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Executive Summary of the Deliverable

Work Package 6 is responsible within COMBO for demonstration activities. It takes inputs from the other technical work packages and will provide feedback from the operator test activities. This is the second deliverable from WP6. The main aim is to describe in detail the different demonstration activities and the current status of the development work.

The structure of the deliverable is based on the previous deliverable D6.1 *"Summary of Planned Experimental Activities and Gap Analysis"*. Specific use cases of fixed-mobile convergence (FMC) have been defined before in WP2 *"Framework definition, Architecture and Evolution"* (D2.1) and have been analysed in formulating the demonstration activities of this deliverable. The architectural targets are based on the work in WP3 *"Fixed Mobile Convergent Architectures"*.

The demonstration activities are structured into

- Structural Convergence – exploring network topology and technology for fixed lines (including Wi-Fi), mobile backhaul and mobile fronthaul convergence and
- Functional Convergence – exploring functions within the network that can be consolidated into common functions, enabling network convergence.

The intention is to use demonstration modules to showcase different aspects of the COMBO architectures and highlight the capabilities and benefits of an FMC network.

Major structural convergence demonstration activities to show a common transport structure for fixed line access, mobile backhaul and fronthaul are related to the different access and aggregation architectures, namely the DWDM-centric architecture and the two different flavours of WDM-PON (wavelength-routed and wavelength-selective) detailed in deliverable D3.3 and currently being standardized in the FSAN group under the name NG-PON2. With respect to functional convergence, major goals are to demonstrate universal authentication (uAUT) and universal data path management (uDPM). Moreover, two implementation variants of a Universal Access Gateway (UAG) – a functional entity currently being discussed within WP3 – are presented. These implementations may be realized in a centralized or distributed fashion.

The demonstration will make use of a specific embodiment of a UAG, where key fixed and mobile functions (nowadays operating separately) such as authentication and data path management are either unified and/or integrated in the same box aiming at providing an effective FMC approach. The deliverable ends with a detailed description of the final demonstration, which will take place at Orange Labs in Lannion, France.

The key achievement of this deliverable is to summarize the different modules developed by the partners and to outline the dependence between and integration of the different modules. The experimental research activities will add to the theoretical and conceptual work undertaken by COMBO. Main findings of the demonstration will be fed back to Work Package 3.

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Glossary

Acronym / Abbreviations	Brief description
2G	2nd Generation (mobile service)
3G	3rd Generation (mobile service)
AAA	Authentication, Assignment and Accounting
ABNO	Application-Based Network Operation
AM	Amplitude Modulation
ANQP	Access Network Query Protocol
APD	Avalanche Photo Diode
API	Application Programming Interface
AWG	Arrayed Waveguide Grating
BBU	Base Band Unit
BER	Bit Error Rate
BSC	Base Station Controller
CO	Central Office
COMBO	COnvergence of fixed and Mobile BrOadband access/aggregation networks
CPE	Customer Premises Equipment
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CS	Content Server
DL	Downlink
DOW	Description of Work
DWDM	Dense Wavelength Division Multiplexing

EMBS	Elastic Mobile Broadband Service
eNB	evolved Node B (base station)
EAP	Extended Authentication Protocol
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FEC	Forward Error Correction
FFT	Fast Fourier Transformation
FMC	Fixed Mobile Convergence (Converged)
FPGA	Field Programmable Gate Array
FP7	Framework Program 7 EU Projects
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
GGSN	Gateway GPRS Support Node
GMPLS	Generalized Multi-Protocol Label Switching
GPON	Gigabit capable Passive Optical Network
GPRS	General Packet Radio Service
GTP	Generic Tunnelling Protocol (or GPRS Tunnelling Protocol)
GUI	Graphical User Interface
HD	High Definition (multimedia/TV)
HW	Hardware
IEEE1588	Institute of Electrical and Electronic Engineers 1588 (Precision Time Protocol)
IMPACT	Part of PIANO+ Group of EU Projects
IP	Internet Protocol

ITU-T	International Telecommunications Union- Telecommunication Standardisation Sector
KPI	Key Performance Indicator
LENA	LTE-EPC Simulator/Emulator
LSP	Label Switched Path
LTE	Long Term Evolution (3GPP standard)
MAC	Media Access Controller
MBH	Mobile Backhaul
MFH	Mobile Fronthaul
MME	Mobile Management Entity
MPE	Multi-Path Entity
MPLS-TP	Multi-Protocol Label Switching – Transport Profile
NFV	Network Function Virtualisation
NGOA	Next Generation Optical Access
NGPON2	Next Generation Passive Optical Network 2
NG-POP	Next Generation Point of Presence
NMS	Network Management System
OADM	Optical Add Drop Multiplexer
OASE	Optical Access Seamless Evolution (Historic EC program) on optical access
ODL	Open Daylight
ODN	Optical Distribution Network
ONF	Open Networking Foundation
ONU	Optical Networking Unit
OOBM	Out-of-Band Management
OTN	Optical Transport Network

PCE	Path Computation Entity
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
P-GW	Packet Data Network Gateway
PHY	Physical Layer Device (interface component)
PIANO+	European Commission Framework 7 Program – PIANO+
PM	Performance Monitoring
PSNR	Peak Signal to Noise Ratio
PtP	Point to Point
pWDM	passive Wavelength Division Multiplexing
QCI	QoS Class Indicator
QoE	Quality of Experience
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
RBS	Radio Base Station
REAM	Reflective Electro Absorption Multiplexer
RLC	Radio Link Control
RNC	Radio Network Controller
ROADM	Reconfigurable Optical Add Drop Multiplexer
RoF	Radio over Fiber
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
RRU	Remote Radio Unit

RSOA	Reflective Semiconductor Optical Amplifier
S11	Reference Point between MME and SGW in LTE
S1-AP	S1 Application Protocol
SaaS	Synchronization as a Service
SDN	Software Defined Networking
SFP+	Enhanced Small-Formfactor Pluggable
SGi	Reference Point between PDN Gateway and the packet data network in LTE
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SC-GW	Small Cell Gateway
SLA	Service Level Agreement
SME	Small Medium (sized) Enterprise
SMSR	Side Mode Suppression Ratio
SOA	Semiconductor Optical Amplifier
SON	Self-Organising Network
SSIM	Structural Similarity Index
SW	Software
TEID	Tunnel End Point Identifiers
TFT	Traffic Flow Templates
TP	Transponder
TUCAN	Project within PIANO+ Program
UAG	Universal Access Gateway
uAUT	Universal Authentication
UDP	Universal Datagram Protocol

UDPM	Universal Data Path Manager
UDR	User Data Repository
UE	User Equipment
UHD	Ultra High Definition (multimedia/TV)
UL	Uplink
ULL	Ultra Low Latency
UMTS	Universal Mobile Telecommunications System
VNF	Virtual Network Function
VOA	Variable Optical Attenuator
VoD	Video on Demand
VoIP	Voice over Internet Protocol
VQM	Video Quality Metric
WDM-PON	Wavelength Division Multiplexing-Passive Optical Network
Wi-Fi	Wireless Local Area Network – Commercial name
WLL	Wavelength Locker
WSON	Wavelength Switched Optical Network
WR	Wavelength Routed
WS	Wavelength Selective
WSS	Wavelength Selective Switch

1 Introduction

The purpose of this document is to detail the adopted modules and planned setups to demonstrate and assess selected architectural, technological and functional solutions along with the approaches being studied and proposed within the COMBO project. For the sake of completeness, the fixed-mobile convergence (FMC) solutions in COMBO are being explored and thoroughly studied in the context of WP3. The description of such FMC approaches is done from a twofold perspective: structural convergence addressed in [1] and functional convergence partly covered in [2]. Both documents (i.e., [1] and [2]) are used as the baselines for devising, developing and running the experimental platforms and setups herein described. Additionally, this document also covers the specific validation of some of the FMC use cases identified and reported in Deliverable D2.1 [3]. Thus the aim of Deliverable D6.2 is to provide a clear view about the specific COMBO FMC solutions that are intended to be demonstrated at the end of the project (also referred to as “COMBO Final Demonstration” planned to be held at Orange Labs, Lannion, France). This work emphasizes on the adopted technologies and enablers and lists the considered COMBO FMC solutions to be validated. Architectural enablers are for example Software Defined Network (SDN)-based control and Network Function Virtualization (NFV). Furthermore, the applied control (e.g., protocols) and data interfaces among the different network entities and elements are described. Last but not least the expected outcomes for the integrated demonstration related to the individual building blocks are outlined.

D6.2 extends and refines the former work done in Deliverable D6.1 (“Summary of Planned Experimental Activities and Gap Analysis”) [4], which identified roughly the targeted demonstrations and proof-of-concepts to be carried out. As a next step D6.2 will be complemented with the final report to be produced in D6.3 (“Report describing results of operator testing, capturing lessons learned and recommendations”), which will summarize the obtained results on top of the D6.2 experimental setups along with the lessons learnt in terms of conclusions and recommendations when deploying some of the studied COMBO FMC solutions. Bearing this in mind, D6.2 documents the current status of the demonstration systems, network entities, tools, functions, etc. being and planned to be developed in the context of WP6.

The general architecture of the global demonstration is depicted in Figure 1. This global validation combines the individually planned demonstration modules addressing particular FMC solutions studied in COMBO. Specifically, as shown in the figure, different access technologies are considered for the sake of demonstrating feasible and effective FMC solutions such as Wi-Fi, mobile (LTE) and fixed lines. Therefore, the required network elements such as mobile eNodeBs, Wi-Fi access points and residential gateways (RGWs) for fixed access networks will be provided in the experimental setup. For the access and aggregation network infrastructures the demonstration platforms will rely on the technologies being adopted by COMBO: Dense Wavelength Division Multiplexing (DWDM) and WDM Passive Optical Networks (WDM-PON). Finally, the novel COMBO concept termed as Universal Access Gateway (UAG) will be validated where specific fixed and mobile functions (nowadays operating separately) are either unified and/or integrated in the same box aiming at providing an effective FMC approach.

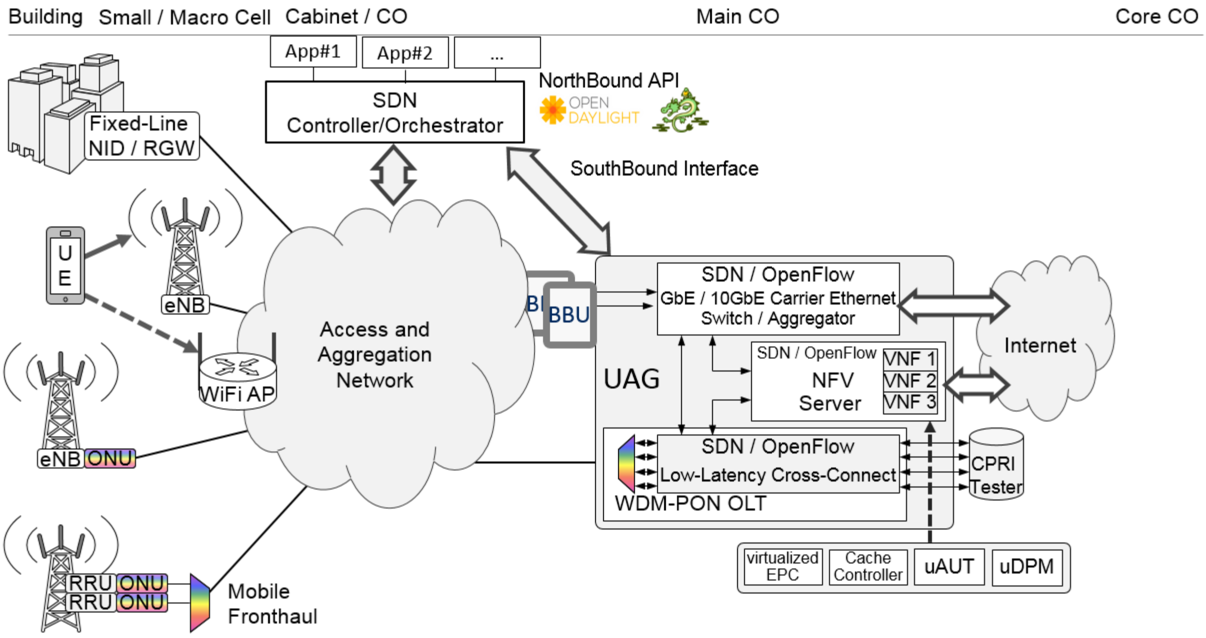


Figure 1: General network architecture and functions addressing WP6 demonstration

As commented above, the demonstration modules and network elements represented in Figure 1 are treated as different sections within the document as briefly described below.

Demonstration module 1 is primarily a structural FMC demonstration activity. Three different access network technologies have been selected, which enable the convergence of different services such as fixed line, mobile backhaul and mobile fronthaul. Details on the structural demonstration activities are thoroughly addressed in Chapter 2.

Demonstration module 2 is primarily a functional FMC demonstration activity. It makes use of functions traditionally hosted on the end-user equipment and in several network equipment units. Major activities in this module are the demonstration of novel concepts and solutions in the context of the UAG functional entity being devised in COMBO, such as universal authentication (uAUT, see Chapter 3 in D3.2 [2]) and the universal data path manager (uDPM, see Chapter 4 in D3.2 [2]). Specific details on the different components constituting both uAUT and uDPM demonstrations are discussed in Chapters 3 and 4.

Chapter 5 shows the development efforts with respect to a distributed and a centralized next-generation point-of-presence (NG-POP). The NG-POP is a location in the network, where the operator could implement multiple functions, including the IP edge for all network types (fixed, Wi-Fi, mobile) [2]. In this regard, Chapter 5 considers the COMBO definitions for each approach according to the real location of the control and data plane FMC functions handled within the NG-POP. For the sake of clarification, the NG-POP can be either located at the main CO (i.e., close to the end user) or at the core CO (i.e., in the core network at the frontier with aggregation network); the former approach is identified as “distributed NG-POP” whereas the latter is identified as “centralized NG-POP” [2]. Each approach provides its own pros and cons, and the aim of the demonstrations in this chapter is, besides validating the feasibility of each one, to clearly state the expected advantages and shortcomings that each approach would bring to the overall FMC network infrastructure. In particular, this chapter describes the different components contained in a potential UAG implementation for the distributed NG-POP approach. Besides detailing the control and data plane technologies used in such UAG implementation, the capability of the UAG is also discussed to host virtualized FMC functions such as uAUT, uDPM and EPC as virtual network functions (VNFs) exploiting the concept of NFV. For the demonstration of a potential implementation of a centralized NG-POP approach, the so-termed Unified Orchestration System is presented. Such a system (based on an SDN concept) aims at providing – in a unified way – the control and configuration of a common aggregation transport network which seamlessly transports both fixed and mobile traffic services. The SDN orchestration communicates and interoperates with the control planes used by fixed and mobile traffic requests and automatically selects and occupies the network resources to accommodate such flows. In this particular case the FMC goal is achieved having a hierarchical entity (i.e., SDN orchestrator) to handle both types of services over a common shared aggregation transport network.

In Chapter 6 the detailed plans for the integration of the different modules into a unified demonstration (referred to as “Final COMBO Demonstration”) at Orange Labs in Lannion, France, are described.

Chapter 7 summarizes the work of the deliverable and outlines the plans for achieving the goals of the final demonstration.

2 Access and Aggregation Architectures Demonstration Activities

So far fixed, Wi-Fi and mobile networks have been independently developed and are, especially in the access network segment, separated in terms of infrastructure (fibres), systems as well as planning, design and operation. Today, there is only a partial convergence in the aggregation network.

The development of a converged access and aggregation network has to cope with the foreseeable network evolution for the fixed, Wi-Fi and mobile networks, including the evolution to 5G. For the fixed access network, this evolution includes node consolidation, concentration of access equipment in the Main CO, and the roll out of a passive fibre network towards the residential customers in an FTTC or FTTH approach. Based on these requirements and restrictions arriving from future mobile evolutions, COMBO proposes options for a converged architecture handling fixed access, Wi-Fi backhaul and mobile backhaul/fronthaul. The system solutions which are to be considered in the following have been selected with regard to the challenging FMC requirements namely capacity (including future scaling capability), reach (also considering site consolidation) and potential transparency (e.g. for transport of CPRI protocol) [1]. As a result *only fibre-optic solutions, which make use of wavelength division multiplexing and which can support passive infrastructure* are considered.

D3.3 [1] proposes NG-PON2 with different flavours of WDM-PON as the main vehicle for structural convergence in the access and aggregation segment of the network. The selected demo platforms are all based on WDM technology in order to be able to support high capacity demand of next generation fixed and mobile services and also guarantee a smooth evolution of legacy access networks.

The following sub-sections aim to describe, in detail, the different demo platforms as well as the supported use cases for the structural demo. Three different approaches have been selected, which cover all relevant scenarios to be used in future FMC networks. In such a way it is possible to investigate this area most completely and identify an optimum architecture.

The first demo platform is based on a DWDM-centric converged access aggregation solution, showcasing the flexibility of the solution with optimal re-use of network resources.

The second demo platform is based on a wavelength selective (WS) WDM-PON convergence solution, showcasing an upgrade of a splitter-based GPON system with point-to-point wavelength services as an overlay.

The third demo platform is based on a wavelength routed (WR) WDM-PON convergence solution, showcasing longer reach than splitter-based architectures and higher capacity (up to 40 wavelengths) with up to 10 Gb/s (uncontended) bandwidth.

2.1 DWDM-centric architecture demo platform

A high level view of the architecture for the first demo platform is shown in Figure 2. The demo platform showcases the flexible control of DWDM wavelength resources and integration with other resources such as radio, packet and IT. The demonstration platform reflects the structural convergence alternatives based on a flexible DWDM-centric data plane as proposed in Deliverable D3.3. DWDM is a mature carrier technology, which has been extensively deployed by network operators and transport providers but, due to its relatively high cost, its deployment has been limited to the backbone network. However, the steady advances in integrated photonic technologies and multi-channel transceivers over the last decade, is expected to bring reduction in cost, power and footprint. Multi-channel transceivers and tuneable lasers are one of the first applications targeted by integrated photonics. Samples and demonstrations are available today (e.g. [5]) and technology maturity could come in a few years.

The motivation for flexibility in the DWDM domain is to efficiently support a wide variety of advanced services across the different domains, to support network sharing and to improve operational efficiency. The full benefits of such flexibility are yet to be explored in D3.4. However, coordination across domains with heterogeneous types of resources is an extremely difficult task with today's rigid network architecture. To address this challenge, we adopt an architecture based on software defined networking (SDN) [6], which makes the network programmable through software. In an SDN-controlled network, a logically centralized controller provides a programmatic application programming interface (API), which exposes networking infrastructure capabilities to higher layer control applications and services, and enables them to dynamically program network resources. The impact of such an API goes beyond traditional network control, since this allows deployment of applications on top of the infrastructure to automatically optimize across heterogeneous domains and quickly instantiate new end-to-end services.

As shown in Figure 2, the proposed control architecture comprises a multi-domain resource orchestration through a hierarchical SDN control architecture across two types of resources: transport and radio access network (RAN). This multi domain controller will be integrated with the DWDM centric demo test-bed, which will be used to demonstrate the benefits of orchestrating the resources of converged network through a practical use-case.

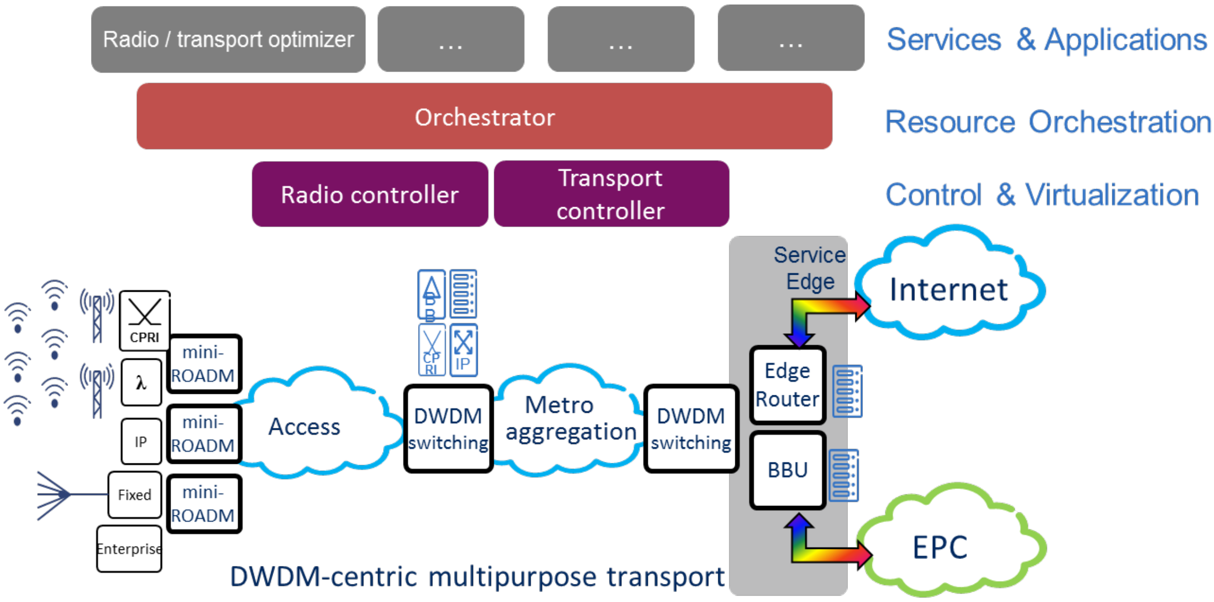


Figure 2: High level view of DWDM centric structural demo architecture

2.1.1 Data plane details

The key data plane components of the demo testbed are Wavelength Selective Switches (WSSs), transponders and fixed filters, as shown in Figure 3.

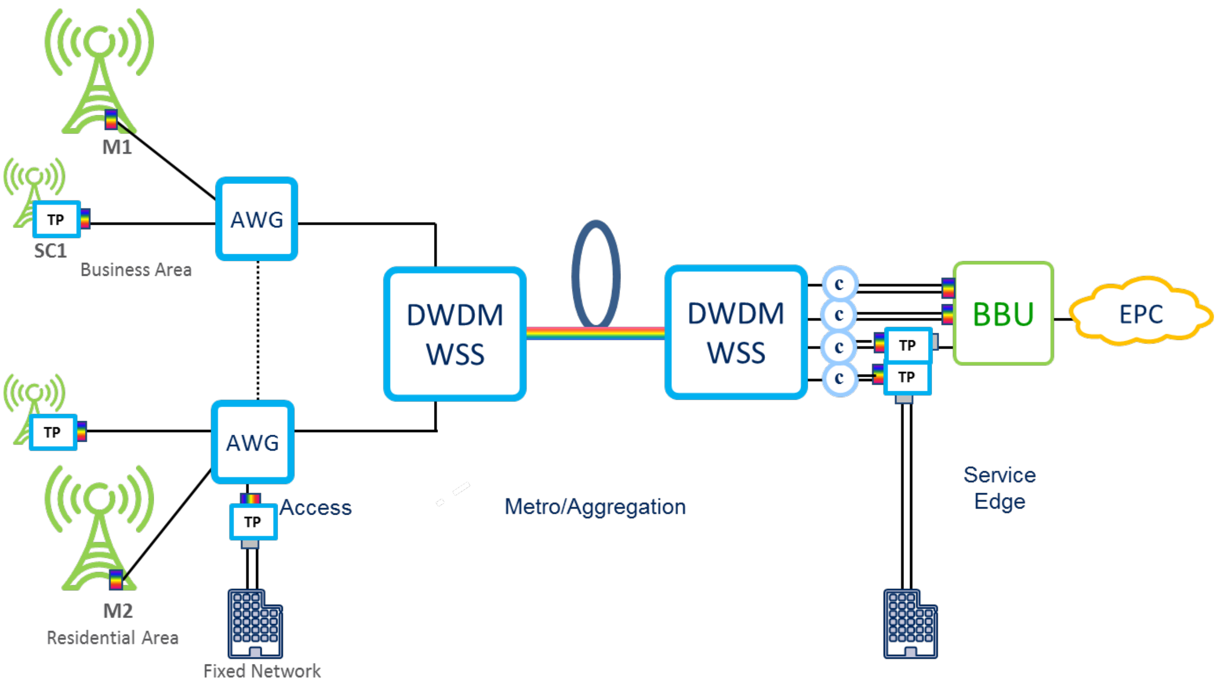


Figure 3: Data plane architecture of the demo set-up and key components

The WSS (Figure 4) is an essential building block of today's WDM optical networks. In a WSS each wavelength can be dynamically switched between a "common" port and one of the tributary ports, independently from other wavelengths. The demo testbed is based on 1x4 WSSs (one common port and four tributary ports). Each WSS is used as a configurable bi-directional 1x4 multiplexer/de-multiplexer with the additional feature that it also can be configured to suppress or totally block an input signal. The input signals from the access and service sides are fed into the tributary ports and multiplexed to the common port, while the input signals at the common port are, depending on the configuration state of the WSS, individually switched to different tributary ports.

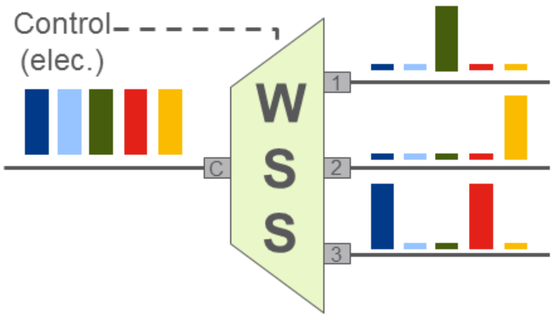


Figure 4: Schematic illustration of a 1x3 WSS

The proposed system architecture also supports flexible arrangement of the demarcation points between the transport provider and the service provider (network operator) domains. When the two domains are managed by the same provider, the DWDM transceivers can be plugged into the client (e.g., RRUs) and service nodes (BBUs). If the two domains are managed by different providers, transponders with grey interfaces on one side and coloured interfaces on the other, as shown in Figure 3, can provide a demarcation point between the transport and service providers. The transponders in the demo platform are equipped with tuneable lasers in order to flexibly inter-connect an optical client with a service interface by performing the necessary wavelength conversion. The client nodes at the access side of the network are connected to AWG filters, which function as fixed add drop multiplexer / demultiplexer for the client signals, while uplink (UL) and downlink (DL) traffic at the service side are separated using optical circulators.

2.1.1.1 Data plane challenges & innovation

Existing DWDM networks employ dual fibre systems with dedicated uplink and downlink ports. In the access segment, single fiber operation will be more or less a requirement. WSSs which traditionally are used in dual fiber solutions are inherently bi-directional devices and can in principle also be used in bi-directional communication systems. In our demo platform the WSSs are utilized in a single fiber bi-directional manner. The main challenge of this is related to potential reflection problems. Such reflections stem from both fibers/connectors as well as within the optical devices (e.g. WSSs) used in the network.

Here we characterize the inherent reflections of the WSS where an input signal at any of the tributary ports may be reflected back to the output tributary ports, creating interference problems with the "real" output signals in these ports. Note that normally, in dual fiber systems, isolators are inserted in the WSS to prevent these types of reflections, in our solution, however, the isolators have to be removed to support bi-directional communication. To illustrate the parasitic reflections, let us consider a simplified 1x4 WSS model, as depicted in Figure 5. Note that in real WSSs the light might pass through several optical elements, e.g., lenses and collimators, before reaching the reflective element.

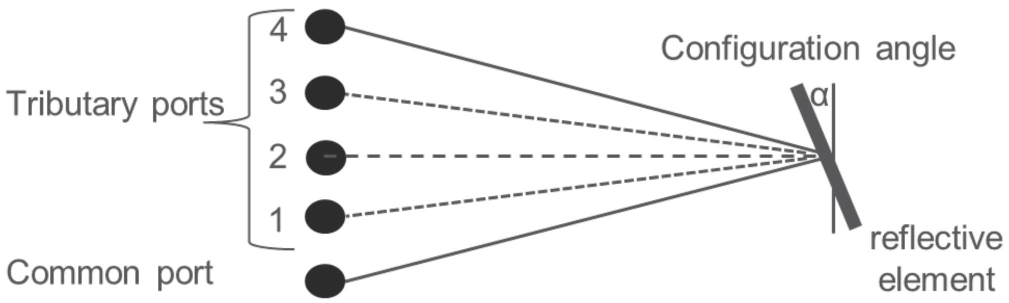


Figure 5: Illustration of reflection problems in WSS

Assume now that the WSS is configured such that the reflective elements in the WSS are positioned to switch the input signal from the common port to tributary port 4, as shown in Figure 5. In view of the relative positions of the different ports, the same configuration may now create a reflective path between tributary ports 2 and 3, while the signal at port 1 is reflected back onto itself [7].

In Figure 6, we show a characterization of the reflections in one of the WSSs of the demo testbed. The reflected signal power at each tributary port was measured by injecting a 0 dBm signal into each of the tributary ports. The same measurement was repeated while the common port was routed to each of the tributary ports.

port 1

In \ Out	1	2	3	4
1	-42	-72	-66	-47
2	-72	-11	-46	-
3	-66	-46	-43	-72
4	-46	-75	-75	-43

port 2

In \ Out	1	2	3	4
1	-21	-61	-66	-47
2	-61	-11	-46	-
3	-66	-46	-43	-75
4	-46	-	-	-43

port 3

In \ Out	1	2	3	4
1	-35	-9.2	-57	-47
2	-9.2	-11	-46	-73
3	-57	-46	-43	-74
4	-46	-73	-	-43

port 4

In \ Out	1	2	3	4
1	-23	-62	-2.9	-46
2	-62	-3.5	-46	-68
3	-3.0	-46	-23	-73
4	-46	-68	-72	-42

Figure 6: Reflected power [dBm] in one of the WSSs,
when all wavelengths routed from common port to ports: 1, 2, 3 and 4.

The following observations and conclusion can be drawn from the table:

- The behavior of the WSS is symmetrical, i.e. the same reflected power from port Y with input on X as from port X with input on Y
- Reflections higher than -40 dB will result in higher BER
- Input signal on port 2 always gives at least -11 dB reflected signal onto itself
- Very high reflected power between ports 1 and 3 as well as from port 2 onto itself when wavelength routed from common port to port 4
- Also relatively high reflected power from port 1 onto itself as well as from port 3 onto itself when wavelength routed from common port to port 4
- All the reflections highlighted above are probably fundamental for this particular WSS design from JDSU, and may cause a problem in a system, if care is not taken to avoid configurations where they occur. However, the reflections measured in two WSS, both from JDSU, are not identical.
- An alternative WSS design that may partly mitigate the problem (without wasting to much space) is to put the common port in the middle and offsetting the ports on one side by half a port width (used in Finisar 1x9 and 1x23 WSSs)

Since wavelengths are controlled individually in the WSS and each wavelength is routed between the common port and a tributary port while the parasitic reflections occur between a second and third tributary port, these reflections should normally not pose any major performance issues to the system as long as the constrictions imposed by the reflections are accounted for by the wavelength controller.

2.1.2 Control and management

To provide a level of dynamicity required to support various use cases we have designed and implemented a multi-domain orchestration architecture based on SDN, which supports dynamic service creation across a heterogeneous set of resources in a resource-optimized manner. The testbed is composed of a DWDM-centric transport network and a mobile broadband network based on LTE. The details of the two control domains together with the hierarchical orchestration architecture are described below.

SDN-Controlled DWDM-Centric Transport Domain: is a dynamic wavelength routed network and provides transport services at the wavelength level. The domain is composed of optical DWDM switches, arrayed waveguide grating (AWG) filters functioning as optical add/drop multiplexers and tunable transponders (TPs) at the edge of the network. The offered wavelength services are programmable through an SDN controller that manages resource allocation in the domain.

Mobile Broadband Domain: provides broadband services to mobile users employing the LTE technology. The segment is composed of LTE access points, deployed according to the centralized RAN (C-RAN) architecture [8]. In the C-RAN architecture the common public radio interface (CPRI) is used to interface between radio remote units (RRUs) and the centralized base band processing units (BBUs). DWDM is the technology of choice for transporting CPRI signals, due to its high bandwidth as well as stringent latency/jitter requirements. Accordingly, this domain employs wavelength services of the transport domain for CPRI transport.

2.1.2.1 Control and management challenges & innovation

The resource orchestration across the two heterogeneous domains is achieved through the hierarchical control architecture depicted in Figure 2. At the bottommost layer of the architecture there are individual (centralized) domain controllers. The Orchestrator at the middle layer of the hierarchy acts as the convergence layer for a unified resource coordination across the two domains. Specifically, the Orchestrator creates a global view of heterogeneous resources/capabilities and exposes it to higher layer applications over its northbound API. The API enables the application/service controllers (Network Apps) to request the required services from the infrastructure, and the Orchestrator then translates the requests to existing resources and accordingly programs the data plane through the corresponding controllers. The global orchestration process enables agile and resource-efficient creation of diverse services across the two domains (optical and mobile).

To realize the transport controller we utilized the open-source OpenDaylight (ODL) [9] as the basis, and extended it with several functions to optimize it for control of large-scale DWDM networks. The first extension includes the design and implementation of southbound plugins for control of existing DWDM network products (i.e., DWDM switches and TPs). The ODL is also extended to support circuit-switched types of services. Additionally, we have integrated an optical path computation element (PCE) into ODL. Finally, ODL is extended with an additional layer of transport abstraction/virtualization on its top, so that all details of the DWDM layer are abstracted and hidden from higher layer controllers (i.e., orchestrator in Figure 2). Specifically, the Orchestrator only sees an abstract representation of the whole transport domain, which makes the service creation process simpler and more scalable.

For controlling the mobile domain we use an existing domain-specific controller that centrally controls the RAN resources. The RAN control functions include, among other things, activation and configuration of cells, the assignment of BBU resources to RRUs as well as management of users' handovers among cells.

2.1.3 Supported use cases

Use Case 5 "Support for large traffic variations between public, residential, and business areas". The basis of this use case is the observation that traffic demand in different geographical location varies not only during the hours of the day but also between weekdays and weekends according to the following pattern:

- During week days, the traffic demand in business areas is very high during working hours, but very low after working hours.
- The traffic demand in residential areas is very high after working hours and also during weekends.

The above pattern reveals the long term behaviour of the traffic and can be predicted to a large extent using traffic statistics. In reality, however, the traffic demand will also include a short term pattern, which due to various reasons, e.g., special events, major accidents, etc. in the area create short term traffic surges on top of the long term traffic pattern. The short term traffic demand in the network needs to be monitored in order to trigger changes in the network to optimize the utilization of radio and transport resources in the testbed.

The solution will demonstrate an efficient use of resources by catering both the long term and short term traffic load variations**.** Another benefit of the flexible FMC solution is its ability to scale up/down network resources based on demand. Based on continuous monitoring of demand and considering scheduled events, the available resources can be utilized more efficiently.

Based on the above stated use case, the solution will demonstrate an efficient use of resources, identified in D3.3, by catering both the long term and short term traffic load variations including:

- Energy savings: scale resources according to demand in order to reduce energy consumption
- Flexible network resource sharing: scale resources of different services or different transport clients in order to efficiently serve demand
- CapEx savings
    - BBU: utilize BBU resources efficiently by flexibly connecting resources to different RRUs based on demand

2.1.4 Detailed process description of the use cases

To demonstrate and evaluate benefits of the multi-domain orchestration, of the flexible FMC network solution, in supporting resource sharing and energy and CapEx savings listed above, we have implemented a use-case that is composed of one service running on top of the orchestrator. This service is an elastic mobile broadband service (EMBS), where the service capacity is dynamically and automatically scaled up and down—when and where needed. This requires the DWDM transport and radio resources to be dynamically utilized in a coordinated manner. We have implemented the EMBS in our testbed by creating a RAN in two areas: business area and residential area shown in Figure 7. Each RAN area is equipped with two RRUs: a macro cell and a small cell. While a macro cell provides the coverage across the area, i.e., the long term traffic demand, the small cell is used to cater the short term traffic demand by providing additional capacity in the area, if and when needed. A total of 4 RRUs (across two areas) are served by a BBU hotel with 3 BBUs.

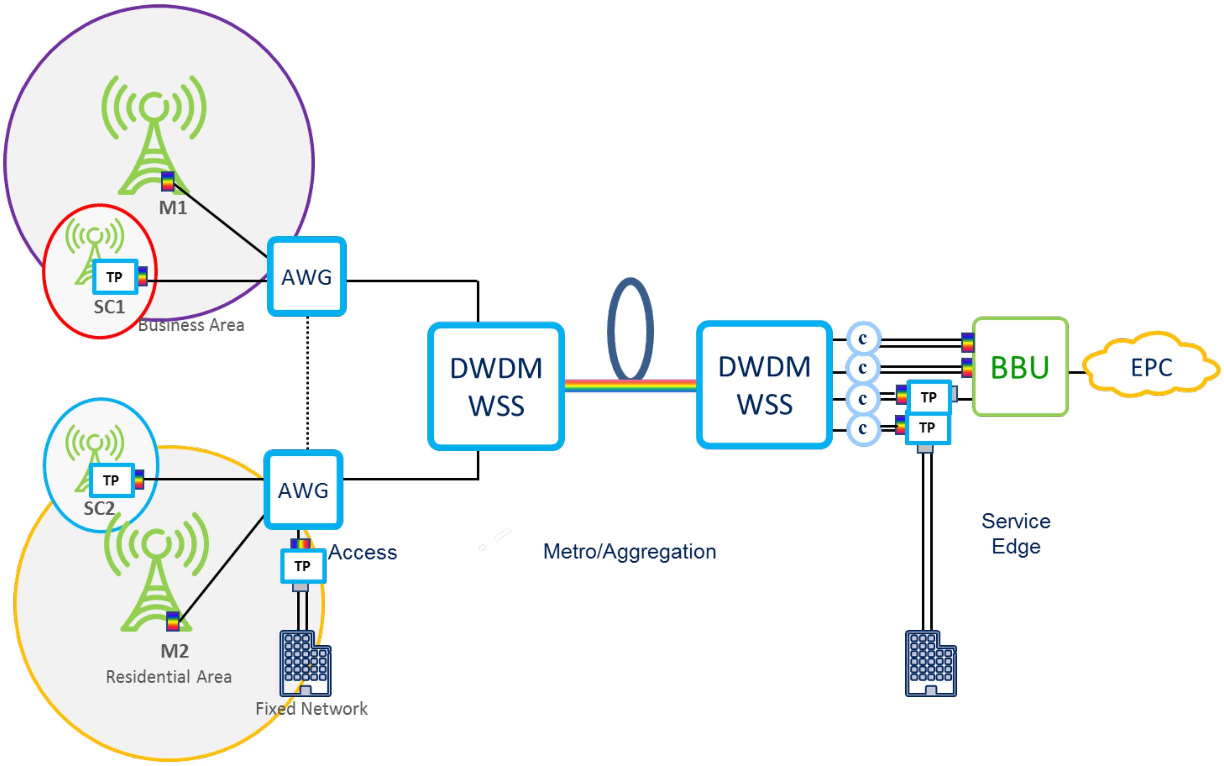


Figure 7: Flexible support of traffic variation in different location

A service management application is created and attached to the Orchestrator's northbound API. The application receives a view of the available radio and transport resources, and continuously monitors the service demand in the RAN, by monitoring the throughput of active cells (via domain controller). In the default operation mode, only the two macro-cells are active providing coverage in both areas. When extra demand is identified by the application in an area, the corresponding small cell is activated. To do that, the application requests the Orchestrator to re-program the testbed to adjust the service capacity, i.e., through de/activating small cells. The Orchestrator translates the request into required configurations in the transport and RAN, and the configurations are applied in the data plane by the corresponding controllers. For example, activation of a new RRU involves: assigning and configuring appropriate BBU resources from the BBU Hotel, and establishing the wavelength connectivity between the RRU and the assigned BBU. In the testbed, only one small cell is activated at a time, to serve the area with a higher demand. This demonstrates dynamic (time-sharing) reuse of resources where a 4-cells RAN requires only 3 WDM connections and 3 BBU resources. In a larger network, obviously, there would be many RRUs and BBUs and the benefit from the dynamic resource allocation would be much higher.

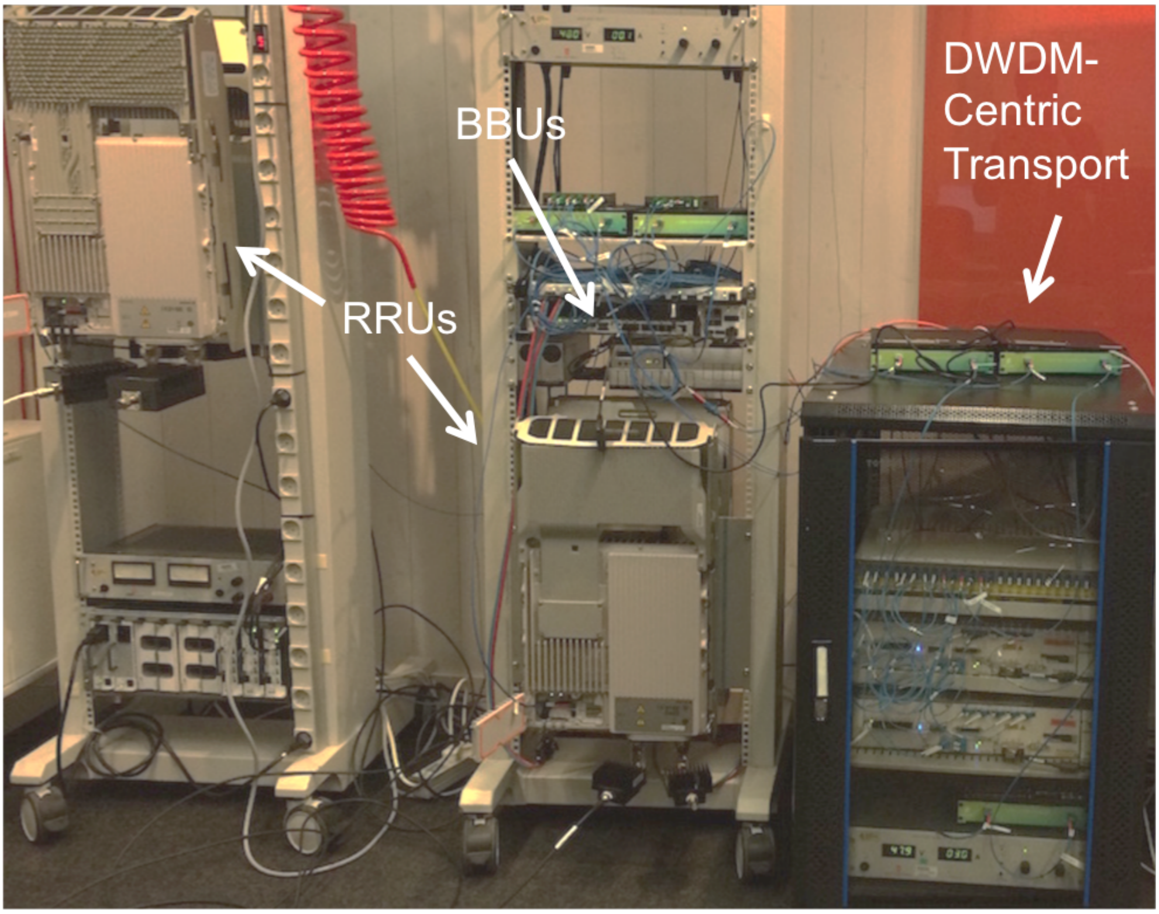


Figure 8: Photo of the demo testbed comprising the RAN and DWDM-centric network that connects to EPC.

We have implemented and successfully run the EMBS in our testbed, shown in Figure 8. The experiments demonstrate the value of a global multi-domain orchestration in a flexible FMC network. Specifically, the orchestration enables a unified control of heterogeneous resources that in turn allows for creation of various services in a resource-optimized way. Among other things, we observe that the DWDM transport resources are smartly shared between multiple services and the gain of resource sharing improves with the size of the network.

2.2 WDM-PON architecture based demo platform

D3.3 [1] has proposed NG-PON2 with different flavours of WDM-PON as the main vehicle for structural convergence in the access and aggregation segment of the network. In this section we describe the details of the two flavours of WDM-PON architectures (wavelength-selective and wavelength-routed) to be demonstrated.

2.2.1 Wavelength Selective (WS) WDM-PON architecture based demo platform

The Wavelength Selective (WS) WDM-PON solution, which is based on tunable transmitter and receiver Optical Network Units (ONUs), aims to be compatible with current FTTH deployments, in which the optical distribution network (ODN) is implemented using power splitters. Thus, this solution is suitable for "brownfield" fibre deployments, and is so the preferred WDM-PON solution for operators which have already deployed power splitters in the field. WS-WDM-PON is an access and aggregation convergent infrastructure solution to upgrade legacy power splitter ODNs with more capacity for offering different fixed and mobile services using WDM without the need to deploy optical components in the field like AWG filters. Moreover, thanks to the use of power splitter components that are wavelength independent, the channel assigned to a particular ONU link can be changed dynamically to other channels, if the ONU detects a bad link status or other particular event or parameter change that is being monitored in real time. This could be exploited in network sharing scenarios in which the same convergent network could implement different services, and also in multi-operator scenarios in which different network operators share the same infrastructure and need to have some degree of freedom for managing the channels they operate dynamically. However, a WS ODN presents some challenges compared to filter based ODNs, mainly related to the use of power splitters in the field. One challenge is the higher insertion loss of power splitters, e. g. 15 dB insertion loss for 1:32 splitting ratio, which requires a higher power budget for the WS-WDM-PON network. Additionally, filtering must be performed on each ONU using tunable receivers, which relies on more expensive ONUs because of the need for a tunable receiver or filter. Other crosstalk issues can also occur due to the use of splitters, as we will further discuss. This could especially be critical in the upstream link, as there is no filter in the field to combine the upstream channels.

The key components of the proposed WS-WDM-PON solution are thus the tunable transmitter and tunable receiver ONU. Current tunable SFP+ transceiver modules (T-SFP+) in the market for use in WDM-PON ONUs do already integrate full C-band tunable transmitters and APD receivers (without any optical filters). There are clear intentions from the most important component manufacturers to develop tunable transmitter and receiver components in the future, but they are not currently available in the market. They will start appearing soon in the course of the evolution of technologies like NG-PON2. However, low-cost tunable filters for NG-PON2 are already available, and those components can be suitable for the WDM-PON ONU to implement the WS-WDM-PON concept. Those filters are typically 4-8 channel tunable filters for NG-PON2, but can be used for WS-WDM-PON, too. In this WS-WDM-PON solution, one of those filters will be used making possible the implementation of the WS-WDM-PON ONU to demonstrate the wavelength selective WDM-PON concept.

2.2.1.1 Data plane details

Figure 9 depicts the data plane architecture of the WS-WDM-PON system. The OLT is based on DWDM SFP/SFP+ C-band transceivers supporting bit rates of up to 10 Gb/s. At the ONU side, tunable SFP+ (T-SFP+) components are used which are also capable for bit rates of up to 10 Gb/s. The solution is also compatible with CPRI line rates required for fronthaul links, including CPRI line bit rate option 7 (9830.4 Mb/s).

The T-SFP+ components of the ONU do integrate C-band tunable lasers and fixed (i.e. without optical filters) APD receivers. The wavelength control and stability of each particular laser is achieved by means of integrated wavelength locker (WLL) on each T-SFP+. This wavelength control could also be implemented in a centralized way from the OLT through communication on the physical layer. In this case, no WLL would be needed on each T-SFP+ of each ONU. Some vendors are following this approach in order to reduce the cost of the T-SFP+ components, and thus the cost of each ONU. This centralized control would imply that the physical layer communication is set up only between OLT TRx and an ONU TRx and works independently. We found that this type of remote wavelength control does not work better than integrated WLL format in some cases due to the need of a parallel communication that could imply an unnecessary load (collect data, analyse data, execute stabilization…), hence we decided to have WLL inside the T-SFP+. Actually, many component manufacturers start to offer price competitive T-SFP+ components with integrated WLLs.

The tunability in the downstream on each ONU is achieved by the use of a low cost tunable filter designed for future NG-PON ONUs. As explained before, those filters are typically 4-8 channel tunable filters, but can be used for WS-WDM-PON, too. The tunability of both laser and filter is managed and controlled from the ONU. Target fibre reach of the solution is that of the typical reach of GPON systems, which is 20 km. In order to achieve that reach with relatively good power budget and splitting ratios of at least 1:32, variable optical amplifiers of gain G = 15-20 dB are used at the OLT side.

As commented during the introduction section, the proposed WDM-PON solution supposes an important upgrade for legacy power splitter based PON systems like GPON, however, WS-WDM-PON is not only a potential replacement for legacy networks for achieving much higher capacity systems, in fact this solution raises the possibility of allowing scenarios where both the new and legacy power splitter based systems coexist together under the same ODN. This new architecture is named a "GPON overlay scenario". Obviously, to achieve the coexistence between these solutions it is necessary to deploy the corresponding optical filters for injecting GPON wavelengths into the unique WS-WDM-PON fibre in a transparent way, note that standard C-Band only AWGs that are used for multiplexing all DWDM wavelength cannot be used for GPON overlay due to its working wavelengths. In addition, GPON overlay implies certain requirements to consider during network design such as power budget and the maximum reach (20 km).

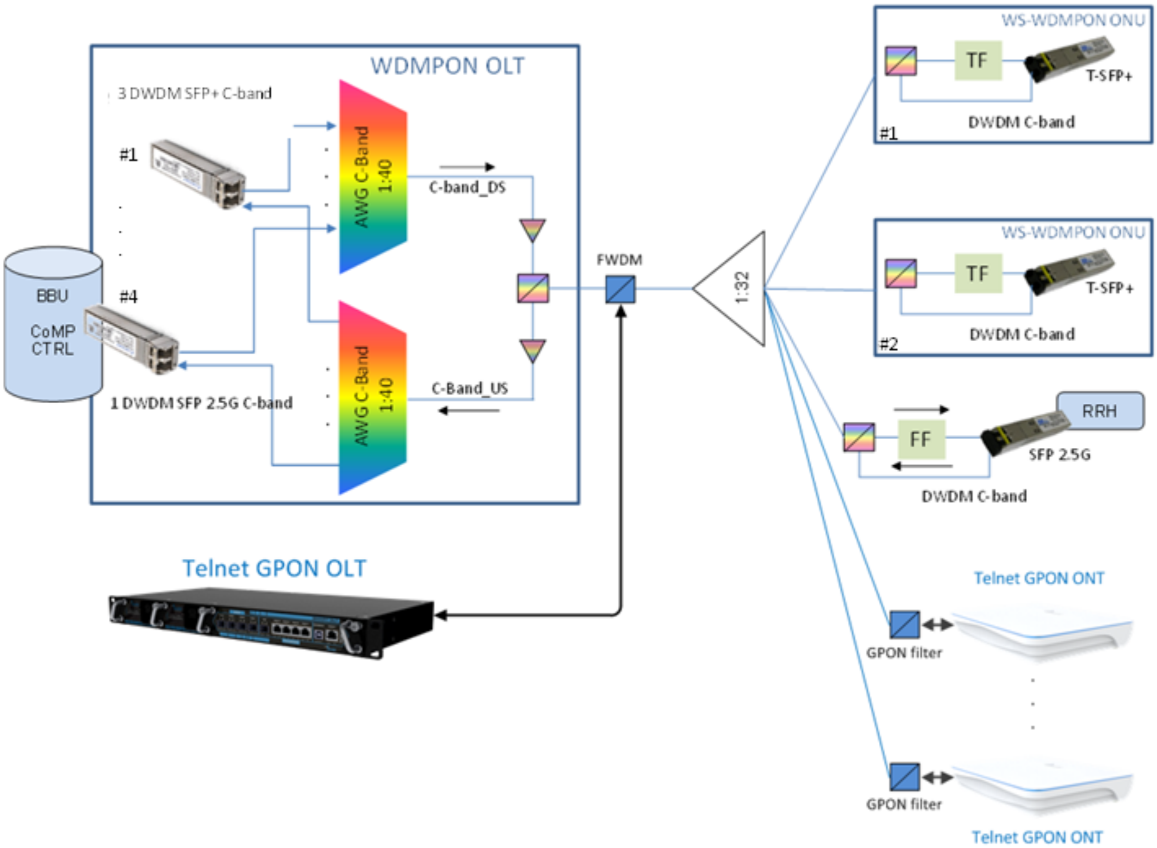


Figure 9: WS-WDM-PON GPON overlay data plane

The WS-WDM-PON system will also be integrated with mobile BBU and RRH of the "DWDM centric" testbed (see section Section 2.1) to demonstrate the transport of 2.5G CPRI links over the proposed system together with 10G fixed access links under a FMC scenario. For achieving this, the BBU will be integrated with the OLT by plugging on its corresponding 2.5G CPRI interface one of the DWDM SFP transceivers of the WDM-PON system. One of the ONUs will then be connected to the RRH also using its 2.5G CPRI interface. This particular ONU will in that way provide a compatible 2.5G CPRI interface to fully interoperate with the RRH and the BBU.

The following figures show the main items that are involved within the proposed solution described in this section. On the one hand, Figure 10 depicts the head-end WS-WDM-PON equipment (WDM OLT) which is based on two main boxes: a 24-port switch whose interfaces are compatible with SFP/SFP+ format and the enclosure of the optical elements and paths (AWGs, amplifiers, couplers…) that form the Telnet product named as WPONverter. The 24 GbE ports can be configured as input or output interfaces according to the requirements of the proposed scenario. On the other hand, both the enclosure and the PCB of the WDM ONU are illustrated in Figure 11. Note that the CPE is a prototype under development that could experience some evolutions up to its market exploitation, actually there are some blocks (testing reasons) that will disappear in the commercial design, however, its hardware main design is finished and it contemplates the corresponding SFP+ interface where the optical 10G module is integrated as well as other interface for management issues, and obviously the LAN ports. The main block is represented by an FPGA that is in charge of hardware and control plane, besides there is also a microcontroller for monitoring.

Figure 10: WS-WDM-PON OLT DWDM channels

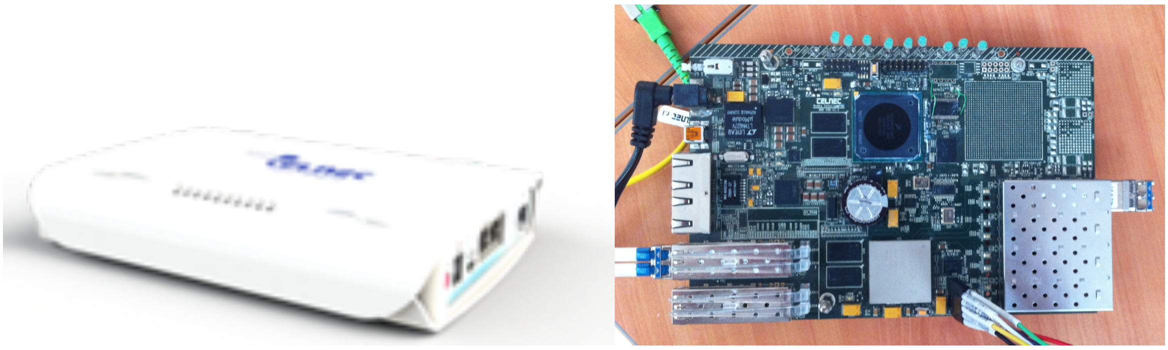


Figure 11: WS-WDM-PON ONT enclosure and printed circuit board

Finally, GPON family products will be used in the final integrated demo such that a GPON overlay scenario can be demonstrated. Both GPON OLT and ONU are shown in Figure 12, from the picture is possible to see the interfaces of the equipment, you can configure the 4-port GbE or the 10G transport port as input ports, defining up to a total of 4 PONs. Regarding the ONU Level 3, any of the 4-port GbE for LAN services as well as the WLAN interface (802.11n MIMO 2x2) can be used for the demo purposes.

Figure 12: GPON OLT and ONT PCB

2.2.1.2 Data plane challenges & innovation

One of the main challenges for the data plane is to demonstrate relatively good power budget and good system performance with the proposed WS-WDM-PON system, which is of extreme importance for its reliability with power splitting ratios used in legacy GPON technology (e. g. 1:32 and higher). A WS ODN with power splitters presents two main challenges compared to filtered ODN for their application to WDM-PON:

- It requires a high power budget of about 33-35 dB for splitting ratios of 1:32 and 20 km of reach
- Interferometric crosstalk can limit the number of channels, which is especially critical in the upstream link

Concerning the power budget, optical amplification will be required at the OLT, which could introduce other issues related to e. g. noise and OSNR degradation, as well as other issues not directly related to the network performance should be taken into account, e. g. cost and laser safety limitations. In this way, different variable optical amplifiers will be used at the OLT (booster high power amplifier and low-noise preamplifier for downstream and upstream respectively) and their gain and related parameters will be optimized, in order to reduce cost and power consumption whilst also taking into account other limitations like the laser safety.

With regard to interferometric crosstalk, it is of extremely importance especially in the upstream link. Once an ONU is plugged in for the first time in the network, the transmitting and receiving wavelengths are not known, and cannot intrinsically be determined due to the splitter in the field, which does not filter any wavelength in contrary to the case of using AWGs. Moreover, an ONU can start emitting light on a wavelength that is already being used by other ONU, if its laser is not fully stabilised, and also in the case of not being able to know its emitting channel in advanced. Those aspects imply the need for the implementation of additional silent procedures and control mechanisms in the ONUs to be able to know in advanced both the transmitting and receiving wavelengths that this ONU is going to use once plugged in for the first time in the network. Different aspects will be taken into account in order to try to reduce this effect. A very good side mode suppression ratio (SMSR) laser will in principle be needed in the T-SFP+ component of the ONU. In general, an SMSR as good as 55 dB is needed in order to reduce crosstalk and so be able to achieve higher WDM count channel system. However, lower SMSR values could also be suitable, if this interferometric crosstalk is controlled in the uplink; which is also related to the ONU silent start procedure control mentioned before. A special control mechanism should be necessary to implement a silent start procedure on each ONU when plugged in to the network for the first time in order to avoid the ONU to start lasing before knowing in advanced an available channel, as well as the receiving channel should also be known in advanced due to the use of splitters in order to tune the tunable filter to the corresponding receiving available channel. This mechanism is also important to reduce interferometric crosstalk, and so relax SMSR requirements of the ONU laser as explained above. The implementation of this silent start procedure will be part of the implementation of the control and management plane of the solution that we describe further.

The main innovation of the proposed solution is the first demonstration of a WS-WDM-PON system which is capable for full ONU tunability at both transmitter and receiver sides, and which is able to operate under a power splitter based ODN, thus also being compatible with FTTH GPON deployments.

Finally, as commented in the previous section, one of the main points and advantages of the proposed solution is the possibility to deploy a GPON overlay scenario thanks to the coexistence within the same power splitter optical network using the same network for FTTH residential services as well as for other services such enterprises, mobile and Wi-Fi. However, this approach requires new challenges in terms of physical constraints, in other words, GPON overlay integration will entail an exhaustive study of the coexistence requirements in order to avoid operation and management issues at OMCI level (GPON standard control layer), e.g., the inclusion of additional optical filters at both CO and CPE sides must not corrupt the corresponding working ranges of DWDM and GPON systems. Besides, GPON overlay has a lower reach compared to an independent WS-WDM-PON solution.

2.2.1.3 Control and management

The control plane of the WS-WDM-PON solution is based on the combination of the following two kinds of management:

- First, Out-of-Band Management (OOBM) control will be used once the ONUs are plugged in for the first time to reduce interferometric control effect and to inform the ONUs what channels are available prior to start transmitting and receiving on a random channel. OOBM will be implemented by the use of a dedicated channel (two wavelengths): one control wavelength for downstream (LambdaC-DS) and one for upstream (LambaC-US), which will be equal for all the ONUs. OOBM will make possible all ONUs to know available transmitting and receiving wavelengths once connected to the network.
- Second, In-Band Management (IBM) control will be implemented once OOBM procedure is set and the link is established for a particular ONU. IBM will be implemented via control/management frames interleaved with transport traffic on working wavelengths. IBM controls dynamic wavelength change once the link is stablished after OOBM procedure is set in case an ONU wants to change to other wavelength, if a particular event occurs, or in case the OLT needs to notify the ONU it must be tuned to other wavelength also in case another particular event occurs.

For the implementation of OOBM and IBM, the following entities will be implemented at OLT and ONU:

- There is a software entity called Control Entity (CE), which is in charge of the overall control plane. The CE is integrated in the OLT equipment and controls both OOBM and IBM. The CE has a general state machine (System State Machine -SSM) and individual state machines for each of the circuits (Circuit State Machine – CSM).
- The SSM is implemented in the CE and has a global vision of the wavelengths that are available in the network, and is in charge of the assignment and modification of the wavelengths to each of the circuits.
- The CSM controls the state of the assignation of each of the circuits, by performing the monitoring of the connectivity between the CE and the ONU. Both CE and ONU do implement the CSM state machine.

The two kinds of management are detailed as follows:

Out-of-Band Management (OOBM):

The communication between the CE and the ONU is performed by means of dedicated static control wavelengths: one for downstream (LambdaC-DS) and one for upstream (LambaC-US) as depicted in Figure 13. Once plugged in for the first time, the ONU tunes the filter to LambdaC-DS and could tune the laser to LambdaC-US; although the ONU laser would be preferably switched off in this state. In Figure 14 it is possible to observe how the OOBM data is implemented within the dedicated wavelengths, the CE is continuously transmitting in LambdaC-DS slotting the time in temporary slots by sending a series of periodic beacon frames. The ONU receives the beacon frames and activates the transmission in LambdaC-US, when a free time slot is found in which available channels are discovered from those frames coming from the OLT. When OOBM procedure is set, the ONU then knows available downstream and upstream channels and notifies the OLT it is going to tune the transmitter and the receiver to two of the available channels e. g. LambdaT-US and LambdaC-DS, via the upstream OOBM link using LambdaC-US wavelength. When receiving ACK from OLT, the ONU can then tune the transmitter to LambdaT-US, and the tunable receiver filter to LambdaT-DS.

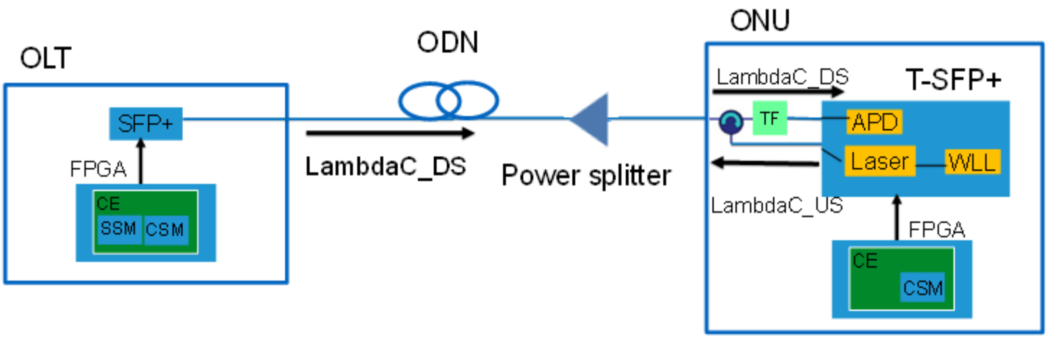


Figure 13: OOBM in the WS WDM-PON system

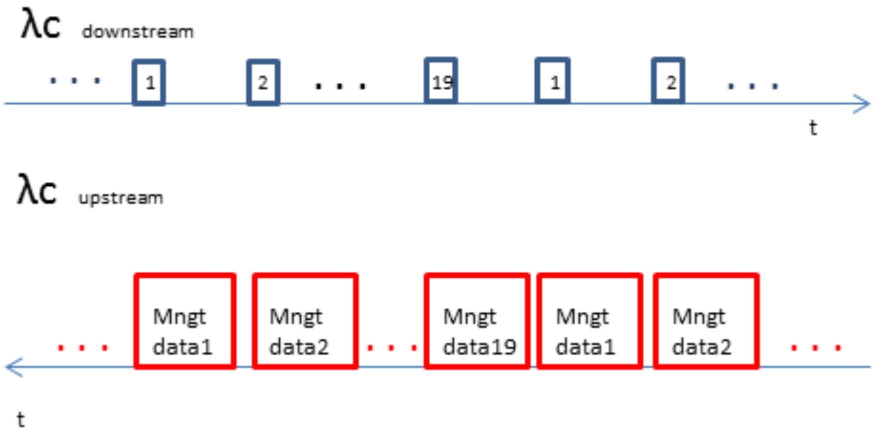


Figure 14: Clients slot-based allocation within OOBM control channels

<u>In-Band Management (IBM)</u>

After OOBM procedure is set, IBM control is then activated over all the established OLT-ONU links to be able to dynamically change the transmitting and or the receiving wavelength on each link when a particular event is detected e. g. bad link status, etc. In this case the communication between the CE and the ONU is now done via the same working wavelengths, e. g. LambdaT-DS and LambdaT-US for downstream and upstream respectively. IBM will be implemented via control/management frames interleaved with transport traffic on working wavelengths.

The following control states are the management functions to be executed by the CE that is implemented within the proposed OLT and that has been defined above:

- Autofind. This state takes place when a certain WDM client equipment boots or when a drop occurs in some network termination. Hence, no carried traffic through the link-under-study because there is not any working wavelength assigned.
    - The ONU starts without wavelength assignment that is the main condition to be able to stablish a communication with the OLT. To

achieve this, the ONU analyses the available WDM channels to occupy via OOBM approach and negotiates with the CE.

  - In case of collisions among ONUs, many retries as are necessary will be executed until a correct wavelength allocation is achieved.
  - When the ONU receives the ACK from CE regarding wavelength request, the client tunes its working wavelength for both transmission and reception.
  - At this point the control approach switches to IMB for this ONT in order to allow future control events. The CE must validate the correct performance of the link, if the behavior is not correct and the corresponding timers expires, the Autofind state restarts again, otherwise, the Autofind process finishes.
- Lambda-request. Once the traffic is carried through the link, a request from the client in order to change its working wavelength is the event that initializes this control state.
  - While the traffic is transmitted via the corresponding WDM channel, the ONU detects a trouble related to the status of the link or the ONU just decides to change its working channel.
  - The new change request is provided via IBM approach.
  - When the ONT receives the ACK from CE regarding wavelength request, the client tunes its working wavelength for both transmission and reception.
  - The CE must continuously validate the correct performance of the link, if the behavior is not correct and the corresponding timers expires, the Autofind state restarts again. Otherwise, the Lambda-request process finishes.
- Lambda-assign. Once the traffic is carried through the link, the CE decides to assign a new wavelength for the link-under-study due to resources reallocation for optimizing the operator network or due to signal degradation. This process is managed by the SSM.
  - While the traffic is transmitted via the corresponding WDM channel, the ONT detects a trouble related to the status of the link or simpler the OLT decides to change its working channel.
  - The new change order is provided via IBM approach. The client tunes its working wavelength for both transmission and reception.
  - The CE continuously must validate the correct performance of the link, if the behavior is not correct and the corresponding timers expires, the Autofind state restarts again. Otherwise, the Lambda-assign process finishes.

2.2.1.4 Control and management challenges & innovation

Control and management challenges are related to the realization of the OOBM and IBM procedures explained before.

The OOBM procedure must be realized in such a way that beacon frames from ONUs to OLT in temporary slots must avoid collisions between different ONUs that access the system at the same time and are requesting the assignment of transmitting and receiving wavelengths simultaneously. Moreover, the implementation of the OOBM procedure has other challenges such as controlling that a particular channel is assigned just to a single ONU so that will never occur the assignment of a particular channel is done to more than one ONU.

The implementation of the IBM procedure is also very challenging because this in-band management will need to allow ONUs for full dynamic wavelength change over the full number of available channels whilst consuming the lowest bandwidth. In this way, a particular ONU could send the OLT the request to change to a new wavelengths when desired based on the discovery of a particular event (low detected power, bad link status, etc.) and OLT can make a particular ONU to change its wavelength also under some particular circumstances based on particular events according to link status. Different alternatives will be evaluated for IBM control procedure:

- No information is sent unless some kind of event should be notified (this option consumes less bandwidth)
- Both CE and ONU are sending control information periodically indicating the link state. This option allows to refresh the CSM at both ends.

Major innovations are the development of a complete control and management plane over a WS-WDM-PON network which allows for full dynamic wavelength control and change over a point to multipoint topology. This could be of high relevance for multi-operator scenarios in which several operators are sharing the same infrastructure but want to manage themselves the channels they are currently using for some of the fixed mobile convergence services they are operating (e. g. fixed residential and business, backhaul and/or fronthaul). In this way, a set of wavelengths can be assigned to a particular operator in a pay-as-you-grow fashion, depending on their needs, and the management of the channels can be done by themselves in real time, and having the degree of freedom to change the assignment of every of the working wavelengths to a different service depending on the status of the particular link and also on new requirements that can arise depending on new network conditions that can be different at a particular point in time compared to the initial status of the network when started to operate those services.

2.2.1.5 Supported Use cases

The following two use cases defined in D2.1 are supported:

- Use case 7 “Converged access and aggregation technology supporting fixed and mobile broadband services”. The demonstration will support single access and aggregation technology supporting fixed services as well as mobile backhaul and fronthaul.

- Use case 8 ”Network sharing”. The WS-WDM-PON here proposed allows for the sharing of a common infrastructure for the transport of multiple services (e.g. fixed residential/business and backhaul and/or fronthaul). Moreover, the proposed control plane allows for dynamic wavelength allocation and change between different services and also between different operators sharing a single multi-service infrastructure. The system has so potential for multi-operator sharing infrastructure purposes.

2.2.2 Wavelength Routed (WR) WDM-PON architecture based demo platform

As an alternative with longer reach and higher capacity a Wavelength Routed (WR) WDM-PON with a filtered WDM-PON technology architecture (Figure 15) based on novel full C-band tunable lasers is investigated. In this solution a WDM multiplexer / demultiplexer routes a single wavelength to an ONU. Typically, the AWG is built in a cyclic fashion, directing a certain wavelength in downstream to a certain ONU and another wavelength (e.g., in another wavelength band) upstream to the CO (compare ITU-T G.698.3 standard [10]). Such a WDM-PON solution is especially suited to the requirements of a converged access/backhaul/fronthaul infrastructure with regard to the bandwidth x reach product (e.g. bandwidth of up to 10 Gb/s per wavelength and reach of > 50 km), which are not supported by today’s existing WDM-PON approaches. A key component of the filtered WDM-PON is a (low-cost) tunable laser to be deployed in each ONU. So far, tunable lasers have not been suitable for access, for cost and complexity reasons. In the newly developed concept centralized wavelength control will be deployed, which allows to leave out individual wavelength lockers in each tunable laser (and with this significantly lowering the module cost because calibration of the laser is reduced a lot and assembly is less complex). The centralized wavelength control is facilitated by imprinting distinct CW pilot tones (i.e. channel labels) onto the upstream wavelengths to enable calculation of individual feedback signals for each ONU for signal power and relative wavelength deviation in the OLT, e.g. by computing a Fast Fourier Transform (FFT) of the etalon and reference diode signals. The feedback signals themselves are transferred back to the ONUs by an auxiliary management and control channel, which can also be implemented by a pilot tone channel in the downstream direction itself carrying a low-bitrate control channel.

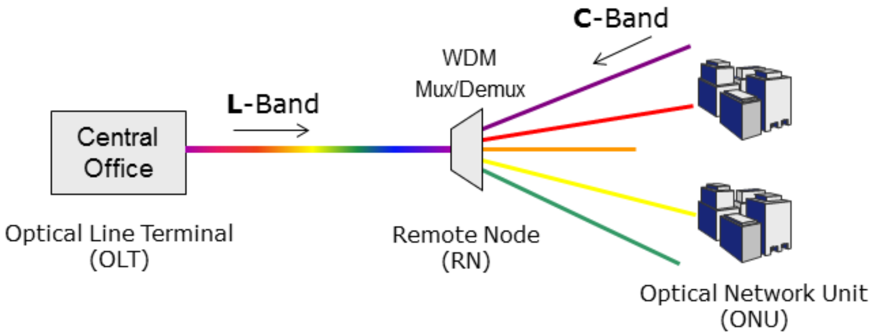


Figure 15: System diagram of the filtered WDM-PON solution using a cyclic AWG at the remote node.

2.2.2.1 Data plane details

In the last years it was not possible to implement and demonstrate WDM-PON with low-cost tunable lasers, simply due to the lack of these lasers. These have become available only very recently (e.g. as a result of an earlier EU funded research project – PIANO+ TUCAN [11]). First samples of these tunable lasers have been integrated in the demonstrator setup supporting bit rates of up to 10 Gb/s (and corresponding mobile fronthaul CPRI data rates up to CPRI line rate option 8). Reach capabilities of more than 50 km have been successfully tested in a lab based demonstration. SFP/SFP+ compliant modules are used at the OLT and ONU, which allow connectivity to various test equipment (e.g. CPRI tester, remote radio head, business/residential customer CPE). The detailed system setup is shown in Figure 16. It can be seen that on the OLT side of the system fixed wavelength L-band SFP/SFP+ modules are used for the downstream. These are multiplexed by an AWG and on the WDM signal an embedded communication channel is imprinted by means of a variable optical attenuator (VOA) with approx. 10% modulation depth. At the remote node the signal is filtered by a cyclic AWG and directed to the attached ONUs. A C/L-band splitter then separates the up- and downstream signals in C- and L-Bands and directs them to the tunable SFP+ component inside of the ONU.

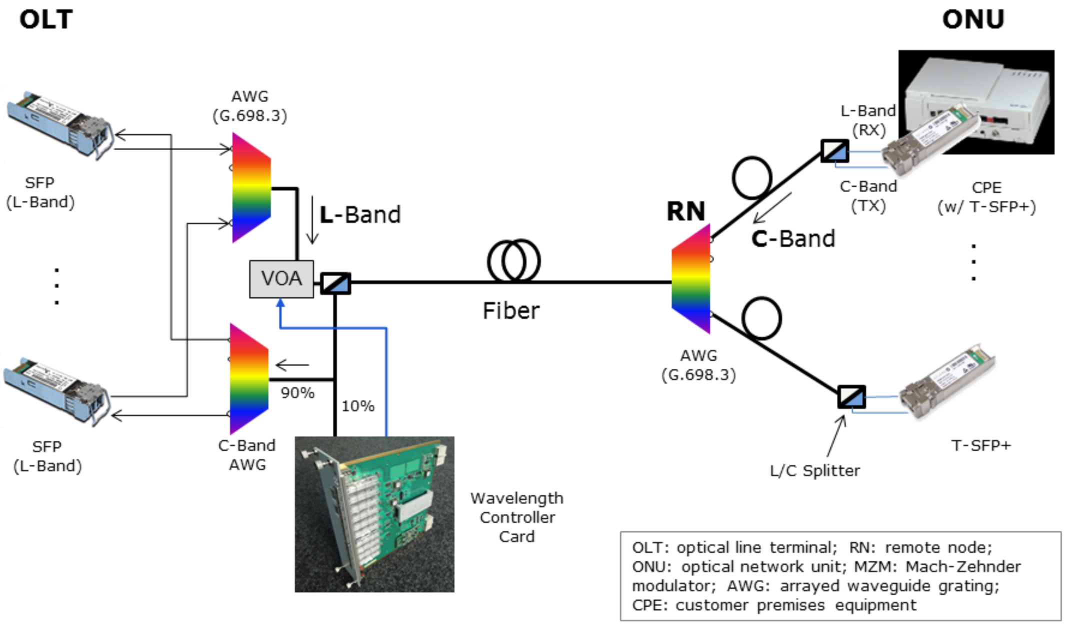


Figure 16: System setup – component level view.

2.2.2.2 Data plane challenges & innovation

Challenges for the data plane are to realize a low-cost tunable laser, which is capable of transmitting up to 10Gb/s at distances >50 km. As the tunable laser is realized “locker-less” a centralized wavelength control needs to be implemented. A key requirement for the data plane is to achieve auto-tuning of the ONU (depending on the AWG port at the remote note it is attached to as depicted in Figure 17) and to maintain the wavelength with high accuracy (± 5 GHz from the ITU-T center frequency as depicted in Figure 18).

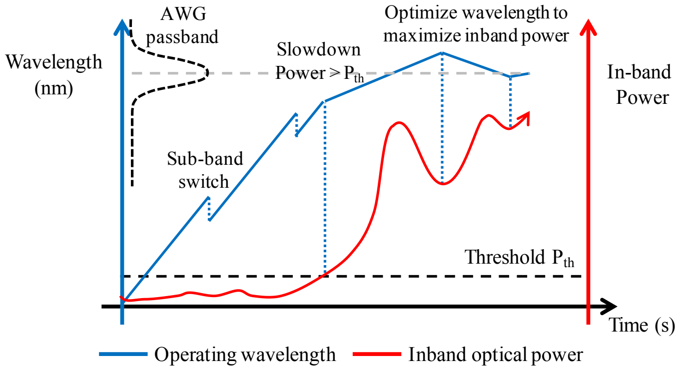


Figure 17: Initial wavelength tuning based on the feedback of received power [12].

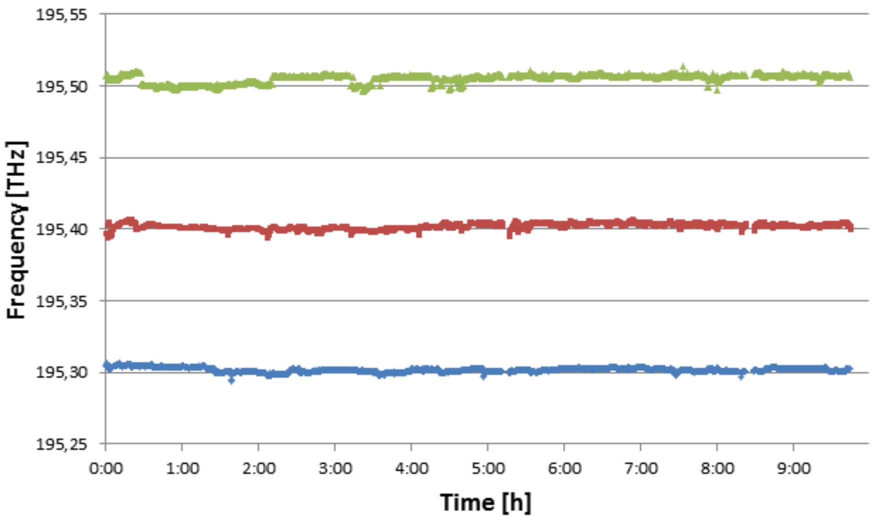


Figure 18: Wavelength accuracy of a 3-channel tunable WDM-PON system over time

Major innovations are the first demonstration of the centralized wavelength control concept (incl. development of the wavelength controller card and pilot-tone based communication channel) and the first demonstration of the system concept (operation of 3 channels with up to 10 Gb/s data signals with arbitrary protocols, e.g. CPRI, Ethernet). In the demonstration transport of Ethernet and CPRI data will be shown (for the latter use of CPRI option 3 is envisioned). A photo of the different components used at the OLT side is depicted in Figure 19.

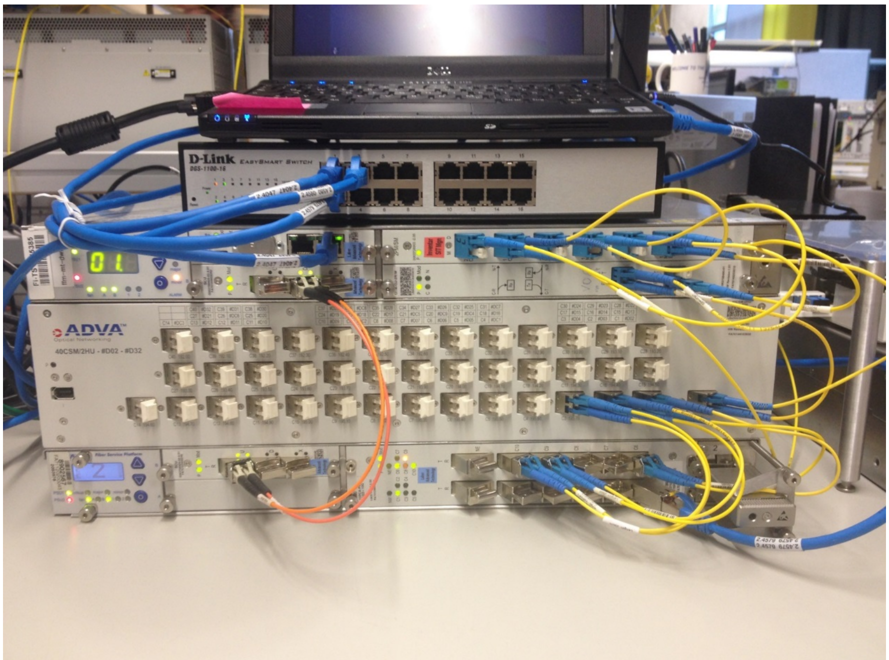


Figure 19: Photo of the OLT comprising aggregation card, MUX/DEMUX AWGs and wavelength controller card (from bottom to top)

On the customer premises side of the system two different ONUs have been developed: a business/residential customer CPE with a (uncontended) line rate of 1 GbE (Figure 20) and a second ONU (Figure 21), which allows up to 10 Gb/s transmission rate with arbitrary protocols (e.g. CPRI or Ethernet).

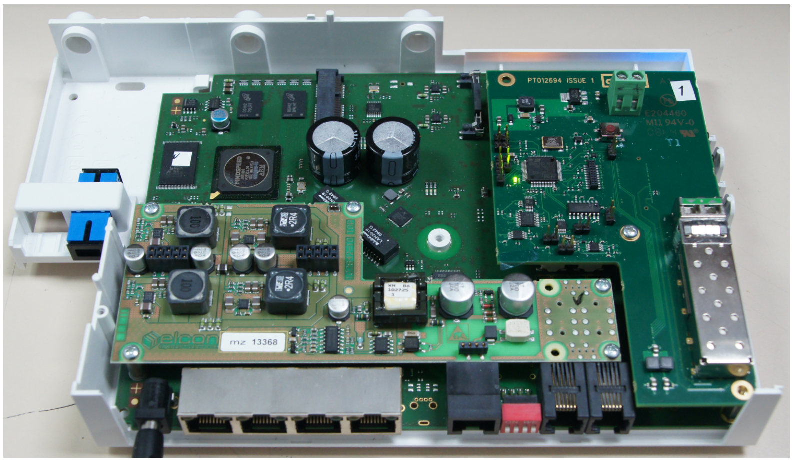


Figure 20: Photo of the 1 GbE CPE, which terminates the WDM-PON and allows connection to a 1 GbE (electrical) LAN. On the right-hand side a sub-PCB is depicted, which terminates the ECC and controls the wavelength of the tunable laser (upstream).

Figure 21: Photo of the 10 Gb/s ONU, which terminates the WDM-PON system and allows connection to various test equipment by SMA connectors.

2.2.2.3 Control and management

Control and management are key features of the tunable WDM-PON system. As stated above the system concept relies on the use of a centralized wavelength controller and out-of-band communication channels (e.g. pilot-tone based) to close the wavelength control loop [13].

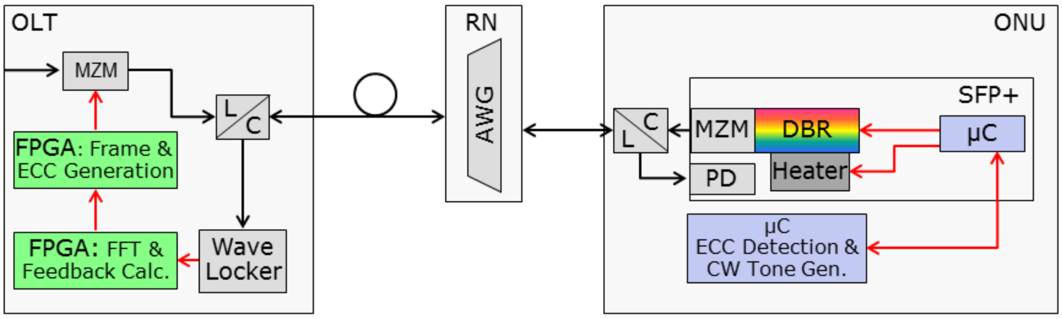


Figure 22: Control and management functions of the WDM-PON system (shown in green and blue boxes).

Therefore a separate channel label for each wavelength is required to distinguish the wavelengths at the centralized wavelength controller and remotely control the ONU tunable lasers. Such a channel label should be realized out-of-band to not depend on a specific protocol or line rate of the actual data signal being transported. Pilot tones are widely used for such purposes and also implemented in our demonstrator.

More specifically the wavelength control is accomplished by applying an AM pilot tone with a unique frquency to the data from each ONU (with approx. 10% modulation depth). As these pilot tones are orthogonal the intensity of each can readily be determined by performing a fast Fourier transform (FFT) on the combined signal at the wavelength locker. Also, to avoid extra penalty on the (high-speed) signal quality caused by the pilot-tone frequencies, they are limited to lie between 100 kHz and 1 MHz. The feedback line can be implemented by a low speed signal carried by a downstream pilot tone which is added on the multiplex downstream signal. This add-on feedback frame is then decoded and processed in the ONUs.

2.2.2.4 Control and management challenges & innovation

Control and management challenges are mostly related to the centralized wavelength control and management of the system performance. The control channel needs to be realized in such a way that it is functional already at very low power levels (even below the threshold of the high-speed data signal) to allow the system to tune to the right channel at start-up. Furthermore, the channels need to be controlled tightly to maintain the wavelengths at the desired frequency.

Major innovations are the development of the control and management channel (realized as an out-of-band pilot-tone based communication channel) and the implementation of a performance monitoring function (s. GUI in Figure 23 showing that channel C2 is tuned correctly to the right wavelength and received power level is -21 dBm).

It should be emphasized at this point that all control and management functions are realized out-of-band. In this way they are independent from the protocol (and bitrate) to be transported. This is especially relevant for an FMC network, which must be able to serve both CPRI (mobile fronthaul) traffic as well as standard data traffic (using mostly the Ethernet protocol).

The demonstration-related work described above has severe relevance for ongoing standardization. This holds in particular for ITU-T SG15-Q.2 / FSAN G.989.x NG-PON2, and here with special respect to the PtP WDM PON part.

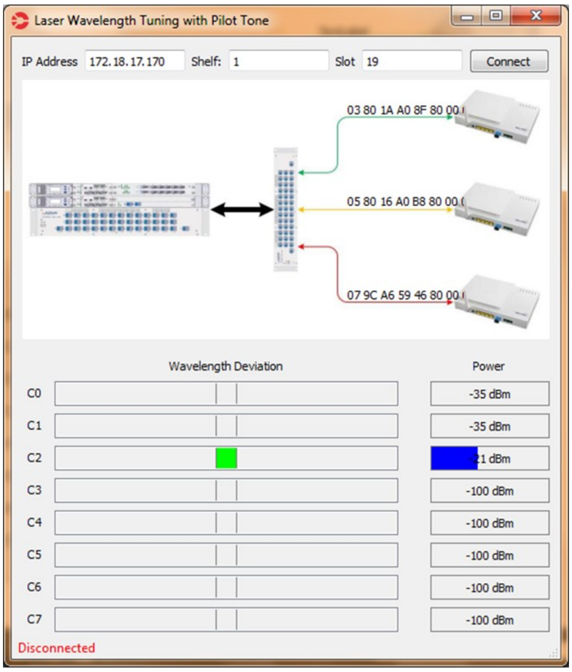


Figure 23: GUI showing relative wavelength deviation from ITU grid and measured power level at OLT (RX) for a tunable WDM-PON system with one active channel (C2).

2.2.2.5 Supported Use cases

The following use cases defined in D2.1 are supported:

- Use case 7 “Converged access and aggregation technology supporting fixed and mobile broadband services”. A single access and aggregation technology will be supported by the demonstration.
- Use case 8 “Network sharing”. Is inherently supported by the demonstration. The physical infrastructure enables multiple services to be transported. Furthermore, a “carriers-carrier” model could be demonstrated (e.g. showing that CPRI streams from different carriers are transported over the same infrastructure).

3 Universal Authentication (uAUT) Demonstration

Deliverable 3.2 [2] identified two Horizontal Targets as intermediate goals for FMC: *Converged subscriber and session management* (HT1) and *Advanced interface selection and route control* (HT2). These sets of FMC generic functions are meant to be implemented by the Universal Access Gateway (UAG): a proposed functional entity encompassing functions for mobile aggregation routers and data plane EPC gateways, Broadband Network Gateway (BNG) and security gateways.

Within the UAG, *Converged subscriber and session management* functionalities are realized by interacting with the Universal Subscriber Authentication server (uAUT) function. Advanced interface selection and route control functions are implemented by the Universal Data Path Management (uDPM) component of the UAG.

This section describes the demonstration of the uAUT module within the UAG. The following section (Section 4) elaborates on Universal Data Path Management.

3.1 Motivation and objectives

The solution proposed by COMBO for HT1 “Converged Subscriber and Session Management” leverages on the 3GPP’s User Data Convergence (UDC) concept [33], namely splitting subscribers’ data repository from the application logic specific to each access type. A single functional block, the “Universal Subscriber Authentication Server” (uAUT), is proposed by COMBO project as a significant improvement of the UDC concept. It links several application logics (called “Front Ends” in the UDC framework) with a single global User Data Repository (UDR). Convergence of authentication mechanisms themselves relies on the Extensible Authentication Protocol (EAP) run over layer 2, allowing negotiation of security mechanisms between the authenticator and the supplicant, according to the requirements of the network and the capabilities of the device. At network level, the uAUT module provides access to a common subscriber authentication platform regardless of the access network. This way, the end-user can be authenticated seamlessly in any network type.

This demonstration is focused on a centralized model, so a centralized uAUT database is used.

The main objective of this demonstration is to validate the seamless authentication of the users in LTE and Wi-Fi networks with the same credentials and without the intervention of the user. In order to reach this main objective, there are some secondary objectives. The first objective is to authenticate the UE in the COMBO deployed LTE network with the USIM card. The second objective is to authenticate the UE in the COMBO deployed Wi-Fi network with the credentials of the USIM using EAP-AKA protocol [14]. The third objective is to authenticate the UE in the COMBO deployed Wi-Fi network using Hotspot 2.0 Release 1 [15] approach.

3.2 Planned setup

This section explains how the setup is planned in order to reach the objectives established in the previous section.

Figure 24 shows the architecture defined in COMBO for the uAUT.

When a “Hybrid” access user tries to access from one of the multiple service providers to an FMC network his or her request is directed to the Universal Authentication Server. This request is gathered by the uAAA front-end which generates a query to the subscriber database. This database obtains the authentication information forwarding the request to the existing servers thanks to the AAA proxy front-end.

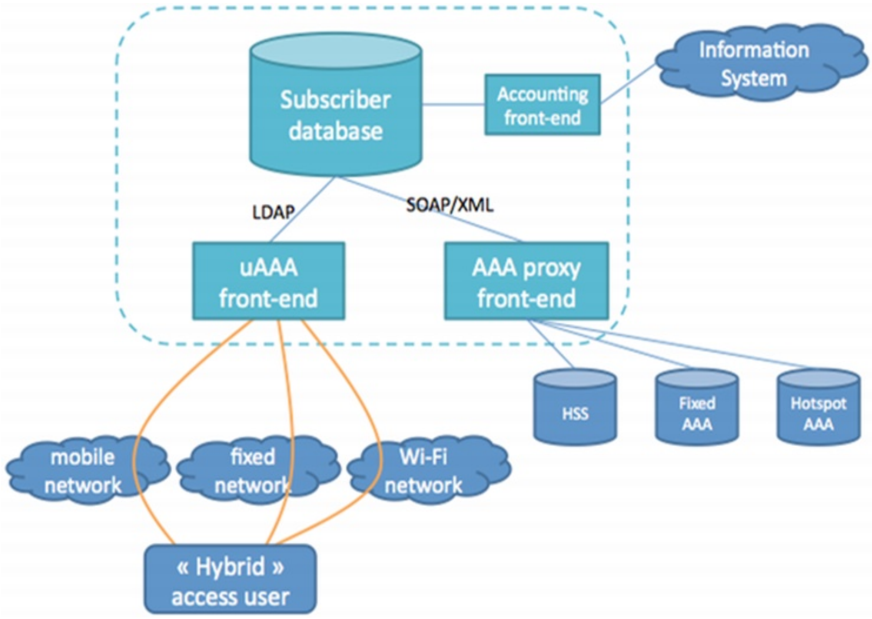


Figure 24: Illustration of hybrid authentication using the uAUT server and front-ends

In order to demonstrate the universal authentication concept that has been briefly explained above, we need the following logical entities:

- A UE with mobile and Wi-Fi radio interfaces that allows a “Hybrid” access user to access to an FMC network from multiple service providers (e.g. one FMC network operator has agreements with two or more Wi-Fi providers in order to provide access to its clients).
- A USIM card in the UE, whose secret is used for authentication on both radio interfaces.
- A mobile base station (eNodeB).
- A mobile core network (EPC), completed with a Home Subscriber Server (HSS), where the same secret is stored that can be found on the USIM card.
- A Wi-Fi access point.
- A Wi-Fi AAA server that provides authentication information to the hotspot.
- A Universal Authentication Server (uAUT), which can have access to the mobile HSS and the Wi-Fi AAA server.

Figure 24 illustrated the universal Wi-Fi–mobile authentication concept with all the logical components on it.

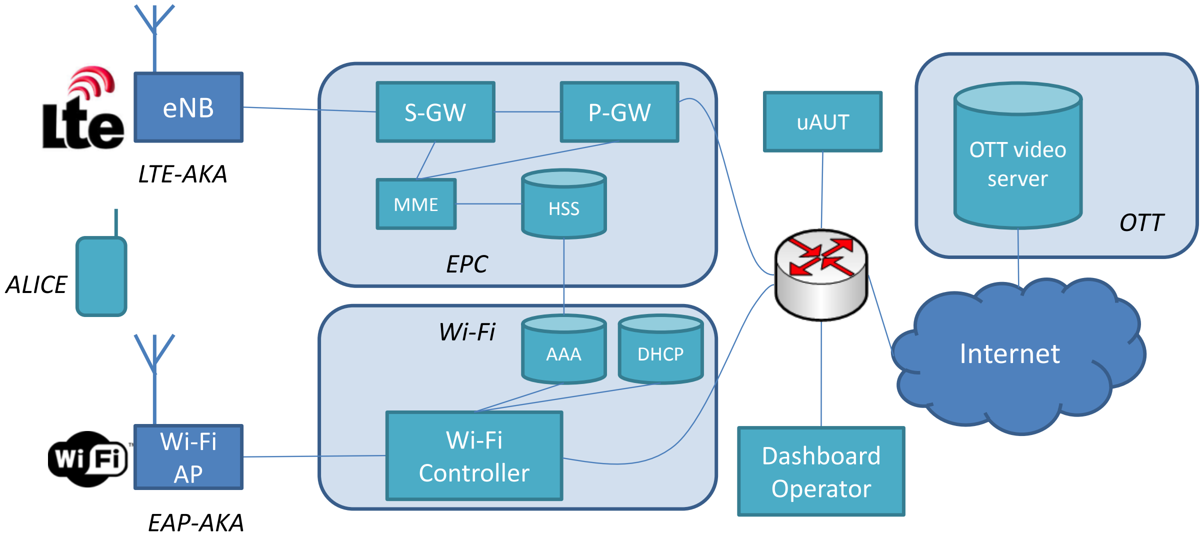


Figure 25: Illustration of the universal Wi-Fi–mobile authentication concept

The following paragraphs will explain the flow that the demonstration follows.

The first step, after starting the EPC of the deployed LTE network, is switching on the user equipment with the SIM installed and verifying that it authenticates correctly in the LTE network and that it has access to the Internet. This part of the demonstration proves that the LTE network configuration is correct.

The next step of the demonstration focuses on the Wi-Fi network. First, the Hotspot 2.0 policy must be provisioned on the user equipment. In this policy the user equipment has the required information to select the correct Wi-Fi Access Point (AP) to connect to [14] and the information for authentication. In this case, the UE is going to authenticate using EAP-AKA protocol with the SIM information. After provisioning the policy, the Wi-Fi AP must be switched on and the UE must connect to the AP seamlessly.

Once this point of the demonstration has been reached and in order to simulate the change between both networks, the AP can be switched off so the UE connects again to the LTE network. On the other hand, if the Wi-Fi AP is switched on again, the UE must connect to the Wi-Fi network seamlessly.

With this deployment, the UE needs to authenticate on all access types, but this authentication is automatic, hidden from the user and is done using the same secret for all access types, the one stored in the USIM card.

3.2.1 Hardware entities and software setup

This subsection depicts the planned hardware and software setup for the demonstration of the universal authentication. Individual hardware components are identified as green rectangles. Software modules are shown as grey boxes. Red and bluish-grey connector lines mark control and data interfaces, respectively.

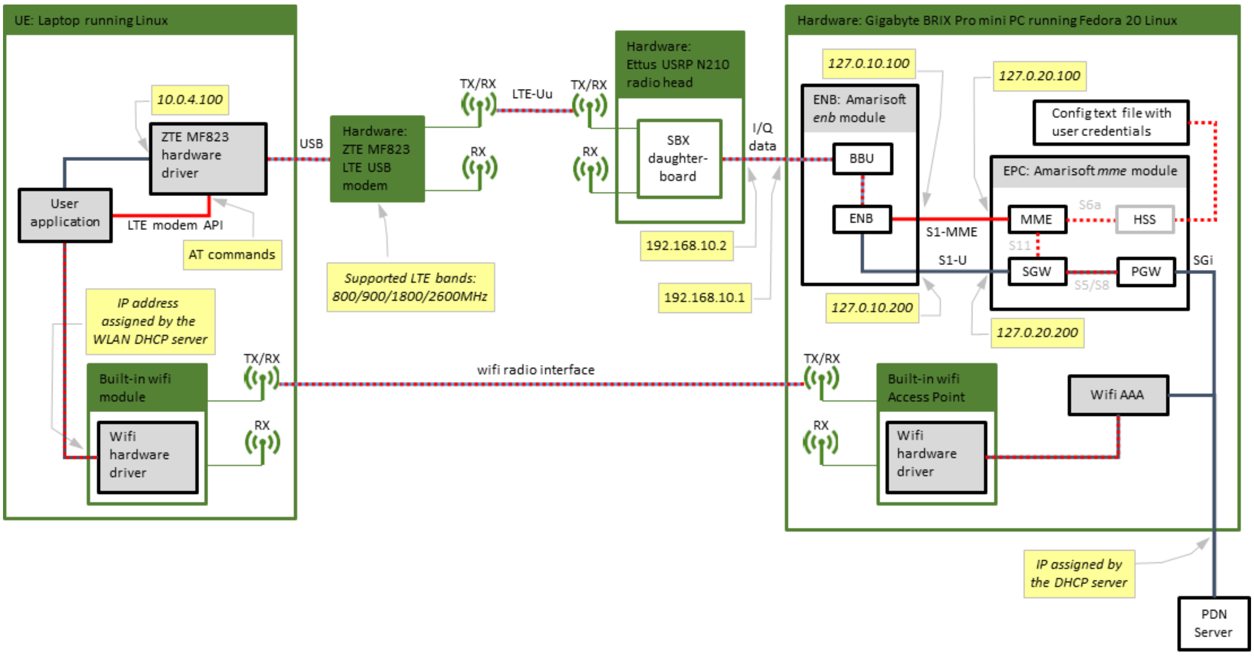


Figure 26: Hardware components, software modules and interfaces in the uAUT demo setup

3.2.1.1 User Equipment

Two different types of user equipment are used, a laptop with Wi-Fi and LTE radio interfaces, and an LTE-capable mobile phone with Wi-Fi as well.

The laptop runs Linux. It has an 802.11b/g/n Wi-Fi radio interface, and in order to provide it with LTE capabilities, this computer uses a ZTE MF823 USB LTE modem [16] with a test USIM card inserted. The laptop is used in the demonstration in order to take advantage of its monitoring capabilities. The authentication software used is Linux WPA/WPA2/IEEE 802.1X Supplicant [19].

Besides the laptop computer, we also use a commercially available LTE-capable Android 5.0 mobile phone with Wi-Fi radio interface and support for Hotspot 2.0 Release 1. In this case the USIM card is inserted into the handset directly, and there is no need for the LTE modem. The mobile phone used for the demonstration has the correct HS2.0 policy provisioned. There is an example of the policy below.

```
cred{
        priority=1
        realm=”fon.com”
        domain=”fon.com”
}
```

The realm identifies the service provider that can authenticate the user of this mobile phone. The policy shown above indicates that this mobile phone can only authenticate seamlessly in the Fon networks. The domain indicates the entity that is operating the AP so, in this policy it means that this phone can only connect to access points that are operated by Fon.

3.2.1.2 USIM card

A test USIM card with a known secret is needed in order to emulate a real scenario. The USIM cards available for the demonstration are shown in Figure 27:

- Anritsu test USIM card
- Agilent AG8960 test USIM card
- R&S CMW500 test USIM card

The UE needs to communicate with the USIM card via a card API. The information to be retrieved from the cards includes the IMSI, and the cyphering and integrity keys required for 4G operation. If the card does not natively support the EAP-AKA authentication and key agreement procedure, then it may be necessary to obtain other USIM cards.

Figure 27: ZTE MF823 LTE USB Modem and USIM test cards

3.2.1.3 Mobile core network and mobile base station

The equipment used for the mobile network is a combination of a mini PC (running the EPC+eNB software), plus a radio head with antennas (running an open source gnu radio implementation). The hardware setup is illustrated in Figure 28.

3.2.1.3.1 Mobile core network

The 4G Evolved Packet Core (EPC) is running on a mini PC with the following specifications: Gigabyte BRIX BXi7-4770R [17], 8GB RAM, 120 GB SSD, 1 TB HDD, Wi-Fi, Bluetooth, 1 built-in Gigabit Ethernet connector, 1 StarTech USB 3.0–Gigabit Ethernet Adapter, OS: Linux Fedora 20.

The EPC software used is Amarisoft Amari LTE 100. The *mme* module implements the MME, SGW, PGW and HSS functionalities of the EPC as one software module. It connects to the ENB via the S1-MME interface (local IP address: 127.0.20.100, protocol stack: [IP | SCTP | S1AP | NAS]), and to the ENB via the S1-U interface (local IP address: 127.0.20.200, Protocol stack: [IP | UDP | GTP-U | IP | <user data>] and [IP | UDP | GTP-C]).

The EPC connects to the Internet via the SGi interface. The IP address of the interface is the same as the IP address of the mini PC as assigned by the DHCP server (protocol stack: [IP | <user data>]). In the demo setup the USB3.0–Gigabit Ethernet adapter is used as the physical SGi interface.

The EPC realizes the HSS functionality through accessing a configuration text file which acts as a subscriber database. Due to the implementation features of the EPC software, the S6a, S11 and S5/S8 interfaces are not observable.

3.2.1.3.2 Mobile base station

As a remote radio head an Ettus/National Instruments USRP N210 kit is used with the following specifications: USRP N210 (2 SMA-Bulkhead RF Cables, Ethernet Cable, Power) + SBX-40 USRP Daughterboard (400 MHz–4.4 GHz, 40 MHz BW) with wide-band dipole antennas [18].

The Amari LTE *enb* module implements the eNodeB (ENB) and the radio baseband unit (BBU) functionalities as one software module, also running on the mini PC. The radio unit connects to the Amari LTE *mme* software module's MME function via the S1-MME interface (local IP address: 127.0.10.100, protocol stack: [IP | SCTP | S1AP | NAS]), and to the SGW function via the S1-U interface (local IP address: 127.0.10.200).

The eNodeB module also connects to the Ettus USRP N210 radio head unit through an I/Q data interface (local IP address: 192.168.10.1). In the demo setup the mini PC's built-in Gigabit Ethernet interface is used. The mini PC has the USRP hardware Driver (*UHD_003.008.000-release*) installed.

The Ettus USRP N210 radio head unit has a built-in Gigabit Ethernet interface for the I/Q interface. The local IP address is 192.168.10.2.

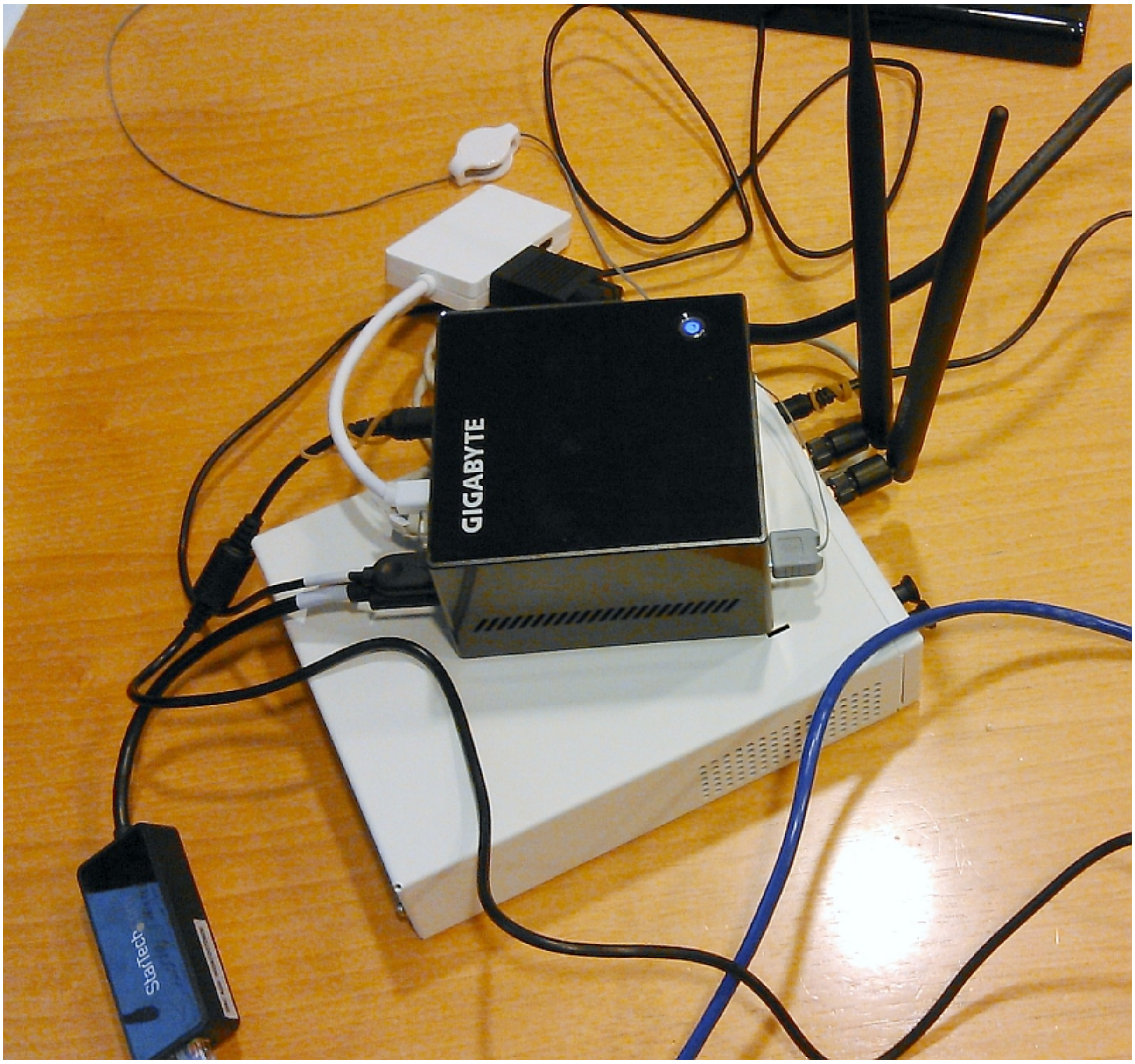


Figure 28: Mini PC running the LTE EPC + ENB software (on top)
and an USRP N210 radio head (at the bottom)

3.2.1.4 Wi-Fi access point

The Wi-Fi access point is a commercial product for residential users with a specific configuration for this demonstration. It works in the 2.4 GHz band, and supports Hotspot 2.0 Release 1. The access points support EAP-AKA as well, in order to implement the authentication of the users.

The access point runs OpenWRT [20] and a custom version of *hostapd*. The most important configuration parameters of *hostapd* are included and explained below:

- *acct_server_addr*: IP address of the authentication server.
- *acct_server_shared_secret*: the access point and the authentication server share a secret in order to authenticate themselves.

- *domain_name*: this is a HS2.0 element that indicates, as explained before, the entity that is operating the access point.
- *nai_realm*: this is a HS2.0 element that indicates, as explained before, the service provider in order to give information to the users about the authentication possibilities in this access point.
- *hs20_oper_friendly_name:* this element configures the operator's friendly name for Hotspot 2.0.
- *ssid:* Service Set Identifier.
- *bssid*: Basic Service Set Identifier.

Hotspot 2.0 Release 1 has been tested as it is a basic part of the seamless authentication in the Wi-Fi side. The setup that can be seen in the following figure has worked and a mobile phone has authenticated in the Wi-Fi network without the intervention of the user, realising a seamless authentication.

This setup is composed of an access point and a mobile phone which supports Hotspot 2.0. The adequate policy has been provisioned in the mobile phone in a previous configuration phase. The authentication has been made using a RADIUS server that implements EAP-TTLS protocol.

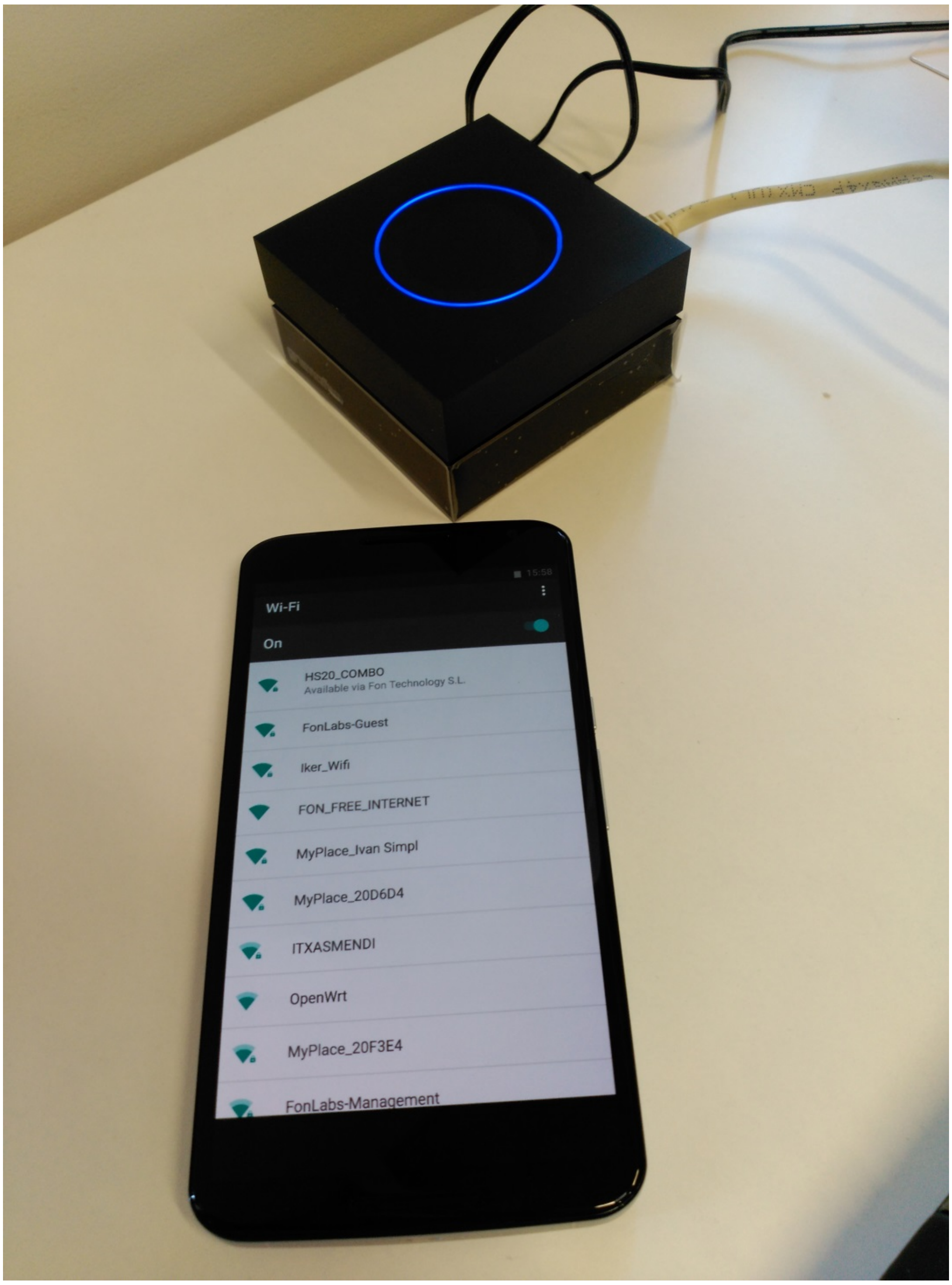


Figure 29: Setup for Hotspot 2.0 preliminary test

3.2.1.5 Wi-Fi AAA server

The Wi-Fi AAA server is an existing RADIUS server with EAP-AKA support. This server is physically in the service provider's facilities as it would be in a real scenario. It runs a version of RADIUS that supports several authentication protocols including EAP-AKA, EAP-TTLS and EAP-TLS. This means that the UE does not need to have a USIM in order to authenticate in this server.

The version of RADIUS is a commercial one that runs over Linux.

3.2.1.6 Universal Authentication Server

The part of uAUT implemented in the UAG is a proxy server that forwards the authentication requests to the adequate authentication server. This proxy server runs over a virtual machine in the UAG infrastructure. It can act as a proxy server forwarding the requests to the existing authentication servers or, alternatively, it can answer itself the authentication requests in some cases.

The mobile secret key in the EPC is stored in a text file in the Amari LTE configuration file. A copy of the mobile secret is stored in the uAUT server.

3.3 Test cases

Two test cases are defined in this demonstration in order to reach the objectives established in Section 3.1.

The first test case demonstrates that the UE with the credentials in the USIM can connect to the mobile network. This test case validates the correct operation of the LTE network integrated with the UAG in the authentication phase.

The second test case demonstrates that a UE can be authenticated in the COMBO deployed Wi-Fi network with the credentials that USIM provides thanks to the UAG. This test case validates that a UE can be authenticated in the Wi-Fi network with the credentials included in the USIM obtaining access to the convergent network.

The second test case is illustrated by the authentication message sequence chart shown below.

The main objective of this demonstration is to validate the correct operation of the uAUT. In order to evaluate this objective, the logs of the AAA servers are monitored.

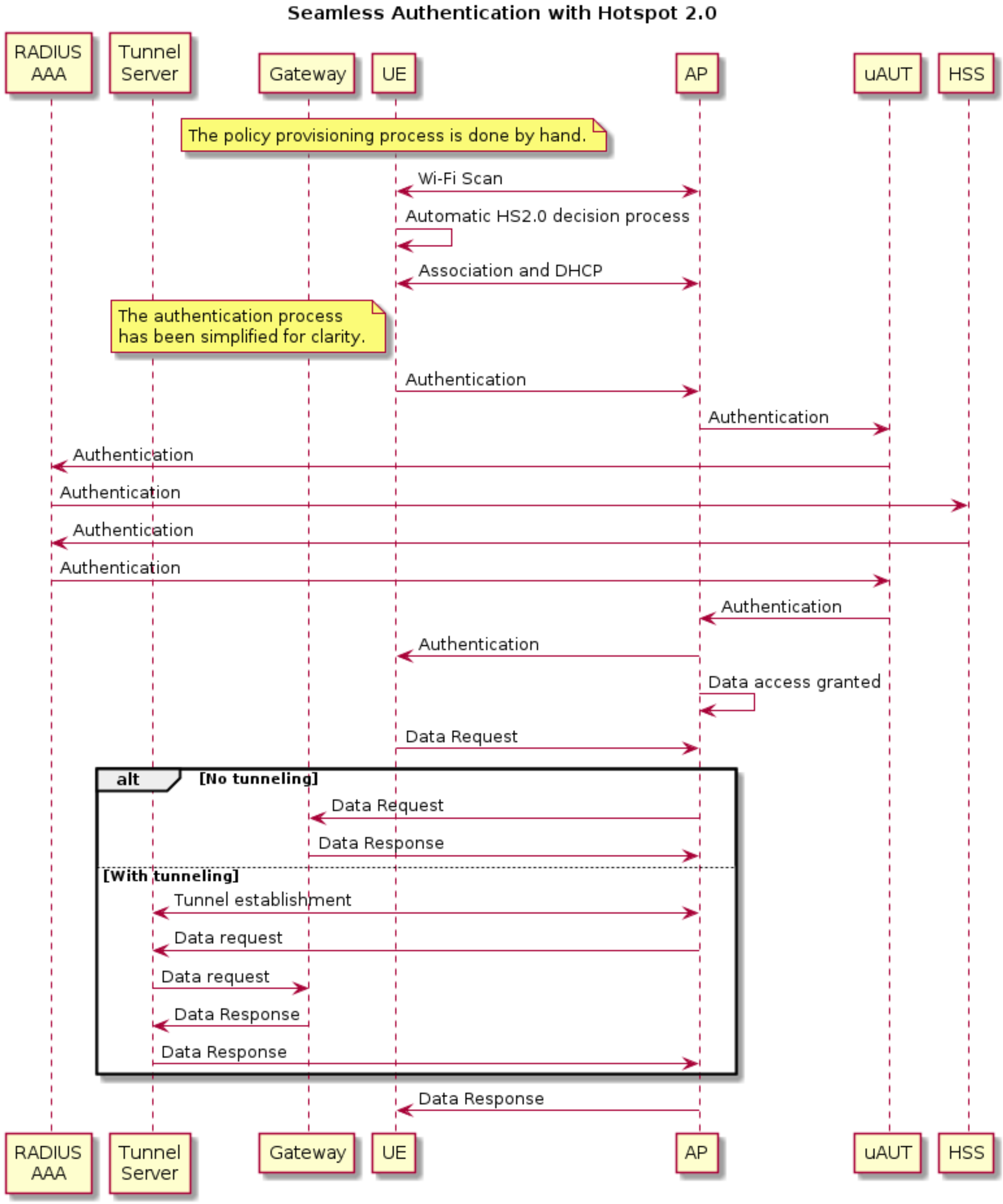


Figure 30: Seamless authentication sequence with Hotspot 2.0

3.4 Supported use cases

This section includes the use cases that are supported by the demonstration of uAUT.

- Use Case 1: “Unified FMC access for mobile devices”. This demonstration includes UE that can access both Wi-Fi and mobile networks

- Use Case 6: “Convergence of fixed, mobile and Wi-Fi gateway functionalities”. This demonstration implements a converged Authentication of the end-user for Mobile and Wi-Fi combining the uAUT at the UAG and EAP-AKA at the Wi-Fi Access Point.

4 Universal Data Path Manager (uDPM) Demonstrations

One major advantage with an FMC network is that the traffic can be transported via several types of infrastructures. It is possible to send packets either over the fixed access connection or via the mobile access connection and still having an entity in the network that is aware that it is the same user. In D3.2 [2], the Multi Path Entity (MPE) was introduced as part of the universal Data Path Management (uDPM) functional block, to realise user aware routing functions, see Figure 31. In the FMC scenario the UE can be connected to more than one data path, advantages in terms of offloading and handover become available. In contrast to the connection control of today, when the UE connects to one data path determined by rules set locally, a more advanced scheme must take more into account. That means the connection control should be transferred to the MPE and be used to maximise the utilitzation of the available infrastructure.

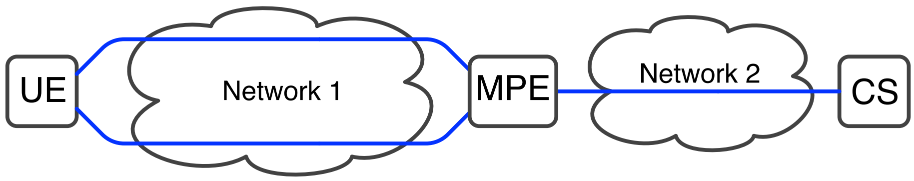


Figure 31: The general structure of a network with multiple data paths to the UE.

As reported in D3.2 the location of the MPE can be set to a variety of places. For setting up an FMC structure it should be somewhere in between the UE and the content server (CS). Hence, the CS is not involved in steering the traffic flow over the data paths, and Network 2 is not affected by the dual connection. To achieve this, the traffic flows entering the MPE from the Network 2 must have a common protocol. If the MPE is part of the UAG and is located at the NG-PoP (centralized or distributed), this common protocol is most likely IP. Then the MPE and the PGW are co-located.

4.1 Motivation and objectives

Managing the data paths in an FMC network can significantly contribute to improve:

- resource utilization
- QoS and QoE
- availability
- energy efficiency

This motivates introduction and demonstration of the universal uDPM functions supporting Data Path Management functions for different network technologies. At the moment, the proposed setup is centralized although a geographical partitioning based on or regions can be considered.

Some of these data path management functions were investigated so far, however, to our knowledge, none of them for multiple technologies as a universal DPM.

4.2 Planned setup

Four different functions are to be demonstrated as examples of uDPM:

- Path coordination and control
- Data path creation and destruction
- Caching
- Decision engine for optimized multi-dimensional handover

We propose an integrated setup as shown in Figure 32. In blue ovals the number of subsections are included, where certain functions are discussed in detail.

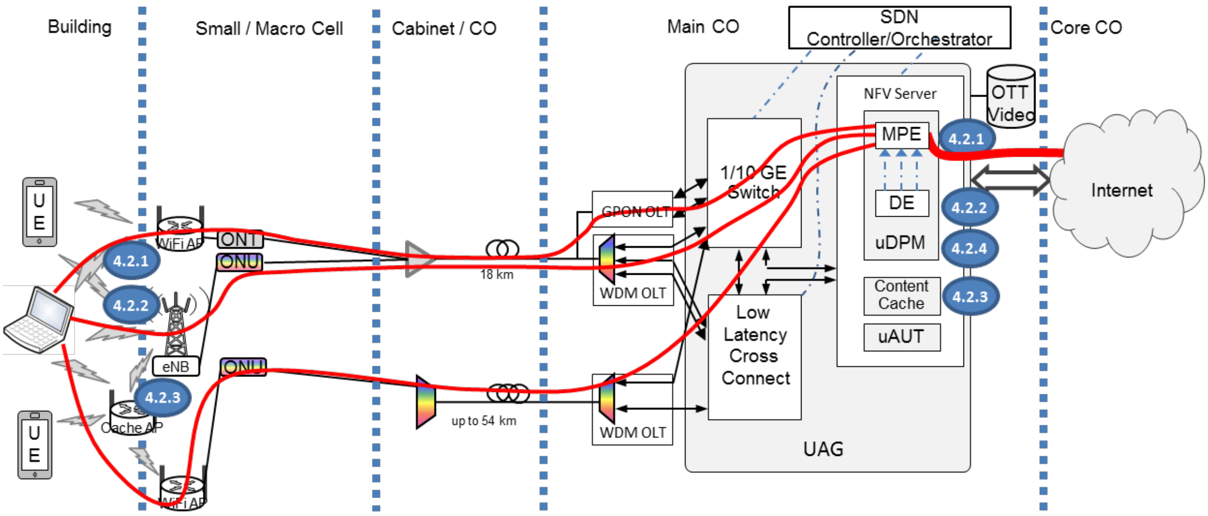


Figure 32: The components and functions of the integrated demo setup

Dual or multiple attachments are going to be demonstrated between the UE and the Internet using the MPE module of the uDPM block that is part of the NFV server in the UAG. SDN controller/orchestrator controls and/or orchestrates the whole UAG as well as its parts, including the NFV server. The three red lines show the data paths, i.e., the data streams in the data plane.

The simple traffic offloading in this setup is the change of the data path from the LTE interface to eNodeB to one of data paths over Wi-Fi.

Caching will be demonstrated in two ways in our integrated demo setup. First, as a cache AP between the UE and the Wi-Fi AP. Second, as a part of the NFV server within the UAG.

The optimized multi-dimensional handover requires a specific Decision Engine, an Access Optimizer Decision Engine that is part of the uDPM module within the UAG. MPE will also be needed to coordinate multiple TCP paths. Both the UE and the MPE block will have to support a multipath protocol, MP-TCP in this demo setup.

4.2.1 Demonstration of path coordination and control

The aim of this part of the setup is to implement coordination for the paths between the UAG and the UE, see Figure 33 (please note that the same approach can be used in a multiple attachment scenario). That is, the UE is connected to the UAG via two data paths, and the UE point of presence seen from the CS through the IP core is at the UAG. The data paths' utilisation is determined from the UAG, which in turn can enable for example handover and offloading to maximise the network infrastructure utilisation.

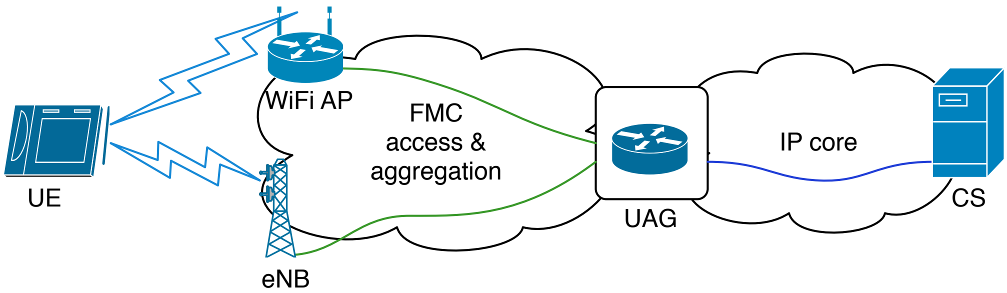


Figure 33: Dual connections between UE and UAG.

Two key points are of importance in the setup. The first point is that the UE should be simultaneously connected to the UAG via two different data paths, one over a Wi-Fi access point and one over an LTE connection. The second point is that the traffic flows over the data paths are controlled from the UAG. With such implementation it becomes possible to steer the traffic between the connections in a way that maximises the QoE for the user and the utilisation of the infrastructure.

In the setup the MPE control is implemented as a Linux virtual machine in the UAG. The data paths over the Wi-Fi access point and the LTE connection are setup using GRE tunnels. In Figure 34 the principle design is shown. The red line represents the data path connecting to the CS somewhere on the Internet. In the setup this is represented by a stand-alone laptop. The green lines represent the data paths for the Wi-Fi connections. From the MPE controller it is connected to the Wi-Fi gateway in another VM, which passes the traffic to the Wi-Fi access point. The yellow lines represent the LTE path. It is passed via the switch to the VM with the LTE EPC software, and further routed out to the eNB. The UE, another stand-alone laptop, is connected to both the Wi-Fi and the LTE via standard equipment.

The individual data paths are set up as GRE tunnels over IP. Then the UAG and the UE are connected via MPTCP, which can be used to coordinate the multi-path connections. The UAG has to be set up as an MPTCP proxy and the connection between the UAG and the CS is independent of the choice of selected data paths to the UE.

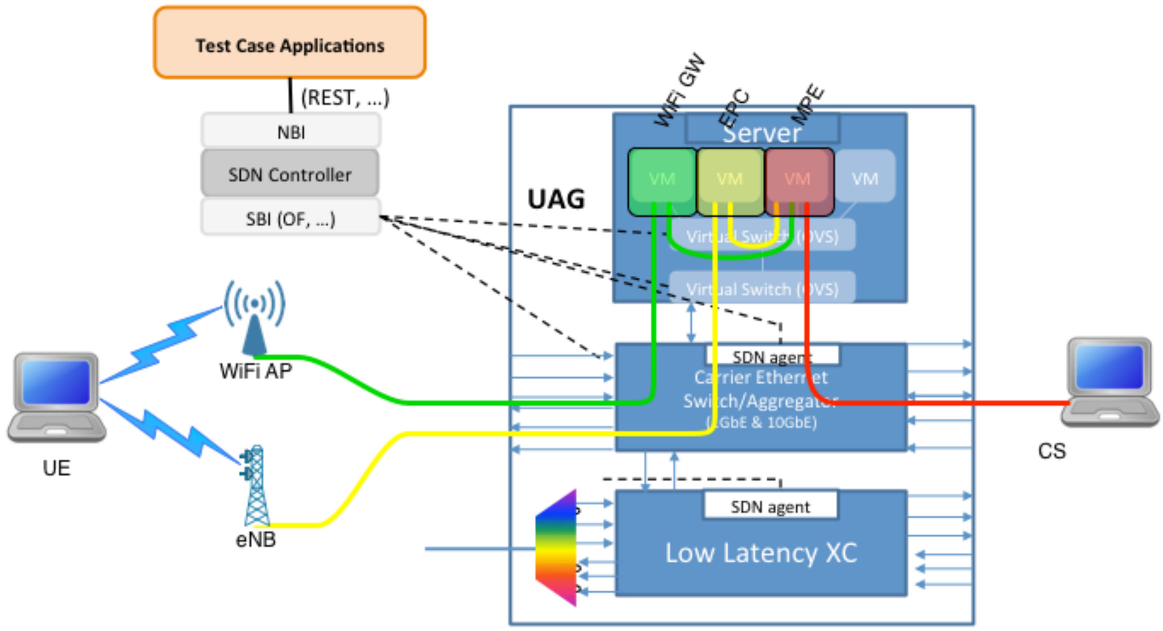


Figure 34: Implementation of dual connection setup using the UAG structure.

For the UAG to have control of the traffic flows between the UAG and the UE it should be able to decide in traffic rules, both in downstream and upstream. For the upstream control it needs to remotely decide on the routing rules in the UE, and for this it is needed to setup a management channel to the UE. For the demo it will be solved using a certain port in the socket address. Then, the control command can be setup using a command line interface between the UAG and the UE. Typical commands to be used from the UAG are (not exclusively)

- avif: Answers with available interfaces
- setpif: Set the preferred uplink interface
- stopif: Stop an interface
- startif: Start an interface

A preliminary sketch of the GUIs used in the UAG and the UE, respectively, is shown in Figure 35. In the GUI there is control of each of the interfaces. There can also be a sniffing capability in the GUI to show which interface is used. Alternatively, e.g. Wireshark [34] can be used to show the packet flows. From the GUI at the UAG the interface selection can be controlled, as well as the usage of the traffic flow in downstream.

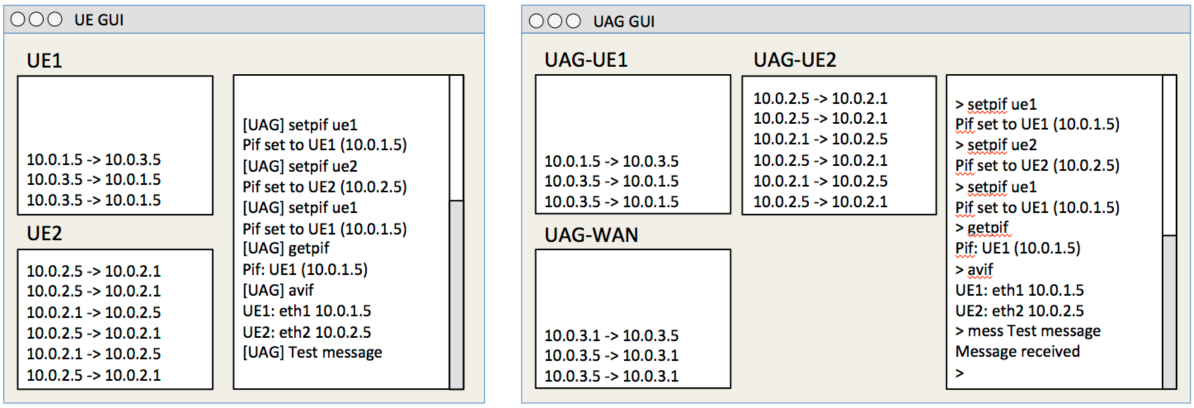


Figure 35: Sketch of setup GUIs at the UE and UAG, respectively.

In the first setup, before the merging of the equipment, the three components UE, UAG and CS are implemented using stand-alone computers. The UE and the CS are laptops, while the UAG is an Intel NUC stand-alone computer. The connections are based on wired connections over a switch. Each of the connections is set to specific VLANs as will be in the final setup. In Figure 36 a first, intermediate, setup for dual data path connection is shown. Here the left laptop implements the UE and the right the CS. The middle computer together with the switch on the table implements the UAG part. The two yellow wires to the left in the switch are connected to the UE laptop and the single yellow wire to the right connects to the CS. The middle white wire is the connection between the switch and the UAG computer, i.e. the MPE controller.

Figure 36: Intermediate setup for dual data path selection.

4.2.2 Demonstration of data path creation and destruction

Data path creation and destruction is an enabler for the functionality of traffic offloading. The aim of this functionality is allowing the FMC network to provide additional information to mobile devices so that traffic can be offloaded from the 4G access to the Wi-Fi access. This section explains the demonstration of this functionality.

To achieve this objective, devices that have Wi-Fi enabled must be able to automatically select and seamlessly connect to the Wi-Fi access of the FMC operator or, if it is the case, to another Wi-Fi access from a roaming partner. The main enabler for this test is Hotspot 2.0 and an API that provides information of the state of the network.

The Wi-Fi Alliance has created Hotspot 2.0 (HS2.0) [15]. HS2.0 provides the ability of discovering Wi-Fi hotspots to Wi-Fi devices and allows seamless authentication. UEs have a policy configured with information of the authorized networks and authentication data. Thanks to the Access Network Query Protocol (ANQP), the UE can obtain information from the network and compare it with the information that it has in its policy. In this way, the UE can recognize the networks in which it can authenticate itself.

There are two releases of HS2.0. One of the main differences between release 1 and release 2 is that on the first one the policy provisioning is not standardized and it is made manually.

In addition to the information that can be obtained using ANQP, UE can obtain information about the state of the network thanks to an API that is being developed in COMBO. This API provides information such as the saturation of the link due to the users connected.

The demonstration is done with two access points and two mobile phones. All this equipment supports HS2.0 Release 1. Moreover, the mobile phones have the correct policies provisioned.

The access points are commercial products designed for residential use with a special configuration. With two APs, a scenario with two Wi-Fi providers is simulated. This way, the demonstration tests not only the traffic offloading from 4G network to a Wi-Fi network, but also the traffic offloading from a Wi-Fi network to another Wi-Fi network.

4.2.3 Demonstration of caching

In this demonstration, we focus on the HTTP traffic, especially video traffic carried by HTTP protocol. The measurement on the 3G traffic in [21] shows that 74.6% of downstream bytes are HTTP traffic in cellular networks, and 52%-59% of redundancy comes from HTTP objects. Moreover, the popularity of web objects follows the Zipf distribution [21] - [22]. Multimedia objects contribute 0.8% by the flow count and 40.6% by the traffic volume. That is to say, a small fraction of large flows (e.g. video, image) dominate the total traffic volume. This allows us to cache only HTTP video streaming while still providing a reasonable level of bandwidth saving in the demonstration.

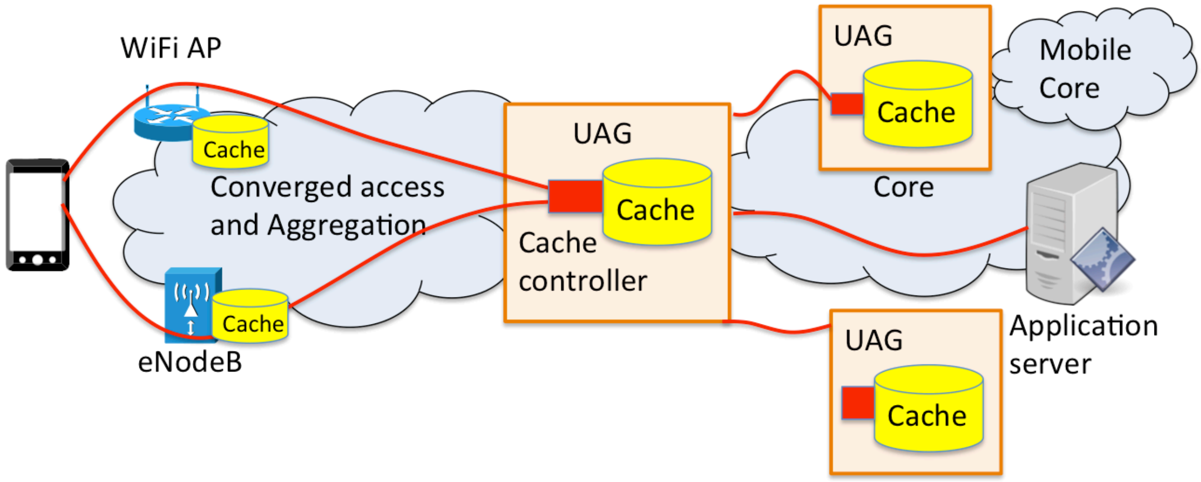


Figure 37: A converged caching solution in FMC

This demo integrates and presents our work of intelligent content prefetcher and SDN controlled cache node in D3.2. Figure 37 shows the use case UC2 that presents converged content caching for unified service delivery in FMC. The main idea is to cache content close to end users in operated controlled public access points, mobile access network and aggregation network. UAG is used in this demonstration as a converged caching point in the FMC aggregation network. The collaborative caching among multiple UAGs can help to reduce the traffic in core network and the traffic exchanged inter-ISPs. The main ideas to enable caching in the access network on APs and eNodeBs are to bring data closer to end users, allow ISPs to reduce redundant traffic on backhaul links, and improve user QoS and users' QoE by serving users' requests locally. Studies relevant to caching in the EPC [21][23] and in the radio access network [24][25] have been made respectively. This is the first demonstration to our knowledge that shows the benefit of caching in the concept of FMC. Finally, an SDN based caching controller can further ameliorate the caching efficiency by optimizing the data flow and content caching.

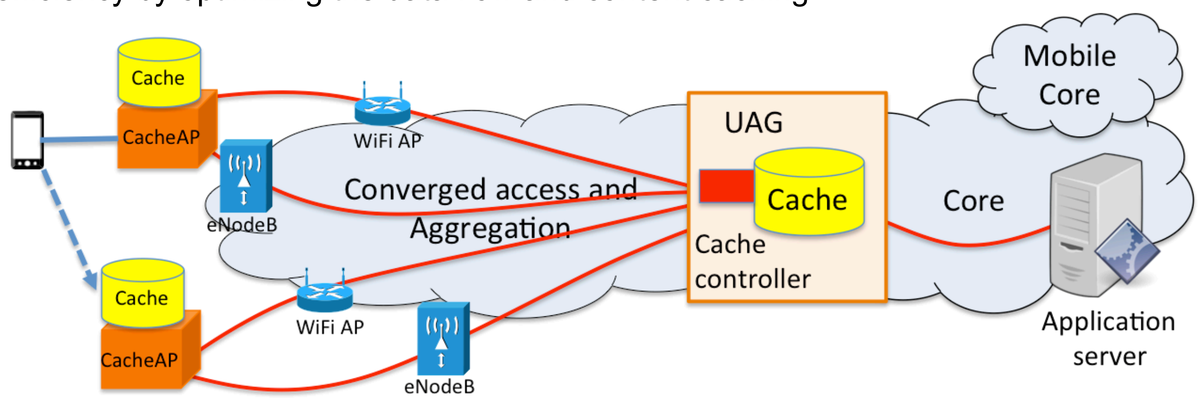


Figure 38: Demonstration topology of caching test case

Figure 38 shows the caching demonstration where we deploy caching functionality in the UAG and introduce a dedicated caching box named CacheAP in an access network. CacheAP is a wireless router with caching functionality having one Ethernet interface and three wireless network interfaces (two Wi-Fi interfaces and one LTE interfaces). UEs connect to the CacheAP by Wi-Fi connections and the CacheAP accesses the Internet by Wi-Fi or LTE network. CacheAP can therefore represent both caching on Wi-Fi AP and eNodeB. In this case, CacheAP can be considered as a converged point in the access network. Here, we only consider CacheAP deployed in public places such as a public access point (in an airport, coffee shop, or hotel), or in large public venues.

Figure 39: CacheAP Prototype

The CacheAP shown in Figure 39 is implemented as an autonomous box machine with one Ethernet interface, one LTE module and two Wi-Fi modules 2.4 GHz with 13 dBm and 5 GHz with 20 dBm. The storage includes 8GB eMMC, 8GB SDcard and 2GB RAM. OpenWRT is used as the operating system of CacheAP. The modularization architecture of CacheAP is shown in Figure 40. The implementation is mainly based on CCN (Content Centric Networking) principle but with different message header and customized design. The cache controller is implemented to make decisions for optimal caching and real-time prefetching. The Disconnection Predictor (DP) server is used to predict the disconnection and reconnection by considering physical layer (signal strength), network layer (delay, loss rate and throughput) and application layer (geography, moving speed, distance to APs, etc.). This information is used to activate the prefetching module that helps to retrieve and store content in advance. The module netfetch and proxy handles the request transfer between HTTP requests and CCN interests.

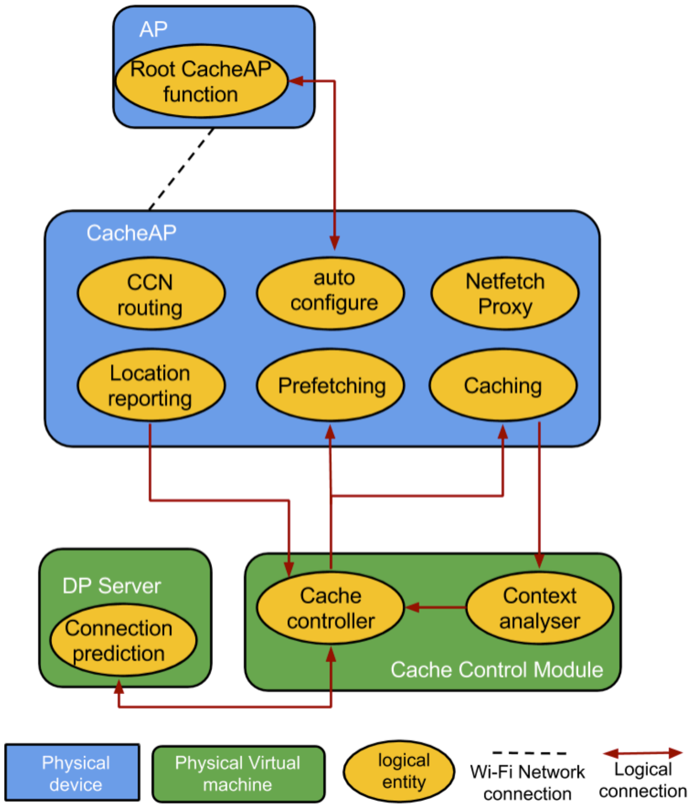


Figure 40: Architecture of CacheAP

The SDN-based cache controller implemented as a virtual machine takes decisions on where to cache or prefetch the content. We assume that the cache controller knows which access node (APs or eNodeB) that CacheAP will be attached to according to the inputs from operators like resource management on UAG. Based on these information, the cache controller can make an optimal caching and real-time prefetching decision. When a client demands a video, the cache controller informs CacheAP which interfaces to be selected to retrieve the video. When the client connects to a new CacheAP, the cache controller asks the new CacheAP to prefetch the video content. As soon as the client makes the handover, the content has been available in the local network.

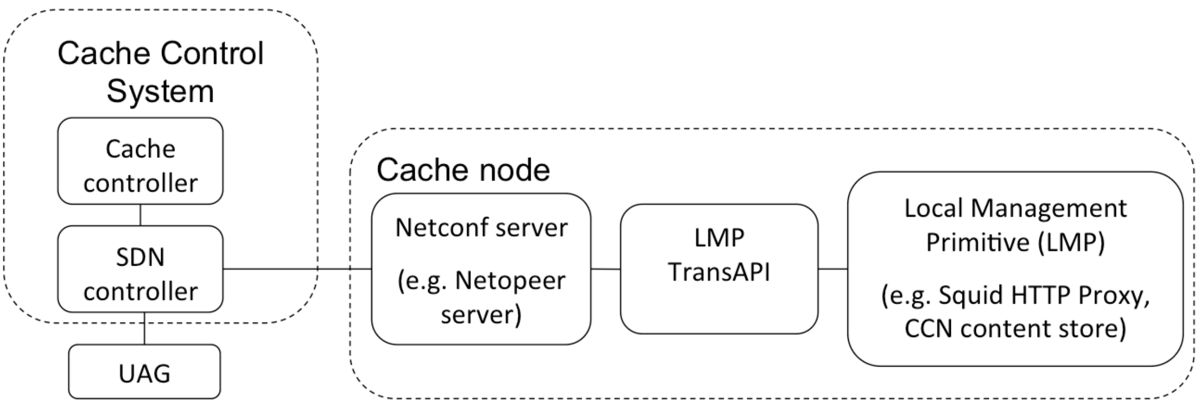


Figure 41: SDN-based cache control system

As shown in Figure 42, the decision engine implemented in uDPM makes the decision about which data path should be selected to fetch the content. Then the decision engine informs the controller of the dual attachment module (that tells the interface selection module running on the CacheAP) which data path to be created. Finally, the caching module on the CacheAP will retrieve the content along the selected data path, and destructs this data path after the data transfer. During the data transfer, the decision engine can also make real-time control to change the data path according to the network status, user movement, etc.

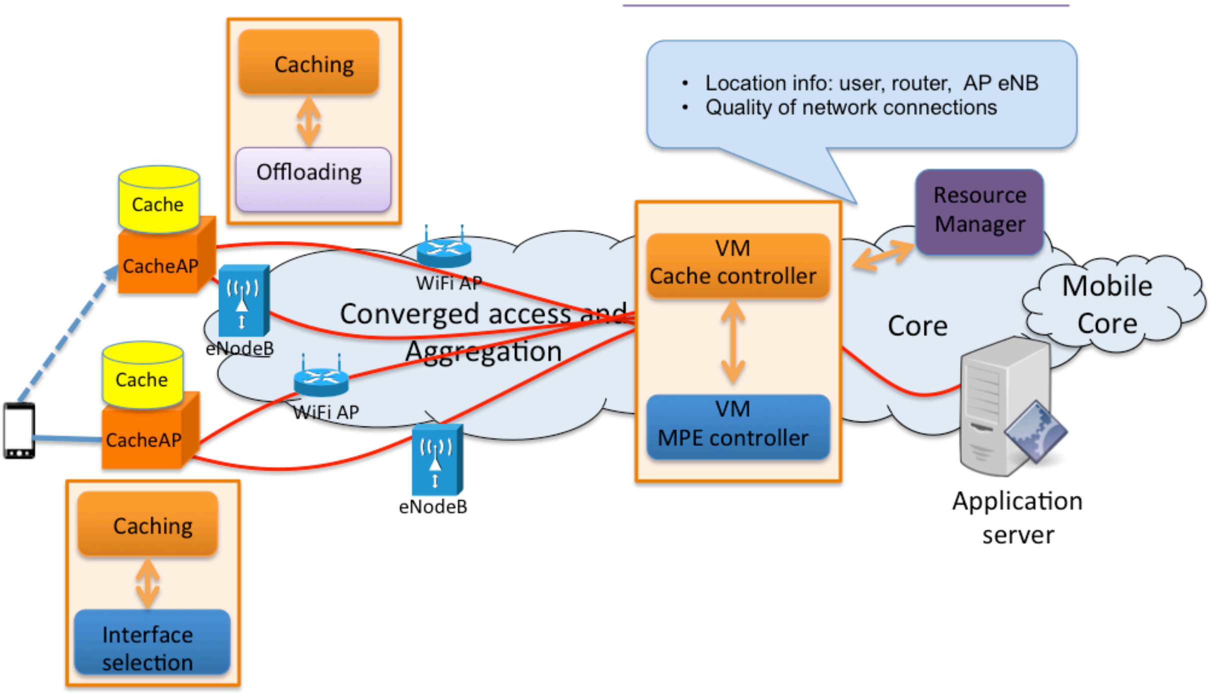


Figure 42: Interfaces between cache module and other test cases

Moreover, content from Wi-Fi or LTE is prefetched according to the prediction of user mobility and the quality of network connections. The cache controller and decision engine will know from the resource manager to which CacheAP the client will connect to in the near future, and then asks this CacheAP to prefetch the requested content.

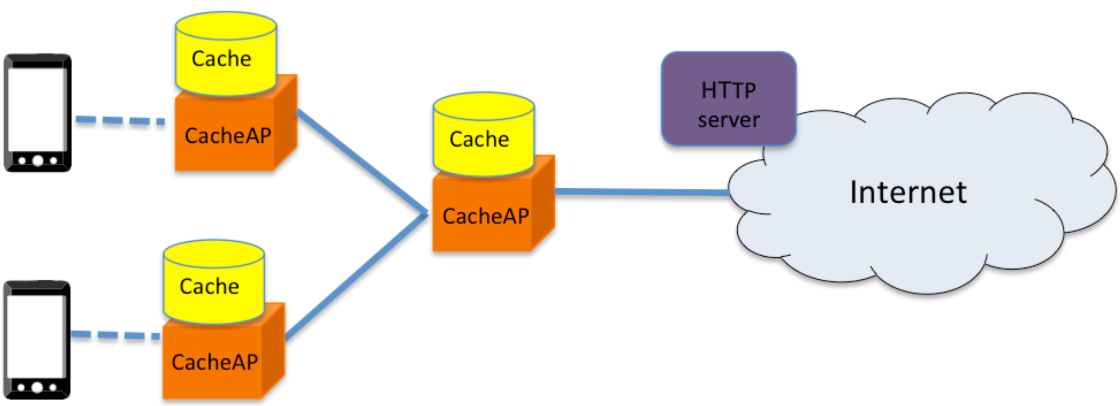


Figure 43: Demonstration topology for caching test case

The primitive work has been demonstrated in 16th international conference on High Performance Switching and Routing (HSPR) in July 2015. Figure 43 shows the topology in the demonstration including three CacheAPs, a HTTP server, and two mobile users. The demo setup as Figure 44 shows a scenario where several mobile users watching a same video, as well as configuration manager that allows network administrator to configure and monitor CacheAPs and their self-organized network. By collaboratively caching the requested videos on self-organized CacheAPs, QoE of mobile users gets highly improved.

Figure 44: Demonstration setup for caching test case

4.2.4 Demonstration of a for multi-dimensional handover

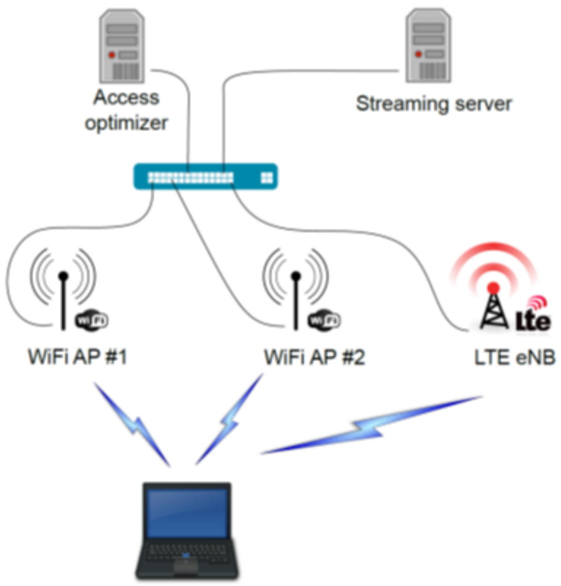
This section explains how the decision engine for optimized multi-dimensional handover is going to be demonstrated. In this demonstration specific implementations of “data path creation and destruction” and “data path coordination” are used.

In this demonstration the following alternative technologies can be included:

- Wi-Fi networks
- 3G (HSPA, HSPA+)
- 4G (LTE) small and macro cell
- Bluetooth

- NFC

For simplicity reasons the demonstration is limited to two Wi-Fi networks, assuming two different operators (ISPs), and the COMBO LTE network as described in Section 3. The demo setup can be seen in Figure 45. Potentially a public network, e.g., a public 3G or 4G network can be added as well.



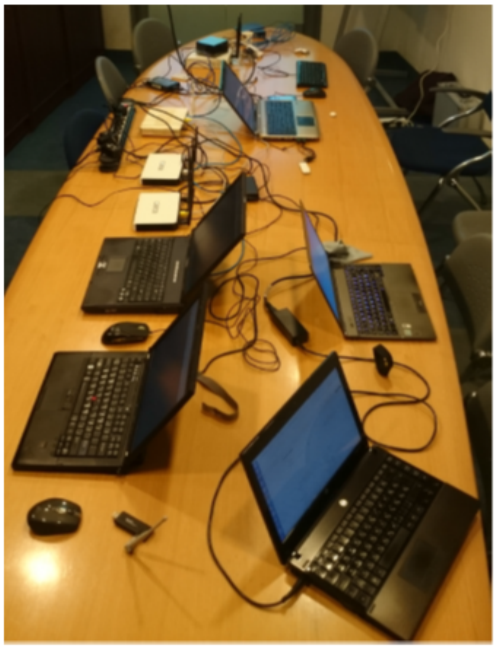


Figure 45: Demonstration setup

Figure 45 (left) shows, that the UE is connected to the Internet by three different paths, via Wi-Fi 1, Wi-Fi 2 and LTE, respectively. The UE is a laptop running Linux as operating system. However, Windows, Android and iOS are considered as well for future testing. The three different Paths are connected to the Internet. A streaming server is also attached to the Internet for demonstrating the seamless changing of interfaces. An access optimizer server is also connected to the Internet. Based on the information collected from UEs, APs and eNodeBs it performs optimisation and decides which interface or interfaces are to be used by certain users.

The optimiser unit can instruct the clients to select a given access network, moreover it can turn on and off any of the access points. The objective is to keep a minimum number of access points active. This instructing can be done in multiple ways, e.g. Google Cloud Notify (GCN) for Android devices or a generic http based approach for any operating system.

While connected, the clients feed information to the access optimizer about the quality of their connection and the access networks in their range. Based on this information the access optimizer decides which access network the client should connect to.

The access optimizer also has the capability to turn access points on or off. Instead of turning off, a low power standby or sleep mode can be used as well. This is done in order to reduce the network's energy consumption.

For example, if the clients of a Wi-Fi network experience congestion, then the optimizer can decide to move some of them to a different network. If the cells of this network are turned off, it will activate them.

Connected clients use a streaming server to stream video over (multipath) TCP. Multipath TCP (MP-TCP) is an IETF effort to provide an extension to TCP which can utilize multiple interfaces for different subflows. It is used to mitigate service interruptions while the client changes access networks.

In the demo each Wi-Fi network has a single access point which is a TP-LINK TL-WR1043ND desktop router. The LTE network also has one eNodeB. Both the LTE core network and the eNodeB is realized by Amarisoft's Amari OTS 100 product as described in Section 3.

Here we will describe a few scenarios to be demonstrated.

Scenario 1

A client moves from one Wi-Fi network to another while streaming video from the streaming server. The effect of the connectivity interruption on the video playback can be observed under different conditions (using one interface or two, multipath or regular TCP).

- In case of a single Wi-Fi interface, regardless whether regular or multipath TCP is used an interrupt of about 8 seconds is experienced.
- If two Wi-Fi interfaces are available, and both are active, with multipath TCP there is no interrupt.

Scenario 2

Two clients connect to the same access point, which at some point becomes a bottleneck. The access optimizer detects this situation and turns on another access point and instructs one of the clients to move to this one.

Scenario 3

If there is a failure in the network, having multiple interfaces active, speeds up the recovery. If MP-TCP is used over these multiple active interfaces, the failure can be seamless.

Scenario 4

If there is a single Wi-Fi interface in the UE, however MP-TCP is supported and there is at least one active additional interface, e.g., the LTE one, then the Wi-Fi to Wi-Fi handover can be made seamless via a Wi-Fi to LTE to Wi-Fi handover.

The four proposed demonstration scenarios will show that

- via optimising the interface selection and connectivity
    1. the QoS / QoE can be guaranteed
    2. availability can be enhanced
    3. power requirement can be reduced
- the users can be handed over without interrupts, i.e., seamlessly
    1. horizontally between geographic locations
    2. vertically between technologies
    3. between operators
- the users can be instructed remotely to change their interfaces between technologies and operators.

4.2.4.1 First demonstration of optimized multi-dimensional handover at HPSR 2015

The demo setup can be seen in Figure 46 ff. show the the first demonstration of the COMBO optimized multi-dimensional handover at the HPSR 2015, July 2, Budapest.

Figure 46: HPSR 2015 demo setup on July 2, 2015, Budapest

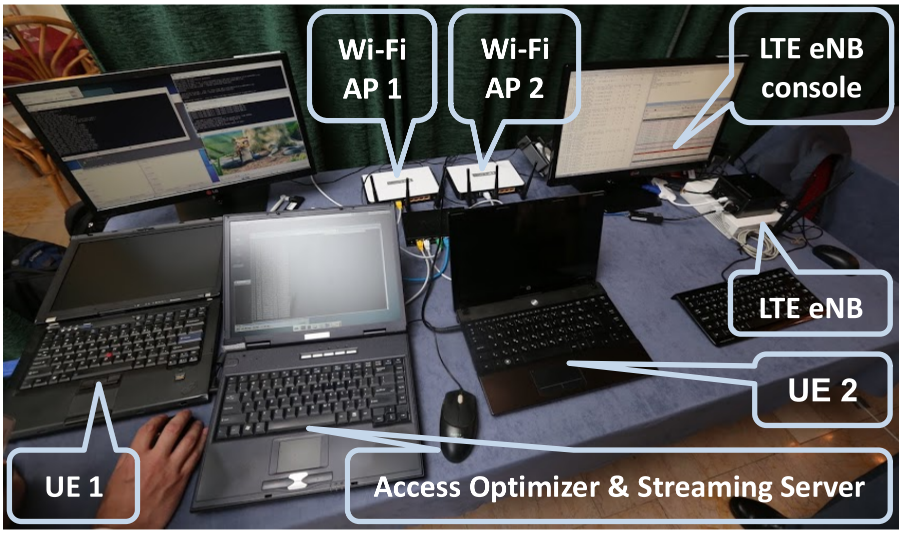


Figure 47: Demo setup with marked components

In the figure above the components of the demo are shown. It has been demonstrated that the video streaming was not interrupted, there was even no quality dergradation while the access optimizer module instructed the UE to change its interfaces between the two Wi-Fi networks and the one LTE network.

The access optimizer initiated access changes for two reasons. First when the quality deteriorated, second, when one of the accesses was interrupted. Remote triggering of interface changes worked smoothly.

5 Distributed and Centralized NG-POP

One of the main outcomes of the COMBO project (as a whole) is the novel proposal and definition of the so-called functional entity UAG, and of the location of the NG-POP in the FMC operator network. In the context of COMBO, the NG-POP is the location where control and data plane functions and elements used for handling fixed and mobile traffic services are converged and/or unified. The UAG is implemented in the NG-POP. The data plane of the UAG presents a common IP edge for fixed, mobile and Wi-Fi services and supports functions for mobile aggregation routers and data plane EPC gateways, Broadband Network Gateway (BNG) and security gateways. The location (NG-POP position) of the UAG could be in the current Central Office (CO) but the preferred approaches are in the main CO or between the aggregation and core networks in the so-called core CO (see D2.1 [3] Chapter 2 *Definition of the reference framework* for more details regarding the different COs). The purpose of this section is to detail the planned demonstrations when considering the location of the UAG at either the main CO or the core CO. In the former, referred to as distributed NG-POP, the idea is to describe the targeted architecture of the UAG network and functional elements and, in particular, the integration of a virtualized EPC (vEPC) running on top of the NFV server within the UAG that instantiates virtual machines. The second solution, called centralized NG-POP, aims at considering that the subscriber's IP edge is at the edge of the core network. In addition to that approach, selected network functions (e.g., EPC MME) are considered to be virtualized into a centralized data center (DC), where a logically centralized SDN controller takes over of the configuration of an aggregation network infrastructure to seamlessly accommodate mobile and fixed services.

5.1 Motivation and objectives

The purpose of both the distributed and centralized NG-POP demonstrations (described in the following sections) is to experimentally validate the feasibility of selected functional blocks defined in both COMBO NG-POP architectures. The definition of both NG-POP approaches and the functions forming the UAG are termed functional convergence within the COMBO WP3 T3.2, where partially some of the solutions are reported in D3.2 [2].

Specifically, in the distributed NG-POP, the implementation of the data plane elements (to seamlessly forward fixed and mobile data traffic) is detailed. Additionally, the NFV server is also described. It runs on top of the UAG allowing instantiating virtual machines where convergent virtualized network functions such as uAUT or uDPM can be implemented. In other words, the demonstration activities described above in Chapter 3 (uAUT) and Chapter 4 (uDPM) will finally be moved into the NFV server of the UAG to conduct the final distributed NG-POP demonstration.

In the centralized NG-POP demonstration, the objective is to perform a proof-of-concept assuming that the data plane of subscriber IP edge is located at the core CO. The aim is that specific network (control) functions, in particular those taking over of the service management (activation/de-activation) are moved into the cloud/DC, e.g., EPC MME. Hence, the main reason is to show a feasible solution addressing the centralized NG-POP where both cloud and SDN concepts are leveraged to attain functional convergence. Specifically, the planned demonstration will validate a centralized and unified SDN orchestrator system which – triggered by (virtualized) mobile and fixed service management applications – is able to automatically program and configure an aggregation network for accommodating fixed and mobile data flows. The unified SDN orchestrator attains specific functional convergence with respect to the seamless management and provisioning of mobile and fixed services over a common transport network (particularly in the aggregation network).

5.2 Planned setup

In the following, specific sections covering the planned setups and demonstrations for both the centralized and distributed NG-POP approaches are detailed. This will constitute the main framework for validating specific functional convergence objectives studied within COMBO project.

5.2.1 Distributed NG-POP

The key component to be located at the distributed NG-POP is the Universal Access Gateway (UAG), which can be implemented in a multilayer and multifunctional equipment (see Figure 48). In a converged access and aggregation network scenario it essentially needs to support Ethernet and packet services from Layer 1 to 3, including Carrier Ethernet connectivity, VLAN tagging and Ethernet switching functions along with SLA monitoring tools that support business and residential fixed line services as well as mobile backhaul services. Also, to fully exploit the network from an FMC perspective, support for fronthaul services and interaction with a centralized BBU capability is required in the UAG.

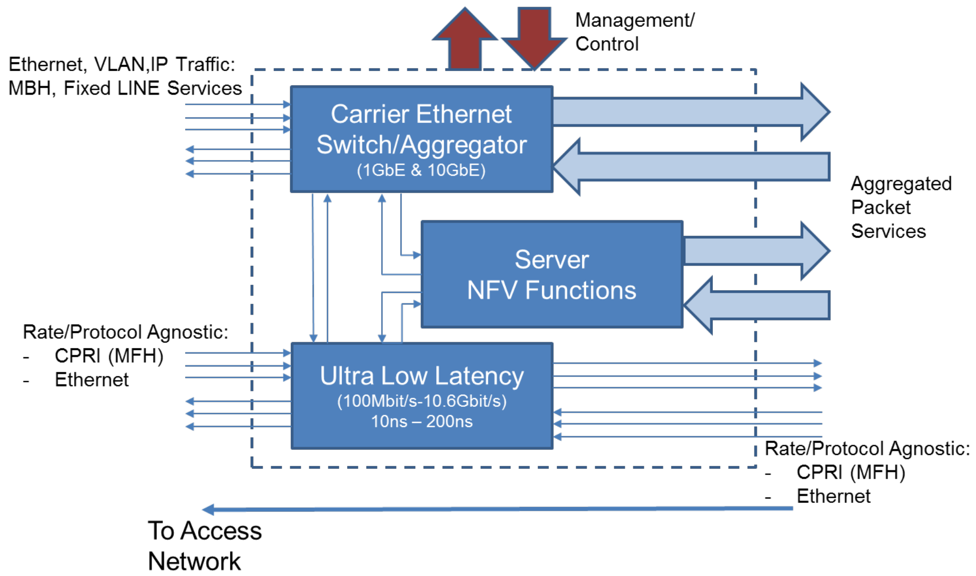


Figure 48: UAG implementation overview

The UAG demonstration platform consists of three primary elements:

1. Carrier Ethernet Switch Aggregator (based on the ADVA FSP150 EG-X, with additional support of OpenFlow control developed in the project)
2. Low Latency Switch (newly developed electrical switching card with very low latency and capability to switch traffic between output ports)
3. NFV Server (commodity Intel-based server, which hosts several VMs and is controlled by OpenStack)

The Carrier Ethernet Switch Aggregator is a commercial off-the-shelf product. It is compliant with various ITU-T, IEEE, MEF and IETF specifications and supports SLA monitoring. It is used to aggregate fixed line traffic as well as mobile backhaul traffic. As a new development in the COMBO project it now can also be configured by an OpenDayLight controller [9] using OpenFlow version 1.3.0.

Figure 49: Photo of the carrier Ethernet switch (ADVA FSP150 EG-X)

The newly developed prototype of an ultra-low latency switch supports data rates from 1 GbE to 10 GbE and the respective CPRI rates (CPRI options 1-8) and can connect up to 5 devices on the client and 5 devices on the network side using SFP or SFP+ modules.

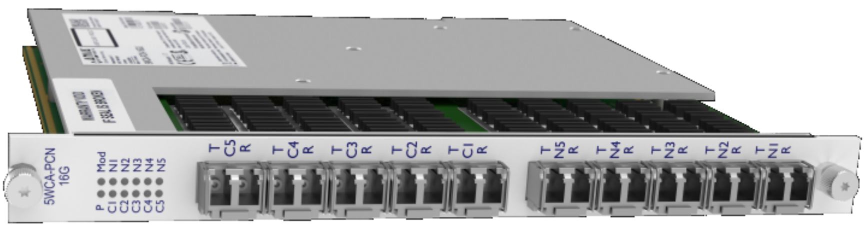


Figure 50: Photo of the low-latency switching card prototype

In a first set of measurements the latency of the card has been analysed in detail showing that it consists of a fixed component of 2.1 ns (due to simple propagation delay) and an additional (bit rate dependent-) factor of approximately 3.5 bit periods due to internal CDR/retiming function (see Figure 51).

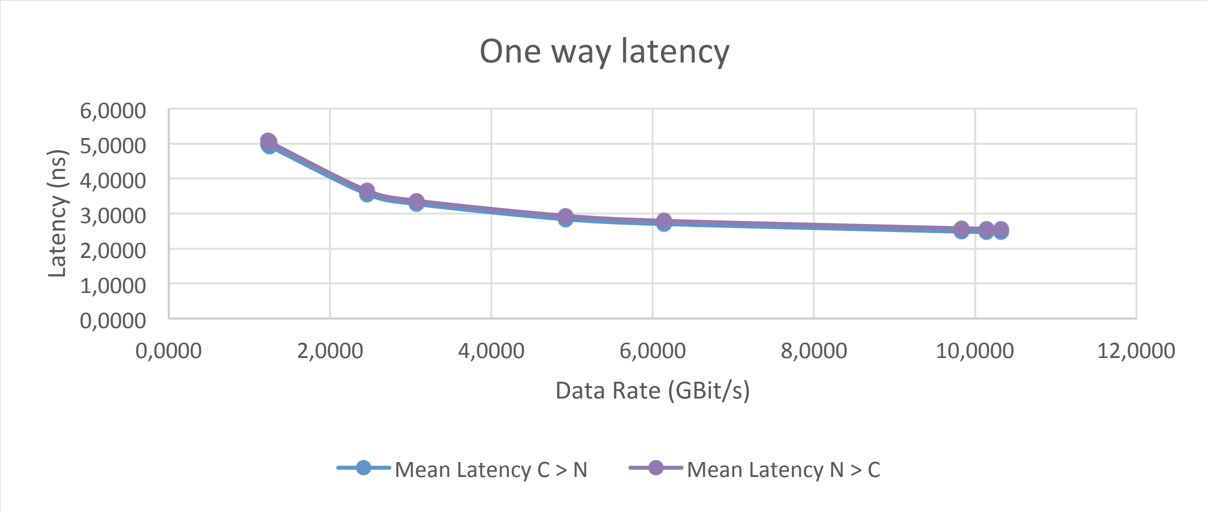


Figure 51: Measured one-way latency of the low latency switch

The NFV server is realized on commodity hardware with the following configuration:

- CPU: Xeon E5-1620 (3.6 GHz)
- RAM: 16 GB
- HD: 2x 1 TB
- 2x Mellanox ConnectX-3 EN 10Gb/s Ethernet card – single SFP+ interface per card
- 2x 1 GbE electrical interfaces

Figure 52: Photo of the NFV server (left) with Mellanox 10 Gb/s NIC (right)

On the NFV server OpenStack will be used as NFV environment with the neutron plug-in to configure networking between the VMs. The implemented architecture is depicted in more detail in Figure 53. As you can see a VMWare ESXI (enterprise class, type-1 hypervisor) is installed on the server without any underlying operating system (“bare metal” operation). On top of that three Ubuntu server VMs are started, which run the OpenStack network node, compute node and cloud controller node functions.

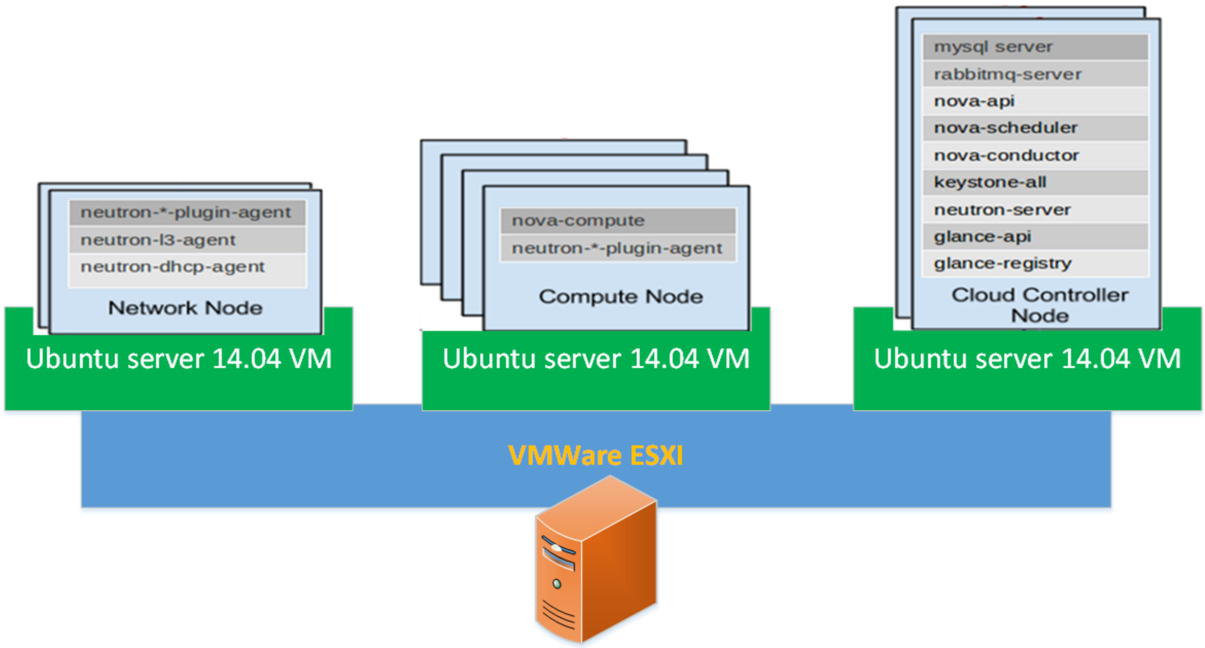


Figure 53: Implemented architecture for NFV server based on VMWare virtualization, Ubuntu server operating system and OpenStack controller.

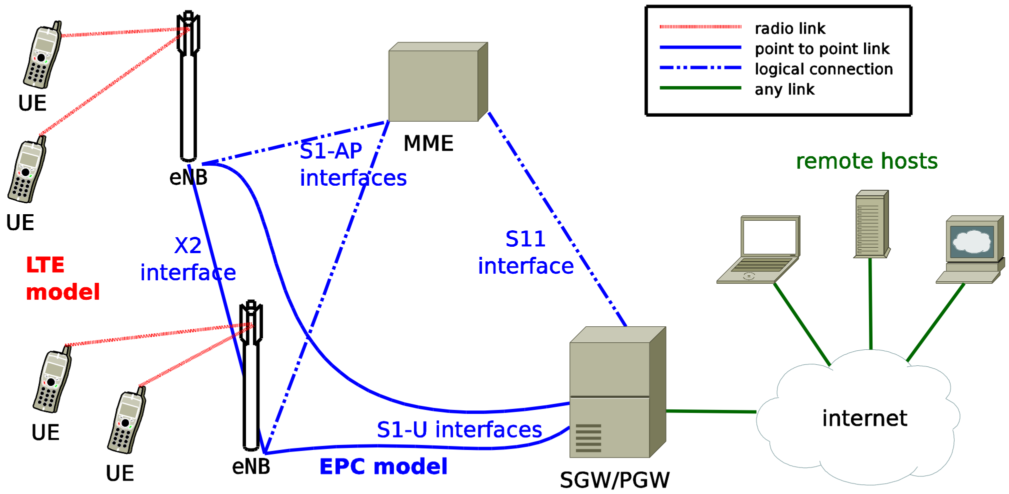
5.2.1.1 Distributed NG-POP network function example: vEPC

In the set of network functions running at the UAG, one of the most interesting is the inclusion of the data plane of EPC gateways (SGW and PGW). Besides supporting the functional convergence over the UAG (i.e., integration of fixed and mobile network functions), it enables distributing PGW functionalities at main COs, much closer to the end user compared to the legacy situation where PGWs are highly centralized in mobile packet core. The overall concept is depicted in Figure 54. This compares a legacy scenario with the distributed NG-POP approach. In this figure, we highlight that the movement of the PGW functionality allows the termination of specific data plane interfaces at the UAG in the aggregation network. Consequently, savings in the core network load (i.e., signalling is not transported towards the core network) are achieved which in turn may lead to potentially improved communication latency perceived by the user equipment.

The following setup can be also considered as an example to instantiate and allocate virtualized network functions (e.g., targeted uAUT and uDPM) in the NFV server of the implemented UAG. In this example, the EPC will be virtualized (vEPC) and run on top of the NFV server co-located with the UAG. The vEPC used for this demonstration will rely on the implementation made in the LTE-EPC Network Simulator (LENA) [26]. LENA is an open-source product oriented LTE-EPC simulator/emulator based on the popular open source ns-3 simulator. The implementation provided by LENA is seen as an alternative to gain flexibility in the demonstration of the vEPC with respect to the other COMBO adopted commercial solution provided by Amarisoft Amari product described in Chapter 3. Furthermore, the option of having both implementations (i.e., LENA and Amarisoft solutions) is interesting since they would provide the opportunity to instantiate two vEPCs on top of the NFV server for multi-operator demonstration purposes.

Some of LENA's key features are:

- Simulated PHY and channel models allowing the realization of experiments with large Radio Access Networks
- Support for emulation with real-time execution
- Transparent bytes: PDUs are implemented as in actual protocol stack implementations (unlike most simulators)
- Possibility to integrate with networking testbeds
- The availability of the source code allows for easy customization of network functions, interfaces, elements and protocols



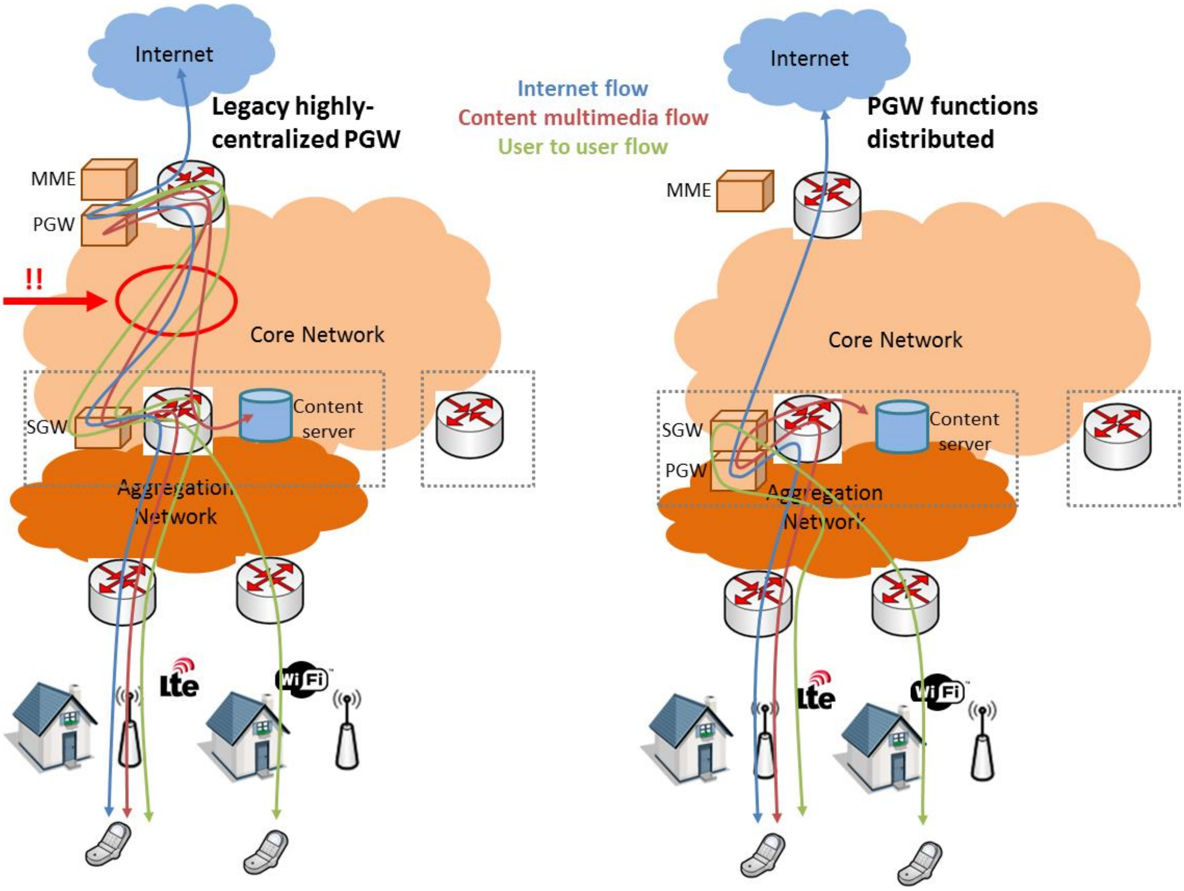


Figure 54: Example network topology realizable with the LENA LTE-EPC network emulator (top); functional convergence leading to the distribution of PGW functionalities (bottom)

The targeted vEPC – UAG demonstration covers two scenarios:

- State-of-the-art EPC: in this scenario, depicted in Figure 55, the LENA EPC is running in a separate machine, acting as the dedicated hardware deployed at the core network in current state-of-the-art network deployments. In this configuration, we note that the EPC control signaling is transported through the core network, and that the transport of data plane traffic using the EPC interfaces results in additional transport overhead.
- Virtualized EPC (vEPC): in this scenario, a virtualized instance of the LENA EPC is running inside the UAG. In such configuration, we note that no EPC control signaling traverses the core network, and that the data plane traffic incurs a reduced data plane transport overhead compared to the state-of-the-art case.

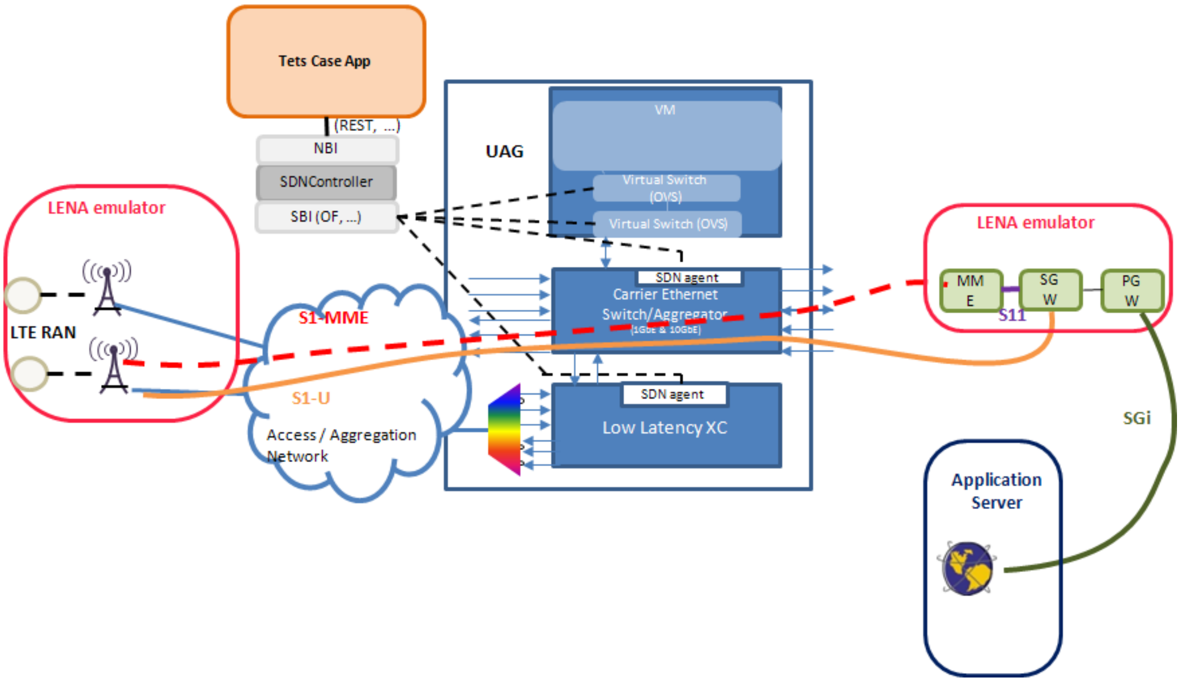


Figure 55: Demonstration setup for the state-of-the-art EPC case

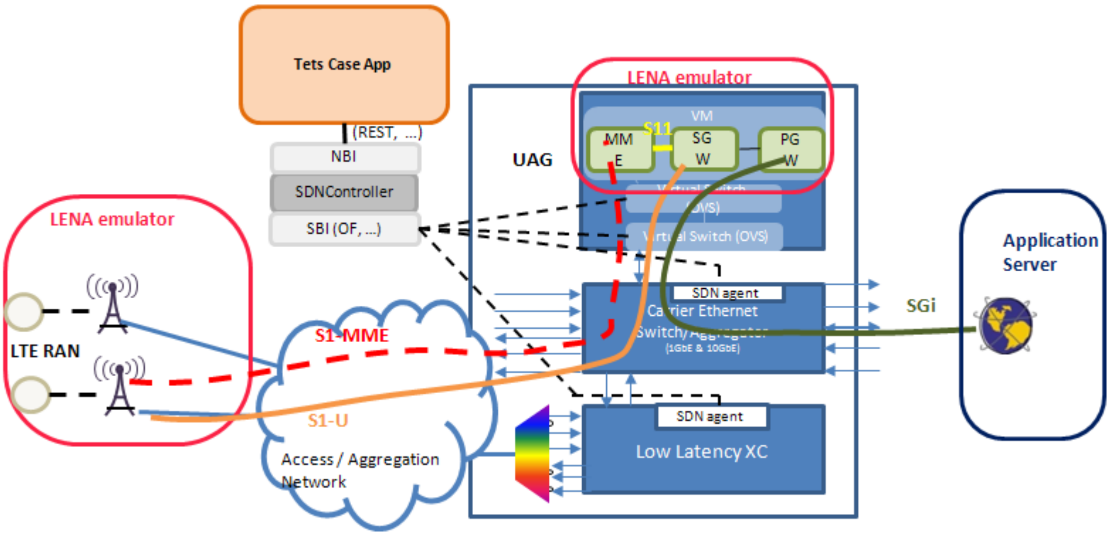


Figure 56: Demonstration setup for the Virtualized EPC case

5.2.2 Centralized NG-POP

In the centralized NG-POP approach the (converged) functions (i.e., control and data plane) are assumed to be located in the core network, at or close to the core CO. At such a location, a cloud infrastructure (i.e., data centers) is deployed by the network operator (see Figure 57). Data center IT resources (i.e., storage and computation) can be exploited for network virtualization purposes dealing with the NFV concept [27]. Indeed, in NFV, selected network functions (e.g., load balancing, deep packet inspection, firewall, etc.) traditionally run in dedicated appliances, are now decoupled from their physical network equipment and moved into the cloud as a Virtual Network Function (VNF). Thereby, the goal is to leverage standard IT virtualization technology executing network functions in “industry standard” servers. This yields network operators important benefits: enhancing the flexibility and innovation, reducing CapEx and OpEx, etc.

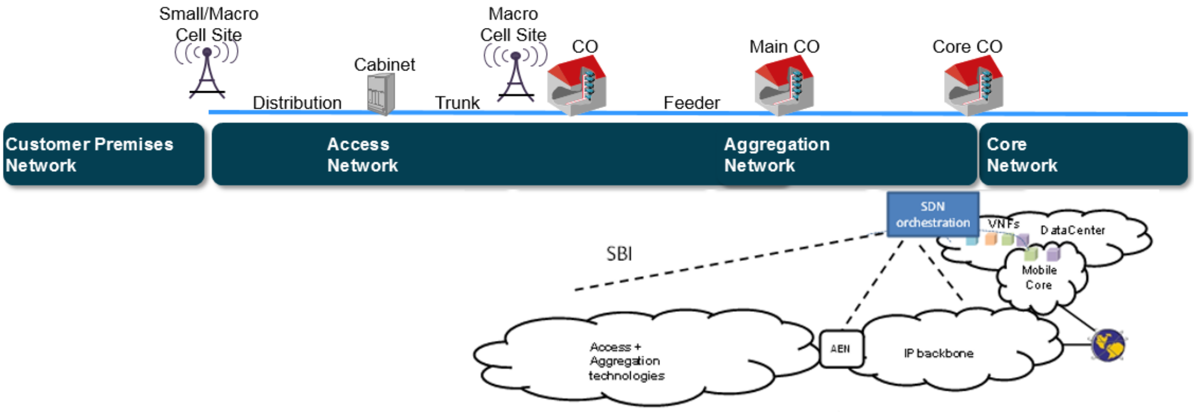


Figure 57: Centralized NG-POP reference network scenario

In the context of COMBO, one of the goals is to exploit NFV principles to favour the targeted fixed mobile convergence (structural and/or functional). To do that, selected VNFs (e.g., mobile vEPC, vBRAS) can be virtualized according to either partial or full models. In the former, only control EPC functions (e.g., MME, SGW-C/PGW-C) are virtualized in the cloud, whereas the user/data plane elements (e.g., SGW-U/PGW-U) rely on physical and dedicated L2/L3 switches. In the fully virtualized model, the user plane is virtualized as well using commodity servers running on virtualized switches (e.g., Open vSwitch).

In the centralized NG-POP, the underlying network infrastructure (e.g., aggregation and core L2/L3 switches) is controlled and configured by a centralized SDN controller/orchestrator (see Figure 57). The SDN controller also communicates with the VNF elements (virtualized at the cloud) via a NorthBound Interface (NBI) to enable the programmability of the network infrastructure for accommodating the (fixed and mobile) traffic flows.

The following setup aims at assessing and validating a candidate NG-POP solution relying on the aforementioned NFV and SDN concepts. To this end, we deploy a unified SDN controller/orchestrator which follows the architecture defined in the IETF Application Based Network Operation (ABNO) [28]. The primary objective of the targeted unified SDN orchestrator is to provide an architectural solution where convergent functions such as the data path creation, path activation, etc. defined in Task 3.2 (specially the uDPM element [2]) are accommodated. The adopted decisions made by the functional blocks forming the unified SDN orchestration are used to program / configure the network when serving UE (mobile or fixed) services.

5.2.2.1 Architecture of the implemented ABNO for functional FMC

The implemented unified SDN-based ABNO orchestrator is depicted in Figure 58. In this specific centralized NG-POP, we assume that functions used to handle the management of UE (fixed and mobile) services are located at the cloud as VNFs. Such functions are referred to as fixed and mobile service applications. Specifically the mobile service application behaves as a proxy to trigger the establishment of the mobile flows (EPS bearers). To this end, the application maintains a direct communication with the EPC MME entity. In other words, whenever an EPS bearer is being signalled via the MME entity, information related to that bearer (e.g., eNB and SGW IP addresses, QoS requirements, etc.) is delivered to the mobile service app. Next, such an app must request the required allocation within the aggregation multi-layer infrastructure to accommodate the mobile EPS bearer. Similar operations are performed to manage the fixed services.

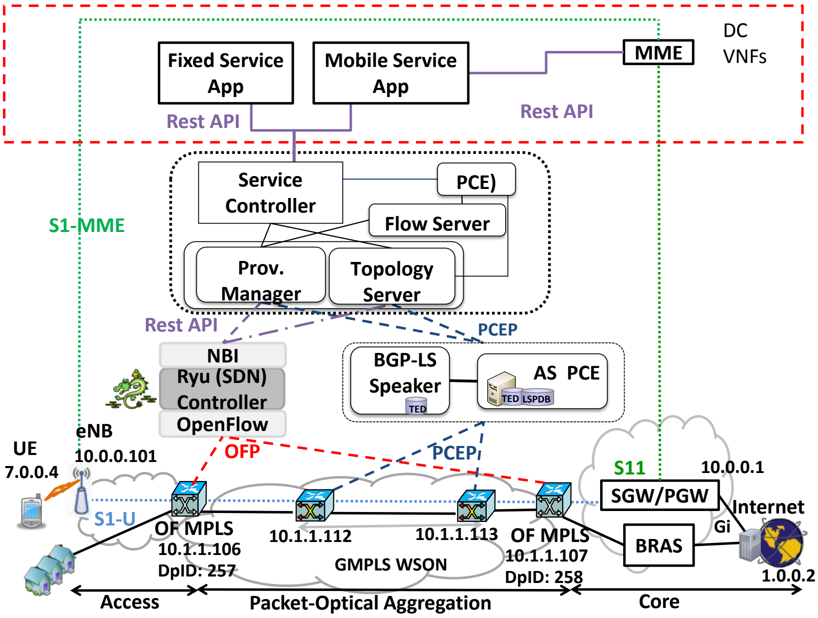


Figure 58: Multi-layer aggregation ABNO orchestrator for functional FMC

Before detailing the ABNO functional elements, we describe the multi-layer aggregation network used to conduct the validation at the data plane (see Figure 59). The multi-layer network infrastructure is available at CTTC labs and leads to seamlessly aggregate and transport both fixed and mobile (IP and Ethernet) traffic flows in an efficient way [29]. To this end, the network combines two switching technologies: packet (3 MPLS switches) and optical (4 WDM ROADMs and OXCs). This allows leveraging the benefits of both worlds, namely, the fine granularity and statistical multiplexing of packet switching and the coarse transport capacity of optical switches. That is, particular mobile / fixed traffic services are tunnelled using MPLS packet connections, which in turn can be aggregated with other packet connections to be finally transported within optical connections towards the core.

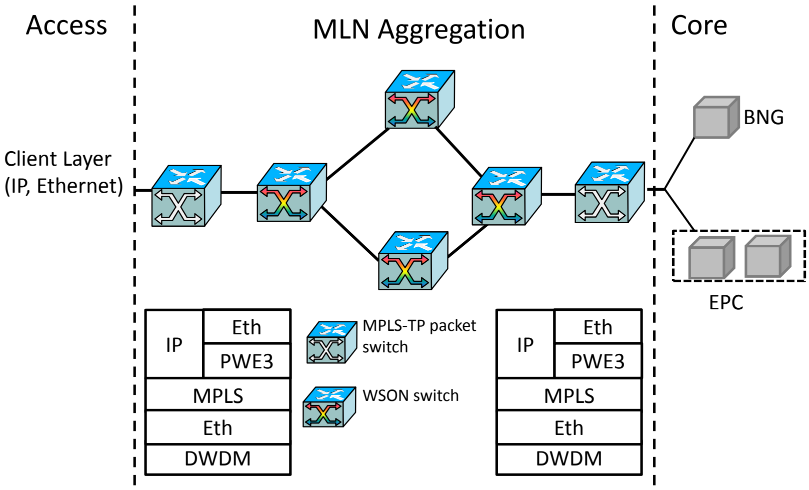


Figure 59: Multi-layer aggregation network integrating MPLS and WDM

In the SDN ABNO orchestrator (Figure 58), the service controller handles the incoming service requests from both fixed and mobile service applications. These applications trigger the service demands (via REST API) specifying the type of service (e.g., MPLS), endpoints (e.g., for mobile connections the eNBs and EPC SGWs), the requested bandwidth and other QoS requirements (e.g., maximum latency). This element can be bound with the generic “decision engine” of the uDPM [2].

The PCE computes a multi-layer path including both packet and optical infrastructures. The objective function of the PCE is to attain the most efficient use of network resources at both layers fostering the packet aggregation into pre-established optical tunnels. The topology server is a database where full (or partial/abstracted) network connectivity and resource attributes at both layers are gathered. This is the input for the PCE computations. The PCE and the topology server are mapped to the “Path Coordination and control” function of the uDPM.

The provisioning manager function coordinates the corresponding SDN controllers to actually conduct the network elements configuration along the computed paths. This function can be associated to the “Data Path Creation and Destruction” function of the uDPM.

As shown in Figure 58, in the aggregation network two heterogeneous control plane solutions (one per switching technology) are adopted:

- The control of MPLS switches is done by an SDN packet controller using an implementation of Ryu controller [30]. It relies on the OpenFlow 1.3 protocol to configure the forwarding of the MPLS nodes (i.e., MPLS tag pop/push).
- The control of optical circuits is handled by an Active Stateful (AS) PCE. This allows instantiating optical connections via a distributed GMPLS control plane.

The logical interfaces/APIs enabling the communication among the aforementioned ABNO elements (including SDN Ryu controller and AS PCE) rely on combining both REST and PCEP interfaces. For instance, when a new MPLS flow transporting an EPS bearer needs to be set up, a multi-layer path is computed by the PCE. The computed path is passed to the provisioning manager which coordinates both the

SDN Ryu controller and the AS PCE to perform the transport network configuration. It allows setting up the MPLS flow associated to the EPS Bearer and (if needed) the optical tunnel accommodating such packet flows. Observe that new MPLS flows can be tunnelled over existing optical tunnels as long as sufficient available bandwidth on those optical circuits exist (i.e., for aggregation/grooming purposes).

The setup is basically formed by three main elements: the LTE-EPC network provided by the LENA emulator [26] (including User Equipment and eNBs), the multi-layer OF-enabled MPLS [31] - optical aggregation network deployed within the ADRENALINE testbed [29] and the unified ABNO orchestrator discussed above. Without loss of generality, the experimental validation aims at transporting mobile services (EPS Bearers) between the eNBs and the EPC (SGW) via the multi-layer aggregation infrastructure. All the mechanisms and functions to do so are automatically coordinated by the ABNO orchestrator. For the sake of completeness, the ABNO operates similarly when fixed services need to be set up.

5.2.2.2 Preliminary results

This section describes the experimental assessment of the unified SDN orchestration for the COMBO centralized NG-POP solution. To do this, we consider a network scenario as shown in Figure 58.

Focusing on the mobile services, once the EPS Bearer is negotiated between the eNB and the EPC MME [32] through the (out-of-band) control S1-MME interface, the MME communicates with the Mobile Service App (running on top the ABNO) to request the transport of EPS Bearer data/user packets (i.e., S1-U interface [32]). The interface between the MME and the Mobile Service Apps is implemented using a REST API. Indeed, a new generic *service call* is defined to request from both Mobile and Fixed Service Apps, multi-layer transport connections handled by the ABNO.

For the EPS Bearers, the service call specifies the endpoint IP addresses (i.e., eNB and SGW), the requested bandwidth (ReqBw) in Gb/s, and specific match attributes (such as mobile data packet attributes). The latter allows mapping EPS Bearers with specific MPLS flows within the aggregation network. Specifically, EPS Bearers use the GPRS Tunneling Protocol (GTP-U) to transport data packets between the eNB and the EPC. Each EPS Bearer flow (S1-U) has an individual Tunnel Endpoint Identifier (TEID), which is carried into the GTP-U protocol. In this work we bind such TEIDs with individual MPLS labels. We apply a policy where every EPS Bearer (with its own TEIDs) is transported over a different MPLS flow. Nevertheless, multiple MPLS flows may be aggregated into a unique optical tunnel.

Figure 60 depicts the flowchart and messages exchanged among the ABNO elements when a (mobile) service call is received. Such a message is encapsulated into a REST POST message (step 1 in Figure 60) specifying the transport service type (e.g., MPLS), the endpoints (eNB at 10.0.0.101; SGW 10.0.0.1), the TEIDs (set to 2) and the ReqBw. Upon receiving the service call request, the Service Controller first determines the ingress and egress MPLS switches connected to the source and destination nodes (i.e., eNB and SGW). Next, the Service Controller sends a PCE Request (PCReq) to the PCE (step 2) with the MPLS endpoints. The PCE computes the route between those MPLS nodes considering the ReqBw. To do so, the PCE must retrieve the network topology. This is achieved via a request to the topology server function (i.e., REST GET Packet Topology). The topology server then asynchronously queries to both the SDN controller (for packet infrastructure) and the AS PCE (for the optical network) to update their respective network status (step 3 in Figure 60).

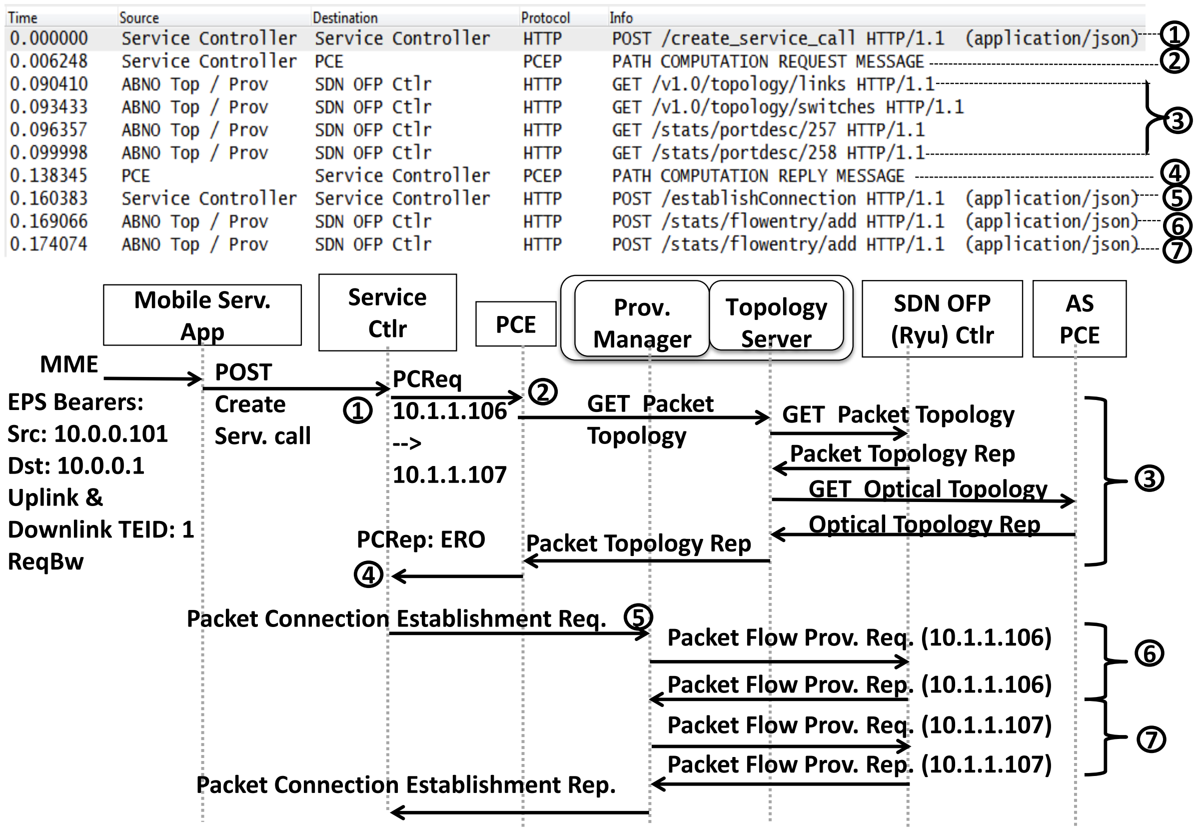


Figure 60: Creation of the mobile service via ABNO controller

Once the network topology is updated, the PCE executes the path computation. If a feasible path succeeds, a PCE response (PCRep) with the computed path (i.e., Explicit Route Object, ERO) is returned to the Service Controller (step 4).

After the path is computed, the setup of the multi-layer transport connection must be done sending to the provisioning manager a Packet Connection Establishment Request message (step 5). This message carries the computed ERO and, for the mobile service, the associated matching rules: TEIDs and source and destination IP addresses of the EPS Bearer. The provisioning manager communicates with both SDN packet controller and AS PCE to perform the configurations on both layers.

As mentioned above, the AS PCE is used when the establishment of a new optical connection is needed requiring the configuration of the optical transceiver (i.e., WDM channel) and the wavelength switching nodes.

On the other hand, in the SDN packet controller, the extended OpenFlow 1.3 OFPT_FLOW_MOD message with experimental matches configures the MPLS nodes according to the EPS Bearer attributes (S1-U interface). For each EPS Bearer, the GTP-U packet is encapsulated and decapsulated over a MPLS tunnel. As shown in Figure 61, the OFPT_FLOW_MOD carries a set of match rules and actions for the MPLS nodes that define the processing and treatment of the data packet (GTP-U) of each EPS Bearer. In the example, the match rules impose that: all the GTP-U packets received over an incoming port with the tuple formed by a determined pair of source and destination IP addresses (i.e., eNodeB 10.0.0.101 and SGW 10.0.0.1), UDP port set to 2152 and the TEID equals to 2, then a MPLS tag (1002) is pushed and the resulting packet is forwarded to the output port towards the optical domain. Similar operations but removing the MPLS tag are done when the EPS Bearer leaves the MPLS domain prior to be delivered to either eNodeB or SGW (downlink and uplink flows).

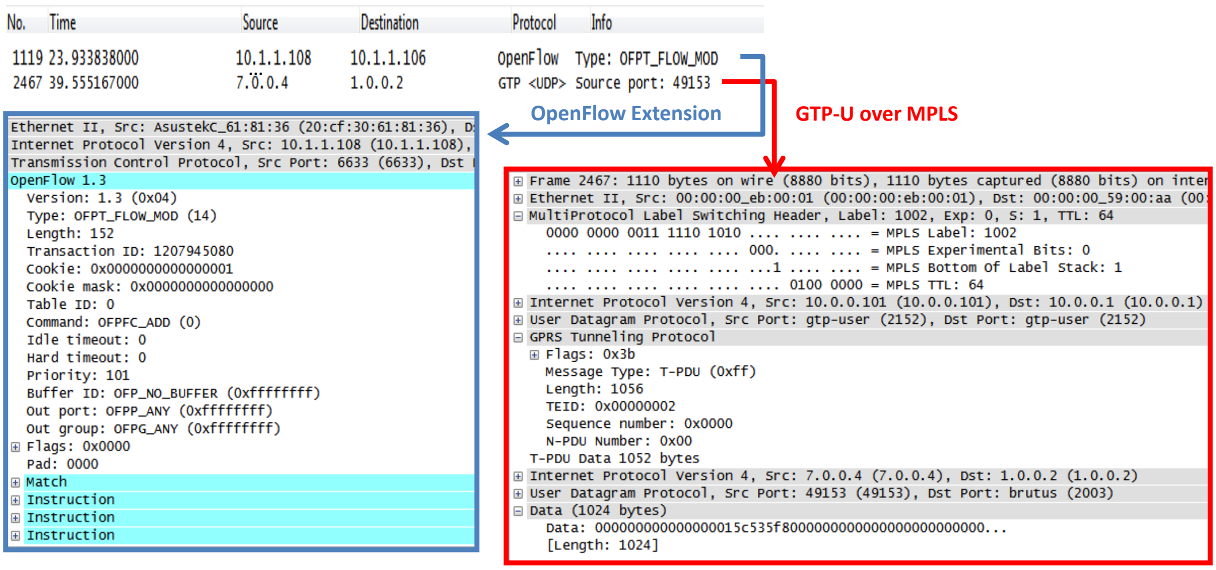


Figure 61: OFP Extension and GTP-U over MPLS

5.2.2.3 Supported use cases

- Use case 7 “Converged access and aggregation technology supporting fixed and mobile broadband services”. A single access and aggregation technology will be supported by the demonstration.
- Use case 8 “Network sharing”. Is inherently supported by the demonstration. The physical infrastructure enables multiple services to be transported. Furthermore, a “carriers-carrier” model could be demonstrated (e.g. showing that CPRI streams from different carriers are transported over the same infrastructure).

6 Plans for Final Integrated Demonstration

6.1 Description of the technical capabilities

The final demonstration will take place in Lannion, France, and will be hosted in Pole Image Réseau (PIR) buildings, just near Orange Labs facilities. PIR will supply:

- 1 room for the integration and the different testing phases,
- 1 showroom for the final demonstration,
- 1 meeting room.

In order to support the integration and testing phases, Orange Labs will provide a part of the instrumentation like CPRI generator / analyser, Ethernet frames generator, Optical Spectrum Analyser (OSA), Digital Sampling Oscilloscope (DSO), optical power meter, power supplies...

An optical infrastructure based on 12 optical rings deployed in Lannion will be used and COMBO project will use some of them for the demonstration.

6.2 Final integrated demonstration description

Figure 62 illustrates how functional and structural convergence is achieved in the final integrated COMBO demonstration.

The setup proposes three flavours of access/aggregation networks, able to support mobile fronthaul but also to backhaul legacy Ethernet traffic from fixed broadband network (residential gateway and Wi-Fi access points) and from mobile network (eNodeB):

- a DWDM-Centric access/backhaul network built with Wavelength Selective Switches (WSSs) and controlled by an SDN controller (Section 2.1).
- two WDM-PON access networks, built respectively with
  - a Wavelength Selective (WS) WDM-PON system (Section 2.2.1)
  - a Wavelength Routed (WR) WDM-PON system (Section 2.2.2)

The demonstration illustrates the distributed NGPOP approach and the concept of the UAG, which provides a converged IP edge for Fixed, Wi-Fi and Mobile access networks (Section 5.2.1). The UAG hosts a converged cache for different wireless accesses (Section 4.2.3) and the uDPM function which provide:

- path coordination and control which allow attaching a mobile UE to the UAG through LTE and Wi-Fi access networks (Section 4.2.1)
- data path creation and destruction which allow traffic offloading from the 4G access to the Wi-Fi access and traffic offloading from a Wi-Fi access to another Wi-Fi access (Section 4.2.2)
- decision engine for optimized multi-dimensional handover (Section 4.2.4)

Last but not least, the demonstration shows how a UE can attach to an LTE network or a Wi-Fi network with the same authentication credentials (section 3): the UAG provides a uAUT mechanism.

The different blue bullets of Figure 62 address previous sections of this document; a CPRI traffic generator/analyser will validate the mobile fronthaul transport on the WDM-PON access networks.

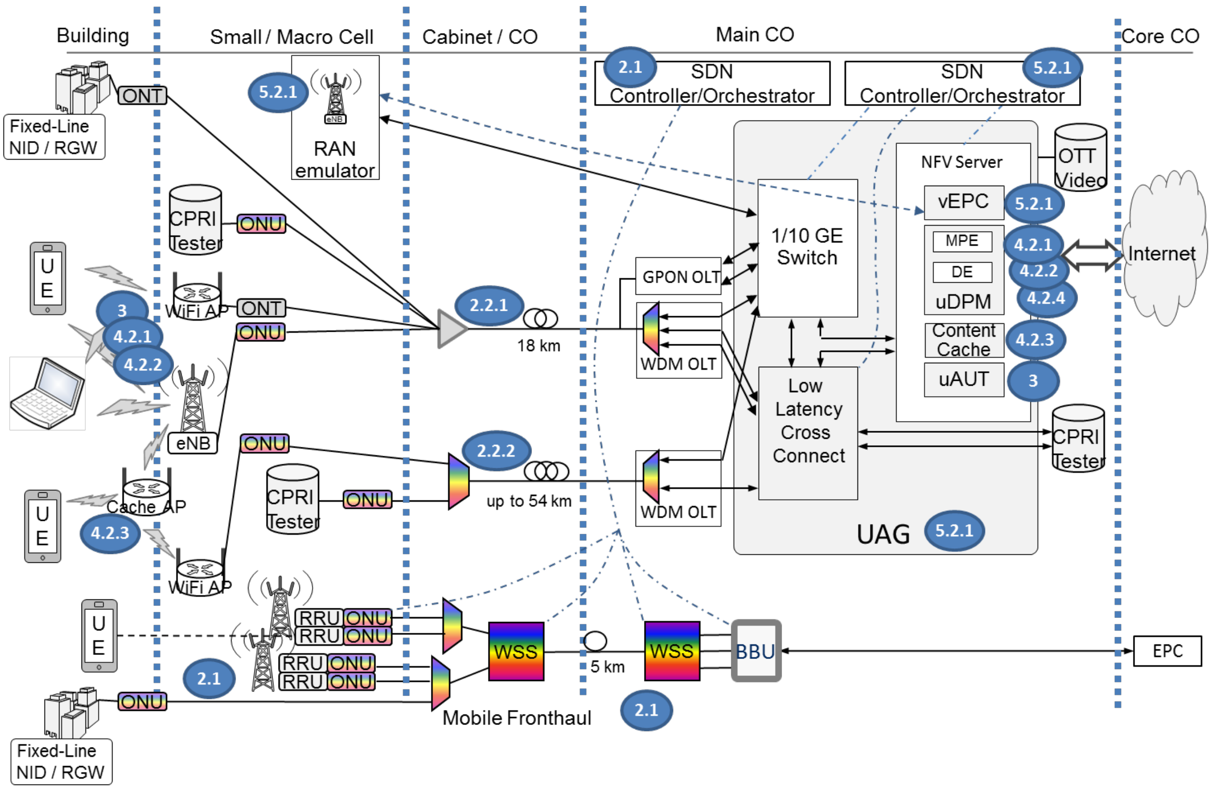


Figure 62: Final integrated demonstration setup

It should be noted that the centralized NGPOP approach is not part of the integrated COMBO demonstration (see Section 5.2.2), which focuses on the distributed NGPOP scenario. The centralized NGPOP approach can be demonstrated in CTTC facilities in Barcelona, Spain. Moving the demonstration was too difficult to achieve in terms of logistics.

The COMBO project has identified different locations in the network where equipment should be installed: Building location, Small/Macro cell location, Cabinet/Central Office (CO), Main CO and Core CO. Figure 63 illustrates the distribution of each FMC component for the final integrated demonstration, according to the architecture studies.

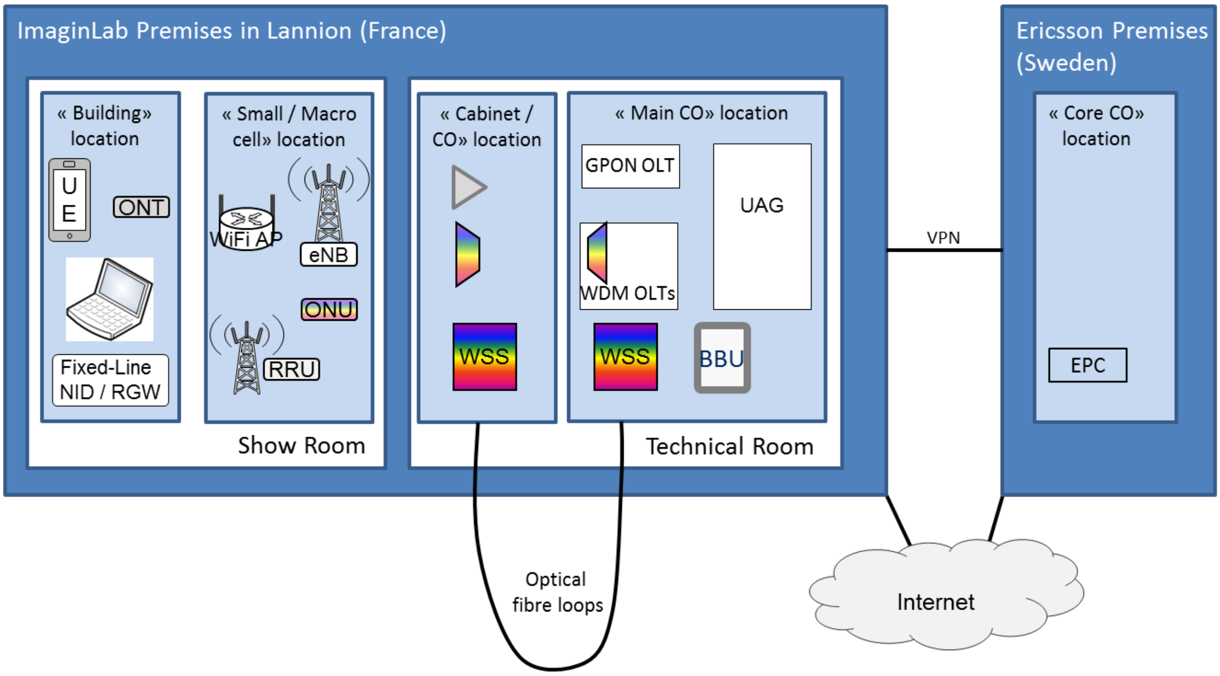


Figure 63: Distribution of each FMC component

UE and APs such as Wi-Fi APs, eNBs and ONUs will be installed in a show room.

Passive optical components such as optical splitters, AWG filters or WSS switches will be located in a technical room, representing a cabinet or a CO.

The UAG and the BBU are also located in the technical room in dedicated racks representing the main CO.

A core EPC will be located in Ericsson's premises in Sweden as part of the Core CO.

7 Conclusion

The demonstration activities planned in COMBO explore the central themes of the project and relate to the specific architectural targets from WP3 namely:

1. A structural demonstration focused on the underlying transport layer and traffic forwarding which together enable Fixed Mobile Convergence of the Access and Aggregation Network, as well as control and functions needed in order to meet a useful demonstration. In particular the following highlights can be used to describe the structural demonstration:
    a. Extensive analysis of Access/Aggregation network focused on structural FMC
    b. Includes DWDM with WSS, WS- and WR-WDM-PON, and GPON technologies
    c. Incorporates a prototype demonstration model of the UAG
    d. Elements of C-RAN are included
2. A functional demonstration focused on specific functions which enable Fixed Mobile Convergence, and in addition exploring the migration of such functions around various parts of the network in order to measure the impact of centralization vs. distribution of functions. In particular, it will be shown:
    a. Convergence of Wi-Fi and mobile services from dual-attachment equipment utilizing multiple features of the FMC network including:
        i. uAUT for authentication of users using multiple access networks
        ii. universal data path management (uDPM)
    b. The use of the UAG to host functions relating to LTE virtualized EPC in a distributed NG-POP approach

To better illustrate the demo – especially the functional entities, imagine the following story of a subscriber (who will be called Alice in the following):

- Alice is on a journey and connects to the Internet through her mobile phone. In this mobile access scenario authentication is done through the SIM card (EPC authentication demo).
- On her way back from the station Alice stops at a restaurant and wants to check her e-mails. She connects automatically to the Internet through a Wi-Fi hotspot (access selection and EAP-AKA authentication demo). The selection is done by the uDPM component hosted in the UAG based on the highest bandwidth to be offered.
- Afterwards Alice walks home and connects to the Internet through her home Wi-Fi access point (WPA or EAP-AKA authentication demo). Again the selected access path is chosen by the uDPM based on the highest offered bandwidth to the user.

- To increase the speed for a particularly large download, Alice wants to combine the best of the two access option available at her home – Wi-Fi and mobile LTE networks (dual attachment demo).

For the operator the advantage over state of the art mode of operation is that he knows and steers through which access solutions Alice is connected.

This deliverable provides a detailed summary of the technical work being undertaken in the work package 6, and also shows the cooperation with other work packages in the COMBO project. The deliverable will be used in the future to guide the integration and final demonstration activities towards the final integrated demonstration at Orange labs in Lannion, France. Furthermore, progress of the partners will be tracked towards the goals outlined in this deliverable. The final deliverable D6.3 will report on the demonstration activities undertaken in Lannion and the lessons learnt from this.

With the development activities outlined, the work package is in a good position to achieve the goals of the development and experimental research activities and will provide valuable feedback to the theoretical and conceptual work undertaken by COMBO.

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