A Web-Based Remote Interactive Laboratory for Internetworking Education

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***Abstract*—A Web-based remote interactive laboratory (RIL) developed to deliver Internetworking laboratory experience to geographically remote graduate students is presented in this paper. The onsite Internetworking program employs hands-on laboratories in a group setting that correlates with the constructivist and collaborative pedagogical approach. This paper discusses the pedagogical and technical considerations that influence the design and implementation of the remote laboratory environment given the constraints of the special hardware and learning outcomes of the program. For wide-ranging usability, the remote Internetworking (INWK) laboratory uses *de facto* networking standards and commercial and broad-band Internet connectivity to ensure real-time secure interaction with equipment. A four-tier role architecture consisting of faculty, local facilitators, remote facilitators, and students has been determined appropriate to maintain academic integrity and ensure good quality of interaction with the remote laboratory. A survey employing a five-point scale has been devised to measure the usability of the remote access INWK laboratory.**

***Index Terms*—Online laboratory learning methods, online networking education, remote interactive laboratory (RIL), remote laboratory facilitation.**

I. INTRODUCTION

THE MODERN university needs to extend lifelong learning opportunities to its students anytime and anyplace to be successful in the global educational marketplace [1]. Online learning is made possible by advancements in network infrastructure and development of voice/multimedia protocols for seamless transport of information [2]. However, the developer of an e-learning system faces several challenges in designing an online laboratory learning environment that ensures strong, effective, accessible, and secure student interaction that best replaces the face-to-face interaction that takes place in on-site laboratories, especially in courses involving high-tech content, such as in an Internetworking[1] (INWK) laboratory environment, which extensively uses networking hardware and computer/simulation software tools. In addition to considering knowledge-domain requirements, the developer must ensure good pedagogy and learning practices given technical constraints with regard to bandwidth, quality of service, real-time interactions, multiple users, and security.

Remote laboratories have been successfully used in electrical engineering education to interact with spectroscopy, measurements, control systems, and simulation laboratories [3]–[10]. However, none of the reported work has addressed the specific issues pertaining to pedagogy, facilitation, scalability, usability, and security within a technical framework, other than mapping the instructional content to appropriate technologies. Examples of such mapping include remote instrumentation [3], [8] use of Java servlets [5], user-friendly interface design [4], [7] and use of broad-band communication [6], [10]. Although such experiences cannot be directly applied to the INWK laboratory, the essential elements of improved learning spaces can be adapted to develop an online laboratory learning system that meets the requirements of scalability, accessibility, interactivity, and modularity. This paper builds on and significantly contributes to existing e-laboratory education research [6], [11]- [12] by demonstrating the feasibility of designing e-laboratory systems for strong student interaction with remote equipment. The e-learning laboratory design framework employs secure, real-time, interactive laboratories and incorporates effective online laboratory learning strategies, including appropriate pedagogy, facilitation, and skill-building techniques to impart knowledge and meet instructional outcome. Pedagogical and instructional-level knowledge conducive to active and collaborative remote online laboratory instruction, incorporating effective remote-site facilitation that mimics the face-to-face interaction in the onsite laboratory, is considered. Integrated authentication and access control that is reusable across geographically distributed educational applications is demonstrated. In addition, the special requirements of online, synchronous, INWK laboratory-based e-education are considered in detail.

The curriculum of a Master's of Engineering in INWK program includes the following: study of transmission of multimedia information over communication networks; characteristics of transmission media; architecture, routing technologies, and infrastructure of different types of networks; interconnection of disparate networks (internets); evolution of, and influences on, network design; and services, applications, and future trends in such networks [13]. These programs are expected to expand online using a remote INWK equipment laboratory that is accessible by remote students through the Internet. The remote INWK laboratory must be designed to offer

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[1] *Internetworking*, as used in this paper, references a program leading to the Master's of Engineering in Internetworking—a program at Dalhousie University, Halifax, NS, Canada.

TABLE I
BRIEF COURSE DESCRIPTION, EQUIPMENT REQUIREMENT, AND LEARNING ACTIVITY TYPE FOR THE INWK–M.ENG. PROGRAM

Course Title	Course Description	Equipment/ Software	Activity type
Intro. to Computer Communications	Fundamental concepts associated with intranets and internets.	Routers, switches, packet analyzer	Lec-50% Lab-40% CP-10%
Mathematics for Internetworking	Markov chains, reliability, stochastic processes, queuing systems, simulation techniques for Internet modeling and analysis.	Software: Minitab	Lec-80% Lab-10% CP-10%
Physical & Data Link Layer Standards and Protocols	Physical layer issues in wired, wireless, and optical communications networks. Data link layer: media access, error control, standards.	Network simulation software: OPNET	Lec-50% Lab-40% CP-10%
Internet Communication Protocols	Transmission Control Protocol/Internet Protocol (TCP/IP) and popular applications.	Routers, PCs with Free BSD software	Lec-40% Lab-50% CP-10%
Network Architecture	Internetworking, bridging and routing algorithms, and encapsulation.	Routers, switches, LAN analyzer	Lec-40% Lab-45% CP-15%
Telecommunica-tion and WANs	Cellular, wireless systems, and wide area networks. Telecommunication transport and signalling standards.	Routers, switches, phones, WAN analyzer	Lec-50% Lab-50%
Real time Operating Systems & Platform Architecture	Real time OS configurations; Internetworking architecture issues: caching, hardware, and software performance.	Software: Borland C++	Lec-45% Lab-45% CP-10%
Emerging Internetworking Technologies	Emerging technologies, design alternatives; theory and practice for a reliable multi-service Internet environment.	Routers, switches, ATM switch	Lec-60% Lab-30% CP-10%
Network Security & Management	Security threats; security protocols; network management protocols; troubleshooting; monitoring network performance.	Routers, switches, LAN /WAN analyzer	Lec-50% Lab-40% CP-10%
Simulation, Modeling, and Analysis	Discrete event simulation, experiment design and optimization, simulation of inter/intranets, comparing system configurations.	Network simulation software: OPNET	Lec-35% Lab-45% CP-20%

Note: Lec – Lectures Lab –Laboratory work CP – Case study/Project work

a high quality of online student interaction with the faculty and the laboratory equipment and enable students to work in virtual teams [14]–[16]. An integrated design approach is undertaken that promotes student interaction with good infrastructure management that can ensure effective learning, better student performance, and achievement of pedagogical goals.

The paper is organized as follows. Section II gives the pedagogical features of onsite INWK laboratory education. Section III discusses the research framework for the design of the RIL. Section IV discusses how the traditional onsite wiring strategies have been modified and tailored for online delivery. Section V describes the online laboratory architecture, implementation issues, and how technical constraints, pedagogy, and instructional goals influence the design and implementation of the Web-based RIL. Section VI discusses the authentication and access control issues in the remote laboratory. Section VII discusses facilitation, and Section VIII discusses instructional strategies employed in the remote laboratory. Section IX presents results that demonstrate the usability of the remote laboratory. Section X provides conclusions and directions for future research.

II. PEDAGOGICAL FEATURES OF ONSITE INTERNETWORKING LABORATORY EDUCATION

In Table I, the course outline, laboratory equipment used, and the learning approach employed in the INWK program is summarized. Table I clearly indicates the emphasis placed on laboratory based INWK education, which accounts for approximately 40% of the overall program content. Lectures account for 50% of course content, and collaborative activities such as case studies and projects account for the remaining 10%. Comprehensive, "hands-on" laboratory experience is provided by employing networking equipment, simulators, and other hardware to immerse the student in a constructive learning environment that employs collaborative activities [17]–[19]. Authentic activities, such as hands-on configuration of INWK equipment, increase student engagement with the subject matter resulting in better knowledge retention [20]. Since most network engineering activities in an enterprise are conducted in a collaborative setting, the laboratory activities are designed to be carried out by students interacting in groups. The hands-on interaction helps apply INWK principles and theories in a practical networking context to teach students troubleshooting techniques and problem-solving skills [19]. Such situated learning transforms the novice students into experts in the context of the INWK community in which they will work [19].

Description of the Onsite INWK Laboratory: The onsite laboratory equipment consists of personal computers (PCs) and servers; networking devices, including routers and switches from vendors such as Cisco Systems,[2] and Nortel Networks[3] local area network/wide area network (LAN/WAN) network analyzers, and network simulation software OPNET.[4] The networking equipment is placed on several racks with each rack having an identical set of routers, switches, and hubs. The equipment consists of Ethernet, token-ring, frame relay (FR), and asynchronous transfer mode (ATM) technologies. The laboratory has access to a DMS-100 telephone switch that provides ISDN and telephone connections. Various network topologies are built by simply connecting pairs of nodes using the appropriate cables. A network of cables and patch panels between equipment racks are used for inter-rack connections. To configure a network device using a command line interface (CLI) and monitor its activities, a PC is attached to the device's console port using an RS-232 cable allowing the student to establish a connection with the device.

III. RESEARCH FRAMEWORK FOR REMOTE INTERACTIVE LABORATORY DESIGN

The e-learning research framework proposed by Alavi and Leidner [21] urges study within the context of pedagogical strategies and learning processes. At the intersection of these strategies and processes are the methods of instructional delivery that can be viewed from student-centric, university-centric, and technology-centric perspectives. E-learning system designers and universities use these metrics to guide the design, development/adoption, and implementation of learn-ware, assessment of e-learning system infrastructure, and measurement of the usability of the system. Specifically, issues in the design of the pedagogical strategy that implements a student-centric learning process in a Web-based remote INWK laboratory system must [22] be able to achieve the following:

- encourage student interaction by employing networking equipment/simulators [1], [23];
- provide real-time response from equipment to engage students actively in achieving learning outcomes;
- provide a collaborative learning environment for group interaction at a remote site;
- match the characteristics of the instructional delivery medium to specific learning outcomes and processes, including the provision of feedback and guidance [25], [26];
- improve system usability to ensure repeat student interaction;
- track student performance to meet learning outcomes.

The university-centric issues in implementing instructional delivery methods include the following [24]:

- curriculum quality;
- instructional pedagogy employed in the remote laboratory;
- technical infrastructure management for delivering learning material;
- system scalability to handle increases in student enrollment;
- continuous student assessment for grading purposes.

From the technology-centric viewpoint, the instructional delivery framework must be able to do the following [24]:

- use *de facto* networking standards and free software to connect the remote site to the central equipment facility;
- use secure interaction between the remote site and equipment facility;
- deliver laboratory notes and other relevant material such as wiring information and diagrams to students at remote locations over the Internet;
- identify the student at the time of initial access to laboratory resources.

A detailed study of the above factors is given in [23] and [24]. The design of the RIL is aimed at delivering an effective remote laboratory experience moderated by the laboratory facilitators. The technical design of the RIL given in Sections IV–VI reflects the progress made by the program in reworking the onsite INWK laboratory to enable students to interact online with the devices at the central equipment facility.

IV. TAILORING LABORATORY WIRING STRATEGIES FOR ONLINE EDUCATION

Students learn fundamental theoretical concepts in lectures. In addition, the lectures discuss and describe the functional and physical features of hardware used in the laboratory. The laboratory description listed in Table I shows that most courses require students to interact with the networking devices enabling them to implement and, thereby, better understand networking concepts. The laboratory component of the various courses requires that students learn how to configure equipment, such as serial, synchronous and asynchronous connections between routers, virtual local area networks, and virtual private networks; configure routing protocols in routers/Layer 3 switches; build, implement, and configure Ethernet/token-ring networks, FR, ATM, and integrated service digital networks; and set up voice/video-over-Internet protocol (VoIP) networks etc.

Issues in Web-Accessed Remote INWK Laboratory: A key issue with the remote delivery of the INWK laboratory is to convert the onsite student interaction (discussed in Section II) with the devices in the laboratory into online, real-time interaction. To allow remote configuration of the networking devices, each rack is equipped with a terminal server. The terminal server acts as a link between the Internet and the student rack and provides users with a single entry point to all devices. A student can now establish a connection to any networking device through the Internet to configure these devices using a command line interface. However, students would still have to build their topologies manually by interconnecting devices with cables, a step that would necessitate their presence in the onsite laboratory. Thus, a second key requirement is for remote students to

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[2] http://www.cisco.com

[3] http://www.nortel.com

[4] OPNET Network Simulation, http://www.opnet.com

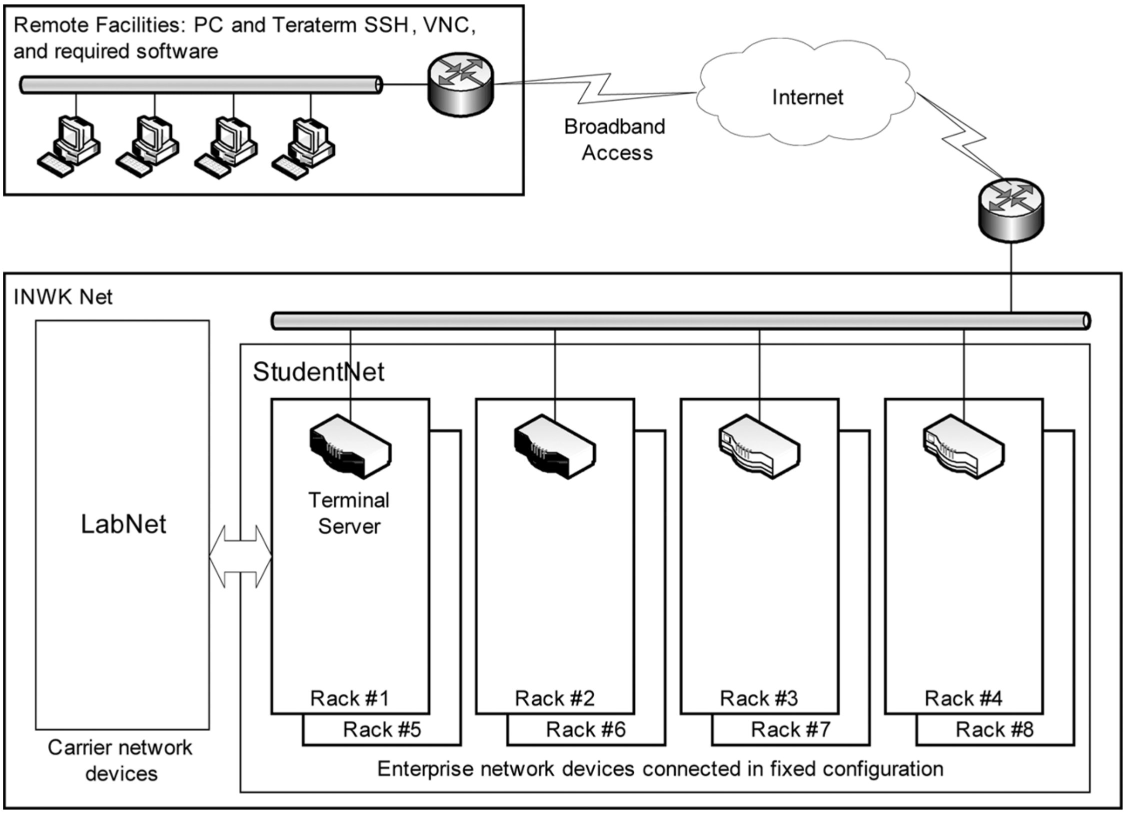

Fig. 1. Logical architecture for remote delivery of INWK laboratories.

build various network topologies without having physical access to the equipment; therefore, the INWK devices must be wired in a manner that allows construction of different network topologies with no change to the physical wiring connections. In this paper, the solution employed uses virtual LAN (VLAN) techniques for Ethernet networks and permanent virtual circuits (PVCs) for WAN networks, employing ATM and FR technologies as explained in the Sections V and VI.

V. ARCHITECTURAL ISSUES IN THE REMOTE INTERACTIVE LABORATORY

The Internetworking laboratory network (INWKNet) consists of a number of enterprise- and carrier-level INWK devices, such as routers and switches. A good strategy to achieve fixed wiring is to group the devices logically and physically into a backbone network and an access network. The backbone network consists of special purpose devices that are commonly found in carrier networks and is configured in a fixed topology. The laboratory backbone network is called the LabNet and resembles a miniature "Internet" that is always available to carry ATM, FR, and Ethernet data traffic. The other INWK devices are organized into a number of student racks, each containing an identical set of devices to be accessed by students, called the StudentNet. The StudentNet devices are used to build topologies similar to the ones found in an enterprise network. The INWKNet mimics a typical network scenario, where small enterprise LANs represented by the StudentNet are connected to a carrier's WAN represented by the LabNet. The logical architecture of INWKNet is shown in Fig. 1.

A. LabNet Architecture

Fig. 2 shows the logical architecture of the LabNet, which is built around three Passport 7440s, multiservice routers. These multiprotocol routers switch data packets over ATM, FR, and Ethernet (IEEE 802.3) networks and allow the building of multiple independent logical networks using the same physical devices. Each logical network is assigned its own physical interfaces, set of protocols, and addressing schemes. The following paragraphs explain how the LabNet devices are used to build Ethernet, ATM, and FR backbones.

Ethernet Backbone: The Ethernet backbone consists of a P8600 multilayer switch that is connected to other LabNet devices as shown in Fig. 2. The P8600 is also connected to each student rack via either 100-Mb/s or 1-Gb/s links. VLANs are used to create multiple Ethernet segments on the student racks. The P8600 backbone switch routes traffic among these student VLANs.

ATM Backbone: When used for constructing ATM networks, the Passport 7440 devices are interconnected as shown in Fig. 2 and represent the public ATM network. A private ATM backbone is constructed using a Light Stream 1010 ATM switch with eight ports. Six ports on the LS1010 connect to the student racks. Two ports are connected to the P7440 devices in the backbone.

Frame Relay Backbone: The FR backbone consists of the P7440 switch, which supports both FR and ATM technologies and Cisco FR emulator. As with ATM, various FR topologies can be constructed in the student racks using PVCs.

ISP Services: As shown in Fig. 2, the Shasta 5000 BSN device is employed to model several logical Internet service providers

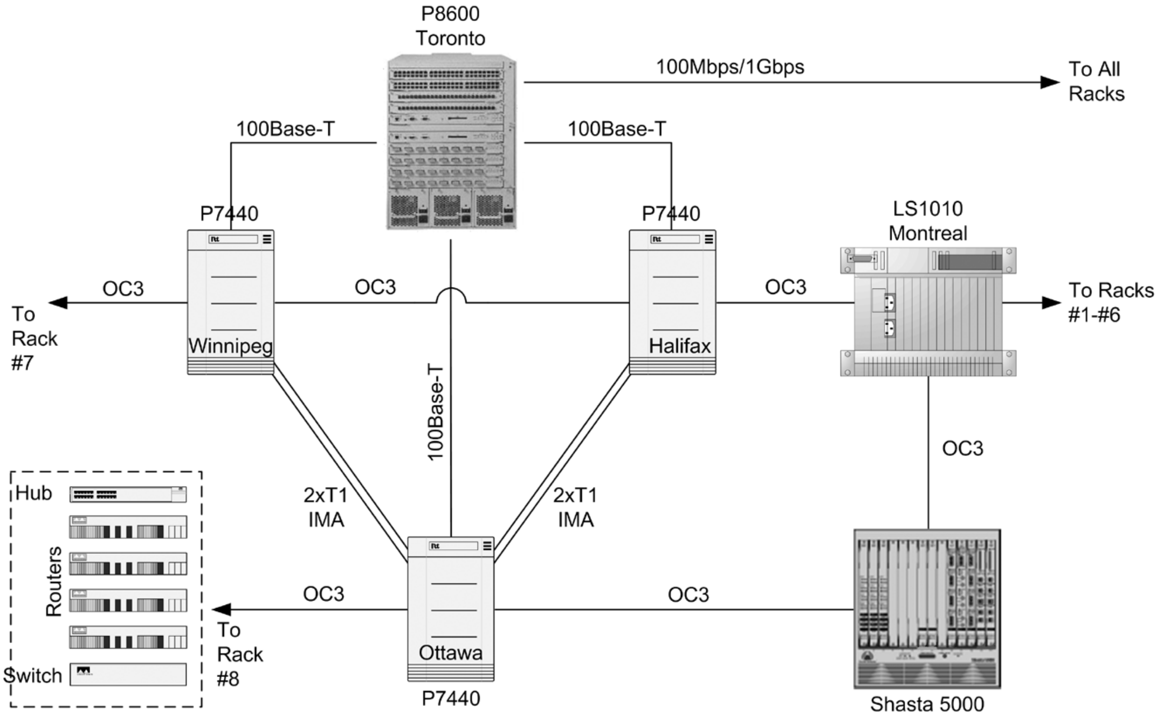

Fig. 2. Logical architecture of LabNet.

(ISPs) and is connected to the other backbone devices via ATM links. The routers in the student rack are connected to the Shasta using ATM or point-to-point protocol (PPP) over Ethernet links. The Shasta 5000 also offers services including firewalls, traffic management, Web caching, and virtual private network services and delivers Internet services via dial-up, digital subscriber line (DSL), cable, or direct connections.

B. *StudentNet Architecture*

The StudentNet consists of equipment placed on eight racks in the central equipment facility. The design of the StudentNet supports multiple simultaneous interactions with the equipment and can be accessed remotely by students through the Internet. Remote access to laboratory hardware in the student racks is achieved by equipping each student rack with a terminal server that connects a device's port to the Internet. The access to the INWK devices, e.g., switches, routers, and protocol analyzers, is through a Web interface. Web pages are used for logging on and accessing the hardware. The terminal servers limit access to authorized users by verifying that the user name and password given by a specific user matches the ones stored in a central database. The StudentNet architecture is designed to be modular with similar equipment in each rack and, hence, highly scalable. Scalability is essential to maintain interoperability and address increases in student enrolment. Each student rack consists of several Cisco 36xx routers, Cisco 3550 switches, Nortel Passport 1100 multilayer switches, and Ethernet and token-ring hubs. Additional student racks can be added without significantly impacting performance and with minimal changes to the LabNet networking equipment or its cabling.

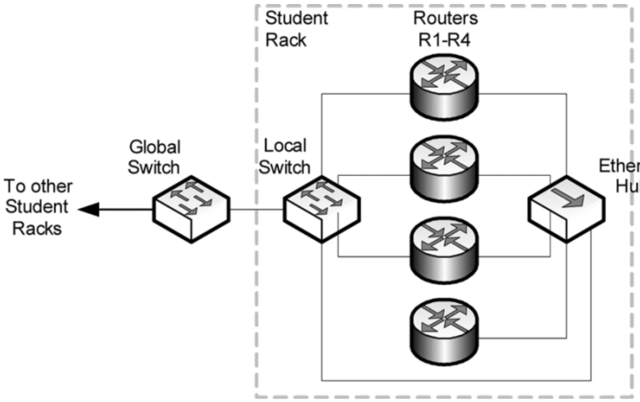

Fig. 3. Ethernet connections in a student rack.

C. *Configuring Network Topologies in the StudentNet*

A description of how various Ethernet, FR, and ATM network topologies are built using the StudentNet equipment is given in this subsection.

Configuring Ethernet LANs in the StudentNet: In Fig. 3, the dotted area represents equipment in each student rack. Equipment outside this area is located in the LabNet. Each student rack has four routers R1–R4, a local switch, and an Ethernet hub that allows groups of students to use them independently.

A key instructional requirement in Ethernet laboratories is to be able to construct both port-centric and segment-centric LANS. Therefore, all routers are connected to a 10-Mb/s hub via one port on each router, and all 10/100base-T ports on three of these routers are directly connected to a local Ethernet switch in that rack. Arbitrary Ethernet network topologies can be built by attaching nodes to ports on an Ethernet switch and assigning them to appropriate VLANs. The architecture shown in Fig. 3

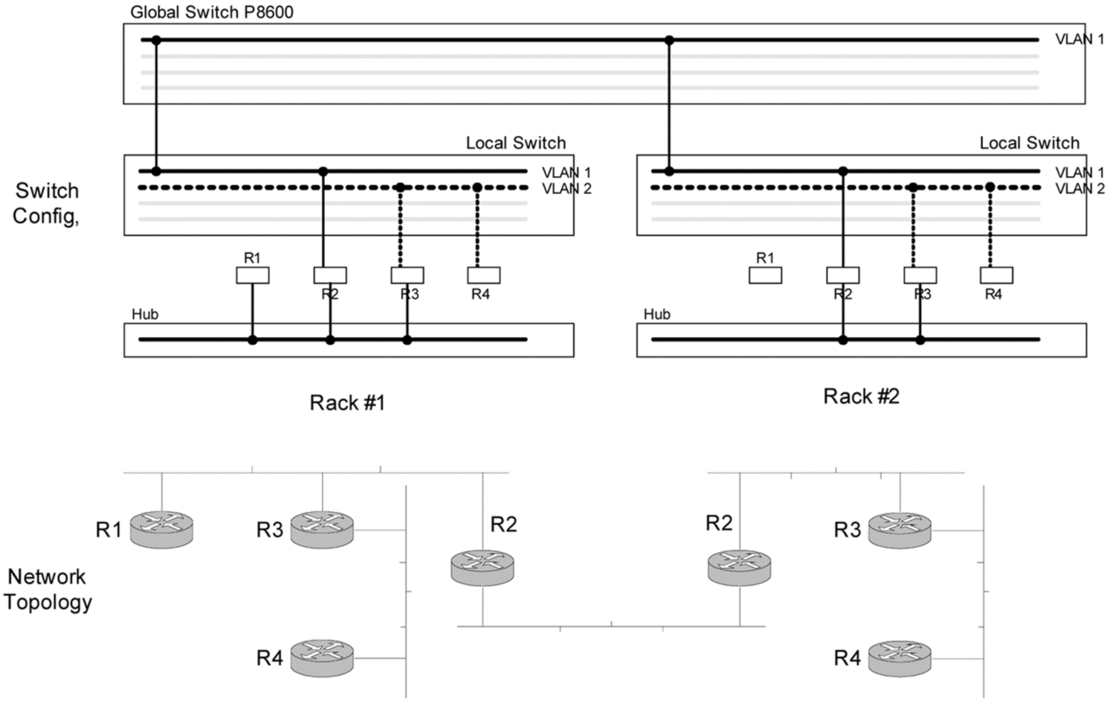

Fig. 4. Various Ethernet topologies using VLANs: Physical and logical connections.

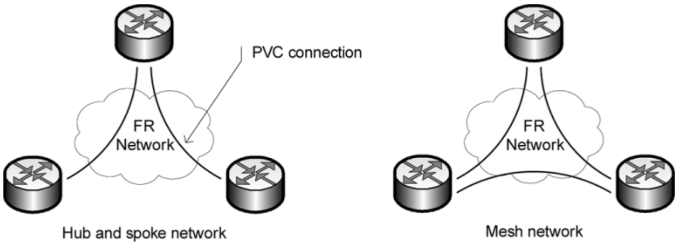

Fig. 5. Frame-relay network in a single student rack: hub-and-spoke and mesh topologies.

allows novice students in early courses of the program to build networks with minimal configuration of the routers, while advanced students are able to create complex topologies using VLANs.

Fig. 4 shows an Ethernet network that spans two student racks. The network topology is translated into VLANs, which are configured in the local switch of each rack. The diagram shows that any two or more routers in the laboratory can be linked via a VLAN that spans two switches at most.

Configuring Frame-Relay Networks: As shown in Fig. 5, a local FR network can be built in each student rack by employing the routers in that rack and is achieved by using PVCs and configuring one router to act as an FR switch. Small hub-and-spoke or meshed topologies can be built within each student rack. As shown in Fig. 6, a laboratorywide FR network can then be built by connecting a single router in each student rack to the global P7440 FR switch in LabNet.

Configuring ATM Networks: Fig. 7 illustrates the connection of the global LS1010 ATM and Shasta 5000 ISDN switch to the routers in a student rack. As shown in Fig. 8, six ports on the LS1010 ATM switch are connected to a router from each student rack to form a private ATM network. The connection between the LS1010 and the P7440 models a typical ATM network scenario where a private ATM campus network is connected to a large public-carrier network. The campus LS1010 ATM backbone is used to carry either ATM traffic or IP packets over ATM between the student racks. With purely ATM traffic, various topologies can be created by configuring PVCs in the student racks. In the case of IP over ATM, the P7440 device forwards IP traffic between Ethernet ports using multiprotocol over ATM.

D. StudentNet Interface Issues: CLI versus GUI

Onsite students access and configure the devices in the laboratory using a CLI or a graphical user interface (GUI). For online student interaction, the laboratories have been redesigned to enable students at the remote sites to access the CLI of most networking devices using the Internet. The CLI was chosen over a GUI because students need feedback from the central equipment facility in near real time and transmitting information using a GUI is relatively slower than CLI. In addition, the CLI is a reliable, direct, and simple method of executing network operating system commands on equipment. Since all options and operations are invoked in a consistent manner, the CLI allows greater flexibility and control and is, therefore, easier to learn and use. In addition, the CLI can be easily used to write scripts to automate repeated configuration procedures. In addition, remotely accessing the CLI requires a communication channel with moderate bandwidth such as that provided by commercial ISPs and, thus, is extremely suitable for use in regions with modest Internet infrastructure.

Some laboratories in the program require the use of LAN/WAN analyzers located at the equipment site to analyze the LAN/WAN traffic. The LAN/WAN analyzers cannot be accessed using the CLI. Similarly, simulation tools such

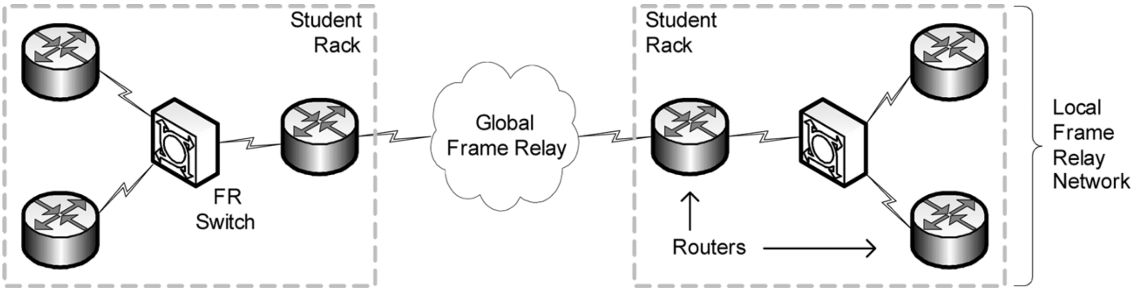

Fig. 6. A laboratorywide FR networks.

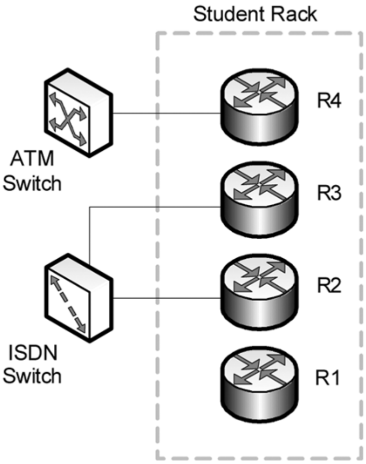

Fig. 7. ATM and ISDN connections.

as OPNET use a GUI. Remote students access these analyzers/simulators at the equipment facility, using Virtual Network Client (VNC) software on the remote site PCs. However, VNC use at the remote site requires a minimum broad-band access capability of at least 56 kb/s per PC.

VI. REMOTE STUDENT AUTHENTICATION AND ACCESS CONTROL ISSUES

Two key issues to ensure secure interaction with the e-laboratory system are 1) verifying the identity of enrolled students and 2) restricting access to educational resources. The authentication, authorization, and accountability features are integrated into one security subsystem that is well suited to securing laboratory equipment accessed through the Internet by a large number of students. Authentication mechanisms identify users, while centralized access control is achieved by restricting remote access to terminal servers using an access control server (ACS) at the equipment facility. All remote users wishing to gain access to laboratory resources are authenticated against the ACS internal database and an external database located in a secure Linux server. The Terminal Access Controller Access Control System Plus (TACACS+) protocol is used as it encrypts the entire body of the packet, including the password, thus making the communication with the ACS server secure. Remote students use Tera Term Secure Shell (TTSSH) software[5] to connect to the terminal servers at the equipment site. TTSSH, a free Windows-based terminal emulator and telnet client software, has been chosen because the university needs to balance the conflicting metric of finding a cost-effective solution, taking into consideration student concerns regarding security and privacy. TTSSH provides secure access by encrypting the communication between the equipment and the student. Fig. 9 illustrates the student authentication system architecture and outlines the steps involved in authentication and authorization. Also included are accounting functions such as tracking user connections and logging system users. The terminal server reports user activity to the ACS in the form of accounting records. Each record contains information, including user name, network device accessed, login/logout time information, and authentication status.

VII. REMOTE SITE FACILITATION ISSUES

The characteristics of a media used in communication can be assessed using media synchronicity theory (MST). The characteristics include the medium's capacity to provide feedback, symbol variety, instruction of multiple students, ability to tune message content, and the capacity to reprocess a message and unambiguousness [25], [26]. MST, when applied to the problem of remote laboratory learning, helps online education designers to match the characteristics of media to specific laboratory learning activities, outcomes, or processes. MST suggests that face-to-face communication supports only a low level of one-to-one interactions but facilitates useful feedback that is helpful in arriving at a group consensus [25], [26]. Most onsite students benefit from face-to-face interaction with instructors in a laboratory environment. Similarly, online graduate-level professional development courses offered to teams of teachers have used online facilitation to mimic successfully onsite face-to-face interaction [27]. In the remote INWK laboratory, facilitation is used in a remote learning scenario to maintain the quality of the educational experience without sacrificing educational standards [1]. This goal is accomplished by appropriately modifying the three-tier role hierarchy of the traditional onsite laboratory, consisting of faculty, laboratory assistants, and students into a four-tier architecture, in which the Tier-2 laboratory assistants are replaced with local-site facilitators at the central equipment facility and remote-site facilitators at the remote site. Facilitation is employed to foster strong student interaction and to maintain academic integrity by a strong demarcation of roles at the equipment site and the remote site. In this architecture, at the university end, Tier-1 consists of the director, administration, and faculty; Tier-2 consists of local-site facilitators at the central equipment facility;

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[5] Tera Term, http://hp.vector.co.jp/authors/VA002 416/teraterm.html

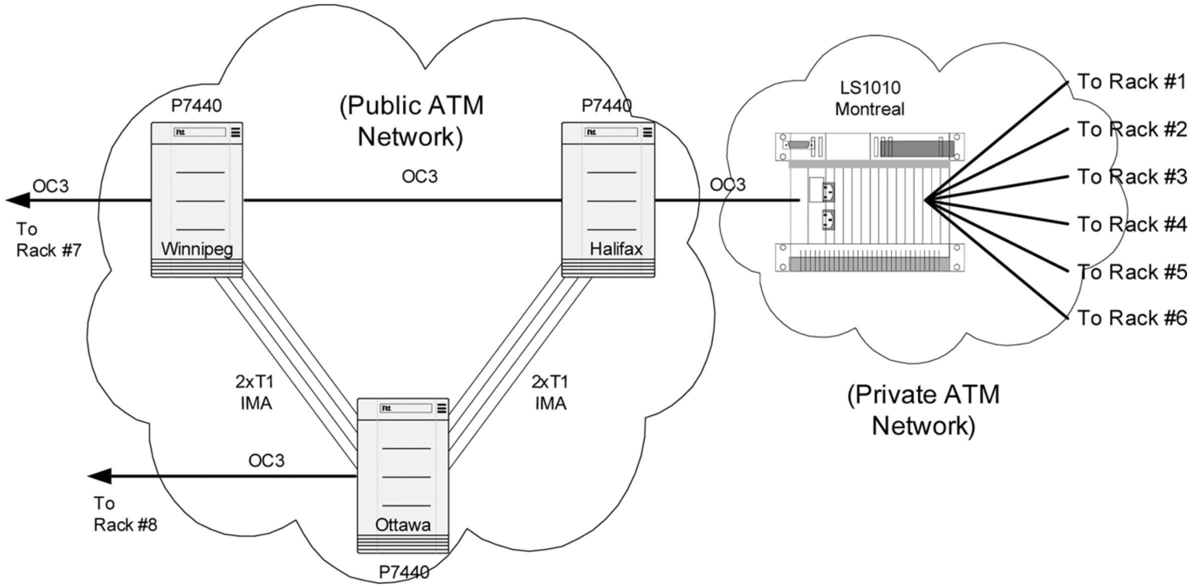

Fig. 8. Connecting a private ATM network to a public ATM network.

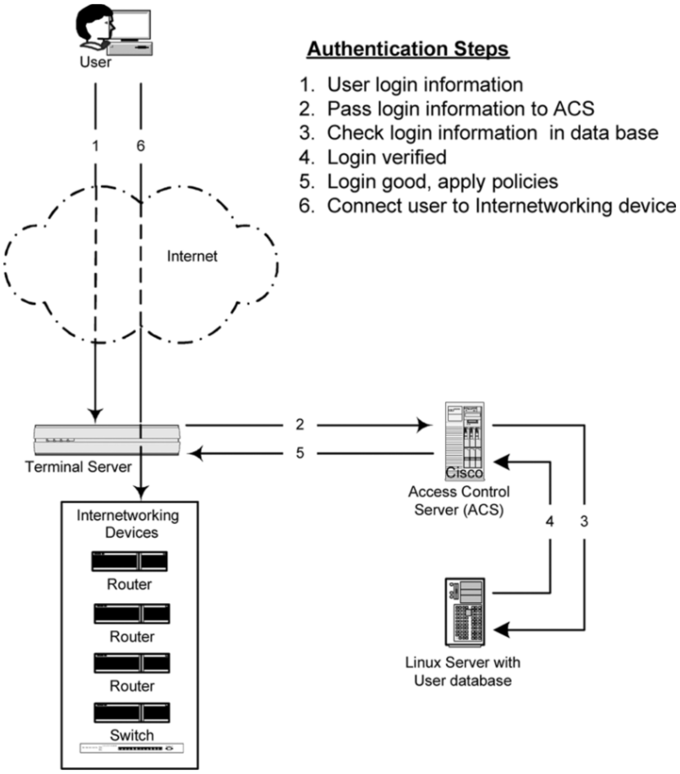

Fig. 9. Remote student authentication and access control architecture.

Tier-3 consists of remote-site facilitators; and Tier-4 consists of the students. In Tier-1, the administrators handle enrolment, registration, and other functions associated with disseminating program information, and the faculty are the sole course content providers in charge of designing an expert INWK curriculum. The faculty administer tests, examine and assess students, and provide feedback on student competencies. The local-site facilitators maintain and update laboratory notes for each course, test and configure the devices in the INWK laboratory for proper use, and create and maintain user account information. The local facilitators are doctoral students or candidates with the INWK program. In addition, they are guided by the faculty to help maintain a dynamic and engaging electronic-laboratory environment that is easy to use. The remote facilitator moderates the face-to-face communication between the students to speed up understanding of new information and in arriving at a consensus. The remote facilitators are former students of the program and have an M.Eng. degree in INWK. Trained adequately, they support, maintain, and upgrade network services on servers and workstations at the remote site and verify that the central equipment facility is remotely accessible.

VIII. REMOTE SITE INSTRUCTIONAL STRATEGIES

Students typically work in groups of two to three per group in the introductory and intermediate laboratory experiments. In advanced laboratory experiments, such as border gateway protocol (BGP) or open shortest path first (OSPF) in network architecture, they still have to configure the networking equipment by group and then have to interact across groups. The remote- site laboratory design must make use of active learning strategies in a collaborative environment [17], [20]. The activities in the remote laboratory are modeled to implement the nine instructional steps as outlined by Gagne *et al.* [28], [29]: 1) gain student attention; 2) inform students of the objective; 3) recall prior learning; 4) present stimuli; 5) provide learning guidance; 6) elicit performance; 7) provide feedback; 8) assess performance; and 9) enhance retention. A typical scenario for remote-laboratory work is discussed in the following paragraphs.

Provide wiring information: The wiring diagrams for laboratory equipment is available form the program website [31].

Activities that capture the student's attention, inform student of laboratory objectives, and recall prior learning: The remote student is given the laboratory handout a week ahead of actual performance of the laboratory experiments. The laboratory handout informs the students of the objectives, learning outcomes, and results to be submitted (Gagne's steps 1 and

2) and helps each student identify skill-building activities for the experiment. This stage of laboratory learning consists of one-on-one interaction between the student and learning content and is employed to teach students the commands used in configuring equipment before actual interaction with networking equipment (Gagne's step 3). Students individually answer questions regarding the physical fixed wiring of laboratory, actual steps used in achieving an outcome, techniques employed to measure/record output or simulation results, and the correct/expected output (Gagne's step 6).

Active remote interaction with INWK equipment—Present stimulus, provide guidance, and elicit performance: The remote and local facilitators ensure that the remote students can interact in real-time with the equipment at the central facility. Active, remote, equipment interaction involves two parts: the first part involves acquiring component skills based on simple tasks, and the second part involves acquiring comprehensive skills based on more advanced concepts. The first part consists of one-on-one interaction between a student and piece of equipment. The second part consists of a group of two to three students interacting with equipment. During the one-on-one interaction, the student has already acquired some knowledge (outlined in previous paragraph) and is ready to configure a particular device interface appropriately (Gagne's steps 4 and 6). The student practices under the guidance of remote facilitator (Gagne's step 5), who then provides correct feedback (Gagne's step 7). The student submits results to the remote facilitator who keeps track of the acquired individual skills (Gagne's step 6).

The student is now ready to proceed to the second and more advanced experimental stage involving group student interaction with equipment and intragroup teamwork (Gagne's steps 4 and 6). This stage of experiment can be thought of as being "directed" by the remote facilitator (Gagne's step 5) and involves collaborative learning strategies. Specifically, the collaborative approach is advantageous when more advanced peer students explain difficult learning concepts or demonstrate advanced equipment configuration to less knowledgeable students, exploiting the power of learning by observation, resulting in better retention [30] (Gagne's step 9). The remote facilitator verifies that the student–group has acquired the aggregate skill sets (Gagne's step 6).

Verifying learning outcomes—Assess performance: The remote facilitator helps to verify that the student has accomplished the experimental outcome and moderates intragroup and intergroup discussion on the results (Gagne's step 6) to achieve learning process convergence [27].

Troubleshooting techniques—Provide guidance and feedback: The remote facilitator identifies the stages of the experiment that are problematic to the students, using an analysis of the evaluation criteria not met by most students, and conveys this information to the local facilitator. To remedy the situation, the local facilitator, in consultation with the faculty, provides remedial guidance by demonstrating troubleshooting techniques using video conferencing from the equipment site (Gagne's step 7). According to Gagne, such corrective feedback is an effective teaching strategy to enhance learning and long-term retention (Gagne's step 9). Video conferencing is used since this medium has high concurrency and moderate feedback characteristics. Video conferencing easily allows remote students to interrupt and seek clarification from the local facilitator and is suitable for conveying information unambiguously to multiple students.

Tracking student progress—Enhance retention and transfer: The remote facilitator collects both individual student and group outcome measures and forwards them to the local facilitator for evaluation purposes (Gagne's step 8). Evidence of student competency in the laboratory include the following:

1) answers to questions;
2) appropriate response from configured equipment;
3) plots and printout of graphical output from simulators;
4) time in which experimental objectives are accomplished;
5) the context in which steps 1–4 are accomplished;
6) analysis and discussion of results.

Teaching and assessment methods that enhance knowledge retention are outlined in [20] (Gagne's step 9). Accordingly, faculty at the central equipment site assess students for competency based on their 1) understanding component skills, 2) aggregation of component skills into comprehensive skills, 3) application of comprehensive skills to solve problems, and 4) analysis and critique of the proposed solution. On obtaining student assessment from the faculty/local facilitator, the remote facilitator may generate a graphical skill map which outlines the competency acquired by the student to motivate the student to acquire the desired competency level.

An example of a typical remote online INWK laboratory exercise requires students to configure, analyze, and troubleshoot the performance of the routing information protocol (RIP). Each group is assigned INWK devices in the StudentNet for configuration. The RIP experiment first requires each student to learn how to configure RIP on a router. In addition, each student captures and analyzes data packets using sniffers or protocol analyzers. The advanced part of RIP experiment consists of observing and analyzing the convergence of the RIP protocol by intentionally generating a link failure event in the network. The convergence of RIP is of prime interest with each student group capturing and analyzing the routing protocol updates on their routers.

IX. RIL USABILITY MEASUREMENTS

The usability of an e-laboratory system is a function of system design and is determined by factors, including ease of use, interactivity with the system, system accessibility, system reliability, availability of online help (including laboratory handouts and wiring diagram information), support for multiple simultaneous interactions, system responsiveness, appropriateness of system response to student input, authenticity and student perceptions about the "state-of-the-art" networking environment, feedback from the laboratory instructor, and hands-on feeling. A survey questionnaire that has been developed based on these 12 issues is summarized in Table II.

Students were asked to rate the usability of the online remote equipment laboratory on a five-point scale, as follows: 1—very poor; 2—poor; 3—satisfactory; 4—good; and 5—very good.

TABLE II
QUESTIONNAIRE USED TO MEASURE THE USABILITY OF THE REMOTE INTERNETWORKING LABORATORY

	On a scale of 1 to 5 rate: (1=Very poor, 2 = Poor, 3= Satisfactory, 4 = Good, 5= Very Good
Q1	Was the INWK laboratory equipment **easy to use?**
Q2	Was the level of **interaction** with laboratory components adequate?
Q3	How was the **response time** of laboratory components?
Q4	Could the router/switches and other networking gear be **remotely accessed** on entering the userID/password)?
Q5	Was the operation of router/switches and other networking gear reliable?
Q6	Did the response from router/switches and other networking gear help you better understand networking concepts and theories?
Q7	Was the **feedback from the laboratory instructor** useful?
Q8	Were **laboratory handouts** and extra online information useful?
Q9	**Was the online wiring diagram information** (cabling between networking gear) useful?
Q10	What was the level of **"hands on" feeling** experienced when configuring/ troubleshooting networks with equipment in Internetworking laboratories?
Q11	Was the networking equipment used in the INWK laboratory similar to the equipment used in a real-world, networking environment?
Q12	Were the **laboratory components** / networking gear in the INWK laboratory (i.e., the router/switches and other networking gear) "state-of-the-art"?

TABLE III
USABILITY: PERCENTAGE OF STUDENT VERSUS RATINGS

	Percentage of students who rated various aspects of the online laboratory experiments as either very good (5), good (4), or satisfactory (3)											
Rating	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Very Good	23.0	15.1	17.3	47.2	22.6	17.3	17.3	26.4	22.6	17.0	18.9	11.3
Very Good or Good	57.7	49.1	67.3	83.0	69.8	71.2	50.0	60.4	67.9	47.2	54.7	47.2
Very Good or Good or Satisfactory	90.4	81.1	90.4	92.5	90.6	98.1	78.9	90.6	90.6	77.4	90.6	86.8

TABLE IV
USABILITY: MEAN, STANDARD DEVIATION, AND CONFIDENCE MEASURES

Rating	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Mean	3.69	3.40	3.73	4.21	3.83	3.87	3.37	3.74	3.77	3.30	3.62	3.43
Standard Deviation	0.98	1.08	0.91	0.97	0.89	0.71	1.19	1.04	0.99	1.22	0.95	0.91
95% CI	0.26	0.29	0.25	0.26	0.24	0.19	0.32	0.28	0.27	0.33	0.26	0.25
90% CI	0.22	0.24	0.21	0.22	0.20	0.16	0.27	0.24	0.22	0.28	0.21	0.21

Note: CI - Confidence interval

The survey was conducted as an anonymous postcourse evaluation of the RIL environment design, organization, and performance. Of a sample size of 65 students over two years, a total of 53 students took part voluntarily in the survey once. In determining the sample size, the factor that played a major role was the student enrollment, consisting of 32 to 33 students each year. Table III gives the percentages of students who rated the 12 different aspects of the online laboratory as very good, good, or satisfactory. Table IV gives the mean rating, the standard deviation, and the confidence measure for the 12 aspects of the remote laboratory.

Tables III and IV show that the students are highly satisfied with the technical design of the RIL environment as reflected by the results for ease-of-use, reliability, accessibility, authenticity, response time, and system response characteristics. Over 90% of the students rated these technical characteristics of the INWK networking equipment to be satisfactory, good, or very good. The networking environment was perceived to be "state-of-the-art" by 87% of students who rated this aspect to be satisfactory, or good, or very good. In addition, the students are highly satisfied with the format of the online wiring information and laboratory handouts since 90% of students rated them to be

TABLE V
ONSITE ISSUES AND THEIR CORRESPONDENCE TO ONLINE USABILITY MEASURES

Onsite Survey		Online Survey	
Issue	Issue no.	Issues	Question no. (See Table 2)
Physical access to equipment in laboratory	I1	"Hands on feeling"	Q10
		Student interactivity with equipment	Q2
Suitability of networking equipment	I2	Authenticity	Q11
		State-of-the-art equipment	Q12
Experience using the laboratory	I3	Ease of use	Q1
		Response time	Q3
		Remote access to laboratory	Q4
		Reliability	Q5
Understand networking concepts	I4	Appropriateness of system response	Q6

TABLE VI
ONSITE VERSUS ONLINE SURVEYS: MEAN, STANDARD DEVIATION, AND CONFIDENCE MEASURES

Measure	Onsite				On line			
	I1	I2	I3	I4	Q2, Q10	Q11, Q12	Q1, Q3, Q4, Q5	Q6
Mean	3.87	3.97	3.57	3.97	3.35	3.53	3.87	3.87
SD	0.86	0.98	1.22	1.07	1.15	0.93	0.95	0.71
CI – 95%	0.31	0.36	0.44	0.38	0.22	0.18	0.13	0.19

Note: CI – Confidence Interval

satisfactory, good, or very good. The level of interactivity is generally considered a key indicator of quality [20]. As indicated in Tables III and IV, although 81% of students rated the interactivity with laboratory components to be satisfactory, good, or very good, only 77% of students rated the level of "hands-on" feeling experienced in laboratory sessions to be satisfactory, good, or very good. Hence, the program needs to improve student interactivity with laboratory equipment and the "hands-on" feeling experienced by the student to improve the quality of interaction between the student and the equipment. In addition, only 79% of students rated the feedback from the laboratory facilitator to be satisfactory, good, or very good, and this aspect showed the most variability. The program needs to train the remote facilitator better in providing timely and useful feedback to the student.

Comparing the online and onsite laboratories: Onsite students were asked to respond on a five-point scale (1—very poor; 2—poor; 3—satisfactory; 4—good; and 5—very good) to the following aspects of the onsite equipment laboratory: the physical access to equipment, the suitability of the networking equipment, their experience using the laboratory, and the help laboratory experiments gave them in understanding networking concepts. Of a sample size of 60 students over two years, a total of 50 students took part voluntarily in the survey once. Specific questions of the online survey were more detailed and refined than that of the onsite survey. However, as shown in Table V, the four onsite issues can be mapped to one or more corresponding online questions to enable comparison.

Table VI lists the mean, standard deviation, and confidence measures for the four onsite issues shown in Table V, used to measure the design and implementation of the onsite laboratory survey and compares these measures with the corresponding figures for the online laboratory survey.

Table VI indicates that, on average, onsite students are more satisfied with the physical accessibility to the equipment than their online counterparts. Similarly, students in the onsite program are more aware of the suitability of the networking equipment employed in the laboratory. The online students consistently rated the authenticity of the networking environment to be lower and perceived the networking environment to be less state-of-the-art than their onsite counterparts. In addition, the onsite students were marginally more satisfied than the online students when asked whether the laboratory equipment helped them understand networking concepts better. However, the online students were more satisfied with their online laboratory experience than the onsite students, and this satisfaction may be attributed to the flexibility that the remote access provides to online students. For example, online students can access the laboratory at a time and from a place convenient to them to perform the laboratory experiments at a suitable pace.

X. CONCLUSION

This paper demonstrates the feasibility of designing e-laboratory systems for strong student interaction with remote equipment. The Web-based, remote interactive laboratory (RIL) environment allows remote students to access and utilize Internetworking (INWK) equipment located at a central equipment facility. The architectural design of the RIL and the instructional strategies employed are tailored to accommodate the special hardware and software requirements of the INWK program. The RIL's technical design is implemented using existing technologies, *de facto* networking standards, free software, and commercial Internet browser to support multiple, simultaneous real-time interactions, and secure information transfer between the remote sites and the central equipment facility. The unique pedagogical and laboratory-based instruction requirements of the INWK program motivate the use of effective remote-site facilitation to mimic the face-to-face interaction that takes place in onsite laboratories. The RIL's four-tier role architecture consisting of faculty and local site facilitators at the equipment facility, remote site facilitators, and remote students have well-defined duties and help maintain academic integrity. The RIL's technical design, instructional strategy, and role architecture model a synchronous, constructivist, collaborative, and directed-learning environment. The RIL is accessible, reliable, easy to use, responsive, and scalable. The RIL helps achieve the pedagogical and instructional goals of the program while continuing to offer quality interaction. Security considerations motivate the design of the access control system employed to limit access to educational and laboratory resources only to authenticated students. Survey results used to measure the usability of the remote laboratory demonstrate the success achieved in designing and implementing a remote access INWK laboratory. Survey results also indicate that the online laboratory is perceived to be easier to use and more flexible than the onsite laboratory because of the former's remote-access capability. However, the online laboratory is perceived to be less physically accessible and less interactive than the onsite laboratory. Additional work is planned to address improving the student interactivity with equipment and better facilitator training. Based on the feedback from the faculty who were involved in both the onsite and the online programs and the students' historical performance measures, including grades, switching to the online remote laboratory format has not resulted in any degradation of the expected learning outcomes.

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