NetWorld 2020 ETP

5G Experimental Facilities in Europe

White Paper

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List of Acronyms

2G	2^{nd} Generation
3G	3^{rd} Generation
4G	4^{th} Generation
5G	5^{th} 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

Table of Contents

Executive Summary

The recent advances of Information Technologies (IT) and the diffusion of ultra-broadband (fixed and radio) connectivity, the dramatic reduction of hardware costs and the wider availability of open source software, are creating the conditions for introducing a deep innovation in the architectural design and in the operations of future telecommunications networks and services. Software Defined Networking (SDN), Network Function Virtualisation (NFV), Cloud/Fog Computing, are just different facets of the same trend called **Network IT-sation** (or Softwarisation); it is about impacting fixed and mobile infrastructures by automating processes, optimising costs, reducing time-to-market, providing better services. At the same time, the Internet of Things (IoT) and Machine Type Communications (MTC) will generate a new plethora of application types, ranging from industrial and mission critical applications to precision agriculture, 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 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 it will bring.

Europe needs a **large-scale experimental platform** able to support through its testing capabilities the development and exploitation of 5G techniques and infrastructures. Though many efforts have been made in Europe in the past years to create test-beds and experimental facilities with the purpose of serving industry and the scientific community, the result is a large number of **fragmented and isolated platforms**. Federation of test-beds was also considered as a solution to fragmentation in some cases; however, the interconnection of facilities initially devised as separate, does not bring to a coherent framework. The complexity of network and IT paradigms that will merge into 5G (cloud networking and processing, distributed versus centralised Radio Access Network solutions, Internet of Things and Machine Type Communications, Device-to-Device links, Software Defined Networking, Network Function Virtualisation, etc) requires a **flexible, large-scale, unified experimental framework** able to serve all industry players in the field, to test the most advanced techniques and solutions in an open-source context.

5G will have to become the pervasive, highly flexible and ultra-low latency infrastructure capable of "bridging" the sheer number of terminals, smartphones, tablets, wearables and any other intelligent machine around users, with the enormous processing and storage power available in the Cloud. From the infrastructure side, this experimental framework should allow testing of different architectural approaches to SDN, NFV, and their deep integration with Cloud/Edge/Fog Computing (e.g., validating the delicate balance of centralised versus distributed control and execution of functions, new operations processes): this includes also testing of (and operating) different **Core and Radio Access** solutions, using frequencies above and below 6 GHz, spectrum cognitive approaches (for specific applications), novel and traditional transmission techniques: it concerns also the integration of Core and Radio Access with Optical Networks (also strictly required to minimize latencies) and Satellite Networks. From the terminal and device side, it should integrate seamlessly all different types of traffic sources and prosumers: **smart terminals, things, machines, body-worn devices and even robots and drones**.

To accomplish this goal, the fragmentation of experimental activities needs to be tackled through focused and concerted actions, aiming at creating a pan-European test-bed open to all projects and stakeholders. Europe needs strong investments in this direction, both from the public and private sectors, in order to create a EU critical mass; such an experimental facility should be designed together with and for the specific goals of major industry players. It should act as a facilitator for the development of 5G technologies in Europe, both for **large and small industry players and entrepreneurs**. The challenge is looking for concrete exploitation in Europe, 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). This document envisages the main requirements and components of such fully integrated experimental framework aiming at 5G exploitations in EU.

Moreover, in order to enable a sustainable and scalable experiment facility, it is recommended to focus initially on development of an **overarching Operating System** (OS). The OS will span from terminals, to the network to the Cloud and it will be the "glue" for sticking together the available experimental facilities for 5G in the EU to produce impact. It should be designed leveraging the available OS solutions and experiences, implemented in open source, and exploited in a way that existing experimental facilities can be integrated rapidly and with minimum effort. Later, this overarching OS will represent the enabling facility for the development of 5G solutions and 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

A fully integrated experimental framework supporting the development and testing of 5G technologies has to, foremost, support the visions that major stakeholders are proposing for 5G, in order to allow proper testing and comparison of the different technological components under a unified environment. Such an experimental framework in Europe 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 perspective. 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 5G pan-European experimental framework able to serve the whole community of industries, including SMEs, and academia;

3) developing an OS as a "glue" for integrating and operating the available experimental facilities for 5G (this was missing in the past experiences of test-beds federations);

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 framework should be designed to feed the European economy, at the same time thorough 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 development of this experimental framework should be based on existing experimental infrastructures in Europe, created in the past years through National or EC funding (for example: the FIRE projects). On the other, a necessary step forward has to be taken, in order to solve the major problem of the existing experimental framework**: fragmentation**; it cannot be solved just by federating previously existing or separately devised test-beds and experimental facilities. Proper **integration** needs to be sought in order to create an ecosystem of test-beds with unified 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.

This White Paper argues that in order to put in place concretely this **integration**, an OS would be useful, acting as a "glue" for sticking together the available experimental facilities for 5G in the EU to produce impact. The two main distinguishing characteristics of the OS will be:

1) starting since the beginning from leveraging what is available in the OS open source development and field-trials for 5G in EU;

2) developing what is missing with an incremental approach, not only covering wired-wireless networks, but reaching also the terminals (e.g., even the more advanced ones, such as machines or robots) and the Cloud.

The OS is a distributed operating system that operates large-scale 5G infrastructures: as such, OS leverages on the analogous concept of Open Network Operating System (ON.OS) being developed by ON.Lab, extending it to 5G infrastructures; OS may complement (or include) management and control functions. A more detailed description of the relations of OS elements with unified platform for management and control layers of 5G, is for further study.

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) 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 is 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, fiber 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. Multiple sites should be deployed in order to facilitate the access to the test-beds from separate parts of Europe, and to create a true **pan-European framework**.

The OS will integrate such ecosystem of test-beds 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, the design and deployment of a fully integrated experimental facility operated with the OS, able to serve the European industry in the next decade, as an accelerator to create an impact in Europe, for **large, medium and small industry players and entrepreneurs**, requires a number of conditions:

i) huge investments from both the public (i.e. EC and National bodies) and private sectors, to design and develop all software and hardware components of the experimental facility, gaining the most from existing test-beds;

ii) true commitment from the main industry stakeholders, which have to perceive such experimental facility as a common platform where to test their solutions under a certifiable framework: service providers, network operators, manufacturers should be involved. This will create the conditions for a pre-industrial adoption of the tested solutions;

iii) strong support from academia, especially in the design phase, to envision an experimental facility able to host existing and future and disruptive technological approaches;

iv) enormous coordination effort, to let this experimental facility really become an ecosystem where the inter-play among the different components follows smooth and clear processes;

v) open and transparent operations of hardware and software resources, as the experimental facility should treat in a fair way all players of the 5G roadmap;

vi) proper dissemination tools to increase the visibility of the experimental facility and 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 on its future.

2 Requirements

A large-scale experimental facility for 5G has to be able to 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, a 5G experimental facility should contribute with validation and operational proof of the following core aspects:

- **designing and developing an overarching OS (in open source)** allowing to operate said 5G EU experimental facilities as a «global platform» in the EU to test 5G services. The 5GOS will be overarching the available OSes, spanning from terminals to the network to the cloud;

- 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 OS should be created, 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. The OS for example, will provide all kind of services expected from an OS, including software and hardware abstraction, low-level device/terminal/node control, implementation of commonly-used functions, message-passing between processes, and orchestration/management capabilities; it will also provide tools and libraries for obtaining, building, writing, and running applications across multiple physical and software resources.

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 results of the bottom-up contributions to this document. The order of presentation is random.

- **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.
- **5G Test Network (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.
- **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.
- **CORE++ (Nokia Networks, 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 (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 (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.
- **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.
- **Link-Aware Opportunistic D2D Communications (Copelabs, Portugal)**: Open source test-bed and experimental Insights into their energy, capacity and QoS benefits. The test bed experimentally demonstrates the energy, capacity and Quality of Service (QoS) benefits of link-aware opportunistic D2D communications. This has done through a novel test-bed which is presented and released open source to the community. The developed testbed modifies the Linux kernel so that it is independent of the particular hardware being used and can be utilized with Commercial Off-The-Shelf (COTS) equipment. The study is based on IEEE 802.11 technologies due to the current lack of LTE-based D2D hardware.

- **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 network uses two main IP address spaces, namely 153.16.0.0/16 for IPv4 and 2610:00D0::/32 for IPv6. The data-plane is based in LISP/VxLAN (RFC6830) while the decoupled control-plane is based on LISP-DDT (http://ddt-root.org), a hierarchically distributed database, which is conceptually similar to the Domain Name System.
- **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 5^{th} 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.
- **PerformLTE (University of Málaga, Spain)** - PerformLTE is a testbed designed to offer a realistic environment to allow controlled and automatic experimentation in LTE/LTE-A and future enhancements.
- **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, Spain)**. 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 Piraeus, 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 North (SICS, Sweden) – It is** a full scale datacenter testlab planned to be built in 2 phases at Luleå University of Technology, Sweden, campus. Owner/host of the testlab is the Swedish Institute of Computer Science (SICS). This laboratory/test facility is planned to 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.
- **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 XiPi and INFINITY projects. 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.

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 an open and fully integrated platform for 5G testing and concrete exploitations. After listing a number of requirements, this White Paper argues that in order to put in place concretely this integration an OS is required acting as a "glue" for sticking together the available experimental facilities to produce concrete impacts. The two main distinguishing characteristics of the OS will be: 1) starting since the beginning from leveraging what is available in the OS open source development and field-trials for 5G in EU; 2) developing what is missing with an incremental approach, not only covering wired-wireless networks (including satellite), but reaching also the terminals (e.g., even the more advanced ones, such as machines or robots) and the Cloud.

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 and MTC, 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 a deep integration of available 5G experimental platforms, which goes beyond a simple federation, by developing (incrementally) an overarching OS that could serve European industry and all projects in the area of 5G to validate solutions and to create socio-economic impact;
R2) The major industries should commit to the use of such integrated 5G experimental platform in order to test their solutions in a shared and certified environment; this will help creating a critical mass 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 and Machine to Machine).

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