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5G Experimental Facilities in Europe

White Paper

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List of Acronyms

2G	2nd Generation
3G	3rd Generation
4G	4th Generation
5G	5th Generation
D2D	Device-to Device
C-RAN	Centralised Radio Access Network
EU	European Union
ICT	Information and Communication Technologies
IT	Information Technology
IoT	Internet of Things
KPI	Key Performance Indicator
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
M2M	Machine to Machine
MTC	Machine Type Communications
ms	Millisecond
NFV	Network Function Virtualisation
OS	Operating System
QoS	Quality Of Service
SDN	Software Defined Network
WiFi	Wireless Fidelity

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Executive Summary

The recent advances in Information Technologies (IT), the diffusion of ultra-broadband (fixed and radio) connectivity, the continuous reduction of hardware costs and the wider and wider availability of open source software solutions, are creating the conditions for introducing a deep innovation in the architectural design and in the operations of future telecommunications networks and services.

We are witnessing a period of rapidly growing interest on the part of industry and academia in Software-Defined Networks (SDN) [1] and Network Function Virtualization (NFV) [2]. The growing interest in these paradigms (re-proposing principles that have been well-known) is most probably motivated by the novelty of the overall context, specifically their techno-economic sustainability and high-level performance. Thanks to these techno-economic trends, SDN and NFV principles will soon impact not only current telecommunications fixed and mobile networks, but also service and application platforms. In fact, SDN and NFV, together with Cloud, Edge and Fog Computing, can be seen as facets of a broad innovation wave, called **Softwarization**, which will contribute to automating processes, optimising costs, reducing time-to-market, providing better services. At the same time, the Internet of Things (IoT), Tactile Internet, Machine Type Communications (MTC), Cloud Manufacturing, Cloud Robotics, etc. will generate a new plethora of services and applications, ranging from industrial (e.g., Industry 4.0) and mission critical ones to precision agriculture, to Smart Cities, etc.

5G (which is not just one step beyond 4G) will be the main "collector" of this coming wave of innovation, bringing a number of different technologies to maturation, convergence and socio-economic impact, thus accelerating the transition towards the Digital Society and the Digital Economy. Europe should be prepared to face this important transformation, ready to capture all the socio-economic opportunities that it will bring.

In order to bring this vision into reality, Europe needs developing and aggregating a "critical mass" of **5G experimental facilities**, capable of exploiting synergies and collaborations, both within and outside Europe, e.g., with similar initiatives in US, China, Korea, Japan. This will go in the direction of joining forces for strengthening Europe in the development and exploitation of 5G infrastructures. There are several ways for pursuing this aggregation of **5G experimental facilities**: for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting the service "platforms of platforms" on top of virtual labs, etc.

Though many efforts have been made in the past in similar directions, a real "critical mass" of **experimental facilities** has not been fully reached yet, thus determining a certain level of **fragmentation**, bringing – in turn - the risk of delaying the socio-economic impacts of 5G.

5G will have to become the pervasive, highly flexible and ultra-low latency infrastructure capable of "networking" the enormous processing and storage power available in the Cloud/Edge with the sheer number of smartphones, tablets, things, wearable and the Fog Computing devices around Users.

From the infrastructure side, this "critical mass" of **experimental facilities** should increase collaboration on interoperability testing of different architectural approaches (e.g., SDN, NFV), their deep integration with Cloud/Edge/Fog Computing (e.g., validating the delicate balance of centralised versus distributed control and execution of functions) and the interworking of new operations processes. For example this includes testing of (and operating) the interoperability of different **Core and Radio Access** solutions (by using frequencies above and below 6 GHz, spectrum cognitive approaches (for specific applications), novel and traditional transmission techniques); it also includes the integration of Core and Radio Access solutions with Optical Networks (also strictly required to minimize latencies) and Satellite Networks.

To accomplish this goal, the fragmentation of experimental activities needs to be tackled through focused and concerted actions, aiming at collaborations between all projects and stakeholders.

Europe needs strong investments in this direction, both to innovate and also to ensure the maintenance and operation of experimental test beds. Investments are required both from the public and private sectors, in order to create a EU critical mass, which should be designed together with and for the specific goals of all industry players. In fact, this “critical mass” of **experimental facilities** will act as an “accelerator” for boosting the businesses of both **large, small, medium industry players and entrepreneurs**.

The challenge is bringing exploitation in Europe to concreteness, by creating new socio-economic opportunities and business ecosystems (e.g., in the sectors from industrial and agricultural mobile robotics, to new service paradigms such as “anything as a service”, from “full immersive experience and communications” to “Cognition-as-a-Service” for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to the Internet of Things).

Moreover, in order to enable a sustainable and scalable experiment facility, it is recommended to dedicate joint efforts to the development of the vision of an **overarching Operating System** (OS) for 5G. This OS, spanning from the terminals, across the network to the Cloud, will be a sort of “glue” for “sticking” together different experimental domains and islands, making them interoperable. For example, this overarching OS should be seen as platform of platforms capable of executing network services and applications; it does not manage the 5G infrastructure itself, but it provides APIs supporting a broad spectrum of control and management applications.

This White Paper does not discuss the possible **verticals** of relevance to the development of 5G. Many of the facilities listed can be used to test technologies for several of the application areas currently envisaged for 5G. In few cases the test beds are specifically focused towards a specific vertical. In this case, this is specified in the short description.

1 Rationale

Developing and aggregating a "critical mass" of **5G experimental facilities** has to, foremost, support the visions that major stakeholders are proposing for 5G, in order to allow proper interoperability testing and comparison of the different architectural frameworks. This should have the ambition to let European companies create the basis for a **shared vision** on what 5G will really be, not only from the technological viewpoint, but also from a business sustainability and regulations perspectives.

The shared vision, proposed by this White Paper, is:
1) embedding 5G into the reality as the "nervous system" of the Digital Society and the Digital Economy;
2) defining a "critical mass" of **5G experimental facilities** to facilitate synergies in the whole community of industries, including SMEs, and academia;
3) pursuing efforts in developing an overarching OS as a "glue" for "sticking" together different experimental domains and islands, making them interoperable.;
4) producing concrete impacts through a number of use-cases overcoming the fragmentation and lack of collaboration between separate Communities and Research Groups (e.g., IT/Cloud Experts, Network Engineers, Robotics Experts, etc).

While this strategy should be put in action to feed the European economy, at the same time cooperation should be found with regions like Korea, China, Japan and the US, to support the vision of a unique global network for the 5G era.

On the one hand the process of creating this critical mass should leverage on existing experimental infrastructures in Europe, created in the past years through National or EC funding (for example: the FIRE projects). On the other, necessary steps forward have to be taken, in order to reduce **fragmentation** and to ensure a better sustainability.

Proper **integration** needs to be sought in order to create a hierarchical experimental ecosystem with interoperable coordination and management. Many of the contributions received to this document describe existing test-beds and facilities of enormous value and potential. However, none of them has the capability to cover all aspects considered as possible technology bricks of 5G, and has the size needed to ensure proper environments for testing 5G in real heterogeneous conditions.

With respect to 2G, 3G and 4G, the 5G network will need a much higher degree of **flexibility and adaptability**, to serve applications with extremely diversified requirements (e.g. units of ms latency, more than 100 Mbit/s throughput per user) that will require separate and co-existing network and cloud approaches.

Moreover, from the radio access network side, the envisaged massive use of small cells, with distributed or centralised coordination and control, the novel backhaul paradigms based on multi-hop links, the many different frequency bands and physical layer techniques under investigation, require the deployment of test beds that in some cases will need to offer **large-scale** experimental facilities with thousands of programmable radio nodes.

From the optical network side, the rapid growth of user demand for increased connectivity, mobility and bandwidth, fibre capacity and reduced latency offered by new spectrally efficient, adaptive transmission, networking, control and management approaches, also require the deployment of large-scale experimental facilities for advanced optical networking experimentation. Moreover, in order to ensure that the 5G network infrastructure can also serve low populated areas (emerging countries, rural areas and possibly sub-urban areas) as well as maritime and aeronautical markets, seamless integration with Satellite

Networks is to be envisaged. These Satellite Networks can offer direct access or backhaul services and may be integrated at the access or at the metro network segments.

The overarching OS will integrate such experimental ecosystem in order to use both existing (e.g. 2G, 3G, 4G, WiFi) and novel radio technologies, both traditional and new networking and cloud paradigms; it should be designed according to criteria based on openness, ease of use whilst being secure in intellectual properties, with repeatable testing capabilities as well as being scalable. Though devised ultimately for serving industry and standardisations processes, its design requires **forward-looking approaches and knowledge of both fundamental and experimental approaches to research**. To this aim, the role of academia should be relevant, to provide proper methodological approach to the design of such ecosystem.

In summary, this proposal will be, able to serve the European industry in the next decade, becoming a sort of "accelerator" to create a socio-economic impact and developments in Europe. However it requires a number of conditions:

i) huge investments from both the public (i.e. EC and National bodies) and private sectors, to collaborate in the design and development of what (e.g., software and hardware components) is required to pursue this goal;

ii) true commitment from the main industry stakeholders, which have to perceive such critical mass of experimental facility as an opportunity where to make interoperability testing of their solutions, even under a certifiable framework: service providers, network operators, manufacturers should be involved, whether large, mid-sized or small enterprises. This will create the conditions for a pre-industrial adoption of the tested solutions;

iii) strong support from academia, especially in the design phase;

iv) enormous coordination effort, to let this experimental critical mass to really become ecosystems of ecosystems where the inter-play among the different components follows smooth and clear processes;

v) open and transparent operations of hardware and software resources, with fair play of all players of the 5G roadmap;

vi) proper dissemination tools to increase the EU visibility in pursuing this vision and to attract the largest number possible of small and medium enterprises, for testing of their solutions;

vii) attention paid to the training of a new generation of researchers with 360^{o} degree knowledge of the different technologies involved in 5G and prone to both fundamental and experimental research;

viii) forward-looking approach; Europe needs to go one step forward, investing in its future.

2 Requirements

A large-scale and hierarchical aggregation of experimental facility/islands for 5G should fulfil a number of requirements; it should be:

- **flexible** enough in order to accommodate many different options in terms of technologies (including separate physical layers, frequency bands, etc.) at the different layers and components of the network;
- easily **reconfigurable** so that experimenters can shape it for the sake of testing their own solutions;

- based on **open source** solutions, to magnify its potential exploiting the competences of the largest possible scientific community;

- able to provide **reproducible** results, in order to guarantee fair and scientific testing and comparison of separate technologies (this might require the inclusion of emulation components);

- **complete**, to allow the inclusion of all components of the 5G ecosystem, from the MNO to the virtual operator, from the end-user to the M2M application field and the IoT, etc;

- **heterogeneous** in terms of radio and optical interfaces tested, as well as of contexts, including body centric communications, vehicular networks, advanced robotics, etc.;

- **site-agnostic**, as far as this is possible, in order to test technologies and solutions in different contexts and to be easily accessible by researchers throughout all Europe;

- **topology-agnostic**, in order to cover all wireless solutions (including cellular and satellite technologies) and topologies (from small cells to macro-cells);

- **pan-European**, crossing several countries in Europe and serving stakeholders and research centers from all EC countries and beyond.

Moreover, it should constitute the basis for the development of 5G technologies in Europe, as well as for **training** a new generation of engineers and researchers prepared to such development. And above all, it should create concrete socio-economic impacts.

In terms of **performance**, the experimental facility should be able to allow testing of 5G technologies having in mind the need to meet some expected levels for KPIs to be properly defined; as a reference list, those mentioned in the Networld2020 White Paper “What is 5G (Really) About” can be considered: throughput, latency, coverage, battery lifetime, harnessing challenge, QoS, service creation time. The same document provides additional elements that should be considered as “soft” requirements (not directly quantifiable): privacy by design, open environment challenge, location and context information, manageability, harvesting challenge, hardening challenge, resource management, flexibility, authentication, charging, energy efficiency.

3 Components

From a more technical viewpoint, these are the needed components:

- designing and developing an overarching OS (leveraging from what is available in open source); feasibility of OS concept might be first evaluated over small clouds of testbeds;

- integration of legacy and novel physical access and backhaul evolutions, including all those listed in the Networld2020 White Paper “Next Generation of Wireless Networks”: millimetre waves, flexible spectrum usage, visible light communications, distributed antenna systems, C-RAN, massive MIMO, hetnets, cooperation techniques, etc.;

- exploitation of software-defined paradigms and virtualization, including concepts mentioned in the Networld2020 White Paper “Network and Service Virtualisation” like NFV and SDN, both for the access and the core network;

- integration of network and cloud based technologies to help the network fulfil the stringent requirements of 5G in terms of latency, coverage and throughput and to manage the enormous amount of data that will be carried by 5G networks;

- development and validation of novel 5G innovation services (e.g. based on IoT/M2M, Robotics, etc), as also emphasized in the Networld2020 White Paper "Mobility/Connectivity and Networking Layer", including the application of software defined networking approaches to IoT, specific solutions for low-complexity devices, cash-based networking, delay tolerant and social based networking, cloud robotics, etc.;

- deployment of a rich application ecosystem, where the continuously evolving trends of the end-user needs and new service models can be tested. Examples are from industrial and agricultural mobile robotics, to new service paradigms such as "anything as a service", from "full immersive experience and communications" to "Cognition-as-a-Service" for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to the IoT and MTC.

These core aspects find their supporting framework on the following three main 5G network components:

a) the **terminals**, including smart devices with high computational capabilities (smartphones, tablets, pcs, etc.), things (sensors, actuators, tags carried by objects and humans) and machines (robots, drones and industrial devices), all acting as "nodes" providing users and applications with any services, or as routers for other nodes;

b) the **network**, including the Radio Access component, backhauling and the Core, which will be indistinguishable;

c) the **cloud**, with its storage and processing capabilities that – in the future - will not just be centralized in big Data Centers but it will be also distributed over a number of network sites (e.g., exchanges becoming mini-Data Centers at the edge) and possibly up to terminals, car, machines, robots.

We are now moving towards **fully software-enabled** automated infrastructures. The experimental facility however, should integrate such three components under a fully unified perspective. An overarching OS should be designed and developed, able to hide the complexity of the network to operators and service providers offering a unique platform with a distributed architecture spanning from terminals to the network to the cloud.

4 Existing Facilities

A number of existing facilities for experimental purposes have been created in the past years in Europe. Some of them are mentioned below; the list is not exhaustive, being the result of the bottom-up contributions to this document. The order of presentation is random.

These resources offer immense opportunity for the European research community to progress research in this area and help to establish the European research community as main player in the development of 5G. However to fully take advantage from this existing infrastructure, a deeper integration that goes beyond basic federation is needed. An overarching OS can provide such integration.

- **EuWIn: European Laboratory of Wireless Communications for the Future Internet** – This joint and distributed laboratory has been created in the framework of the Network of Excellence Newcom# and will be maintained after its end through the participation to subsequent networking projects

(COST Action IRACON). EuWIn integrates the competences and test-beds of three sites; one at the University of Bologna/CNIT, Italy (IoT protocols and indoor localization), one at EURECOM, France (including the OpenAirInterface) and one at CTTC, Spain (radio interfaces for 5G systems and indoor/satellite localization). The individual lab sites are also described as separate items below.

- **Openair5GLAB@EURECOM (EURECOM, France)** – This laboratory is part of EuWIn and it provides truly open-source solutions for prototyping 5th Generation Mobile Networks and devices. EURECOM has created the OpenAirInterface (OAI) Software Alliance (OSA), a separate legal entity from EURECOM, which aims to provide a similar ecosystem for the core (EPC) and access-network (EUTRAN) of 3GPP cellular systems with the possibility of interoperating with closed-source equipment in either portion of the network. OAI will be used in several EC funded project after Call 1 for 5G.
- **RadioNetworks@UniBO (University of Bologna, Italy)** – This laboratory is part of EuWIn, and is partly developed in collaboration with Telecom Italia Labs; it provides facilities for testing network architectures, protocol stack and air interfaces for the Internet of Things with particular emphasis to the comparison of architectures for the integration of the IoT into 5G networks. More than 200 devices (partly fixed and partly mobile) are available and share the same programmable software architecture including 802.15.4 systems, 802.15.4a UWB devices and LoRa systems.
- **EuWIn@CTTC (CTTC, Spain) -** The laboratory is part of EuWIn, and it explores key future challenges faced by radio interfaces in wireless systems with particular emphasis on energy efficiency, spectral efficiency and the interplay with positioning capabilities. Three testbeds are available: 1) the GEDOMIS® testbed, which comprises a complete set of baseband prototyping boards (FPGA and DSP-based), signal generation equipment, RF front-ends, signal analysis instruments, and a channel emulator for the prototyping of PHY layer of 5G systems such as FBMC; 2) a GNSS receiver lab station, including a set of GNSS antennas and LNAs, a reference GNSS multi-constellation receiver, a benchmark of COTS GNSS receivers, an SDR radio interface and a GNSS signal generator; 3) OpenInLocation - an Indoor localisation testbed.
- **5GTNF (5G Test Network, Finland)** – It coordinates and combines the research and technology development activities from the 5G infrastructures built under Tekes' 5th Gear programme. TNF creates a single coherent entity from the numerous smaller test networks around Finland (5GTN, CORE++, TAKE-5 and FUHF, below) and represents them as an integrated innovation platform to the research community, industry and other interested parties on both national and international level. With this approach, the 5GTNF covers all relevant 5G research areas ranging from the programmable core network infrastructures (including the utilization of the Software Defined Networking and Network Functions Virtualization concepts) to dense and heterogeneous access network configurations (including small cells and Internet of Things use cases). More efficient and intelligent use of the available spectrum (including different spectrum sharing techniques and utilization of the Ultra-High Frequency band in cellular communications) is also covered together with the related business and regulation issues.
- **5GTN (VTT Technical Research Centre of Finland Ltd, University of Oulu, Nokia Networks, Finland)** is a research project, building a 5G test network at Oulu, Finland. In the test network, critical new technologies can be developed and it will allow testing of the performance of the novel technologies in a realistic environment. The Mission is to build a scalable 5G test network enabling future business models and service development as well as testing and developing a key 5G technology components and related support functions. Main focus is in 5G radio and IoT and 5G test network feature evolution follows 5G research and standardization progress, acting as a verification platform for theoretical 5G research.
- **CORE++ (VTT, Nokia Networks, Centria University of Applied Sciences, Finland)** - CORE++ trial environment provides a unique environment for spectrum sharing trials with live LTE networks on several frequency bands (licensed, unlicensed and shared bands). The trial environment consists of capabilities for demonstrating the feasibility of latest spectrum sharing concepts (e.g. Licensed

shared access (LSA)) including adjustment of live LTE networks according to varying spectrum availability.

- **TAKE-5 (Aalto, VTT, Nokia Networks, Finland)** - TAKE-5 creates of a multidisciplinary and open research platform for investigation and experimental evaluation of innovative ideas in networking and services for 5G. The platform and 5G network functions are incrementally built and refined after each implemented extension. TAKE-5 objectives consist of research and initial test-bed setup for piloting new 5G business and services. TAKE-5 will optimize and verify the cloudification concepts of network functions and 5G radio solutions as the key enablers for efficient and cost effective mobile broadband infrastructure. TAKE-5 will address security and software defined networking (SDN) technology to control 5G and verify end to end services performance, agility while maintaining strict requirements on delays and reliability.
- **FUHF (Turku University of Applied Sciences, VTT, Nokia Networks, Finland)** - The objectives of the FUHF project, are to research the changing media environment, long-term media consumption formats, and especially evaluate and strategize around their impact on business models for different actors, that is, mobile operators, broadcasters, mobile network manufacturers, and broadcast network providers/operators. From a technical perspective, the FUHF project studies Supplemental Downlink (SDL) and LTE broadcast technologies. Test environment consists of DVB network and mobile network.
- **Netleap (Nokia Networks, Aalto University, Finland)** network is fully functional real life Cloud based LTE evolution network with both outdoor and indoor coverage in Finland. It supports both research and innovation projects. It is part of Nokia Innovation Laboratory ecosystem hosted by Nokia Networks. Net Leap Network offers a real-life lab and testing environment, especially suited for Industrial Internet and Cloud edge computing research.
- **IMB5 (Nokia Networks, Germany)**: Integration of Broadcast and Mobile Broadband in LTE/5G – Two test beds located in Munich and Erlangen, Germany for the purpose of testing the capabilities and limitations of current LTE eMBMS for nationwide broadcast infrastructure. Results will be used to create an optimized system architecture for eMBMS based networks and to develop input for modifications of the standards, esp. in 3GPP. The project started in March 2014 and is driven by a consortium including Nokia, IRT (Institut für Rundfunktechnik), Bayerischer Rundfunk, Fraunhofer IIS, University of Erlangen and Rohde & Schwarz.
- **5G Lab Germany (TU Dresden, Germany)** is an interdisciplinary team with more than 500 researchers and aims to deliver key technologies for enabling 5G. The 5G Holistic Testbed consists of several connected test-beds which enable holistic research approaches for areas from silicon, wireless, networks, edge clouds and applications. The 5G Physical Layer test-bed consists of a core hardware platform with four NI PXI units and several USRP-RIOs, spectrum analyzers, channel emulator, networking hardware, which enable test and evaluation of novel physical layer schemes, in indoor as well as outdoor environments. The 5G Network layer test-bed consists of 150 meshed mobile devices (e.g. smartphones, drones, mobile robots) with a research focus on networking coding to enhance meshed, multi-hop, multi-path and secure communication. Several 5G tactile application test-beds are also used.
- **Flexible testbed for 5G millimeter wave communications (SINTEF-ICT-CS, Norway)** - The purpose of the testbed is to test and demonstrate MIMO techniques and PHY and MAC communication protocols for 5G systems at millimetre wave frequencies. It is based on flexible SoC platforms from Xilinx and 60 GHz transceivers from Hittite. In particular, emphasis is put on the evaluation of the effects of realistic hardware impairments and propagation conditions on the performance, in order to limit power consumption and complexity of beamforming algorithms while ensuring fast network discovery.
- **mHOP: Experimental testbed for device-centric wireless networks (Universidad Miguel Hernandez de Elche, Spain) -** mHOP is a real-time experimental platform for the study of the connectivity and end-to-end performance of device- centric wireless networks, in particular Multi-

hop Cellular Networks (MCN) using mobile relays and Device-to-Device (D2D) communications; D2D communications are based on the 802.11 standard. The platform operates using live cellular networks, and allows evaluating the performance benefits of MCN over traditional cellular systems, and the operating conditions under which such benefits can be obtained. The mHOP nodes include sniffer and GPS software tools to monitor and geo-reference all the performance measurements both at the cellular and D2D links. mHOP has been evolved to integrate opportunistic networking both at the D2D and cellular connections. The code for the link-aware opportunistic (multi-hop) D2D communications scheme is released open source to the community at www.uwicore.umh.es/opportunities/Opp-D2D.html

- **Antelia (University of Vigo, Spain)** – Antelia is the antenna test laboratory of the University of Vigo that is under the supervision and operation of the Radio Systems research group. The facilities available at Antelia include an anechoic chamber where a spherical far field measurement system is implemented. The measurement system is based on a Rohde-Schwarz ZVA67 4-port Vector Network Analyzer. Antelia has implemented a quality system according to ISO/IEC 17025:2005 "General requirements for the competence of testing and calibration laboratories". ENAC (the Spanish national accreditation entity) has granted Antelia the accreditation ENAC 1141/LE2222 to perform the test "Antenna gain measurement (1 GHz – 50GHz)".
- **PhotonLab (ISMB, Italy)** – It is a joint initiative by Istituto Superiore Mario Boella and Politecnico di Torino (Italy); it is a large experimental facility focused on the study of the physical layer of optical communications networks. Thanks to a fruitful cooperation with an Italian alternative telecom operator, the PhotonLab has access to a dark fiber infrastructure of a total of 240Km of SMF fiber going across the city of Turin and is organized in 8 rings of different lengths, from 10Km to 40Km, whose ends are in the laboratory. Such infrastructure could be used for testing optical fronthaul and backhaul solutions for 5G networks.
- **5G Playground (Fraunhofer FOKUS, Germany)** – It represents a comprehensive environment for the development of 5G technologies, integrating a large set of standard based real implementation toolkits addressing testbeds including radio signaling and core network functionality (Open5GCore), SDN functionality (OpenSDNCore), M2M functionality (Open5GMTC and OpenMTC) as well as an overarching virtual network environments orchestration and federation functionality represented by the OpenSDNCore orchestrator and the in-development OpenBaton toolkit. 5G Playground provides the functionality for easy development of new product prototypes, benchmarking and validation, testbed-as-a-service and the means to completely replicate the infrastructure at customer premises (Testbed-to-Go).
- **Comnets (TUHH, Germany)** - The wireless sensor network testbed at Hamburg University of Technology Institute of Communication Networks (ComNets) aims at performance evaluation for safety critical communication. It was motivated by the group's experience in project with the aircraft industry (Airbus, Lufthansa Technik) and their approach to model, test and certify components and systems.
- **OVNET Experimental Overlay Network (CBA UPC BarcelonaTECH, Spain) -** The OVNET is a joint effort among academics, research laboratories, major companies (e.g., Microsoft, Facebook, and Verisign) and operators (e.g., Level3) to provide a worldwide experimental facility. The experimental network has around 200 nodes in 27 countries and has its own IP address space (one /16 IPv4 and one /32 IPv6 prefix). The network uses Open Overlay Router (http://openoverlayrouter.org) technology which is controlled by a NIB and it is integrated with OpenDayLight. Such overlay technologies are key drivers of Over-the-Top overlay services.
- **Communications Research Laboratory (Universidad Carlos III de Madrid, Spain)** - The Communications Research Laboratory has the goal of developing, analysing and prototyping wireless communications systems with applications to mobile communications, space and security. Wireless applications include next generation cellular (LTE-A and beyond), metropolitan access (WiMAX), wireless area networks (WLAN) and wireless sensor networks (WSN).

- **Fit/CortexLab (INRIA Socrate Team, France)** - CorteXlab counts with more than 80 nodes in two main types, namely Wireless Sensor Networks (WSN) and Software Defined Radio (SDR). The test-bed can be used remotely to run radio experiments in state-of-the-art future communications techniques, such as the ones considered for the 5th generation of cellular systems.
- **JOLNet: a geographical SDN network test-bed (Telecom Italia, Italy)** - The JOLNet network test-bed is aimed to deploy an SDN geographical overlay network facility, in order to extensively and concretely assess the SDN and virtualization technologies and its operational impact.
- **Real-Time Emulation, Characterization, and Validation of Millimeter-Wave Front-/Backhauling Links (Fraunhofer IIS labs, Germany)** - The objective of the facility is to allow full system validation of wireless high-rate links. It comprises equipment for high-rate signal generation, validation and characterization of millimeter-wave transmission, as well as data-analysis and validation.
- **Over-the-Air Testbed in the city of Erlangen (Erlangen, Germany)** - The objective of the facility is to allow field testing, characterization and validation of waveforms and software applications of 4G systems and beyond. Different environments (urban, suburban, highway, rural, forest) are covered by the experimental network, to perform live testing under various conditions and transmission types (unicast LTE-A, broadcast/multicast eMBMS).
- **FORTE: Facility for Over-the-air Research and Testing (Technical University Ilmenau, Germany)** - SatCom: Main objective for SatCom on the move system tests is the overall system performance under realistic but repeatable conditions. OTAinVEE: The objective of the facility is to allow full validation and characterization of complex wireless communication systems under reproducible conditions in a virtual electromagnetic environment using wave field synthesis.
- **AINE: Advanced IP Network Emulator (INDRA Sistemas, Spain)** - AINE is a real time emulation software running as a user process on a Linux based platform, used for performance characterization of communication networks, particularly satellite communication systems, providing IP over Ethernet interfaces to test real applications on the modelled packet networks. This emulation tool includes ETSI-TISPAN standardized functional blocks (RCEF and RACS) to integrate it within an IMS (IP Multimedia Subsystem) service provision with end-to-end QoS guarantee. This allows the integration of the tool in environments where satcom-terrestrial networks convergence is under test.
- **5TONIC: 5G Telefonica Open Innovation Center (IMDEA, Spain) -** The test-bed is designed for partner companies to evaluate the feasibility and costs of a given technology, via a realistic evaluation of technology choices. Its core functionality is divided in two mean areas; 1) 5G Virtual Software Network Area, with a specific focus on: Network Function Virtualization, Software Defined Networking, security services, network control and management planes, cloud services, signaling; and 2) 5G Wireless Systems Area, with emphasis on: air interface, duplexing, multiplexing, media access control, spectrum, interference, mobility tracking, all considering single- and multi-RAT scenarios. The testbed consists of four main components: terminals (smart devices, things, sensors), network (both radio and Core), a distributed cloud architecture, and services (with end-to-end integration).
- **P2E: Patras Platforms for Experimentation (University of Patras, Greece)** - P2E since its first operation have been transformed to a remote experimentation facility. The latest years P2E follows ITU-T Y.30012 recommendations on Future networks, objectives and design goals. P2E evolves into the design objectives of Service awareness, thus broadening the range of offered services.
- **PerformNetworks (University of Málaga, Spain)** - PerformNetworks (formerly PerformLTE) is a testbed integrated in the Future Internet Research and Experimentation (FIRE) EU initiative, designed to offer a realistic environment to allow controlled and automatic experimentation in LTE, LTE-A and beyond networks. The testbed is based on COTS solutions (both in the radio and core network), SDR and conformance testing equipment; and supports the combination of these elements to generate an hybrid deployment mixing cutting edge research developments with commercial equipment. PerformNetworks offers different layers of abstraction, i.e.: different

exposure of network functionality, in order to support experimenters coming from many different domains (namely app developers, vendors, operators, service providers, etc.).

- **Wireless Networking Laboratory (University of Oulu, Finland)** - The WNL is intended to become an important infrastructure for enabling real-life testing of the existing and perspective radio and optical wireless communication technologies for 5G (WMAN, WLAN, WPAN/WBAN, VLC), their interoperability and ways of integration, and experimental characterization of the physical communication channels.
- **5G Experimental Facilities (University of Bristol, UK)** - The facility aims to create a unique, fully flexible, programmable and open experimental platform for all networks and IT technologies. It enables user-defined experimentation with physical and emulated technologies under realistic, controllable, predictable, secure and repeatable conditions.
- **CTTC 5G end-to-end experimental platform (CTTC, Spain)** - The existing experimental facilities cover complementary technologies from terminals, sensors and machines to radio access networks, aggregation/core networks, and cloud/fog computing,. Specifically, the existing experimental facilities involved are: i) the ADRENALINE Testbed® for wired fronthaul/backhaul (SDN-enabled packet aggregation and optical core network, distributed cloud and NFV services in core and metro data-centers); ii) the EXTREME Testbed® and LENA LTE-EPC protocol stack emulator for wireless fronthaul/backhaul and mobile core (SDN-enabled wireless HetNet and backhaul, edge datacenter and distributed computing nodes for cloud and NFV services); iii) LTE/5G PHY prototyping based on FPGA (GEDOMIS® testbed) and software-defined radio (GEDOMIS® testbed and CASTLE simulator for rapid prototyping and highly reconfirguration), and Satellite (CASTLE simulator), iv) LTE/5G analog front-end µwave & mmwave (antenna, power amplifier, filter, mixer, ...) including digital predistortion (SHAPER testbed), and finally; v) the IoTWorld Testbed (sensors, actuators and wireless/wired gateways) combined with energy harvesting devices.
- **AMAZING: Advanced Mobile wIreless Network playground (Univ. of Aveiro, Portugal)**. Free access wireless testbed composed by 24 fixed nodes located at the rooftop of Instituto de Telecomunicações – Aveiro, complemented with 50 additional mobile devices which can roam freely.
- **VISTA: Virtual Road Simulation and Test Facility (Technical Univ. Ilmenau, Germany)** - The objectives of VISTA are the characterization and test of automotive communication systems and antennas with a special focus on Over the Air and MIMO measurement techniques. Also electromagnetic compatibility (EMC) analysis issues of communication and vehicle systems are addressed. VISTA allows the emulation of communication scenarios in combination with a simulated driving scenario, therefore enabling tests of these systems under realistic driving conditions.
- **DIWINE: Dense Cooperative Wireless Cloud Networks (Univ. of York, UK)** - This testbed is currently under development within the DIWINE project funded by the EU FP7 framework, with some interim implementation showing proof-of-concept already available. It will demonstrate a future Smart Meter Network (SMN) system which will exhibit a number of characteristics that will also be required by 5G systems.
- **Experimental Facilities for Optical Wireless Trials towards 5G (Fraunhofer HHI, Germany; Czech Technical University, Czech Republic; Scuola Superiore Sant'Anna, Italy; Univ. of Edinborough, UK)** - It is proposed to use optical wireless to accelerate implementation, test and validation in particular of advanced 5G interference management techniques.
- **CARMEN: A Cognition Network Testbed (Univ. of Padova, Italy)** - CARMEN is to build a flexible testbed that makes it possible to observe and act upon both in-stack and out-stack parameters, i.e., both on the communication protocols and the device sensorial peripherals. The final objective is to exploit this rich set of information to improve the whole network performance experienced by mobile users by applying cognitive-network techniques.

- **UoP's Association to Experimental Facilities (Univ. of Peloponnese, Greece)** - The objective of the facility is to integrate and experimentally validate novel as well as legacy access network solutions with respect to their ability to support heterogeneous LAN/last-mile systems in the access. The facility includes the integration and demonstration of data-plane (DP) systems as well as the corresponding activities in opensource SDN-oriented control-plane developments and its associated integration to carrier-grade control and management plane (CP/MP) frameworks.
- **Computer and Communication Systems laboratory (CCSL)** – CCSL has installed a Remote EMF Monitoring System (REMS) in the majority of Greek islands in order to monitor the level of electromagnetic radiation as well as the occupancy of licensed and unlicensed wireless spectrum bands. From each remote station we acquire a dense set of 240 measurements per day which gives us an accurate view of the usage of the entire available spectrum throughout the coverage area.
- **VirNet@Unibo: Cloud Virtual Networking and SDN Experimental Facility (University of Bologna, Italy)** - The primary goal of VirNet@Unibo is to provide a platform to test and analyse architectures to provide networking services in a virtual environment in the cloud. It exploits both SDN and NFV concepts and the full openness of the infrastructure allows to experimentally asses future-oriented solutions and improvements in network virtualization technologies, SDN controllers, network service chaining as well as end-user SDN-enabled applications.
- **5GIC campus testbed (Univ. of Surrey, UK)** - The main objective of the 5GIC testbed is to facilitate experimentation of algorithms, techniques and novel concepts for the future 5G wireless system; the test facility will allow testing of all aspects of a future system in a real-life network deployment. In addition to advanced radio access technologies, the test-bed is designed to experiment new ICN/CDN techniques for both IoT and 5G mobile traffic. The whole test-bed covers an area of more than $4km^2$ comprising rural, urban, dense urban and motorways.
- **Future Networks Innovation Lab (Italtel, Italy)** - The facility is aimed to the application of the NFV and SDN concepts for improving multimedia real time communications and M2M/IoT services. The facility is based on a distributed architecture under SDN control, based on the interconnection of different sites hosting multimedia and M2M traffic sources and/or Datacenters hosting cloud applications, including edge Datacenters, i.e. distributed infrastructures implementing service wherever they are most effective.
- **WST: Wireless Actuator and Sensor Network Testbed (Univ. of Parma, Italy)** - The main objective of the WASN Lab Testbed is to create an innovative Internet of Things experimental environment. Its purpose is to support the design, development and test of applications and services on real hardware. In contrast with available testbeds for IoT, WST will hide low-layer details to end users, and it will offer a simple, high-level programming framework to develop final applications on top of the IP layer (IPv6 and IPv4).
- **i2CAT's OpenFlow-enabled islands (i2CAT, Spain) -** The I2CAT Island's main objective, as part of the OFELIA facility, was to address the need to test and evaluate innovative solutions and ideas in real network environments, in addition to simulations or laboratory setups. This is achieved by means of building and operating a multi-layer, multi-technology and geographically distributed Future Internet test-bed facility, where the network itself is precisely controlled and programmed by the experimenter using the OpenFlow technology. The FIBRE Island follows the same principle since it is designed as an extension of the OFELIA island, but with focus in the federation with heterogeneous test-beds.
- **OpenSAND** is an user-friendly and efficient tool to emulate satellite communication systems, mainly DVBS2/RCS2. It provides a suitable and simple means for performance evaluation and innovative access and network techniques validation. Its ability to interconnect real equipment with real applications, provides excellent demonstration means. Initially developed by Thales Alenia Space in the frame of European Commission R&D projects, R&T CNES studies and internal research, it is now promoted by CNES (French Space Agency) as a reference open-source software tool. See http://opensand.org/

- **SICS ICE (SICS North, Sweden) –** It is a full scale datacenter testlab planned to be built in 2 phases at Luleå University of Technology, Sweden, campus. First phase is operational. Consists of compute pods with 200 servers, 3600 cores, 4 TB RAM, up to 7 petabytes hard disk. Owner/host of the testlab is the Swedish Institute of Computer Science (SICS). This laboratory/test facility meet the needs of the new booming datacenter industry along the complete value chain. Driving development of IoT, big data, cloud, 5G networks, it all ends up in a mega-datacenter. The offering include for example an open Hadoop platform, bare-metal servers, datacenter measurements data monitoring and automation.**B<>COM (France) –** B<>COM provides a testbed to test security aspects of SDN based networks. Moreover, it provides a scalable, flexible and accessible framework for testing 5G network components, working on OpenStack and OpenDayLight. B<>COM is focusing on Network Function Virtualization and is also working at radio physical level especially on Multi-Radio Access Technologies.
- **KU Leuven Networked Systems (KU Leuven, Belgium)** - The test facility consists of 45 FPGA-enabled software radios (90 antennas) that can be configured in various ways to explore the benefits of many networking architectures relevant to 5G and beyond: from central antenna configuration for Massive MIMO to distributed configurations representing small cells or distributed antenna systems (cloud-RAN). The testbed can hence be used to explore the benefits of central versus distributed control, and centralised versus distributed antenna placements.
- **OneLab** (UPMC, France) - The OneLab facility provides single entry point for federated infrastructures, a common API and a Portal to browse and reserve resources of different technologies, from Wireless or IoT based to Cloud based like OpenStack or distributed at a global scale on Internet. The federated platforms include FIT-IoT, FIT-CortexLab, FIT-Wireless, III IoT-Lab, PlanetLab Europe, NITOS Volos, FUSECO Playground, Virtual Wall and w-ILab.t.
- **5G Wireless Innovation Center, Argela, (İstanbul, Turkey)** - 5GWiN based in Istanbul and Silicon Valley focuses on software defined future radio access technologies. Current projects listed as ULAK to develop 4G base station, short and long range Small Cell, programmable C-RAN. The center holds expertise more in radio technologies, self-organization, programmability and NFV. 5GWiN has a full access to Türk Telekom and several other operators to test and validate the findings in real network environments in addition to simulations or laboratory setups. Current expertise and facilities are converging towards a multi technology federated test bed facility that can be remotely connected and programmed through SDN.
- **EHU-OEF (University of the Basque Country, ES)** – The OpenFlow Enabled Facility is one of the oldest OpenFlow based facilities that is currently being used both on production and for research activities. It physically consists in a 10 Gbs backbone with 1 Gbps trees linked with OpenFlow Switches that implement a layer 2 virtualization mechanism that frees to the experimenter every part of the Ethernet Layer except MAC source and destination addresses to experimenters. It's connected to the Basque and Spanish NRENS (I2Basque and RedIRIS) through 10Gbps. It has recently been upgraded to support the deployment of services through the use of Service Graphs and with Universal Nodes to support and hybrid SDN based Network Function Virtualization mechanism. The facility provides to each experimenter's slice the possibility to deploy their own OpenFlow controller. The facility is particularly well suited to experiment with networking applications that require full control over the frame format, or in which VLAN or other Layer 2 headers.
- **iMinds (University of Ghent, Belgium)** - iLab.t technical testing offers access to the hardware, measurement equipment, user-friendly software tools and professional technical expertise needed to efficiently prototype, develop, and test innovative ICT innovations. iMinds has 3 generic testbeds: (1) The Virtual Wall (http://ilabt.iminds.be/iminds-virtualwall-overview) for all testing and experimentation activities related to wired networks and solutions (e.g. distributed software and service evaluation, scalability evaluation, validation of protocols, stress testing, …), (2) The w-iLab.t testbed (http://ilabt.iminds.be/iminds-wilabt-overview) for testing and experimentation activities

in the field of wireless networks and solutions covering different technologies and platforms (Wi-Fi, embedded sensors, Bluetooth, LTE, various SDR platforms), and (3) iMinds Homelab (http://ilabt.iminds.be/homelab) offering a residential test environment and innovation incubator for stimulating collaboration and cross-fertilisation between stakeholders in the field of research, development and innovation.

- **Network Implementation Testbed using Open Source platforms - NITOS (University of Thessaly, Greece)** – It is a remotely accessible and configurable testbed established through the EU Future Internet Research and Experimentation (FIRE) initiative. The testbed is equipped with cutting edge fully programmable networking equipment (LTE-A, LTE, WiMAX, WiFi, ZigBee, Software Defined Radio equipment, hardware OpenFlow switches, Cloud Computing infrastructure). The testbed is deployed in three different locations. The equipment provided is based on both Open Source software, enabling the deployment of novel services and protocols towards 5G communications, and commercial solutions. The testbed can be parameterized in order to setup a multitude of different topologies, whereas GEANT connectivity is provided as well.
- **5G-EmPOWER testbed (Create-Net, Italy)** - 5G-EmPOWER developed by Create-Net is a unique and open toolkit for SDN/NFV research and experimentation over wireless and mobile networks. Its flexible architecture and the high-level programming APIs allow for fast prototyping and validation of novel services and applications. 5G-EmPOWER blurs the line between radio and core segments introducing the concept of Programmable Network Fabric which abstracts the radio and packet processing resources available in a network. Our architecture builds upon a single platform consisting of general purpose hardware (e.g., x86) and operating systems (e.g., Linux) in order to deliver three types of virtualized network resources, namely: forwarding nodes, packet processing nodes, and radio processing nodes. The platform currently supports programmable LTE/LTE-Advanced eNodeBs and WiFi Access points in the radio access and a mixed wired (Ethernet) and wireless (mmWave) mesh backhaul.
- **5G Center for Innovative Networks (NETAŞ, Turkey)** - 5GNET based in Istanbul focuses on wireless access technologies and performs combined functionalities with a wide function equipped laboratory and venture capital. 5GNET focuses to develop 4G base station, Mobile Edge Computing (MEC), LTE core network, IMS core with VoLTE, DRS-Diameter Route Server, RCS, VoWiFi, IOT, Cyber Security and multimedia applications. 5GNET has an access to operators and several other test suites to validate the findings in real network environments in addition to simulations or laboratory setups. The test bed facility in the center holds several cutting edge radio equipment and simulators.
- **5G:haus (Deutsche Telekom, Germany)** – DT has set-up a European wide program for the coordination, planning, and carrying out of 5G related experiments, tests, and field trials. As Deutsche Telekom is present in many European countries, branches such as Czech Republic, The Netherlands, Austria, and Germany will participate in the 5G:haus. Testing topics are amongst others base line technologies, 5G radio access technologies, service creation mechanisms, control plane issues, and network management.
- **Com4innov** is a consortium providing the framework for testing solutions and services on next generation networks and technologies, including M2M applications.
- **Imaginlab** is an open platform thought for interoperability tests in fixed and mobile networks.

A special mention is needed with respect to the outcomes of the INFINITY project, and in particular the XiPi portal. Information on more than 230 ICT infrastructures are described in the XiPi portal with all relevant details. Furthermore, the INFINITY project delivered the INFINITY roadmap for investment into infrastructures, and the Common Description Framework, which can be used to describe infrastructures in a harmonized manner. These tools should be further considered as useful elements for the definition of a 5G experimental facility. In addition, current 5GPPP/phase1 projects may have already now several useful 5G testing environments.

5 Summary and Conclusions

The current fragmentation of experimental activities in Europe needs to be tackled through a shared and concerted effort, aiming at creating a critical mass of experimental facilities for reinforcing EU-wide cooperation, synergies, for making 5G interoperability testing and for accelerating 5G to concrete socio-economic exploitations. After listing a number of requirements, this White Paper argues that in order to put in place concretely this vision for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting service ”platforms of platforms” on top of virtual labs. An overarching OS is a possible means to get there. The two main distinguishing characteristics of this overarching OS will be: 1) leveraging on what is available in terms of open source developments; 2) developing what is missing with an incremental approach, not only addressing fixed and mobile networks (including satellite), but reaching also the smart terminals (e.g., even the more advanced ones, such as machines or robots) and the Cloud Computing facilities. With this OS, in the future, we can imagine one consolidated 5G infrastructure abstracted out by virtualization. The very same infrastructure can be the servicing layer of everything that is needed. Costs, speed to market and paradigms are differentiating factors. Benefits are tremendous; the system will function with fewer pieces of hardware that are less specialized and cheaper variety.

Though aimed at serving (large, medium and small) industry in Europe, an effort from all research stakeholders (industry, academia, research centres) is needed.

6 Recommendations

The advances and diffusion of ultra-broadband (fixed and radio) connectivity and Information Technologies, the dramatic reduction of hardware costs and wider availability of open source software, the development of novel application fields driven by the revolution of the IoT, Tactile Internet, MTC, Cloud Manufacturing, Cloud Robotics, etc. are creating the conditions for introducing a deep innovation in telecommunications and ICT networks and services. 5G (which is not just one step beyond 4G) will be the main “collector” of this coming wave of innovation, bringing a number of technologies to maturation and socio-economic impact, accelerating the transition towards the Digital Society and the Digital Economy. Europe should be prepared to face this important transformation, ready to capture all the socio-economic opportunities that this will bring.

In particular, the following actions are recommended:

R1) EC should invest in facilitating the aggregation of a “critical mass” of **5G experimental facilities**, capable of exploiting synergies and collaborations, both within and outside Europe, e.g., with similar initiatives in US, China, Korea, Japan. This will go in the direction of joining forces for strengthening Europe in the development and exploitation of 5G infrastructures. There are several ways for pursuing this aggregation of **5G experimental facilities**: for example by interconnecting test-beds and field-trials at different levels (hierarchically), by making interoperable open and closed experimental islands, by exploiting service ”platforms of platforms” on top of virtual labs, etc.

R2) The major industries should support this “critical mass” of **5G experimental facilities**, in order make interoperability tests of their solutions in a certified environment; this will help facilitating the exploitation and adoption of 5G services in the EU;

R3) Academia should invest in experimental research training a new generation of researchers prone to both fundamental and experimental activities;

R4) Efforts should be made to have small, medium enterprises and entrepreneurs involved in the 5G experimental platform in order to create and develop new ecosystems (e.g. in areas from industrial and agricultural mobile robotics, to new service paradigms such as “anything as a service”, from “full immersive experience and communications” to “Cognition-as-a-Service” for EU Citizens and Smart Cities, from Self-Driving Transportation Systems to Internet of Things, from Tactile Internet to Machine to Machine, to Cloud Manufacturing, etc.).

As a document that is complementary to the other White Papers delivered by Networld2020, all recommendations included in the latter should be implicitly added to the list above.