Developing Web-based Interactive Tools for Teaching Computer Networking Courses

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Abstract

To maintain a networking lab can be very challenging, considering the rapid evolvement of networking technologies that requires constant software updates and hardware upgrades. To catch up with the pace of technology advancement in the industry, academic institutions spend a big portion of their operation budget each year to keep the networking lab up-to-date. Apparently, in recent years, the stagnant budget seriously limits the capacity of keeping the lab equipment to a state-of-the-art level.
This paper summarizes a lab development project supported by an NSF grant. Various web-based software tools were adopted or developed so that lab exercises can be conducted in a simulated and remote lab environment. Before the construction of this lab, lab instructions were only performed on the limited resources of physical equipment. A part of this web-based lab solution employs the latest virtualization technology, delivering the full functionalities of real physical equipment. Combined with distributed lab components, students from both the DE (Distance Education) and face-to-face sections are able to conduct lab exercises via the Internet or on their local machines from anywhere at any time. In addition to the software simulation module, lab manuals, course documents, class lectures, and instructor lab demonstrations in rich multimedia formats were created as additional teaching tools and embedded into this online teaching environment. Students were required to use these tools to conduct self-study and lab exercises as supplement to the in-class lectures to fulfill the quality assurance requirements of the curricula. The web solution eased the burden of system administration, improved the availability and accessibility of our network lab, and reduced the cost to the minimum. More than 120 students per year who are enrolled in the four core courses in the computer networking major are directly benefited from the project. The outcomes from this project were documented and disseminated into 5 institutions overseen by ECU's regional networking academy program for engagement and outreach purposes.

Introduction

The ever evolvement of network technologies brought pervasive use of broadband Internet access to the most American families. Although the notion of using the Internet for information sharing has been tremendously broadened than the sole purpose of academic collaboration that the Internet was originally created for more than a half century ago, the Internet remains being a key means for people to learn and conduct research. In recent years, there has been a trend of moving teaching material online in the higher education for the new 21st-Century education model. Through synchronous and asynchronous online

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tools, today's students are experiencing an enhanced blended learning environment that is better or equivalent to the traditional face-to-face classes. While the flexibility of online learning allows people to learn from anywhere, there are challenges facing the distance education that teach classes completely online. One of these challenges is the difficulties of conducting online hands-on instruction in lab-based classes, especially in engineering and technology curricula, in which student hands-on skills are considered critical component of the learning objectives.

To address this challenge, remote lab access[1-3], software simulation[4-7], and virtual instrumentation[8-10] have been the hot research topics in academia. This paper summarizes the author's current and previous research[11-13] in creating a remote lab that consists of both software simulation and hardware instrument tools for computer networking and information security curricula, provides the best practices of using distributed and centralized cloud computing technologies to support both teaching and learning, and compares various technologies that are either in open-source or obtained for free with academic license.

REMOTE LAB TECHNOLOGIES

Software Simulation

NS (Network Simulator), developed by national research laboratories and top research universities and funded by NSF, has been the major software simulation tool for network research for more than 20 years. It is a discrete-event simulator in which the routing algorithms are written in C++ as pre-built into the library while the events are configured using OTcl language. Due to the unpopularity and the slow learning curve of OTcl, NS is seldom used in classroom teaching. The new version of NS, NS3, is still under the GPL license and provides free download of its source codes. OPNET is the commercial counterpart of NS. It has a rich set of modelers that support the latest wireless and other 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. There are more than 10,000 Cisco Networking Academies worldwide offering networking and security courses through Cisco training curricula [14]. Most of these academies are colleges, universities, and high schools. The popular CCNA (Cisco Certified Network Associate) program consists of 4 courses, covering IP addressing, LAN, WAN, routing, wireless, switching, security, QoS, and other networking technologies. Other Cisco curricula are built on top of the CCNA program by adding advanced topics in VoIP, wireless, and security. Among the Cisco simulators developed in the past decade,

Packettracer is the most widely used by the Cisco academies because it's developed by Cisco and built into the CCNA curriculum. However, Packettracer is only able to simulate the basic functionalities of the Cisco switches and routers. Many features of the physical Cisco appliances are not supported. This is also why Cisco requires both Packettracer and the physical lab for teaching its curricula.

Remote Access to Physical Labs

Many hardware appliances in IT fields are equipped with remote control modules that allow engineers to login via the Internet and configure, manage, maintain, and troubleshoot these appliances remotely. A Telnet or SSH (Secure Shell) session can be used to create a direct channel for the remote users to gain control of the appliance if the appliance is assigned a public IP address on the physical interface facing the Internet. Due to the limited number of public IP addresses, it is difficult to assign or manage unique public IP addresses to all the appliances. A common solution in the industry is to create a VPN connection between the user and a VPN server that works as the gateway of the remote lab. Once authenticated by the VPN server, the user will be assigned a virtual private interface that bridges user's public network to the private network behind the VPN server. Through the VPN channel, the user's machine is virtually added into the remote LAN (local area network). This allows direct communication between the user's machine and an AS (access server) that connects to all the lab appliances through the console ports. The VPN approach added security and remote login functionalities to the lab management process. It is an excellent solution to the industry settings in which only a small number of administrators are authorized to manage a large number of remote appliances; and these people perform the management tasks in professional manners.

In the academic settings, the VPN approach needs modifications to accommodate the hands-on training requirements for a number of reasons. First, a large number of students are accessing to a relatively very small number of appliances. Students usually need a concurrent access to multiple appliances for one lab exercise. A typical networking lab is equipped with two pods of equipment that allow no more than two users to use the lab simultaneously. Therefore, a lab reservation and management system is critical to arrange lab time for each student. Second, the lab system should be resilient to student's misconfiguration, which is the major cause of system lockout and crash during training. For example, students usually lock themselves out from the lab by creating unnecessary password or erase major software components. To guarantee availability of the subsequent lab sessions, a self-recovery mechanism should be implemented to restore the lab to a predefined state after each student lab session. Third, log files need to be created to record student operation and configuration during each lab session for grading or evaluation purposes. Students also appreciate features that allow them to store files and start the next lab session from where they have been left from the previous sessions. Thus, creating a file database to store and manage user files is necessary.

NDG's Netlab is a complete hardware solution to physical lab remote access. The center piece of Netlab is a hardware gateway that interfaces the Internet for remote access and connects all the lab appliances in the lab. Users login to a web server hosted on Netlab,

reserving and operating on the lab appliances remotely through graphical web interfaces. The student operation is recorded before the system is scrubbed for next lab session. Netlab is currently maintained by NDG, a not-for-profit company. The product is charged for an annual service fee.

Lab Emulation

Virtualization technologies have been pervasively used in both industry and academia to reduce the cost of standalone servers. Similar to server virtualization using VMware and Virtualbox, the operating systems of networking appliances can be hosted virtually on the computer memories; so a complete rack of routers, switches, security appliances can be emulated on a much less expensive computer. Although the emulated appliances can't perform the same speed and possesses the same amount of computing power of the real routers and switches, they have exactly the same functionalities of their physical counterparts if proper interfaces are installed because the real operating systems are fully migrated to the hosting computers. Therefore, it is perfect to use emulation in academia. In a previous study, Software tools have been programmed to manage the virtualized Cisco IOS's. A graphic interface is designed to fully accommodate the teaching needs of multiple course curricula. Many functions that facilitate teaching can be programmed and embedded into the emulated lab to create a complete software package with both lab and teaching materials. For example, student operation recording, lab appliance restoration, lecture and lab demo videos, course documents, and multiple user concurrent access for teamwork and instructor-led training have already been embedded into the emulated lab. Most important of all, the emulated lab is easy to manage with the lowest possible cost among other lab solutions.

NETWORK LAB ARCHITECTURE

In the past years, we have implemented a lab architecture that incorporates various online and offline lab components, enabling students to conduct lab exercises from anywhere. Figure 1 shows the lab structure.

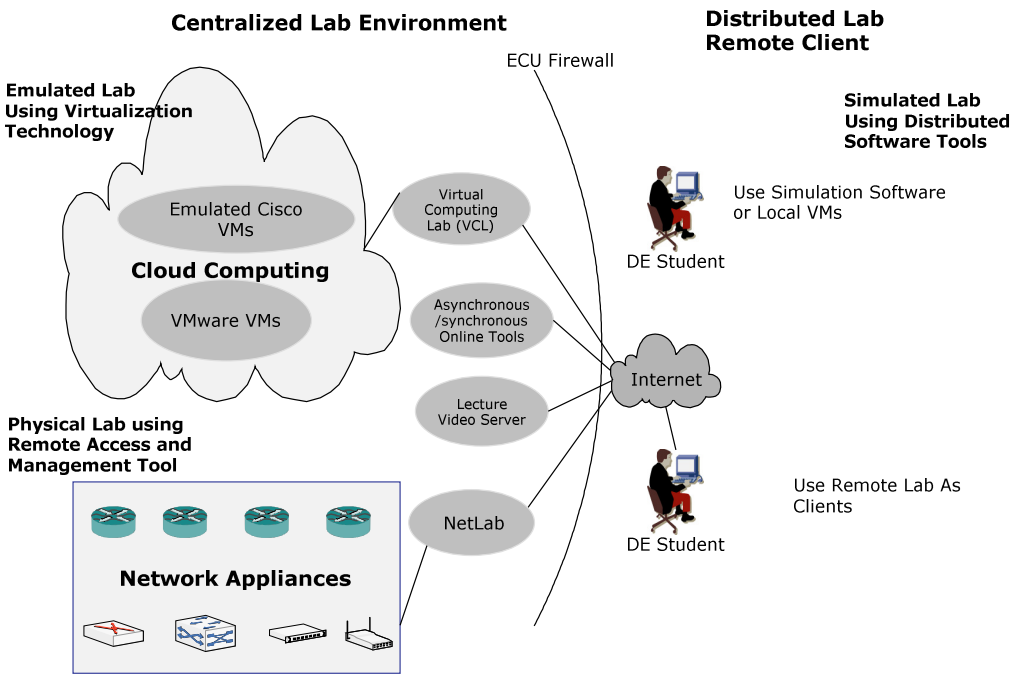

Figure 1. Computer Networking Lab Structure and Components

Key Lab Components:

1. Distributed lab

Students can install the distributed components to their local machines so they can work on the basic labs when they don't have internet access. The distributed lab components include the lab simulation software, such as PacketTracer and OPNET, and the VMs (virtual machines) that are created specifically for networking courses. Although the network simulators have limited functionalities comparing to the physical equipment, they have well-designed GUIs for students and can be run fast on PCs. The VMs, usually hosted on VMware Player or Virtualbox environment, can create a secure LAN environment for the students to simulate multiple interconnected PCs on their local machine. This approach works very well for the network security courses in which multiple Windows and Linux VMs are distributed the students. However, if complicated lab topology with VMware VMs and network appliance VMs, student usually have difficult time setting it up locally.

2. Physical Lab

The physical lab is managed through NDG's Netlab system. Users login, reserve, and manage lab sessions through a web server hosted on Netlab. The hardware portion of Netlab connects the lab access server and all the physical lab appliances. Figure 2 shows the student's view after a successful login. The authentication and lab reservation are completed on a standard browser. No software installation is required for the lab except for enabling Java. Other management functions, besides lab reservation, are also

implemented. For example, students are able to store and manage their configuration files through the online system.

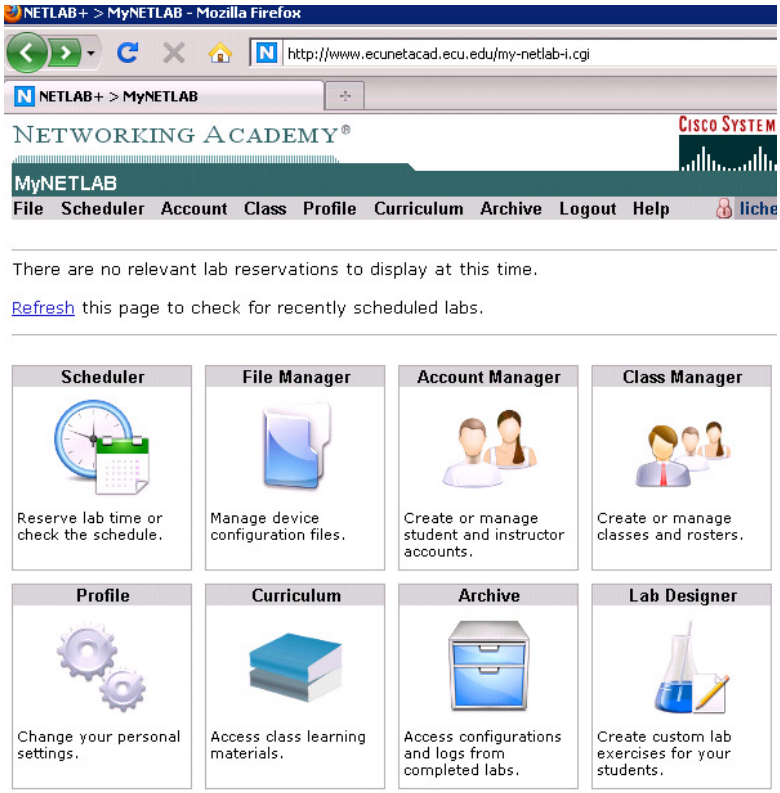

Figure 2. NDG's Netlab Web Lab Management Interface

Figure 3 shows Netlab's lab configuration window. The configuration is also conducted within the browser. No Telnet session or any client-side software is needed. The figure shows an initialization process of 20 minutes before the students can use the lab after the reservation is done. It is because the system needs to delete the configuration from a previous lab use and restore the lab appliances to predefined "clean" state. Without Netlab, students need to manually complete the process and take a similar amount of time. After the lab is initiated, students can click the lab components on the graphic interfaces to start the configuration windows. In the following figure, the configuration can be conducted on 4 routers, and 5 PCs. Upon the finish of a lab, students can save the configuration by clicking the "save" button. The system will store the files to a database so the students can revisit them or the instructors can grade the students based on these files.

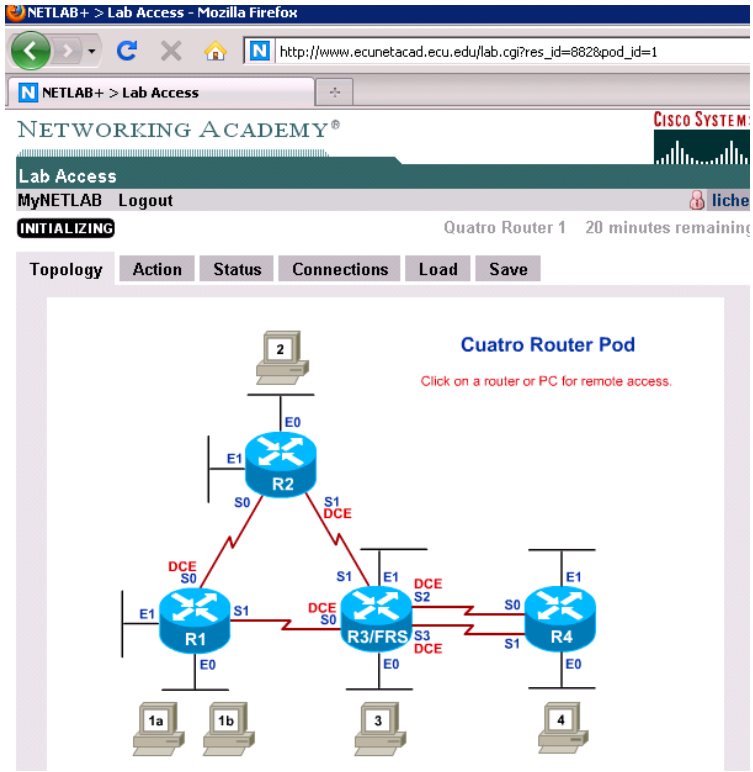

Figure 3. Netlab's Lab Configuration Web Interface

3. Emulated Remote Lab

The emulated virtual lab appliances can provide all the functionalities of a physical lab, with faster lab restoration speed and more convenient lab management environment. Software tools need to be created for an operation environment that is equivalent to the physical lab with remote access functions. In the past years, the graphical interactive interfaces, with the network topologies used in multiple networking and security courses were created. Interactive buttons, course teaching material, configuration tools, are all embedded to a software package, named Dr.Li's Network Studio. This software can also build up the communication between Cisco VMs and VMware VMs through internal TCP/UDP connections; so a complete computing environment with networking /security appliances and multiple workstations with windows and Linux operating systems are emulated on a single computer. The online lab delivery system of this software tool is either VCL or VMware Labmanager. They will be introduction in the subsequent sections.

Figure 4 shows the system design of the memory allocation and VM communication running on the background of the emulated lab. Figure 5 displays the graphic interface designed for the newly released 2010 CCNAS (Cisco Certified Network Associate Security) curriculum. The user-friendly interface allows users to control the emulated security appliances through the intuitive buttons and graphics. The interface shown in Figure 4 emulates three routers, three switches, and three Virtual PCs. All the VMs of routers, switches, and PCs are hosted within one piece of system memory. The Ethernet and serial port connections are simulated through the internal UDP ports. Each emulated

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appliance can be accessed via Telnet sessions. The Virtual PCs are hosted on VMware Workstation and networked to the hosting machine through a VMware virtual switch. One Ethernet port of each Virtual PC is bridged into the emulated switches.

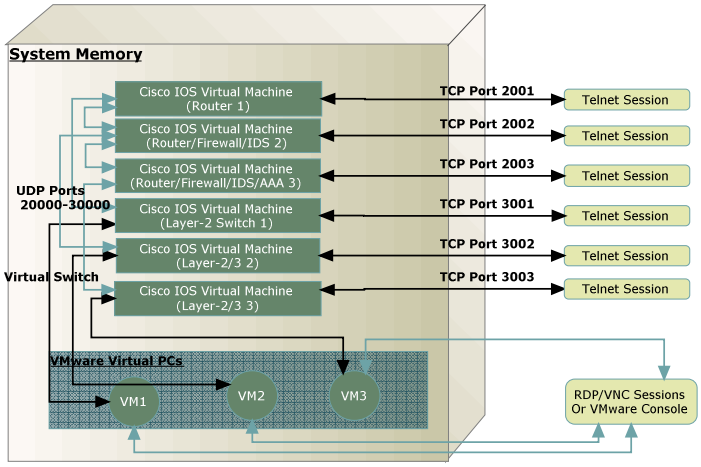

Figure 4. Memory Allocation and Simulated Connections among Virtual Machines

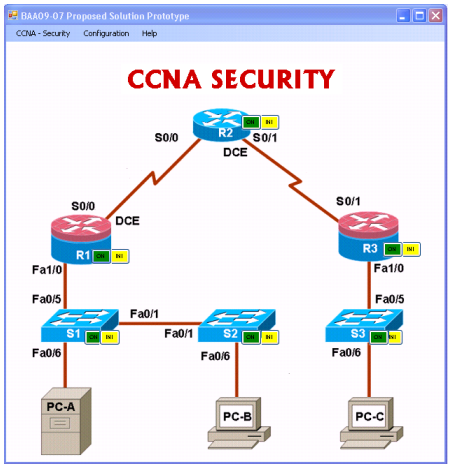

Figure 5. The CCNAS Lab Interface

Figure 5 shows the user interface of the security module that allows users to interact with the emulated security lab. The emulated lab is programmed in C#. The interface displays the network topology and capacity of each appliance. Routers 1 and 3 have the built-in security capacity and can be run as firewalls, AAA servers, and IDS/IPS appliances. The buttons attached to the routers and switches can be turned on/off to fast-restore the emulated appliances to the initial state.

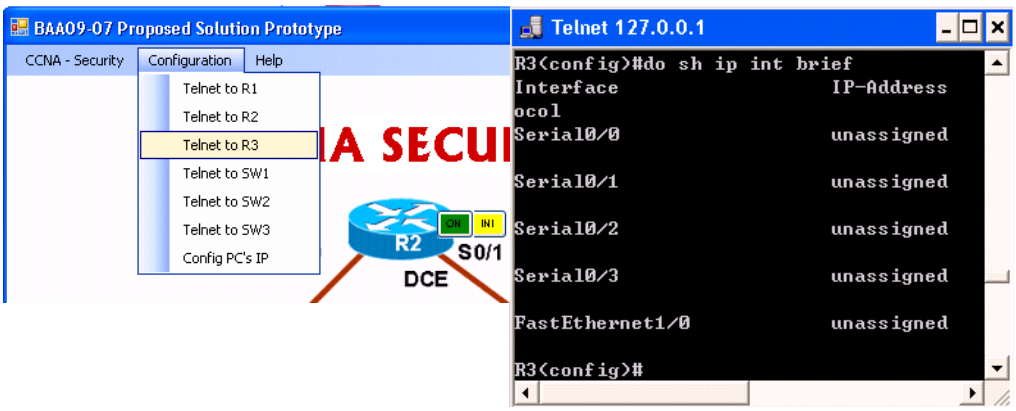

Figure 6. Configure Rotuer3 through Telnet Session and CLI Interface

Users can configure the networking and security appliances via Telnet sessions. Figure 6 illustrates the configuration process on Router 3. Configuring the emulated appliances by using Telnet and CLI (Command-line Interface) is identical to configuring the real physical appliances.

Three Virtual PCs are connected to the switches. These PCs are configured as servers or clients to perform network management, security auditing, traffic monitoring and packet sniffing tasks. As illustrated in Figure 7, two Linux and one Window XP operating system virtual images are bridged into the emulated Cisco network on designated UDP ports. A number of security software applications are installed for conducting the lab exercises and research. These applications include SDM (Security Device Manger), SSH (Security Shell) client, Wireshark, Kiwi-Syslog, VPN (Virtual Private Network) client, AAA (Authentication, Authorization, and Accounting) server, Radius sever, and IDS/IPS (Intrusion Detection/Prevention System) software.

Figure 7. Two Linux and One Windows VMs are Bridged into Emulated Network

The emulated lab not only creates a complete remotely accessible network and security lab but also presents itself as a standalone education tool that has course material, lectures, and lab instructions in video format embedded into it. Students are able to conduct a self-paced study on the security subjects by following the video lectures and instructions. The author has created these videos and hosted them on a security web server. Figure 8 illustrates that students can read the teaching material and watch the instructional videos via links on the dropdown menu from the software tool.

Figure 8. Embedded Course Material and Lecture Videos

Besides the above discussed CCNAS lab, there are 8 networking lab interfaces for both graduate and undergraduate courses developed on Dr. Li's Network Studio. The author is the director of ECU regional Cisco Networking Academy that oversees Cisco Networking program offered in 14 local colleges and high schools in the region. The emulation tool is not only used in the ECU's networking courses but also in the "Train-the-trainer" program that trains the instructors who teach the Cisco curricula in these local academies.

Emulated Lab Hosting And Management Systems

The emulated lab is hosted both on ECU's VCL (Virtual Computing Laboratory) and the VMware vCenter LabManager Systems. The software, Dr. Li's Network Studio, is installed to a Windows 2008 Server image. When this VM is hosted on VCL, Students can reserve each lab session for up to 6 hours and are able to conduct lab exercises remotely via the Internet. The VCL's current capacity can allow more than 40 concurrent users to have access to the security lab images, meaning that 40 security labs are available 24/7. Comparing to our physical lab that consists of only two physical Pods, the emulation approach greatly improves the lab availability and accessibility. When the reserved image becomes ready, student can connect to this virtual machine through Windows RDP (Remote Desktop) connection. The IP address, username, and password of this virtual machine is displayed on a webpage and also sent to the student through email. The reservation window is shown in Figure 9. Also as seen in Figure 9, the lab load time is less than 1 minute on VCL, which is much faster than the physical lab that requires about 20 minutes to scrub and start all the lab appliances.

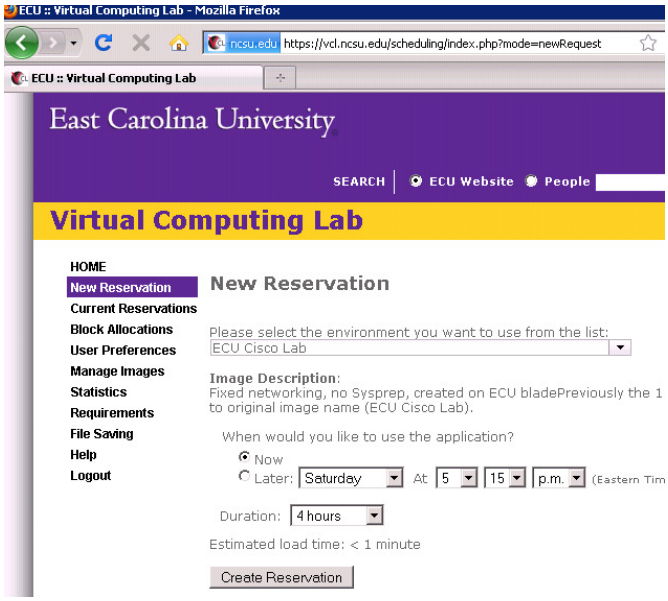

Figure 9. VCL Lab Reservation Interface

VCL is an open source application developed by NCSU under GNU open license. It allows user to reserve a remote virtual VM and connect it through RDP/VNC. It is a non-persistent environment, which means once the student logs off, no modifications made to the VM are able to be stored. This guarantees that the lab is always in a clean startup state every time the student uses it. Labmanager is very similar to the VCL approach. It also allows student to reserve VMs remotely. The differences are first Labmanager can be accessed through any web browser. Second, labmanager is a persistent environment. Which means the student can use the same image during the whole course. All the changes can be saved. Once the system crashes, the VM can always be restored to a pervious stable state. Figure 10 shows the LabManager system that allows students to deploy pre-built operating system images and use the emulated lab on a standard browser window.

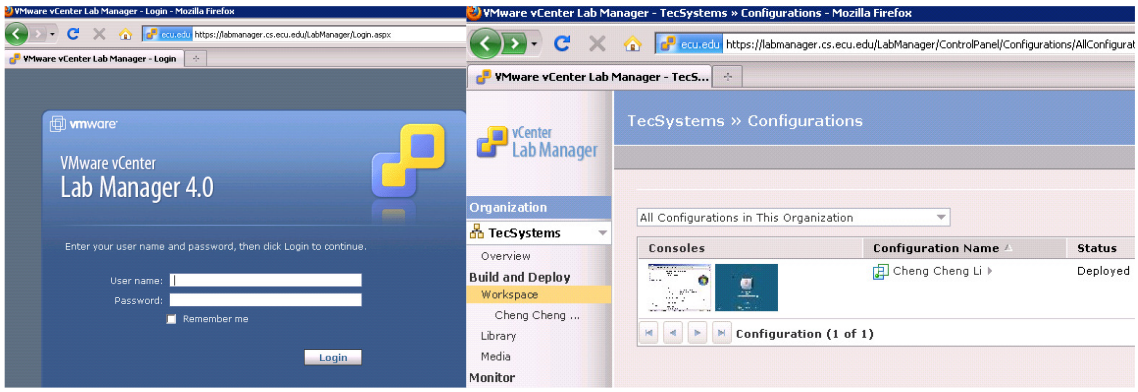

Figure 10. LabManager Login and VM Deployment Windows

Course Management Systems

In addition to the virtual and physical labs, the students can access a number of learning tools or popular course management systems remotely. Students can access the course site, assignments, write posts on the forums at the Blackboard systems used mainly at ECU. Other asynchronous tools supported by ECU are Moodle, Sakai, and SharePoint for course management and collaboration purposes.

Course lectures and lab instructions are created in multimedia formats and hosted on a video server. By watching the videos, students are leaning more static contents of the courses online while using the face-to-face time in the class for discussion and other interactive activities with the instructor. This leads to a balanced and effective blended learning environment by shifting student efforts to online and asynchronous learning while promoting self-studying.

Centra is the synchronous teaching tool hosted at ECU. It is a like professional web-conferencing system specifically designed for classroom simulation. It has advanced teaching features, such as application sharing and whiteboard. The chat sessions can be recorded for re-watch. It is used for teaching lectures, online real-time discussion, office hours for Q/A, and student team project collaboration.

RESULTS AND DISCUSSIONS

The lab system described in the above sections has passed the testing phase. It is now fully deployed and used as the major teaching tool in the core computer networking and security courses. Student reviews on the emulated lab, VCL, and LabManager environments have been conducted in three courses. The overall student satisfactions are high. 78% students agree the current lab structure allows them to perform lab exercise from anywhere at any time. 83% students agree the emulated lab provides a better or equivalent lab experience to the physical lab while the availability and initial setup speed are improved. Based on instructor and IT technician's reviews, we are also in the process of transit from VCL to LabManager environment so that students can have a persistent lab and the technicians can obtain better professional support from VMware. Plus, the LabManager system is free for academic and research use.

Through the lab system, the instructors have the flexibility to design labs that are tailored for particular courses, so that advantages and benefits of each lab component can be maximized. For example, the simulation tools have user-friendly interfaces and well-developed tutorials developed. Despite of the limited network simulation functions, they are excellent for teaching the entry level computer networking courses. The physical lab, mimic the real-world industry settings, gives students the hands-on experiences that are required in advanced networking courses, especially the higher level Cisco Curricula. The emulated lab is very easy to be programmed to interface with other software tools, such as VMware VMs, traffic generators, packet sniffers, and security tools. So, it can be used for general networking and security courses. It is also exclusively used in the graduate

courses because there are more research contents in the graduate curricula than hands-on training.

Acknowledgements

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Biographies

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