Remote Laboratories for Optical Circuits

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***Abstract*—This paper presents a remote laboratory implementation for an optical circuits course. The process from design and implementation towards assessment and continuous improvement phase is outlined. The design of the experiments involved the research on remote access technology and the investigation of best practices for an experimental setup. The first pilot implementations were used to determine the possible shortfalls during an "Introduction to an Optical Communications" course in fall 2004 at the University of Colorado, Boulder, and an "Optical Circuits" course in fall 2005 at the University of Houston, Houston, TX. After improvements, two experiments were pilot tested during spring 2006 at the University of Houston. Assessment of learning outcomes and teaching methods were performed. The remote access methods, in addition to the delivery of the class and lectures, are presented in the paper. Delivery of a class with remote laboratories and videotaped lectures are also outlined under future directions of this project.**

***Index Terms*—Distance education, optical circuits, optical communications, outcomes assessment, remote data acquisition, remote laboratories.**

I. Introduction

TECHNOLOGICAL advances lead to automation and remote control of data acquisition instruments at the engineering workplace. Students with the most exposure to remote control technologies will best understand these automated technologies. A mainstay of engineering education has been the "hands-on" laboratory. The fast-paced changes in the technological environment requires the engineers and technologists to keep up-to-date with the new hardware layers as they emerge. Process control software is now a vital element of any new hardware by enabling this hardware to be controlled remotely. The remote control software component shifts the hands-on nature of design and programming of the new systems constructed from that new hardware towards a computer-controlled work culture. The Internet itself evolves through this interplay between hardware and software advances. The advent of the Internet has allowed for a whole new teaching paradigm, that of online learning. The advent of widespread and inexpensive broadband services allows for new dimensions in online learning whether they are real time interactive video conferencing of class material or asynchronously accessed and controlled streamed lecture material, laboratory instructional videos, and even laboratory simulations that can be performed by the student.

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The increasing costs of a university education and cuts in federal support for student aid and loans are compelling the university systems to look for more cost effective methods to provide a high quality learning environment. Technological advancements have allowed for remote learning sites to be created at the larger firms involved in engineering, but a real need is for online education which can be accessed in a time-efficient manner for both the learner and teacher. For most styles of learning, however, dynamic interaction with the learning environment is more effective than static perusal of reading materials. Bandwidth increase and data compression now allow for streaming of lectures. Combined with chat rooms, some video-equipped, techniques are available for dynamic interaction. However, experimentation is a pervasive need within engineering education, and one that is hardest to address in a learning-effective and a cost-effective manner.

Online education has been growing in a great degree as the result of the industrial need for training [1], [2]. Broadband access to the Internet is beginning to have an effect on the content of such materials [3], [4]. A consensus holds that video streaming is preferable to static placement of material on a website. The efficacy of live streaming (large scale teleconferencing) versus asynchronously accessible streamed video on learning may be an open question. Studies exist, such as [5] on the learning outcomes for software-based remote access laboratories.

The National Instruments website [6] mentions various remote laboratory efforts performed using the LabView, e.g., an optics-related laboratory demonstrated at Stanford as part of a pilot program initiated in 1997. The work has been reported in numerous conference publications [7]–[11] and in a more recent article [12]. In addition, STEM (Science, Technology, Engineering, and Mathematics) educational symposia have been interested in the remote teaching strategies as outlined in [13]–[15].

Remote laboratory implementations on optics are available, such as [12] and [16]; however, these studies did not investigate how to parse an experiment into a simulation and a remotely controlled experiment. They also did not investigate the effect of imperfection of technology used to implement remote laboratories on student learning. This project addresses the former cited issues and concentrates on the learning materials on optical circuits with application in telecommunications. The authors of this paper have presented results in [17] on a remote-controlled optical time domain reflectometer for optical circuits.

Optical fiber communications concepts, such as light sources, fiber transmission loss and dispersion, light detectors, and information error rate (bit error rate) are main concepts taught in the lectures. This paper describes the design and implementation of remotely controlled laboratory experiments that will help develop hands-on skills while familiarizing future technologists with software-controlled systems. The experiments were pilot tested and assessed in optical communications related courses at the University of Colorado, Boulder, in fall 2004, and the University of Houston, Houston, TX, in fall 2005 and spring 2006.

The paper is organized as follows. Section II presents teaching and learning objectives. Prelaboratory activities are described in Section III. Section IV outlines the implemented experiments, while Section V presents assessment and evaluation of the pilot test. Future work is presented in Section VI.

II. Teaching and Learning Objectives

The laboratories outlined in this paper are part of the optical circuits course being offered in the collaborating institutions. The course concepts include optical light sources, fiber link characterization, fiber transmission characteristics, optical detector characterization, and transmission performance parameters. The course lectures cover the fundamental principles of optical fiber transmission systems. The overarching goal of the course is to prepare the students for the new developments in telecommunication industry, where a tendency towards a more lightwave-based network exists. The main challenges that are addressed in this paper are summarized in the following subsections.

A. Teaching Objectives

The objectives of the laboratory design include the following main thrusts from an educational point of view.

1) **To determine what set of fundamental concepts of optical circuits can most effectively be addressed in the laboratory environment**. Determination of fundamental concepts was accomplished during the planning phase (June 2004–June 2005) of this project. Because some restrictions exist on what can be remotely controlled, some concepts may be difficult to show through a remotely controlled experiment. The laboratories will be implemented with six main fundamental concepts during spring 2007. However, a revisit to these concepts will depend on the results of the outcomes assessment.
2) **To determine how to parse a given experiment into a simulation and a remotely controlled experiment**. The simulation part of an experiment has outmost importance in the delivery of remote laboratories. The fundamental concepts are illustrated in a model provided by the simulation. This objective will impact the understanding of educational delivery methods in remote laboratories, e.g., perfect results of a fundamental concept through a simulation model might create confusion when the student is presented with the real-life experience that conflicts with the actual laboratory results (including noise, system imperfections, etc.). The simulation should be able to address the imperfections in close to real-life cases.
3) **To separate the effect of the imperfection of the technology employed in transmitting the information to the student from the imperfection of the teaching methodology**. This objective will help the education community understand the challenges of remote laboratory delivery across the disciplines. The technological advances have enabled self-practice virtual laboratory environments with a broadband connection. However, the data acquisition and integration of a laboratory setup into one interface with an instructor is still challenging for most institutions. To separate the technological imperfections from the shortcomings in the teaching methodology, the assessment methods have to be designed with careful consideration [18].

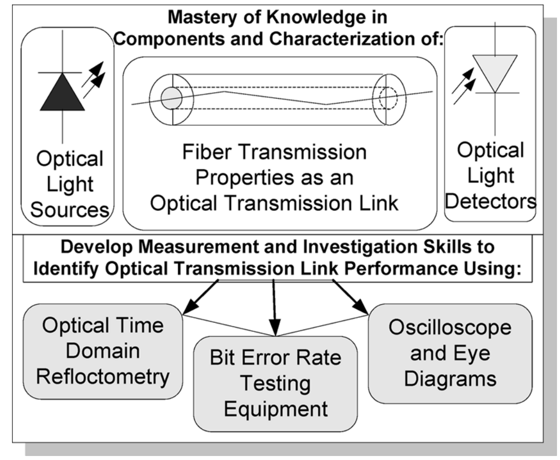

Fig. 1. A depiction of an archetypical fiber optic link with source and detector. The diagram illustrates that the experimental themes may address specific hardware components and more general performance characteristics of a fiber system as a communication link.

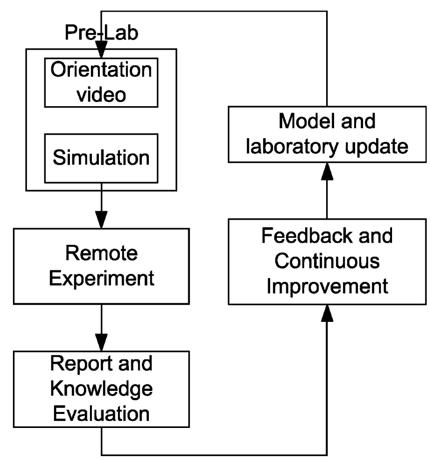

Fig. 2. Teaching strategy model.

B. Learning Objectives

The experiment themes are summarized in Fig. 1.

The following is the list of the proposed laboratories. These laboratories were chosen based on the first objective. Because of the simple and direct nature of their concepts and the equipment requirements, the first two laboratory concepts have been pilot tested.

- Optical light sources: Characterize optical sources that are used in optical circuits; the laser diode and the light emitting diode.
- Fiber link characterization: Examine the properties of an optical link: optical fiber connection loss, determination of fiber link length, attenuation coefficient, and limits.
- Transmission link properties: Determine the material dispersion effect on communication link over fiber link. The results are then employed to determine bandwidth x length and bit-rate x length of a link for both laser and LED.

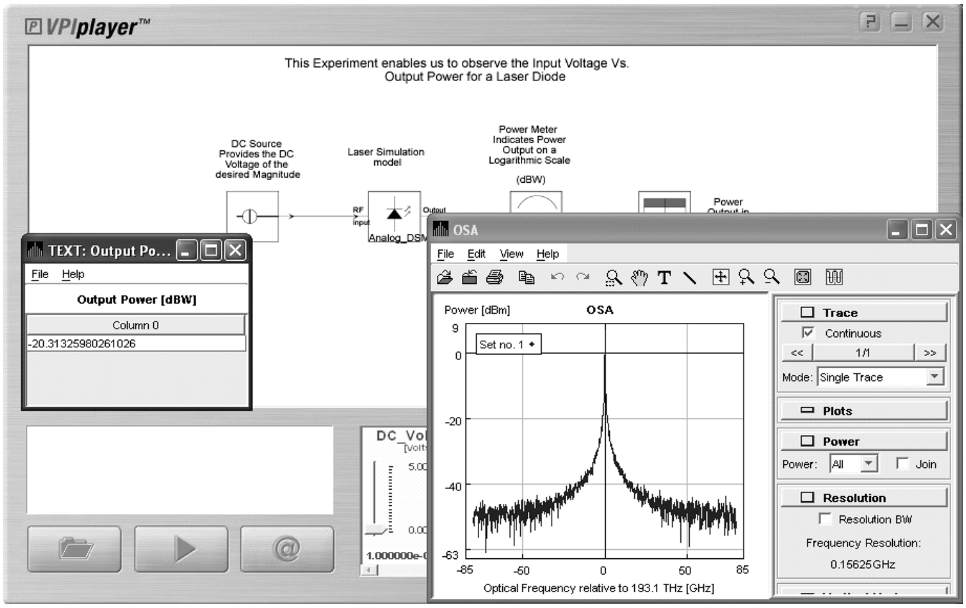

Fig. 3. Simulation results for laser spectrum and power output. The laser spectrum line-width can be measured using the OSA screen on the right. The power output can be monitored on the powermeter popup window on the left.

- Optical light detectors: Characterize optical detectors that are used in optical circuits using parameters such as wavelength dependence, responsivity (response rate of an optical detector), and bandwidth.
- Bit error rate (BER) investigation: Measurement of the performance of optical circuits using BER and appreciation of the effect of noise, attenuation, and dispersion on BER.
- Eye diagram investigation: Generation and evaluation of eye diagrams for optical circuits and appreciation of the effect of noise, attenuation, and dispersion.

III. Pedagogical Strategy

The pedagogical strategy is shown in Fig. 2. The students are given the theoretical background on concepts in class and then are asked to perform prelaboratory activities, such as orientation video and simulation, and laboratory procedures online. All 16 students were required to perform the remote laboratory practices. The simulation and the orientation video are the prelaboratory activities. The learning outcomes depend highly on both the hands-on experience to be gained through the remote laboratories and the understanding of fundamental concepts in each experiment. Whenever the remote laboratory has a shortcoming of relaying the big picture of an experimental setup, the orientation video should fill in the gaps in equipment familiarization and setup details. Similarly, simulation should be able to provide a larger scale experimentation venue for comparison of parameters that have a high degree of importance in the concepts. After completing the prelaboratory section, a student performs the remote experiment part in which he/she interacts with real equipment.

A. Simulation

The simulations are prepared using the VPI software (manufactured by VPIsystems, Holmdel, NJ) for optical systems. The VPI tool provides development environment that mimics real breadboard environment (Fig. 3), giving a student a sense of how real systems are implemented. The actual modeling software is being used to create system scenarios. Then, the simulations are saved as an executable file to be played later using VPI's free run-time engine, VPI Player [19]. The simulations include a variable parameter that can be set to various cases. This parameter gives the students a tool to change the conditions of their observations. Although the students cannot set up a system using the VPI Player, they can observe the setup on the screen and play with the variables governing the experiment. This restriction is a result of limited licenses which will not serve all the students in the classroom. Also, the player feature gives a good opportunity for students to focus on the concept rather than the use of the software tool.

The player window has a start (play) and stop button, and the parameters to be changed according to the concepts. The program is easy to use. The results of the simulation can be an optical power meter output, an optical spectrum analyzer (OSA) screen, or an oscilloscope time domain diagram.

The second experiment that was performed involves fiber link attenuation. The simulations were for multimode and single-mode fibers with varying propagation distances. The VPI Player window with results is displayed in Fig. 4. Results are the power measurements at the input and output ports of various distances of propagation through multimode or single-mode fiber.

B. Orientation Video

Orientation video has the recordings of the instructions for the simulation software and the remote access mechanism outlined by the instructor. The available technologies vary from institution to institution. Polycom iPower has been used to prepare this first orientation video displayed in Fig. 5.

C. Remote Experiment

Student connects to the experiment using the Web-based client that connects to the LabView Web server. The LabView

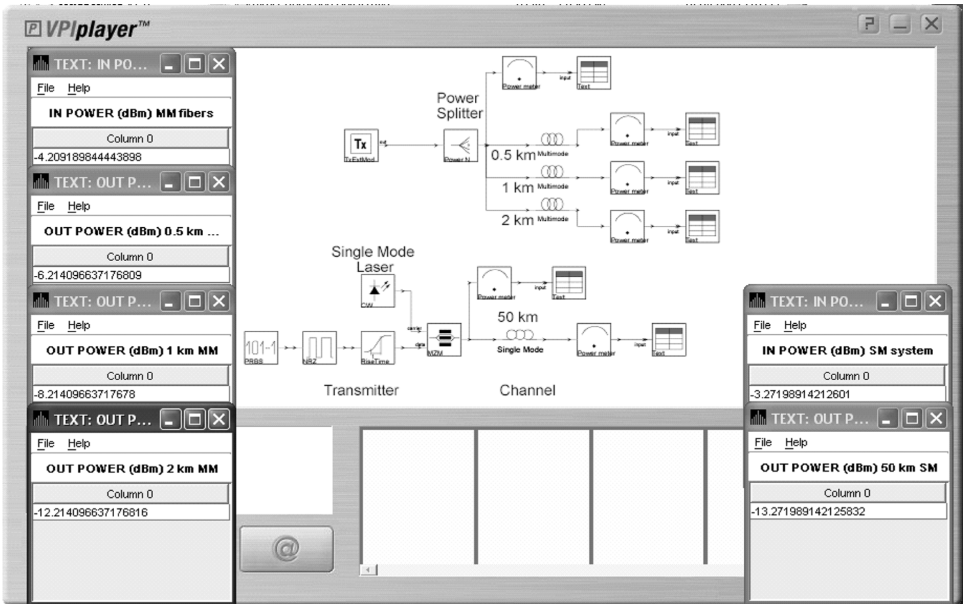

Fig. 4. Simulation window for fiber link loss analysis. The input power to the links is displayed by the power meter popup windows and their corresponding output power levels. Link budget calculations can be calculated using these results.

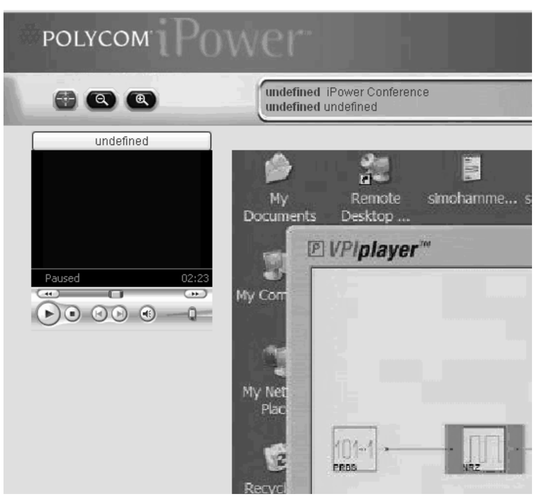

Fig. 5. Video of instructions on simulation program. The orientation video is a substitute for a conceptual presentation in a remote laboratory setting.

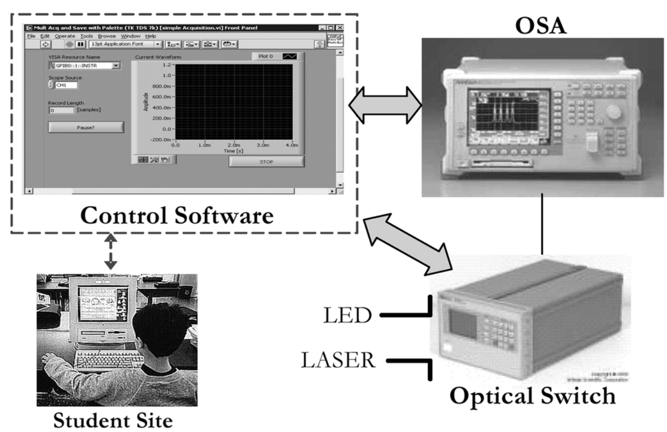

Fig. 6. An optical switch enables the selection of the concept while being remotely controlled by the virtual instrument program that also controls OSA through a general purpose interface bus (GPIB) connection.

server is developed using the LabView program and then posted as Web server using built-in LabView tools. The student will have access directly to the virtual experiment and will control the remote experiment. Students have multiple parameters to configure the experiment and collect data and record the results.

IV. Implementation of Experiments

Each experiment manual consists of six sections. At the end of the manual, references are provided for further information on the concepts.

1) **Objective**: Student learning objectives of the experiment are listed.
2) **Equipment**: List of equipment and instruments is provided.
3) **Prelaboratory**: Information on the fundamental concepts of the experiments is given in a complementary fashion to the context of the lectures. Prelaboratory is focused on the practical aspects of the instruments and the measurement techniques.
4) **Simulation**: A complementary simulation model is provided. Some parameters have a range of values to be set and measured for different scenarios.
5) **Procedures**: The remote laboratory measurement and testing procedures are listed. Tables and different experimental settings are presented.
6) **Knowledge evaluation**: A couple of fundamental questions are posed to the students to test the transferability of the knowledge gained in the experiment.

Three experiments that were implemented and pilot tested are described below.

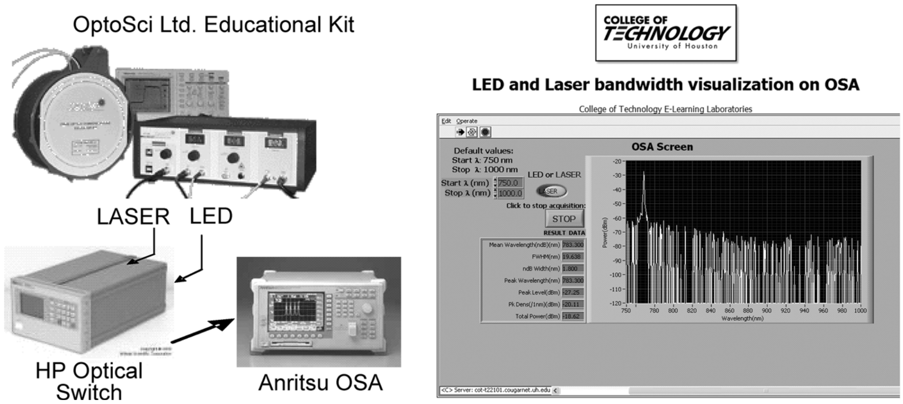

Fig. 7. Setup for experiment no. 1 with a snapshot of remote access window. The OSA has a feature to analyze the optical power and bandwidth of the signal. The analysis result is displayed as an indicator on the screen.

A. Experiment No. 1: Optical Source Characterization

The experiment compares the light-emitting diode and laser diode (multimode) spectral characteristics. The simulation of this experiment gives an overview of how different the bandwidth characteristics of these sources are. During the experiment, students observe the spectra of the sources using the data acquisition screen of the optical spectrum analyzer. The setup at the laboratory includes the LED and LD sources connected to an optical switch that is controllable via the LabView data acquisition program. The output of this switch is connected to the OSA which also is controlled via the same LabView program. The connections are outlined in Fig. 6.

The setup in Fig. 6 gives an overview of how the access mechanism works. The actual experimental setup is displayed in Fig. 7. The laser and LED sources are connected to a switch that is remotely controllable. The output of the switch is connected to the OSA. The OSA screen and switch controls are displayed on the remote control window through the LabView Web server. Students can access the remote laboratories using ActiveX plug-in on their Web browser.

B. Experiment No. 2: Optical Fiber Link Attenuation and Fiber Connectors

The experiment covers the concept of light attenuation over propagation through fiber. Multimode and single-mode fiber are compared in terms of their attenuation coefficient. Insertion of a patchcord provides the loss introduced through a connector. Setup for this experiment has a patch cord of negligible length and a reel of 1.2 km of multimode fiber. The peak powers can be compared to measure the attenuation per unit distance.

C. Experiment No. 3: Hands-On Skills Transferred From Remote Labs

This experiment is conducted to assess the teaching methods on its transferable skills from the remote access to the hands-on environment. The experiment is composed of the concepts of both of the remote access experiments: light source characterization using the OSA with bandwidth comparison and fiber-link attenuation characteristics for multimode and single-mode fiber. The students are asked to form teams of three people each and connect fiber ends to construct the setup and adjust the view of the spectrum analyzer for better comparison of bandwidths of the sources. In addition to the OSA, they were able to use an optical power meter. This exercise is designed to simulate a typical on-campus laboratory on optical circuits except that the students were asked to perform similar experiments to the ones they conducted during their e-labs.

V. Outcomes Assessment

The assessment plan encompasses both formative and summative assessment methods. The experiments are being developed at the University of Houston (UH). However, the other institutions and experts from industry are providing feedback on the teaching methodologies and the performance of the remote access laboratories. The outcomes to objectives mapping is illustrated in Table I. The table maps course objectives to the program objectives as required by the Accreditation Board for Engineering and Technology (ABET).

The first section of the learning outcomes belongs to technical mastery of knowledge in optical circuits. And, their corresponding learning outcomes according to ABET TC2K are listed in Table I. In addition, an investigation side of learning objectives is needed. To assess the learning outcomes with the learning objectives in mind, the assessment methods are developed as listed in Table II.

Summative assessment methods involve a project demonstration and the final application of the skills by the graduates of the class. This assessment method will help the project shape the portability and flexibility of its methods. Student perception surveys are being initially used to steer project evaluations. The expert opinion surveys are useful to keep the project up-to-date with its technological advancement. The formative assessment methods are being conducted as the experiments are pilot tested in classes. The initial results, from spring semester of 2006, are presented here.

A. Student Opinion Survey

A two-tier student opinion survey was performed. First, a free-form manner was used, where students wrote down their experience as they were browsing the remote connection screen. The second one was conducted after the experiment to see how students felt about how much they learned. (Authors can be contacted to share the assessment instruments.) Two

TABLE I
OBJECTIVES AND LEARNING OUTCOMES WITH ABET TC2K CRITERIA

Learning Objectives	Student Outcomes					
	2a	2b	2c	2f	4b	4c
1	X	X	X	X	X	
2	X	X	X	X	X	
3	X	X	X	X	X	
4			X	X		X
5			X	X		X

Learning Objectives

1. Characterize optical sources and detectors commonly used in optical circuits.
2. Examine the transmission characteristics of optical links.
3. Determine the bandwidth of a given transmission fiber using time and frequency domain measurement techniques.
4. Measure and test the transmission performance of optical circuits using a bit-error-rate-tester instrument by identifying the effects of noise, attenuation, and dispersion.
5. Measure the transmission link performance of a system using eye diagram measurement techniques using an oscilloscope by identifying the effects of noise, attenuation, and dispersion.

Student Outcomes

Mastery of knowledge of optical communication system components and their characteristics.
2.a. an appropriate mastery of the knowledge, techniques, skills, and modern tools of their disciplines;
2.b. an ability to apply current knowledge and adapt to emerging applications of mathematics, science, engineering, and technology;
2.c. an ability to conduct, analyze, and interpret experiments, and to apply experimental results to improve processes;
2.f. an ability to identify, analyze, and solve technical problems;
4.b. competence in the use of analytical and measurement equipment common to the discipline and appropriate to the goals of the program.

Develop investigation skills to identify communication bit-level error sources and characteristics.
2.c an ability to conduct, analyze, and interpret experiments and to apply experimental results to improve processes;
2.f an ability to identify, analyze, and solve technical problems.
4.c. develop student knowledge and competence in the use of standard design practices, tools, techniques, and computer hardware and software appropriate to the discipline and goals of the program.

TABLE II
FORMATIVE AND SUMMATIVE ASSESSMENT ACTIVITIES

Outcomes	Assessment Methods
Formative Assessment	
Mastery of Knowledge in Optical Components	- Tests and pre-laboratory activity reports - Faculty evaluation rubrics - Student perception surveys - Interview and visits by industry
Develop Investigation Skills in Link Error Characterization	
Summative Assessment	
Mastery in hands-on skills by developing innovative e-learning methods in laboratory instruction	End-of-semester project demonstration at the physical laboratory (every semester)
Develop transferable skills in optical systems applicable to biotechnology, communications, networking, etc.	

questions directly address the student knowledge acquisition. In addition, the demographics of access methods are also collected. The remote labs had no dialup connections. The results of the opinion surveys are listed in Table III. In general, students expressed the need for demonstration of the setup in an orientation video. In addition, they asked for more controls of the instrument or better explanation of each control that is being displayed on the remote control screen. The concern about ease-of-use also appeared in survey results where over 30% were unsatisfied. The orientation video has been addressed partially in the current implementation and the extent of that development is a work in progress. Controls of the instruments are being added as more experiments are being developed. However, a tradeoff in speed of connections and Web-server capacity enables an almost real-life experience with a remote setting, which is also a work in progress. For example, the fiber-loss laboratory involved individual power measurements; whereas, the laser characterization required fast display of an optical spectrum with flexible controls on the wavelength ranges. The difference in requirements presented a less effective learning experience for a laser characterization case than in fiber loss in Table III.

TABLE III
STUDENT OPINION SUMMARY

	Strongly Disagree	Disagree	Agree	Strongly Agree
Optical Sources				
The laboratory improved my understanding of laser.	17%	8%	75%	0%
Wavelength ranges were easy to set and observe.	8%	33%	50%	8%
Fiber Links				
My understanding of fiber link loss is improved.	0%	11%	61%	28%
Power level after each fiber link was easy to measure.	0%	6%	72%	22%
Remote Access				
The remote control speed was enough to do the laboratory.	3%	10%	59%	28%
The remote control panel software was easy to use.	3%	31%	45%	21%
The instrument control was clear.	7%	10%	63%	20%
The remote laboratory provided a similar experience to a hands-on laboratory.	6%	26%	65%	3%
The laboratory manual was easy to understand.	10%	19%	61%	10%
The Web interface was easy to follow and understand.	6%	10%	74%	10%
The pre-laboratory was helpful in understanding and performing this laboratory.	3%	16%	65%	16%

B. Student Success and Transfer of Skills to Hands-On

Students have been very successful in their experiments. All of the sections of the experiment are completed. The average grades in the experiments have been very high. The end-of-semester laboratory has been a hands-on implementation of the knowledge and investigation skills presented in the remote laboratories. Another survey that directly compares the skills of remote and hands-on laboratories is conducted in this experiment. Most of the students felt comfortable with their interface to the real instruments. Authors believe time will be required to observe the success of the students in transferring their skills to other fields.

VI. FUTURE WORK

The teaching strategy has been updated to include a setup instructions video. The instructions on how to connect the optical circuit, showcases of the equipment used in the labs, and instructions on the measurements to be taken during each laboratory are included. Some state-of-the-art laser controls and various links with a communication analyzer will be added to the experiments. The class will be conducted in a hybrid fashion. Lecture will provide the necessary background to understand the prelaboratory. In the second week, the students will continue with the virtual laboratory. And the sequence of lecture, prelaboratory, lecture, remote laboratory will be maintained for a three-credit course in an interdisciplinary setting. Another online two-credit laboratory is being developed at the University of Colorado.

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