Software Defined Networks and Network Function Virtualisation
Testbed within FIRE+

Virtual 5G Core Networks in SoftFIRE

Virtual 5G core networks offered to experimenters in the SoftFIRE federated testbed

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1 Introduction

3GPP [1] core network in LTE and its evolution towards 5G are driven by various vertical use-cases / businesses, which are likely to be supported by means of 5G network slices. Such network diversification, which is envisioned to support heterogeneous applications, creates multiple challenges for network operators and telecommunication equipment vendors.

The experience of the EU project SoftFIRE [2] that brings NFV and SDN capabilities to a completely virtualized and multi-site federated infrastructure spanning multiple countries in Europe is useful for the following reasons. First, by constructing a Federated Testbed and an Orchestrated Virtualization Infrastructure, SoftFIRE paves the way towards **concurrent and conflict free execution** of radically different network scenarios, which can mimic network slicing. Second, learning from its open calls [3], the project discovered and defined **sets of problems** to be dealt with during 5G network operation and offers **managed solutions** that are generic for NFV/SDN/5G environments. Third, providing the infrastructure for innovative experiments, SoftFIRE has identified and prototyped several **levels of programmability** that are useful for provisioning and managing 5G network slices.

1.1 5G challenges

Operator core networks are expected face pressure to handle the requirements of 5G applications. While most of the new requirements are related with 5G radio, the increased number of (lightweight) concurrent subscribers (the case of massive IoT), the need for reduced latency (the case of critical MTC), and the bandwidth demand (the case of broadband experience), are also affecting the core network components.

The core network has to perform over a wide spectrum of different use cases, ranging from those with a large number of subscribers which are essentially idle for a long time and send very few data items, to those with a high number of subscribers that use high priory services, like voice and video. Use case also range from those with IoT devices that are mostly static, to those with highly mobile subscribers that are using high bandwidth.

1.2 NFV-SDN opportunities: Benefits of the SoftFIRE approach

The opportunity for packet core networks to sustain the above challenges is to increase their level of programmability by means of NFV-SDN. Network Function Virtualization (NFV) [4][5] and Software Defined Networking (SDN) [6] are two technologies promising to change the way networks are controlled, programmed and managed. In addition to a shift in how networks are “controlled”, there are other impacts due to their adoption. The way in which networks will be managed is going to deeply change (realizing the goal of integration between control and management). Management tasks will be nearly undistinguishable from control or real time functions. In addition, the two technologies push for a radical shift in how control and management and service functions are realized introducing the programming dimension.

Programmability is an essential feature of 5G core, but if the security of interfaces, underlying mechanisms and systems is not guaranteed, then it becomes a risk rather than an opportunity, hence security solutions prototyped and analysed by SoftFIRE within its federated multi-site and multitenant environment might be also of interest.

As SoftFIRE project demonstrated [7] the required core network customization / deployment for a particular use case can be done in minutes instead of weeks as today. The SoftFIRE approach allows running multiple core networks in parallel, with each of the cores being optimized for the specific use case. Different cores can be even launched on demand if a new situation needs a different instance or kind of Evolved Packet Core (EPC). Moreover, the SoftFIRE orchestrator makes core network elasticity easy: each core can be scaled based on actual usage or demand.

In summary SoftFIRE software core network benefits are as follows: easy configurable software toolkit implementation, the means for wireless ready applications, fast and cost-effective prototyping, easy and reproducible automatic deployments, and scalability.

The rest of this white paper is structured as follows. Section 2 briefly introduces the SoftFIRE project and details its two core networks: (*i*) Fraunhofer FOKUS Open5Gcore [8][9], and (*ii*) 5G Innovation Centre (5GIC) [10] mobile core, in terms of their features, structure, virtualization and automation; together with the OpenBaton orchestrator adopted by the Project [11]. The section concludes by briefly presenting two sample experiments that used SoftFIRE's 5G core networks. Then, in Section 3, some supporting technologies that SoftFIRE has developed to run these 5G core networks are outlined. Finally, as concluding remarks, some known issues and some directions for future work are discussed in Section 4.

2 5G Core Networks in SoftFIRE

Project SoftFIRE offers virtual 5G core networks to its experimenters in its two component testbeds, namely Open5GCore at Fraunhofer FOKUS [12] and 5GIC testbed at University of Surrey [10]. Experimenters can interact with the virtual 5G core deployments through standard 3GPP core network interfaces. The two testbeds offer indoor and/or outdoors random access connectivity (RAN) connectivity on standard off-the-shelf LTE radios.

In this section of the white paper, these two 5G core network are introduced, by presenting their main features and capabilities.

2.1 Open5Gcore at Fraunhofer FOKUS

Open5GCore [8][9] is offered by Fraunhofer FOKUS. Its features and structure are as follows.

2.1.1. Open5GCore features

Open5GCore represents a complete reset of the packet core related activities addressing in a more pragmatic way the needs of 5G testbeds for FOKUS and for partner activities. Open5GCore Release 3 is based on a new accelerated software platform including:

- Fundamental 5G/4G core network components, enabling the interconnection with standard LTE eNBs, off-the-shelf smartphones, and upcoming 5G base stations and devices,
- NB-IoT extension of the packet core, addressing the massive IoT use case requirements,

- IMS support addressing the basic multimedia services for mobile broadband support use cases,
- Benchmarking support – providing means for quantitative evaluations based on synthetic workload generation and trace injection,
- WLAN support – integrating the functionality of trusted non-3GPP access networks,
- Elasticity – support for dynamic control plane deployments and workload steering,
- LTE/5G signalling – enabling the research of time sensitive radio communication at RLC level.

2.1.2. Open5GCore structure

The Fraunhofer FOKUS Open5GCore toolkit as shown in Figure 1, is a practical implementation of carrier-grade networks towards 5G environments. It mirrors, in a prototypical form, the pre-standard advancements on the core network, radio network integration, distributed management and virtualisation.

The Open5GCore aims at providing support and speeding-up research, facilitating know-how transfer from Fraunhofer FOKUS towards partners. It serves as a consistent basis for research projects with meaningful results, enabling fast and targeted innovation, hand-on fast implementation, realistic evaluation and demonstration of novel concepts and technology opportunities.

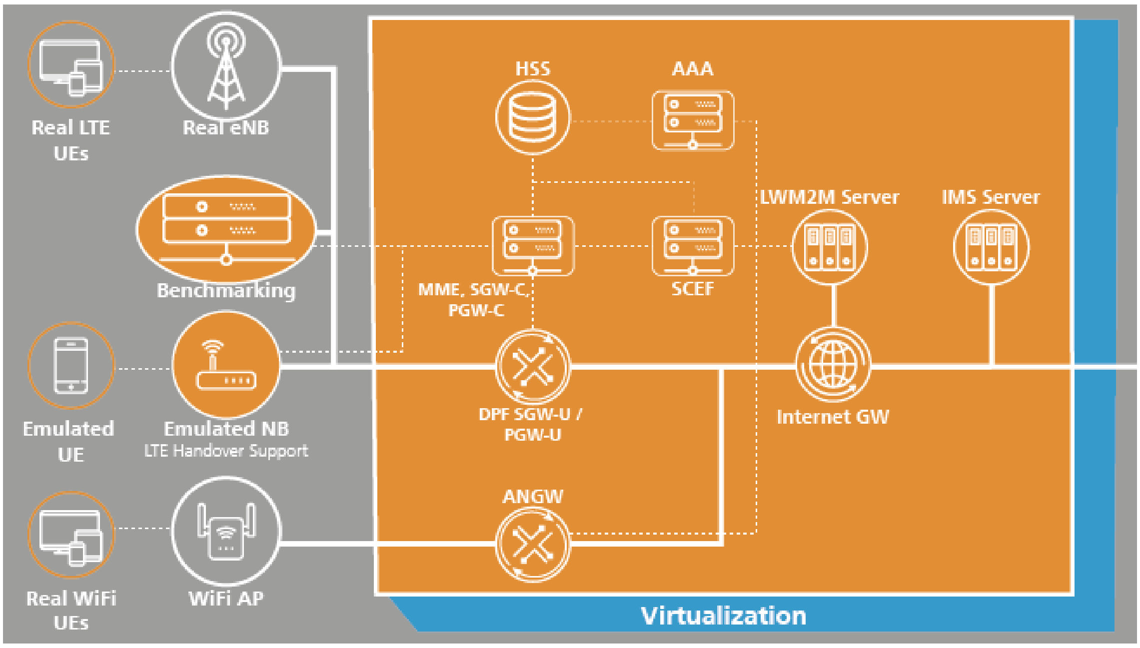

Figure 1. Open5GCore at Fraunhofer FOKUS.

2.1.3. Open5GCore implementation details

The Open5GCore toolkit [8][9] represents a software implementation of the 3GPP EPC Release 11 standard [13]. It is designed as a fully virtualized core network for the 5G environment. The main components are:

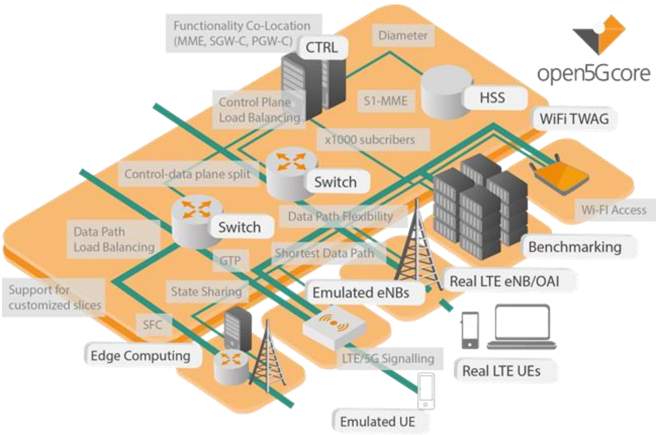

Figure 2. Open5GCore Release 3.

- **HSS** (Home Subscriber Server) is a subscriber repository that contains all the user subscription information. It provides support functions for mobility management, call and session setup, user authentication and access authorization.
- **MME** (Mobility Management Entity) is responsible of all the Control Plane functions related to subscriber and session management. It is also in charge of subscriber related radio control procedures. It also handles Inter Radio Access Technology (RAT) handovers.
- **SGW** (Serving Gateway) is the access gateway of the 3GPP network and the endpoint of the packet data interface towards E-UTRAN. It forwards the uplink data traffic from the RAN to the PGW and serves as anchor point for intra and inter RAT handovers (in case of handover between eNodeBs or between LTE and other 3GPP accesses).
- **PGW** (Packet Data Network Gateway) provides connectivity to external packet networks and is the point of interconnection between the EPC and the PDN. It performs multiple functions such as policy enforcement, packet filtering, charging and IP address/IP prefix allocation for the UE, which is maintained for the duration of its active communication, independently from the network location.

To these components additional ones are committed to be added in the next releases:

- **PCRF** (Policy and Charging Rules Function) represents the central policy engine which enables differentiated QoS and charging. A basic set of functionality enabling default and dedicated bearers establishment will be included.
- **TWAG/ePDG** (Trusted Wireless Access Gateway/evolved Packet Data Gateway) – the gateway for trusted and untrusted non-3GPP accesses including authentication and forwarding, however without the IPsec encapsulation for non-3GPP accesses

According to the SDN principle, as adopted in the 5G system (TS 23.501 [15] and TS 23.502 [16]), the architecture presents the separation between control and data plane. In particular, the control functionality currently located in the SGW and PGW are split from the data path. As a result, the number of components doubles generating two different switches (SGW-U and PGW-U) and two additional control components (SGW-C and PGW-C). All control functions (MME, SGW-C and PGW-C) are placed within the same virtual machine, maintaining the complete functionality of the 3GPP EPC (the 3GPP interfaces are internal to the control virtual machine), and data path entities (SGW-U and PGW-U) are located in the same machine, as shown in Figure 3.

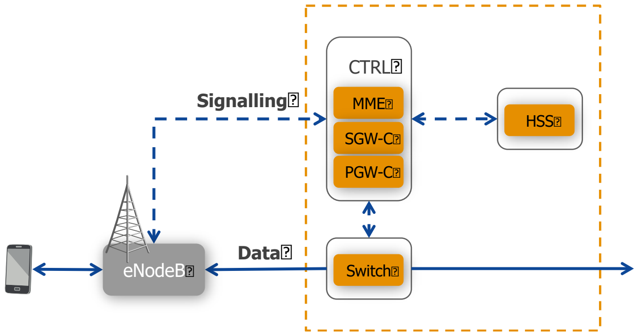

Figure 3. Open5GCore control-data plane split deployment.

Open5GCore includes its own benchmarking tool (see Figure 4), capable of generating workloads and to acquire and process resulting data. It was designed to assess the performance of a virtualized packet core solution for different number of subscribers and different number of eNBs. It provides simple and efficient functionality with configurable tests to be run, in order to monitor and evaluate the system under test. The benchmarking tool, as well as the testbed are dimensioned for up to 10.000 connected devices, enabling the evaluation of the performance of the system and of further innovations as well as of the capabilities of the backhaul and of the virtualization infrastructure.

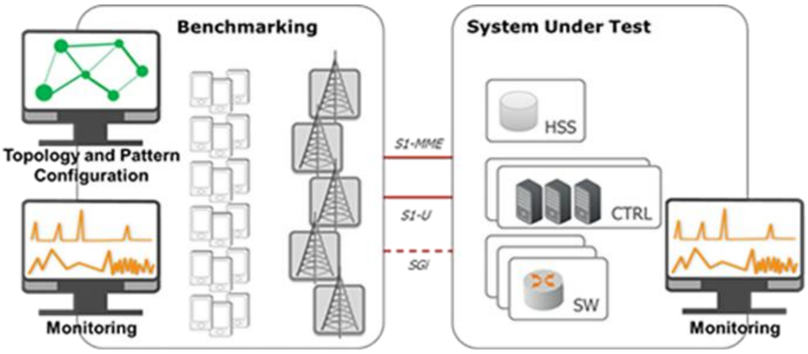

Figure 4. Benchmarking tool architecture.

Open5GCore Release 3 enables a realistic running testbed beyond 3GPP release 13, including multiple standard procedures as defined in 3GPP TS 23.401 technical specification [13], which are listed in Table 1.

Table 1. Open5GCore Release 3 key features.

Procedure	**Description**
Network attachment (E-UTRAN)	User registration is a mandatory process so that the subscriber can receive service from the network.
Network detachment (explicit/implicit)	User de-registration is the counterpart of registration. Once it is performed, the terminal has no more access to the network.
SGW relocation	The procedure allows the MME to trigger Serving GW relocation.

Network triggered service request (paging)	The inactive user in idle state is activated when there is new downlink traffic.
Tracking Area Update	The inactive user in idle state reports its current location to the network, periodically and when the TA timer expires.
UE triggered service request	The inactive user in idle state wishes to get activated when there is new uplink traffic.
S1 Release	The S1 connection is released when the user becomes inactive and thus not connected to any aNodeB.
Dedicated bearers support	The service request is used for establishing dedicated bearers with different QoS classes
X2-based intra-E-UTRAN handover	An handover procedure is performed from a source eNodeB to a target eNodeB using the X2 reference point. In this procedure the MME and SGW are unchanged.
S1-based intra-E-UTRAN handover	When there is no direct communication (X2 interface) between source and target eNodeBs, the MME is no longer transparent to the handover process and acts as a signalling relay between the two eNodeBs.

Open5GCore integrates also a set of new functionalities in order to address the IoT, MEC and network slicing principles.

2.1.4. Virtualization and automation in Open5GCore

Open5GCore integrates with standard LTE/LTE-A/NB-IoT LTE base stations (a spectrum license is required) and WLAN enabling real network deployments within testbeds.

Open5GCore is highly customizable, enabling the deployment of instances addressing the needs of the specific use cases. The source code license option extends the offer with ultimate flexibility for easy customization and prototype developments. For end-to-end use cases, Open5GCore integrates with Open5GMTC for massive IoT use cases, the OpenSDNCore for backhaul management, and OpenBaton for cloud deployments and Kamailio IMS for massive broadband use cases.

2.2 5GIC virtualized mobile core network at University of Surrey

The 5GIC core network is provided by the 5G Innovation Centre (5GIC) in University of Surrey. Its features and structure are presented in the following.

2.2.1. Features

The 5GIC component testbed in SoftFIRE has provided its experimenters with a mobile core network with various additional features added on top of a traditional EPC. Such features are aligned with 3GPP's directions envisioned for future 5G networks. These features are listed in the following.

2.2.1.1. *Control and user plane separation*

The virtual core network at 5GIC is based on the concept of Control and User Plane Separation (CUPS), which enables separate control and user plane network slices. Basically, the PGW and SGW each has been divided into two components, one for performing the control plane (CP) operations, whereas the other one is dedicated to user plane (UP) operations. For PGW, these are PGW control plane (PGWc) and PGW user plane (SGWu) components, respectively. Similarly, for SGW, now there is an SGWc and an SGWu component. The task of a control plane component is to interact with its user plane counterpart and modify its user plane functionality when this is necessary. It also interacts with other CP elements of the mobile core, such as MME.

2.2.1.2. *Faster user plane*

The user plane components SGWu and PGWu have been packaged as a single component, called the Packet Processing Entity (PPE). This effectively has collapsed the GTP (GPRS Tunneling Protocol) tunnel between on the S5 interface between them. One less GTP tunnel in the packet core is effectively less user plane latency, which is desired for 5G networks.

2.2.1.3. *Faster control plane*

The mobile core network’s core network elements, i.e. the MME, HSS, and the new control plane components PGWc and SGWc have been packaged as a single component, called the Control Plane Node (CPN), which runs on a single virtual machine. This feature avoids the additional latency in the control plane in the alternative case in which each element runs on a separate virtual machine, or in different systems. A single CPN VM provides connectivity to the RAN equipment, and control plane operations with LTE mobile units. The CPN VM is shared by all experimenters.

2.2.1.4. *Context-aware user plane operations*

The core network includes user plane control (UPc) components, supporting operations for different user equipment (UE) contexts, such as UE mobility, most frequently used type of service (ToS), UE type, and so on. Basically, the 5GIC component testbed in SoftFIRE provides a mobile application called the 5gD (5G Device), which collects UE context and then delivers this context to the context processing engines running at the mobile core. Based on the delivered context, the mobile core informs the 5gD on which network slice to use for its data connectivity, based on the 5gD’s location, mobility, radio, and traffic context.

2.2.2. Structure

To support context-awareness, the core network is logically organized as a Flat Distributed Cloud (FDC), which consists of clusters of micro cell areas, where each cluster has a single macro cell. FDC is depicted in Figure 5. Each macro cell is logically associated with a context engine, called the Cluster Controller (CC), and each micro cell is logically associated with a context engine, called the Cluster Member (CM). This architecture supports distributed network functions envisioning ultra-dense deployment.

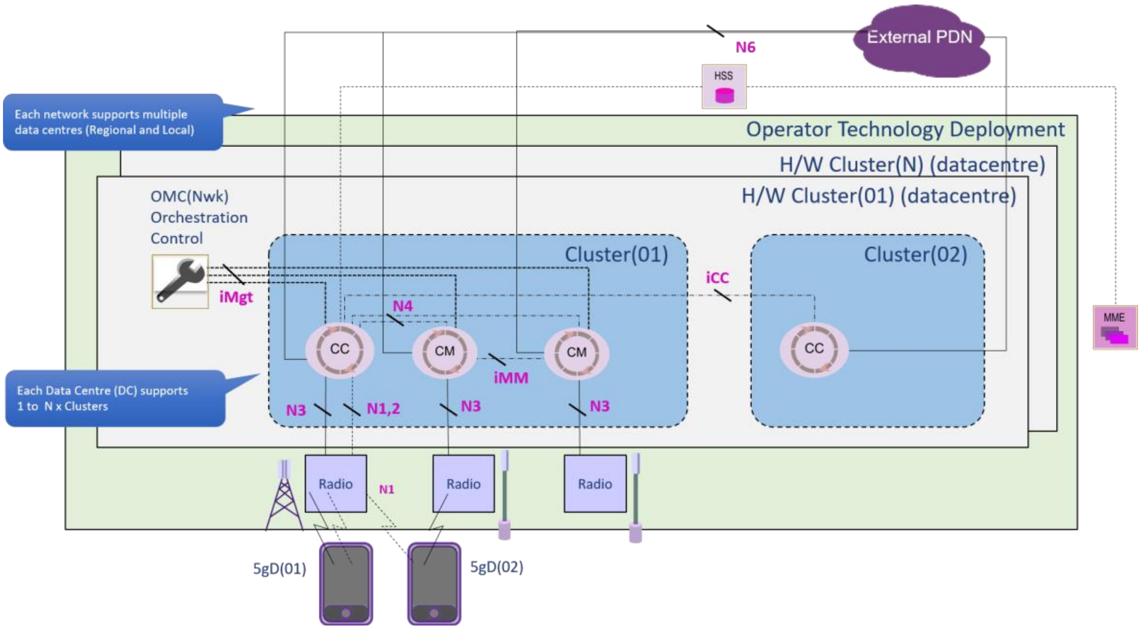

Figure 5. Flat Distributed Cloud (FDC) architecture [17]; 5gD: 5G Device, i.e. a 5G UE.

The 5gD on a UE communicates with the particular CC which is responsible for all context-aware operations in the cluster area where the UE is located. Based on the collected context information from the UE, such as its mobility profile, the CC makes a decision on where the UE must be camped on, and performs context-aware user plane anchoring. This decision affects the UE's user plane. Delivery of UE context from UEs to the CC, and the control messages between the UEs and the CC is performed by a new context delivery transport protocol, called the MetaData Protocol (MDP).

In FDC, a mobile has dual connectivity: one for its control plane and the other for its user plane. The control plane interface appears in TS 23.501 [15] as the N1 interface between the UE and the Access and Mobility Management Function (AMF). Within a cluster, the control plane of a user equipment (UE) is on N1 via the macro cell, and the user plane, which is on the N3 interface, is either on one of the micro cells or on the macro cell, depending on context decision made by the CC.

2.2.3. Virtualization and automation

The 5GIC component testbed in University of Surrey offers a dedicated core network slice to each SoftFIRE experimenter that would like to have mobile network data connectivity services. This is possible due to the fact that the core network is divided into user plane (UP) and control plane (CP) network slices. Each experimenter has their own UP network slice, whereas a single CP slide is shared by all experimenters.

Experimenters in SoftFIRE have been provided with the ability to use context-aware operations. Each experimenter has been provided with two different user plane node (UPN) network slices, one for dedicated user plane operations at cluster level, called the UPN(CC), and the other for dedicated user plane operations at micro-cell level, called UPN(CM). Based on the user profile, the core network automatically decides which network slice the experimenter's data traffic should be camped on.

Each UPN(CC) and UPN(CM) pair provided to an experimenter is packaged as a UPN Network Service, called NS(UPN). The shared control plane network slice is the control plane node (CPN). The network slices are shown in Figure 6.

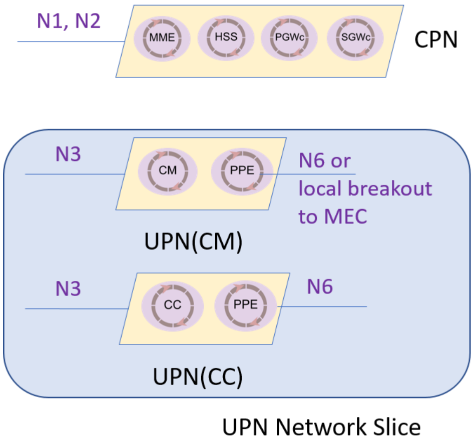

Figure 6. Network slices provided to a SoftFIRE experimenter (N1,...,N6 are 5G core network interfaces).

2.3 Sample use of the core networks of SoftFIRE

2.3.1. DozeroTech: The SWVR experiment

This experiment, called *Software-Defined Wireless Virtual Reality Gaming on SoftFIRE* (SWVR) by DozeroTech [18], utilized the virtualized Open5Gcore core network to validate their mobile Virtual Reality gaming solution. The experimenters basically developed server software that can be integrated into gaming servers to adapt the Audio/Video output of the Game for mobile terminals that are connected wirelessly to a gaming server. The output from the server is then processed and transmitted to a User Equipment (UE) to display, and the control input from the User is sent back to the server to control the player's avatar in the gaming environment. The components of the experiment are shown in Figure 7 below.

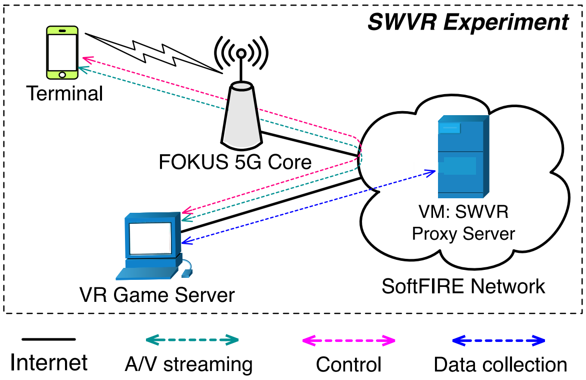

Figure 7. SWVR experiment overwiew.

This kind of applications rely on low latency between the mobile device and the gaming server to be able to provide a synchronized feedback of the Virtual Reality content to the captured user Inputs from the Mobile terminal.

The experiment used the 5G core as a black box system to connect the mobile terminal to the SoftFIRE distributed network. All the components of the experiment were carefully deployed on the Fraunhofer FOKUS testbed to minimize latency that would be introduced by the VPN links towards other testbeds. By using this approach, the latency between the VR terminal and the VR game server was as low as 50ms. The VNF approach of the core network would allow further optimization of the latency by customizing the VNFs that are involved in the data path.

2.3.2. Intellia ICT: The EXPERIENCE experiment

This experiment was conducted by the company Intellia ICT [19] during the 3rd Wave of Experimentation of the SoftFIRE project. The experiment aimed at making performance analysis of the company's provided virtual Augmented Reality (AR) solutions that run on the virtualization platform offered by the SoftFIRE. The motivation for the experiment was to support low latency and increased Quality-of-Experience (QoE) for all the users of the network, which are necessary requirements for immersive AR applications.

The AR scenarios were decompiled in a series of VNFs (AR content, storage, execution, content delivery) that were accessed via the provide 5G UPN(CM) slice dedicated to this experimenter on the 5GIC component testbed of SoftFIRE. The experiment was allocated with a separate UPN(CM) slice that connected the VMs running AR VNFs and the UEs that run AR applications. The experiment investigates the capability to insert these VNFs in an on-demand way, with respect to AR content storage, processing, and delivery, so as to achieve programmability in the network infrastructure. To achieve this, an external NFV controller software as well as a custom monitoring manager that includes a pre-configured Zabbix server were run by the experimenter.

A series of stress testing scenarios were applied to assess the performance of the infrastructure under different requirements imposed by AR applications in terms of three directions: (i) *network capacity*, (ii) *network latency, and (iii) uniform user experience.* This exercise was aimed to reveal best practices and adaptive strategies for the optimal delivery of AR content to UEs.

3 Supporting Technologies for 5G Core in SoftFIRE

The EU project SoftFIRE has designed and developed a framework for federating multiple testbeds, providing their functionalities as a service to external experimenters. Located in three countries in Europe, SoftFIRE's testbed runs virtual mobile core networks and enables future 5G applications and solutions to its experimenters.

The use of the 5G core networks provided by SoftFIRE required an easy to use and modular software structure, so that experimenters could easily deploy their virtualisation solutions that can work with standard mobile network interfaces, minimising manual configuration of network components. This effort was of course towards the general goal to meet the requirements arising from running an experimentation platform which needed to support various 5G virtualisation experiments.

Running 5G Core networks in a reliably, efficiently, with sufficient carrier-grade performance, and in a scalable way (to support multiple experimenters) required the project to ensure that the following four supporting technologies were in place:

- An efficient and fully integrated and orchestrated virtualisation testbed,
- Enabling experimentation via an extensible and reliable experimenter enablement layer, i.e. a Middleware, which ensures scalable deployment of virtual resources
- Sufficient level of programmability offered to experimenters, so that 5G Applications can be realised, hence giving the opportunity for experimenters to use the offered 5G Core network capabilities,
- Extensibility and repeatability in mobile core network support by means of virtual network slices, which are orchestrated and dedicated for different experimenters.

The Project hence made extensive efforts to meet the above four fundamental requirements, which collectively have enabled 5G core networks as an experimentation feature offered to its experimenters.

3.1 Constructing a reliable testbed

SoftFIRE's first white paper [20] provides a technical overview of the federated virtualised infrastructure, outlining its capabilities, and shares the experiences gained in building such infrastructure. During the construction phase, the several lessons were learned as listed in the white paper, some of which are:

- Testbed interfaces must be certified, sufficient level of security must be in place,
- A community of experts are needed to tune an experimentation infrastructure, to meet the demands of multiple experiments running on the platform at the same time and offering differing technology solutions, with various types of requirements,
- Programmability must be considered as whilst building the testbed, and the interfaces to be provided to experimentation must be carefully chosen, keeping in mind that experimenters require as many open interfaces as possible, yet it is also important to ensure platform's stability and resilience to errors, which may require to limit the set of interfaces exposed to experimenters.

3.2 Service enablement and scalable use of virtual resources

Further experience was gained by the Project, while developing its novel Middleware layer, which has made it possible to support more than 30 experimenters. SoftFIRE white paper [21]. The paper also explains the issues faced by the Project during its first year, and then explains how these issues have been addressed.

The most important design decision was the migration from SFA/RSpec to TOSCA resource definitions. The need for such migration was not obvious at the Project's beginning, but then become obvious with the difficulty in integrating FIRE tools (jFED, FITEagle) with TOSCA-based resource definitions that were needed to support experimenter requirements. These issues were:

- Some overlapping of functionalities between the FIRE tools and MANO,

- Experimenter requirements to have some level of access to directly use some of the APIs provided by Open Baton, which was not possible through the FIRE tools,
- Limited set of features exposed by FIRE tools, limiting experimentation capabilities,
- The concept of lifecycle of the experiment has gained a more complex definition in SoftFIRE compared to the SFA 2.0 (2010).

Furthermore, there were other generic requirements that the Project needed to support:

- To provide an environment where experimenters could make use of NFV and SDN resources at the same time, without performing complex integration and development operations underneath, i.e. SDN as a resource, besides generic NFV resources,
- To ensure basic interworking and programmability features are available and reliably maintained while experimenters use platform resources, which requires to define experiment workspaces in a structured way; i.e. concurrency, multi-tenancy,
- To provide monitoring and security resources, especially those functionalities that are highly sought after by experimenters,

These considerations led the project into the development of the SoftFIRE Middleware[1], fully devoted to NFV/SDN/5G technologies. It runs an Experiment Manager software, that provides resource abstraction, and enables categories of virtual resources to experimenters.

3.3 Programmability with NFV and SDN in SoftFIRE

Programmability is an essential feature in an experimentation platform. It is also required to achieve new 5G solutions and experiments that interact with the 5G Core networks provided by the Project. SoftFIRE white paper [22] describes the programmability features provided by SoftFIRE's federated virtualization testbed, by exposing a number of its Application Programming Interface (API) sets. Programmability in SoftFIRE occurs at several levels [23].

At the top level, the Experiment Manager allows reservation of the platform's virtualization resources (virtual network functions (VNF), network services (NS), and COTS resources) for various experiments. This is done by uploading CSAR (Cloud Service ARchive) packages to the Middleware, where a CSAR package contains experiment descriptions and life-cycle event descriptions. Notably, the Experiment Manager itself allows high level of customization due its modular structure with loose coupling of its modules.

The next level of programmability is via resource API sets.

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[1] SoftFIRE provides all of its Middleware source code on publicly available github repositories [26] in order to allow future developments and reuse of the code on similar experimentation platforms. All Middleware managers were built with python softfire-sdk, which is publicly available on github as source code, and also on PyPi python package repository as binary.

The third programmability level is related with VNF orchestration, including powerful VNF lifecycle management. Notably, the Open Baton NFV orchestrator used by SoftFIRE has a modular architecture that can be easily extended to support various use cases. Additional extensions of the orchestrator can be accomplished using the Open Baton SDKs to develop new modules or to extend the existing ones.

The final level of programmability is achieved via (*i*) the SDN controller access to provide a more fine-grained programmability of the open virtual switches that connect virtual machines (VMs) running on the platform, and (*ii*) the OpenStack Service Function Chaining (SFC) [24] modules, which allow experimenters to define SFC with a higher abstraction layer than the SDN controllers do.

3.4 5G core network slicing on a virtualised infrastructure

SoftFIRE provides sliced mobile core network components to its experimenters. This makes it feasible to support many experimenters using 5G Core network capabilities simultaneously. The core network slicing technology, its features and benefits are explained in SoftFIRE white paper [25]. Thanks to efficient programming of the core network virtualisation components, and the efficient orchestration procedures, the Project has demonstrated deployment of core network slices in less than two minutes.

In one of its 5G core networks, the Project followed the Flat Distributed Cloud architecture (FDC, see Section 2.2) based on the concept of Control and User Plane Separation (CUPS, which facilitates support for different vertical markets), and featuring context-aware user plane anchoring (at a micro cell when stationary, or at a macro-cell when mobile), and distributed network functions envisioning ultra-dense deployments. Starting with this architecture, the Project further demonstrated the opportunities of the virtualization of FDC components as VNFs; this way each SoftFIRE experimenter is provided with a dedicated user plane network slice.

The corresponding metadata files are used for the deployment and orchestration. Besides feasibility demonstrations, the 5G core network deployment has also been used by some SoftFIRE experiments: (i) a novel multi-access and traffic offloading scheme that achieves user data traffic control, (ii) performance analysis of a set of Augmented Reality (AR) solutions, (iii) a network slicing solution targeted at edge networking applications.

3.5 Virtualisation technologies supporting a virtual mobile core

Besides the above-mentioned four main requirements, the virtualisation platform itself needs flexibility and high performance that is required by carrier-grade mobile networks. In 5G, virtualisation technologies play a crucial role as they provide flexibility, scalability, and low operational costs.

NFV aims to virtualize all physical network resources, which allows the network to grow without the addition of more devices. Off-the-shelf virtualisation servers host virtual network functions running mobile core network components. In this regards, the deployment and run-time performance of the virtualisation controllers is crucial. A mobile core on a virtualisation environment should run as efficiently as a software core can, so that the added benefits of virtualisation are not nulled by poor performance. SoftFIRE has demonstrated that virtual mobile core can indeed provide similar throughput and latency as compared to non-virtualised mobile core, yet the Project points out that further improvement is necessary in virtualisation technologies to improve traffic performance, and also that this promising technology can indeed deliver the high performance that operators require in 5G.

SDN abstracts physical networking resources and moves decision-making to a (virtual) network control plane. In this approach, it separates the network control plane which decides where to send traffic, and in some cases to modify it. SDN is needed for autonomous operations in which the network would adapt to the changes in the mobile core, traffic load, and customer requirements.

NFV does not depend on SDN (and vice-versa) and can be implemented without it. However, SDN is expected to improve the performance of NFV solutions, and assist NFV to achieve its dynamic operations, by its features such as Service Function Chaining (SFC). This capability simplifies and accelerates deployment of NFV-based network functions. Furthermore, a fully-automated end to end mobile network requires SDN to dynamically modify and add traffic flows when network slices are instantiated, modified, and terminated. SDN should also meet the Quality of Service (QoS) requirements of mobile network traffic flows, by means of providing the necessary bandwidth, reliability-guarantees, and robustness.

3.6 Security as a service to support virtual core networks

A necessary direction for the industry in virtual core networking technologies is to offer programmable security functions that are specialised for mobile networks. This is more interesting and less tackled than existing solutions related with platform security. Service providers could potentially offer the ability to secure and protect mobile services accordingly to customer needs and perspectives, instead of re-using the security mechanisms implemented in a virtualisation platform. Towards this, SoftFIRE introduces a virtual Security as a Service paradigm as outlined in its white paper [27], which is flexible for programmable and interoperable 5G platforms. With specialized security solutions integrated with virtual mobile network services, customers can be provided with tailored network services according to their needs and preferences.

4 Concluding Remarks

Though SoftFIRE is a project providing an experimental NFV-SDN infrastructure, its experience and lessons learned are of importance to future 5G core network solutions. This white paper introduces the virtual 5G mobile core networks offered by SoftFIRE to its experimenters.

The project offers mobile core network slices, each dedicated to a single experimenter. This provides an isolated experimentation environment to 5G application developers. The experimental platform of the Project offers sufficient programmability for experimentation with 5G applications and solutions. Both SDN and NFV resources are provided by the testbed to assist various types of experiments. Furthermore, SoftFIRE has realised one of the first examples of orchestrated virtual mobile core. However, further work is needed to support these virtual slices with enhanced SDN in the transport network, which is integrated with operations of mobile core network slices, supporting fully autonomous operations. Hence, the

Project notes that in commercial network deployments, full integration of NFV and SDN is necessary to enable end-to-end network slicing, which involves multiple stake-holders, including transport network operators, VNF vendors, service providers, and mobile network operators. This requires much more maturity of virtualisation platforms.

The Project also notes that the scale and scope of SoftFIRE has aimed at programmers, yet not all the features that allow fast programming can be provided in an experimental platform. This is due to the differences in the component testbeds and the security controls imposed by different administrative domains. Service level agreements (SLA) do not apply during the experimentation phases, which are essentially the periods of time when experimenters can test their solutions on an experimental platform.

Finally, SoftFIRE notes the power of SDN and NFV in supporting 5G mobile core virtualisation, and applications targeting at 5G networks. On the other hand, virtualisation platforms require further improvements so that fully automation can be realised, and the benefits of virtualisation, i.e. flexibility and scalability, can be observed without sacrificing performance.

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List of Acronyms and Abbreviations

Acronym	Meaning
5G	Fifth Generation Mobile Network
API	Application Programming Interface
APN	Access Point Name
HSS	Home Subscriber Server
LTE-A	Long Term Evolution Advanced
MANO	Management and Orchestration
M2M	Machine-to-Machine
MME	Mobility Management Entity
MTC	Machine type Communication
NFV	Network Function Virtualisation
NFVO	Network Function Virtualisation Orchestrator
ODL	OpenDaylight
OVS	Open Virtual Switch
PCRF	Policy and Charging Rules Function
PGW	Packet data network Gateway
PoP	Point of Presence
RAN	Radio Access Network
SDN	Software Defined Network
SEM	SoftFIRE Experiment Manager
SGW	Serving Gateway
SSP	SoftFIRE Software Portal
TWAG/ePDG	Trusted Wireless Access Gateway/evolved Packet Data Gateway
VLAN	Virtual Local Area Network
VM	Virtual Machine
VNF	Virtual Network Function
VNFM	Virtual Network Function Manager
VPN	Virtual Private Network

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