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PerformNetworks: A Testbed for Exhaustive Interoperability and Performance Analysis for Mobile Networks

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Abstract

PerformNetworks (formerly PerformLTE) is a FIRE facility located at University of Málaga devoted to LTE and 5G technologies experimentation. This testbed is one of the first to provide mobile technologies in FIRE, featuring a unique combination of commercial-off-the-shelf technology with conformance and research equipment. This chapter will provide the details about the testbed which provides mobile connectivity through different experimentation scenarios, moving between emulation and real-world environments. The configurations offered cover a broad spectrum of experiments, from applications and services to innovative network solutions. The chapter will also describe the experiences in the context of FIRE including: the federation with Fed4FIRE technologies; the use of experimentation technologies like those in the FLEX project, the support for several experiments (MobileTrain, SAFE and LTEUAV) from SMEs coming from different sectors; the exploitation as the core testbed in two new H2020 FIRE+ Innovation Actions and the evolution of the testbed to overcome future challenges in mobile networks research and innovation.

Keywords: LTE, 5G, Mobile Communications, QoS, QoE.

6.1 Introduction

PerformNetworks[1] is a testbed which is building and maintaining an experimentation eco-system, that will provide access to experimenters, to state-of-the-art mobile technology. Its primary objective is to provide an advanced and realistic experimentation environment for researchers, developers, manufactures, SMEs and mobile operators.

The testbed is intended to address the main trends of current mobile deployments, providing tools to characterize the behavior of networks under different conditions, providing insights into how the protocols and the services can be optimized. It is therefore very important to give developers, mobile operators and manufactures a very accurate view of any component of the network behavior in order to implement the right policies regarding resources management.

PerformNetworks supports developments and the improvement of deployments around mobile technologies through:

- Delivery of a full testing platforms that properly support the configuration of full stack mobile technologies including radio access network, core network and performance measurements.
- Delivery of measurement tools, for discovering the precise impact of radio and core configurations on devices and applications. This is critical for device manufacturers and operators to ensure that applications and devices can take full advantage of the potential offered by upcoming 5G mobile technologies.
- Delivery of advanced results based on the correlation of data collected at different points of the network and at different levels of the protocol stack, to obtain a complete characterization of mobile applications under different radio and core configurations.

PerformNetworks can play many roles in the field of mobile experimentation, as a first approach it can be used as a platform to track-and-trace network configurations and the QoS delivered at the users level. Power consumption is also a major issue in the design of mobile devices and in mobile applications, and also greatly affects the quality of the subscriber experience. Therefore accurate measurements of power consumption in mobile devices are provided.

The testbed also aims to become a reference interoperability platform where manufacturers and researchers can check the interoperability of

[1]http://performnetworks.morse.uma.es/

commercial and/or experimental solutions. Finally mobile devices are one of the first point of contacts with the new mobile technologies and the testbed supports the interconnection of commercial and experimental devices as well as the installation of external applications.

PerformNetworks has been successfully used in several experiments as part of Fed4Fire project, and is used in several FIRE projects: FLEX, TRIANGLE and Q4HEALTH.

6.2 Problem Statement

The objectives of PerformNetworks are in line with the future technological requirement of 5G networks, which directly relate to User Experience, Device, System Performance, Business Model, Enhanced Service, Management and Operation, as stated in [1].

Now that the mobile Internet has come of age, the main stakeholders and also other small actors need access to realistic and extensive experimentation to ensure the success of their solutions. Simulations and theoretical solutions are not enough to test the performance of their solutions. All too often it is difficult to correlate data from simulations with the real world, this is why our testbed comprises real hardware, such as commercial mobile devices and eNodeB emulators, which include real signal processing, base stations and an EPC (Evolved Packet Core).

Moreover this equipment is very expensive and so unaffordable for researchers, developers or SMEs. The PerformNetwork testbed provides all these stakeholders access to an environment where they can deploy and test their solutions.

Another important fact is that the vast majority of testbed's users have only a limited knowledge of mobile technology. In most cases they are looking to test their solutions in a very realistic mobile scenario, however they do not know how to configure the testbed to meet their testing requirements. This is why consultancy is also an important part of our testbed, we translate their testing requirements into test plans which reproduce the network conditions that are relevant for them.

Finally, even in the case experimenters have the resources and the knowledge to deploy their own testing network it is difficult to deploy real pilots due to spectrum regulations. Besides the technical issues, researchers have to reach agreements with operators who are the owners of the spectrum and might be sceptical about leasing it. This is why we offer three different scenarios. As a first option, the experimenter can use the most controlled and configurable platform, a complete proprietary LTE network, built on top of a eNodeB emulator, employed by certified laboratories, where radio conditions can be fully configured and mobility scenarios can be reproduced. Once the configurations have been evaluated in this scenario, the same experiment or new experiments can be validated with real eNodeBs deployed in a proprietary LTE network integrated by commercial eNodeBs and an EPC. In the last scenario, PerformNetworks enables the remote evaluation of the experiments by providing access to on-the-shelf devices connected to LTE commercial networks deployed in Málaga.

6.3 Background and State of the Art

This section provides an overview of the different mobile networks tools and platforms for research and experimentation currently available for experimenters, depicting their capabilities. Firstly, the available tools, an then the commercial solutions, are described. A brief overview of some of the most important European testbeds, devoted to wireless communication, is also given.

6.3.1 Research Tools for Wireless Communications

There are some tools that can be used for experimentation (besides commercial equipment). The most widely used in research papers are the simulators, mainly ns-3 and Riverbed Modeler (formerly OPNET). Simulators can provide inexpensive, systematic results but the reliability of these results can vary depending on the problem and the tool used.

One of the most common simulation tools is ns-3[2] which includes some functionality for LTE. The support is provided by the LTE-EPC Network Simulator (LENA) [2], an open source module that was designed to evaluate some aspects of LTE systems such as Radio Resource Management, QoS-aware Packet Scheduling, Inter-cell Interference Coordination, Dynamic Spectrum Access as well as simulate End-to-End IP connectivity. The ns-3 framework can be used as an emulator, although the performance results can be limited [3].

Riverbed Modeler (formerly OPNET) is a commercial solution that provides an LTE simulation platform designed according to 3GPP

[2]https://www.nsnam.org/

Rel. 8 specifications. OPNET implements most of LTE's basic features and also includes powerful statistical evaluation tools.

Open source implementations for Software Defined Radio (SDR) are becoming very popular, the price of the hardware has lowered and the availability and quality of the solutions is better. These types of solutions can provide a realistic environment with total control of the stack, the major drawback to them is the coverage specifications.

Open Air Interface (OAI)[3] wireless technology platform offers an open-source software-based implementation of LTE UE, E-UTRAN and EPC, compatible with many different SDR solutions such as ExpressMIMO2, USRPs, BladeRF and SodeRa. The solution was created by Eurecom[4] and is now managed via the OAI Software Foundation (OSA). OAI includes tools to configure, debug and analyze several aspects of LTE layers and channels and can interact with commercial equipment [4].

Another solution gaining popularity is the LTE libraries (srsLTE and srsUE)[5] designed by Software Radio Systems (SRS)[6] compatible with SDR applications and covering compliant with the 3GPP Release 8. The srsLTE library provides common functionality for LTE UE and eNB with support, when available, of the VOLK acceleration libraries. srsUE is based on srsLTE and provides the basic functionality of an LTE UE.

The emulator equipment can provide very realistic results operating with commercial devices whilst maintaining a high level of reproducibility in the results. This type of equipment normally provides end to end functionality and sometimes can also include the effects of the channel. The major drawback is the price of the solutions which is very high and the focus on the radio access which limits interoperability with the EPC network. These emulators are traditionally provided, to be used in design verification, conformance testing and/or signaling protocol testing.

For instance the E7515A UXM by Keysight Technologies[7] is conformance testing equipment for Release 10 LTE devices. UXM allows users to validate the functional and RF performance of their UEs, providing end-to-end LTE-Advanced connectivity as well as a highly configurable network and radio access parameters. The unit is capable of providing data rates of up to 1 Gbps

[3]http://www.openairinterface.org/
[4]http://www.eurecom.fr/en
[5]https://github.com/srsLTE/srsUE
[6]http://www.softwareradiosystems.com/
[7]http://www.keysight.com

in downlink, multiple cells, carrier aggregation, MIMO and fading emulation all provided in a single box.

An example of a signaling protocol tester is CMW500 by Rohde & Schwarz[8], which provides developers of wireless devices access to a radio access network emulation, including a network operability test. This equipment offers MIMO 2X2, multi-cell and data rates up to 150 Mbps in the downlink and is able to support other technologies such as 2G, 3G and Wi-Fi.

6.3.2 Wireless Testbed Platforms

There are many different platforms available for mobile experimentation, like [5], where European 5G platforms are described. In the context of FIRE, there are three main testbeds: Fuseco, NITOS and w-iLab.t. The role of ORBIT is also very important as it provides one of the most common experimentation frameworks, OMF. The ORBIT testbed[9] is a wireless network emulator for experimentation and realistic evaluation of protocols and applications. ORBIT provides a configurable mix of both cellular RATs (WiMAX and LTE) and Wi-Fi, together with Bluetooth, ZigBee and SDR platforms.

Fuseco Playground[10], by Fraunhofer, is an open testbed for R&D of mobile broadband communication and service platforms. Fuseco integrates several RATs (DSL/WLAN/2G/3G/LTE/LTE-A) together with M2M, IoT, sensor networks and SDN/NFV. This testbed can be used directly at the Fraunhofer premises in Berlin, and in many cases, remotely.

The NITOS Future Internet Facility [6], is a testbed which provides support for research into wired and wireless networks. NITOS provides a heterogeneous experiment environment, including Wi-Fi, WiMAX, LTE and Bluetooth wireless technologies, SDR, SDN and sensor networks. The NITOS testbed can be used remotely.

w-iLab.t[11], by iMinds, is a wireless testbed for the development and testing of wireless applications. w-iLab.t offers two different LTE networks for testing, including both ip.access femtocells and SiRRAN EPCs. Furthermore, this testbed provides Wi-Fi, sensor node and cognitive networking experiment platforms. w-iLab.t testbed is accessible remotely.

[8]https://www.rohde-schwarz.com
[9]http://www.orbit-lab.org/
[10]https://www.fokus.fraunhofer.de/go/en/fokus_testbeds/fuseco_playground
[11]http://ilabt.iminds.be/iminds-wilabt-overview

6.4 Approach

Since its inception the focus of the PerformNetworks testbed has been to provide access to the researchers with the wide array of tools present in a commercial scenario without losing the control and configuration options available in the academic world. With this approach the testbed's users gain two advantages over the deployment of the simulators usually used in the scientific realm. On the one hand, thanks to the use of commercial equipment the researchers have the same level of access as the network operator and can perform realistic tests without the simplifications and assumptions that are part of using simulators in the experiments. On the other hand the researcher maintains all the flexibility of access to every layer of the network without fear of disrupting the normal operation of a commercial operation setup.

This flexibility usually imposes an additional burden on the researcher tasked to interconnect and configure all the nodes of the test network. So, having experienced these problems first hand, the testbed team has created a set of sensible defaults and ready-to-use configurations so researchers, while still being able to change the network as needed, only have to focus on the important parts of their tests.

The way to achieve this relies on the interchangeability of most of the components available to researchers and is based on the experience and knowledge accumulated by the testbed operators during the initial setup and the many experiments running over it. Based on the feedback from researchers, the testbed team can suggest architectures and configurations that best adapt to a specific experiment, run while maintaining a low-level complexity for the parameters that falls outside the scope of the experiment. This in turn guarantees an optimal performance.

Figure 6.1 outlines the architectural components a researcher may choose to use in his experiments:

- A commercial *Evolved Packet Core* (EPC) from Polaris Networks[12] with all the entities upgraded to the 3GPP standard Release 11. The experimenter has direct access to the *Mobility Management Engine* (MME), *Serving Gateway* (SGW), *PDN Gateway* (PGW), *Home subscriber server* (HSS), the *Policy and Charging Rules Function* (PCRF), and the new entities *Access Network Discovery and Selection Function* (ANDSF) and the *Evolved Packet Data Gateway* (ePDG).

[12]http://www.polarisnetworks.net/

- A virtualization server where the experimenter can deploy several virtual machines and interconnect them in an arbitrary way to increase the complexity of the setup. One typical use of this component is to install network software, for example *Open vSwitch*, to route the traffic to and from the EPC with different priorities.
- Commercial small cells to be used as *eNodeB.*
- Several *Software Defined Radio* (SDR) cards that can be used as *eNodeB* with the appropriate software, like *OpenAirInterface*, in case the researcher requires access to the code running the nodes.
- The *T2010 Conformance Tester* from Keysight Technologies which is used by mobile manufacturers worldwide to precisely measure the radio performance of new devices. The ones present of the testbed have been modified, as described in the following sections, to provide standard connectivity to commercial core networks, offering full end to end experimentation scenarios.
- An array of attenuators, RF switches, channel emulators and equipment to measure power consumption in the device under test.
- Various COTS UE with Android and Linux operating systems where researchers can install their own apps and programs.

Using this equipment the testbed offer to experimenters an iterative approach. The experimenter can go to the fine tune of the components of the network

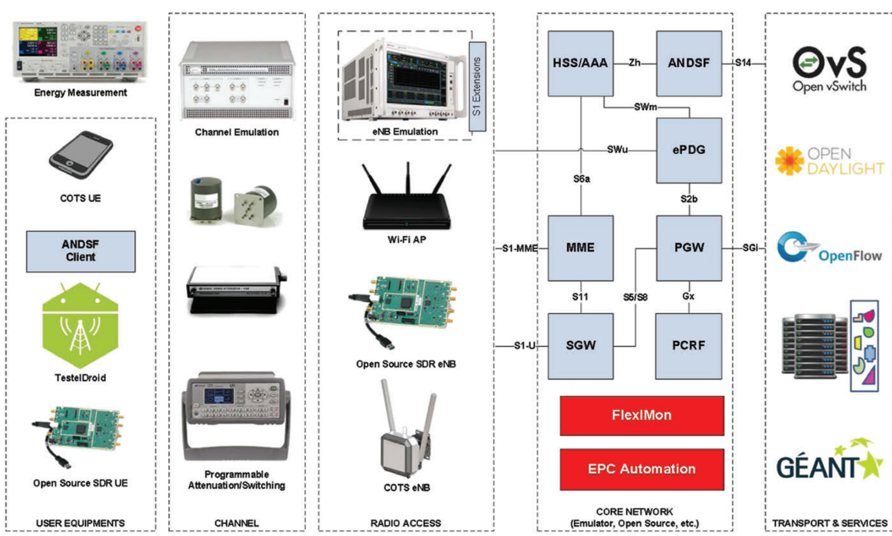

Figure 6.1 PerformNetworks architecture.

including the effects of the channel on a controlled environment using conformance testing equipment. In these scenarios they can obtain reproducible and systematic results maintaining a realistic environment where they can use commercial UEs and EPCs. In a more advanced stage of their research experimenters can validate their approach employing an indoor deployment, using commercial base stations to have an idea on how their solutions could perform on the operator networks but also using eNB based on SDR if they need modifications on the radio access stack. Finally researchers can use commercial deployments to measure the performance on real networks but also obtaining information on several KPIs of the radio access.

6.5 Technical Work

An important part of the technical work on the PerformNetwork testbed has consisted in the interconnection of the different equipment, the use of heterogeneous equipment hardens the interoperability. Several tools have been also designed for the use of the testbed. In this section a modification to the T2010 conformance testing equipment to support standard S1 interface is described. Fleximon is an interoperability tool designed to provide remote monitorization of communication interfaces. There have also been some developments to provide support for some federation technologies such as OMF resource controllers or aggregate managers.

6.5.1 T2010 Standard S1 Interface Extension

The *T2010 Conformance Tester* by Keysight Technologies allows manufacturers to test LTE end-to-end connections in a highly configurable way. Its primary function is to ensure new UE models adhere to the *3GPP* standard, but it can also be used to test non-ordinary conditions such as different power profiles, fading scenarios or exotic resource assignment. The *T2010* measuring capabilities are concentrated in the lower level of the stack, but it also implements most of the eNodeB protocols as well as a basic EPC emulation, so the UE being tested acts as if it is connected to a real LTE network.

The objective of the *T2010 Standard S1 Interface Extension*, developed at the University of Malaga within the framework of the *FlexFormLTE* project, was to extend the functionality of the T2010 with a standard *S1* interface so the user would be able to choose between the limited emulated *EPC* or connect to a fully functional external one. A complete *S1-MME* module was created, with hooks to the existing interfaces of the T2010 so control and user planes are created in the upper levels while maintaining the radio connection to the UE controlled by the equipment.

Thanks to the extension developed within this project the testbed now has a powerful new tool, combining the feature-rich T2010 physical and radio configuration with a realistic connection to a commercial *EPC*.

6.5.2 Fleximon

One of the main challenges a mobile network researcher faces during a experimentation campaign is how to extract signaling information from the components without disrupting the normal operation of the system. The control software usually only reports an aggregate of the events that have been recently fired in the network without detailed information about the data passed between the entities involved. One way to obtain this information is to capture all the traffic in a specific interface of the EPC, but the operator is usually reluctant to give the researcher access to their internal network and the amount of data captured this way can be overwhelming. *FlexiMon* is a tool within the scope of the FLEX project designed with this scenario in mind. The objective is to provide the network operator with a tool that opens a data path to the experimenter without modifying the network workflow, and gives the researcher a powerful platform where he/she can develop monitoring and statistic analysis software for that data.

It comprises two independent modules, written in C++ to lower the penalty hit in performance and with portability between different systems as a requirement. The first module, aptly called *FlexiCapture*, runs in any device with access to the network interface between one *eNodeB* and its corresponding MME. From there it identifies the traffic of protocols configured by the researcher (currently *SCTP*, *GTP* and/or *S1AP*) without altering the flow of data between the two entities. A copy of any matching packet is then relayed to the other module called *FlexiView*, which is running in the researcher's desktop, to be processed. *FlexiView* can save the traffic it receives in *pcap* format for future analysis with any standard tool like, for example *Wireshark*[13], but its main feature is an API which can be used to implement any real time processing in the traffic. With it a researcher can easily extend the monitoring capabilities of the application as if it were running inside the operator network. Also, to fully integrate this tool within the framework used in several *FIRE* projects, there is also the possibility to send the measurement results to an *OML* server for storage in a database.

[13]https://www.wireshark.org/

The following is a not intended to be an exhaustive list of modules which have already been implemented using this API:

- Identification and monitoring of an specific user as soon as it connects to the network.
- Amount of data and throughput of each user being monitored.
- Basic sanity checks in the *GTP* and *SCTP* protocols using the periodic *echo request* and *responses* used in them
- Several performance figures in the *S1* interface such as attach procedure duration, dedicated bearer creation success rate, etc.

6.5.3 TestelDroid

UE devices in PerformNetworks run Testeldroid [7], our custom tool for monitoring device performance parameters and data traffic, to collect experiment data. We have modified Testeldroid so that it sends that information as an OMF stream to an instance of an OML database which we are also running in our testbed.

TestelDroid is a passive monitoring software tool for Android devices. This tool collects not only simple metrics such as throughput, but also radio parameters such as received signal strength, radio access technology in use, the actual IP traffic and more to obtain a fully detailed picture to help characterize the traffic performance of mobile applications.

6.5.4 FIRE Technology

Currently, the experiment control is done through an OMF experiment controller (EC) deployed on one of our nodes. This controller can be accessed via SSH. We have also deployed a web frontend to the experiment controller called LabWiki [8], created by NICTA[14].

As described the PerformNetworks testbed has a moderate number of specialized pieces of equipment. Most of this equipment offers an interface based on SCPI (Standard Commands for Programmable Instruments), which is used to control its operation through a Resource Controller (RC) which triggers the configuration commands to the instruments. An specific Resource Controller for SCPI instruments have been developed, which is based on an XML definition that provides a mapping between high level functionality of the instruments and SCPI commands. However to support our latest equipment the Resource Controller available through the official distribution of the OMF

[14]https://www.nicta.com.au/

framework has been used, this will simplify the integration of future versions of the OMF framework. For the pieces of equipment that do not support this interface specific configuration scripts, that are also issued via a standard RC, have been designed.

PerformNetworks has deployed GCF, an implementation of SFA AM (Aggregated Manager) created by GENI[15], as its solution for resource discovery and provisioning. Due to the nature of the testbed, consisting mainly in specialized hardware, reservation is manual and exclusive, i.e. only a single experiment can be run on top of it at any one time.

The AM provides a federated SSH access to the Experiment Controller (EC) of the testbed. Resource description is done via RSpecs. The current RSpec definition of the testbed provides a monolithic specification of the EC of the testbed. This definition can be used to gain SSH access to the EC of PerformNetworks using, for example, the jFed Experimenter GUI tools.

The EC also contains the reference experiments described in OEDL. The experimenters can modify and launch their customized experiments using OMF EC procedures available in the EC. Figure 6.2 provides a general picture of the orchestration framework deployed in the PerformNetworks testbed.

6.6 Results and Achievements

The PerformNetworks testbed has been integrated in several of the EU FIRE initiatives. The first integration of the platform was performed in Fed4Fire where the PerformLTE testbed was federated to be exposed to third parties as well as remotely operated. This federation was initially based on an SCPI-enabled resource controller for industrial equipment [9] developed by the MORSE group and the provision of an aggregate manager and several experiment controllers to enable remote ssh access to external users.

6.6.1 SME Experiments

In the context of Fed4FIRE several SMEs have run their experiments on PerformNetworks, gaining access to highly complex and expensive equipment which they have used to improve their businesses. Some of these experiments are MobileTrain, SAFE and LTEUAV.

MobileTrain was an experiment executed by Naudit[16] and consisted in several test campaigns to improve their QoS tools using packet-train [10]

[15]https://portal.geni.net/
[16]http://www.naudit.es/

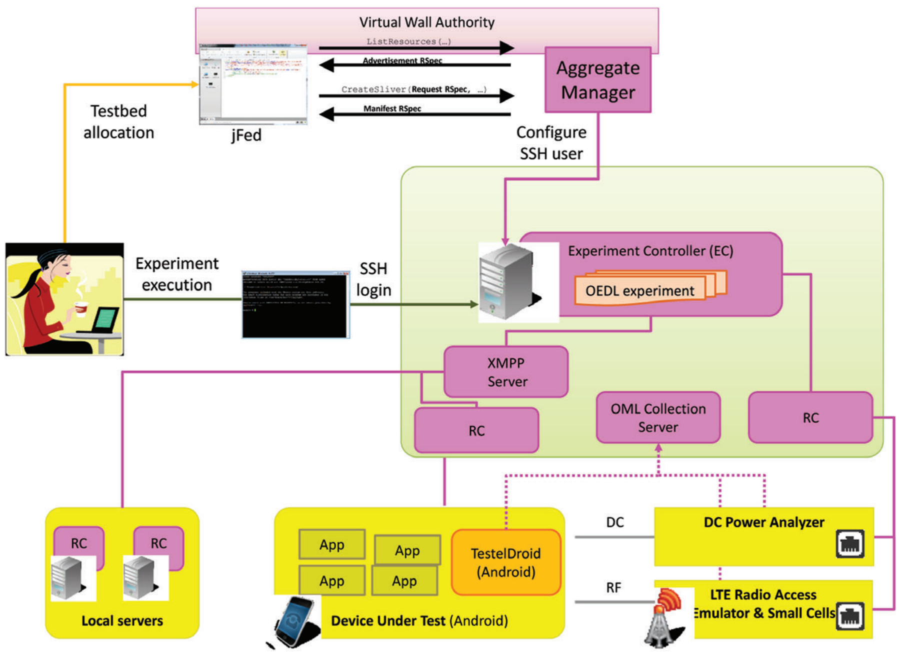

Figure 6.2 PerformNetworks orchestration architecture.

measurement techniques. The setup was based on the T2010 emulator that provided the LTE connectivity with a dedicated stratum 2 Precision Time Protocol (PTP) which was deployed for this experiment to obtain more accurate one way delay measurements.

SAFE, an experiment run by RedZinc[17], was motivated by the need to study the performance of LTE-transmitted video in emergency situations. The video was streamed live via a wearable platform designed by the company. They also had developed an engine to produce QoS enforcement in the network which was integrated, during the experiment, with the IMS interface of the testbed's core network. This experiment used an Alcatel Lucent *pico-cell* prototype that was employed in scenarios that required dedicated bearer establishment (generated via the Rx interface of the EPC) and the T2010 conformance testing equipment to emulate scenarios with mobility. As a result of the experiment, RedZinc were able to develop their own Rx driver to communicate with standard core networks and they obtained a first optimization of

[17]http://www2.redzinc.net/

their BlueEye platform over LTE networks. Furthermore SAFE was the origin of a subsequent collaboration between RedZinc and MORSE that resulted in the Q4Health project[18].

LTEUAV was run by Aeorum[19], a company that develops solutions based on computer vision, unmanned vehicles management and artificial intelligence. Several of these solutions are based on Unmanned Aerial Vehicles (UAV) and the focus of the experiment was precisely to optimize of the communications for these types of scenarios. The main problem the company encountered was the optimization of the video streaming captured from the UAVs so, to improve the performance, they used mobile communications as well as the traditional radio frequencies communications available in these scenarios. To improve the video streaming several test campaigns were undertaken using the T2010 emulator as a controlled reproducible environment. The experiment consisted in optimizing of the different video parameters, such as video feed resolution, frame rate and encoding, based on the response of the video under certain channel conditions such as LTE signal strength and the speed of the UAV (emulated by the Doppler effect).

6.6.2 FIRE Projects

PerformNetworks is used in several FIRE projects. It is integrated into the FLEX project, which was specifically oriented towards LTE and 5G experimentation. The testbed was also federated with the FLEX technology with the development of an LTE.rf controller for the T2010, which was extended to support standard S1 communications, and the EPC. With these new capabilities, the PerformNetworks testbed was used to perform interoperability testing with the different pieces of equipment present in other testbeds of the project so as to identify any potential problems. This resulted in an interoperability report which presented all the results and suggested guidelines to improve the definition of experiments involving different FLEX platforms.

In 2016 two new innovation actions using PerformNetworks have been accepted, the results of which will be a testbed improvement to accelerate time to market of products from companies in different sectors. One of these actions is the *Triangle* [11] project (described with more detail in chapter REFERENCE_TO_TRIANGLE_CHAPTER). In this project PerformNetworks is going to be evolved to support different experimenter profiles, trying

[18]http://www.q4health.eu/
[19]http://aeorum.com/

to provide them with useful tools in a language they can understand. The project focuses on 5G certification so several extensions to the testbed are foreseen, such as the introduction of LTE Release 12 equipment, supporting very high throughput, the interconnection of certification equipment with commercial core networks via Software Defined Network enabled switches and the exploration of dual connectivity to support heterogeneous wireless communications. The other action is the *Q4Heatlh* [12] project (described in more detail in chapter REFERECE_TO_Q4HEALTH_CHAPTER) which is the natural continuation of the Fed4FIRE experiment SAFE. In Q4Health PerformNetworks will be extended to support ultra low latency services by combining NFV and SDN techniques, the EPC has been upgraded to support Release 12/13 features such as seamless handover with non 3GPP technologies or MME relays, and a new optimized version of the RedZinc BlueEye platform is expected to be ready by the end of 2018.

6.6.3 Research Activities

PerformNetworks is also used by the MORSE group with research an academic purposes. The research activities are developed for many different reasons, gathering requirements for future releases of the testbed, improving the experimental interfaces and optimization and characterization of mobile networks.

The exploration of new functionality for the testbed has resulted in different research contributions. In order to improve the support for mission critical communications in the testbed by means of Commercial-Off-The-Shelf (COTS) technology, the use of the standards were analyzed on [13], driven by the particular use case of LTE communications for railway signaling. In this paper the requirements for railway communications which include traffic prioritization, broadcast services, location dependent addressing, etc. were analyzed, providing standard alternatives when available, and providing a quantitative analysis of the fulfillment of these requirements. In [14] the future standard architecture for IoT applications is analyzed, covering aspects such as the addressing, energy consumption, and congestion avoidance.

In [15] a framework for VoIP measurement analysis, including MOS estimation based on Perceptual Evaluation of Speech Quality (PESQ), RTP processing and more, was developed and used to extract voice measurements from test campaigns involving the public Spanish high speed railway. This tool has been also used in cooperation with Spanish operators wishing to have a characterization of their network and its basic extraction engine, named

TestelDroid, is available on the Google Play Store[20]. A more detailed analysis was performed in [16], that was not only limited to voice calls (around 400 calls were performed) but also included FTP and ping measurements providing a comparison between two Spanish mobile operators.

From the results of these measurement campaigns the limitation of using third party networks became clear. Operators were not willing to open up their networks so more complex measurements could be taken, and even less inclined to setup their equipment to optimize certain services. A campaign of measurements to see the performance of prioritized railway signaling traffic over live networks giving coverage for high speed trains was studied and finally in the context of the Tecrail[21] project a setup to perform such measurements was designed. An agreement with an Spanish operator was reached and Alcatel Lucent provided LTE base stations which were deployed along the railway tracks. These base stations were connected to the PerformNetworks EPC, giving access to all the measurements on the network and also enabling the configuration of a service level agreement for the different services under test by means of the establishment of dedicated radio bearers on the network. Additionally an emulated European Train Control System (ETCS) service, designed by AT4 Wireless[22], was used on top of this infrastructure. The combination of emulated and commercial equipment in a realistic environment provided support to a unique experiment and became one of the distinguishing features of the PerformNetworks testbed that started to evolve in this direction.

This VoIP toolset was then used with the T2010 to provide and test end-to-end connectivity under different channel conditions. In this setup, measurements from the LTE network stack (e.g.: MAC BLER/Throughput, CQI, etc.) could be extracted and were correlated with the measurements from the application level, providing insights into how certain network conditions translate into QoE performance indicators. Energy consumption has also been explored with the tools of PerformNetworks, for instance in [17] a runtime verification system was developed based on the measurements extracted from commercial devices, that were stimulated with execution traces. In [18] the use of the T2010 and a power analyzer offered results on the power consumption of mobile phones when performing voice calls over an LTE network under different network conditions and also with different network configurations.

[20]https://play.google.com/store/apps/details?id=com.ad.testel
[21]http://www.tecrail.lcc.uma.es
[22]https://www.at4wireless.com/

The provision of experimentation interfaces has also been explored in several research papers. For instance in [9] we described the approach taken to support OMF/OML on the testbed that consisted in the abstraction of the functionality of the instrument in an XML definition. This XML provides the mapping between the high level functions of the equipment and the low level configuration which is done by means of SCPI commands. This is used by a resource controller which interprets high level commands to trigger the appropriate configurations and a transformation tool, that generates the OEDL interface based on the XML file. The use of this approach considerably simplified the integration of other experimentation interfaces such as LTE.rf, which could be done by implementing a different transformation. In [19] the modifications done to TestelDroid in order to support SCPI commands and the OML library are described. With the new modifications, the tool was integrated with the rest of the SCPI compliant equipment already present in the testbed and is now able to generate real-time measurements in an OML database.

PerformNetworks can offer many different types of results and is now being evolved to attract more users, especially those with little background in mobile communications, and to support future 5G mobile communications acting as a testbed enabler.

6.7 Discussion

PerformNetworks has evolved considerably over the last few years. The main focus has been to provide highly realistic experimentation environments while maintaining a high level of customization and flexibility. This trend is still very much present in the PerformNetworks testbed roadmap but more requirements have been identified.

PerformNetwork should offer consultancy services. Many of the external experimenters using the testbed are not experts in wireless communications, they come from different domains and their solutions make use of the wireless connectivity. The testbed interfaces were designed with the figure of research experimenters in mind, an expert on mobile communications who wished to set up all the components of the network. However most of the experimenters are from many different domains, normally vertical sectors, and lack the knowledge and time to learn how to setup the full network. From the second quarter of 2016 onwards PerformNetworks has offered its consultancy services via the University of Málaga branded as the UMA Mobile Network Laboratory.

Another important aspect of the experiments for future mobile communication is the scale. One of the targets of 5G technologies is to increase user capacity by 1000, and the role of IoT in future technologies is clear and comes with capacity requirements. To enable these experiments PerformNetworks is following two main research lines. On the one hand going live by broadcasting on commercial frequencies is considered a key aspect to facilitate these experiments. To do so it is mandatory to engage operators which are the owner of spectrum licenses. Obtaining their permission to broadcast can be difficult, normally (the regulation is different in every country) they have legal responsibility on the signals broadcasted in their frequencies. A possible idea could be to share their frequencies and/or equipment via RAN sharing technologies. The other enabler could be in the form of massive UEs emulators, that could be implemented with SDR technologies.

Open equipment is very important to enable future mobile communications. The testbed is trying to provide as many modifiable components as possible, like for example OpenAirInterface (PerformNetworks is part of the OpenAirInterface Software Alliance), which provides source code for UE, eNB and EPC; or srsUE[23], which centres on the UE. The PerformNetworks tools which are not protected by intellectual properties agreements with third parties will also become open source.

In addition, MORSE will also cover new research projects that will be part of future releases of the testbed, some of these topics are:

- SDN Applications validation and verification. The use of formal methods and runtime verification is currently being explored.
- NFV functionality, especially the CloudRAN features. There are ongoing efforts to implement new network functions to enable optimized network procedures and low latency communications.
- Mission critical communications are still on the testbed's radar, especially those involving high speed scenarios, such as railways, high availability or ultra low-latency services.
- Advanced network probes. In the last few years probes for the core network and Android phones have been developed, so the testbed will be extended with new tools to provide even more information from the stacks, making them deployable on commercial mobile networks.

6.8 Conclusion

This chapter has provided an overview of the PerformNetworks testbed from its origin to its future evolution. The testbed has been used by many different companies as well as by the MORSE group both for research and

[23]https://github.com/srsLTE/srsUE

innovation activities. We have described some of the challenges present in mobile experimental platforms and have provided an overview of the different tools which might be useful to the testbed's users, as well as the status of the most relevant FIRE testbeds in this field.

We have also depicted some of the implementations and integrations that have been done in the context of the testbed. This includes the extension of a conformance testing equipment to boost the number of available scenarios with channel emulation, the implementation of an interoperability tool capable of monitoring a communication interface remotely, providing information and statistics of the status of the different processes in the network. An Android application to perform drive tests of QoS and QoE has also been provided, together with some details on the implementation of the different experimentation and federation interfaces.

Some of the external experiments executed on the platform have been described with details about their requirements and their achievements. We have also outlined the research activities of the group, covering the analysis of different services on both live and emulated networks, the execution of pilots to enhance the realism of the deployments, the correlation of the information from different levels of the stack and the efforts to provide of remote access interfaces. Finally we have discussed future research activities for the testbed including some details on its possible roadmap.

We expect that PerformNetworks will become a reference platform for future 5G technologies and will attract more experimenters, by offering simplified interfaces as well as consultancy services to improve their products or research.

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