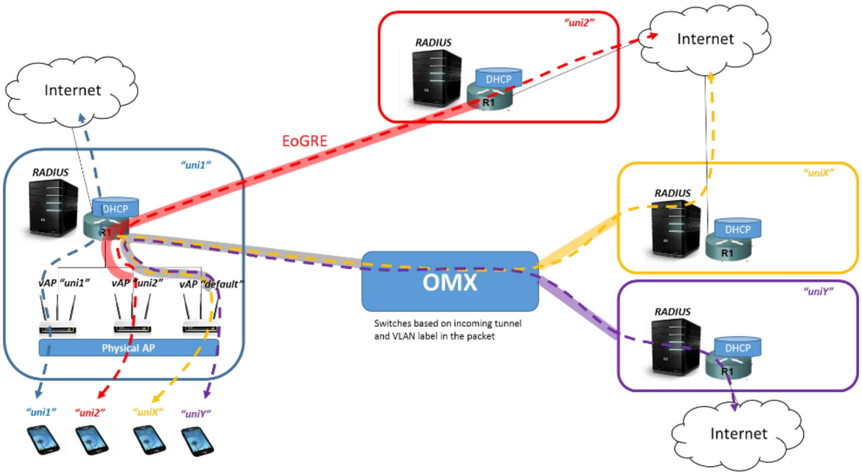

Figure 3.6: L2 tunnelling for inter-domain mobility, comprising direct tunnels and OMX routed tunnels

3.4.2.2 *L2 VLAN configuration*

There are two more options for achieving seamless roaming in the inter-domain scenario:

1. **Joint mobility group**: Each domain should buy and install the equipment that supports it. After successful authorisation of the user, their information should be sent to a common database and made available to all controllers. If a user device switches from an AP connected to one controller to an AP connected to another controller, it should automatically connect to the new network without the need for re-authorisation.
2. **Dedicated L2 network (VLAN):** for users from individual universities. Whereas most eduroam users are from one city, common base VLANs (dedicated L2 network) should be assigned to each university from that city and an additional VLAN to service all users from outside this city. In each VLAN, the network services are supported by the "home" institution. With this solution, users moving around a city receive the same IP address and other network services as shown in Figure 3.7, during re-authorisation for transition from one network to another: The solution:
    a. Requires a RADIUS VLAN attribute-value pair to be implemented by each connected domain, and recognition of adjacent domain users. Network equipment should be capable of supporting VLAN attributes across the implementation.
    b. Requires a dedicated inter-connection between domains outside the general "Internet" connectivity to enable to establish mobility exchanges locally where adjacent domains meet.
    c. Can be further coupled with the vAP implementation below to avoid unnecessary re-authentication.

3. **Public area hot-spot implementation**: This should be launched in order to prevent interruptions related to user re-authentication when changing from one AP to another in areas with eduroam service (e.g. city wireless networks) managed by one institution. Such solutions are already used in several countries where the NRENs broadcast eduroam over a WLAN infrastructure running through the city (e.g. PSNC – Poznań). In situations when users move within a city's wireless network area they are required to be authorised once to access the

network. When users change location, they also change the associated AP. However, the new AP is managed by the same wireless controller as the previous AP, so the user has no need to be reauthorised, as the controller remembers their first access. Additionally, thanks to the implementation of dedicated VLANs for each local university (and a dedicated one for users outside the city) users fall within the same IP range area in all locations. This produces a seamless connectivity experience without any interruption to the services.

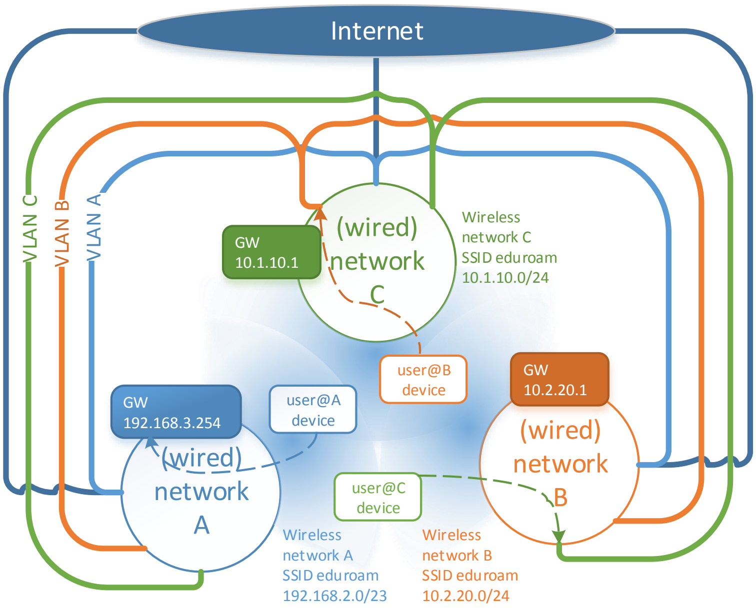

Figure 3.7: Static dedicated VLANs configuration for adjacent eduroam domains

3.4.3 Integration with LTE

Research and education users are rapidly adopting mobile devices and a nomadic work style, both on and off campus. Such users want to be online anytime and in any place. Consequently, ICT plans at research and education institutions are increasingly considering choices that favour wireless technology. To meet the users' needs and push the boundaries of technology, NRENs need to work together to remove barriers to mobile communication and provide an attractive and seamless mobile experience for the research and education community. From a technical perspective, this requires a mobile extension of today's footprint: a mobile exchange that connects the NREN's infrastructure with existing mobile service providers. Two alternative types of mobile exchanges are considered:

1. **A mobile exchange on layer 2:** This means that the IP address is provided by the NREN or the institution. Authentication poses a challenge as mutual authentication of the packet network and the SIM is mandatory before users are allowed on a network. Access to the mobile exchange should preferably be based on credentials stored at the R&E institution. Note that this still means that the mobile operator must forward user credentials, as the 3G/4G standards do not support the end-to-end equivalent of EAP.

2. **A mobile exchange on layer 3:** From the point of view of the mobile service operator this means that their gateway to the internet (or access point name, residing on a packet gateway or a GGSN) is connected to the network infrastructure of the NREN. After users have authenticated their SIM, the operator provides them with an IP address and associates them with the peered network beyond the gateway. A subscription with the mobile operator is mandatory.

The mobile exchange on layer 3 uses the fixed infrastructure to offload users from the mobile operator's network. The mobile exchange on layer 2 uses the 3G/4G network as a pass-through network. This adds particular value if the NREN implements a full MVNO construction with ownership over the keys on the SIM. Ownership of the SIM is what makes the mobile exchange on layer 2 in particular an interesting solution as it enables:

a. *Change of the operator* who owns the 3G/4G access (pass-through) network without swapping the SIM in a device.
b. *Using the SIM to gain access to eduroam.* This removes the burden from institutions to authenticate smartphone devices and tablets on eduroam. The device uses the network code stored on the SIM instead of the username. The institution proxies this parameter to the NREN which then authenticates the SIM by means of e.g. EAP-AKA'. This is an authentication method that can be used without making any changes on today's network federations.
c. *Using the SIM to gain access to other IT resources* such as buildings, rooms or printers.
d. *Fixed mobile integration*. NRENs can make plans for solving fixed mobile convergence at institutions, integrating the NREN's normal fixed-line service offering with a mobile solution.
e. *Using the SIM for accessing federated services.* The SIM is an application on a smartcard. Other applications can be added to the smartcard for secure access to other federated services (e.g. mobile PKI).
f. *Indoor 2G/3G/4G within the institution.* Resilient access networks are installed by academic hospitals (e.g., because they rely on the timely delivery of SMS) and at various institutions that have to contend with steel and/or foil on the windows of newly built buildings that block outdoor signals. This is often solved using indoor 2G/3G solutions offered by mobile operators, requiring the installation of a distributed antenna system (DAS). The mobile operators connect this DAS to their radio installation points, transporting radio signals over fibres into the buildings. A DAS often requires a dedicated infrastructure that uses thick coax cables. This infrastructure complements the institute's Ethernet infrastructure. A solution that makes use of the existing Ethernet infrastructure is far more appealing for institutions. One way of realising this is by enhancing existing Wi-Fi access points with a 2G/3G/4G module or by using LTE on the unlicensed Wi-Fi spectrum.
g. *Innovation on the SIM.* The ability to authenticate the SIM allows innovation on the SIM itself. Examples include mobile learning and stronger authentication for on-line tests.

3.5 Prototyping and Modelling Results

The Poznan Science Center includes buildings that house the labs of several universities and institutes, including the Technical University, the University of Adam Mickiewicz, the Institute of Bioorganic Chemistry, the Polish Academy of Sciences Poznan branch and the Poznan Supercomputing and Networking Centre, some of which have their own wireless infrastructure. This made it an ideal location to set up L2 VLAN based inter-domain roaming.

The background hardware used is:

- Meru controller 3000 with AP 301.
- Cisco controller 5500 with AP 2700i.
- Cisco AP 1300.
- Freeradius AAA server.

PSNC is responsible for providing guest access to the wireless networks.

Traffic for when users move from one eduroam wireless network to another eduroam wireless network managed by other institution was tested with satisfactory results – users retain the same IP addresses, and remain in the same L2 VLAN, and their connections are not interrupted, e.g. SHH sessions, , multimedia streaming (e.g. from YouTube), etc..

Another test was conducted to prove the virtual AP inter-domain roaming concept. The implementation was carried out in the laboratory of i2Cat in Barcelona. The setup depicted in Figure 3.8 has been developed and deployed to test the viability of the proposed vAP solution.

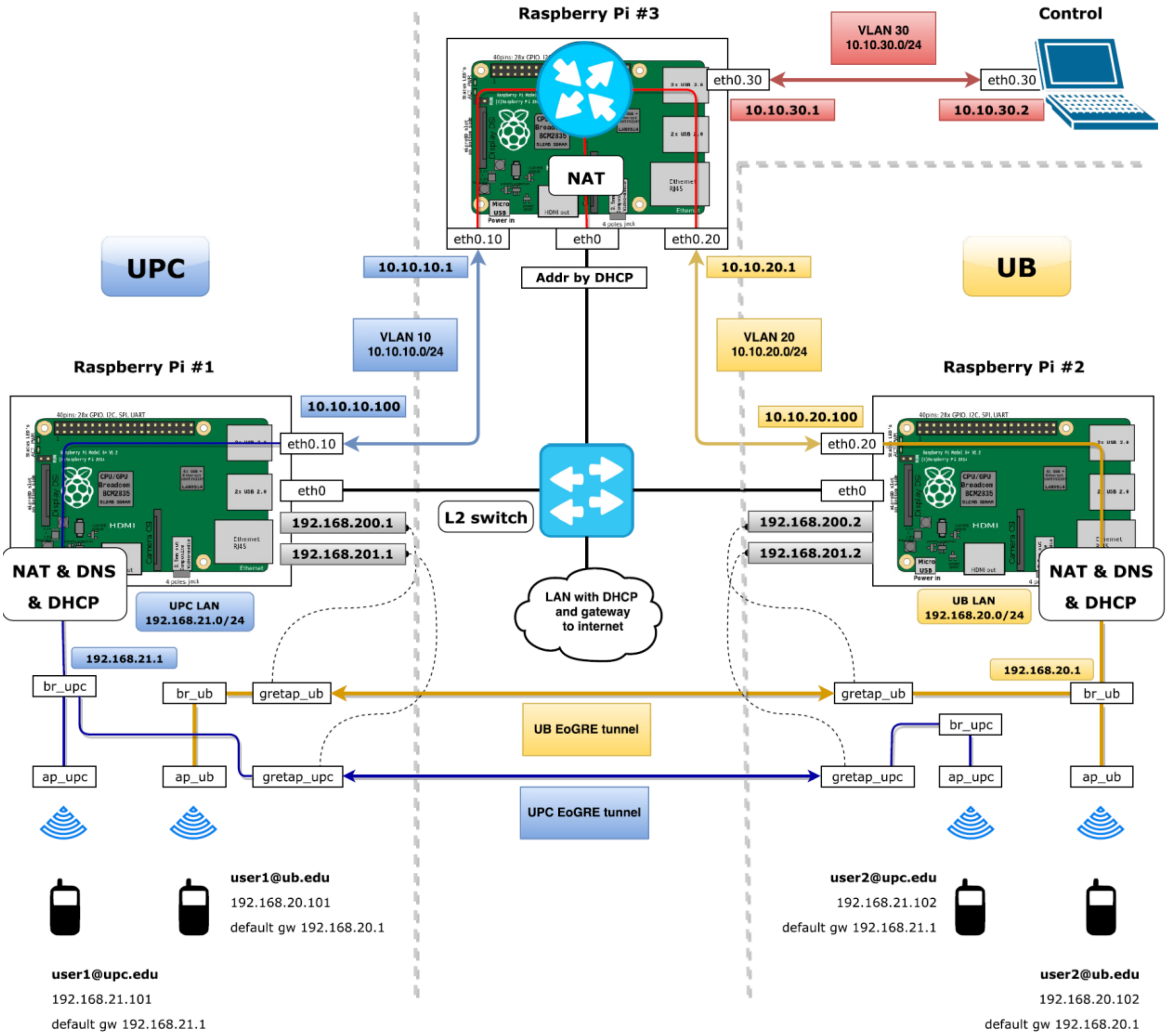

Figure 3.8: vAP testbed set up

The testbed developed represents two eduroam realms (UPC and UB) offering wireless connectivity and a backbone network inter-connecting them. Each realm offers NAT, DNS, DHCP and a local freeradius to its home users, as well as two virtual AP instances (vAPs) representing the home and remote eduroam realms. The Ethernet over GRE (EoGRE) tunnel bridges the vAP representing the remote domain linking the UPC and UB realms. Hence, traffic from the remote vAP is always bridged back to its home network, and thus the UE retains the same IP context. Finally, the Raspberry Pi in the middle offers routing and proxy Radius services between the two realms.

The proposed vAP functionality does not exist in current Wi-Fi implementations available in Linux. vAP modules were developed and integrated into several Wi-Fi components available for the Raspberry Pi:

- A REST API that allows to remotely instantiate and configure vAPs in a standard Linux box using hostpad [hostpad]. The API is also used to set up the corresponding EoGRE tunnels, and to configure hostpad parameters such as the white/black MAC filters required to steer a user terminal to the corresponding vAP representing its eduroam realm.

- The hostpad program in Linux, which implements Wi-Fi Access Point functionality in user space, was modified to force user Wi-Fi clients to connect to the correct vAP. An eduroam user connecting to the system for the first time will always initially attach to 'default_vap'. Once connected, the Wi-Fi client will start an EAP Authentication procedure during which the supplicant in the user terminal will disclose its eduroam realm together with its MAC address to hostpad.

Figure 3.9 illustrates the interactions between the different software modules integrated in the UPC and UB Raspberry Pi devices.

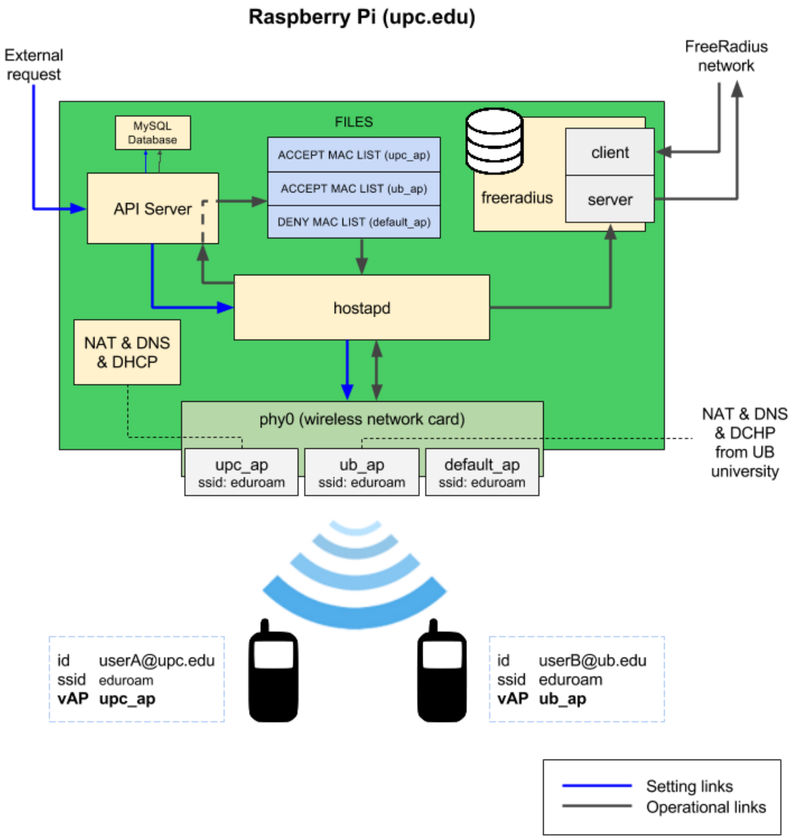

Figure 3.9: Software modules in UPC and UB RPi devices

Finally, the proposed design and implementation were evaluated according to the two essential metrics: the differences of AP selection in different UE types and switchover delays.

Differences in reaction to vAP steering algorithm across implementations of User Equipment

An initial sample of 12 different smartphones that cover a significant portion of the market were analysed. Figure 3.10 depicts the connection times measured for each User Equipment (UE) type when the MAC is unknown, while Figure 3.11 illustrates the same for when the MAC is known. Figure 3.10 shows a wide variation in the times that different smartphones need to enter the network when their

MAC address has not yet been registered. The reason for this variation is the presence of proprietary client association logics on each device.

According to the proposed vAP steering algorithm, when a client eventually selects 'default_vap' the normal EAP authentication process starts in order for hostpad to discover the MAC and eduroam realm of the device, upon which an EAP Failure and Disassociation message are transmitted to remove the device from 'default_vap'. At this point, the following three types of client behaviour are observed:

1. Clients that upon receiving EAP Failure and Disassociation try to immediately reconnect, but this time only the correct vAP is selected since the MAC filters are already configured.
2. Clients that upon receiving EAP Failure and Disassociation wait N seconds before attempting a reconnection, where we have observed N to vary between 7 and 15 seconds.
3. Devices that upon receiving an EAP Failure and Disassociation in some cases do not attempt to reconnect automatically. For these devices though, if the user taps to connect a second time the connection proceeds correctly because the MAC filters are already configured, as illustrated in Figure 3.11.

It is worth noticing that despite the additional delay introduced by the proposed vAP steering mechanism, in many practical situations smartphones connect to an eduroam network in the background without explicit user intervention. It is considered that in this case the additional delay introduced would not be a problem. In addition, if the mechanism is combined with intelligent policies for maintaining lists of known MAC addresses, which could for example be kept at the wireless controller, in practice performances would be close to those depicted in Figure 3.11. The actual hardware implementations of this solution will be dependent upon the sizes of their MAC address tables. Further study is required to develop the mechanisms to overcome this limitation.

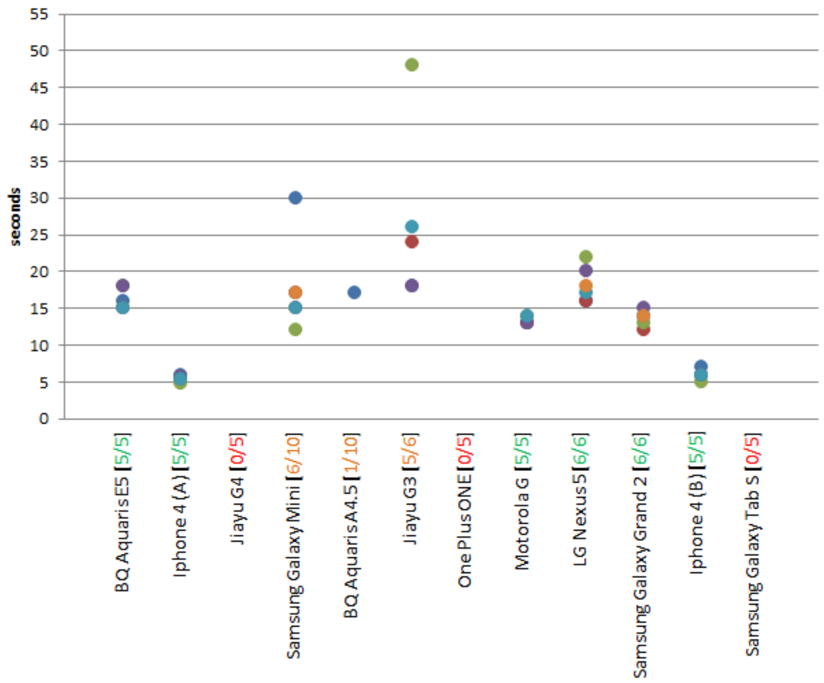

Figure 3.10: Connection time when the device is not known to the system

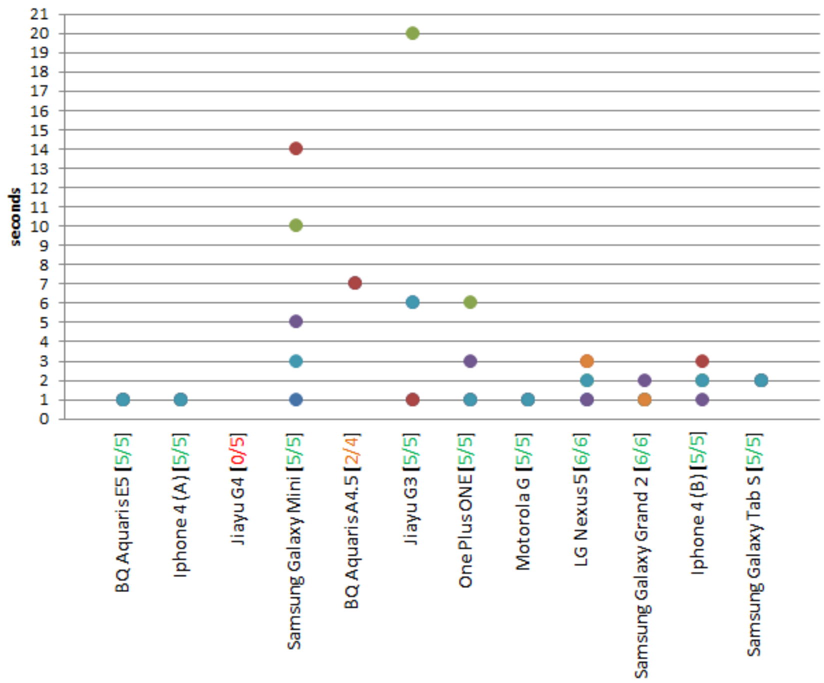

Figure 3.11: Connection time when the device is known to the system (the MAC lists are configured)

Switchover delays between home and foreign vAP

After validating the impact of the proposed vAP steering mechanisms on a wide set of client devices, a functional validation of the overall system design was carried out using an iPhone 4 as client. It was observed that when configured with UPC eduroam credentials the iPhone always connected to the vAP representing UPC, both when it physically connected through the Raspberry Pi representing the UPC realm or through the Raspberry Pi representing the UB realm. The iPhone therefore always obtained the same IP address regardless of whether it connected through UPC or UB. As recorded in the testbed, the delay introduced by the EoGRE tunnel in obtaining an IP address was negligible.

Plans for future work include possibly expanding the test sample to validate the vAP steering behaviour, and deploying this service in a real campus environment.

3.6 Mapping the Service to the GÉANT/NREN Infrastructure

Scope	Analysis
Metro and campus	<u>Wi-Fi as a service</u>: Wi-Fi as a service, eduroam as a service and similar architectures are more suitable to be deployed on a wider scale where there is a possibility of reaching a great number of users. National and pan-European scale is recommended.. <u>Inter-domain roaming</u>: the use case for inter-domain roaming service is the geographical proximity of different eduroam realms. Such proximity is most prominent in Metro areas. Inter-domain mobility and open mobility exchange platforms are to be placed between eduroam providers. <u>eduroam expansion</u>: The use case for eduroam expansion in metropolitan areas is closely associated with hotspot availability in the locations of concentration of general public. eduroam availability in hotspot locations has proven to be valuable attribute for the R&E community. <u>Potential users</u>: Individual R&E members who require seamless access to the wireless data transmission medium while moving between different eduroam-enabled locations. Interconnecting institutions effectively extending their wireless coverage in a federated way. R&E community able to use recognizable eduroam service in public areas. <u>Potential benefits</u>: Availability of highly integrated immersive learning and research content to community members. Traffic policing in accordance with the rules of “home” institution. “Guest” traffic offload to the agreed partner. Extension of eduroam coverage.

Scope	Analysis
National/ NREN	Wi-Fi as a service: The most prominent placement of Wi-Fi as a service is within national or regional R&E network operators who have the necessary technical and organisational expertise to provide such a service. Inter-domain roaming: The inter-domain roaming between national-scale entities. The use case for such a national-scale roaming proposal is integration with mobile (3G/4G) providers. eduroam expansion: The use case for eduroam expansion on the national scale are agreements with national public hotspot infrastructure providers, e.g. airports. Potential users: R&E institutions that do not have necessary resource to deploy high quality Wi-Fi/eduroam network. R&E community members accessing resources from public spaces. Potential benefits: Secure and authenticated access to the network, seamless connectivity for immersive applications such as video conferencing and streaming.
Pan-European/ GÉANT	Wi-Fi as a service: The collaborative nature of NRENs and R&E communities is a key enabler for sharing experiences, software solutions, services, and processes. GÉANT should facilitate implementing such a platform for the R&E community. The actual pan-European implementation of radio-access services is very far from the local scope of these services, and thus is not feasible. Inter-domain roaming: Inter-domain roaming is out of scope for pan-European implementation. eduroam expansion: eduroam expansion to public areas is based on mutual agreements with the operators in these areas, which are within the scope of metro or national networks. eduroam as a service (Radius as a service, IDM as a service): The only pan-European service to facilitate the implementation of eduroam are multi-tenancy RADIUS services and IDM services for small institutions. These can be and are made available from local NRENs, but are also considered by GÉANT as part of the the work of GN4-1 SA5 Task 7 (eduroam as a service). Potential users: The R&E community, NRENs or university departments will benefit from the information/experience sharing platform. It will facilitate the human network and human capital development within the region. NRENs and their constituencies will benefit from centralised RADIUS/IDM resources that will allow the streamlining of eduroam or even eduroam-like service deployments. Potential benefits: Increase of expertise level in the region, human capital development, cost savings for smaller R&E institutions and NRENs that rely on the centralised RADIUS/IDM service.

Table 3.2: Integrated mobility architecture mapping to GÉANT/NREN ecosystem

4 Further Work

The examined service prototypes and architectural solutions have different levels of maturity and therefore different Technology Readiness Levels (TLRs) as shown in Table 4.1. Their scoping determines their future placement within the GÉANT/NREN ecosystem and the GÉANT operational model.

GÉANT operations and service level (SA), required TRL>8 (system complete and qualified)
1. The GÉANT optical platform does not easily support alien wave transmissions, but GÉANT signals can be transported as groups of alien waves or a portion of a spectrum (super-channel) on optical infrastructure owned and operated by NRENs. 2. With a wide variety of use cases described and operational in a growing number of cross-border fibres and photonic cross-connects the concept of shared infrastructure and spectrum has been proven and is well established. NRENs provide alien waves to each other and GÉANT as an operational service. It is a TRL 8 service as demonstrated within the relevant production environment. Future work shall continue in this direction with the ultimate goal of all available NREN optical infrastructure forming a basis for GÉANT network and services. 3. Further advance of this services while in operation should include the refining of procedures, SLAs, and information flows between partners offering and using alien waves.
GÉANT prototyping (JRA), required TRL >5 (technology validated in relevant environment)
1. Alien wave services are relevant to all scopes within the remit of the GÉANT/NREN eco-system. Further research will have to address the use of NREN optical infrastructures for the GÉANT network: a. GÉANT as a multi-domain optical monitoring platform aggregating inputs from NREN-based agents. The collaborative nature of the GÉANT ecosystem provides a unique opportunity to establish such monitoring services with NRENs, gaining visibility in multi-domain optical paths. b. Current CMon development and demonstrations have successfully achieved TRL6. It has been demonstrated in the relevant production environment, and has a good position to become a GÉANT service success-story. CMon or any other option for multi-domain monitoring will have to be included in future prototyping activities to reach full production status. c. Support of 100G PM-QPSK alien waves over distances exceeding the 1500-2000km range or alien waves using higher-order modulation or high-spectral efficiency, such as 16QAM. In such a scenario, regeneration may be required and regeneration as a service option will be investigated. This aspect has not yet been investigated from an operational point of view. d. How to lower the threshold for other NRENs to take-up alien waves. (COLO service as part of the Alien Wave service, 3R, sparing, repair, etc.). e. How to better interface modern CD and grid-less systems to older systems. (Interoperability and legacy use-cases).

f. Introducing Transport SDN for multi-vendor, cross-layer control and the optical layer, including control and orchestration of Alien Waves. g. Advanced deployment and governance models. When increasing numbers of customers make use of an alien wave, the implementation of a different control and management model, or even a different model of ownership (e.g. a buy-in model with shared ownership per CBF or Photonic Exchange), might be considered. A trigger for this could the need for massive investments such as the introduction of Raman Amplification h. What would be the best requirements for a photonic system when tendering for a system to be used only for Alien Waves and related services. **2.** The integrated wireless access architecture proposals outlined here do not fall within the scope of a further pan-European GÉANT project. The only service within the remit of GÉANT network is eduroam as a service including multi-tenancy RADIUS and IDM. It has been addressed by the efforts of GN4-1 SA5 Task 5 and will be the subject of further research in future projects.
GÉANT platform for community research and sharing of experience, no TRL requirement
1. As regards Wi-Fi as an NREN service, the SURFnet demonstration described in this document, as well as the work of several NRENs, including ARNES, HUNGARNET, LITNET, EENET, and numerous others, to provide Wi-Fi for schools have proven that demand is high at institutions for such a service. Service implementation data also indicates that the service has to be tailored closely to meet the specific requirements of each customer, and has specific implementation features in each NREN. 2. As the demand for wireless connectivity continues to grow, eduroam will need to incorporate carrier-grade features beyond roaming to continue being an attractive service for end users. The essential factors hindering eduroam's expansion are associated with the availability of the skillset to properly deploy and maintain the Wi-Fi network, with the same wheel being re-invented at each institution. The availability of Wi-Fi and eduroam as a service is thus a key enabler for further integrated multi-domain coverage. It should be noted though that while the research in this deliverable has proven the feasibility of WiFi as a service within an eduroam setup, additional work is required in order to incorporate them into a production-ready eduroam service within a three-year timespan. 3. In order to allow future eduroam service administrators to deploy policies in the wireless domain tailored to specific eduroam realms further work is required on two fronts: a. Extending support for this feature in open source frameworks such as OpenWRT/Linux Embedded systems and AAA systems, where more efficient alternatives than the virtual AP approach proposed in this deliverable should be investigated, such as including a user-scheduling framework within the mac80211 wireless drivers. b. Studying the portability of the proposed solution to the most widely available commercial campus WLAN vendors, and providing a software abstraction layer to hide the particularities of each vendor-specific API. Such a software abstraction should provide a uniform interface between the eduroam AAA layer and a particular vendor's WLAN solution to configure wireless policies. c. In countries where many people use eduroam, the load on Radius servers tends to grow fast. The NREN could be the place to solve these problems, e.g. by introducing Radius as a service or by offering 2G/3G/4G services. The ownership of the SIM allows mobile devices to use the SIM for the authentication process hence unburdens the Radius servers at the institutions. Guest access problems

are another issue experienced by the eduroam community. This includes the situation where guests without an eduroam account wish to access to the Wi-Fi infrastructure **4.** Inter-domain mobility: The proliferation of institutions delivering an eduroam service in a given geographical area introduces mobility problems that can seriously undermine the eduroam user experience. In order to progress into the adoption of inter-domain eduroam solutions, further analysis is required of the mobility related protocols supported by major vendors, as well as of the detailed design and scalability of the proposed Open Mobility Exchange (OMX), which could be implemented using available SDN tools and should be demonstrated under realistic traffic conditions.

Table 4.1: Further work directions

5 Conclusions

The concluding section of this deliverable is aimed at those readers who may be considering the implementation of the proposed architectural solutions. The requirements and evaluations for each service are set out in checklist form in Table 5.1 below.

No	Requirement	Evaluation
Alien wave services check-list		
1	Model the implementation of alien waves in the optical network.	The model has to show the effect on existing services, the foreseen alien wave transport parameters. The modelling tool used, e.g. [MOMoT], depends on the network complexity.
2	Consider the length of optical path.	The length of primary optical path and any backup paths has to be considered for consistency with the capabilities of transmission equipment. Current terrestrial equipment supports distances up to 2000km, without OEO conversion.
3	Define and agree on the technical parameters of alien waves across the network	The reference parameter list is provided in Appendix B. The parameter list may vary for the same network depending on the actual topology as outlined in the use cases (see 2.3)
4	Operate own optical layer network.	Own operation of at least a portion of an optical spectrum is necessary for alien wave services.
5	Able to configure and implement the service	Operation of the network is not sufficient. Those wishing to run alien waves must be able to do it themselves as support from the underlying parties, e.g. vendors, will be minimal.
6	Partners must agree on the operational model	This includes the technical parameters of the alien waves themselves (as at item 2), but also operational procedures, SLAs, service hours, exemptions, contacts, and the flow of information.
7	Monitor service parameters internally as well as end-to-end	Deploy any proprietary or publicly available monitoring tool. CMon is the only tool available to monitor the multi-domain network and acquire information from the actual interfaces outside the provider's domain (see 2.5.2). Other tools (e.g. zabbix, observium) can be modified to monitor the alien waves. It is essential that partners agree on which tools are used so that the multi-domain monitoring data is available via centralised interface.
8	Availability of partner information	GÉANT should facilitate the use of alien waves amongst NRENs by establishing a portal with the relevant information about partner technical capabilities,

No	Requirement	Evaluation
		modelling information and tools, and multi-domain monitoring.
Inter-domain roaming using L2 VLAN interconnection		
1	Close collaboration between network engineers and parameter harmonization	Necessary to avoid conflicting allocations of resources, e.g. VLAN IDs.
2	Define the partner responsible for guest access	Guest access will require dedicated resources (dedicated L2 VLAN and IP range), usually provided by the largest partner
3	Define the type of context association by each partner	Usually the network contexts are assigned in two ways: statically, based on the realm, e.g. staff.uni.edu, or dynamically, based on user ID and response from the RADIUS server.
4	Create the table of associations for each user (if dynamic association is used) and filters for incoming and outgoing attributes at AAA servers.	It is necessary to make sure that AAA servers will ignore all VLAN association attributes from other AAA servers outside the inter-domain roaming scope, and not send any VLAN association attribute to AAA servers outside the inter-domain roaming scope.
5	Provision all agreed VLANs to Wi-Fi traffic termination points.	Traffic termination points may be Wi-Fi controllers or access-points themselves.
Inter-domain roaming based on vAP		
1	Establish communications with representatives from target eduroam domains with whom a roaming relationship is desired	Required to pre-setup direct EoGRE tunnels with roaming partners. Check what kind of tunnelling technology is supported by the roaming partner. Assumption hereafter is that it supports EoGRE.
2	Setup EoGRE tunnels with direct roaming partners	IP connectivity with the target roaming partner is required. Tunnel termination point may be the remote Wi-Fi controller or a regular router depending on the vendor deployed in the remote campus. After instantiating the tunnel, testing is required to determine that it is up and running.
3	For each target roaming partner instantiate a vAP in the physical AP where overlapping coverage between the two providers is expected.	The Wi-Fi management system of the deployed vendor should be capable of deploying vAPs.
4	Bridge the per-realm vAP with the corresponding EoGRE tunnel termination end-point for the target roaming partner.	This step will ensure that all traffic coming from a given vAP will be forwarded to the corresponding realm's home network. This step should be tested between the roaming partners.
5	Associate each vAP to a particular eduroam domain by means of an appropriate Radius policy.	This step will force user devices to associate to the appropriate vAP depending on their eduroam domain. The deployed Wi-Fi solution must be able to support this capability. See for example the method introduced in section 3.4.2.
Wi-Fi as an NREN service		
1	The expertise needed to deploy and maintain Wi-Fi has become too complex. Institutions are looking for a partner to resolve Wi-Fi problems and NRENa are suitable candidates to fulfil this role.	The expertise has to be available to implement/operate the local infrastructure and infrastructure at the customer sites. The partnership is needed to offer a Wi-Fi service that will use all Wi-Fi features and possibilities, tailored to the education community.

No	Requirement	Evaluation
2	Scalable Wi-Fi architecture from the technical perspective	Allows a flexible set of policies, adaptable to the various institutions.
3	Common platform where the same problems are occurring and are being solved	Although Wi-Fi is standardised, bugs and features of various vendors require different solutions/workarounds for clients. Adopting a single solution with a single point of entrance that explains the solution/workaround is an effective way of minimising problems for end-users.
4	Help desk facilities	The basic requirement to interact with the customers while the service is in operation of and a common way of instructing help desks at various institutions.
5	Processes and organisational dedication to the service	Implementation and further operation of the service has to be clearly specified and documented.
6	Leverage on features for education	Wi-Fi as an NREN service has a broad momentum and hence enjoys advantages with vendors towards building functionalities needed to facilitate and improve the education process.

Table 5.1: Proposed architecture implementation checklist

Appendix A AWS Questionnaire and NREN Responses

Table A.1 below presents the set of questions constituting the questionnaire on Alien Wavelengths as a Service (AWS), which was answered by 20 participants including GEANT and NORDUnet. Participant responses are given in Table A.2.

A.1 AWS Questionnaire

Q1	Do you know what an “Alien Wavelength” is?
Q2	Do you agree with this definition of what an Alien Wavelength is? An “Alien Wavelength” is a modulated channel (carrying digital user data) that travels transparently through multiple domains which is running different vendor equipment compared to where it originates from.
Q3	Have you discussed Alien Wavelengths within your organization?
Q4	Have you or your organization participated in an Alien Wavelength trial or setup?
Q5	Have you received requests from users in your network to establish an Alien Wavelength connection?
Q6	Does your organization plan to deploy Alien Wavelength within your own network
Q7	Does your organization plan to deploy an Alien Wavelength to interconnect with neighboring domains via cross-border-fiber?
Q8	Please describe a potential application scenario of Alien Wavelength in your network, possibly based on a user request or your own needs
Q9	What do you think about the potential benefits of Alien Wavelength in your network?
Q10	Please specify the WDM equipment vendor your network is currently using, including product line identification (e.g., ADVA FSP2000, not just ADVA)
Q11	Does your organization have a deployed Cross-border fiber with neighboring organizations (NRENs)?
Q12	What is your organization’s Dark Fiber footprint? If possible specify contract type and duration in case DF is leased by another provider.

A.2 Tables of NREN Responses

	PIONIER/PSNC	ARNIEC/RoEduNet	GARR
Q1	Yes	Yes	Yes
Q2	Yes	Yes	Yes
Q3	Yes, we consider this technology	We already tested: Cisco wavelength over Ciena optic. http://ieeexplore.ieee.org/xpls/icp.jsp?arnumber=6955326	Yes, we are interested in the technology but have not had any customer requests Other (Please specify): we are interested in the technology because we operate two distinct platforms in our network. So we do not have customer requests but an "inside" request to understand the technology
Q4	Yes	Yes	Yes
Q5	It's confidential	No	Yes: It was not an user, but we discussed the possibility with a neighboring NREN
Q6	Yes	Yes	Yes
Q7	It's confidential	There are plans to connect using alien wavelength with RENAM (Moldova)	we started to discuss with RENATER a plan to implement Alien wavelength technology on a x-border fiber infrastructure in order to share the costs of it.
Q8	It is useful technology for extent scope of our network	The only reason for using alien wavelength would be to reduce costs.	we plan to use AW in our network to implement a smooth transition from the older platform, based on Huawei OpTix OSN8800 - deployed on North Italy, and the new one, based on Infinera DTNX - deployed in the South Italy.
Q9	It can potentially save us money through using multi-vendor equipment in the network It can potentially bring us new clients/services For operational purposes in case of swap of DWDM provider	It can potentially save us money through using multi-vendor equipment in the network	It can potentially save us money through using multi-vendor equipment in the network For operational purposes in case of swap of DWDM provider

	PIONIER/PSNC	ARNIEC/RoEduNet	GARR
Q10	ADVA FSP3000r7	Ciena CPL	Huawei OpTix OSN8800 - deployed on North Italy, - Infinera DTNX and ATN deployed on South Italy
Q11	Yes	Yes	We have X-border fiber through Switzerland (SWITCH) and Slovinia (ARNES)
Q12	We have own fibre infrastructure with no limitation	About 6000 km of DF in the national network (the contract ends in 2025) and 150 km cross border fiber (owned by RENAM) between RoEduNet (Iasi) and RENAM (Chisinau)	GARR footprint is ~ 14000 Km - about 9000 are IRU - the remaining part are 6 years loan.

	SWITCH	SURFnet	NIIF Institute
Q1		Yes	Yes
Q2	Yes	An "Alien Wavelength" is a photonic signal generated by equipment of different make than the make of the photonic system or any photonic signal that travels through at least one domain that administratively differs from the domain the photonic signal was generated in.	Yes
Q3	Yes	Yes: We are operating several alien waves both in out cross border fibers as well as in the production network.	Yes, we are interested in the technology but have not had any customer requests
Q4	Yes, we had customer requests	Yes	No
Q5	A customer has it's own dark fibers between A and B. And they asked for alien wavelengths as a backup.	Yes: Signals for researches, time and frequency transfer signals and 100G waves.	No
Q6	Yes	Yes	I don't know
Q7	Nothing planned at the moment. But ready to do so.	We currently offer Alien waves on our Amsterdam-Hamburg fiber. We're also running alien waves for partner NREN's NORDUnet and PSNC	I don't know
Q8	We use alien wavelengths for ourselves to setup IP connections (in addition to transponder links). And	Currently in our network the service platforms contain DWDM pluggables. These are alien to the	Multi-site university with WDM system want to have multiple lambdas.

	SWITCH	SURFnet	NIIF Institute
	from the customer perspective, it can be useful if the customer runs its own optical transport system but would like to use our fiber infrastructure (e.g. to setup backup routes without leasing additional dark fibers).	photonic system as they are not in the same administrative domain (despite it is all SURFnet). The NGE is managed and controlled in a different way compared to the photonic layer. This allows us to skip the transponder / OTN layer.	
Q9	It can potentially save us money through using multi-vendor equipment in the network We already need it to service client needs For operational purposes in case of swap of DWDM provider	It can potentially save us money through using multi-vendor equipment in the network We already need it to service client needs It can potentially bring us new clients/services For operational purposes in case of swap of DWDM provider	For operational purposes in case of swap of DWDM provider
Q10	ECI Apollo (mainly 9608; no OTN backplane)	Ciena CPL line (The pizza boxes)	Alcatel-Lucent 1830 PSS
Q11	Yes	Amsterdam - Hamburg, Amsterdam - London, soon Amsterdam Geneva.	Yes : Szeged-Subotica
Q12	About 3'000 km of leased dark fiber. We don't lease door-to-door fibers but patches from different providers (about 50 companies). About 70% is from one provider. With the biggest providers, we do have a framework contract (between 10 and 15 years). The fibers are usually leased for 10 years.	You can find an overview of our footprint here: https://www.surf.nl/diensten-en-producten/surfinternet/netwerktopologie-surfnet7/index.html. We have different providers for the different parts. The 15 IRU's for the core network are about to expire, we're working on renewal.	more than 85% of university/research sites connected via DF

	CESNET	EENet	GÉANT
Q1	Yes	Yes	Yes
Q2	AW can also be unmodulated. One prime example is stable frequency which is continuous wave (CW). Another example could be some very slow signals (accurate time or something similar or different) which seem to be 'almost unmodulated' when compared to high speeds 100/200/400G and 1T and beyond. Also 'digital user data' is perhaps unnecessarily restricting - AW can also carry 'analog user data' if users wish to carry analog information.	Yes	An example of an alien wavelength is a DWDM wavelength that is established between a transmitter and a receiver and then transported over the DWDM system either of a different vendor or of the same vendor but in a different domain. In the case of a multi-domain alien wavelength, the alien wavelength is transported over multiple DWDM systems from

	CESNET	EENet	GÉANT
	And perhaps - AW is a signal, not a 'channel'. Channels looks like empty places/holes in the available DWDM spectra. AW is a real signal/light/stream of photons. Our suggestion is: An “Alien Wavelength” is a modulated or unmodulated optical signal (carrying digital or analog user data) that travels transparently through multiple domains which is running different vendor equipment compared to where it originates from.		different vendors, where no optical-to-electrical-to-optical (OEO) regeneration is used at the boundary between the two DWDM systems.
Q3	Yes, we had customer requests	Yes, we are interested in the technology but have not had any customer requests	GÉANT uses alien waves
Q4	Yes	No	Yes
Q5	time/frequency transfer or very simple request for connectivity over other network	No	No
Q6	Yes	No	Yes
Q7	Yes	No	Investigation between DFN, GÉANT and PSNC being discussed for alien wave connectivity between Hamburg & Poznan and with GÉANT CESSNET and PSNC for alien wave connectivity between Poznan & Prague
Q8	Time/frequency, connecting customers.	n/a	see above question
Q9	It can potentially save us money through using multi-vendor equipment in the network We already need it to service client needs It can potentially bring us new clients/services For operational purposes in case of swap of DWDM provider	It can potentially bring us new clients/services	Sharing infrastructure amongst community partners
Q10	Cisco 15454 MSTP, Czech Light equipment	Transmode TM	Infinera DTNX
Q11	Yes	Yes, Other: Funet/Nordunet in Espoo	No
Q12	total 6400km, 1510km Cisco, 4890km Czech Light (including CzechLight on 2000km single bidirectional transmission)	10 year IRU	leased on 8 year term ending 2020/21

	Kaunas University of Technology / LITNET	CARNet	GRNET SA
Q1	Yes	Yes	Yes
Q2	Alien wave is modulated photonic channel that travels transparently through single or multiple domains (networks) running the equipment produced by different vendors	Yes	Yes
Q3	Yes: We deploy alien wave services internally (using 3rd party SFP+/XFP transceivers) and externally servicing the network of government institutions.	No we do not operate our infrastructure and therefore it's impossible to deploy	Yes, we are interested in the technology but have not had any customer requests
Q4	Yes	No	No
Q5	We deploy alien wave services internally (using 3rd party SFP+/XFP transceivers) and externally servicing the network of government institutions.	No	No
Q6	Yes	No	No
Q7	It would be interesting to try alien-wave setup with the PIONIER network, where LITNET has CBF interconnection. Currently we've interconnected transponders back-to-back	No	No
Q8	we see three use cases: a) metro networks. LITNET plans to overhaul metro networks in two biggest cities in 2016-17. DWDM/CWDM passive components and 3rd party interface transceivers will be used extensively to re-create organizational infrastructure logic on a physical layer. b) national service. With the deployment of 40 lambda MDUs, the alien wave services are the most effective way to implement L1 connectivity. c) international connectivity and shared spectrum. LITNET is ready to submit parts of infrastructure and unused spectrum to the international projects and collaborations in exchange for at least portion of the same services on the international links.	We do not have our own WDM network	No user request received up to now

	Kaunas University of Technology / LITNET	CARNet	GRNET SA
Q9	It can potentially save us money through using multi-vendor equipment in the network We already need it to service client needs It can potentially bring us new clients/services For operational purposes in case of swap of DWDM provider	I don’t see any possible use of AW	It can potentially save us money through using multi-vendor equipment in the network For operational purposes in case of swap of DWDM provider
Q10	Transmode TM3000 Platform.	We do not have our own WDM network	ECI 9624/9603
Q11	Yes	No	No
Q12	~1000 km, of which 770km is a ring over the major cities, full ownership of the fibres (purchase, not IRU). and 100 km short term lease to the Poland border. Rest DF infrastructure is in the cities.	We have about 130 km of our own DF and leased DF (contracts are year by year)	Around 10.000kms dark fiber infrastructure under 15 year IRUs

	HEAnet	NORDUnet A/S	UNINETT
Q1	Yes	Yes	Yes
Q2	I don't believe an AW has to travel through multiple domains to be called an AW. For me an AW is any wave that originates on one vendors equipment and is transported transparently across a different vendor’s equipment.	I think this definition is a bit confusing and can be misinterpreted. I preferred this one: An alien wavelength is a DWDM wavelength that is established between a transmitter and a receiver and then transported over the DWDM system of another vendor.	Yes
Q3	We have two customers using AW in our passive metro CWDM network. We also have tested one AW across our ROADM optical network.	Yes, we had customer requests	Yes, we are interested in the technology but have not had any customer requests
Q4	Yes	Yes	Yes
Q5	We have 2 customers using AW in our passive metro CWDM network. I expect this does not meet your definition of an AW.	We had a request from SURFnet to carry an AW between Copenhagen and Hamburg in our ALU equipment. This AW is no longer operational.	No
Q6	Yes	Yes	Yes

	HEAnet	NORDUnet A/S	UNINETT
Q7	No	This is already done in Brussels in cooperation with SURFnet where SURFnet connects in Brussels to NORDUnet equipment. The whole spectrum is shared.	No
Q8	We are planning on building a new IP network. It is hoped that the core of this network will be at 100G. We are investigating using 100G transponders and also 100G DWDM optics in the IP equipment. We won't know which option will be used until the tender is concluded. I expect the choice will be made on price rather than on technology/operations.	To provide connectivity between our OTN nodes where we don't have our own fiber infrastructure. This has been already done to connect Amsterdam to London and Hamburg using SURFnet's optical infrastructure.	Router to Router connection
Q9	It can potentially save us money through using multi-vendor equipment in the network For operational purposes in case of swap of DWDM provider Other (please specify): AW just provide more flexibility and options to the network designer. It could also lead to costs savings and less parts/spares/maintenance.	Savings in transponders and fiber infrastructure by means of cost sharing with other NRENs	It can potentially save us money through using multi-vendor equipment in the network
Q10	ADVA FSP3000 R7. 9HU shelf with 40 channels. We have 2 and 8 degree WSS but we only use a maximum of 3 directions at any location.	CIENA CN6500 platform	Coriant, hiT7300
Q11	No, JANET has fibre between Ireland and the UK and they provide 10G circuits to GÉANT to provide connectivity to HEAnet over the JANET fibre. They do not use AW. JANET also provides HEAnet with a 10G circuit from Dublin to Belfast, but once again not an AW.	With SURFnet in Brussels, other possible candidates are SUNET and PSNC	Yes: Norway-Sweden
Q12	HEAnet leases fibre from 6 different fibre providers. We have approximately 2500Km of dark fibre. 1200Km of our fibre is non-commercial based on a	NORDUnet leases fiber infrastructure from different vendors in Norway, Sweden, Finland, Denmark, Germany (towards Hamburg) and all the way to	http://drift.uninett.no/stat-q/load-map/uninett,,traffic,peak

	HEAnet	NORDUnet A/S	UNINETT
	contract by the department of communications and the national electricity company. The remaining 1300Km is provided via tenders. The contracts typically are 7 or 10 year leases.	London. I have no information about contract type or duration.	

	AMRES	SUNET/NORDUnet	DeiC
Q1	Yes	Yes	Yes
Q2	Yes	Not necessary by multiple domains. It could be the same vendor but it's not controlled and managed by the same system as the alien wave travels over.	Yes
Q3	No, we do not see a need for it	SUNET are building a new network, where all waves are going to be alien. 100G waves in the routers over a DWDM system from another vendor	Yes, we are interested in the technology but have not had any customer requests
Q4	No	Yes	Yes
Q5	No	We have been running timing project. Where ultra stable light source has been run over the network as alien. We have also been running 1GE waves for management traffic as alien. We are also running 10GE waves from routers as alien.	No
Q6	No	Yes	Yes
Q7	Maybe in future to enable GÉANT connectivity over our own DWDM equipment which is being planned	We plan to run 100G uplink between NORDUnet and SUNET as an alien wave.	It is one of the possibilities we explore to connect the Danish and Swedish locations of the European Spallation Source
Q8	Enable GÉANT IP service and GWS service over fibres owned or leased by AMRES.	The biggest application is to move the transponder functionality away from the optical platform and into the routers and reduce the interconnection interfaces. Also for research experiments like time transfers.	For 100G connections in our coming DWDM system, we are planning to use the pluggable optics directly from the routers instead of B+W and 100G transponders
Q9	It can potentially save us money through using multi-vendor equipment in the network	It can potentially save us money through using multi-vendor equipment in the network	It can potentially save us money through using multi-vendor equipment in the network

	AMRES	SUNET/NORDUnet	DeiC
	For operational purposes in case of swap of DWDM provider	We already need it to service client needs It can potentially bring us new clients/services For operational purposes in case of swap of DWDM provider	
Q10	We are not using DWDM equipment.	Ciena Corestream and Ciena 4200. Ciena 6500(the Ciena 6500 runs as a alien wave over the Ciena Corestream) and in some cases also the Ciena 4200 running alien. The next network deployed next year will be ADVA FSP_3000	ALU 1626LM, but we are in a call for tender process to upgrade at the moment
Q11	We have CBF towards: Hungary, Croatia, Bosnia and Herzegovina, Bulgaria and Romania. Only CBFs towards Hungary and BH are operational at the moment. In other countries NRENs do not have the connectivity to the border.	Between UNINETT and FUNET in the North of Sweden	We are planning one with SUNET to connect ESS in Lund
Q12	IRU till the end of 2026. About 3800km of dark fibre in Serbia and CBF mentioned in previous answer.	SUNET leases Dark Fiber covering all of Sweden.	15+5 year IRUs purchased over the years from 2000 and onwards. We have approx. 3700 km DF

	ARNES	RENATER
Q1	Yes	Yes
Q2	It can be the same domain, but using equipment from different vendors	No. According to us, multi-domain is a particular case of AW. This definition is too narrow. For example : As a sub use case of spectrum sharing, AW is a DWDM grid compliant(G698 standard type) signal that travels transparently through single or multiple domains (networks) running different vendors equipment or under other administrative responsibilities.
Q3	we are using them	Yes. We are currently using them in a short distance use case (no inline amplifiers). (Depending on the AW definition, we also deployed time/frequency signals)
Q4	Yes	Yes, we made several AW trials.

	ARNES	RENATER
Q5	No	No
Q6	Yes	Yes
Q7	We are using them on CBF to Italy.	No
Q8	Our needs: DWDM network from ADVA & CWDM/DWDM pluggables in Cisco switches	We currently use AW links to quickly give capacity to some major nodes. We also use them for operating purpose during our deployment when we plan to de-install inline amplifiers. We also plan to use them to stitch multi-vendor at photonic layer directly.
Q9	It can potentially save us money through using multi-vendor equipment in the network	Pros : 1-Economical, we could save money by renting DWDM channels and reducing interface modules. 2-Data transport efficiency – the data are carried out without useless headers. (Better latency ?) 3- Faster Lead Time to Deploy Cons : A- Need to be more mature and more industry support.
Q10	ADVA FSP3000	Alcatel: PSS1830 and 1626/1696 Ciena : CN4200 Coriant (new) : Hit7300 and mTera
Q11	Yes: Sežana/Trieste, Nova Gorica/Gorica	Yes. DFN and GARR (under progress)
Q12	1.600 km. Leased for >= 2 years	13000 km of DF. Contract type: IRU 10 years.

Appendix B Data Exchange Parameters for Alien Wave Provisioning

Parameter	Unit	Optional/ Mandatory	Comment
Test required	Yes/No	Mandatory	Provider indicates if a test is required in order to check impact or the verify parameters that are not known or cannot be supplied
Min. Input power of a wave	dBm	Mandatory	Provider needs a certain input power to make equalization possible without excessive attenuation of other waves
Max. Input power on a port	dBm	Mandatory	Provider can only perform limited attenuation on an input port or on a wavelength
Typ. Input power of a wave	dBm	Mandatory	Provider indicates a preferred input power for a wave.
Min. Drop power of a wave	dBm	Mandatory	Provider must indicate the min. drop power that customer may expect
Max. Drop power of a wave	dBm	Mandatory	Provider must indicate the min. drop power that customer may expect
Typ. Drop power of a wave	dBm	Mandatory	Provider must indicate the typical drop power that customer may expect
Allowed power drift on add port	dB	Mandatory	Power drift that is allowed before provider sees alarm
Expected power drift on drop port.	dB	Mandatory	Most drop ports assume that any power in a power range that meets transceiver specs is OK as long as it does not fluctuate. Within the range slow drift is perfectly acceptable.
Switching of alien wave allowed	Yes/No	Optional	Indicates if a customer is allowed to switch power. Power changes usually occur either orchestrated when waves are added/deleted or in case of a failure. Photonic systems may not be robust against frequent power flaps.

Number of waves allowed on add port	#	Mandatory	On some ports it may not be possible to add or drop multiple waves, even if the ports are filtered because port power is measured and used by the control software
Number of waves allowed on drop port	#	Optional	Some receivers that deploy broadcast and select can handle power from other waves on the same receiver. This is not trivial as the DWDM receiver design must support this
Center Wavelengths / Frequencies	nm/THz	Mandatory	Wavelength and Frequencies must match the wavelength plan of the provider in case of multiple providers or CBFs the list will include the corresponding free waves
Bandwidth per wave	GHz	Mandatory	Provider must now how much bandwidth is requested. Customer must know the bandwidth that can be allocated.
Low Wavelength / Frequency	THz	Mandatory	In case of FlexGrid
High wavelength / Frequency	THz	Mandatory	In case of FlexGrid
Number of tributary waves	#	Optional	This is required to assess the total power in case of FlexGrid systems.
Launch power per section	dBm	Optional	Provider must protect other waves
Out of band ASE (Broadband) acceptable on add	Yes/No	Optional	In case AWs are inserted and are not filtered per wave, ASE may seep through onto other waves in the system.
Demarcation points	-	Optional	Address / Floor / Room / Cage / Rack / ODF / port etc. Type of connector
Chromatic Dispersion	ps/nm	Optional	Total chromatic dispersion measured at a specified wavelength.
PMD	ps DGD	Optional	Including maximum and minimum observed
OSNR	dB	Optional	OSNR at the output of the link
FEC	[]	Mandatory	FEC rate of reference transceiver. Can be used instead of OSNR under the assumption that OSNR is gaussian and no linearities are present.
Fiber Type		Mandatory	Type of fiber such as SSMF, SMF28, SiCore
Modulation classes supported / forbidden		Mandatory	Provider indicates modulation classes he accepts or excludes such as ASK/NRZ

Length of the link	Km	Mandatory	Length of the link
Number of EDFAs	#	Optional	Number of EDFAs
Longest span length	Km	Optional	
Average span length	Km	Optional	
Total attenuation in fiber	dB	Optional	
Total attenuation in non-fiber (pads, ROADMs etc.)	dB	Optional	
Figure of Merit	[]	Optional	The sum of all (from dB to a.u. converted) gains needed on all EDFAs to compensate losses, final drop span excluded
Number of ROADMs	#	Optional	Indicates the number of filtering ROADMs in the path. (This may be needed by customer to verify if the DWDM TRX can be used)

References

[Aruba] http://www.arubanetworks.com/techdocs/ArubaOS_61/ArubaOS_61_UG/VirtualAPs.php

[Ciena] http://www.ciena.com/

[Cisco] https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/Multi-SSID_Deployment_Considerations

[Cisco_ATF] http://www.cisco.com/c/en/us/td/docs/wireless/controller/8-1/configuration-guide/b_cg81/b_cg81_chapter_010100100.html

[Cisco nLight] Cisco nLight™ Technology: The Value of a Multi-Layer Control Plane for a Converged IP+Optical Transport Network Architecture, 2012 http://www.cisco.com/c/en/us/products/collateral/switches/catalyst-3750-series-switches/whitepaper_c11-718853.html

[Cisco_QoS] http://www.cisco.com/c/en/us/td/docs/wireless/access_point/12-4_3g_JA/configuration/guide/ios1243gjaconfigguide/s43qos.html

[CMon] https://www.terena.org/publications/tnc2014-proceedings/16-trupti-kulkarini-CMON.pdf

[CMon IG] https://forge.geant.net/forge/display/cmon/Documentation

[Compendium 2014] https://www.terena.org/publications/files/Compendium-2014.pdf

[Cox, J.] Jeffrey Cox, SDN Control of a Coherent Open Line System, 2015 https://www.osapublishing.org/abstract.cfm?uri=OFC-2015-M3H.4

[D12.1_DJ1.2.1] GN3plus deliverable D12.1 (DJ1.2.1) Network Architectures for Cloud Services, March 2015 http://geant3plus.archive.geant.net/Resources/Deliverables/Documents/D12-1_DJ1.2.1_Network-Architectures-for-Cloud-Services.pdf

[D5.27_DS1.1.2] GN3plus Deliverable D5.27 (DS1.1.2) Regional Study Report, May 2014

[Dial Telecom] http://www.dialtelecom.cz/download/1401788894_bcea/PL+Alien+Lambda.pdf

[ECOC] http://www.ecoc2014.org/uploads/Workshops/WS3/Google%20-%20Workshop%20-%20Test%20Protocols.pdf

[EoGRE] http://www.cisco.com/c/en/us/td/docs/ios-xml/ios/interface/configuration/xe-3s/ir-xe-3s-book/ir-eogre.html

[G.698.2] https://www.itu.int/rec/T-REC-G.698.2-200911-I/en

[G.698.3] https://www.itu.int/rec/T-REC-G.698.3-201202-I/en

[GÉANT_OSD] GÉANT Open Service Description, 2015.pdf

[Geihs et al.] Kurt Geihs, Wolfgang König, Falk von Westarp, Networks: Standardization, Infrastructure, and Applications, Physica-Verlag GmbH & Co, 2002

[GLIF] https://www.glif.is/publications/press/20110330.html

[GN3-11-074_DJ1.3.2] GN3 Deliverable DJ1.3.2 Architecture Considerations for Federated Backbone Networks Study, May 2011

[hostpad] https://w1.fi/hostapd/

[IP/OC WP] http://www.tid.es/sites/526e527928a32d6a7400007f/assets/532c7ce328a32d4d710006bd/White_paper_IP_Optical_Convergence__1_.pdf

[Juniper ADVA] Juniper ADVA Packet Optical Convergence, Reducing total cost of ownership in de-layered networks, 2014 https://www.juniper.net/assets/kr/kr/local/pdf/whitepapers/2000582-en.pdf

[Lach et al.] Hong-Yon Lach, Christophe Janneteau, and Alexandru Petrescu, "Network Mobility in Beyond-3G Systems", IEEE Communications Magazine, July 2003

[Linux] https://wireless.wiki.kernel.org/en/users/documentation/iw/vif

[mobile_data] https://compendium.geant.org/reports/service_for_nren/mobile-data

[Nelson et al.] Lynn E. Nelson, Guodong Zhang, Martin Birk, Craig Skolnick, Rejoy Isaac, Y. Pan, Christian Rasmussen, Graeme Pendock, and Benny Mikkelsen, A Robust Real-Time 100G Transceiver With Soft-Decision Forward Error Correction, Journal of Optical Communications and Networks, Vol. 4, No. 11, November 2012 http://acacia-inc.com/wp-content/uploads/2013/09/RT-100G-Transceiver-with-SDFEC-Article.pdf

[McRae, N.] BT100G Coherent IPoDWDM / Alien Wavelength Trial https://indico.uknof.org.uk/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=25

[MOMoT] http://geant3plus.archive.geant.net/opencall/Optical/Pages/MOMoT.aspx

[NETCONF] R. Enns, Ed.: “Network Configuration Protocol (NETCONF)”, RFC 6241, ISSN: 2070-1721, June 2011

[Peters, B.] Peters, B. (2013). Alien Wavelengths: operational and economical perspectives. In Proc of WDM & Next Generation Optical Networking, 2013

[Proxy_ARP] http://www.cisco.com/c/en/us/support/docs/ip/dynamic-address-allocation-resolution/13718-5.html

[Snoeren et al.] Alex C. Snoeren and Hari Balakrishnan “An End-to-End Approach to Host Mobility” http://nms.lcs.mit.edu/papers/e2emobility.pdf

[T13SG15 Q6/15] ITU-T SG 15 Report 20 “Report of Working Party 2/15, Optical technologies and physical infrastructures (Geneva, 22 June - 3 July 2015)”.

[Vusirikala et al.] Vijay Vusirikala, Bikash Koley, Tad Hofmeister, Vinayak Dangui, Valey Kamalov, and Xiaoxue Zhao, Scalable and Flexible Transport Networks for Inter-Datacenter Connectivity, 2015 https://www.osapublishing.org/abstract.cfm?uri=OFC-2015-Tu3H.1

[Wakim et al.] Walid Wakim, Theodor Kupfer, Peter Lothberg, Hojjat Salemi, Matthias Berger, 100G Coherent DWDM Interop and Pluggable Technology Review, 2013 http://www.stupi.se/Standards/100G-long-haul4.pdf

[YANG] M. Bjorklund, Ed.: “YANG - A Data Modeling Language for the Network Configuration Protocol (NETCONF)”, RFC 6020, ISSN: 2070-1721, October 2010

[Zhang, L.] Lixia Zhang, “What should the future Internet be centered on: Information, Service, Mobility, or User?”, INFOCOM 2015 Panel

Glossary

3GPP	The 3rd Generation Partnership Project
5G	5th generation mobile networks or wireless systems
AAA	Authentication, authorization, and accounting
AP	Access point
ARP	Address resolution protocol
ASON	Automatically Switched Optical Network
AW	Alien Wave
AWS	Alien Wave Service
CAPEX	Capital expenditure, i.e. funds used by a company to acquire or upgrade physical assets, such as property, industrial buildings or equipment
CBF	Cross-Border Fiber
CMon	Circuit Monitoring
CMon HQ	CMon Headquarter
COLO	Colocation
CPS	Circuit provisioning system
CW	Contention Window
DAS	Distributed antenna system
DB	Data base
DF	Dark fibre
DHCP	Dynamic Host Configuration Protocol
DNS	Domain Name System
DWDM	Dense Wavelength Division Multiplexing
eduroam	Global service that provides secure roaming connectivity
EoGRE	Ethernet over GRE
FEC	Forward error correction
GLIF	Global Lambda Integrated Facility
GMPLS	Generalized Multiprotocol Label Switching
GRE	Generic Routing Encapsulation
GUI	Graphical user interface
HQ	Headquarter
IDM	Identity-driven management
IPSEC	Internet Protocol Security
ITU	International Telecommunication Union
ITU-T	Telecommunication Standardization Sector, one of the three sectors of the ITU
KPI	Key performance indicator

LAA	License Assisted Access
LAN	Local Area Network
LTE	Long-Term Evolution, a standard for wireless communication of high-speed data for mobile phones and data terminals
LTE-U	LTE-Unlicensed
LMA	Local Mobility Anchor
MAC	Media access control
MAG	Mobility Access Gateways
MIB	Management Information Base
NAT	Network address translation
NMS	Network management system
ODP	Open Data Plane
OEO	Optical-Electronic-Optical
OFC	Optical Fiber Communication Conference and Exhibition
OID	Object Identifier
OLE	Open Lightpath Exchange
OLS	Open Line System
OMX	Open Mobility Exchange
OPX	Off-premises extension
OTN	Optical Transport Network
PBA	Proxy Binding Acknowledgement
PBU	Proxy Binding Update
PMD	Polarization mode dispersion
PMIPv6	Proxy Mobile IPv6
QPSK	Quadrature phase-shift keying
RA	Routing Advertisement
ROADM	Reconfigurable optical add-drop multiplexer
Rx	Receive
Rx/Tx	Receive/transmit
SDH	Synchronous Digital Hierarchy
SDN	Software-defined networking
SMART	Specific, Measurable, Achievable, Realistic, Time-bound
SNMP	Simple Network Management Protocol
SP	Service Provider
SSID	Service Set Identifier
TRL	Technology readiness levels
Tx	Transmit
UE	User Equipment
UPC	Usage Parameter Control
vAP	Virtual Access Point
VLAN	Virtual LAN
WMM	Wireless Multimedia Extensions