

Teaching Networking: A Hands-on Approach that Relies on Emulation-based Projects

António Nogueira, Paulo Salvador

DETI - University of Aveiro/Instituto de Telecomunicações
Aveiro, Portugal

e-mail: {nogueira,salvador}@ua.pt

Abstract—Computer networking is an inescapable reality of our days, being part of the curricula proposed by almost all universities. Effective learning and teaching of networking, however, require students to gain hands-on experiences in developing projects, which will help them to understand basic concepts as well as the strengths and limitations of the technology. At our university, we devised a new approach to teach networking concepts by requiring students to develop emulation-based projects in parallel with traditional theoretical classes and practical classes involving real networking equipment. The effectiveness of this teaching methodology was evaluated formally by the students' opinions and classification marks, and informally, in discussions within the teaching team. This paper describes the global philosophy behind this new teaching methodology, as well as its implementation approach and obtained results. The evaluation results that were achieved, representing a clear improvement of past results, allow us to conclude that the proposed approach is very promising. In fact, the emulation-based hands-on approach is able to motivate students and smooth their learning curve since they are close to reality and, at the same time, have the freedom to work everywhere at anytime and are free from boring physical connectivity problems.

Keywords—Practical teaching; networking project; emulation; GNS3.

I. INTRODUCTION

Computer networking became an indispensable part of our daily life. Many books have been written on this topic, which is being taught in both undergraduate and graduate level courses. Although students learn a lot of concepts in traditional courses, they do not have enough hands-on experience with real networks or in-depth understanding of how things work in practice. In order to circumvent these shortcomings, many universities developed lab-based networking courses [1][2][3], which are very useful to teach concepts but are not able to cover as much material as traditional courses due to the lack of time and resources. Most of the times, these labs do not scale to hundreds of students. Besides, in the austerity days we are facing it is very difficult to buy expensive networking equipment in order to equip one or several functional laboratories.

Therefore, we need to design new networking experiments that are focused on teaching essential networking topics, while taking availability of resources into account. Simulation and emulation seem to be good compromises between the need to use virtual environments

and the connection to the real world that should not be broken. There are several networking software tools that can be used to analyze, emulate and simulate computer networks. Among the different possibilities, Graphical Network Simulator, version 3 (GNS3) was the chosen emulation environment [14]; it is basically a hardware emulator (called a hypervisor) that creates a virtual environment on a host computer (running Windows, Linux or Mac). By running Cisco Internetwork Operating System (IOS) software on the hypervisor, the student can create complex networking scenarios with the real look and feel of hardware devices because he is interacting with the real IOS that is running on virtualized routers.

Based on this rationale, we devised a new approach to teach networking concepts by requiring students to develop emulation-based projects in parallel with traditional theoretical classes and practical classes involving real networking equipment. In this paper, we describe our experience of introducing an emulation-based project as a key pedagogical method for teaching advanced computer networks in a specific course, named Networks Architecture, which belongs to the third year of the undergraduate level. A three-threaded teaching approach was adopted for this course, comprising: (i) theoretical classes; (ii) practical classes, where real networking equipment is used and (iii) a network project that allows students to gain practical experience and a deeper understanding of the key concepts of network protocols and technologies.

The lecture and practical threads use face-to-face teaching, group work and discussion, allowing a deep interaction between students and teachers. In the network project, students are typically organized in groups of two people and have several tasks to accomplish "after hours": after designing and dimensioning a medium to large size corporate network, they have to configure and test it in GNS3.

The effectiveness of this teaching approach was extensively evaluated, formally by the students' opinions and classification marks and informally in discussions within the teaching team. The quite good evaluation results that were achieved, particularly when compared to results from previous years, allowed us to conclude that this approach is very promising. The hands-on approach is very important to motivate students, because they can "feel" the network and, at the same time, have the freedom to work

everywhere, anytime, and get rid of the cables and connectivity problems.

The remaining part of the paper is organized as follows: Section II discusses some teaching issues that should be taken into account when planning a computer networking course; Section III briefly discusses some relevant network simulation and emulation tools; Section IV presents the network project that was designed, including its description, tasks and resolution strategy; Section V presents the most relevant outcomes; finally, Section VI presents the main conclusions.

II. TEACHING ISSUES

Besides the continuous changing nature of computer networking and the heterogeneity in students' backgrounds, there are some other obstacles of teaching and learning this subject. First of all, the underlying principles are complex and very abstract to many students (they do not find an easy connection to reality).

Besides, the layered approach that is frequently adopted is considered inadequate by most of them, since there is not a clear identification of the functionalities of the different layers, as well as a clear separation between them.

Since most students lack practical experience, they have difficulties to understand common networking problems and overcome difficulties. Providing a hands-on practical experience to students is also problematic because some academic environments do not have the adequate resources. Networking labs are still quite expensive.

The sequence of subjects' coverage can also affect learning. Traditionally, top-down [4] and bottom-up [5] approaches have been intensively used, both on Computer Science and Engineering courses. However, a non-linear path on the coverage sequence seems to be the best choice in most situations.

In order to address some of these concerns, we changed the pedagogical approach that was usually followed in the Networks Architecture course by introducing an emulation-based project in parallel with traditional theoretical and practical classes. Besides the two hours/week theoretical classes and the three hours/week laboratorial classes (where students interact with real networking equipment), the network project adds two more hours/week to the course workload in order to allow students to gain a deeper understanding of the key concepts of network protocols and technologies. The project is developed by groups of two students and spans from the first to the last week of the course (usually, this period corresponds to 15 weeks). The project evaluation is based on a practical demonstration and an oral examination (so, group elements can get different marks) and the obtained mark has a weight of 40% in the global course mark (the weights of the theoretical exam and the lab activities are equal to 40% and 20%, respectively).

III. NETWORK SIMULATION AND EMULATION TOOLS

The deployment of real networks is not practical and can be really expensive depending on the size of the network and the number of computers, routers, switches or other network devices that have to be used. Nowadays, there are many software tools that can be used to perform network simulation and some of them can recreate exactly any detail of a real network. This allows an easy network deployment, with the benefits of saving space, money and time.

A. Network Simulator

Network Simulator (NS), developed by research laboratories and top research universities and funded by National Science Foundation (NSF), has been the major software simulation tool for network research for more than 20 years. Its most popular version, NS2, is a discrete-event simulator in which the routing algorithms are written in C++ as pre-built into the library, while events are configured using OTcl language [6]. Due to the unpopularity and the slow learning curve of OTcl, NS is seldom used in classroom teaching.

The last version of NS, NS3 [7], is under the General Public License (GPL) and provides free download of its source codes. The core of NS3 is written in C++ and has a Python scripting interface. Protocol entities are designed to be closer to real computers and NS3 includes support for virtualization, using lightweight virtual machines [7].

B. OMNeT++

Similarly to NS2 and NS3, OMNeT++ is also a public-source, component-based network simulator with Graphical User Interface (GUI) support [8]. Its primary application area is communication networks. OMNeT++ has generic and flexible architecture, which makes it successful also in other areas like Information Technology (IT) systems, queuing networks, hardware architectures, or even business processes.

OMNeT++ components are called modules and are programmed in C++. The components are then assembled into larger components and models by using a high-level language. The simulation kernel can be embedded into all kinds of different users' applications.

C. OPNET

OPNET is the commercial counterpart of NS [9]. It has a rich set of modelers that support the latest wireless and emerging network technologies. The user friendly interfaces are intuitive to use for creating network topologies, configuring and simulating network traffics, and collecting and visualizing data. The OPNET IT Guru academic version is free for teaching and research in academia. Many universities are adopting OPNET in teaching general networking courses because it has intuitive user interfaces and lab manuals for popular textbooks.

Both NS and OPNET are excellent tools for conducting research or teaching general network concepts. However, their configuration process is very different from the real-world networking or security devices that are dominated by Cisco appliances.

D. Cisco Packet Tracer

Cisco Packet Tracer is a network simulation software developed by Cisco to support its Networking Academy Program. This software provides visual network simulation and allows creating networks with an almost unlimited number of devices. The configuration of the network devices is made through a command-line interface, similarly to real equipment. It also provides tables, diagrams and other visual representation and offers a multiuser functionality that permits multiple users to work on the same project through the Internet [10].

Packet Tracer has two operation modes: the real-time mode that shows how real devices behave and the immediate network response to any network change; the simulation mode, which is directed to background concepts and allows controlling time intervals, data transfer rates and bandwidth and manipulate the propagation of data packets through the network. This software supports the possibility of inserting interface cards into modular routers and switches, creating virtual networks over real ones.

The most important limitations of Packet Tracer are related to its performance and to the lack of support for some important advanced networking mechanisms and protocols.

E. NetSim

Network Simulator (NetSim) is a Cisco network simulator developed by Boson, a company that provides material to prepare students for IT certification exams from Cisco, Microsoft CompTIA, and others [11]. It uses the Boson's proprietary Network Simulator, Router Simulator and EROUTER software technologies to simulate a real network and is available on three different versions, each one with specific characteristics and directed to a different certification.

NetSim supports up to 42 routers and 6 switches, on a total of 200 devices on the network. It simulates network traffic using virtual packet technology and provides Telnet or Console modes to interact with the network devices. This software is not open-source, which is a clear handicap for educational purposes.

F. Graphical Network Simulator v3

GNS3 [12] was introduced many years ago, when an open-source hypervisor called Dynamips was written to emulate Cisco routers. Dynamips was intended to emulate Cisco IOS hardware and was fairly complicated to use. So, a GUI was added to manage the process of the hypervisor, which is exactly what is called GNS3. So, GNS3 is the front-end for multiple hypervisors, including Dynamips and Qemu, with the latter being used to emulate hardware used by the Cisco Adaptive Security Appliance (ASA) firewall.

While Dynamips is responsible for the back-end operation of emulating routers with real IOS images, GNS3 uses Dynagen as the text-based front-end to establish communication with Dynamips [12]. GNS3 also supports other machine emulators and virtualizers like Qemu [16], Virtualbox [17] or Pemu [18]. This allows a user to simulate networks with a wide diversity of devices, like Cisco ASA and Private Internet eXchange (PIX) firewalls, Cisco IPS,

Juniper routers or hosts (based on different operating systems, like Linux, Windows, MacOS X).

So, GNS3 affords anyone with a computer a way to practice network topologies. But it goes beyond that: users can quickly set up routers and firewalls, using simple drag-and-drop actions on the screen. It is easy to add Ethernet connections between devices or add hardware modules to routers in the virtual GNS3 topology for more complex network designs.

Another relevant advantage of GNS3 is the possibility of connecting the virtual network to the real world, with real devices, besides the ability to perform packet capture and analysis using Wireshark [13].

Layer 2 Ethernet switching inside of a GNS3 topology is limited to the switchport modules that can be added to the virtual routers inside GNS3, which do not support the full layer 2 switching capabilities that a physical switch would provide.

GNS3 also has some other limitations: its throughput is limited to 1000 packets per second in the virtual environment, it can consume a large amount of real and virtual memory and it can achieve high Central Processing Unit (CPU) usage levels [14]. Although GNS3 already includes some tools to prevent this memory and CPU usage levels, we should always take into account that the higher the number of routers and network devices, the higher will be the consume [15].

In summary, we can say that, in spite of these limitations, GNS3 is one of the most valuable tools for practicing, proof-of-concept design, protocol analysis and verification.

IV. NETWORK PROJECT

In order to address the different topics of the Networks Architecture course, we devised a network project that could be solved incrementally and whose solution could be implemented in GNS3. In line with the course objectives, the most relevant topics that should be studied and implemented in this project are: definition of Virtual Local Area Networks (LANs), Internet Protocol, version 4 (IPv4) and IPv6 addressing, internal routing based on the Routing Information Protocol (RIP), RIP next generation (RIPng), Open Shortest Path First, version 2 (OSPFv2) and OSPFv3 routing protocols, multicast routing, Quality of Service (QoS) mechanisms, IPv4/IPv6 transitions mechanisms, Internet Protocol Security (IPSec), Access Control Lists (ACLs) and network management based on scripting.

A. General Problem Description

Let us suppose that we want to design, implement and test the communications infrastructure of a medium to large size company. We will start by presenting the problem enunciation that was proposed to students of the Networks Architecture course.

Company Example, Inc. has a strong Research and Development (R&D) component and will expand its facilities in Aveiro (currently, they are composed by a single building), with two new three-floor (adjacent) buildings. The company will also create two new branches, one in Lisbon and another in San Jose, California. The old Aveiro network

should not be changed, but its connectivity with the new buildings and with the Internet should be assured.

The first floor of each building is reserved for the production zone; the second floor of the first building is reserved for sales and client support and the last floor of the first building is reserved for the administration offices; floors 2 and 3 of the second building are reserved to R&D.

Let us suppose that each production floor has: (i) 12 production points (machines/robots), (ii) 3 technical verification zones (machines/terminals), (iii) a meeting/reception room and (iv) a videoconference room. The sales and client support floor has: (i) 50 sales rooms, (ii) 2 meeting rooms to contact clients via videoconference and (iii) 50 workplaces for client support. Each R&D floor has: (i) 20 laboratories, each with at least 8 workplaces, (ii) 4 rooms reserved to engineering development, (iii) a lounge top workers/visits. The administration floor should support 20 persons and includes 2 videoconference rooms.

At the Lisbon and San Jose branches, the company will have single 2 floor buildings, with the first floor being reserved for R&D laboratories (25 researchers per lab) and the second floor being reserved for local administrative services (15 persons).

The company will have communication services (data, voice and video) implemented over IP, as well as a video-surveillance system and 3 internal Internet Protocol Television (IPTV) channels.

Finally, the company has two datacenters (services and storing) in Aveiro and San Jose that will support the different activities: administration/planning (management archive), R&D (scientific archive and data processing) and public services to employees and general community via Internet.

B. Objectives

For the three new networks of the Example, Inc. branches, students have to:

- Present the Open Systems Interconnection (OSI) Layer 2 networks subdivision (VLANs design).
- Define the public IPv4 addressing scheme (assuming that the company owns network 193.2.2.0/24 in Portugal and network 195.1.1.0/26 in the USA) and the private IPv4 scheme and the respective translation mechanisms.
- Define the IPv6 addressing scheme (assuming that the company owns network 2002:C:C::/48 in Portugal and network 2001:F:F::/48 in the USA).
- The company has two Internet access contracts with Portuguese ISPs PT1 and PT2 for the Aveiro and Lisbon sites, respectively.
- All network sites should include a wireless network divided in two distinct VLANs, with distinct permissions. All network sites should also have internal IPTV channels. We can assume that each site has its own independent multicast video server.
- ISP PT2 does not support IPv6 addressing/routing. Propose and implement a solution that allows full IPv6 connectivity between the Portuguese network sites of the company in case of a complete failure of ISP PT1 (the default IPv6 connectivity provider).

- In order to guarantee the confidentiality of some communications, students should configure a Virtual Private Network (VPN) IPsec between the company sites and define the respective routing policies (i.e., which traffic should be transported by the VPN). Besides, they should configure a secure connection between the old and the new datacenters in the Aveiro site.
- Based on the underlying structure and configurations, students should define and configure mechanisms of traffic differentiation that implement the QoS policies that are necessary for the network services in operation.
- Students should also develop a scripting system that can be used to support network monitoring and management. In a first phase, the system should identify all network equipments (routers and switches), their interfaces and the corresponding link loads.

C. Specific Tasks

In order to achieve the above mentioned goals, students have to perform several specific tasks:

- Design the logical network architecture and the corresponding physical mapping.
- Define the characteristics/capabilities of the different network equipments.
- Define the (virtual) local networks.
- Define the IPv4 and IPv6 addressing schemes.
- Make some extra definitions (like for example budget, non-network equipments, etc.).
- Configure the access layer and define the interconnection/addressing of the terminal equipments.
- Configure the IPv4 unicast routing.
- Configure the IPv6 unicast routing.
- Implement private addressing translation mechanisms.
- Configure the multicast IPv4 and IPv6 routing.
- Implement QoS policies.
- Configure the IPv4/IPv6 transition mechanisms.
- Configure internal secure connections and external secure connections between branches (as well as the corresponding routing mechanisms).
- Write monitoring scripts (in bash language).
- Perform some extra configurations (control access rules, Dynamic Host Configuration Protocol (DHCP) server, user VPN server, etc.).

Although these tasks can be solved in a slightly different order, students should be aware that some of them are dependent on others. So, this list of tasks is given to students, in order to guide them in their starting efforts.

D. Resolution Strategy

As happens in most situations, the best strategy to solve this exercise is to split it into sub-exercises.

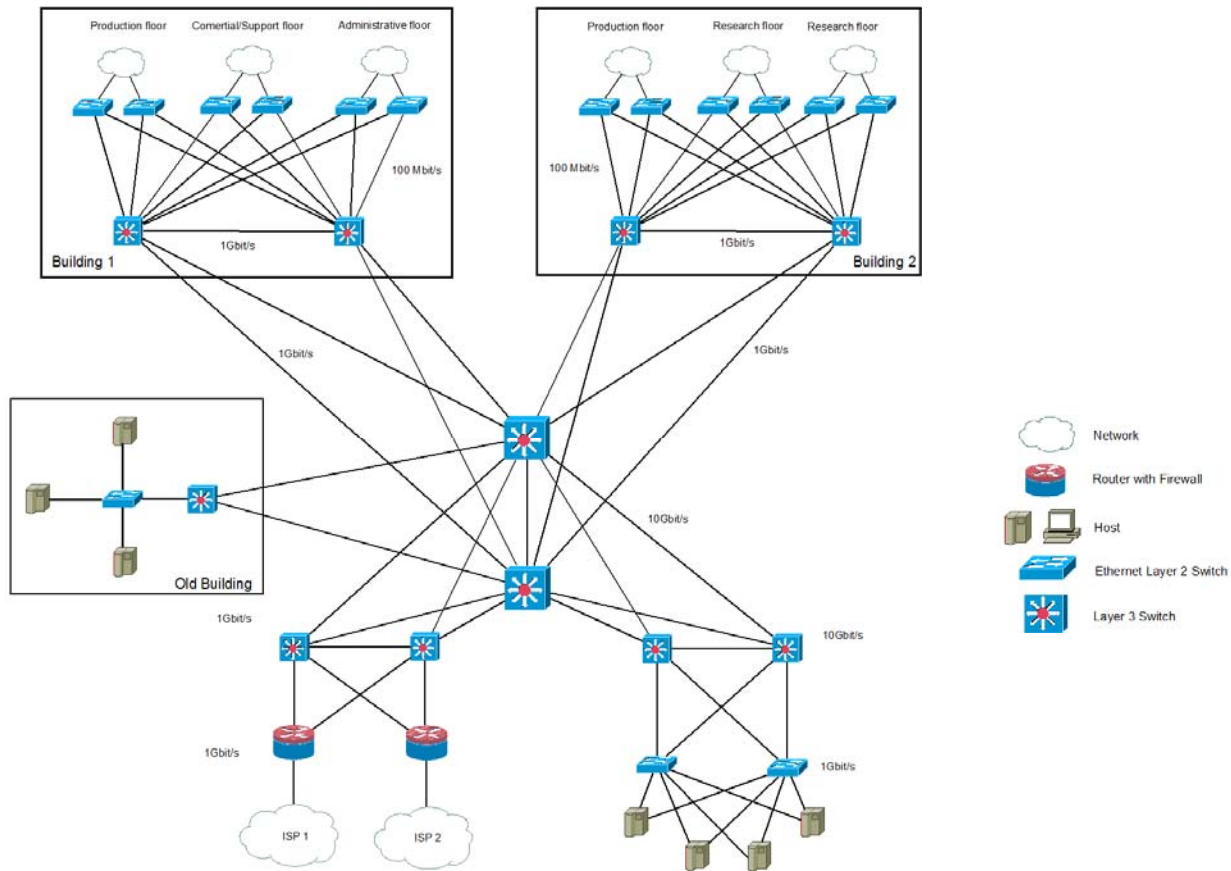


Figure 1. Network topology for the Aveiro site.

Actually, this approach has two main advantages: each sub-problem is easier to address and the computational resources that it will require (using GNS3) are substantially lower than the resources that would be needed to solve the complete problem.

So, the first step should be to look at each company site, designing, configuring and testing its own network. Following this approach, Figs. 1, 2 and 3 illustrate the topologies of the networks that could be designed for the Aveiro, Lisbon and San Jose sites, respectively. In this design phase, a correct definition and dimensioning of the access, distribution and core layers is crucial for the remaining phases of the project. In this phase, the students, usually, interact a lot with their teachers in order to find the best solution. After this effort, the definition of the different VLANs and the addressing issues are the most relevant topics that have to be addressed.

These high-level networks (corresponding to the company sites) are implemented and tested separately in GNS3: obviously, a last experiment should be dedicated to the interconnection of these networks, where each one corresponds to the communications infrastructure of a different company site.

On the other hand, the students must also specify the design and implementation details of the network

corresponding to each floor, which were represented as generic clouds in the higher level network diagrams of Figs. 1, 2 and 3. As an example, Fig. 4 presents the network topology for the Research floor infrastructure. Quite similar topologies should be designed for the other floors.

Besides specifying the network equipments (type, model, characteristics, number of the interfaces, interfaces types, etc.), students have to present and discuss the network topology of these lower level networks. Obviously, this refinement process should be repeated until the desired level of detail is achieved.

After completing the design and dimensioning phases, the project enters in the implementation phase: here, all network connections, equipments, configuration details, GNS3 performance mechanisms (like the *Idle PC* feature), should be conveniently addressed. Troubleshooting methodologies are crucial in this phase. Usually, this phase also implies a lot of interaction between students and teachers.

Finally, the testing phase is used to validate the implemented network(s), eventually changing some of the decisions that were previously taken. So, this is a closed-loop process that can go through several iterations.

V. EVALUATION

The effectiveness of the three-thread teaching approach was evaluated in several ways: informally, in discussions within the teaching team, and formally by the students' opinions and classification marks.

Regarding the first evaluation criteria, the merits of this teaching methodology were consensual among the teaching team. Actually, everyone felt that students were more engaged with the course and spent a higher number of hours studying and working on these networking topics. So, the satisfaction degree of the teaching team was quite high.

The students' opinions were obtained through a written questionnaire that is part of the Quality Assurance Plan of our university. The most important results obtained are the following: the global satisfaction with the course was rated by students with 7.11 out of 8, while the appropriateness of the proposed activities to the course objectives was rated with 7.38 out of 8. These results are generally very good, and when compared to the results obtained for the same items in the previous Academic year of 2012 (6.68 and 7.02, respectively), allow us to conclude that a very positive evolution was achieved.

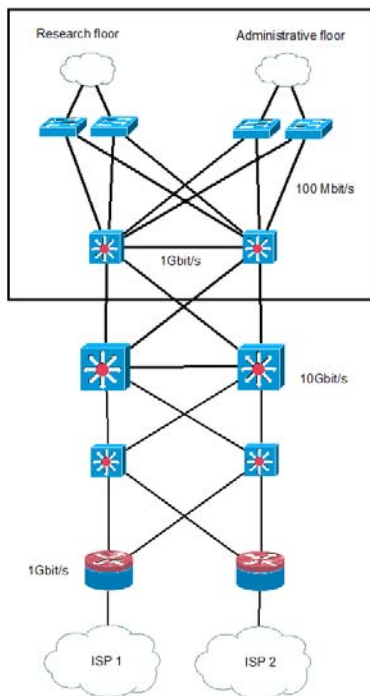


Figure 2. Network topology for the Lisbon site.

Finally, we should look at the course classification marks. Figures 5 and 6 show the marks obtained in 2012 and 2013, respectively, for a total number of students equal to 54 in 2012 and 50 in 2013. The number of students that failed in this course decreased from 25.93% in 2012 to 10.00% in 2013. This is a very relevant result, since we were able to substantially increase the success rate of this course. If we look at the average mark obtained by well-

succeeded students, we can see that it increased from 12.1 (out of 20) in 2012 to 12.53 in 2013. Although only two students were able to achieve a classification of 17 (Very Good) in 2013, the most important slice of students was able to reach a quite satisfactory mark of 13 out of 20.

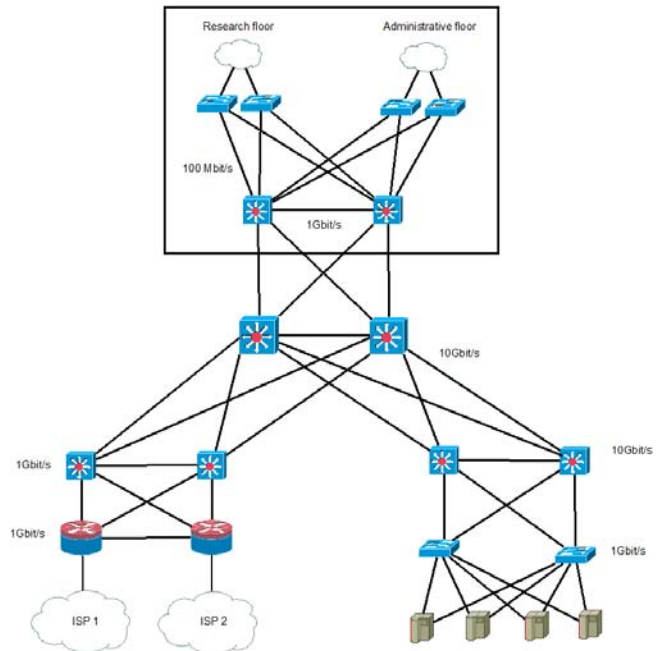


Figure 3. Network topology for the San Jose site.

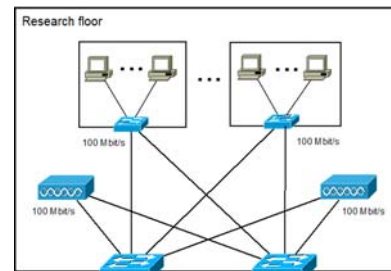


Figure 4. Network topology for the Research floor of the Aveiro site.

Regarding the marks that were obtained in the emulation-based project itself, we can say that they were quite high: with few exceptions, all students were able to obtain marks of 16 and higher (out of 20), marks that are typically higher than the ones they are able to obtain in the theoretical exam. This is clearly related to the practical nature of this component and to the interest that this type of work clearly induces in students.

The quite good results that were achieved in the different evaluation criteria, particularly when compared to the results from the previous year (where no project was proposed to students), allow us to conclude that this multi-thread teaching approach is very promising.

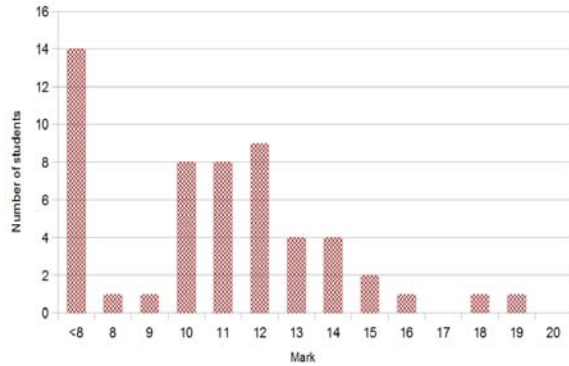


Figure 5. Classification results of the Networks Architecture course - 2012.

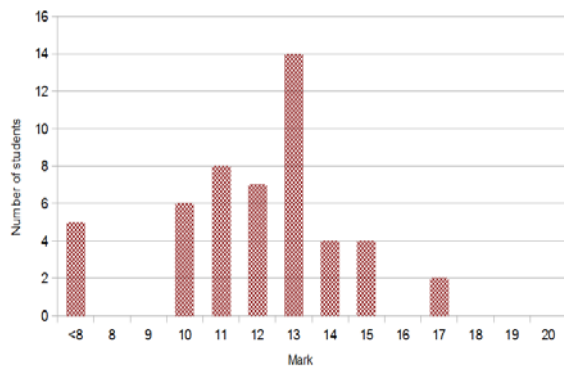


Figure 6. Classification results of the Networks Architecture course – 2013

The hands-on approach promoted by face-to-face lab classes and emulation-based networking projects is very important to motivate students, because they can “feel” the network and, at the same time, have the freedom to work anytime and everywhere and get rid of the cables and connectivity problems.

VI. CONCLUSIONS

This paper describes our experience of introducing an emulation-based project as a key pedagogical method for teaching advanced computer networks. A three-threaded teaching approach was adopted in a third-year undergraduate course, comprising theoretical classes, practical classes involving real networking equipment and a network project that allows students to gain practical experience and a deeper understanding of the key concepts of network protocols and technologies.

The effectiveness of the used teaching approach was evaluated formally by the students’ opinions and classification marks and informally through discussions within the teaching team. The quite good evaluation results that were achieved, particularly when compared to results from previous years, allowed us to conclude that the proposed approach is very promising. In fact, the hands-on

approach can motivate students because they are more engaged to reality but, at the same time, have the freedom to work everywhere and do not suffer from physical connectivity problems.

ACKNOWLEDGMENT

This work was supported by Fundação para a Ciência e a Tecnologia (FCT) of Portugal, under the auspices of project PEst-OE/EEI/LA0008/2013.

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