Using Future Internet testbeds as a tool for the practical study of digital networking

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Abstract

In this paper, we discuss how Future Internet testbeds can be useful not only for experimenters but also for teaching networking classes, both in conventional environments and in the context of online courses. Access to experimental testbeds allows students to have hands-on experience that is impossible to provide with local resources in most organizations. This use of testbeds allows society to make use of idle resources and to profit from the public investments made in these infrastructures. Our work makes use of the FIBRE testbed, a research facility composed by a federation of 13 local testbeds located in different research and education organisations in Brazil and Europe. The paper contains a step-by-step description of how a student could use the FIBRE testbed in an example laboratory assignment involving routing.

Keywords: Future Internet testbed, hands-on classes, coursework

1. Introduction

Over the last ten years, the need to experiment with novel protocols for the Future Internet has resulted in the construction of a number of network testbeds. The best known of these experimental facilities include GENI in the USA (Geni, 2014)], AKARI in Japan (Akari, 2008) and various testbeds of the FIRE programme in the EU(FIRE,2014) In these and similar testbeds, close attention has been paid to the question of providing effective programmable network elements (routers and switches) at low cost.

The main reason behind the construction of Future Internet (FI) testbeds is the need for experimenting with new architectures, protocols and techniques in isolated environments, in order to gain insight into advantages and disadvantages of these proposed solutions and evolve the current Internet. To allow for experiments with the necessary scale and heterogeneity, FI testbeds must provide a large number of resources in different categories, and are thus not easy to construct and maintain. With this in mind, some NRENs are starting to offer testbeds as a service (GÉANT, 2014) targeting computer network research groups.

It is widely accepted that the Internet needs urgently to evolve and that research in this area is important and must be supported by funding agencies. On the other hand, not much attention is given to the development of human resources for this area. Undergraduate and graduate students take classical computer network classes that have had the same structure for many years, either using only theoretical performance models or resorting to simulation for a more empirical study of protocols. Real-world laboratories are seldom used, due mostly to the difficulties of maintaining them. However, their use can enhance the student experience in two important ways. In the first place, real machines and programs often exhibit behaviour that is different from what was described in the simulation model (Jain, R. 1991). Secondly, hands-on laboratory classes are notoriously motivating: over years of teaching computer networks and distributed systems, we have observed that students tend to enjoy seeing their programs running on real world environments and feel that they have accomplished more in this situation.

In this paper, we discuss how Future Internet testbeds can be useful for teaching both as a complement to conventional classes and in the environment of online courses. Our work makes use of the FIBRE testbed (FIBRE 2014) a research facility composed of a federation of 13 local testbed nodes, located in different research and education (R&E) organisations in Brazil and Europe.

The remainder of the paper is organized as follows. Section 2 describes the FIBRE testbed. Section 3 discusses some ongoing initiatives related to teaching in GENI and FIRE. Section 4 discusses the use of FIBRE for teaching and presents a step-by-step description of how a student could use the FIBRE testbed in a laboratory assignment. Finally, Section 5 contains some final remarks.

2. The FIBRE Testbed

Since around the year 2000, increasing problems in maintaining and extending the current Internet architecture have resulted in a correspondingly increased interest in research into new architectures, accompanied since 2005 by the planning and construction of experimental facilities to be able to validate at scale the properties of new architectural proposals. A significant contribution was introduced by the OpenFlow architecture (McKeown, N. et al. ,2008), , in which high-performance switching hardware is combined with a software-controlled, table-based, implementation of the control plane, which can easily be modified by the user, in this case, an experimental network designer. This architecture is proposed as an extension to production network element design, and most switch and router manufacturers already sell OpenFlow-capable hardware.

The FIBRE testbed was constructed in the scope of a project funded by the 2010 Brazil-EU Coordinated Call in ICT, jointly funded by CNPq (the Brazilian Council for Scientific and Technological Development) and by the European Commission within its Seventh Framework Programme (FP7). The testbed is currently composed of ten nodes (a.k.a. islands) located in Brazil and three in Europe.

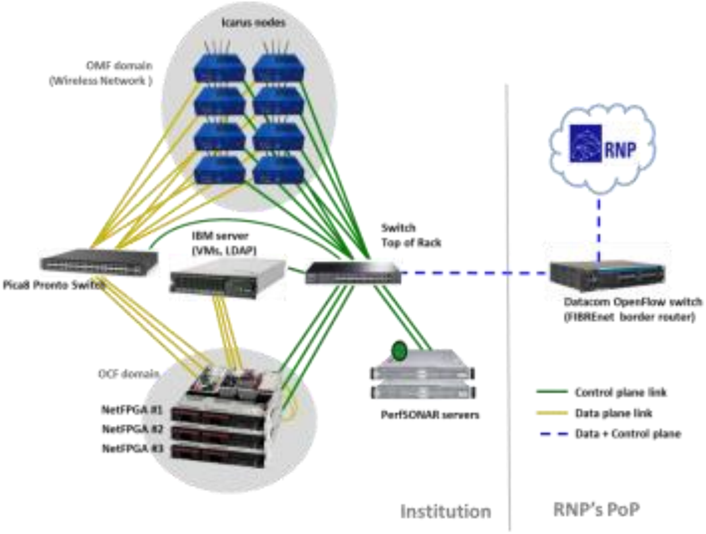


Figure 1. Overview of a FIBRE island in Brazil.

Each island has a common nucleus of OpenFlow-capable switches, together with their controller(s), as well as a cluster of compute and storage servers, appropriately virtualised, and (usually) a cluster of virtualised wireless nodes. Each site integrates its own site-specific resources to FIBRE, such as wireless access testbeds (Wi-Fi, WiMAX, 3G/4G), OF-enabled equipment, optical networks or even more complex testbeds with heterogeneous resources and their own control framework (e.g.: the Emulab(2014) [cluster at USP). Figure 1 illustrates a typical Brazilian FIBRE island, with its common facilities and external connectivity.

One of the challenges for network environments for experimentation is scale. Because experimentation networks are supported by real hardware, a large topology requires controlled multiplexing of the resources of the underlying physical system, to provide manageable virtual resources. The FIBRE testbed uses multiplexing techniques to slice control and data traffic based on a specific OF controller, the FlowVisor (Azodolmolky, S., 2012or channel scheduling for wireless, in order to virtualize resources like processing nodes, network devices and networks. It is worth mentioning that virtualization does not provide strict scientific fidelity, because the experiments are based on shared, rather than dedicated, physical resources. However, there are good reasons for relaxing this constraint: 1) some applications, like peer-to-peer systems, even though requiring large topologies are not resource-intensive; 2) the strict scientific fidelity requirement might be dispensable for many applications; and, 3) multiplexing allows more efficient use of limited hardware resources.

From the start, the project team decided that FIBRE should include the following Control and Monitoring Frameworks (CMFs): OFELIA Control Framework (OCF) (Sune, M , 2014) OMF (Rakotoarivelo, T., Ott, M., Jourjon, G., Seskar, I.,2010) and ProtoGENI (Duerig, J et al. 2012) The use of different CMFs represents a gain for the project as it allows the simultaneous orchestration of three complementary classes of resource: OpenFlow resources, wireless resources, and emulated resources. All CMFs were customized for use in FIBRE.

As aforementioned, federation is a key issue in the design of the FIBRE testbed. In fact, one of FIBRE's goals was to design a framework where all the CMFs adopted can work together complementing each other, in addition to federating different instances of the same CMF. In its first phase, the FIBRE testbed is being accessed through a simple web interface (see Section 3). An important component in FIBRE's architecture is MySlice (Augé, J., 2013) [, a software layer that enables the creation of a federation abstraction, integrating the different FIBRE testbeds using the Slice-based Federation Architecture (SFA) (Petersen, L. et al,

2010) . This interface is based on a web client that allows users to interact with the great volume of results generated by each testbed island.

The distribution of FIBRE islands is shown in Figure 2. The integration of these resources creates a large-scale network. In Europe, there are three islands: one at i2CAT (Spain), one at the University of Bristol (UK), and one at University of Thessaly - UTH (Greece). The Brazilian part of the testbed is composed of ten islands widely spread across seven Brazilian states. Each island is controlled by one or more CMFs. Figure 2 shows the set of CMFs available in each island, and the network that connects them, called the FIBRE backbone.

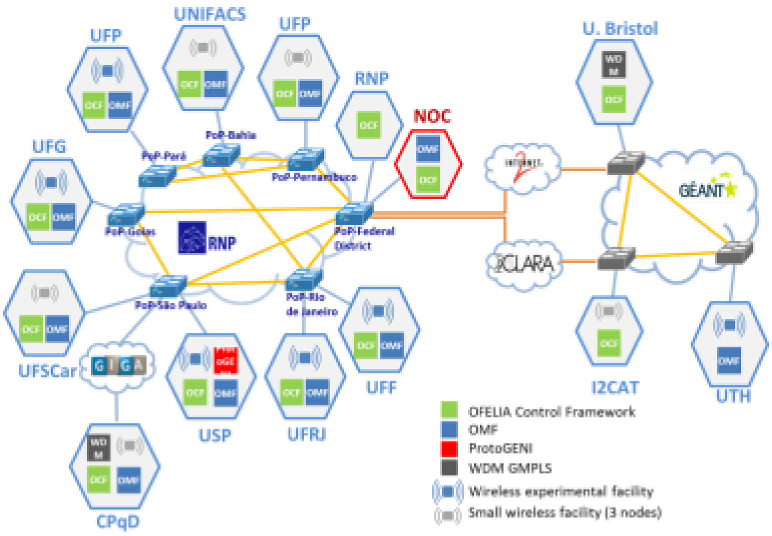


Figure 2: The FIBRE testbed

Each island in FIBRE monitors its resources using Zenoss, an open-source application for network management. Zenoss provides a web interface that allows administrators to monitor availability, performance, and events. Using Zenoss, a publicly available web page with information about network and virtual machines is made available to experimenters.

3. Initiatives in teaching in Future Internet testbeds

Future Internet testbeds have been the focus of several projects, around the world, over the last decade. Among these projects, GENI seems the one to have most actively advanced the use of the testbed in classes, with resources and direct support available to instructors. (Here we are not considering tutorials and training directed at researchers, but concentrating instead on learning activities.)

From 2012 on, GENI has been running training sessions specifically directed to teaching assistants (TAs). The GENI wiki (GENI WIKI) contains a section devoted to instructors. Besides detailed advice on planning classes that use the GENI testbed and downloadable material for classes, this section provides a number of example assignments. The last GENI conference (GEC21), held in Indiana, USA, on October 2014, included a panel discussion on the use of GENI in the classroom.

This dissemination effort seems to have frutified and a significant number of courses using GENI have been created, many of which explore the testbed for hands-on practice with wireless protocols and applications, whilst others focus on evaluation techniques and even cloud computing (Calyam, P.; Seetharam, S.; Antequera, R.B, 2014, Ricci, R.2014). These are mostly courses taught in a conventional format with homework and lab assignments that use the testbed.

Recently, the Department of Electrical and Computer Engineering at the NYU Polytechnic School of Engineering has also been developing a number of MOOC (massive open online courses) modules(FIRE,2014)], each of them covering a topic related to networks or distributed systems and containing hands-on activities that are carried out in the GENI testbed. The courses are offered through edX, the organization created by Harvard and MIT to provide openly available interactive material.

In 2013, the European Union 7th Framework Programme launched the Forge project [12], linked to the FIRE initiative (FIRE, 2014) Forge has as its motivation the use of the infrastructure made available by FIRE not only for research but also for learning. The project will develop widgets and materials that enable instructors and students to easily set up experiments related to educational activities. The idea is not only to increase the usage of FIRE facilities but to raise FIRE awareness in the long term, lowering the thresholds for experimenters to explore Future Internet testbeds.

4. Using FIBRE in the Classroom

Telecommunications and computer-science-related undergraduate programs typically contain a networking course in their curricula. Nowadays, hands-on classes in computer networks usually rely on software tools and virtual machines to teach practical classes in laboratories. Some of the most widely adopted tools are the Network Simulator (The Network Simulator) Cisco's Packet Tracer (Cisco Packet Tracer) and OMNeT++ (OMNet++). However, there remains a large gap between simulation and hands-on experiments. Through the use of a large-scale testbed, students can become familiar with building a virtualised, software-defined network, spanning multiple, geographically distributed nodes. This allows them a more concrete understanding of the current protocols and of their limitations, besides motivating more people to work in related research areas. Testbeds can provide an ideal environment for teaching conventional protocols, as virtual routers and machines can be configured to contain only the desired layers in the protocol stack, leaving students to re-implement the missing layers. Testbed portals provide repositories for virtual machines, facilitating the task for the instructor, who can upload the stripped-down versions, and for the students, who can configure the desired number of nodes and request that the indicated virtual machine be loaded on them. Once the virtual network is built, students could carry out network experiments before saving their virtual network and freeing-up the computational and network resources involved.

The implementation of the experimental facilities in Brazil, as well as their integration with the European facilities, offers a valuable infrastructure for research and education. In this section, we will describe how students can use the FIBRE testbed to configure and execute a static routing experiment in a dedicated virtual network through the OFELIA Control Framework (OCF) (Sune, M et al, 2014)

OCF was originally created in the context of the OFELIA testbed project but today it is supported by a wider community in which FIBRE and GEANT participate. From the point of view of experimenters, the available underlying network substrate is fully controllable through explicit and dynamic configurations based on the FlowSpace OpenFlow abstraction. Once a FlowSpace is set up, the instructor can proceed with the allocation of an OpenFlow controller, either remotely or in a local virtual machine, while students can participate by setting up the virtualized network and performing their experiments.

4.1 Experiment Description

We describe here the setup of a simple static routing experiment using the OCF. This experiment demonstrates how to create virtual machines and how to allocate a specific isolated network topology within the FIBRE network. The goal of theexperiment is to setup the routing as indicated by Figure 3; i.e. packets from endhost1 sent to the IP address 192.168.2.30 on endhost3 should be routed via endhost2.

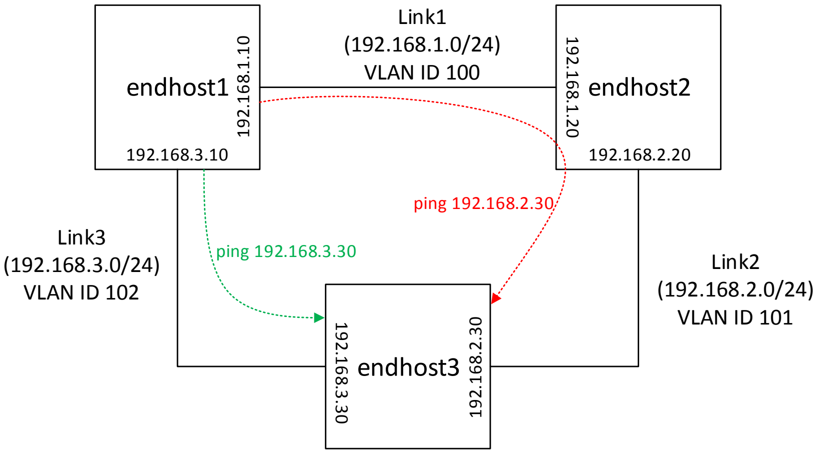


Figure 3.Static Routing Experiment.

In this experiment, we use three virtual machines in different sites of the testbed (end-hosts in Figure 3) connected through three isolated networks in a mesh topology. Each network link is an independent virtualized network that is dynamically allocated on top of the experiment data plane with a specific VLAN ID (100, 101 and 102 in this case). The endhost2 must be configured to forward packets coming through its network interfaces.

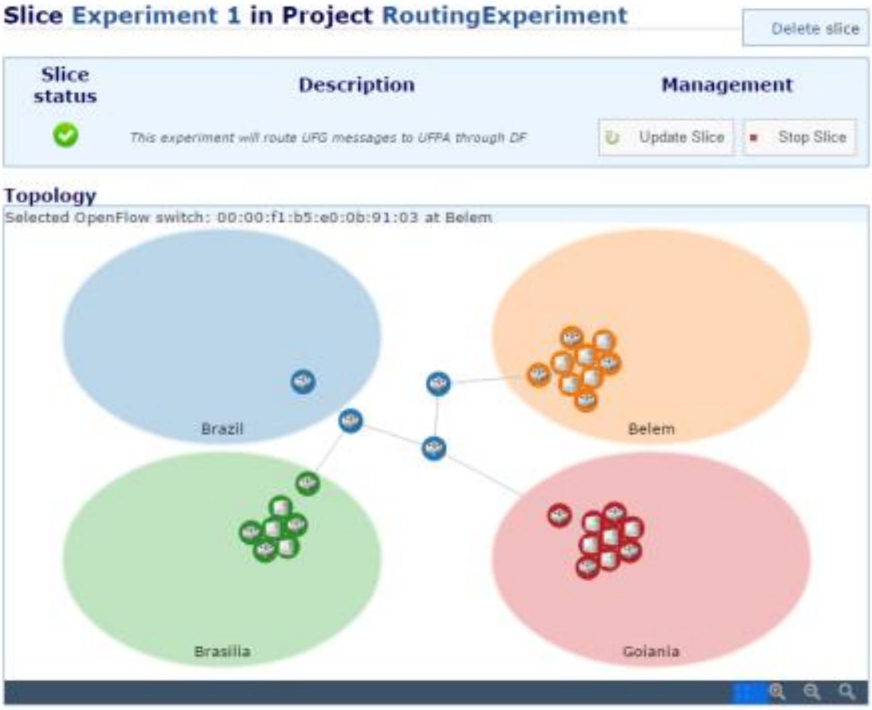
4.1.1 Setting up the experiment

OCF uses the concept of “slice” to describe an experiment. Slices describe the resources to be used and the associated configurations, and encompass the state of the experiment. Once the student has permission to participate in an experiment, he or she can either use existing slices associated to this experiment, or create new ones. When creating a new slice, information such as name, description and expiration date (the slice life-time) must be provided. After slice expiry, the FIBRE island may deallocate the reserved resources.

To set up an experiment, a student must first request access to a project in the OCF interface. Students can see and modify configurations in projects for which they have been granted permission. These permissions are usually granted by the project owners (teachers).

The experimenter must begin the setup of the experiment by making a reservation of the desired resources on the appropriate OCF instance. For cross-island experiments, experimenters must access the OCF instance running at the NOC and add to their project the necessary aggregates from all desired islands; experiments configured by an OCF instance running at an island may use only its own local resources.

On the Slice Management page (Figure 4), the Topology panel shows the physical topology of the resources in the aggregates available to the slice. These resources may comprise the available OpenFlow switches, virtualization servers, and the connections between switches and servers.



Slice Experiment 1 in Project RoutingExperiment

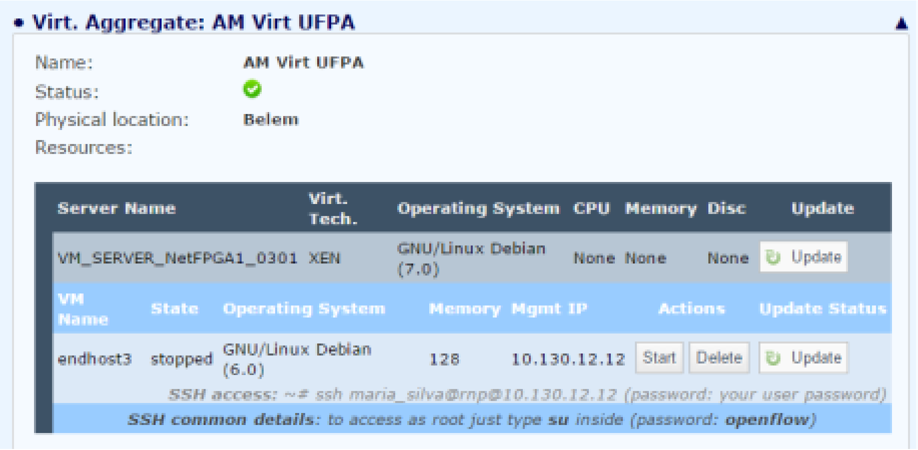
Slice status	Description	Management
✓	*This experiment will route UFG messages to UFPA through DF*	Update Slice ■ Stop Slice

Topology

Selected OpenFlow switch: 00:00:f1:b5:e0:0b:91:03 at Belem

Figure 4. Physical topology of the experiment slice

Virtual Machines (VMs) for experiments are created in a Computational Resources area on the Slice Management page (Figure 5). During the creation process, the VM will be granted an IP, which will be displayed in the Topology Panel and the Computational Resources area. This IP is only reachable through FIBRE's VPN. VMs may be started, stopped, rebooted or deleted by clicking on the respective action link in the Computational Resources area. Experimenters can create as many VMs as needed for their experiment.



• Virt. Aggregate: AM Virt UFPA

Name: **AM Virt UFPA**
Status: ✓
Physical location: **Belem**
Resources:

Server Name	Virt. Tech.	Operating System	CPU	Memory	Disc	Update
VM_SERVER_NetFPGA1_0301	XEN	GNU/Linux Debian (7.0)	None	None	None	Update

VM Name	State	Operating System	Memory	Mgmt IP	Actions	Update Status
endhost3	stopped	GNU/Linux Debian (6.0)	128	10.130.12.12	Start Delete	Update

SSH access: ~# ssh maria_silva@rnp@10.130.12.12 (password: your user password)

***SSH common details:** to access as root just type **su** inside (password: **openflow**)*

Figure 5. Computational Resources area.

To use OpenFlow resources, experimenters are required to add OpenFlow resources to their slice and specify an OpenFlow Controller for the experiment. On the Slice Management page in the OpenFlow Aggregate area (Figure 6), data paths (consisting of id and port number) that are available in the slice can be selected in the Topology panel to define FlowSpaces for the experiment. When the slice starts, a specific VLAN ID is reserved for each defined FlowSpace on the data plane. Every virtual machine instantiated has a dedicated interface that is connected to the data plane network.

Name: AM OF UFG
Status: ✓
Automatic approval: ✓
Physical location: Goiania
Resources:

Flowspace	Associated OpenFlow Interfaces
VLAN ID: 102 - 102	**OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 1 **OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 4 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 26 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 48
Flowspace	**Associated OpenFlow Interfaces**
VLAN ID: 101 - 101	**OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 1 **OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 4 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 26 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 48
Flowspace	**Associated OpenFlow Interfaces**
VLAN ID: 100 - 100	**OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 1 **OpenFlow Switch:** 00:00:00:00:00:00:89:02 - **Port** 4 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 26 **OpenFlow Switch:** 67:8c:08:9e:01:62:d6:42 - **Port** 48

Openflow controller: tcp:10.136.12.89:6633
Actions:
Remove from slice:

Figure 6. OpenFlow Aggregate area.

Once the FlowSpaces are selected and the VMs are created, the user must set the controller IP address to match the VM that hosts the OpenFlow controller. To carry out the experiment, the student starts the slice on the Slice Management page. This will trigger a FlowSpace request to the OpenFlow switches involved and make sure all the VMs in the slice are active.

Within the slice, the experimenter can use the VMs as end-hosts and the FlowSpaces (allocated on the OpenFlow switch fabric) as the network data-plane. Students can access the running VMs through SSH, using their FIBRE username and password over FIBRE's VPN. Students can then install on the VMs any OpenFlow controllers or arbitrary software that is needed for their experiment (a set of OpenFlow controllers are pre-installed in the VM images, but students can also provide their own controller implementation.).

4.1.2 Configuring and running the experiment

In this section, we go through the network configuration procedures to configure the static routing experiment of Figure 3. For this experiment, we allocated three FlowSpaces and three virtual machines. The topology of each reserved FlowSpace is shown on Figure 7.

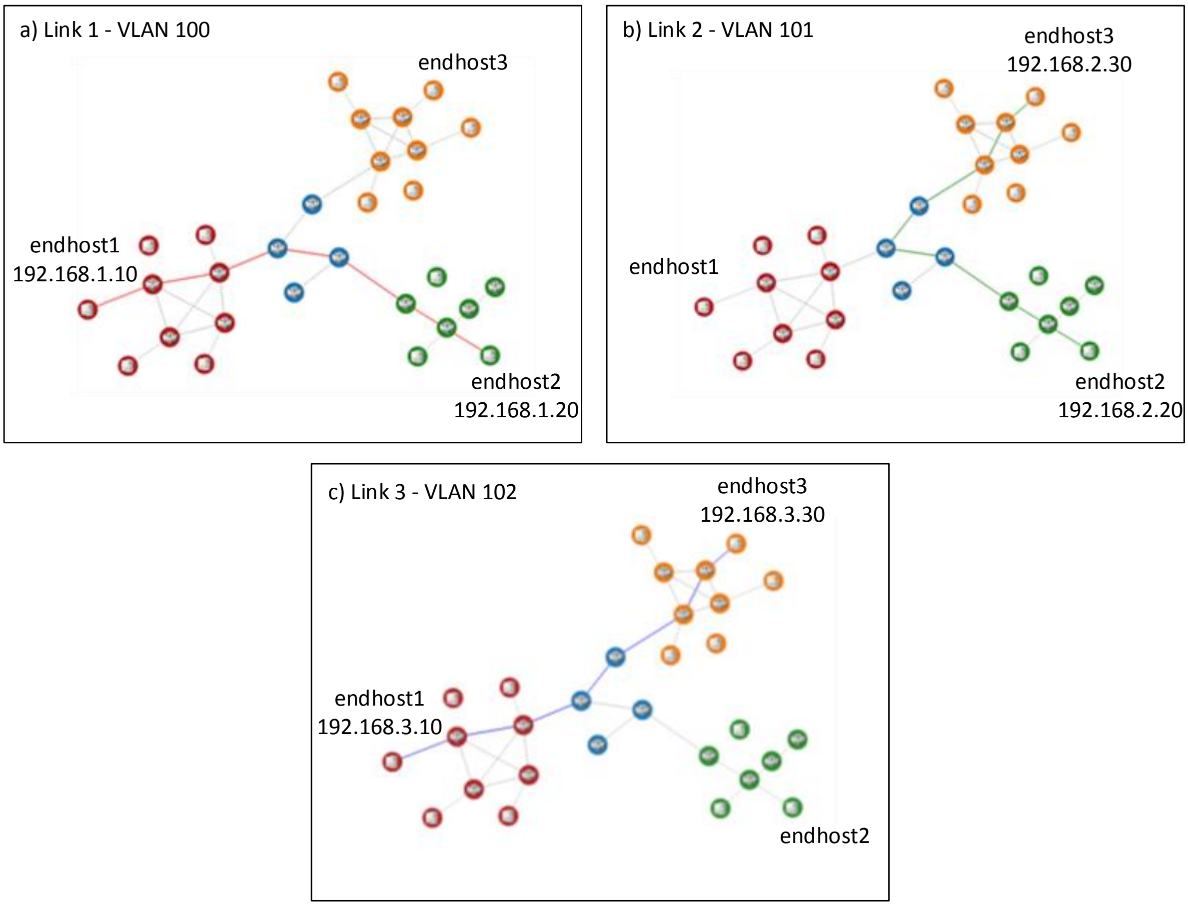


Figure 7. The experiment virtual network topology.

An additional VM is created to host the experiment OpenFlow controller, such as Floodlight (Floodlight OpenFlow Controller) POX (POX OpenFlow Controller or Ryu (Ryu SDN Framework), acting as a L2 learning switch. A L2 learning switch learns the mapping between MAC addresses and ports by watching packets. If the switch has already seen a particular destination, it can send to exactly one port; otherwise, it must flood the packet out all ports like a hub to find out the corresponding destination.

To configure the data plane network in the instantiated VMs, the student must access each VM through the provided control plane IP via SSH and configure the virtualized network for the experiment according to the configuration shown in Figure 3. For example, Listing 1 contains the steps for configuring network interfaces, VLANs, IPs and routing of the endhost1 VM.

```
root@endhost1:~# vconfig add eth1 100
Added VLAN with VID == 100 to IF -:eth1:-
root@endhost1:~# ifconfig eth1 up
root@endhost1:~# ifconfig eth1.100 192.168.1.10
root@endhost1:~# vconfig add eth1 102
Added VLAN with VID == 102 to IF -:eth1:-
root@endhost1:~# ifconfig eth1.102 192.168.3.10
root@endhost1:~# route add -host 192.168.2.30 gw 192.168.1.20 eth1.100
```

Listing 1. Configuring the endhost 1 for the routing experiment

After configuring the network of all end hosts, the experimenter must enable packet forwarding in the endhost2 VM with the command shown in Listing 2.

```
root@endhost2:~# echo 1 > /proc/sys/net/ipv4/ip_forward
```

Listing 2. Enabling IP packet forwarding in the endhost2 VM.

Finally, the experimenter can verify the correctness of their configuration by using the ping command in the endhost1 VM, as described in Listing 3. Note that the round trip latency of the first packet is greater because of the behaviour of L2 learning switch dynamic port discovery.

```
root@endhost1:~# ping 192.168.2.30
PING 192.168.2.30 (192.168.2.30) 56(84) bytes of data.
64 bytes from 192.168.2.30: icmp_req=1 ttl=62 time=641 ms
64 bytes from 192.168.2.30: icmp_req=2 ttl=62 time=53.0 ms
...
```

Listing 3. Testing the routing experiment.

Through the procedures described in this section, students and educators can use the FIBRE testbed to allocate the dedicated virtual networks and virtual machines necessary for setting up a basic network routing experiment that spans multiple sites.

5. Final Remarks

In this paper, we have discussed the use of Future Internet experimentation resources for teaching classes on computer networks. With the use of FI testbeds in computer-network classes, we believe the next generation of researchers will be more capable of dealing with architectural experiments and of continuously evolving the current Internet architecture. Additionally, the use of a large-scale testbed introduces the students to a real-world situation, instead of using software tools to simulate networks in the laboratory.

Currently, the FIBRE testbed encompasses eight (8) universities in Brazil, with 25 of its academic researchers also involved in teaching network classes. Altogether, these professors reach 53 different training courses, ranging from undergraduate to doctorate levels. A recent survey conducted on these participants revealed that in 2014 only four (4) professors used the FIBRE testbed in the classroom, but that the great majority plans to do so in the near future. However, some of the participants expressed concern with making students use an infrastructure that is not yet mature or completely reliable.

In order to ensure the sustainability of large-scale infrastructures such as the FIBRE testbed, a general concern is to attract users. Although FI testbeds are essential for the evolution of the Internet, in general experimenters do not consume all of their capacity. Exploring this unused capacity to enhance education in related areas is important, not least because this enhanced education may also help to further comprehension of the field.

Following the example of GENI Education (GENI Education FIBRE also plans to enhance its support to educators. Future dissemination activities should target educators by teaching them how to use the FIBRE testbed in their classes. Additionally, FIBRE should provide a repository of practical activities (exercises) that could be applied to their students. This would build a community of educators, feeding them with teaching materials similar to “teachers' editions textbooks”.

Ultimately, the dissemination of the use of Future Internet experimentation infrastructures is also a way for society to make better use of the large investment involved, often carried out with public resources.

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Biographies

Iara Machado is an Assistant Director in the Directorate of R&D at RNP. She coordinates working groups related to Advanced Application projects. All this activities involve extensive collaboration with the Brazilian networking research community. She has also worked for more than 19 years in Brazilian Telecommunication Company (Embratel) as Management System Architect. Graduate in Physics from the University Federal of Rio de Janeiro (UFRJ) and got a Master Degree in Computer Networks from the University Federal Fluminense (UFF). Iara was in charge of the FIBRE's working package that deployed the testbed infrastructure in Brazil.

Leandro Ciuffo is a Manager in the Directorate of R&D at RNP, in charge of interacting with cultural and scientific communities concerning new approaches to advanced network use. Since 2011 he also coordinates the dissemination activities of the FIBRE project, as well as the RNP's R&D Programme on Advanced Applications for Remote Visualization, which includes streaming of ultra-high-definition media. From 2006 to 2009 he worked in Grid Computing and e-Science projects at INFN-Catania (Italy), being responsible for dissemination and user support activities. Leandro holds a M.Sc. in Computer Science from the Federal Fluminense University (UFF), in Brazil.

Gustavo Dias is a Coordinator of Research and Development at RNP. Gustavo holds a Master degree in Systems Engineering and Computing at Federal University of Rio de Janeiro (PESC/COPPE). His work at RNP includes supporting Future Internet, e-Science and e-Culture collaborations.

Michael Stanton is a Director of Research and Development at RNP. After a PhD in Mathematics at Cambridge University in 1971, he has taught at several universities in Brazil, most recently as professor of computer networking at the Federal Fluminense University (UFF) in Niterói, Rio de Janeiro state. Between 1986 and 2003, he helped to kick-start research and education networking in Brazil, including the setting-up and running of both a regional network in Rio de Janeiro state (Rede-Rio) and RNP. He returned to RNP in 2001, with responsibility for R&D and RNP involvement in new networking and large-scale collaboration projects.

Noemi Rodriguez is an Associate Professor at the Catholic University of Rio de Janeiro (PUC-Rio). Her main interests are Distributed Systems and Concurrency. She is a close collaborator with RNP in the area of Middleware.

Tiago Salmito is a researcher at Pontifical Catholic University of Rio de Janeiro (PUC-Rio), where he obtained his PhD in Concurrent Programming and Distributed Systems. He also rdination of research projects at the R&D directorate at RNP.