

# COMPUTER NETWORKING TEACHING EXPERIENCES USING COTS ROUTERS AND VIRTUAL ENVIRONMENTS: THE UC3M LABORATORY

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## Abstract

Teaching computer network design and operation is complex due to the distributed nature of its operation, the high number of configuration parameters, the different possible failure modes to which they should cope, etc. Experimentation with real equipment is clearly a required step in the learning process, but this usually requires lots of resources, both in terms of equipment and personnel. In this paper, we describe the teaching framework deployed in the Telematics Engineering Department of the University Carlos III of Madrid, based on two main teaching innovations: a) the use of a real laboratory – built using commercial of-the-shelf devices – in which student teams interact with simple scenarios with commercial devices; and b) the use of a virtual laboratory, that provides the flexibility to allow students to focus on more complex problems.

**Keywords** - Innovation, technology, computer networks, COTS routers, virtual laboratory.

## 1 INTRODUCTION

Computer network design and operation are very complex despite the apparent simplicity of its components due to the distributed nature of its operation, the high number of configuration parameters, the different possible failure modes to which they should cope, etc. Theoretical exposure to this technology is clearly not enough for a future engineer, but experimentation with real equipment requires lots of resources, and therefore it is expensive in terms of equipment cost and teacher's dedication. Therefore, a need for innovative teaching approaches allowing the student to interact in a gradual path from basic networking scenarios to handle complex multi-node and multi-configuration scenarios, in an efficient and affordable way, is required.

This paper is based on the teaching experience of the Telematics Engineering Department of the University Carlos III of Madrid [1]. This experience motivated the need for some of the innovations, which are described in this paper, together with a report of results obtained so far, some lessons learned and future work.

University Carlos III of Madrid offers different bachelor and master degrees on Computer Science and Telecommunication engineering in which computer network design and operation is a fundamental component of several courses. On average (this depends on the particular degree and also, to some extent, to the degree configuration chosen by the student), a student of one of these degrees attends to 3-4 courses on computer networks involving experimentation with real equipment on a laboratory. This accounts for approximately 60 hours of work in the laboratory, without considering the additional time each student has to devote in advance to prepare specifically for this work. From our experience we have learned that the laboratory experimentation with high performance equipment is at the same time a) an unavoidable step for the students, which helps them understand the concepts covered during the theoretical lectures; and b) an incredibly complex activity, due to the amount of resources needed (both in terms of equipment and personnel), and the limited number of hours planned for laboratory experimentation.

Based on the above, we identified the following three main innovations to improve both the students' and teachers experience in the learning process:

1. Use in the laboratories of as many commercial of-the-shelf (COTS) devices as possible. In this way, students learn to deploy, interconnect and configure high performance production equipment – as the one they would find in their future working environment. However, this equipment is typically very expensive, inconvenient to store, and delicate. Therefore,

whenever it is possible, it is better to use COTS equipment, although this involves developing a customised environment in order to adapt the devices to behave – at least for our teaching purposes – as the high performance equipment.

2. Use of virtual laboratory environments as a complement to the experimentation with real devices. This allows the students to decouple their learning process from limiting factors such as room or device availability. A virtual environment should resemble as much as possible the equipment and deploying scenarios of the real laboratory so that students could use it to prepare their laboratory sessions. This also provides lecturers with an additional tool to propose additional exercises to complement and/or extend the material covered in the laboratory sessions. Finally, the virtual laboratory is a tool that enables advanced students to deepen their knowledge by means of an unconstrained interaction with it.

In this paper, we describe the teaching framework deployed in the Telematics Engineering Department of the University Carlos III of Madrid (UC3M). This framework currently benefits from the aforementioned innovations, that is: a) the use of a real laboratory (described in Section 2) – built using commercial off-the-shelf (COTS) devices – in which student teams interact with simple scenarios with commercial devices; and b) the use of a virtual laboratory (described in Section 3), that provides the flexibility to allow students to focus on more complex problems. Section 4 provides a comparison between the real and virtual laboratories, analysing their capabilities and how to combine their use in a computer networks oriented course. Section 5 reports our teaching experience using this framework, while Section 6 concludes the paper and enumerates some of our current ongoing innovation efforts.

## 2 REAL LABORATORY DEPLOYMENT USING COTS ROUTERS

Experimentation with high performance equipment is an important step in the learning process of a student of an engineering degree. The advantages provided by such experimental work are twofold: on one hand, it helps the student to fully understand and apprehend the underlying principles of computer networking. On the other hand, it provides the student with practical capabilities and experience using high performance equipment (e.g., deployment and configuration of routers to meet a particular set of design criteria).

Deploying networking scenarios to challenge the students' capabilities in a real testbed poses several difficulties, namely:

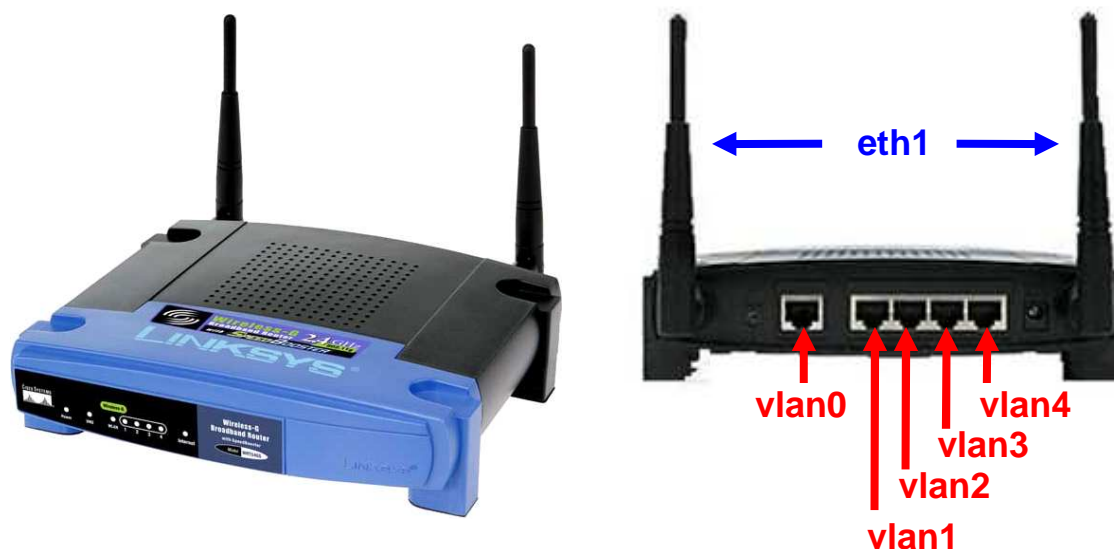
- It is hard to find devices that are flexible enough to meet all the requirements of the heterogeneous topics covered in the different courses. Buying a dedicated set of hardware to address each teaching objective is impractical for many reasons (initial acquisition costs, maintenance costs, replacement costs, storage costs, time required by the students to learn the basics of each type of device, etc.), so the use of a single type of device is preferable.
- Acquiring real-life equipment for teaching purposes quite hard, mainly because of high costs (the cost of just one single device might be prohibitive in certain cases), but also because of external factors (some vendors do not sell to teaching institutions or do not accept requests for small quantities).
- Using closed firmware/software devices pose some burdens on the flexibility of use of the equipment. While it is true that real-life equipment typically does not allow to be modified, being able to adjust/adapt to some extent the hardware used for teaching brings some interesting advantages (e.g., the devices might be modified so the complexity posed by them to solve a particular problem can be adjusted – for example, to reduce the time spent by the students to get familiar with the use of the devices).

In the past, we used an expensive router (around 600€ per unit) for teaching routing in the laboratory. This router was equipped with an ISDN, an Ethernet and a serial interfaces. The number of potential networking scenarios that could be designed and deployed with such a device was rather limited, and unnecessary complexities arose (e.g., for some exercises students had to go through the whole process of configuring the ISDN interfaces, while the exercise goal was not related at all with ISDN technologies), and required costly extra infrastructure (e.g., an ISDN switching fabric). Both the teaching and learning experience using those routers were not completely satisfactory, and this motivated us to look for alternative approaches.

The solution adopted to replace the old existing teaching platform used in the laboratories is based on a very cheap and widely available device, the Linksys WRT54GSv4 (or its equivalent model: the Linksys WRT54GLv1.1). These routers are

- Small, and therefore easy to store,
- cheap, 80€ at the time we bought the first units in 2006, while the WRT54GLv1.1 model has a cost of 52€ per unit at the time of writing this paper, and
- very popular home and office broadband routers (therefore, easy to find and buy).

These Linksys routers are equipped with a 200 MHz MIPS processor, an IEEE 802.11b/g Wireless Local Area Network (WLAN) interface and an IEEE 802.3 Ethernet interface connected to a Virtual LAN (VLAN) capable 5-port switch. Besides, these devices exhibit an interesting and very useful feature: it is possible to configure them with new firmware based on Linux so they can be easily customised to include the features needed for teaching purposes. All these features (it is cheap, equipped with multiple and modern interfaces, and its firmware being easily modified) made this router a perfect candidate for replacing the old and expensive model we were using in the laboratory.



**Fig. 1. Router Linksys WRT54GS. Front and rear view (configuration of network interfaces)**

In order to adapt the router to our teaching purposes, we performed multiple modifications and extensions to the router [6]. Among them, we highlight the following:

- In the original configuration, the router has two VLANs configured on the Ethernet switch (the port tagged as 'Internet' belongs to one VLAN, while and the ports '1' to '4' belong to a different VLAN). For the laboratory setup, we configured the router to have 6 different (5 wired, 1 wireless) network interfaces (see Fig. 1) by configuring appropriately the internal VLAN switch.. In this way, we obtain a high number of network interfaces, which provides us a great flexibility to deploy larger and more complex scenarios.
- We replaced the original firmware of the routers with an open source Linux distribution (OpenWRT WhiteRussian RC6 [2]). This allowed us to customise the firmware to fit to our teaching requirements, as we detail next:
  - Several routing protocol daemons based on the Quagga suite [3] were installed in the router. In particular, Routing Information Protocol (RIP), Open Shortest Path First (OSPF), and Border Gateway Protocol (BGP) protocols are supported by the router. These daemons were also modified with the goal of making the router's behaviour – from a configuration interface point of view – as similar as possible to the Cisco IOS configuration interface (which is the most common configuration interface used by real routers). In this way, the students learn how to access and perform different configuration tasks using a widely available routers' configuration "language".

- In addition to the routing configuration interface described above, a second way of accessing the devices is provided. This way is based on SSH and enables the student to connect remotely to a Linux console in the router (see Fig. 2), as this is the most flexible and powerful mechanism to configure the wireless interface settings. Note that the Quagga routing suite cannot be used to modify the WLAN configuration, and web-based configuration tools do not allow modifying all the WLAN settings.
- Special attention was devoted to ensure that the routers are not prone to misconfiguration, either accidental or intentional. In particular, students are only granted the permissions required to perform networking configurations, without being able to change other configuration parameters or perform any modifications in the routers. Besides, each time the router is booted, a default configuration (identical for all the routers) is loaded, overwriting any previous changes. This mechanism ensures that all the routers behave exactly in the same way after rebooting, so students are provided with a safe way of starting from scratch in case they make a mistake. This proved to be quite useful, for example, to recover from wrong IP configurations of the network interfaces that could break connectivity to the router (and therefore the access to its configuration interface).

Our laboratory, with capacity for 50 students, can be equipped with up to 170 of these COTS routers. Some of our teaching experiences using these devices are reported in Section 5.1.

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Terminal
Archivo  Editar  Ver  Terminal  Solapas  Ayuda
it007:~> ssh root@192.168.1.1
root@192.168.1.1's password:

BusyBox v1.00 (2007.07.11-20:08+0000) Built-in shell (ash)
Enter 'help' for a list of built-in commands.

  U C 3 M  -  I T
  01010101 01000011 00110011 01001101 - 01001001 01010100
=====
SW prácticas routers D. Ingeniería Telemática Universidad Carlos III
Basado en OpenWRT White Russian (RC6) http://www.openwrt.org/
Más información (manuales, etc.) en: http://www.it.uc3m.es/linksys/
Versión 2                2007-07-11                cjbc@it.uc3m.es
=====
root@OpenWrt:~#

```

Fig. 2. SSH access to the router's Linux console

### 3 VIRTUAL LABORATORY

Cost is not the only limiting factor to deploy and efficiently run a teaching laboratory. Room and equipment availability are also critical factors to be taken into account. Even with a large number of routers available, each pair of students could handle no more than 6 routers, since a higher number becomes unmanageable, in particular, because the physical set-up is too complex to be deployed in the student's workplace.



really replicate a real scenario in a virtualised environment, where students would have to correctly define the interconnections of the different network nodes and would be able to test the operation of the network upon interface disconnections or wrong interconnections.

- UViL provides a shell-like interface for each host and router of the virtualised scenario. Fig. 3 shows a simple example of the virtual laboratory. The network topology of the scenario virtualised in this example is shown in the middle of the figure, while a screenshot of the actual UViL running is shown in the upper left side of the figure.
- UViL currently runs only on Linux. UViL is installed on all the PCs of our teaching laboratories. Students can use it either at the University or remotely through SSH access. We are currently working on including UViL as part of a Linux live DVD, to be distributed among students, so that they can also use it at home without the requirements of having an Internet connection or a Linux system already installed.

#### **4 REAL VS. VIRTUAL LABORATORIES: WHAT CAN BE DONE AND WHEN THEY SHOULD BE USED**

It might appear that the virtual laboratory is a perfect candidate to substitute the real one, reducing the associated costs and without the inherent limitations of the real laboratory. However, our approach considers UViL as a complementary tool in the teaching process, to be used together with the experimentation with real devices. We next describe how to combine the use of the real and virtual environment in a generic computer networking course:

1. The real laboratory is first introduced to the students, so they get familiar with the environment. A very simple exercise (not involving many nodes or complex configurations) is recommended at this stage. We suggest starting with the real laboratory because it is very important for the students to understand the complete picture of network design and deployment: role of the nodes, interconnection of them, how to get access to the configuration interface and start practising how to use it. Once the students have achieved a certain level of knowledge of this, they can start using the virtual laboratory.
2. Then, UViL is introduced to the students. The virtual laboratory is configured by the instructors so all the network topologies that the students will have to deploy and configure in the real laboratory sessions are made available (including the first simple session that was described above)., Therefore, the students can check in the virtual lab the test configurations before the real laboratory sessions. In this way, the use of the virtual laboratory helps the students – who often complained about the lack of available laboratory time to finish their assignments – to improve in advance their configuration skills.
3. Simultaneously with the use of UViL, experimentation with real equipment continues. Even though we have a virtual laboratory available, the real one should always be the main focus of the course, since it is the only teaching mechanism that is able to resemble all the problems and challenges that students would have to face in real life.
4. Either in parallel with the previous step, or some weeks after presenting the virtual environment, exercises additional to the ones proposed for the real laboratory can be proposed by the instructors (these assignments might be mandatory or optional). The students use the virtual environment to solve these exercises.

#### **5 TEACHING EXPERIENCE**

In this chapter we report on our teaching experience with students of the University Carlos III of Madrid so far.

##### **5.1 Experience from using COTS routers in real laboratory**

Our first prototype of COTS teaching router was developed during late 2006 and introduced in some pilot courses in the second term of 2006/2007, with a total number of students around 100. A second version was developed in 2007, being in this case used in all our courses starting in 2007/2008.

We present the results of the subject called “Laboratorio de Redes y Servicios de Comunicaciones” (Communication Services and Networks Laboratory), 2nd course of Technical Telecommunications

Engineering, Telematics especiality. In this subject, we replaced the old routers we were using with the COTS ones. In addition to the cost considerations we have already mentioned in 2, there are two quantitative metrics that we can analyse in order to assess the improvement – in terms of the learning experience of the students – enabled by the use our COST teaching routers:

- Complexity of the networking scenarios proposed to the students. Although it is not trivial to define this metric, a rough idea can be obtained by just taking the total number of nodes (routers and PCs) involved in each scenario.
- Average students' grade. We compare the grades the students obtained in the practical sessions using the old routers and using our new COTS-based routers. This is a direct and very representative metric of the effect of our teaching innovation on the learning success of the students.

Table 1 shows the values of these two figures of merit. It shows the average grade improvement after introducing the use of the new routers (it should be noted that during the first year in which we started using the COTS routers, the exercises and network topologies were exactly the same that during the previous year). On subsequent years we increased considerably the complexity of the exercises (not only in terms of involved network nodes) requiring also the communication among the initially different isolated groups, therefore increasing the difficulty of the course, although the average grade increased as well.

**Table 1. Metrics results to evaluate the improvement achieved by using the COTS routers**

Year	Total # nodes involved	Average grade
2004/2005	5	6.75 (/10)
2005/2006	5	7.58 (/10)
2006/2007	5	8.17 (/10)
2007/2008	7 x number of groups	8.82 (/10)

## 5.2 Experience from using the virtual laboratory

Our first prototype of UViL was developed during late 2007 and introduced in some pilot courses in the second term of 2007/2008, with a total number of students around 100.

Let take as a sample of study one particular subject (called “Tendencias en Sistemas Telemáticos”: Trends in Telematics Systems, 3rd course of Technical Telecommunications Engineering, Telematics speciality). In this course we proposed an optional exercise to the students that had to be solved using the virtual laboratory. The 46.5% of the students did the optional exercise during the first two years of the pilot. Additionally, the average grade of the students in the laboratory exercises improved an 8.5% after introducing the virtual environment (it is worth highlighting again that UViL allows the students to test the configurations in advance before the laboratory sessions).

## 6 CONCLUSION AND FUTURE WORK

In this paper we have introduced and described two main innovations currently in use in our computer networking design related courses at the University Carlos III of Madrid. We first replaced the routers used in the laboratory sessions with highly configurable COTS routers properly customised to fulfil our teaching purposes. Then, we developed a virtual environment, allowing the students to improve their network configuration skills outside the laboratory, and providing the instructors with a useful tool to propose additional exercises to the students. Results obtained so far show that these two innovations have improved the learning experience of the students.

Another difficulty posed by the use of practical experimentation for teaching in the area of computer networking is that student's performance is usually hard to grade. Because of that, a third innovation we are currently working on consists in the use of automatic correction tools (both for the real and virtual laboratories). With these tools, students would obtain feedback to guide their learning process without the participation of a laboratory instructor.

## 7 ACKNOWLEDGEMENTS

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