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FORGE: An eLearning Framework for Remote Laboratory Experimentation on FIRE Testbed Infrastructure

Alexander Mikroyannidis[1], Diarmuid Collins[2], Christos Tranoris[3], Spyros Denazis[3], DaanPareit[4], JonoVanhie-Van Gerwen[4], Ingrid Moerman[4], Guillaume Jourjon[5], Olivier Fourmaux[6], John Domingue[1] and Johann M. Marquez-Barja[2]

[1]Open University, UK
[2]TCD, Ireland
[3]University of Patras, Greece
[4]IMEC, Belgium
[5]CSIRO, Australia
[6]University Pierre & marie Curie LIP6, France

Abstract

The Forging Online Education through FIRE (FORGE) initiative provides educators and learners in higher education with access to world-class FIRE testbed infrastructure. FORGE supports experimentally driven research in an eLearning environment by complementing traditional classroom and online courses with interactive remote laboratory experiments. The project has achieved its objectives by defining and implementing a framework called FORGEBox. This framework offers the methodology, environment, tools and resources to support the creation of HTML-based online educational material capable accessing virtualized and physical FIRE testbed infrastructure easily. FORGEBox also captures valuable quantitative and qualitative learning analytic information using questionnaires and Learning Analytics that can help optimise and support student learning. To date, FORGE has produced courses covering a wide range of networking and communication domains. These are freely available from FORGEBox.eu and have resulted in over 24,000 experiments undertaken by more than 1,800 students across

10 countries worldwide. This work has shown that the use of remote high-performance testbed facilities for hands-on remote experimentation can have a valuable impact on the learning experience for both educators and learners. Additionally, certain challenges in developing FIRE-based courseware have been identified, which has led to a set of recommendations in order to support the use of FIRE facilities for teaching and learning purposes.

17.1 Introduction

The Forging Online Education through FIRE (FORGE)[1] FP7 project is focused on making practical and effective use of Future Internet Research and Experimentation (FIRE)[2] facilities by utilising them as eLearning resources for higher education institutions. FORGE offers engineering teachers and students access to world-class FIRE testbed infrastructure, while shielding them from the physical and sometimes political complexities of accessing and using experimentation equipment. This has the benefit of maximising the usage of expensive equipment to own, operate and maintain while simultaneously raising awareness of FIRE facilities among teachers, students and future researchers.

FORGE achieves its goals of experimentally driven research by complementing traditional classroom and online courses with interactive remote laboratory experiments. Our approach promotes the development of critical thinking and problem solving skills in students by turning them into active scientific investigators, equipped with world-class experimentation facilities (Marquez-Barja et al., 2014, Mikroyannidis et al., 2015, Jourjon et al., 2016).

FORGE acts as the glue that binds the eLearning and FIRE communities together (see Figure 17.1). This is achieved using the FORGEBox framework, which offers the environment, software components and resources to support the creation of HTML-based online educational material capable accessing virtualized and physical FIRE testbed infrastructure. FORGEBox is supported by the FORGE methodology, which helps course designers with establishing course requirements, identifying and integrating with suitable FIRE facilitates, authoring educational material and course deployment into interactive eBooks, Learning Management Systems (LMSs) and Virtual Learning Environments (VLEs). To support interoperability with existing LMSs and VLEs,

[1]http://ict-forge.eu
[2]http://cordis.europa.eu/fp7/ict/fire/

Figure 17.1 eLearning, FORGE and FIRE research facilities.

FORGEBox uses eLearning technologies such as the Learning Tools Interoperability (LTI) standard and SCORM. Additionally, FORGEBox captures valuable quantitative and qualitative learning analytic information based on the Experience API (xAPI) specification. This information can help optimise and support student learning and assist with course evaluation and future adaptation.

FORGE has produced experimentation courses covering a wide range of networking and communication domains, which have been undertaken by more than one thousand students across ten countries. Our research has shown that the use of remote high-performance testbed facilities for hands-on remote experimentation has had a valuable impact on the learning experience for both educators and learners. With the success of initial prototype courses, FORGE also created several advanced electrical engineering courses covering topics such as LTE and OFDM. The on-going FORGE open call courses such as the Internet Measurements MOOC[3], the partnership with Cisco[4] and the Go-Lab[5] projectalso prove its continuing progress. In spite of these successes however, there are several aspects that can be improved related to security, authentication, scalability and sustainability beyond project duration.

This chapter is organised as follows. In Section 17.2, we outline the problem statement in terms of online education and maximising FIRE testbed resources. This is followed by a synthesis of research into learning design theories and online labs for teaching telecommunications related content

[3]https://www.fun-mooc.fr/courses/inria/41011/session01/about

[4]PT Anywhere: http://pt-anywhere.kmi.open.ac.uk/

[5]FORGE widgets available via the Go-Lab project portal: http://www.golabz.eu/search/node/forge

in Section 17.3. In Section 17.4, we briefly describe the overall FORGE framework in terms of user roles, education and architectural requirements. Section 17.5 outlines the FORGE methodology for the production of FIRE testbed enabled courses and FORGE learning analytics. It also surveysfive post-graduate courses developed and deployed by project partners using the FORGE methodology. In Section 17.6, we discuss issues and challenges related to utilising FIRE facilities for educational purposes. Finally, Section 17.7 offers concluding remarks.

17.2 Problem Statement

Higher education is currently undergoing major changes, largely driven by the availability of high quality online materials, also known as Open Educational Resources (OERs). OERs can be described as "teaching, learning and research resources that reside in the public domain or have been released under an intellectual property license that permits their free use or repurposing by others depending on which Creative Commons license is used" (Atkins et al., 2007). The emergence of OERs has greatly facilitated online education (eLearning) through the use and sharing of open and reusable learning resources on the Web. Learners and educators can now access, download, remix, and republish a wide variety of quality learning materials available through open services provided in the cloud.

The OER initiative has recently culminated in MOOCs (Massive Open Online Courses) delivered via providers such as Udacity[6], Coursera[7] and edX[8]. MOOCs have very quickly attracted large numbers of learners; for example over 400,000 students have registered within four months in edX[9]. Also, in the four years since the Open University started making course materials freely available in Apple's iTunes U, nearly 60 million downloads have been recorded worldwide[10]. More recently, the Open University established FutureLearn[11] as the UK response to the emergence of MOOCs, in collaboration with premier British institutions such as the British Council, the British Library and the British Museum.

[6]http://www.udacity.com/
[7]https://www.coursera.org/
[8]https://www.edx.org/
[9]http://www.guardian.co.uk/education/2012/nov/11/online-free-learning-end-of-university
[10]http://projects.kmi.open.ac.uk/itunesu/impact/
[11]http://www.futurelearn.com/

These initiatives have led to widespread publicity and also strategic dialogue in the education sector. The consensus within education is that after the Internet-induced revolutions in communication, business, entertainment, media, amongst others, it is now the turn of universities. Exactly where this revolution will lead is not yet known but some radical predictions have been made including the end of the need for university campuses, while milder future outlooks are discussing ‘blended learning’ (combination of traditional lectures with new digital interactive activities). The consensus is however that the way higher education students learn is about to change radically.

The FIRE initiative holds the potential to contribute to these emerging trends in higher education, as it offers a wide range of experimentation facilities that can be used for teaching and learning online. FIRE’smission is to ensure that the European Internet Industry evolves towards a Future Internet containing European technology, services and values. Through the FIRE initiative and other similar regional and global initiatives a variety of facilities have been established to enable such experimentation. These facilities cover a plethora of different domains belonging to the Future Internet ecosystem, such as cloud computing platforms, wireless and sensor network testbeds, Software Defined Networking and OpenFlow facilities, infrastructures for High Performance Computing, Long Term Evolution (LTE) testbeds, smart cities and so on. However, the corresponding cost both for the establishment and operation of these infrastructures is not to be neglected. Hence, optimal usage of the facilities is desired by its owners, a goal which in general is not yet achieved today. To increase the usage, several steps can be taken.

One approach is to raise the awareness of the facilities within communities that are less familiar with the FIRE initiative. Another is to use the infrastructure not only for research and development, but also for other activities such as teaching through a constructivist approach. This means that students would be enabled to take certain initiatives in their learning, by setting up and conducting scientific experiments based on FIRE. In this way, using FIRE facilities for teaching computer science topics or other scientific domains would not only increase the usage of the facilities, it would also raise FIRE awareness in the long term since the students/experimenters of today are the researchers of tomorrow. And if educational materials were available that actually enable new types/areas of experimentation through FIRE, this would further lower the threshold for experimenters to explore new facilities and technologies.

The FORGE project offers a solution to this problem by adopting the latest trends in education in order to introduce the FIRE experimental facilities into the eLearning community. FORGE promotes the concept of experimentally-driven research in education by using experiments as an interactive learning and training channel for both students and professionals by raising the accessibility and usability of FIRE facilities. The goal is to create an open FORGE community and ecosystem where educational resources, collaborative tools and proposed experiments are offered and contributed for free.

17.3 Background and State of the Art

17.3.1 Learning Design

In this section we outline the various pedagogical theories associated with the process of designing courseware, or Learning Design as it is also known in the literature of Technology-Enhanced Learning (TEL). Learning Design (LD) is the act of devising new practices, plans of activity, resources and tools aimed at achieving particular educational aims in a given situation. LD should be informed by subject knowledge, pedagogical theory, technological know-how and practical experience. At the same time, it should also engender innovation in all these domains and support learners in their efforts and aims (Mor and Craft, 2012).

A learning design captures the pedagogical intent of a unit of study. It offers a broad picture of a series of planned pedagogical actions, rather than detailed accounts of a particular instructional event as might be described in a traditional lesson plan. As such, a learning design provides a model for intentions in a particular learning context that can be used as a framework for design of analytics to support faculty in their learning and teaching decisions (Lockyer et al., 2013).

The field of LD emerged in the early 2000s as researchers and educational developers saw the potential to use the Web to document and share examples of good educational practice. Smith and Ragan (2005) have proposed that LD might be more accurately described as Design for Learning. Some common definitions for LD are the following:

> *"A 'learning design' is defined as the description of the teaching-learning process that takes place in a unit of learning (e.g., a course, a lesson or any other designed learning event). The key principle in learning design is that it represents the learning activities and the*

> *support activities that are performed by different persons (learners, teachers) in the context of a unit of learning."* (Koper, 2006).
>
> "*A methodology for enabling teachers/designers to make more informed decisions in how they go about designing learning activities and interventions, which is pedagogically informed and makes effective use of appropriate resources and technologies. This includes the design of resources and individual learning activities right up to curriculum-level design. A key principle is to help make the design process more explicit and shareable. Learning design as an area of research and development includes both gathering empirical evidence to understand the design process, as well as the development of a range of Learning Design resource, tools and activities."* (Conole, 2012).

These definitions suggest two seemingly opposing approaches. However, Falconer et al. (2011) suggest that LD has two origins in TEL. The first one is the construction of computer systems to orchestrate the delivery of learning resources and activities for computer-assisted learning. The second is in the need to find effective ways of sharing innovation in TEL practice, providing an aid to efficiency and professional development for teachers. Therefore, Koper's definition represents the first TEL origin, while Conole's definition is derived from the second.

The most easily understood and adapted common elements within all learning designs include the following (Lockyer et al., 2013):

- A set of *resources* for the student to access, which could be considered to be prerequisites to the learning itself (these may be files, diagrams, questions, web pages, etc.).
- *Tasks* the learners are expected to carry out with the resources (prepare and present findings, negotiate understanding, etc.).
- *Support mechanisms* to assist in the provision of resources and the completion of the tasks; these supports indicate how the teacher, other experts, and peers might contribute to the learning process, such as moderation of a discussion or feedback on an assessment piece (Bennett et al., 2004).

Figure 17.2 provides an example learning design visual representation showing three common categories of resources, tasks, and supports.

In order to ensure that a learning design is sound, the learning outcomes should be in line with the assessment that is used to test for the achievement

Figure 17.2 Learning design visual representation (Lockyer et al., 2013).

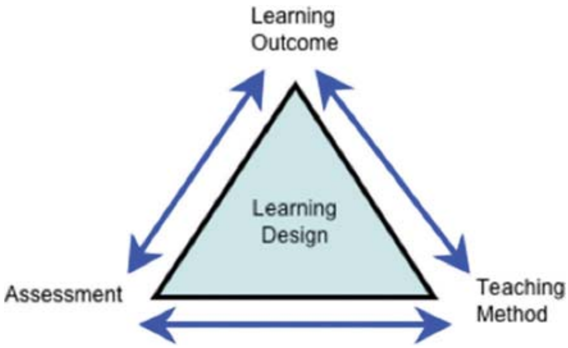

Figure 17.3 The instructional triangle of learning designs[12].

of learning outcomes. In addition, both learning outcomes and assessment should be aligned with the teaching method. Biggs (2011) refers to this as the "constructive alignment". The relationship between these three concepts can be represented as a triangle and it is often referred to as the "instructional triangle of learning designs", as shown in Figure 17.3.

With regards to the different skills that teachers need in order to implement a learning design successfully, Mishra and Koehler (2006) present the Technological Pedagogical and Content Knowledge (TPACK) model (see Figure 17.4). The TPACK model can be used as a foundation for analysing the pedagogical and technological elements of LD. The TPACK model puts emphasis on the intersections between Technological Knowledge, Pedagogical Knowledge and Content Knowledge, and proposes that effective integration of technology into the curriculum requires a sensitive understanding of the dynamic relationship between all three components.

The Instructional Management Systems (IMS) Learning Design (IMS-LD)[13] specification expresses a standardised modelling language for representing learning designs as a description of teaching and learning processes. The main objective of the IMS-LD specification is the provision

[12]http://www.open.edu/openlearnworks/course/view.php?id=1154
[13]http://www.imsglobal.org/learningdesign

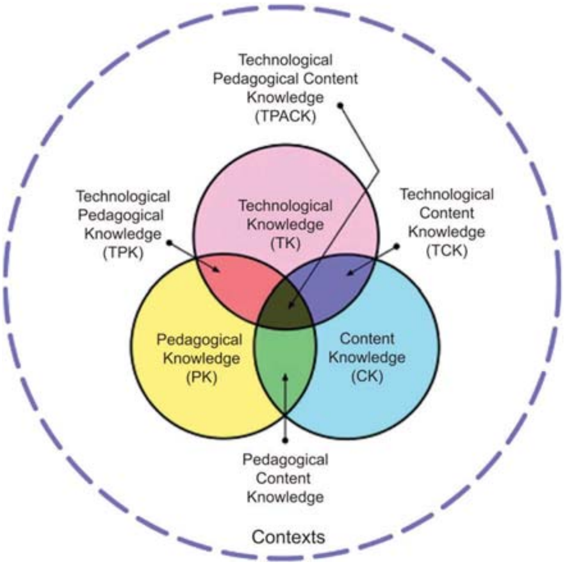

Figure 17.4 TPACK model of educational practice.

of a containment framework of elements that can describe any design of a teaching-learning process in a formal way. Thereby, the originally intended objectives of IMS-LD are (Koper, 2009):

- The standardised description of an adaptive learning and teaching process which takes place in a computer-managed course, i.e. these courses: are "developed" before they are used; can be used by different groups/classes of learners at different times (principle: "Develop once, run many times"); are managed by the computer (here: Runtime), not by the teacher; are designed to achieve certain learning outcomes for a given target group (prerequisites) as effective and efficient as possible for the individual learner.
- The support of all types of learning designs based on various pedagogical approaches.
- To have the learning and support activities at the centre, not the content.
- To provide an integrative framework for a large number of learning content such as IMS Common Cartridge (IMS-CC)[14], IMS Content Packaging (IMS-CP)[15], IMS Question and Test Interoperability Specification

[14]http://www.imsglobal.org/commoncartridge.html
[15]http://www.imsglobal.org/content/packaging/

(IMS-QTI)[16], Sharable Content Object Reference Model (SCORM)[17] as well as collaboration/communications services (e.g. audio/video conference, forum, and virtual classroom).

17.3.2 Online Labs

Online laboratories have been designed and operate under different themes in order to train students and enhance their skills in higher education programs (Harward et al., 2008). Depending on the methods used to access and to trigger the equipment at the backend facility and the technology used in the front-end graphical interface, from three to six different categories have been defined (Diwakar et al., 2013, Frerich et al., 2014, Bose, 2013). We can summarize these taxonomies into three categories:

1. Virtual labs, which are software-based laboratories, empowered by simulation tools.
2. Remote labs, based on remote experimentation on real lab equipment.
3. Hybrid labs, which combine the above two by processing output data from real measurements into simulation tools.

There are several works that describe the approaches that different universities and/or projects have applied to enable engineering-related online laboratories. Most of the approaches rely on simulation, providing virtual labs for teaching robotics (Abreu et al., 2013), electronic circuits (Bagchi et al., 2013), control systems (Diwakar et al., 2013) or a broad list of engineering disciplines (Bose, 2013).

Few approaches have been publicly proposed for teaching telecommunications related content in remote labs. Bose and Pawar (2012) proposed a remote lab called Virtual Wireless Lab where students can learn about the foundations of wireless signal, with concepts such as antenna radiation pattern, gain-bandwidth product of an antenna, cross polar discrimination and Signal Noise Ratio (SNR). The architecture proposed presents a front-end Adobe Flash enabled web page to access the back-end, which uses LabView to interface with telecommunications equipment such as spectrum analysers, oscilloscopes and signal generators. The eComLab supports a similar configuration and instruction by using a dedicated VNC-based virtual machines (VMs) managed by a gateway server that allows remote lab configuration and experimentation on Emona DATEx and NI ELVIS boards (Gampe et al., 2014). These VMs have direct access to the board hardware supporting

[16]http://www.imsglobal.org/question/
[17]http://www.adlnet.gov/scorm/

direct experiment control. A user can access these machines using a regular web browser with support for Flash and Java plugins. Due to the tools and equipment used by Virtual Wireless Lab and eComLab architectures, they do not support open easy to use interfaces for configuration, data collection, resource sharing, etc.

In contrast, the Smart Device specification (López et al., 2015), initiated by the Go-Lab EU FP7 project, advocates all devices (clients or servers) use common interfaces such as metadata, logging, data collection, configuration, and so forth to simplify communication between a remote labs, external services and applications. This is supported by: open protocols; WebSockets, which uses asynchronous bidirectional communication between client and server; and Swagger, a JSON-based description language for RESTful web services that easily integrates with WebSockets. Smart Device metadata is exposed on the Internet enabling applications, services and other devices to interact with the remote lab. Telecommunications courses, such as the oscilloscope lab available on Go-Lab project platform[18], can utilise the Smart Device specification to support design, integration and promote usability. These principles of openness and ease of use are similarly philosophies followed by the FORGEBox framework.

17.4 The FORGE Framework

The overall architectural approach of FORGE is displayed in Figure 17.5 and covers FORGE user roles (i.e. learners, course designers, instructors, and so forth) and requirements. The architectural approach is towards accomplishing our initial FORGE challenges include:

- To make the reservation of resources in (different) facilities easy for both teachers and learners;
- To allow easy fast experimentation control, from various devices and means, during the learning process;
- To know the identity of the user who is currently performing an experiment that was initiated from within a client web browser;
- To access resources that can only be reached over IPv6 or over a VPN;
- Avoid breaking the logical flow of an educational experiment when the user behaved unexpectedly;
- To allow multiple users sharing the same experiment;
- Handle a large number of simultaneous users.

[18]http://www.golabz.eu

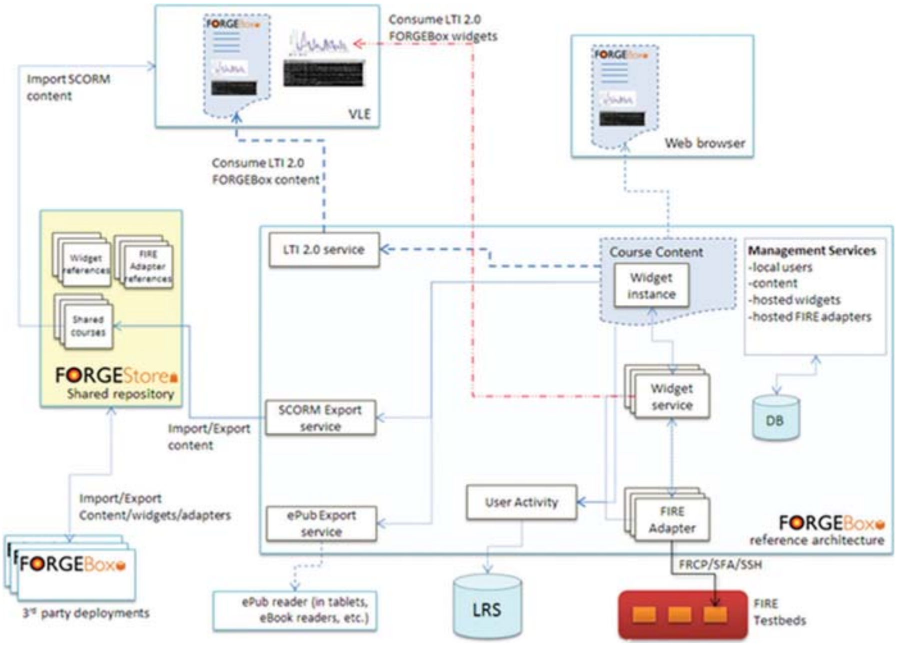

Figure 17.5 FORGE architectural approach.

It is also important to use existing eLearning technology and try to seamlessly integrate it with our FORGE artefacts. Thus, all developments made in our core entities, consider open and well known eLearning technologies. We investigated solutions of exploiting these eLearning technologies in two areas: interoperability and means to study user behaviour while learning on top of FIRE. These technologies are the Learning Tools Interoperability (LTI) standard, SCORM and the Experience API (xAPI), commonly known as the Tin Can API.

LTI adoption provides better integration between FORGE technology and existing LMSs and VLEs. LTI provides a seamless experience for learners while interacting both with the LMS/VLE content and the remote FIRE resource. Consequently, LTI makes it much easier for organizations to adopt and use the FORGE technologies and integrate them with their own already deployed learning systems. xAPI on the other hand allows instructors to study learners' behaviour while interacting with a facility.

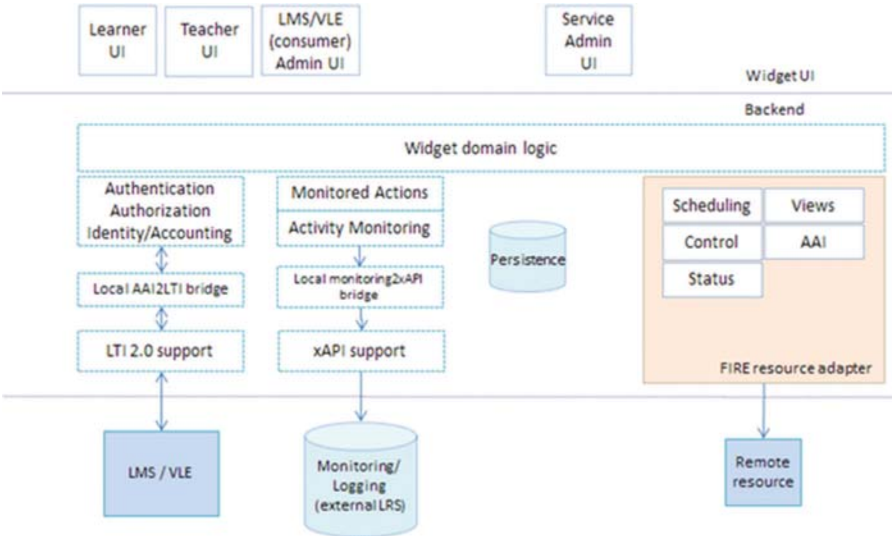

Figure 17.6 Reference architecture for a FORGE widget.

To address the above, we created a reference architecture for widgets and FIRE adapters that support interacting with remote facilities of FIRE through a VLE. Figure 17.6 displays our proposed reference architecture for a widget, with architectural components that a developer would need to implement in order to achieve the most desirable result of bridging learning with FIRE remote resource interactivity. Since widgets are web services hosted somewhere on the Internet ready to be consumed by other web content, the architecture defines both the widget UI as well as the backend domain logic and core architectural components. Next we discuss supported usage roles and each architectural component. These supported roles are:

- **Service Administrator**: the user responsible for the whole widget web service. Service Administrator can login to the host machine and administer the service that provides the widget to consumers. Service Administrator can also manage for example users, registrations etc. The use cases are specific to the capabilities that the widget service will offer. E.g. the administrator of the ssh2web widget can allow specific domains that can use the service.
- **LMS/VLE Administrator**: responsible to integrate the widget to the target learning system LMS/VLE or even in an eBook. He needs to

pay attention to the widget documentation, how it is delivered (i.e. as a URL), its API, it's LTI compatibility, etc. For example, an administrator responsible for a Moodle installation could visit FORGEStore and read the documentation of the widget. Then he could register the widget into the Moodle environment by using the LTI registration URL of the widget service.

- **Teacher/Instructor**: defines the behaviour and settings for a specific course. He can also use the interface to reserve resources or setup the testbed.
- **Learner**: interacts with the widget and the remote resource during the learning process.

The widget UI is the main component that a user uses to interact with the widget. To behave correctly, the Widget service must know the context that it works under, in order to properly display the equivalent UI according to the user role. Thus, if possible, the widget should be aware of:

- The consumer service into which it is hosted and operating (i.e. is it an LMS/VLE, the VLE URL, an eBook, etc.);
- The kind of consumer (i.e. its capabilities, browser, tablet etc.);
- The identity of the current user and his role;
- The current course (content or page reference).

All this information can be passed either through a widget API (e.g. passing URL parameters) or via more modern ways such as the LTI API. According to the user role there should be different UIs. Thus some first requirements for a widget service should be:

- An API to call the widget and pass user identity and context;
  - For this, LTI usage is encouraged
- Specific endpoints (URLs) that will service each user according to his role
  - E.g., service administrators visit http://www.mywidgeturl.org:8080/admin
  - E.g., a VLE admin visits http://www.mywidgeturl.org:8080/lti/register

It is not necessary for widgets to implement all these user interfaces. For example, the FORGE widgets of Teacher Companion Lab courses don't need to provide a Learner UI since they can be used only by Teachers.

17.5 Courseware and Evaluation

In this section the FORGE methodology is presented. It has been developed based an analysis of the state of the art in educational technologies with a specific focus on remote laboratories and online learning. We also outline the FORGE mechanisms for collecting learning analytics information based on a synthesis of available research and using existing technologies and standardisation efforts. Finally, we provide an overview and evaluation of five FORGE courses presented to over one thousand students.

17.5.1 The FORGE Methodology

One of the main goals of FORGE is to enable educators and learners to access and actively use FIRE facilities in order to conduct scientific experiments. We thus follow a constructivist approach to education where learning takes place by students creating artefacts rather than assuming the passive role of a listener or reader. Our approach is based on a wide range of studies that have shown that with the right scaffolding competent learners benefit greatly from constructivist or learning-by-doing approaches (De Jong, 2006, Hakkarainen, 2003, Kasl and Yorks, 2002). The experiment-driven approach of FORGE contributes to fostering constructivist learning by turning learners into active scientific investigators, equipped with world-class experimentation facilities.

From a learning technology perspective, FORGE is building upon new trends in online education. More specifically, in online educational platforms such as iTunes U, as well as in MOOCs, we see the large-scale take-up and use of rich media content. These include video in a variety of formats including webcasts and podcasts and eBooks, which can contain multimedia and interactive segments. In particular, eBooks provide a new level of interactivity since specific learning text, images and video can be closely integrated to interactive exercises[19]. In the context of the European project EUCLID[20] (EdUcationalCurriculum for the usage of Linked Data), we have been producing such interactive learning resources about Linked Data and delivering them in a variety of formats, in order to be accessed from a

[19]http://www.youtube.com/watch?v=KXCHKYsi1q8
[20]http://www.euclid-project.eu

variety of devices, both mobile (tablets and smartphones), as well as desktop computers. Building on this work, FORGE is producing interactive learning resources targeting a wide range of mediums and devices in order to maximise its impact on the eLearning community.

FORGE is enabling students to set-up and run FIRE experiments from within rich related learning content embedded as widgets inside interactive learning resources. Widgets are powerful software components that can be reused across different learning contexts and for different educational purposes. They offer a simple interface and can accomplish a simple task, such as displaying a news feed. They can also communicate with each other and exchange data, so that they can be used together to create mashups of widgets that complement each other. The portability of widgets as bespoke apps that can be embedded into a variety of online environments ensures that the FORGE learning solutions implemented as widgets have a high reusability factor across multiple learning domains and online learning technologies. Within FORGE, widgets enable educators and learners to access and actively use Future Internet facilities as remote labs in order to conduct scientific experiments. Learners and educators can setup and run Future Internet experiments from within rich related learning content embedded as widgets inside interactive eBooks and LMSs.

The FORGE methodology for the production of FIRE-enabled course consists of the following steps(Mikroyannidis et al., 2016):

- *Specifying course requirements.* In this step, the educator specifies the overall course requirements, including the learning objectives of the course, the required skills, the skills that will be acquired by learners after completing this course, the course timeframe, the number of learners and the method of delivery (online, face-to-face, or blended).
- *Identifying FIRE facilities.* In this step, the educator identifies the FIRE facilities that will suit the course requirements. These FIRE facilities will be selected based on their suitability for the learning objectives of the course and its associated skills. The number of learners and timeframe will also play a role in selecting a FIRE facility based on its availability. The first and most important task is to identify the *facility features* which match the intended course content. When someone, for example, wants to include experimental exercises using specially developed wireless transmission protocols, a facility should be chosen where one has permission to adapt the radio drivers or where one can

use cognitive radio devices, etc. A basic overview of the most prominent facility features covered in Fed4FIRE[21] portal.

- *Authoring educational content.* The educational content that will form the learning pathway of the course is authored in this step. Finding open educational resources that are suitable for the course is quite important, as these can be reused, adapted and repurposed to fit the course learning objectives and other requirements. These resources can have the form of text that describes the theory behind a specific exercise, questionnaires with multiple-choice options, videos with lectures, videos with instructions on how to conduct the exercise, images and diagrams about the architecture and topology of the required components, graphical representations of the desired results etc.
- *Integration of FIRE facilities and content.* In this step, the selected FIRE facilities and the educational content of the course are integrated in order to form the complete learning pathway. FIRE facilities are commonly integrated as widgets, which can be reused across different learning activities for different learning purposes.
- *Deployment.* The deployment of the course for delivery to learners is performed in this step. Depending on the course requirement for delivery (online, face-to-face, or blended), the educator can deploy the course within a LMS, a VLE, or as an interactive eBook.
- *Evaluation.* In this step, the educator evaluates the success of the course, based on qualitative feedback received from learners via surveys and questionnaires, or via quantitative data collected by Learning Analytics tools that track the interactions of learners with the course materials and with each other.
- *Reflection and adaptation.* By analysing the qualitative and quantitative data collected from the evaluation of the course, educators have the opportunity to reflect and draw some conclusions not only about potential adaptations and improvements to the course, but also, and most important, on the impact of the course on the students and their skills and knowledge acquired.

Figure 17.7 summarizes the FORGE methodology, showing the steps to be followed in order to deploy, create, use, and/or reuse a FORGE course. As depicted, two main phases should be considered: a) Course preparation, and b) Course deployment. In each phase, different processes are defined in order to

[21]http://www.fed4fire.eu

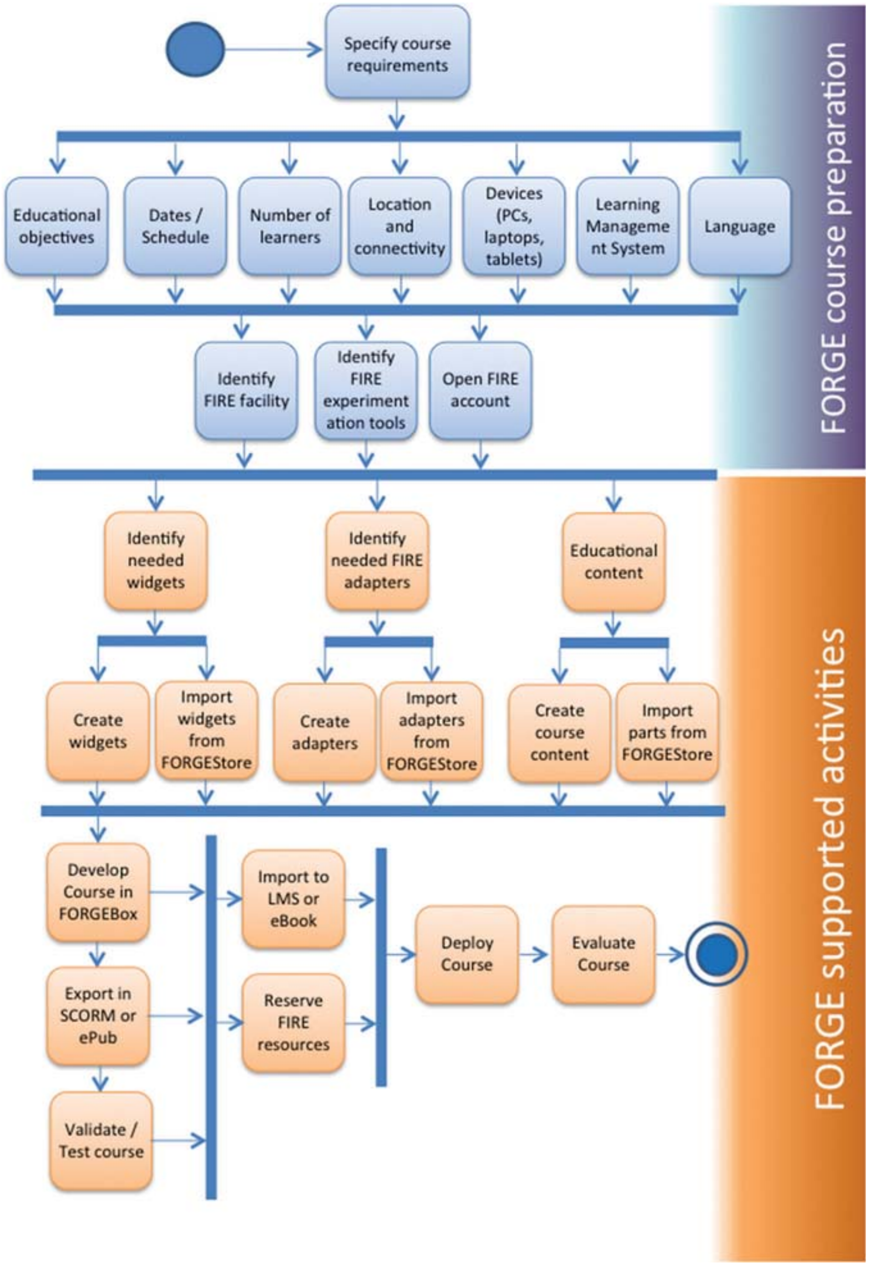

Figure 17.7 The FORGE methodology flowchart.

guide course developers and learners towards a successful course deployment and learning experience.

17.5.2 Learning Analytics

Learning Analytics can be described as the *"measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning and the environments in which it occurs"*.[22] The field of Learning Analytics is essentially a *"bricolage field, incorporating methods and techniques from a broad range of feeder fields: social network analysis (SNA), machine learning, statistics, intelligent tutors, learning sciences, and others"* (Siemens, 2014).

Learning Analytics applies techniques from information science, sociology, psychology, statistics, machine learning, and data mining to analyse data collected during education administration and services, teaching, and learning. Learning Analytics creates applications that directly influence educational practice (Shum et al., 2012). For example, the OU Analyse[23] project deploys machine-learning techniques for the early identification of students at risk of failing a course. Additionally, OU Analyse features a personalised Activity Recommender advising students how to improve their performance in the course.

With Learning Analytics, it is possible to obtain valuable information about how learners interact with the FORGE courseware, in addition to their own judgments provided via questionnaires. In particular, we are collecting data generated from recording the interactions of learners with the FORGE widgets. We are tracking *learner activities*, which consist of interactions between a *subject* (learner), an *object* (FORGE widget) and are bounded with a *verb* (action performed). We are using the Tin Can[24] API (also known as xAPI) to express and exchange statements about learner activities, as well as the open source Learning Locker[25] LRS (Learning Record Store) to store and visualise the learner activities.

Figure 17.8 depicts the widget-based architecture adopted in FORGE. The FORGE widgets use LTI 2.0[26] for their integration within a LMS. The FIRE

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[22] 1st International Conference on Learning Analytics and Knowledge – LAK 2011 https://tekri.athabascau.ca/analytics/

[23] https://analyse.kmi.open.ac.uk

[24] http://tincanapi.com/

[25] http://learninglocker.net/

[26] http://www.imsglobal.org/toolsinteroperability2.cfm

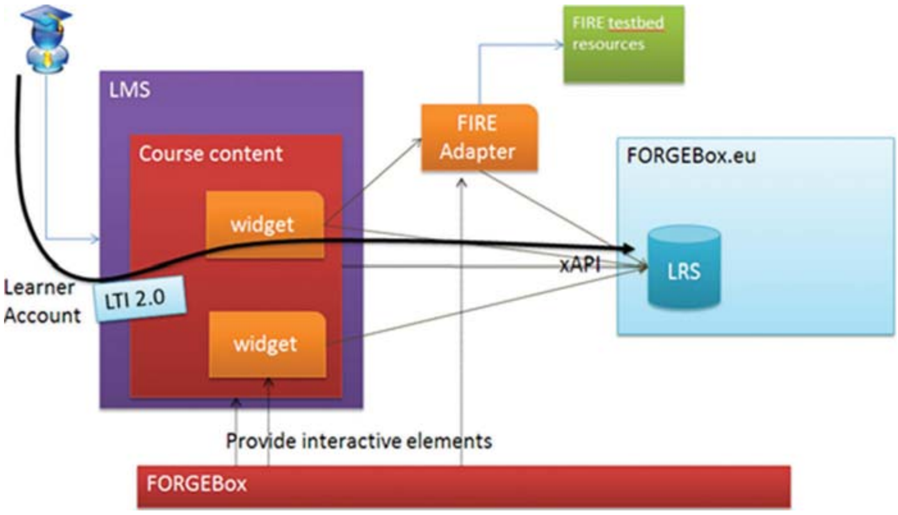

Figure 17.8 The widget-based FORGE architecture for learning analytics.

Adapters function as a middleware between the FORGE widgets and the FIRE facilities (testbeds), while the FORGEBox layer offers a seamless experience while learners are performing a course, reading content and interacting with FIRE facilities. All the interactions performed by users on the course content and the widgets are recorded and stored in the Learning Locker LRS using the xAPI.

Learner activities on the FORGE widgets typically include the initialisation of an experiment, setting the parameters of the experiment and, finally, completing the experiment. Therefore, the learner activities captured by the FORGE widgets use the following types of xAPI verbs:

- *Initialized*[27]: Formally indicates the beginning of analytics tracking, triggered by a learner "viewing" a web page or widget. It contains the (anonymised) learner id and the exercise/widget that was initialized.
- *Interacted*[28]: Triggered when an experiment is started by the learner, containing the learner id, the exercise and possible parameters chosen by the learner. These parameters are stored in serialized JSON form using the result object, as defined by the xAPI.

[27]http://adlnet.gov/expapi/verbs/initialized
[28]http://adlnet.gov/expapi/verbs/interacted

- *Completed*[29]: The final verb, signalling completion of an exercise by the learner. We can also include the duration that a learner took to perform the experiment, formatted using the ISO 8601 duration syntax following the xAPI specifications.

More specialised learner activities are also recorded by the FORGE widgets depending on the functionalities offered by each widget. For example, the PT Anywhere[30] widget, which offers a network simulation environment, records the following types of activities, reusing already defined vocabulary[31]:

- *Device creation, update and removal*: We use the verbs “create”, “delete” and “update” from “http://activitystrea.ms/schema/1.0/”.
- *Link creation and removal* (i.e., connecting and disconnecting two devices): The link creation and removal is expressed as a user creating a link that has its two endpoints defined as contextual information. Another alternative could have been to use non-existing connect/disconnect verbs to express that a user connects a device to another one (the latter should have been added as contextual information). However, we chose the first alternative because it reuses already existing verbs.

FORGE provides learners with Learning Analytics dashboards in order to raise their awareness of their learning activities by providing an overview of their progress or social structures in the course context. Learners are offered with detailed records of their learning activities, thus being able to monitor their progress and compare it with the progress of their fellow learners. Additionally, the Learning Analytics dashboards targeted to educators provide an in-depth overview about the activities taking place within their courses, thus making the educators aware of how their courses and experimentation facilities are being used by their students.

17.5.3 WLAN and LTE (iMinds)

iMinds has created two ‘flipped labs’ (for blended learning in a ‘flipped classroom’) for learners to better understand what is affecting the data throughput over two different types of wireless networks. One lab is using a Wireless Local Area Network (WLAN) network with Wi-Fi technology while the other lab is using a 4G cellular network with Long Term Evolution (LTE) technology. By changing parameters in web based ‘widgets’ with a cross-platform and

[29]http://adlnet.gov/expapi/verbs/completed
[30]http://pt-anywhere.kmi.open.ac.uk
[31]https://registry.tincanapi.com

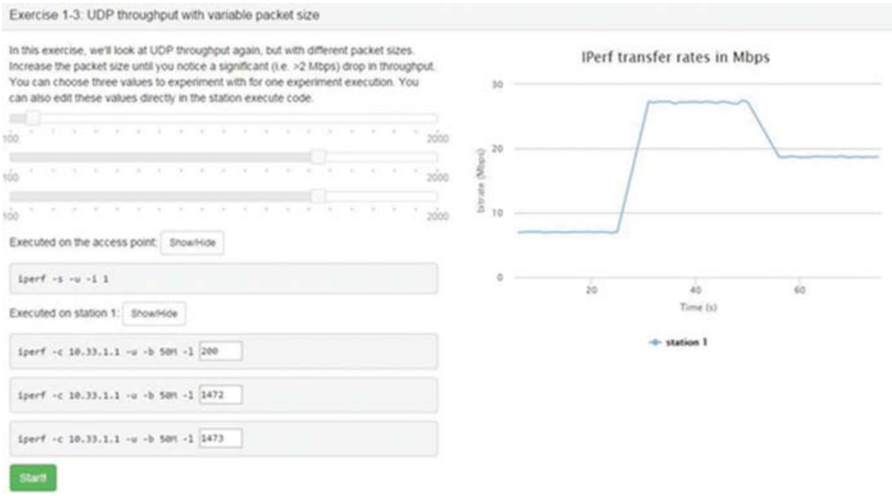

Figure 17.9 Screenshot of a web-based learner interface at the iMinds' WLAN and LTE lab.

easy-to-use interface (which is integrated in e.g. a LMS, eBook or any web page), learners can see the resulting throughput in a graph, based on the measurement results that are being collected from a real live experiment at the FIRE facilities of iMinds. Various back-end 'adapters' enable the communication between the front-end widgets and the actual resources at the FIRE facilities via the jFed CLI.

These labs were traditionally taught with local hardware, but were ported via the FORGE project to FIRE facilities. We now benefit from the resulting 'flipped labs' because the automating of the lab configuration simplifies lab sessions organisation at any given moment and at any given location. Furthermore, more advanced hardware of FIRE facilities can be used that would otherwise be unavailable locally.

The course is executed on two FIRE facilities, operated by iMinds: the w-iLab.t wireless testbed and the Virtual Wall (see Figure 17.10). The actual experimentation machines are located in the w-iLab.t testbed, where they are dynamically selected from 75 wireless nodes, depending on availability. These machines are controlled from a node of the Virtual Wall, a testbed consisting of 400 multi-core servers.

The Virtual Wall node contains the interactive course components and is responsible for controlling the wireless nodes with an "cOntrol and Management Framework" (OMF) Experiment Controller. All user interactions go

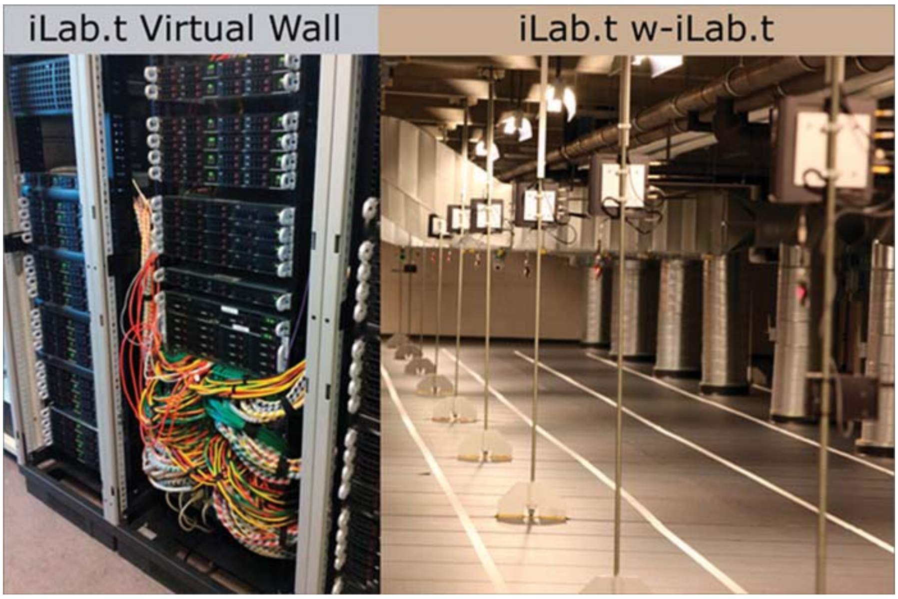

Figure 17.10 iMinds' iLab.t testing facilities used for the WLAN and LTE labs.

through this machine, which uses adapters and widgets, developed within FORGE, for executing and visualizing the experiments. Thanks to our extensions within the widgets and adapters, multiple learners can simultaneously access the interactive course and share FIRE resources.

The WLAN lab was executed for the first time for about 90 students in February 2015 at Ghent University (Belgium). Next additional executions took place at Trinity College Dublin (Ireland) in February 2015 for about 25 students and at Universidade de Brasil (Brazil) in May 2015 for about 20 students. During 2016, the WLAN course was executed a few more times: once again at Ghent University in March 2016 for about 90 students, once again at Trinity College Dublin in March 2016 for about 25 students, once again at Universidade de Brasil in May 2016 for 8 students and once at Universitat Politècnica de València (Spain) in December 2015 for 6 students. The LTE course was also deployed and executed in 2016: once at Ghent University in April–May 2016 for about 90 students and once at Universitat Politècnica de València (Spain) in December 2015 for 6 students.

Both teaching methods are possible for executing the WLAN or LTE lab: 'in-classroom' versus 'self-assessment'. When taught 'in-classroom', the lab

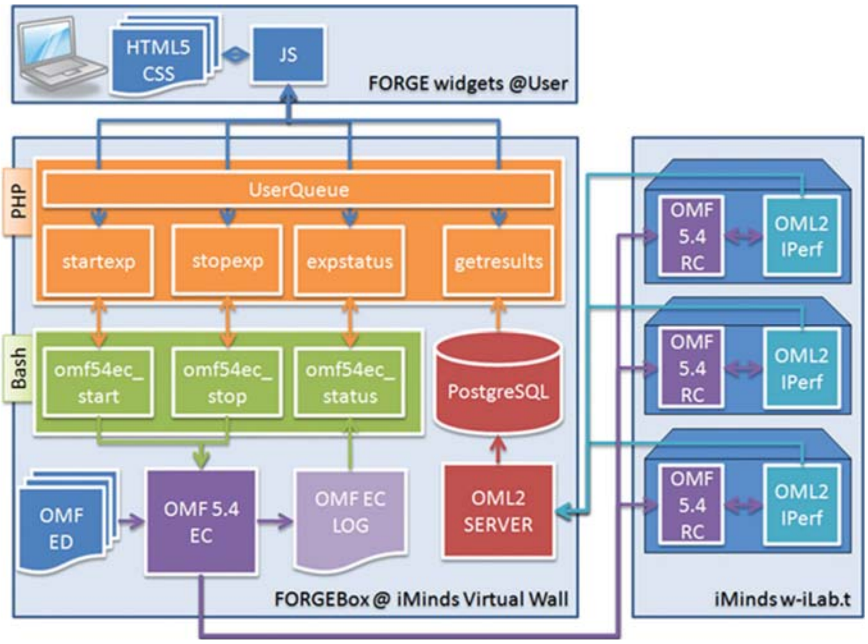

Figure 17.11 Interaction of different components between learner and FIRE facilities for the iMinds' WLAN and LTE labs.

was organized to last for 2–3 hours and took take place in a computer lab room where students could perform the FIRE experiments online with coaching of university staff members. The students answer the lab questions on paper or online and staff members corrected these afterwards. When taught as 'self-assessment home assignment', the students were given some time (typically about two weeks) to perform the lab individually at the time and the moment of their choice. The lab questions, which students had to answer, were converted to allow automated correction (i.e. multiple choice questions, numeric answers and 'fill-in-the-gap' questions) within a dedicated (Moodle-based) system to make this self-assessment possible and to provide immediate feedback to the students.

We also collected both qualitative and quantitative feedback from the students themselves. The qualitative feedback was collected via a survey, using 5-Likert-scale statements and some open questions. For quantitative feedback, learning analytics were applied using TinCan API, Learning Locker etc. In Figure 17.12, we have plotted the average score for each of the different qualitative survey questions, both for 2015 and 2016 for students at Ghent

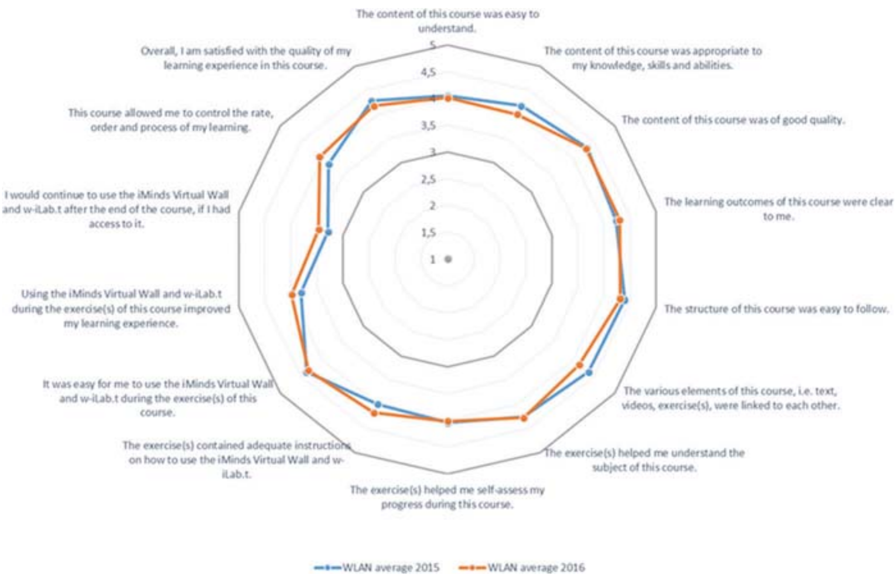

Figure 17.12 Average score for the qualitative survey questions.

University. These had to be quoted on a 5-Likert-scale (1: strongly disagree, 3: neutral, 5: strongly agree). We notice very good scores for the different statements, averaging around ‘4’ (“agree” with the statement) and the scores are consistent for 2015 and 2016. This indicates we were able to implement a successful course concerning its quality, effectiveness and ease of use.

Some student quotes from the surveys, which represent the general tendency, are mentioned below:

- *“The iMinds wall was easy to use”*
- *“Hands on approach”*
- *“No configuration hassle”*
- *“Actually learned some interesting concepts”*
- *“Cool new concept”*
- *“I could “pause” the session whenever i wanted and resume when i had time.”*
- *“Modern and interactive learning environment”*
- *“I surprisingly enjoyed this Lab session a lot more than I thought I would”*
- *“The FORGE system is amazing!”*

The students were also asked whether they liked the overall concept of the home assignment or if they would have rather preferred traditional lectures and labs in-classroom. The results in Figures 17.13 and 17.14 show that more than 4 students out of 5 prefer this way of blended learning.

Based on the collected quantitative learning analytics information, teachers could analyse the most common mistakes students make and adapt their course to explain certain parts better. Furthermore, the activity of the different students could also be tracked and compared to their automated score within the self-assessment home assignment. This allows also to identify students who have cheated by extracting students who provide the correct answers to a question without having performed the necessary related experiment.

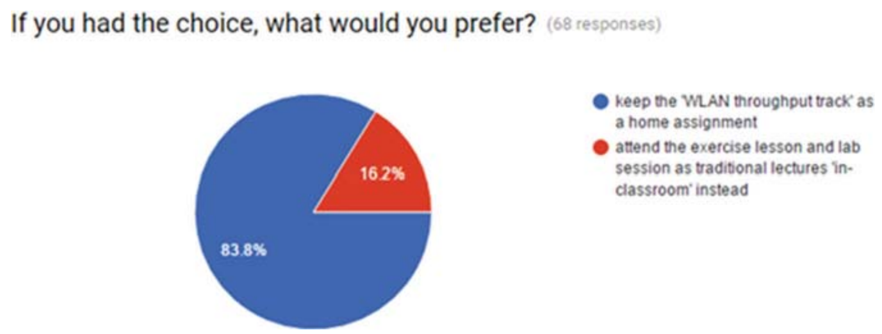

Figure 17.13 Preference of students (in 2016) for using the WLAN course as online home assignment versus teaching this via traditional in-classroom lectures.

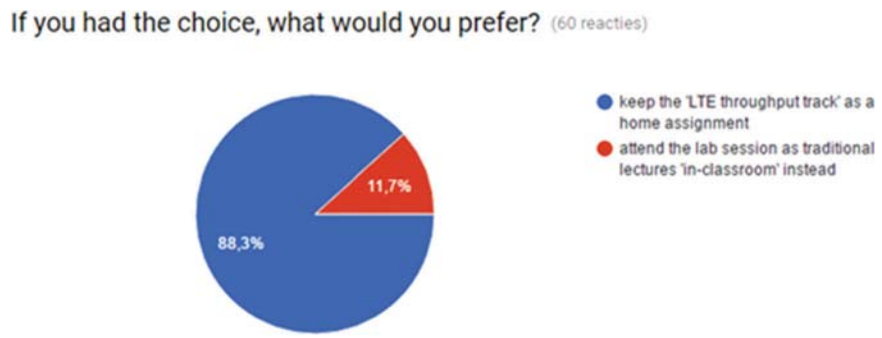

Figure 17.14 Preference of students (in 2016) for using the LTE course as online home assignment versus teaching this via traditional in-classroom lectures.

17.5.4 TCP Congestion Control and Metro MOOC (UPMC)

Université Pierre et Marie Curie (UPMC) run the PlanetLab Europe (PLE) Network Operation Center (NOC). Thanks to its experience, it invested in PLE related widgets and FIRE adapters for setting up a prototype course – UPMC TCP Congestion Control. This in turn supported the launch of an external course called METRO MOOC. The UPMC TCP Congestion Control prototype course focus on a fundamental mechanism of TCP. After few exercises illustrating the congestion control mechanisms, real traces of long distance traffic are performed on the PLE facility and are analysed with a packet analyser tool. The development of the course itself is in line with the methodology described by FORGE.

Concerning the execution of the course, the initial planning was to include the course inside a basic networking teaching unit, taught in French and in English for several kind of students (Classical students, part-time industry students and EIT-digital Master School students). The course took place in October 2014 and October 2015, each time for one week. The PLE resources reservation and the teaching team preparation were done the week before. The maximum number of student groups at the same time guided resource reservation (students work in pair in all tutorials works). The maximum number of students in a group at the same time was 2, and there was a total of 30 student groups. All groups perform the course during the same time. Therefore, we made reservation of 1 PLE slice with 66 nodes: 33 Clients (30 + 3 spare nodes) and 33 servers. The only resource where the pair must be alone is the client to generate a correct capture. The 33 servers can be shared and are supposed to serve 3 clients each. We used a dedicated tool to make the reservation on the PLE slice to generate all the configurations. Figure 17.15 shows an example of the configuration.

The UPMC prototype course was executed two times in the classroom with a web interface on the computer where students usually make their practical work. Groups of 30 students worked in pairs with one tutor. These course labs follow a 2-hour lecture about Congestion control theory. The labs last for 4 hours but the remote lab part is quite short and is only needed to get some remote traces to analyse locally with the tools commonly used by students. The qualitative feedback was collected via a survey. The demographic information concerning the student include the following:

- 2014 web based UPMC course: 168 students
    - 160 French speaking/8 English speaking (ICT Digital)
    - 23 female (14%)/124 male (86%)
    - Most of the student are in the 21–30 age slot (average 22.3)

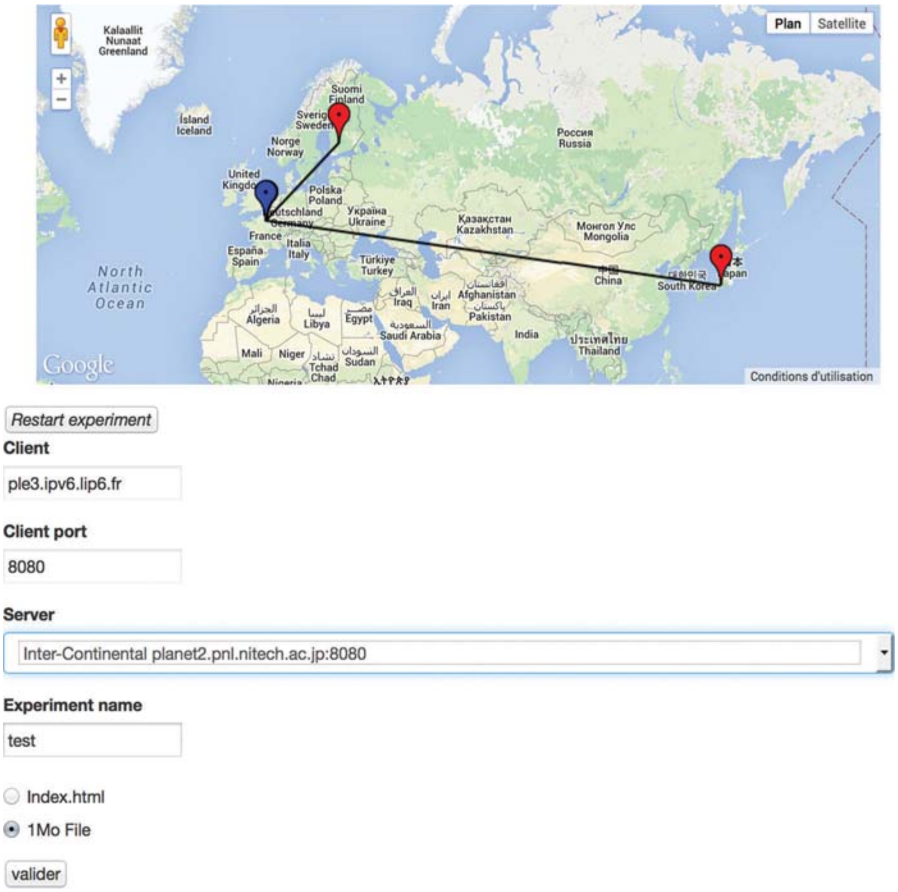

Figure 17.15 The TCP congestion control widget.

- 2015 web based UPMC course: 150 students
  - 144 French speaking/6 English speaking
  - 26 female (17%)/124 male (83%)
  - Most of the student are in the 21–30 age slot (average 22.4)

In Figure 17.16, we have plotted the average score of each different question, both for 2014 and 2015.

UPMC also provided assistance with the creation of an external course called: “The Internet Measurements: a Hands-on Introduction” MOOC, which is offered by the French national e-learning platform France Université Numérique (FUN). This course has been developed with the METRO FORGE

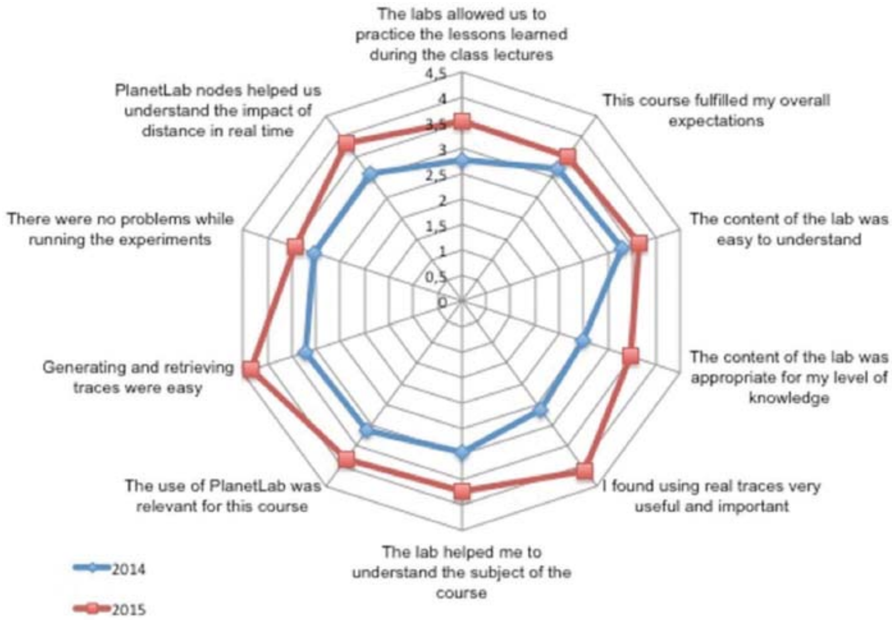

Figure 17.16 UPMC lab course questionnaire average score (2014 and 2015).

open call project proposed by INRIA. This MOOC is intended to attract as much as 5,000 students. It has been open to public since 23 May 2016 and also uses PLE testbed for experimentations such as ping, traceroute and iperf. There are potentially hundreds of requests coming to the PLE testbed every minute in the MOOC context along with the usual usage by the researchers and PLE members. It is quite obvious that PLE can't handle such a high volume of requests coming almost every minute. In order to not overload the testbed side, the MOOC developed a REST API based solution with job scheduling. All the MOOC experiment requests are stored directly in a NoSQL document based database at the beginning with a job status "waiting to be executed". There are several agents (threads) checking the new jobs as soon as they arrive and based on the job already in hand they schedule and process the new jobs. The agent also calculates an estimated time of executing the new jobs and informs the users to come back after a certain time period to check the results. When the agents are free to take new jobs they process them and change the job status to "executing" and then to "completed". In this way the agents don't overload the testbed by scheduling the time to process new jobs. It is worthwhile to mention that, all available PLE nodes are used for the MOOC. No nodes are reserved in advance, the agents do it in real time. That is to say, at this moment all the available PLE nodes will be visible to the students and they have the liberty to select any nodes of their choice to perform their experiment. If a node goes down while performing the experiment the user will receive an error message.

Some preliminary participation results from the MOOC:

- 1824 registration
- 1440 participants have 0% score (no exercise resolved)
- 155 certificate (score >50%)
- 27 participants have 100% score

In the latest edition of the FIRE PLE adapters, we have used all the PLE nodes available at the time of experiment. A service is running in the background checking the availability of PLE nodes every few minutes. By *available* we mean that all the PLE nodes that are up and running at the time of experiment not all the PLE nodes that are not reserved. Since PLE uses virtualisation for each reservation, a single node can be reserved by several users at the same time. Due to this powerful feature, the learners are given all the PLE nodes for experiment through a dropdown list. In order not to overload a specific node, we use a queuing mechanism. If multiple learners choose a specific node, we put them in the queue on a first come first serve basis. We also gave them an estimated time to completion of the experiment. For the moment, we're allowing only 2 experiments to run simultaneously on a single node. This can be scaled to more if the node is capable of handling it. Another reason for not allowing more than 2 experiments simultaneously is not to interrupt the usual usage of these nodes for the other PLE users. Figures 17.17–17.19 describe how the queuing system works for PLE.

Figure 17.17 Experiments in queue before sending to PLE.

Traceroute example 1	1 month, 3 weeks ago	job completed	View
TCP congestion	22 seconds ago	executing job	View
TCP congestion	34 seconds ago	executing job	View

Figure 17.18 Experiment sent to PLE.

Traceroute example 1	1 month, 3 weeks ago	job completed	View
TCP congestion	45 seconds ago	job completed	View
TCP congestion	57 seconds ago	job completed	View

Figure 17.19 Experiment completed and result available.

17.5.5 OFDM (Trinity College Dublin)

In this course, students investigate how Orthogonal Frequency-Division Multiplexing (OFDM) wireless signals work by connecting students to advanced research hardware to investigate the sometimes troublesome digital multi-carrier modulation method as applied to wireless communications. Through this experience, students gain an appreciation of the most important factors in the use of OFDM for wireless experiments by exploring the configuration and use of real radios.

TCDs OFDM course runs completely on IRIS software defined radio (SDR) testbed facility. The IRIS testbed consists of 16 flexible radio USRP units each connected to a virtual machine that runs an SDR such as IRIS or GNU Radio. Resources are provisioned automatically by the gateway server, which also supports initialization of experimentation services such as measurement point data collection. A conceptual diagram of IRIS's virtualized cloud resources, radio hypervisor, user experiments and physical equipment is shown in Figure 17.20.

This course has been taught in the lab environment where students execute remote experiments on TCD's wireless testbed with support from a lab instructor. It has been presented nine times over the last twelve months in Brazil, Mexico and Ireland to a total of 148 students running at least 1,400 experiments. There are currently two versions of the course. The first version has been presented to approximately 132 students. To date, the second version

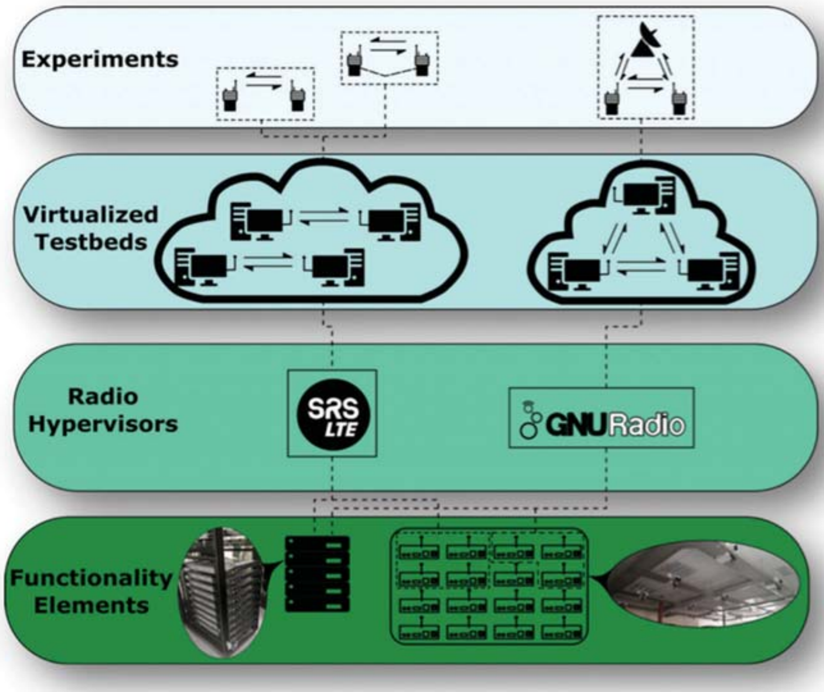

Figure 17.20 TCD's IRIS testbed.

of the course has been presented to 16 students running remote experiments from Brazil. At present, teachers reserve the testbed for use in a remote experimentation based lab.

Evaluation information was collected from students after execution of the first version of the course using the standard FORGE 5-Likert scale questionnaire template. A screenshot of sample summary feedback received from students using TCD's testbed is available in Figure 17.21. In general, over 90% of students who participated the lab agreed that the OFDM experiments helped them to understand the concepts being taught in the lectures. Additionally, over 90% agreed that they were aware the experiments were being run remotely on TCD's wireless testbed while over 76% agreed that the web interface helped to reduce the difficulty of the lab. Furthermore, over 90% of student agreed the lab helped them to self-assess their progress. Finally, almost 80% of students surveyed would like to use the testbed facility in the future if they had access to it. More detailed instructor feedback was also gathered, but in an informal manner via email. In general, the information received

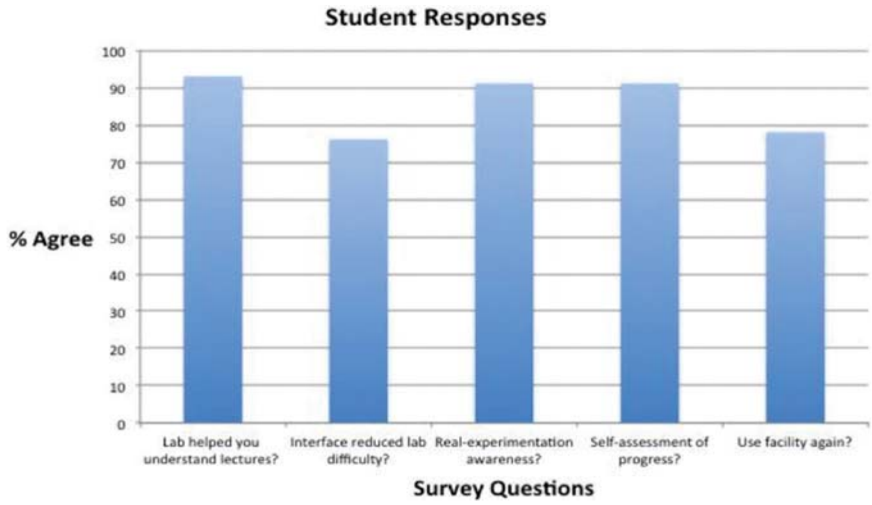

Figure 17.21 Responses from survey of first version of TCDs OFDM course.

about the course, content and structure was very positive from both students and teachers. However, several requirements to improve the course were also identified. These included the need for a more scalable, responsive, sustainable and reusable system with the ability to provide real-time information to end-users.

This feedback led directly to the course being redesigned and redeveloped to use GNU Radio, an open source SDR with a large user and developer community. This change was required as TCDs IRIS SDR system used in the first version of the course, which is flexible and adaptive for advanced wireless research and experimentation, was determined to have a much smaller development and support community than GNU Radio. It was decided that this would affect the long-term sustainability of the existing course and the development of future advanced SDR courses. Additionally, existing components developed by other users in GNU Radio could be easily incorporated into existing and new courses, which can reduce course development and testing time.

Furthermore, another change to the course involved collecting measurement data in real-time. This is now collected using OML and presented by JavaScript-based interactive widgets to students. A screenshot of sample real-time graphs displaying data received from TCD's IRIS testbed from the second version of the OFDM course supported by GNU Radio are available in Figure 17.22.

Figure 17.22 Real-time constellation measurements.

As the OFDM course architecture was almost completely redeveloped, we could only recycle the control component widget developed in the version 1 IRIS implementation. However, we reused and expanded a graphing widget developed by iMinds to support the generation of frequency, time, waterfall and constellation graphs from an SQLite database. Additionally, we utilized NICTA's OMF Measurement Library for the collection of real-time measurement point data during experiment execution. We also implemented some basic learning analytics, to help determine what commands were being executed by students primarily for technical support purposes. Furthermore, we developed an XML adapter to support users sending configuration parameters to GNU Radio in real-time.

GNU Radio is the most dependable, reliable, reusable and sustainable SDR platform to support remote experimentation on the IRIS testbed. This has been validated in a recent deployment of the OFDM course to 16 students in University of Brasilia, Brazil who were able to change OFDM parameters, send data packets and monitor USRP activity in real-time. Aside from some minor bugs experienced during course execution, positive feedback about the system stability and responsiveness and graph visualisation has been received from both students and teacher. Finally, the integration of learning analytics has helped the OFDM course implementers detect weaknesses in course design helping to further improve the quality of the online lab.

17.6 Discussion

FORGE has been investigating how FIRE facilities, which have been built primarily for research purposes, can be reused and adapted for teaching and learning purposes. The project has provided evidence that FIRE testbeds can function as world-class remote laboratories for educators and learners and can be used for online experimentation within a variety of learning contexts. However, the usage of FIRE for educational purposes also raises certain issues and challenges that the FIRE facilities have not encountered before (or not in a high degree).

A first challenge is security related. FORGE has created different web-based educational widgets that run on a web server, which can be part of the experiment itself. The experiments are thus executed and manipulated by the web server (via web based requests by the learner) rather than directly by the learner. The resources and accompanying widgets/adapters on the web server might furthermore not have been reserved by the learner himself/herself, and the learner might thus be controlling (via a web server) resources that were reserved by someone else (typically by the educator). This requires using a kind of 'proxy' or 'speaks-for' mechanism, securely allowing the sharing of resources amongst multiple FIRE accounts.

Another significant challenge lies in the fact that there is no common reservation system in place for all FIRE facilities. Depending on the scarcity of resources used by a lab, a certain reservation mechanism should be in place to guarantee the availability of the interactive exercises during a lab. When a group of learners (e.g. all students within the same classroom) are following the same course and executing the same experiments, a large number of FIRE resources will be required at the same moment of time. When the specific FIRE resources, which are needed, are scarce, a (very) high resource occupation will be imposed on the hosting FIRE facility. In order to still accommodate the experiments of the different learners while not overloading their own facility, FIRE facilities need to elaborate their policy strategy into different categories (e.g. 'best effort' or 'premium') to force a more well-thought usage of the facility by learners and experimenters alike. A FIRE facility would also need to provide some sort of reservation mechanism to guarantee resource availability to the learner in case of pre-planned lab sessions, while the FORGE widgets and adapters hide the specific reservation and scheduling mechanic for the learner. These policy strategies and associated business models are subject to the sovereignty of the different FIRE facilities. To limit the number of simultaneously used FIRE resources

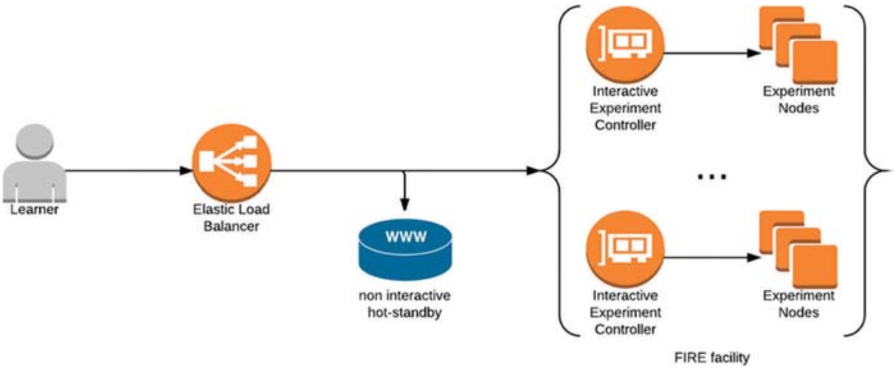

Figure 17.23 Load balancer with multiple experiment instances and graceful degradation via hot-standby.

by different learners, some of the FORGE adapters also add intermediate functionality by e.g. implementing a scheduling or queuing mechanism to allow multiple learners to share the same FIRE resources. A common reservation mechanism across FIRE testbeds would solve this additional complexity and would also provide an incentive and clear implementation path for FIRE facilities.

Since most FIRE facilities only offer 'best effort' resource availability, even with reservation, there is always the possibility of resource or total testbed failure. Even if there is no possible recourse to alleviate these kind of failures, a graceful degradation system can lessen the impact on the learner. A fall-back mechanism to a non-interactive version of the lab with a clear message to the learner can significantly increase the user experience. Ideally this fall-back mechanism would also allow to seamlessly switch back to the interactive version once connectivity is restored to the FIRE facility resources and retain any previous experiment results. This challenge can be solved by using existing load balancing techniques and software for redundant web services, as illustrated in Figure 17.23.

17.7 Conclusion

FORGE complements online learning initiatives with laboratory courses for an in-depth and hands-on learning experience. The constructivist approach of FORGE is based upon the notion of the experiment. FORGE allows students to create and conduct experiments using interactive learning resources within a comprehensive learning context. Towards this goal, the project has established a technological and pedagogical framework for remote labs and online experimentation, by defining a methodology for the design, delivery and evaluation of FIRE-enabled courseware.

FORGE has produced a wide range of networking and communication-courses, which have resulted in over 24,000 experiments undertaken by more than 1,800 students across 10 countries worldwide. FORGE has thus provided evidence that FIRE testbeds can function as world-class remote laboratories for educators and learners and can be used for online experimentation within a variety of learning contexts. Additionally, the project has identified certain challenges that have emerged from developing FIRE-based courseware, leading to a set of requirements and recommendations for supporting the use of FIRE facilities for teaching and learning.

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