SDN-Based Architecture and Procedures for 5G Networks

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***Abstract*—This article presents a *plastic* architecture for the advanced 5G infrastructure based on the latest advances of SDN, NFV and edge computing. The novel approach consists of three levels of control, i.e. Device, Edge and Orchestration Controllers, fully decupled from the user plane and backwards compatible to current and future 3GPP releases. The proposed control layers implement a unified security, connection, mobility and routing management for 5G networks. The new concept of SDN-based connectivity between virtualized network functions (applications) enables multidimensional carrier grade communication paths without the utilization of tunneling protocols. Our architectural solution dramatically reduces the end-to-end latency for mission critical type of traffic, yet guarantying a large degree of freedom, dependability and reliability, which are the most important and stringent requirements of 5G.**

Keywords—5G; SDN; NFV; Edge Computing.

I. INTRODUCTION

The design of 5G network architecture, functions, protocols and corresponding procedures is driven by the expected packet data traffic increase together with requirements placed to mobile networks and devices by next generation services. A comprehensive list of scenarios and use cases is still being compiled, including high resolution video streaming, mobile broadcasting, tactile internet, machine type communication (MTC), vehicle to vehicle communication (V2V) etc. All these services can be translated into requirements e.g. in terms of system throughput, end to end latency, massive number of devices to address, reliability, robustness etc. No matter how challenging each requirement might be, the point to stress here is that 5G network shall be able to efficiently enable *diverse services*, connecting *diverse devices*, and exploiting *diverse access networks*. For example, 5G network shall enable the downstream of high resolution 3D videos on wireless tablets, requiring 30-50 Mb/s for a single video transmission (before channel coding), as well as connecting hundreds of thousands of static sensors to a remote server, transmitting few kilobytes of data per day or, again, supporting mission critical machine communications in in-coverage and out-of-coverage scenarios. Hence, *heterogeneity* of requirements will be the keyword. It is worth noting 3GPP and ETSI are already planning functional improvements to 4G, to cope with the diversity of use cases (see, e.g., [1] and [2], where ad-hoc solutions for M2M communications and multicast broadcast multimedia services were analyzed). On the other hand, emerging Software Defined Networking (SDN) and Network Functions Virtualization (NFV) paradigms provide new means and methods to instantiate and operate networks/services, reducing costs and boosting performance. The development of such technologies will substantially affect the networks architecture evolution, the same way as IP shaped the transition from 2G to 3G and 4G. Based on past experience, it is quite straight forward to predict a smooth transition from 4G to 5G through an intermediate 4.5G release, with enhancements in LTE/SAE architectures, probably heading to OPEX/CAPEX reduction, while exploiting SDN and NFV capabilities to implement network nodes (e.g. eNBs, MME, S/P-GW, HSS, etc.) in a virtualized edge cloud environment. OpenEPC is an example of implementation of 3GPP compliant Evolved Packet Core (EPC), where upper layer network functions (network applications) run on Open Flow controllers [3]. The transition to 5G will be then achieved once a single framework will make it possible to efficiently provide the expected end user experience and meet the target performance: 1000x higher wireless area capacity, 10Gb/s link speed for a true immersive experience, hyper connectivity to 100 billion of things and, especially 5x lower E2E latency than 4G (1ms is the target for tactile Internet and force control for mobile cognitive objects) and 90% energy saving per provided service [4], [5].

Several attempts to define SDN-based 5G architectures are currently available in the literature, yet these contributions are far too high level (generic), lacking of focus, and key details on the novel enabling technologies are not provided. In [6], the authors presented a generic software defined wireless network architecture, where common Core Network (CN) functions and a number of Radio Access Networks (RANs) are orchestrated by a single Mobile Network SDN Controller. The proposed architecture, compared to 4G (LTE), enhances the RANs with programmability and transport network layer is realized by programmable switches (L2) and routers (L3). In that work, both an “evolutionary” and a “clean slate” approaches were proposed. The first approach allows incremental enhancements of existing deployed networks. In this case, the SDN controller implements the required standardized interfaces. In the latter approach, control plane functions are directly programmed into the SDN controller. On the same line, in [7], authors discussed a 5G mobile network architecture spanning over two layers: a Radio Network, providing only a minimum set of L2 and L1 functionalities, and a Network Cloud dedicated to all upper layer functionalities. This work, mostly focused on radio access related issues, proposes a lean protocol stack by consolidating the redundant functionalities of Access Stratum (AS) and Non

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Access Stratum (NAS) signaling. Numerous procedures for mobility management (MM), session management (SM) and security management can be simplified or potentially removed. On the user plane (UP), dynamic network deployment and ability to scale are achieved by merging RAN L2 and gateway functionalities in the core network. Another notable proposal can be found in [8]. This paper describes an all-SDN network architecture featuring hierarchical control capability. More specifically, the paper focuses on a 5G control plane aiming at providing Connectivity Management as a Service (CMaaS), with a "unified" approach to mobility, handoff and routing. According to the authors, "Unified" relates to the merger of RAN and CN functions, which are implemented as applications running on one or more hierarchical controllers.

In this paper, we harvest some sound concepts from prior art and we describe in detail the architecture blueprint proposed in [9]. To the best of our knowledge, that article presents the very first attempt to develop a "plastic" 5G architecture, where control functions are neither bound to any specific logical element, nor to any pre-determined physical infrastructure, yet fully compatible with 3GPP communication systems. In this work, our goal is to detail the logical architecture, functions, interfaces and procedures, where both control and data planes adapt to functional and performance requirements of services.

This article is organized as follows. Section II presents the proposed plastic architecture for 5G. In Section III, we describe relevant signaling procedures for communication management. Section IV discusses the benefits of the proposed solution, especially in terms of end-to-end latency with respect to 4G systems. Conclusions are drawn in Section V.

II. 5G HIGH LEVEL ARCHITECTURE

A. *Three Levels Control Architecture*

The same design principles which drove the evolution from 3G to 4G networks have been inspiring the 5G architecture this paper proposes: network flattening and separation between control plane and data plane. Additionally, in the proposed architecture, 5G network functions implementation can be either "centralized" or "distributed at the edge", depending on functional and non functional performance requirements of the supported services. To this end, traditional control and data plane logical network elements have been decomposed into sets of applications or modules, which can be dynamically instantiated in the cloud infrastructure according to network operation or service requirements. The architecture relies on a unified control plane, made by three *logical* controllers: the Device Controller, the Edge Controllers and the Orchestration Controller [9]. The 5G unified control plane, sketched in Fig. 1, includes both AS/NAS control plane as well as management plane functions.

B. *The Device Controller*

The *Device Controller* (DC) is located in the device and it is responsible for the physical layer connectivity to the 5G network. In particular, in a 5G scenario where devices are expected to have a plurality of radio and wired access capabilities, the DC handles Access Stratum functions such as access selection and network selection.

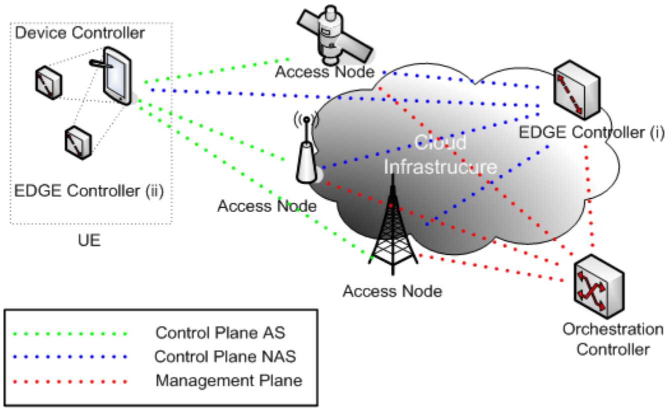


Fig. 1. 5G Unified Control Plane

C. *The EDGE Controllers (i) and (ii)*

The *EDGE Controller* (EC) implements the 5G network control plane, including Network Access Control, Packet Routing and Transfer, Mobility and Connection Management, Security, Radio Resource Management functions. In other words, referring to legacy 4G networks, the EC inherits the AS/NAS functions performed by eNodeB and MME [10]. The implementation of the EC is distributed (diluted) over the cloud infrastructure via a set of interconnected Control Applications (C-Apps). Each C-App is dedicated to a subset of network control functions. Key C-Apps are Connection (Session) Management (CM), Mobility Management (MM), Security (Sec), Authorization & Authentication (AA), Admission Control (AC), Flow Management (FM) and Radio Access (RA) applications. To allow full separation between control and data plane even on the radio link, the RA App is further split into RA^D and RA^C Apps. For an attached UE, RA^C App manages the Control (C) plane while, possibly instantiated on a different Point of Presence (PoP), the RA^D App manages the Data (D) plane.

Since one of the key use cases for 5G is mission critical machine communication [11], which has to be supported also in the out-of-coverage scenario (i.e. when one or all the connected machines cannot directly communicate with the network) mobile devices might be required to support some AS/NAS functions. For this reason, the proposed architecture distinguishes between Edge Controller (i) and Edge Controller (ii), the first being composed by C-Apps instantiated in the edge cloud infrastructures [12], the second temporarily or permanently implemented on a mobile device.

D. *The Orchestration Controller*

The *Orchestration Controller* (OC) coordinates the utilization of cloud resources (computational, memory, storage, and networking). The OC inherits some of the 4G network management functions [10], as it is responsible for the allocation and maintenance of resources required to instantiate both 5G control and data planes.

The OC is composed by the *Resource Orchestration* (RO) module and *Topology Management* (TM) module. The RO module defines how to allocate physical resources to instantiate EC Control Applications. In other words, the RO determines the embedding solution for the virtual control and data planes to be instantiated within the cloud infrastructures. The TM module directly manages the physical resources. The TM is composed by a TM-A (Topology Management – Apps) modules and a TM-L (Topology Management – Links) modules, which handle virtual machines and virtual links respectively, required to instantiate and connect EC C-Apps.

The RO is a centralized module with whole cloud infrastructure visibility, while TM-L and TM-A are distributed modules interacting respectively with SDN-based Control Platforms and Cloud Management Platforms.

Alike the EC C-Apps, the OC modules are virtual network functions embedded in data centers. They allow flexibility and adaptability of the Control Plane, which can be dynamically reconfigured according to changing conditions of network engineering requirements defined by the network administrator and/or service performance requirements. Reliability of OC modules and management plane links are important topics that are left for further studies (FFS).

E. Resource Orchestrator and Edge Controller functions

To complete the definition of the proposed 5G Unified Control plane, it is necessary to associate network AS/NAS and management functions to the correspondent OC modules and EC C-Apps. Table I indicates which network functions each C-App and Module is performing. The table includes the key set of 4G AS/NAS and management functions [10], extended with some 5G peculiar functions.

F. 5G Data Plane

In our architecture we followed a clean-slate design approach for 5G data plane, enabled by SDN technology.

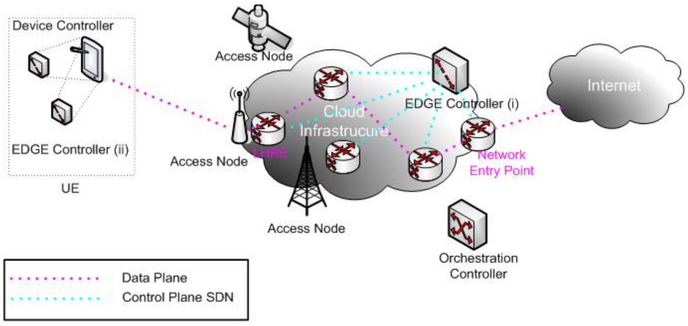


Fig. 2. 5G Data Plane

Neither dedicated data plane network elements (like 4G SGW and PGW for instance), nor unique logical elements for the whole attached device population (like gateways or mobility anchor points) will be defined. Simply, when a device performs network attachment, an address shall be allocated and a Last Hop Routing Element (LHRE) shall be associated to it, as shown in Fig. 2. The LHRE chains the radio access point (AP) of the device to the backhaul infrastructure. Additionally, when attaching to the network, a forwarding path for the device shall be established by the FM-App.

The forwarding path shall allow packets generated by the device (or directed to) to be forwarded to a Network Entry Point (or to the device LHRE).

AS/NAS Function Class	Function	Hosting Element	C-App/Module
Network Access Control	Network/Access Network Selection	Device Controller	UE RA App
	Authentication and Authorization	Edge Controller (i)	AA App
	Admission Control	Edge Controller (i)	AC App
	Policy and Charging	Edge Controller (i)	Charging App
Packet Routing and Transfer	Packet Routing	Edge Controller (i)	FM App
Mobility Management	User Reachability	Edge Controller (i)	MM App
	Tracking Area Management	Edge Controller (i)	MM App
	Paging	Edge Controller (i)	MM App
	Handover	Edge Controller (i)	MM App
Security	AS Security Control	Edge Controller (i) and (ii)	Sec App
Radio Resource and Resource Management	Radio Connection management	Edge Controller (i) and (ii)	CM App, RA App
	Forwarding Path management	Edge Controller (i) and (ii)	CM App
Network Management	Control Plane overload control	Orchestration Controller	RO Mod, TM Mod
	Data Plane overload control	Orchestration Controller	TM Mod
	5G C-plane instantiation	Orchestration Controller	RO Mod
	5G C-plane maintenance	Orchestration Controller	TM Mod
	Load balancer	Orchestration Controller	TM Mod
Addressing Functions	DNS address resolution	Edge Controller (i)	CM App
	Address Allocation	Edge Controller (i)	CM App
Proximity Service	Proximity Discovery	Edge Controller (i) and (ii)	Location, Proximity App
	Direct Communication	Edge Controller (i) and (ii)	Location, Proximity App
Relaying	Relaying	Edge Controller (i) and (ii)	CM App, MM App
Mutual Authentication	Mutual Authentication	Edge Controller (ii) and Device Controller	MA App

TABLE I. AS/NAS AND MANAGEMENT FUNCTIONS MAPPING ON 5G UNIFIED CONTROL PLANE

The Network Entry Point (NEP) identifies the boundary beyond which the physical infrastructure is not under the OC and EC control. Note different attached devices may have different NEPs. Establishing a forwarding path requires the FM-App to select available links to embed a virtual link between LHRE and NEP, and SDN controllers to set forwarding tables on switches belonging to the SDN based cloud infrastructure.

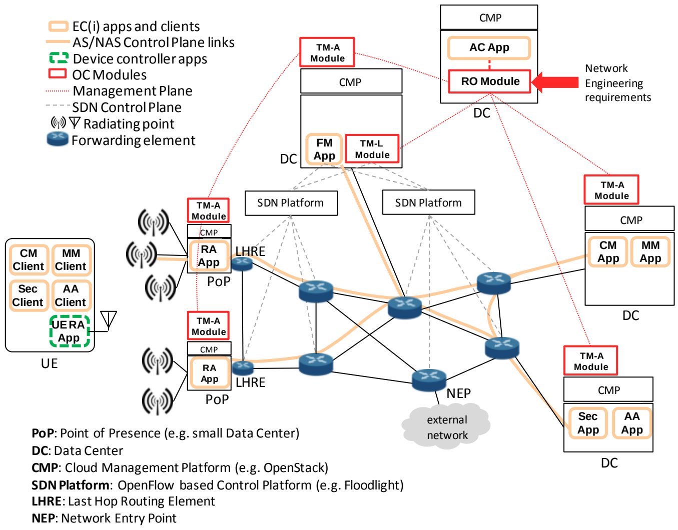
The wireless connection between the radio access point and the device shall be managed by the RA App of EC(i). At service request, the required QoS shall be enforced over both the wireless connection and the forwarding path.

In the case of device to device (D2D) communication, only D2D wireless connection shall be present. The connection in that case shall be managed by the RA App, located either in the EC(i) or in the EC(ii), in the in-coverage or out-of-coverage scenario respectively.

III. 5G HIGH LEVEL PROCEDURES

A. *Control Plane Instantiation*

In our architecture the RO Module manages the allocation of resources to the EC(i) C-Apps. The RO has abstract knowledge of the underlying infrastructure, mediated by TM modules that handle the virtualized substrate. In multi-domain or multi-technology environment, the RO may require resources from TM modules belonging to other networks via cloud-to-cloud APIs.



PoP: Point of Presence (e.g. small Data Center)
DC: Data Center
CMP: Cloud Management Platform (e.g. OpenStack)
SDN Platform: OpenFlow based Control Platform (e.g. Floodlight)
LHRE: Last Hop Routing Element
NEP: Network Entry Point

Fig. 3. 5G Unified Control Plane and SDN Control Plane

Each TM module handles provisioning and monitoring within a single domain and single technology. As shown in Fig. 3, the TM-A modules controls the cloud computing resources provisioned by Cloud Management Platforms (e.g. OpenStack, just to mention an open source CMP) and the TM-L module controls the virtual links maintained by SDN-based Control Platforms (e.g. Floodlight). The TM modules report resource state and availability to the RO Module, which runs algorithms to find embedding solutions for virtual infrastructure into networking and cloud resources [13].

The instantiation of the Control Plane consists of:

- Embedding the EC(i) apps while fulfilling network engineering requirements (e.g. network planning requirements, energy consumption constraints, operational cost constraints, geographical distribution of the devices, etc) and service performance requirements;
- Configuring virtual links with appropriate latency and bandwidth to interconnect EC(i) control applications.

The procedure for the initial instantiation of the Control Plane is described in Fig. 4. The TM Modules updates periodically the RO Module about availability and state of the substrate resources. In step 1, a network engineering requirement message triggers the embedding algorithm (step 2) in the RO Module. The implementation of the NE requirements may result in instantiating (or de-instantiating) C-Apps in the cloud infrastructure controlled by TM-A modules (steps 3.a-5.a) and new Control Plane links in the SDN-based infrastructure controlled by TM-L modules on top of SDN Platforms (steps 3.b-5.b).

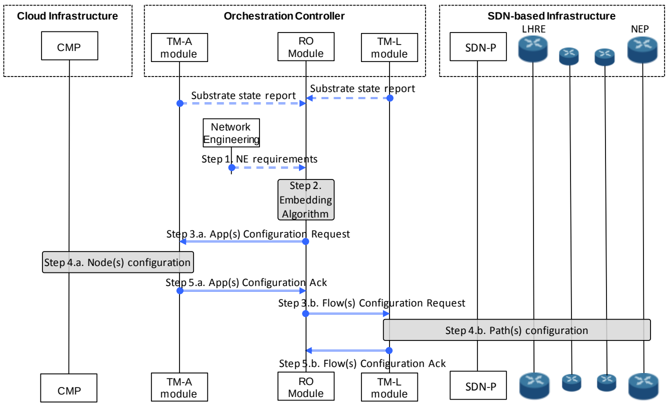


Fig. 4. Control Plane Instantiation

B. *Initial Attachment*

The 5G initial attach procedure is described in Fig. 5. This procedure is managed by the EC(i), assuming that a EC(ii) is not involved.

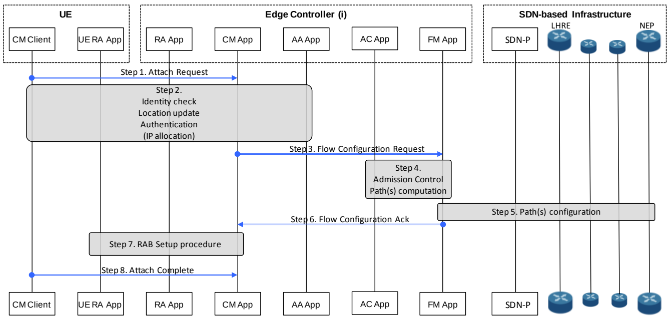


Fig. 5. Initial Attachment

In step 1, the Connectivity Management (CM) Client in the UE sends an Attach Request to the CM App in the EC(i). The CM client includes in the request the UE identity information as well as the reason of the attachment; for instance, to get assigned an IP address. The request triggers step 2 involving UE identity check, update of the UE location, authentication and, if requested, the allocation of an IP address. The implementation of these procedures may significantly affect the time elapsed to complete this phase.

At the completion of step 2, the CM App requests the FM App to define and implement the default rules to handle traffic directed to or generated by the UE. This Flow Configuration Request is handled by AC App and FM App in step 4.

Depending on the type of attachment, the FM App determines the high level rules for network configuration. For instance:

- Packets directed to the UE shall be routed to the LHRE (Last Hop Routing Element) connected to the access point that serves the UE;
- UE generated packets directed to an external device (not managed by FM App) shall be routed to FM App network entry points (NEPs);
- UE generated packets directed to an internal device shall be routed to destination.

The rules are checked by the Admission Control App, which determines how to realize the requested path based on the knowledge of physical infrastructure topology and utilization.

In step 5, the FM App deploys the rules in the SDN-based platform using the appropriate policy defined for the attachment type. For peculiar attachment types related to low latency services, a proactive deployment of the forwarding rules shall guarantee the required performance. If latency requirements are relaxed or undefined, the forwarding rules can be reactively dispatched by the SDN controller whenever an SDN switch needs to resolve the forwarding of the first packet of a data flow belonging to the UE.

The CM App, after receiving the acknowledgment to the flow configuration request (step 6), triggers the RAB (Radio Access Bearer) setup procedure (step 7). The UE CM client completes the procedure by sending the Attach complete message.

C. *Device triggered Service Request*

Figure 6 describes the procedure for a device triggered Service Request.

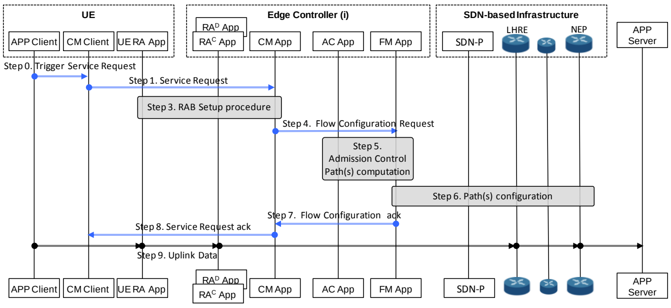


Fig. 6. Device triggered Service Request

Triggered by an application client, the CM client in the UE sends a Service Request to the CM App including the Identity information of the UE and, optionally, of the application. The CM App initiates the RAB establishment (step 3) and the flow configuration in the SDN-based infrastructure (steps 4-7).

The RAB may involve different RA Apps from the one that received the Service Request; for instance, Control Plane and Data Plane could be managed by different RA Apps. The step 3, 5 and 6 are similar to those introduced for the Initial Attach Procedure, with the sole difference that radio bearer and forwarding paths are related to a dedicated bearer, which QoS requirements may depend on the device capabilities, on the specific service instance or on the application requesting the service.

When the establishment of radio bearer and forwarding paths is completed, the CM app acknowledges the Service Request to the UE (step 8). Finally, in step 9, the application client can start sending data to the App server.

D. *Device Mobility Management*

The handover procedure in case of Mobility Anchor relocation (i.e. LHRE change) is depicted in Fig. 7. The device is initially camped on a Serving (S) cell controlled by the S-RA^C App with data connection to S-RA^D App. The Handover Preparation phase (step 1) is initiated by S-RA^C App when radio link quality measurements indicate a better service cell exists. During the preparation phase, the Target (T) cell and corresponding T-RA^D App and T-RA^C App are identified. The required resources are then reserved in the target cell. Then, the Execution Phase takes place (step 2). The S-RA^C commands the UE to camp on the cell controlled by the T-RA^C App. Radio connection is established to T-RA^C App for control plane and to T-RA^D App for data plane. The MM App updates information on UE location, the CM App selects the LHRE associated to T-RA^C and T-RA^D Apps (T-LHRE) and the FM App configures temporary UL data forwarding from T-LHRE to S-LHRE. The handover procedure is completed with the Forwarding Path Switching phase (step 3), where the CM and FM App trigger the reconfiguration of SDN-based cloud infrastructure to allow packets generated by the UE and forwarded to the T-LHRE to reach their destination, as well as to allow packets directed to the UE to be properly forwarded to the T-LHRE. The SDN-based cloud infrastructure is configured by the SDN-P (SDN platform controller) upon trigger by FM App.

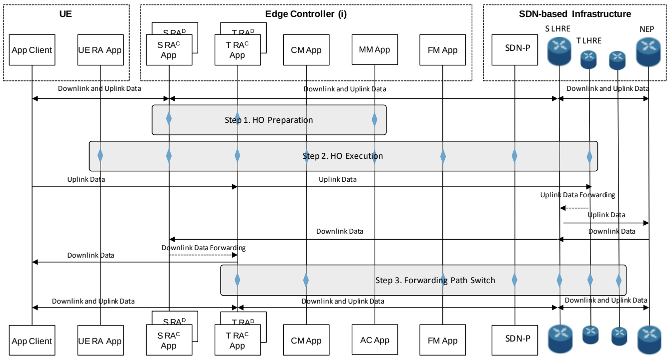


Fig. 7. Handover with Mobility Anchor Relocation

IV. BENEFITS OF THE PROPOSED ARCHITECTURE

Reconfigurability, the key feature of the *plastic* architecture proposed in this paper, shall allow 5G network operators to dynamically instantiate logical architectures, implementing network functions, services and corresponding states in the optimal location within the cloud infrastructure, according to network engineering requirements and target KPIs. This will lead to strong performance improvements, e.g. on latency, which is regarded as one of the key 5G KPIs to enable delay critical next generation services. In 4G networks (assuming ideal radio condition and system unloaded) the Initial Attach procedure takes around 310-350ms, and the most critical contribution to the latency is the processing delay to query HSS and PCRF, estimated to be around 200ms [14]. The proposed Initial Attachment procedure will significantly reduce this delay, for two main reasons: first, appropriate instantiation of CM and AA Apps will speed up the signaling procedure for authorization, authentication, policy and charging rules definition. Additionally, the implementation of front end AA Apps will allow defining local and smaller (and hence, faster to query) per-service subscriber databases. The target AA App to query will be determined by the CM App according to the Attachment Type info included in the Attach Request sent by the device. This will lead to an estimated delay reduction of up to 60%.

The proposed architecture *does not make use of tunneling protocols*, e.g. GTP in 3GPP. The GTP tunnel set up during the 4G default bearer establishment in the Attach procedure takes around 40ms. In the 5G Attach, this phase is replaced by the configuration of forwarding paths in the SDN-based network, which is expected to last around 20ms, leading to a further 50% latency reduction. This performance improvement is also valid for the Device Triggered Service Request, as well as Handover with Mobility Anchor Relocation procedure.

The latency for establishing the forwarding paths can be actually reduced to zero by pro-actively configuring the SDN-based infrastructure for devices performing mission critical services. The "always-on" concept already proposed for EPC, consisting of establishing EPC bearers and IP connectivity after the device is powered on, can be deployed as pre-configuration of forwarding tables instead of reserving bandwidth for the GTP tunnels.

In addition, for delay critical services, the U-plane latency can be reduced by implementing ad-hoc virtual link embedding algorithms in the FM modules to ensure the cloud infrastructure is optimally utilized while fulfilling service latency requirements.

V. CONCLUSIONS

In this paper, we proposed a novel *plastic architecture* for the advanced 5G network infrastructure by harvesting the latest advances of Software Defined Networking, Network Functions Virtualization and edge computing platforms.

The proposed architecture, functions and procedures have the potential to become the "de facto" solution for 5G, which is expected to be the "Nervous System" of the Digital Society and Digital Economy. In fact, the adoption of new service models enabled by 5G, such as "Full Immersive Experience", enriched by "Context Information", and "Anything as a Service" will truly contribute to an inclusive and sustainable economical growth and help cope with the grand challenges of our Society systemically.

Low latency and ultra-high reliability are the most stringent performance indicators that need be supported to realize this vision, and our solution appears to be technically feasible and business viable to achieve this goal.

Ultimately, we would like to state clearly that the views expressed herein are solely those of the authors and do not necessarily represent the ones of their affiliate.

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