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Demonstration of Next Generation Point of Presence for Fixed-Mobile Convergence

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***Abstract* - Distributed data centers can benefit fixed and mobile service operators alike. Upcoming 5G technologies will force network operators to redesign current network infrastructure to deal with a high set of requirements (e.g., increased traffic load, reduced latency, improved cost and energy efficiency etc.). An appealing solution focuses on rolling out the so-called fixed mobile convergence in broadband networks. Fixed mobile convergence aims at providing a shared infrastructure (i.e., transport solutions and common points of presence) as well as a set of universal functions and operations (i.e., authentication, accounting, path control and management, caching, etc.) regardless of the access network type (fixed, mobile or Wi-Fi). In our vision, convergence is attained by developing a next-generation point of presence based on characteristics of geographically distributed data centers. The new point of presence can be defined as the location for the common subscriber IP edge of fixed, Wi-Fi and mobile networks alike. For a given area, user traffic connections, from different access technologies, are terminated within this single, shared location hosting selected and common network functions and operations. To this end, we exploit the benefits of adopting both networking trends Software Defined Networking and Network Function Virtualization. This work reports on the successful validation of the devised and deployed next generation point of presence demonstrating true fixed mobile convergence. The targeted convergence is attained by providing support for heterogeneous (control and data plane) network functions for mobile core, Wi-Fi gateway and fixed services inside the point of presence.**

Keywords* - *Universal Access Gateway; Fixed Mobile Convergence; Next Generation Point of Presence; SDN; NFV.

I. INTRODUCTION

As our previous work [1] has shown that a Software Defined Networking (SDN) deployment can significantly improve performance for high radix Data Center topologies such as hypercube, torus or jellyfish (e.g., as far as 45% more throughput per node), the complexity of scaling such networks proved to be an issue.

While the conventional trend regarding data centers is focusing on increasing their size and performance, an alternative approach turns towards a geographical distribution of data centers in key places throughout the network (e.g., Next Generation Points of Presence - NG-POPs) and closer to the customers. Hosting business critical applications and IT infrastructure closer to the office location is preferred, in many situations [2], over the choice of a distant central location for reasons mainly related to lowered costs and latency.

Even though adoption of the afore mentioned topologies could not target conventional data centers, we could argue that a geographical distribution could alleviate the requirements of scaling internal networks to very large sizes. Distributed data centers could become a suitable deployment for high radix-networks therefore benefiting from the performance and resiliency advantages highlighted in [1].

Deployment of distributed data centers can provide added value not just for business applications. Mobile Cloud Radio Access Network (C-RAN) [3] architecture also seeks to apply data center technologies to allow for increased bandwidth, highly reliable, low latency interconnections in Base Band Unit (BBU) pools. C-RAN imposes a set of stringent network

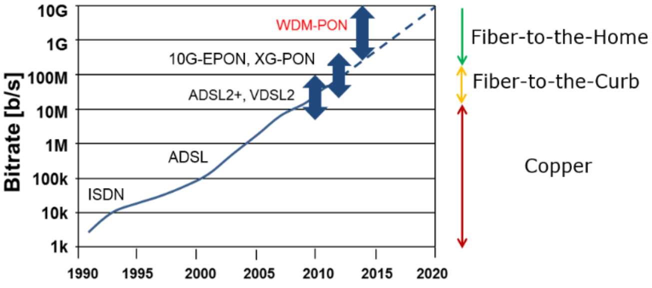


Figure 1. Evolution of access technologies [4]

requirements (in terms of increased traffic load, ultra-low latency, high availability, etc.) to support advanced services that network operators will need to provide. In this context, it is widely accepted that such infrastructures will deploy these services combining multiple resources such as networking (i.e., transmission, switching, etc.) and IT (i.e., computing, storage) [3].

In this work, we aim to introduce and demonstrate an NG-POP based on the characteristics of distributed Data Centers, that is able to service fixed and mobile access users alike and ultimately provide the basis for true Fixed-Mobile Convergence (FMC). Towards this objective, in Section II we provide a brief introduction into the concept of FMC and the motivation behind a shared access infrastructure. The following chapter proposes the architecture for a distributed NG-POP (dNG-POP) detailing on its envisioned functionality. In Section IV, we describe the implementation of a full-scale demonstration setup representing a physical fixed mobile converged access network with a dNG-PoP at its center. Finally, we report the results from the first experimental demonstration and successful validation of the dNG-POP architecture for FMC access networks as part of the EU funded project, COMBO [5].

II. Fixed Mobile Convergence (FMC)

The undergoing standardization process for next generation mobile networks (i.e., 5G) is expected to increase 1000-fold the wireless capacity introduced in 2010 and at the same time densely pack wireless links connecting up to 100 times more devices [6]. Such a prediction leads to assumptions on developing totally new backhaul and possibly adopt fronthaul technologies in order to cope with the increase.

As highlighted in Figure 1, fixed access networks have been experiencing a significant increase for over two decades with no anticipated growth rate reduction. Ever changing multimedia and streaming services providing HD quality, or the newer UHD or even 3D formats, are some of the major bandwidth-hungry drivers today. Some of the current technologies trying to cope with these requirements, like the most often used DSL or cable over hybrid fiber-coaxial (HFC) infrastructure, offer connections of hundreds of Mb/s restricted however to a few hundred meters. In most cases already, fiber is deployed closer and closer to the end user surely leading to a fiber-to-the-home (FTTH) solution replacing copper.

Besides the increase of the overall throughput, as aforementioned, other 5G service and network demands (e.g., low latency, energy-efficiency, reduced Capital Expenditure (CapEx) and Operational Expenditure (OpEx), etc.) need to be addressed by the network operator. These requirements are handled from and end-to-end perspective covering several network segments and multiple technologies (i.e., mobile, Wi-Fi, packet and optical switching, etc.). As a consequence, this end-to-end vision significantly challenges network operators, which aim at rolling out targeted 5G networks in a cost-efficient manner to maintain their competitiveness.

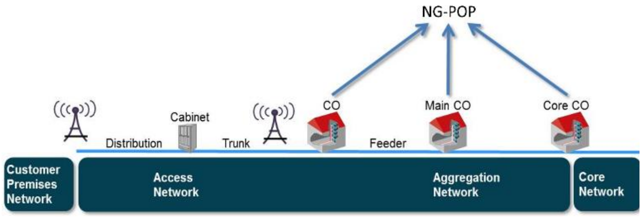


Figure 2. Reference locations for Fixed and Mobile Network Integration NG-POP (CO: Central Office)

Bearing the above aim into mind, an appealing approach gaining momentum to deploy cost-efficient 5G network is based on integrating and merging traditional independent network infrastructures for fixed and mobile traffic services into a common network and having a common set of control functions. This is referred to as FMC and currently is envisioned within the 5G networks roadmap [7].

We have previously shown in [8], that a FMC architecture should target solutions for cost-efficient FMC from a twofold perspective: structural and functional convergence. The former focuses on sharing and unifying equipment/technologies (at both access and aggregation network segments) to transport seamlessly both fixed and mobile traffic (e.g., via a WDM-PON infrastructure). The latter refers to a common set of control functions (e.g., unified control and management, authentication authorization and accounting (AAA), etc.) to handle any access service type. Both objectives can be achieved by deploying the network architectures based on an NG-POP. NG-POP is defined as a network location featuring a number of control and data plane FMC-driven capabilities, e.g., unified IP layer gateway (Universal Access Gateway - UAG), BBU hostel (for C-RAN applications), caching server for content delivery networks, unified authentication, etc. When NG-POPs are distributed in a large number of locations, close to the user, they can also host access node functions such as OLTs or BBU pools for C-RAN applications.

Two NG-POP scenarios are foreseen, highlighted in Figure 2: i) a distributed approach, NG-POPs deployed in a large number of locations, between access and aggregation networks (i.e., Central Office – CO – or main CO – on a higher aggregation level than a regular CO however still not connected directly to the network core); ii) a centralized deployment where NG-POPs are placed in a small number of locations, e.g., between the aggregation and core networks.

Both implementations leverage the benefits of current networking trends: centralized SDN control, and instantiation of Virtualized Network Functions (VNF) in commodity servers (applying the Network Function Virtualization - NFV

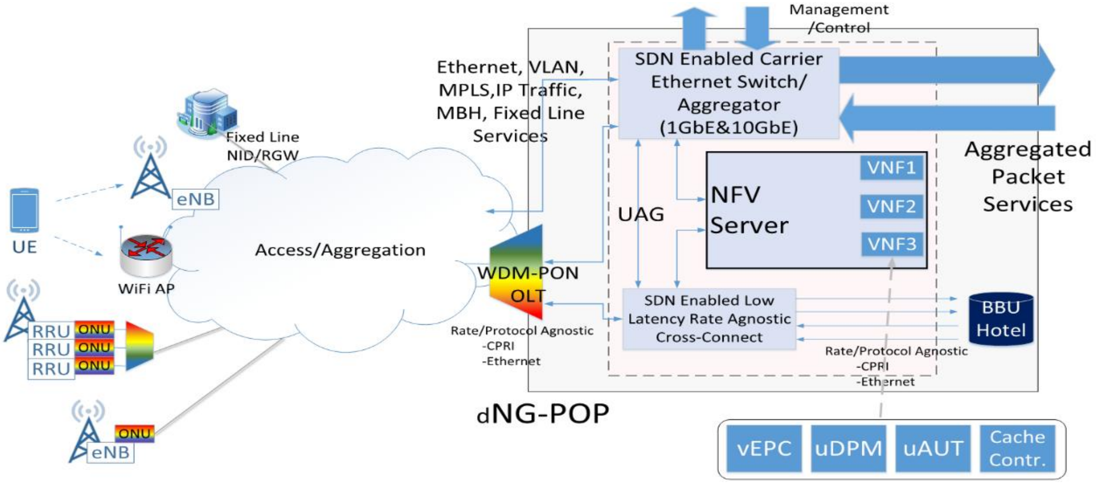


Figure 3. Fixed Mobile Convergence system architecture with a shared Access/Aggregation network converging in a NG-POP. (UE: user equipment; UAG: Universal Access Gateway; vEPC: Virtual Evolved Packet Core; uAUT: Universal Authentication; uDPM: Universal Data Path Management)

concept). In this work, we will focus on the demonstration of a dNG-POP deployment.

A. FMC Fronhaul Network

Structural convergence in the access and aggregation segment requires not only more capacity, but also extensive reach and potential transparency [9]. To this end, the wavelength division multiplexing passive optical network (WDM-PON) is adopted to handle fixed access, Wi-Fi traffic, and mobile fronthaul, as shown in Figure 3. The WDM-PON technology is able to cope with the high capacity demand of expected 5G fixed and mobile advanced services, and also guarantee a smooth evolution of the legacy access networks. In our demonstration, two different types of WDM-PON [10] are explored for different use cases, namely, a Wavelength-Selective (WS) WDM-PON and a Wavelength-Routed (WR) WDM-PON. The WS-WDM-PON is feasible to be upgraded from the legacy power splitter based optical distribution network, by using both tunable transmitter and receiving filters in the Optical Network Unit (ONU). Alternatively, the WR-WDM-PON adopts a novel full C-band tunable laser at the ONU, and a cyclic WDM multiplexer/de-multiplexer at the remote node to route a single wavelength to the corresponding ONU. Such a WDM-PON solution is especially suited to the aforementioned requirements of a converged infrastructure with regard to the bandwidth × 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.

B. Distributed NG-POP Architecture: Main Features

A feasible implementation of the dNG-POP architecture targeting FMC objectives is depicted in Figure 3. The main components (building blocks) are highlighting along with the access network infrastructure used to connect transparently various client access technologies to the dNG-POP entity. The main physical components, upon which the dNG-POP is built are:

- An NFV server
- A low-latency cross-connect
- A provider Ethernet switch/aggregator

The role of the NFV server focuses on providing support for the functional convergence. That is, the aforementioned VNFs are hosted onto an off-the-shelf server running a customized cloud environment. Breaking the static one-to-one BBU-RRH (Remote Radio Head) implemented by BBU hoteling is realized through the low latency cross-connect. Such a cross-connect complies with the rigorous latency and jitter timing requirements of the Common Public Radio Interface (CPRI) [11] between the RRH and the BBU agreed on by major system vendors. Aggregating the various user connections from a number of access devices onto higher line rate links is done by the provider Ethernet switch/aggregator. In addition, it is also responsible for identifying the various access channel types and isolating them into VLANs.

The functional role of the dNG-POP can be concentrated in the scope of a UAG seeking to provide control over all user sessions by taking advantage of resources available within each access network. In our implementation, the NFV server represents the unique point in the network where data flows of any user coming in from any type of network can be accessed by the control plane.

Moreover, the need to have a centralized, intelligent network entity that can dynamically allocate and reconfigure data paths converging inside the UAG has led to the adoption of an SDN approach. The control plane functionality (network element configuration) of the Ethernet, the NFV server

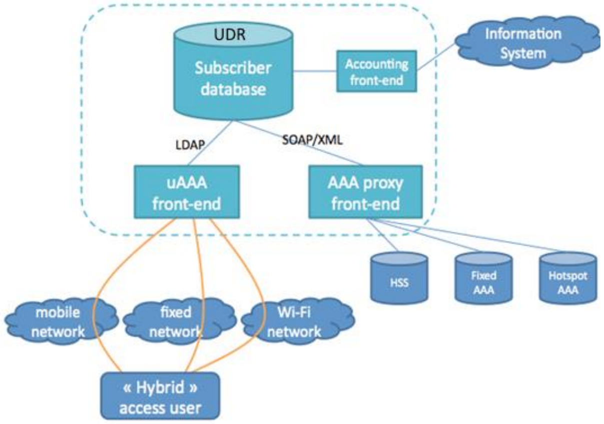


Figure 4. uAUT architecture (AAA: Authentication Authorization Accounting; HSS: Home Subscriber Server; UDR: User Data Repository)

internal network and the cross-connect switches is handled by an SDN controller (relying on the OpenDayLight implementation) via OpenFlow [12] and NETCONF [13] interfaces, respectively.

The devised dNG-POP architecture is targeting a pool of use cases, which are executed to validate a number of different network functionalities running on the NFV server such as the uAUT, uDPM, vEPC (virtual Evolved Packet Core) and vCache. The functional convergence covers both control and data plane functionalities and are discussed in the following sections.

1) Universal Subscriber and User AUThentication (uAUT)

Resource access control is one of the most important functions in a network regardless of the access technology. Indeed, there are specific authentication techniques for each network type. In a standard scenario with multiple access network types, an operator needs to assign credentials for users in each network and solve the authentication and the accounting in each of them independently. This is not efficient since separated and isolated mechanisms and databases need to be maintained by the network operator, which increases the complexity of the whole system.

The proposed Universal Authentication (uAUT) system is a basic function of the UAG that offers support to all additional control plane functions of the NG-POP. Its main task is to provide authentication authorization and accounting to users associated with all access networks serviced by the NG-POP. Its usage is mainly restricted to the initial phase of a service setup (e.g., provisioning policies at the network attachment) and accounting of the service delivery for billing and auditing purposes. uAUT serves as a unique contact point within the UAG for all subscriber data and authentication related functions, regardless of the access type employed.

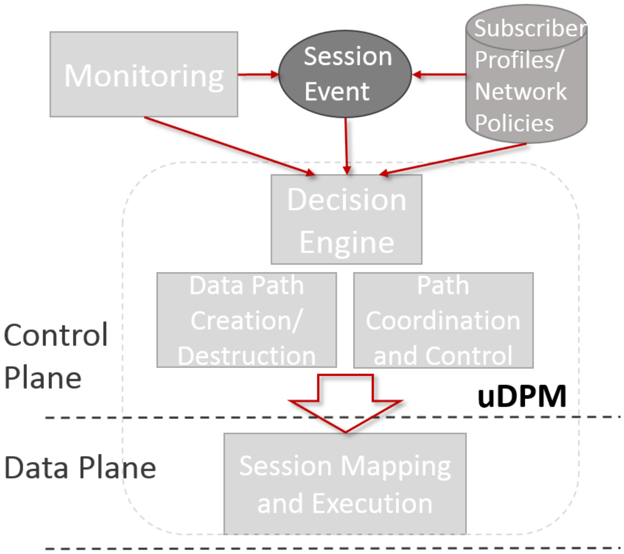


Figure 5. Universal Data Path Management (uDPM) functional blocks

The proposed uAUT architecture, maintaining legacy compatibility, is presented in Figure 4. The architecture is based on the User Data Convergence concept [14] and supports a layered architecture, separating the user data storage from the application logic. The view is extended by storing the user data in a unique User Data Repository (UDR), which provides a unified view for subscriber management to the information system (billing, accounting, statistics etc.). Dedicated entities handling application logic, named front-ends (FE) represent the links between fixed/mobile network services and the user database. Examples of network services that need to access user data include: mobile Home Subscriber Server (HSS), Wi-Fi hotspot AAA, broadband AAA, Policy Control and Relay function etc.

The UDR hosted by the uAUT server allows the service provider to identify all user connecting to any access type. By mapping to the correct profile, users can receive access to the converged services such as unified accounting, seamless authentication to application platforms (e.g., IPTV, VoD) and Over-The-Top (OTT) partners.

From the user point of view, the uAUT functional block provides a common subscriber authentication platform allowing the UE to login from both Wi-Fi and mobile networks. This is accomplished by using the same credentials stored in the SIM card. In the experimental demonstration, a vEPC instance running on the NFV server stores the authentication key in the EPC Home Subscriber Server – HSS function. The so-called hybrid access is achieved by accessing the mobile credentials through the common AAA proxy front-end. Further in-depth technical details on the proposed hybrid access architecture have already been presented in [15] and demonstration results are described in Section IV.

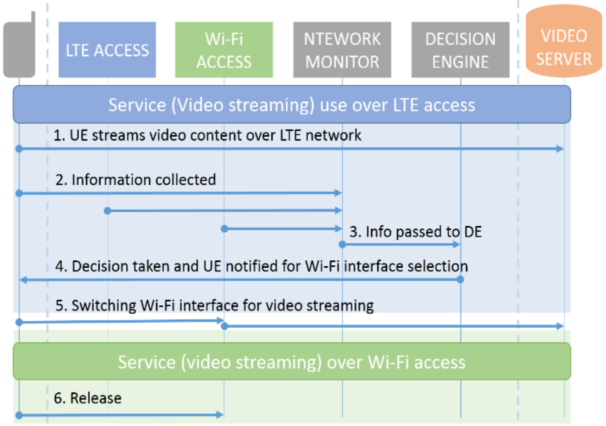


Figure 6. Decision Engine Operation workflow example

2) Universal Data Path Management (uDPM)

High proliferation of mobile broadband communications targeting 5G networks is expected. An important objective of FMC, which addresses this concern is mobile traffic offloading and handover. Implications like metro and core offload are also foreseen. Allowing users to roam between fixed/mobile/Wi-Fi networks and transport traffic via several types of interface requires a converged subscriber and session management as well as an advanced interface selection and route control. This set of functional blocks fulfil the scope of a Universal Data Path Management (uDPM). The uDPM is the main entity of the data path control functions performed within the UAG responsible for providing the UE session continuity.

From a FMC user's perspective, which is connected to various access points, numerous data paths can be used concurrently for increased Quality of Experience (QoE) or as backup for seamless handover. Multipath TCP (MPTCP) is a TCP extension [16] making use of end-to-end path diversity and maintaining backward compatibility. Protocol operation establishes several different TCP subflows (e.g., remote/local IP and port) for concurrent data traffic managed by a main MPTCP connection (between two end points). In our scenario, the use of MPTCP enabled UEs and content servers mitigates connection interruptions at network access switch over.

Moreover, the uDPM architecture consists of several interconnected and dedicated functions as shown in Figure 5. These functions control and handle session mappings of each individual UE to multiple data paths. A monitoring function that collects user and network state information can create a session event relative to a UEs activity (e.g., application launch request, interface change request, data forwarding process etc.) and trigger the uDPM functional block. Session event notifications include signal degradation detected by the UE or network, discovery of a new access point, applying a network policy or a subscriber profile, etc.

A Decision Engine (DE), being in part under the operator's control, uses an algorithm to check network operator policies and subscriber's profile rules. The algorithm relies on multi-criteria decision making required by processing multiple rule categories. The output of the DE can involve creating/destroying data paths (data path creation/destruction block) or seamless network handover in terms of session continuity (path coordination and control).

When a session is based on multiple paths, there is a coordination requirement of those data paths within the uDPM architecture and is conducted by the Path Coordination and Control element. This element ensures session continuity where data traffic is transferred correctly and effectively over a number of established paths.

Session mapping execution, as part of the data plane, applies session mapping decisions taken by the DE by relying on the control of both "path creation/destruction" and "path coordination and control". Session packets are forwarded or filtered on the data path and subflows are merged in MPTCP connections.

The DE algorithm can take into account different sources of information for its internal computations, like: network related information (Wi-Fi APs and mobile BS location, traffic load, energy consumption etc.), subscriber information (profiles or QoS classes) or content information (cached content). A workflow exemplifying the Decision Engine mode of operation is displayed in Figure 6. In the first step, a UE requests the stream of an internet video over an LTE network. The network monitor function (polling UE, LTE and Wi-Fi interface and network status) feeds the decision engine algorithm. Evaluating the input information according to its preconfigured targets (e.g., cost and bandwidth optimization), the DE decides to switch the streaming session from LTE (lower bandwidth and higher cost) to Wi-Fi (higher bandwidth and lower cost). This is done by notifying the UE to switch the active connection from its mobile data to its Wi-Fi interface. Finally, the UE streams the video content over Wi-Fi. Demonstration results for FMC relevant use cases are detailed in Section IV.

3) Content Distribution System

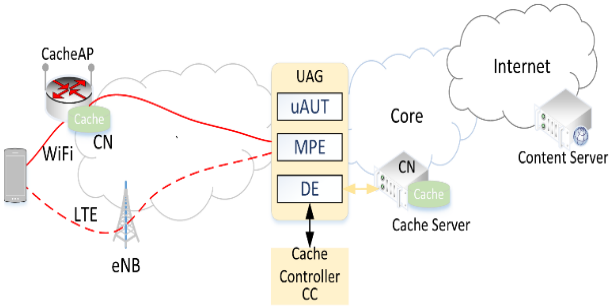


Figure 7. Converged content delivery system

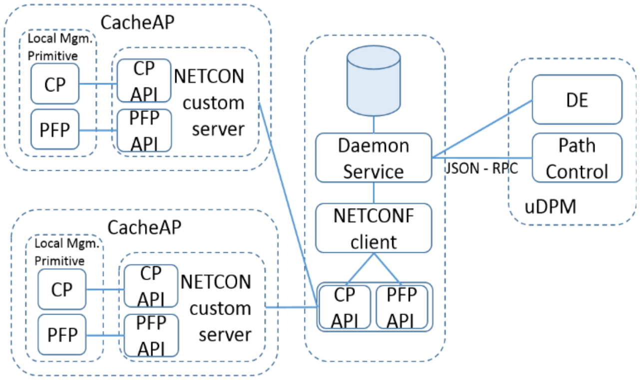


Figure 8. Caching/Prefetching system architecture [21] (pp. 64);

Content distribution techniques aim at reducing the redundant traffic in the network and improving quality of delivered services. A converged Content Delivery Network (CDN), in the context of FMC, can achieve this goal with better reliability, scalability and performance.

Caching efficiency is directly proportional to the user density on a network segment. The less population, the less useful caching is. In this regard, research studies have shown that in fiber access networks (i.e., with 30.000 clients) as well as in xDSL infrastructures, more than 30% of the traffic can be reduced due to the fact that almost half of the requests are cacheable [17] and [18]. The situation is somewhat different in the case of a mobile networks. According to the studies made in [19], caching at the base station (i.e., inside the evolved Node B - eNB) or at home gateway does not bring improvements. However, implementing a content delivery solution in a converged network, the advantages can be multiplied with a collaborative caching algorithm. Measurements performed in [20] support the cooperation between telecom and CDN providers. Such a collaboration leads to an additional traffic decrease of 12 to 20% if collaborative content caches located in NG-POPs are implemented.

A content delivery system is developed, shown in Figure 7, comprising of a Cache Node (CN) and a Cache Controller (CC). In this custom implementation, the CN, located in the home gateway in the form of a Cache Access Point (CacheAP is a wireless access point with caching functionality) but also in the NG-POP, executes the caching and prefetching. The virtual Cache Controller (vCache) installed in the NFV server (within the NG-POP) is responsible for managing the caching functionality and providing Caching-as-a-Service to content service providers.

The content delivery system relies on the uAUT functionality even though in the first authentication phase (when the user authenticates in the network) the uAUT does not influence the delivery service execution. However, extending the authentication from the network level to the service level requires interaction between uAUT and the content delivery system. The goal is to provide transparent service delivery using a unified authentication process.

The caching system architecture explained in detail in [21] (pp. 64) and used in this demonstration (Figure 8) is divided in three main components:

- A CN in the form of a CacheAP based on a custom NETCONF server implementation and a local management primitive that manages the local caching/prefetching actions.
- The CC composed of a daemon service that exchanges JSON based Remote Procedure Calls (RPCs) with the uDPM module; a NETCONF client for communicating and managing the CN; and a data base that stores: CN config, user requested content and content already cached in the CN.
- A uDPM module described in the previous section with a DE and Path Control functions.

There is a tight dependency between the content caching system and the uDPM as seen in Figure 8. When the number of hits on a specific content increases over a predefined limit (i.e., threshold), the content provider can trigger the caching procedure indicating the content (stream URL). The Decision Engine provides the needed resource information regarding UE location (client ID and IP, cacheAP IP) and network performance. This information is required by the input of the the cache controller to make an optimal caching decision in order to prefetch the contents in a CN (closer) to the UE.

Further details on the caching-system implementation can be found in [21] (pp. 63 – 66) and [22].

III. FMC DEMONSTRATION SETUP

The FMC setup (shown in Figure 9), used for an integrated demonstration, was deployed aiming at validating the feasibility and evaluating the efficiency of the proposed dNG-POP concept and its developed features.

TABLE I. Demonstration setup elements

UE	Laptops and smartphones located in the customer premises area;
Access endpoints	Heterogeneous endpoint access equipment containing LTE base stations (eNBs), Wi-Fi access points (APs), caching AP;
Fronhaul network	A WR and a WS WDM-PON systems enabling the shared access network infrastructure to carry transparently Wi-Fi, mobile (LTE), CPRI and fixed subscriber traffic; The transmission is made over 18 km span of Lannion city fiber ring showcasing the capability of real field deployment;
dNG-POP	dNG-POP (located at the main CO) implements the set of control and data plane functionalities needed by the common subscriber IP edge for all traffic types (i.e., fixed, mobile and Wi-Fi)

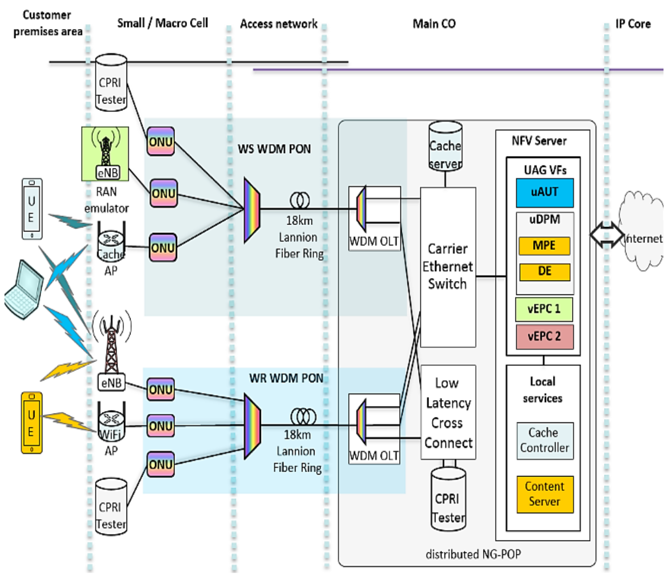


Figure 9. Demonstration setup overview

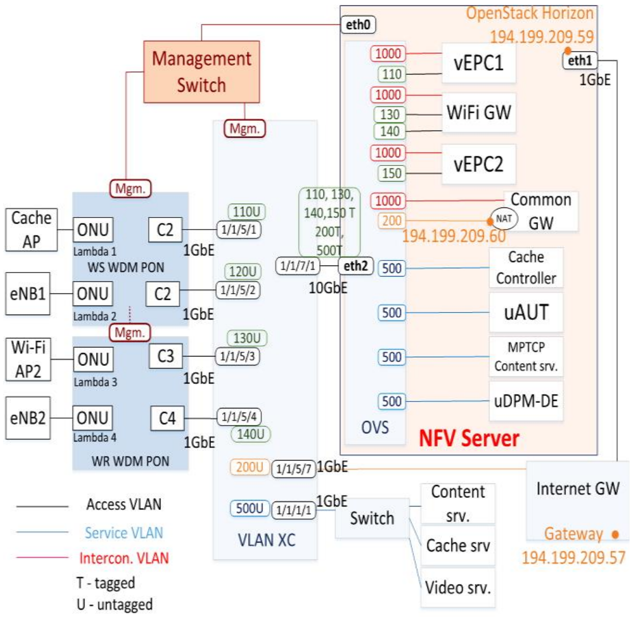


Figure 10. Network control plane overview with VLAN setup assignment

The main elements and technologies constituting our experimental setup are listed in TABLE I.

A. *Shared fronthaul network: WDM-PON*

Two WDM-PON systems (i.e., WR and WS) have been tested in parallel, in this demonstration, to evaluate the capabilities of shared fronhaul network solutions.

- WS-WDM-PON: the system comprises of an ONU with tunable transmiters and receivers providing CPRI transport capabilites for fronthaul requirements based on power spliters compatible with legacy FTTH setups. A WS-WDM-PON OLT, two 10 Gb/s tunable WS-WDM-PON ONUs, two CPRI interfaces and a CPRI tester were deployed and demonstrated in Lannion.
- WR-WDM-PON: the setup incorporates a low-cost ONU laser and the wavelentght locker functionality is implemented in the centralized OLT. A cyclic WDM multiplexer/de-multiplexer at the remote node then routes an individual wavelength to the corresponding ONU. As shown in Fig. 9, two 1 Gb/s tunable ONUs (i.e., one terminating an eNB and one for the WiFi AP) and one 10 Gb/s tunable ONU (i.e., used for CPRI link transmission tests), were deployed and demonstrated in the demo.

B. *dNG-POP setup*

At the core of the dNG-POP, the NFV server is built on an OpenStack cloud system. Features like automated configuration and on-demand resource deployment make OpenStack an ideal platform for our demonstration. The support for allocating various computing and networking resources for each targeted functionality, isolating them into individual projects (e.g., EPC, uAUT and uDPM) is perfectly tailored for our setup. In this scenario, we observe that multiple (and independent) instances of the same functionality could be instantiated within the NFV server as long as sufficient (computing) resources are available. This provides the dNG-POP with the capability of supporting multi-operator network function instantiation. This means that different operators may have their own network functions deployed within the same physical host (NFV server) but without having visibility of other operator's network functions. To show this, two instances of the mobile core (i.e., vEPC1 and vEPC2 in Figure 9) were deployed as VNFs onto the NFV server.

The network control plane overview with VLAN assignment in Figure 10 shows the seamless synchronization achieved between the OpenStack cloud environment and the hardware infrastructure. In this sense, the UAG's Carrier Ethernet switch (ADVA FSP 150EG-X) acts as a VLAN cross-connect, isolating individual connection types into separate VLANs with unique IDs. In our setup, the access channels are numbered from VLAN 110 through 160. More exactly, VLANs 110 and 150 are used for identifying the LTE S1 interface control and data traffic backhauled from the two eNBs over the WDM-PON to the corresponding vEPCs. Multiple wireless APs destined for individual test cases are mapped with VLANs 120 through 140, and the cacheAP is on VLAN 160.

The stand-alone local services (e.g., video, content, caching servers) and testers are grouped into a common service VLAN

TABLE II. WDM-PON systems performance. [21] (pp.88 – 90)

WDM-PON	Latency	BER
WR	130 ns	10^{-12}
WS	91,59 ns	$2.3\cdot10^{-15}$

500. The interconnection channel supporting network function chaining is handled in VLAN 1000. On this VLAN, installed on the NFV server, a Common Gateway handles the network address translation (NAT) for all VNFs providing them with Internet access.

Maintaining a Layer 2 network setup continuity from the physical infrastructure inside the NFV server was accomplished by configuring OpenStack to have access to the provider network through its SDN enabled Open Virtual Switches – OVS. A 10 GbE optical line card was set up to connect to the Carrier Ethernet switch and the NFV server to effectively handle the user data plane traffic for all targeted test cases. Even though in our demonstration we used a manual configuration of VLANs, in a real live deployment an automated SDN controller assignment is expected.

IV. EXPERIMENTAL VALIDATION

The demonstration of the proposed and implemented capabilities of universal authentication, user mobility and content caching solution is carried out by individual test cases, which are executed over the setup detailed in the previous section.

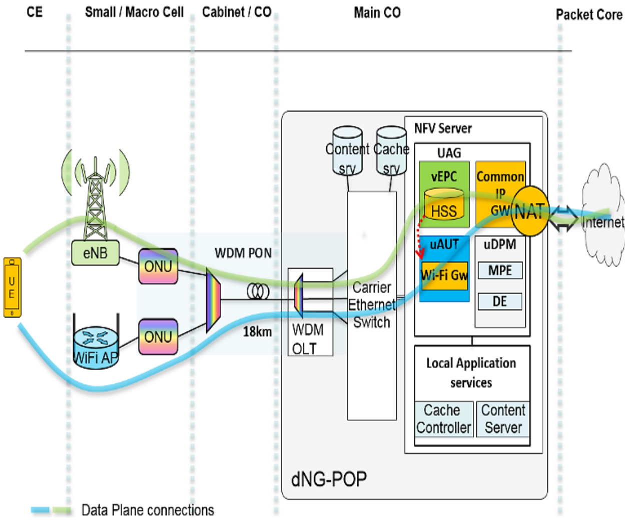
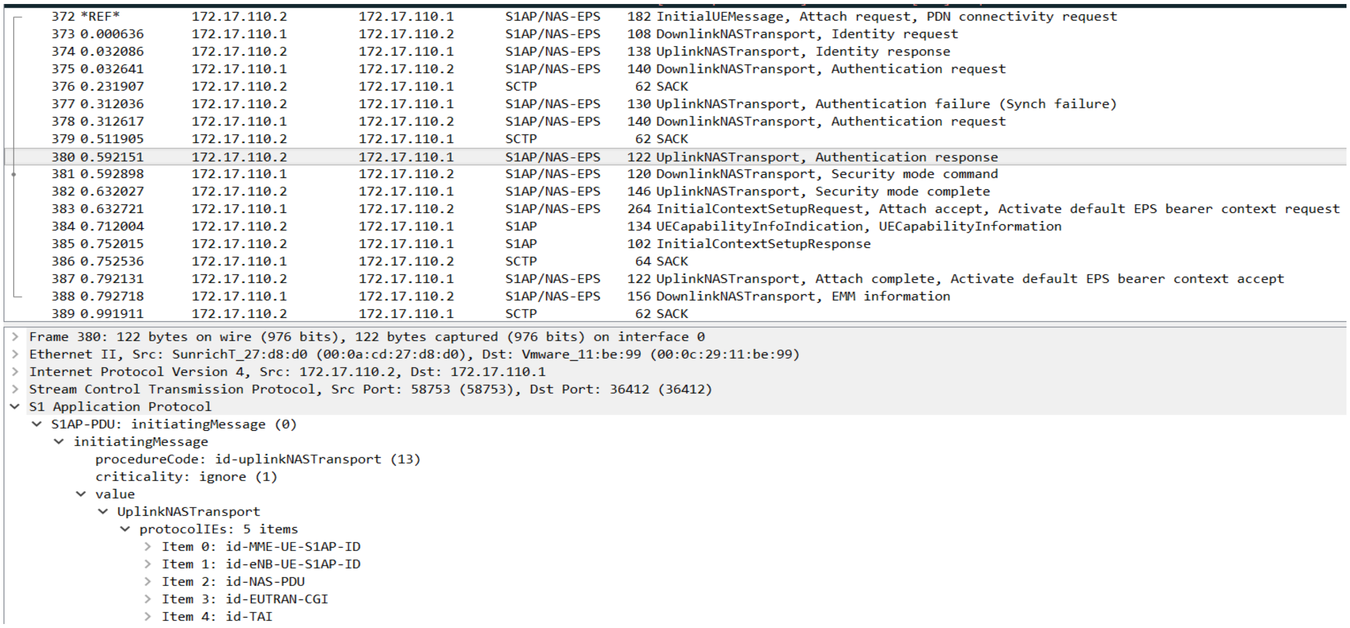


Figure 11. Universal Authentication (uAUT) demonstration overview

A. *Fronthaul network evaluation*

Tests carried out on the experimental WR-WDM-PON system, supporting the functional demonstration, show compliance with the CPRI standard even at the highest line rates (9.83 Gb/s). In the demonstration report [21], we have shown that the maximum jitter specifications on the receiver and the transmitter side are fulfilled. Measurements performed also showed that the system induced latency is as low as 130 ns equivalent to a signal propagation over 26m of



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372 *REF*      172.17.110.2   172.17.110.1   S1AP/NAS-EPS  182 InitialUEMessage, Attach request, PDN connectivity request
373 0.000636   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  108 DownlinkNASTransport, Identity request
374 0.032086   172.17.110.2   172.17.110.1   S1AP/NAS-EPS  138 UplinkNASTransport, Identity response
375 0.032641   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  140 DownlinkNASTransport, Authentication request
376 0.231907   172.17.110.2   172.17.110.1   SCTP           62 SACK
377 0.312036   172.17.110.2   172.17.110.1   S1AP/NAS-EPS  130 UplinkNASTransport, Authentication failure (Synch failure)
378 0.312617   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  140 DownlinkNASTransport, Authentication request
379 0.511905   172.17.110.2   172.17.110.1   SCTP           62 SACK
380 0.592151   172.17.110.2   172.17.110.1   S1AP/NAS-EPS  122 UplinkNASTransport, Authentication response
381 0.592898   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  120 DownlinkNASTransport, Security mode command
382 0.632027   172.17.110.2   172.17.110.1   S1AP/NAS-EPS  146 UplinkNASTransport, Security mode complete
383 0.632721   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  264 InitialContextSetupRequest, Attach accept, Activate default EPS bearer context request
384 0.712004   172.17.110.2   172.17.110.1   S1AP          134 UECapabilityInfoIndication, UECapabilityInformation
385 0.752015   172.17.110.2   172.17.110.1   S1AP          102 InitialContextSetupResponse
386 0.752536   172.17.110.1   172.17.110.2   SCTP           64 SACK
387 0.792131   172.17.110.2   172.17.110.1   S1AP/NAS-EPS  122 UplinkNASTransport, Attach complete, Activate default EPS bearer context accept
388 0.792718   172.17.110.1   172.17.110.2   S1AP/NAS-EPS  156 DownlinkNASTransport, EMM information
389 0.991911   172.17.110.2   172.17.110.1   SCTP           62 SACK
```

```
> Frame 380: 122 bytes on wire (976 bits), 122 bytes captured (976 bits) on interface 0
> Ethernet II, Src: SunrichT_27:d8:d0 (00:0a:cd:27:d8:d0), Dst: Vmware_11:be:99 (00:0c:29:11:be:99)
> Internet Protocol Version 4, Src: 172.17.110.2, Dst: 172.17.110.1
> Stream Control Transmission Protocol, Src Port: 58753 (58753), Dst Port: 36412 (36412)
v S1 Application Protocol
  v S1AP-PDU: initiatingMessage (0)
    v initiatingMessage
        procedureCode: id-uplinkNASTransport (13)
        criticality: ignore (1)
      v value
        v UplinkNASTransport
          v protocolIEs: 5 items
            > Item 0: id-MME-UE-S1AP-ID
            > Item 1: id-eNB-UE-S1AP-ID
            > Item 2: id-NAS-PDU
            > Item 3: id-EUTRAN-CGI
            > Item 4: id-TAI
```

Figure 12. LTE attach procedure (Wireshark capture trace) containing the authentication phase (LTE S1 interface: used for communication between eNB and EPC)

optical fiber. The prototype implementing the centralized wavelength control provided a stable throughput throughout the demonstration. The tuning speed of the POP system was measured, on average, at around 180 s. For a larger scale deployment, the tuning time should be improved

Evaluation of the WS-WDM-PON system using an Integris Mobile Access Network Performance Tester showed a consistent latency of 91.59 ns and a BER of $2.3 \cdot 10^{-15}$ measured for 2.45 Gb/s data rate. System attributes of the WDM-PON systems used in the demo are listed in TABLE II.

B. *Universal Authentication (uAUT)*

Two access points are set up to provide simultaneous network connectivity to UEs through wireless and LTE access network types (Figure 11). Both the Wi-Fi AP and the eNB are connected through the same access network infrastructure (i.e., WDM-PON) to the UAG’s NFV server where the vEPC Wi-Fi Gw and uAUT are instantiated as individual VNFs.

A UE is used to test the authentication by presenting a SIM card with the common set of credentials. Using the SIM, the UE can transparently and seamlessly authenticate in both access technologies (i.e., mobile and Wi-Fi).

The first step in the functional use case is the validation and evaluation of user authentication in the LTE network. In this scenario, the user request is sent from the eNB to the vEPC over the S1 interface. The entire LTE user-attach procedure (Figure 12) was measured (on average) at 650 ms, including the user authentication phase, which took around 279 ms. Measurements were performed with the use of Wireshark, a network protocol analyzer.

In the second step, the user performs a switchover to the Wi-Fi network. Upon the users’ authentication request, the Wi-Fi AP is configured to send the connection request to the uAUT server residing on the NFV server. The request is processed by the uAUT, which compares the credentials received from the user with the credentials stored in the HSS element of the vEPC VNF. Retrieving the credentials from the HSS was accomplished by implementing an extensible authentication protocol framework for UMTS (EAP-AKA). Measurements showed that authentication phase took 10ms over Wi-Fi.

C. *User mobility demonstration*

The second scenario executed reports the offloading and handover process especially between mobile and wireless networks. This allows a UE to efficiently use the network resources. For the user mobility demonstration, two UEs, the LTE eNB and two Wi-Fi APs (TP-Link TL-WR1043ND), the uDPM VNF have been employed as well as a MPTCP Content Server positioned in the Local Services area of the dNG-POP (Figure 13).

Using a custom API, the uDPM-DE provides information to the UE regarding the access method selection. In this context, a set of feasible scenarios is executed outlining automatic and even seamless handover process. The lack of service interruption during the handover was ensured by the use of MP-TCP function in the NFV Server.

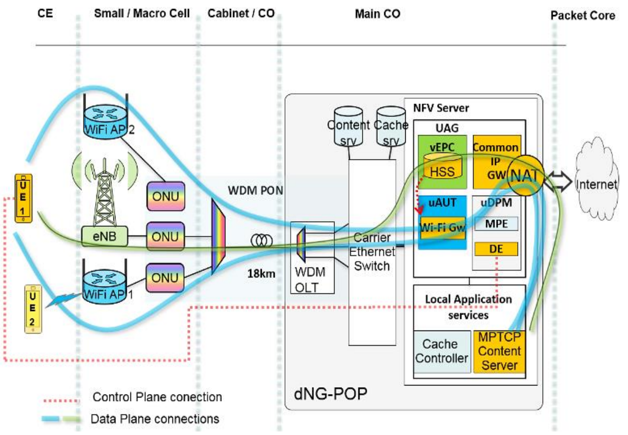


Figure 13. User Mobility demonstration overview

Three use cases have been conducted in order to demonstrate and evaluate the efficiency of the uDPM functionality:

- a plain Wi-Fi to Wi-Fi handover corresponding to a use case in which a UE will be transferred to another AP when the current wireless link is saturated;
- a Wi-Fi to LTE handover corresponding to a use case where a UEs’ ongoing connection will be switched from the current saturated AP over to LTE;
- A Wi-Fi_1 to LTE to Wi-Fi_2 handover. This use case is an improvement on the first test where there is a gap in the connection switch, which is now filled by a transient LTE connection.

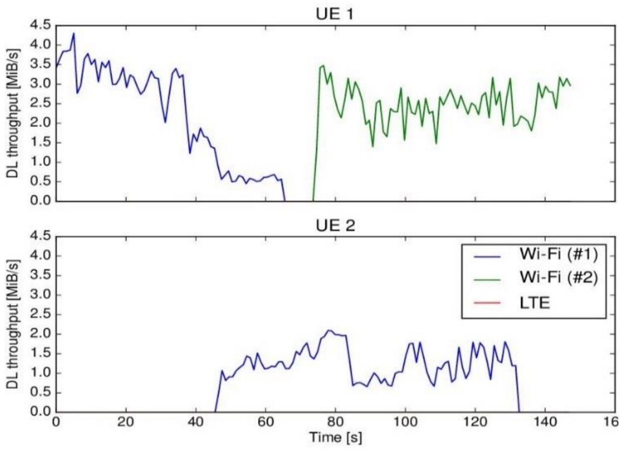


Figure 14. Wi-Fi to Wi-Fi handover – connection gap visible

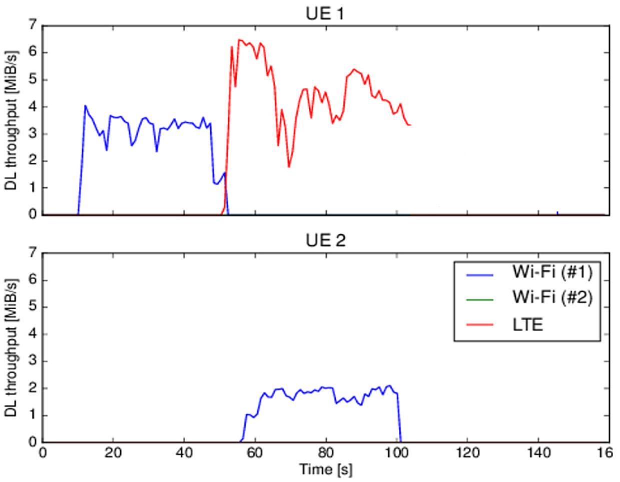


Figure 15. Wi-Fi to LTE handover – no connection interruption

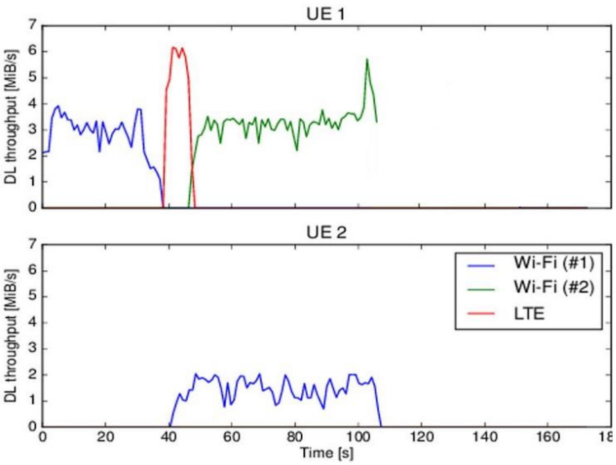


Figure 16. Wi-Fi to LTE to Wi-Fi handover – no connection interruption

Firstly, a Wi-Fi roaming from one AP to another was tested. A connection was established between the UE1 and the content server by requesting a video stream over Wi-Fi_1. Soon after, a second UE (UE2) connected to the same AP starts a download and saturates the link.

The DE that is monitoring the network state, triggers the handover of UE1 to the available Wi-Fi2 AP in order to offload the former wireless link. As observed in Figure 14, there is a connection gap of about 10s during the handover, which is the result of using a single wireless interface on the client device.

The second test case shows a Wi-Fi to LTE handover triggered by the DE in similar circumstances as the previous one. When the Wi-Fi link is saturated, the DE triggers the switchover to the available LTE interface. In Figure 15 we can observe the seamless transition between the two networks. The connection is uninterrupted because the UE can be connected simultaneously to both networks.

The last test case provides a solution to bridge the connection gap between inter Wi-Fi handover by transiently switching from Wi-Fi_1 to LTE then over to Wi-Fi_2. We notice in Figure 16 that employing this method, video streaming was uninterrupted. We also observe a small overlapping traffic pattern in the case of LTE to Wi-Fi_2 handover due to packets duplication over the two MPTCP subflows. However, data is correctly reassembled by the master MPTCP session.

D. Content Delivery Service (content caching)

For the caching demonstration, an SDN-based Cache Controller VNF (vCache) is instantiated on the NFV server. It decides where (e.g, at either access network device – CacheAP- or the dNG-POP) to cache or prefetch the content. The CC and uDPM-DE are coordinated to instruct any UE to connect to a different CacheAP as long as the QoS is degraded due to congestion in the CacheAP node or if a better connection is available.

For the test case two UEs and two CacheAPs (mobile AP with caching and routing capabilities) have been employed. Two test cases have been performed, one highlighting the caching ability and one focusing on the prefetching execution.

In the first caching test case (Figure 17), A UE streams a video from the internet (i.e., YouTube source) with a bandwidth requirement higher than the network bandwidth allocated. Traffic Control (TC), a linux network utility used for traffic shaping, was used to set video bandwidth limitations. The QoS of the video is visibly degraded (long startup delay, frequent interruptions). After the request, the content is cached automatically in the CacheAP. When the second user (UE2) requests the same content, the video is delivered from the CacheAP and the observed quality is greatly improved (no more buffering timeout periods).

The second prefetching test (Figure 18) make use of two CacheAPs and one UE. The Cache Controller holds the responsibility of making an optimal prefetching decision based on user profile information (user ID, URL of video played) as well as network status (network address, current AP, destination AP) received from the DE. Once the CC has

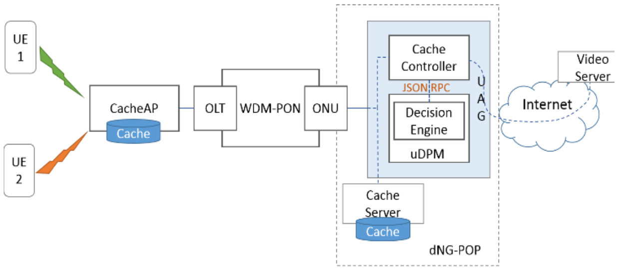


Figure 17. First caching test case demonstration: UE 2 requests the same video content as UE 1 after it was cached in the CacheAP;

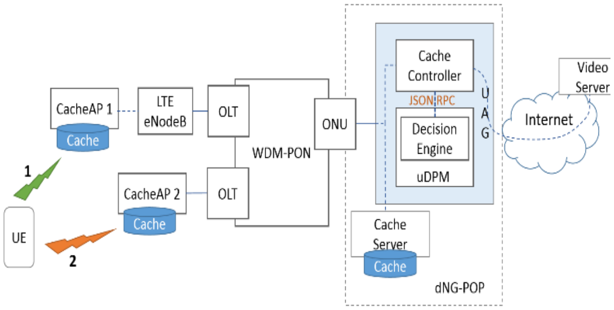


Figure 18. Second caching test case demonstration: CC prefetches the video content on second CacheAP when UE switches to another network.

computed the caching location (CacheAp address) the decision is sent back to the DE, which will handle the interface selection mechanism for the end user. The trigger of the prefetching is a UE handover from the first CacheAP (LTE network) to the second one (fixed line). This situation can correspond to multiple scenarios (e.g., current network saturation, a user arriving home and switching to the local network etc.). The switchover commanded by the DE is also passed to the CC along with source and destination AP. The CC then retrieves, from the user profile, the video URL and sends it along with the fetch command to the destination AP. By the time the UE has switched interfaces, the video has already started being cached in the second AP.

E. Client channel bandwidth testing

In order to consolidate the demonstration of the fully integrated setup and evaluate its impact on the end user, we tested the TCP bandwidth from each network access type (Wi-Fi, LTE, fixed). As seen in Figure 19, TCP bandwidth and latency were measured between a client and a common IP core gateway on the NFV server regarded as the reference point. Iperf, an IP network measurement tool and ping were used to measure the performance on each channel consecutively. Relevant settings like Maximum Transmission Unit (MTU) with a default value of 1500 MTU and test intervals of 10 s were configured. A test report capture of an LTE network is present in Figure 20.

The results obtained for testing each network access technology are compared in TABLE III. We mention that the tests were executed individually and independent of other measurements. As expected, best performance is experienced over a fixed line, followed by Wi-Fi and LTE.

TABLE III. Client channel network performance test results

Network access connect.	Throughput (Mb/s)		Latency - round trip (ms)		
	Uplink	Down link	Min.	Avg.	Max.
LTE 1	43.5	45.4	16.94	18.01	21.80
LTE 2	26.4	55.1	40.79	53.92	68.76
Wi-Fi	63.5	72.1	1.72	2.382	3.19
Fixed line	676	781	0	0	1

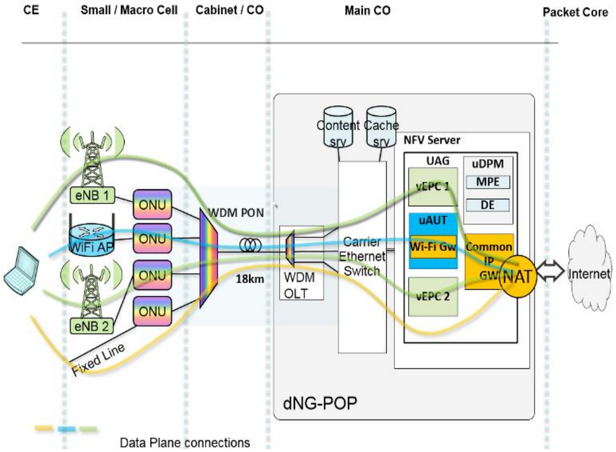
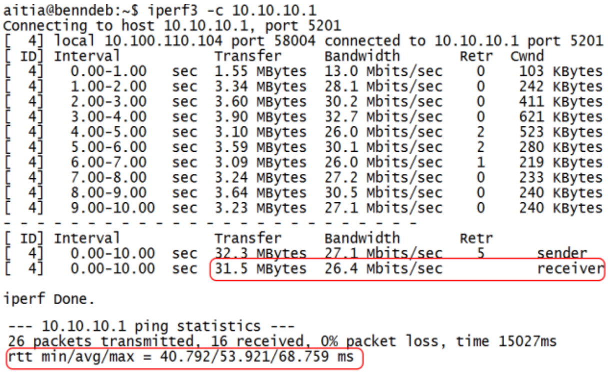


Figure 19. Overview of client channel bandwidth test

We identify the NFV server as the most relevant throughput limitation point of the setup (especially for connections over the fixed line). The limitations are the result of several internal network virtualization layers of the OpenStack Cloud stock distribution. Nonetheless, bandwidth optimizations can be achieved with cloud distribution tuning or hardware acceleration mechanisms.

V. CONCLUSION

The dNG-POP architecture, based on the characteristics of distributed data centers, is devised to leverage the advantages of SDN and NFV concepts. In particular, the UAG supports dedicated control and user plane VNFs related to access networks/technologies (e.g., vEPC) and common VNFs applicable to any traffic flow regardless of the access networks (e.g., uDPM and uAUT). Even though a series of benefits result from adopting the presented architecture like


```
aitia@benndeb:~$ iperf3 -c 10.10.10.1
Connecting to host 10.10.10.1, port 5201
[  4] local 10.100.110.104 port 58004 connected to 10.10.10.1 port 5201
[ ID] Interval           Transfer     Bandwidth       Retr  Cwnd
[  4]   0.00-1.00   sec  1.55 MBytes  13.0 Mbits/sec    0    103 KBytes
[  4]   1.00-2.00   sec  3.34 MBytes  28.1 Mbits/sec    0    242 KBytes
[  4]   2.00-3.00   sec  3.60 MBytes  30.2 Mbits/sec    0    411 KBytes
[  4]   3.00-4.00   sec  3.90 MBytes  32.7 Mbits/sec    0    621 KBytes
[  4]   4.00-5.00   sec  3.10 MBytes  26.0 Mbits/sec    2    523 KBytes
[  4]   5.00-6.00   sec  3.59 MBytes  30.1 Mbits/sec    2    280 KBytes
[  4]   6.00-7.00   sec  3.09 MBytes  26.0 Mbits/sec    1    219 KBytes
[  4]   7.00-8.00   sec  3.24 MBytes  27.2 Mbits/sec    0    233 KBytes
[  4]   8.00-9.00   sec  3.64 MBytes  30.5 Mbits/sec    0    240 KBytes
[  4]   9.00-10.00  sec  3.23 MBytes  27.1 Mbits/sec    0    240 KBytes
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth       Retr
[  4]   0.00-10.00  sec  32.3 MBytes  27.1 Mbits/sec    5             sender
[  4]   0.00-10.00  sec  31.5 MBytes  26.4 Mbits/sec                  receiver

iperf Done.

 --- 10.10.10.1 ping statistics ---
 26 packets transmitted, 16 received, 0% packet loss, time 15027ms
 rtt min/avg/max = 40.792/53.921/68.759 ms
```

Figure 20. LTE client channel bandwidth test report example (Iperf and ping tools); (rtt – round trip time).

reduced footprint, rent, cooling and power consumption, etc. further work is required to automate network resource allocation by integrating the setup in an SDN framework.

FMC is seen as one of the key strategies for deploying future 5G networks aiming at satisfying, in a cost-efficient way, the stringent requirements imposed by advanced services. Within the FMC concept, the deployment of a common and unified functional entity, referred to as UAG, allows the seamless termination at the IP layer of fixed, mobile and Wi-Fi user traffic flows. By adopting such principles, the network architecture and operation can be simplified which leads to enhanced OpEx and CapEx, critical for next generation networks.

Our implementation of the UAG concept, with all the required VNFs, has been successfully validated through the experiments presented, targeting both the control and data planes. Fixed, mobile and Wi-Fi access users were able to establish their sessions demonstrating the FMC capability of the UAG. To this end, a common authentication process (i.e., uAUT) for any service type was provided. Data path management and content caching capabilities were validated through various use cases that have proven an increase in QoS offered and in user mobility. Finally, the UAG provides an attractive platform for exploiting the network sharing concept between multiple network operators

ACKNOWLEDGMENT

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REFERENCES

[1] B. Andrus, V. Mehmeri, A. Autenrieth, J. J. V. Olmos and I. T. Monroy, “Evaluation of SDN enabled data center networks based on high radix topologies,” Proc. of the 12th International Conference on Systems and Networks Communications (ICSNC), 2017.

[2] I. Narayanan, A. Kansal and A. Sivasubramaniam, “Right-sizing geo-distributed data centers for availability and latency,” 37th International Conference on Distributed Computing Systems (ICDCS), 2017.

[3] China Mobile Research Institute, “C-RAN: the road towards green RAN,” white paper, 2011.

[4] S. Pachnicke et al., “The frontiers of optical access networks,” International Conference on Optical Network Design and Modeling (ONDM), Pisa, Italy, May 2015.

[5] EU funded ICT project COMBO. Accessed on 01.06.2018. [Online]. Available at: http://www.ict-combo.eu/

[6] A. Gupta and R. K. Jha, “A survey of 5G network: architecture and emerging technologies,” IEEE Access, vol. 3, pp. 1206-1232, August 2015.

[7] ICT-COMBO alliance white paper “A universal access gateway for fixed and mobile integration,” April 2016.

[8] S. Pachnicke, B. Andrus and A. Autenrieth, “Impact of fixed-mobile convergence,” International Conference on Optical Network Design and Modeling (ONDM), Cartagena, Spain, May 2015.

[9] S. Gosselin et al., “Fixed and mobile convergence: which role for optical networks?,” Journal of Optical Communications and Networking (JOCN), vol. **7**, no. 11, 2015.

[10] Z. Tayq et al., “Fronthaul performance demonstration in a WDM-PON-based convergent network,” European Conference on Networks and Communications (EuCNC), Athens, Greece, June 2016.

[11] Common Public Radio Interface (CPRI) - interface specification (V.6.0), August 2013.

[12] N. McKeown et al., “OpenFlow: enabling innovation in campus networks,” ACM SIGCOMM: Computer Communication, vol. 38, iss. 2, pp. 69-74, 2008.

[13] M. Bjorklund et al., “Network configuration protocol (NETCONF),” RFC 6241, June 2011. Accessed on 01.06.2018. [Online]. Available at: https://tools.ietf.org/html/rfc6241

[14] 3GPP Technical Specification 23.335, User Data Convergence (UDC), stage 2, release 9, June 2010.

[15] T. Mamouni et al., ”Universal AAA for hybrid accesses,” European Conference on Networks and Communications (EuCNC), Paris, 2015.

[16] A. Ford et al., “TCP extensions for multipath operation with multiple addresses,” RFC 6824, Jan. 2013.

[17] E. Nygren et al., “The Akamai network: a platform for high-performance internet applications,” SIGOPS Operating Systems Review vol. 44, no. 3, pp. 2-19, August 2010. (DOI: 10.1145/1842733.1842736).

[18] C. Imbrenda et al., “Analyzing cacheability in the access network with HACkSAw,” International Conference on Information-Centric Networking (ICN), Paris, France September 2014. (DOI: 10.1145/2660129.2660135).

[19] S. Elayoubi and J. Roberts, “Performance and cost effectiveness of caching in mobile access networks,” International Conference on Information-Centric Networking (ICN), San Francisco, USA, September 2015. (DOI: 10.1145/2810156.2810168).

[20] G. Nam and K. Soo Park, “Analyzing the effectiveness of content delivery network interconnection of 3G cellular traffic,” International Conference on Future Internet Technologies (CFI), Tokyo, Japan, June 2014. (DOI: 10.1145/2619287.2619297).

[21] EU ICT-COMBO project deliverable 6.3, ”Report describing results of operator testing, capturing lessons learned and recommendations,” 27 July 2016. Accessed on 01.06.2018. [Online]. Available at: http://www.ict-combo.eu/data/uploads/deliverables/combo_d6.3_wp6_2016-07-22_adva_v1.0.pdf

[22] Z. Li et al., “ICN Based Shared Caching in Future Converged Fixed and Mobile Network,” International Conference on High Performance Switching and Routing (HPSR), 2015.