An Optical Communication Design Laboratory

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***Abstract*—A senior-level design laboratory course is described, in which an optical fiber communication network is expanded or improved by successive generations of students. In this evolutionary approach, student teams base their work on the final written reports of students in previous course offerings. In addition to its primary goal of providing a high-level technical experience, the course requires multidisciplinary teamwork and provides incentive for the development of effective oral and written communication skills. Results of four offerings of the course are presented.**

***Index Terms*—Capstone design, fiber optics, interdisciplinary design, optical communications.**

I. Introduction

THE multidisciplinary nature and advanced technical level of optical communication systems present formidable challenges when developing a design laboratory course on the subject. Optics, communications, and electronics expertise at advanced levels are necessary to provide a meaningful design experience for seniors. In addition, the prerequisite course structure must be carefully designed, and must include appropriate laboratory courses that give students the necessary skills.

A primary objective in developing our course was to form an industry-like environment for students. For example, an industrial design team could be given the task of upgrading an existing device or system that was designed and built by a team that no longer exists. The new team is forced to rely entirely on the written documentation of the previous team, and on the observations and measurements they are able to perform on the existing device or system. The team must carefully document their activities for the benefit of themselves and of future groups.

In our design course, an optical fiber communication network is the evolving system. In each offering, the students are given the final reports of the previous student groups and are given one or more objectives involving the expansion or improvement of the network. The most recent report also contains relevant suggestions for future activity, including possibly one or more designs for new components or system substructures. The new group must review these designs and judge their merit before proceeding.

In our view, advantages of this approach to a senior design experience include: 1) students are required to begin their design work in the middle of a project, rather than from the start; they are thus forced to understand and interpret the work of others, and must learn to channel their creative talents to build on prior work; 2) optical fiber communication involves the connection of multiple disciplines; students must therefore learn how to use multidisciplinary teamwork to make meaningful progress; 3) students are forced to obtain most of the vital information from the written reports of past teams; they will thus develop an appreciation for the importance of clear and thorough written documentation.

II. Design Course Logistics and Prerequisite Structure

At the beginning of each course offering, the instructor defines the objectives for the term and offers initial guidance on procedures. The students choose a leader, organize themselves into one or more teams as necessary, and decide how the work is to be allocated. The instructor gives technical information when needed, but otherwise plays the role of an observer, noting progress and individual performance. Lecture time is used for round-table group meetings that are run by the student leaders. The instructor participates in these meetings primarily by raising questions (when considered necessary) that pertain to technical issues, team logistics, or planning issues—all of which are addressed and answered by the students. The instructor provides advice on request, but the students must otherwise solve their own problems and make their own decisions.

Students at Georgia Tech enter the design course (EE4053) with a background consisting of a lecture and a structured laboratory course in fiber communications (courses EE4051 and EE4052, respectively). In the structured lab, they are given hands-on training in optical fibers, light sources, and detectors, fiber test and measurement equipment, and in methods of evaluating the performance of a basic fiber communication link.

As originally conceived, we envisioned a more complicated progression of design, design review, construction, and testing that involved the participation of students in the structured laboratory course, and which we reported previously [1]. In this, the suggestions and designs of the outgoing 4053 group were given to the 4052 students in the next term to be reviewed. Results of these reviews were then passed on in writing to the

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next 4053 group. The last group would then build and test the proposed device should the design review be favorable. Again, only written communication would occur between the three groups. This plan was found to be impractical (at least in the quarter system) because excessive time is required for the 4052 students to gain a sufficient level of knowledge of the project to allow a meaningful design review. The impending change to semesters at our institution may allow the possibility of incorporating the original three-group plan. A program similar to our current one, but within a different engineering discipline, has been reported [2].

III. The Fiber Network

The initial student group's task was to design and construct a four-subscriber optical network that would eventually be capable of supporting data rates of up to l Gbit/s, and in which the maximum loss (between the transmitter and receiver of farthest separation) is no greater than 30 dB. They were given several choices of network topologies, including ring, star, and bus geometries. A unidirectional bus topology was chosen because, among the choices, it required the fewest number of splices; in their reasoning at the time, splice losses would dominate the loss budget. As noted by subsequent groups, the first group did not account for the need to synchronize the network; this required four additional optical taps and the associated splices, which were incorporated by a later group. Also, they did not allow for the eventual need to include wavelength division multiplex (WDM) splitters and combiners for two-wavelength operation, a possibility which they did discuss at the time.

The network in its present form, in which the additional taps and WDM couplers are present, is shown in Fig. 1. The first group constructed the basic network, which did not include the added taps and WDM's. Commercial combiners and taps were used to connect the transmitter and receiver modules to the single-mode fiber bus line. Fiber connections were made using mechanical splices (Ultrasplice), which allowed the network to be opened at various points for testing. Spools of fiber were included to separate adjacent transmitters by an average distance of 1.5 km. Equivalent spacing was used between receivers. The maximum calculated system loss of the first group's design was within the 30 dB requirement, but the network in this form did not have taps from the bus that would supply clock and data signals to each transmitter (thus allowing synchronization).

A synchronous time-division multiplex scheme, originally suggested by the faculty, was chosen to operate the network. In it, the clock and data optical signals are at different wavelengths, with the clock at 1.3 μm and data at 1.55 μm. The two are combined on the bus or separated when leaving it by using optical WDM couplers. The data frame as originally envisioned consisted of four data slots, each being 8 b long and each being assigned to one of the four transmitters. A fifth slot at the beginning of the frame contains the header, composed of a sequence of eight "one" bits. Block diagrams showing network operation at the electronic level are shown in Figs. 2 and 3.

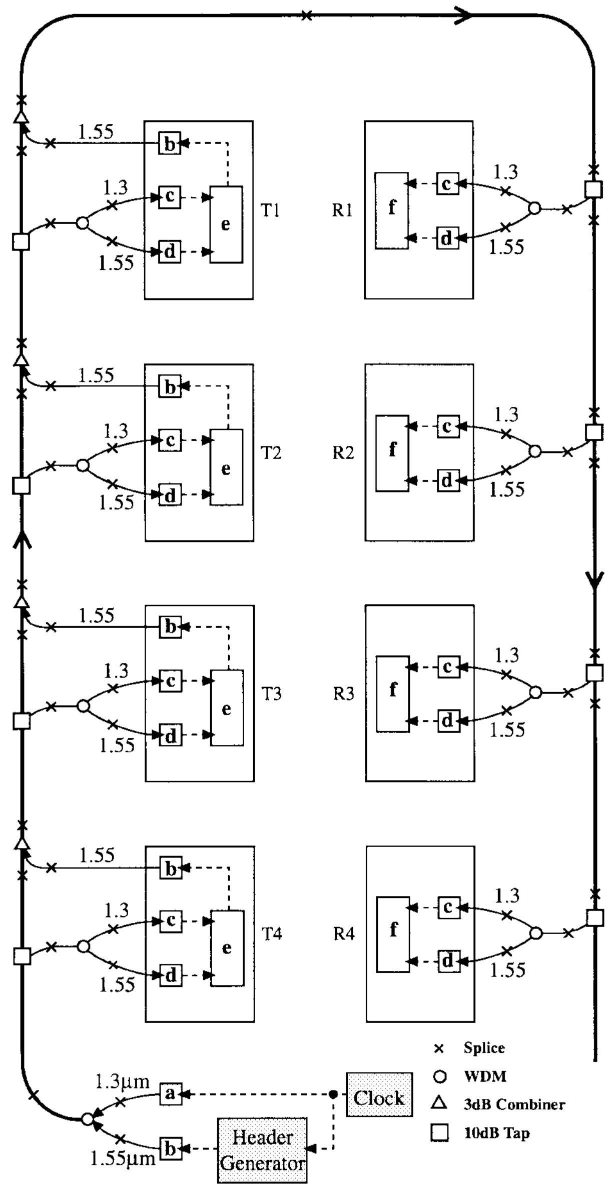

Fig. 1. The fiber network, showing subcomponents at the head, transmitter (T), and receiver (R) stations which are labeled as follows: (a) 1.3 μm E/O converter, (b) 1.55 μm E/O converter, (c) 1.3 μm O/E converter, (d) 1.55 μm O/E converter, (e) multiplexing electronics, and (f) demultiplexing electronics. Optical fiber paths are shown as solid lines; electrical paths are shown as dashed lines.

In addition to designing and building the fiber network, the students were to design and construct all circuitry that would generate, multiplex, and demultiplex the frame in electrical form. This included frame and header generation, data generation and insertion onto the appropriate frame slots, and data retrieval from the frame, in which the identities of the transmitter and the intended receiver were established.

The circuit designs interface with commercial hybrid transmitter and receiver packages, which play the roles of electrical-to-optical (E/O) and optical-to-electrical (O/E) converters, respectively. Their use obviates the need to involve the students with laser drive circuitry or with the details of optical receiver design, although this may be included at later stages of the project. For transmission and detection at 1.55 μm,

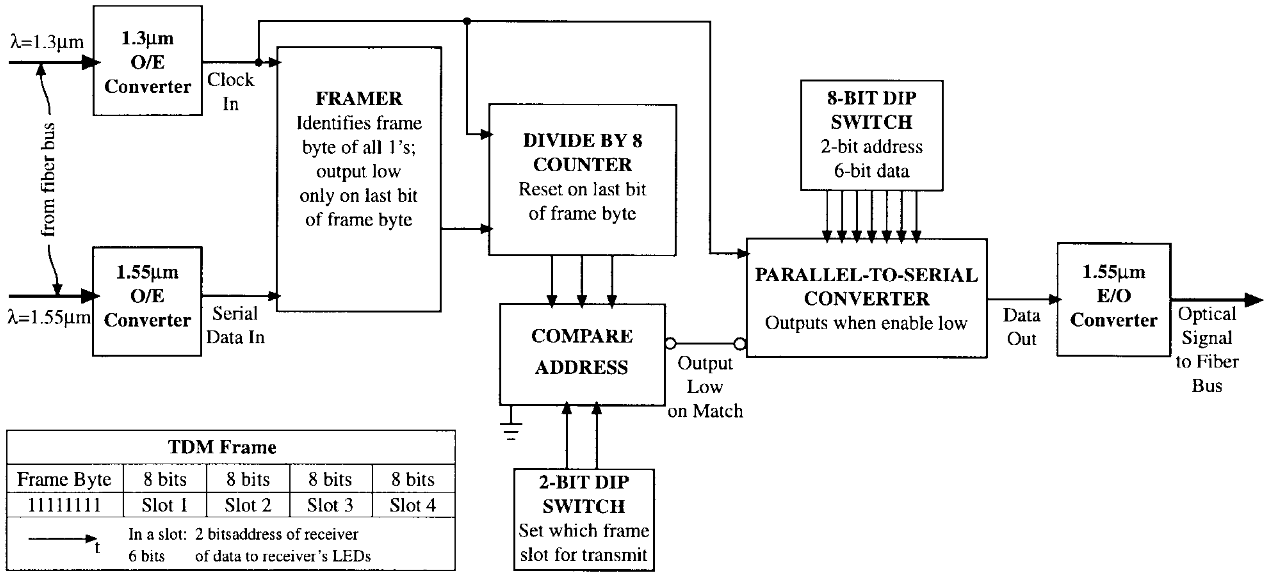

Fig. 2. Block diagram of a transmitter (T) station as shown in Fig. 1, in which an 8-b word is generated and inserted into the proper slot in the frame (inset). The output is routed to the E/O converter and is then coupled onto the fiber network.

Laser Diode Inc. models TL-1165 and RT-1554 are used for E/O and O/E conversion, respectively. The TL-1165 requires either ECL or PECL inputs. The RT-1554 detects the optical signal and generates a PECL electronic output. For operation at 1.3 μm, Laser Diode Inc. model TL-1163 (E/O) and Hewlett-Packard model DLR-1040 (O/E) units are used, which operate in the same manner as the 1.55 μm units.

The second student group began work on the circuitry, in addition to further work on the optical network; these efforts were continued by the third and fourth groups. The second group decided to design and build the circuitry using TTL logic, since the students had the best understanding of this. Their plan was to interface their circuits with the hybrid transmitters and receivers using operational amplifiers. Additional tasks on the optical network involved reconfiguring it for synchronous operation by adding clock input taps at the transmitter stations. Operation at 1.3 and 1.55 μm was enabled by adding WDM couplers at appropriate positions. A data rate of 50 MHz was established as the goal for this stage in the project.

An additional task that was undertaken in the fourth offering is the computer simulation of the network. This was done using the Optics and Photonics Advanced Laser Simulator package (OPALS) [3], which runs with LabVIEW [4]. The OPALS package contains a comprehensive collection of virtual instruments (VI's) which enable the realistic simulation and interconnection of many optical devices. These include sources, detectors, modulators, and fibers, all of which have adjustable operating parameters. Connections between devices are performed graphically using the standard LabVIEW tools. Simulation studies would include, for example, bit-error rates as functions of losses in specific elements at any point in the network. As of the end of the fourth term, the network simulation was complete, but parametric studies were not performed.

Subsequent groups based most of their efforts on the work of the first two groups, and discovered many problems associated with prior decisions with which they were forced to work. This is illustrated in the following work summaries, taken from the final reports of all four groups, which include the main conclusions and recommendations of each group.

Group 1, Winter 1997 (one team, eight students).

Fiber Network: Bus architecture was chosen. The network was constructed using conventional single mode fiber for operation at 1.3 and 1.55 μm. Input taps from bus to transmitter stations were not included. All taps were commercial 10 dB units, joined to the fiber using mechanical splices. Results of the loss test from transmitter 1 to receiver 1 (having the closest proximity) were satisfactory. Breaks in fiber and bad splices made loss tests involving the other transmitter and receiver stations impossible.

Conclusions: The network cannot be reliably assembled without loss measurements being made after each component is added. Mechanical splices proved unstable over time and produced inconsistent losses on a day-to-day basis.

Recommendations: Re-assemble network and replace all mechanical splices with fusion splices for better stability.

Group 2, Spring 1997 (two teams, six students).

Fiber Network (team 1, two students): 10-dB taps from bus line to transmitters were added to allow network synchronization. WDM couplers were added at the inputs to each transmitter and receiver to allow separation of clock and data signals. Mechanical splices were retained, as original mounting methods of the previous class were suspect. Splicing expertise was perfected, but excessive losses occurred over all transmission paths. No output at any receiver location was observed when sending light from transmitter locations 3 and 4.

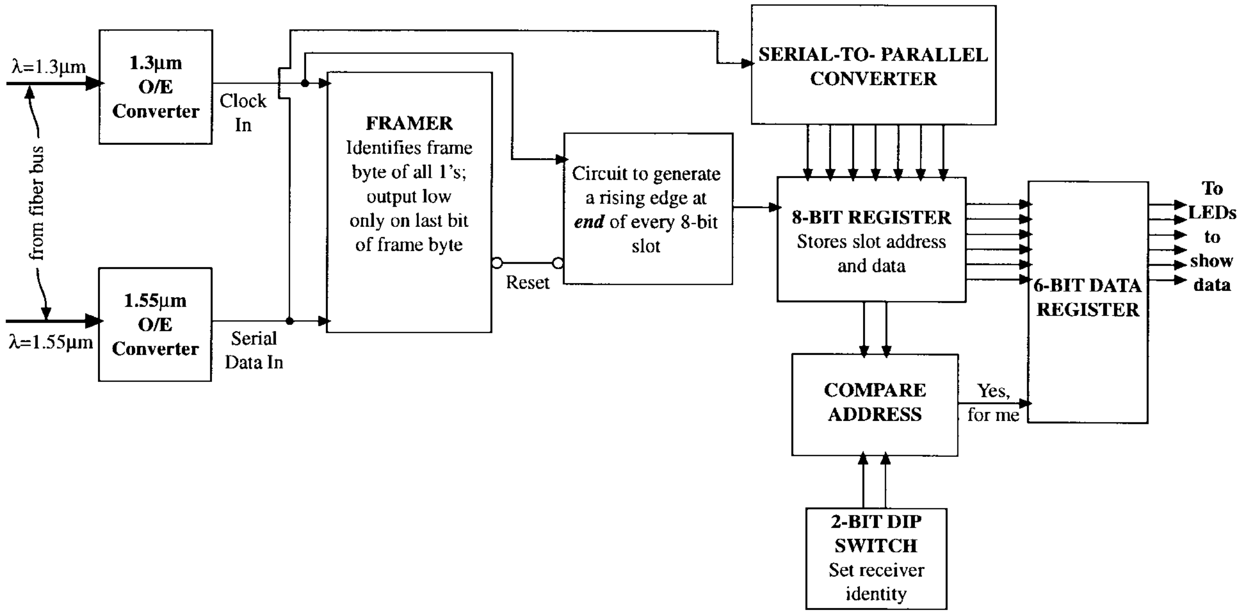

Fig. 3. Block diagram of a receiver (R) station as shown in Fig. 1, in which an O/E-converted frame is analyzed to determine if a message is present and whether the receiver identity matches the intended destination.

Frame Generator (team 2, subtask 1, one student) and *Transmitter Logic* (team 2, subtask 2, two students): The group designed and built the final (printed circuit) versions using TTL. The units performed well up to 10 MHz, but performance degraded at higher frequencies.

Receiver Logic (team 2, subtask 3, one student): This unit was designed and a breadboard prototype was built using TTL. It was found not to work properly.

Conclusions: Splice loss still appears to be the dominant problem in getting the network functional. TTL-based circuitry must be converted to ECL if data rates that exceed 10 MHz are to be realized.

Recommendations: Network loss problems should be addressed by additional work on splicing technique. TTL logic should be converted to ECL.

Group 3, Winter 1998 (two teams, nine students)

Fiber Network (team 1, four students): Mechanical splice to fusion splice conversion was begun. The network was disassembled and components were tested. Upon rebuild, it was found that losses were still too high. It was noted that using 10-dB taps as combiners (to couple light from the transmitter stations onto the bus) resulted in excessive loss. Losses in transmission between transmitters 1 and 2 to receivers 1 and 2 had been reduced to acceptable levels.

Frame Generator and Transmitter Logic (team 2, subtasks 1 and 2, 3 students): The TTL logic designs of previous class were retained, but were converted to ECL by chip replacement. Did not function properly.

Receiver Logic (team 2, subtask 3, two students): The logic was re-designed using TTL design methods, and was built using ECL chips. The unit did not function properly.

Conclusions: 10-dB taps should not be used to introduce signals from the transmitters onto the bus. Splice losses were still too high. Conversion from TTL to ECL is not a simple matter of chip replacement.

Recommendations: 10-dB combiners should be replaced with 3-dB units (an order was placed by this group). Training in ECL design is required before any attempt is made to redesign the logic circuitry.

Group 4, Spring 1998 (two teams, nine students)

Fiber Network (team 1, four students): 10-dB combiners were replaced with 3-dB units, resulting in substantially reduced losses. Additional splice replacement was performed. Splicing technique was mastered—low-loss splices are now routinely performed. An unexplained intermittent loss was discovered. The network was reassembled. Computer simulation was begun, using OPALS. The program was completed, but studies using it were not performed.

Frame Generator (team 2, subtask 1, one student): ECL training was requested by all students, and was given. The clock was successfully implemented using an ECL voltage-controlled oscillator. The frame generator was redesigned using ECL and was breadboarded. The unit performed mostly as expected, but exhibited spiking behavior that was thought to arise from parasitics associated with the breadboard layout.

Transmitter Logic (team 2, subtask 2, three students): It was decided to assign frame slots to receivers instead of transmitters. The logic was redesigned using ECL and was constructed on breadboard, but not tested.

Receiver Logic (team 2, subtask 3, three students): The logic was redesigned using ECL, built on breadboard, and tested. A problem was observed with the ECL counter, possibly due to layout problems.

Conclusions: Using all four 3-dB combiners will not allow sufficient power to reach receiver 4. There is uncertainty as to whether logic performance problems are related to parasitic effects or misunderstandings on how the ECL circuitry is functioning.

Recommendations: Repeaters should be introduced for the two wavelengths after receiver 2, or other network topologies should be investigated toward the aim of reducing losses. Circuits should be simulated using appropriate software to remove layout effects, and to confirm correct designs.

IV. Observations of Student Performance

From the above summary, it can be seen that progress in obtaining a working network has been slowed by a number of factors, many of which can be attributed to our insistence on student independence in their decision-making. In the logic design effort, the decision to use TTL in the beginning was based on the students' familiarity with it, and on the idea that interfacing with the ECL-based hybrid transmitters and receivers could be accomplished. They could have chosen ECL in the beginning and requested training in it, as did a later group. Once ECL was adopted, the need to simulate their designs was made very apparent by the need to confirm the viability of their basic designs and to isolate possible design errors from packaging problems that occurred in the prototypes.

In the optical network, incorporating the additional taps and WDM couplers needed for synchronization increased the maximum loss beyond the original 30-dB budget. The original group, which was given the task of choosing the network topology, had not foreseen the need for these additional components, and so had not accounted for them in their decision to use bus topology. This left the subsequent groups in the uncomfortable (and possibly untenable) position of having to overcome very high network losses in order to make all four stations workable. Students were encouraged to review the network design, but opted instead to solve the existing splice and tap problems before moving further. The results of these efforts indicated that the network is usable with the loss budget allowed by the optoelectronic components (40 dB), if only three transceivers are employed. The move to three stations instead of four is in fact more sensible when considering the design of the logic, since the data transmission frame would consist of four slots instead of five. This is consistent with the basic requirement of using quantities of 2^n in logic design.

Student responses to the challenges presented by the course were generally favorable. As seen in the summaries, they would typically divide themselves into two subgroups—specializing in the electronics or optics aspects, respectively. A primary project leader was chosen, whose job was to oversee all aspects of the work, and to assume primary responsibility for assembling the final report. Subgroup leaders were selected on a rotating basis, in which every student would assume the leadership position for one week. Each subgroup leader was responsible for an oral presentation and a written memo on the group progress at the end of his/her term. Once the objectives for the term were made clear, faculty intervention was seldom necessary, and in fact was found to be not wanted by the students.

V. Perceived Benefit and Future Directions

We measure success not primarily by the amount of progress in the network over each term, but by the perceived growth in the students during this time. It is clear that our nonintervention policy could have slowed progress on getting the network operational. It is our opinion, however, that the true worth of the experience has been in forcing the students to make progress—of whatever magnitude—on their own, as self-governing teams. Whether success or failure results, the lessons and experiences are still of significant value. Student comments in conversations subsequent to the courses have been consistent with these observations. Another benefit to the students is that they are made acutely aware of the value of clear written documentation.

Once operational, the current network will likely be upgraded by increasing the data rate and by increasing the capacity through more advanced WDM implementations. As the sophistication level increases, however, the learning curve for each new group becomes steeper. To accommodate this, additional material on the network will be incorporated into the prerequisite courses, so that students enter the design course with good familiarity with the network, and with the knowledge needed to improve it.

VI. Conclusion

We have demonstrated an evolutionary approach to a senior level optical communication system design experience, in which successive student groups improve on an existing fiber communication network, having only the written documentation of the previous groups on which to base their efforts. Four offerings of the course have been successful, in that definite progress has occurred, and since a learning and maturing process in the student groups has been evident. Students obtain the experience of multidisciplinary teamwork, and gain a strong appreciation for clear written documentation.

References

[1] D. Blumenthal, J. Buck, J. Hughes, M. Ingram, H. Owen, J. Uyemura, and C. Verber, "Development of an optical communication design laboratory," in *Proc. ASEE Annu. Meet.*, Poster Session 1626, Los Angeles, CA, June 26, 1995.

[2] D. T. Rover and P. D. Fisher, "Cross-functional teaming in a capstone engineering design course," in *Proc. 1997 Frontiers Educ. Conf.*, Pittsburgh, PA, Nov. 5–8, 1997, pp. 215–219.

[3] OPALS is manufactured by Virtual Photonics Pty Ltd., Parkville, Australia.

[4] LabVIEW is manufactured by National Instruments, Inc., Austin, TX.

John A. Buck (S'79–M'84–SM'89), photograph and biography not available at the time of publication.

Henry W. L. Owen, III (S'78–M'80), photograph and biography not available at the time of publication.

John P. Uyemura (S'73–M'78–SM'89), photograph and biography not available at the time of publication.

Carl M. Verber (M'74–SM'86), photograph and biography not available at the time of publication.

Daniel J. Blumenthal (S'91–M'93–SM'97), photograph and biography not available at the time of publication.