Compact Disc Players in the Laboratory: Experiments in Optical Storage, Error Correction, and Optical Fiber Communication

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***Abstract*—The compact disc player is a synergy of optics, communication theory, digital signal processing, and control engineering. This familiar consumer product may be employed as a cost-effective laboratory instrument to teach the fundamentals of optical storage, error detection and correction, and optical communication. The compact disc audio system, from analog input, through optical storage and distribution, to audio reproduction, provides an excellent model of a complete real-world optical transmission and storage system. A series of experiments, which illustrate some of the more significant operational principles of the compact disc player, are presented in this contribution. Optical read-out and the physics of information density are explored through a set of experiments in optical storage. Error detection and correction are studied experimentally by evaluating the performance of the compact disc player's error control system. The design of an optical fiber communication system is studied by extracting the channel bit stream from a compact disc player, transmitting it over an optical fiber link, and then reinserting it back into the compact disc player for audio reproduction.**

***Index Terms*—Compact disc, error correction, optical fiber communications, optical storage.**

I. Introduction

THE household compact disc (CD) player represents an absolute marvel of modern optical and electrical engineering. This amazing consumer product was conceived through the marriage of several sophisticated systems and technologies. These systems may be employed to illustrate fundamental principles from a variety of disciplines including optics, communication theory, digital signal processing, and control engineering.

The familiar CD player employs some of the most impressive engineering technology to be marketed as a consumer product. It was originally designed using communications concepts and is often considered as a transmission system that brings sound from the studio into the living room [1]. Consequently, the CD player is ideally suited for teaching digital communication concepts including modulation codes, error correction codes, and digital signal processing. The disc itself provides valuable insights into the optical storage of information — calculating the storage capacity of a CD from its dimensions, the wavelength of illumination, and basic laws of optics, is an excellent exercise in the application of fundamental physical principles. The sophistication of the common CD player coupled with its availability makes it a very cost-effective alternative to the expensive laboratory instruments usually required to demonstrate these advanced concepts. The CD player also has significant pedagogical value because important physical phenomena can be illustrated with an instrument that is generally very familiar to the student.

The CD player is employed in the laboratory sessions of two senior undergraduate courses taught in the Electrical and Computer Engineering Department at Dalhousie University, Halifax, NS, Canada, namely, Optical Electronics (ECED 4350) and Technology and Applications of Fiber Optics (ECED 4421). The laboratory sessions based on the CD player are now entering their sixth year of successful operation. Currently, the laboratory time for both courses is divided into two parts. During the first part, students are introduced to the basic optoelectronic devices (emitters and detectors) and engineering design principles (power and bandwidth budgets) which are traditionally taught as part of an introductory laboratory course. During the second part, after the students have a firm grasp of the basics, the CD player is introduced as a practical application. Students attend a workshop where they are introduced to the CD player and its operation. The emphasis is on the CD player subsystems that the student will need to understand in order to successfully complete the laboratory exercises. Groups of two or three students work with their own CD player and complete the experiments outlined in this contribution. The authors have found the approach of employing a familiar device to teach complicated ideas to be very effective. The experiments based on the CD player have great educational value and at the same time are enjoyable for the students.

This paper is organized as follows. A series of experiments and sample calculations that introduce the fundamental principles and the physical limits of optical storage are presented in Section II. The discussion follows the natural flow of the information signal from the coded bit pattern on the CD through to optical detection and the resulting eye pattern. The mode of CD rotation is experimentally determined and the tracking and focusing subsystems are also studied. The operation of the CD player's error detection and correction systems are examined in Section III. An experimental system and a method are presented which permit the student to measure the symbol error rate of a typical CD and the corresponding symbol interpolation rate achieved by the error correction system. The disc is an inexpensive source of a very sophisticated digital data stream. Similarly, the CD player is a cost-effective instrument designed to

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readout, demodulate, and decode the complex data stream. The CD player is employed in Section IV to construct an optical fiber communication link. The channel bit stream is removed from the CD player, transmitted across an optical fiber, and then reinserted back into the CD player for demodulation, decoding, and digital-to-analog conversion. Concluding remarks are presented in Section V.

II. Optical Storage

According to legend, the audio CD was designed to hold an entire performance of Beethoven's Ninth Symphony without interruption [2, p. 324]. The newer DVD (digital versatile disc), which was designed to hold an entire MPEG-2 motion picture, achieves a storage capacity of 17 Gb using four optical recording planes [3]. These optical formats have become the preferred media for the distribution of audio, video, and computer data, however, the concepts employed by these systems are not traditionally taught to students. A series of experiments, which introduce the fundamental principles of optical storage, are presented in this section. The discussion follows the natural flow of the information signal from the coded bit pattern on the CD through to optical detection and the resulting eye pattern. The CD player and its operational principles are reviewed in this section where appropriate, however, the presentation is by no means complete. A more detailed account may be found in the following recommended journal articles [1], [4]–[6] and books [2], [7]–[9].

A. Optical Storage Capacity

The information density of an optical storage format is determined by the size of the spot of light employed to read the information from the disc and the type of code used to represent the information. In the CD audio system, light from a semiconductor laser is focused by an objective lens to a diffraction limited spot on the information layer of the disc. The intensity distribution of the spot is called an Airy pattern and consists of a bright central disk surrounded by several rings of decreasing intensity [10]. The diameter of this blurred spot is not immediately obvious because it does not have a well-defined edge. The spot radius is generally defined to be the radius of the Airy pattern where its intensity first falls to zero. In this way, the scanning spot corresponds exactly to the central Airy disc (without the rings) and has a radius given by

$$r_0 = 1.22\lambda\frac{f}{D} \approx 1.22\frac{\lambda}{2\mathrm{NA}} \tag{1}$$

where

- λ wavelength of the illuminating light;
- f focal length of the objective;
- D diameter (or clear aperture) of the objective lens.

The ratio of focal length to lens diameter is called the f-number of the lens. In finite conjugate systems, such as CD player pick-ups and microscopes, the image and object distances are finite, and the ratio is generally expressed as a numerical aperture (NA) rather than an f-number. The NA of a lens describes its light gathering ability. For a well corrected lens system, the NA is approximately equal to one over twice the system's f-number. In general, a high NA lens collects the most light, produces the smallest Airy disk, and has the smallest depth of focus. It is clear from (1) that the size of the Airy disk is proportional to the wavelength of light and inversely proportional to the NA of the lens.

It is a useful exercise to estimate the storage capacity of a CD based on the wavelength of illumination and the NA of the objective lens. First we will assume a simple modulation code where one bit of digital information is recorded per Airy disk. In this simple model, one might imagine the binary "1's" and "0's" to be recorded as Airy-disk-shaped regions on the CD surface, referred to as *lands* and *pits*, which selectively reflect or scatter incident light. Later we will experimentally measure the pitch of a CD's spiral track and utilize the actual linear data density afforded by the eight-to-fourteen modulation (EFM) code employed in the CD audio system to more accurately estimate a CD's storage capacity. In EFM, a binary "1" is coded as a transition from a land to a pit (or vice versa) and a binary "0" is coded as the absence of a transition.

First one must assume that one bit of digital information can be recorded using an area of CD surface equal to that of the Airy disk. The storage capacity is then simply the total usable area of the CD divided by the area of the Airy disk

$$\text{Capacity} \approx \frac{A}{\pi r_0^2} = \frac{A}{\pi}\left(\frac{2\mathrm{NA}}{1.22\lambda}\right)^2 \tag{2}$$

where A is the usable area of the disc. The digital information is recorded in an annular region of the CD called the program band that extends from an inside radius of 25 mm to an outside radius of 58 mm, providing a useable storage area of approximately $A = 86.05$ cm^2. The optical head in a typical CD player employs a semiconductor laser that emits at $\lambda = 780$nm and an objective lens with NA$= 0.45$. This typical optical head produces an Airy disk of diameter $2r_0 = 2.11$ μm (the Airy pattern full width at half maximum is 0.89 μm). Employing these values and assuming one bit of digital information per Airy disk spot, the raw storage capacity of a CD is approximately 2.5 Gbit.

The sequence of information bits, called the channel bit stream, is recorded on a CD as a long spiral track starting at the inside edge of the program band and running toward the outside edge, opposite to the direction of a conventional vinyl LP record. A more accurate estimate of the storage capacity is calculated from the total length of the spiral track and the number of bits that can be coded per Airy disk diameter. The spiral track structure stamped into a CD is composed of a sequence of lands and pits which contain the coded information. The tracks are spaced at regular intervals in the radial direction and define a constant track pitch. A small region of a CD, perhaps 1–2 mm in diameter and containing approximately 1000 tracks, resembles, and behaves like, a one-dimensional diffraction grating. If a small region of the CD is illuminated with coherent light, the resulting diffraction pattern is easily analyzed to determine track pitch. The experimental setup is illustrated in Fig. 1. The disc is illuminated with a Helium–Neon (He–Ne) laser beam and the zeroth- and first-order diffracted beams are shown incident on a viewing screen. The angle between any two of the diffracted beams is measured and then employed in the grating equation to calculate the track pitch [11], [12].

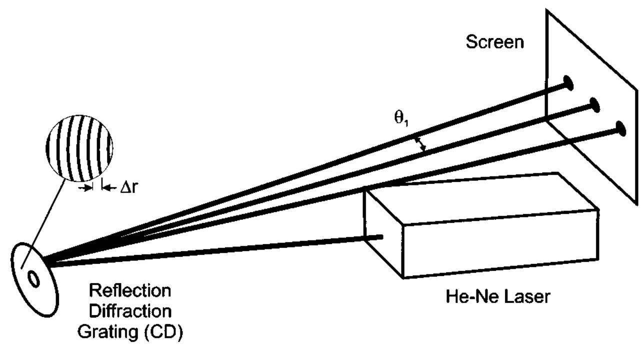

Fig. 1. CD track pitch measurement. The track pitch is determined by illuminating the CD with He-Ne laser light and applying the grating equation. The nominal track pitch is 1.6μm.

If the CD is positioned such that the beam is almost normally incident, the grating equation for normal incidence

$$\Delta r \sin\theta_m = m\lambda \quad (3)$$

may be employed, where

- θ_m angle subtended by the mth-order diffracted beam;
- λ illuminating wavelength;
- Δr track pitch.

A measured value correct to within a few percent of the nominal pitch of 1.6 μm is easily calculated (some disc manufactures employ a subnominal track pitch in order to store additional information). The track pitch can also be measured using a bright white light source rather that a He–Ne laser [13], [14].

The experimentally determined track pitch and the physical dimensions of the program band are used to calculate the length of the spiral track and estimate the storage capacity of the CD. If the long spiral track is considered to be a series of concentric tracks, the number of concentric tracks in the program band is simply

$$N(r_1, r_2) = \frac{r_2 - r_1}{\Delta r} = \frac{58\text{ mm} - 25\text{ mm}}{1.6\ \mu\text{m}} = 20\,625 \quad (4)$$

where r_1 and r_1 are the inner and outer radii of the program band (the number of tracks, $N(r_1, r_2)$, is defined as a function of inner and outer radii to simplify the notation employed in the following section). The total length of the spiral track in the program band is simply the number of concentric tracks multiplied by the average track circumference

$$L(r_1, r_2) = 2\pi\frac{r_1 + r_2}{2}N(r_1, r_2) = 5378\text{ m}. \quad (5)$$

For the first estimate of the storage capacity, it was assumed that one bit of digital information could be recorded with a pit or land equal in area to that of an Airy disk. The CD system employs a channel modulation code called EFM which allows more than one bit of information to be recorded per Airy disk diameter. In EFM, more than seven-channel bits may be stored per Airy disk diameter. Because the physical length of one channel bit is much smaller than the diameter of the Airy-disk readout spot, the bit stream must meet certain run-length requirements; specifically, there must be at least two binary "0's" between each "1." The EFM code belongs to the NRZI (nonreturn to zero inverted) family of modulation codes where a binary "1" causes an inversion or a transition from a land to a pit (or vice versa) and a binary "0" results in no change of state. A consequence of the run-length restriction is that more than eight channel bits are required to record a single 8-bit data byte. Each 8-bit data byte to be recorded on the CD is mapped into a unique 14-bit channel symbol that meets the EFM run-length restrictions. The increase in the number of bits which can be recorded per Airy disk diameter more than offsets the overhead introduced by the EFM code resulting in a larger overall storage capacity.

It is possible to record about 7.6 channel bits per Airy disk diameter if the channel bit stream meets the EFM run-length restrictions (the smallest possible land or pit, representing the three-bit sequence 100, is 0.833μm in length). The storage capacity of a CD in channel bits is therefore

$$\frac{7.6\text{ bit}}{2r_0} \cdot 5378\text{ m} = \frac{3\text{ bit}}{0.833\mu\text{ m}} \cdot 5378\text{ m} = 19.4\text{ Gbit}. \quad (6)$$

The channel bit stream is read from the CD at $4.3218\text{Mbit} \cdot \text{s}^{-1}$ and so the maximum duration of a CD is $(19.4\text{Gbit})/(4.3218\text{Mbit} \cdot \text{s}^{-1}) = 75\,\text{min}$. Neglecting the frame overheads (synchronization and merging bits), the storage capacity of the CD in data bits is $8/14$ of the channel bit capacity or 11.1Gbit. This capacity is more than four times larger than the 2.5Gbit capacity calculated previously assuming a single data bit per Airy disk.

B. Angular and Linear Velocity

The disc of a disc-based storage device may spin with either a constant angular velocity (CAV) or a constant linear velocity (CLV). Under CAV, the number of rotations per unit time is held constant — the traditional LP record spun at exactly $33(1/3)$r/min and modern hard disk drives spin at 5400r/min or faster. Some optical video discs employ CAV to record exactly one complete video frame per revolution and in this way simplify the implementation of special effects such as still frame and slow-motion playback. The CAV mode of operation promotes very short seek times (the disc's speed of rotation does not have to be adapted during a rapid radial movement of the readout spot) and requires very simple drive electronics for the spindle motor. The disadvantage is that it does not make very efficient use of the storage medium. Under CAV, the linear speed of the scanning spot is a function of its radial position on the disc. If a CAV is selected such that the storage density on the first track is optimized, the storage density on all other tracks will be suboptimal (track length increases as one moves out from the center of the disc, however, the number of bits stored per track remains constant). The CD system employs CLV for recording in order to make the most efficient use of the storage medium. The linear speed of the spot is held constant at $1.25\text{m} \cdot \text{s}^{-1}$ and the angular speed of the disc depends on the spot's radial position on the disc.

The CD audio system employs CLV for optical readout. Modern CD-ROM drives generally spin at a multiple of $1.25\ \text{m} \cdot \text{s}^{-1}$ in order to provide data transfer rates equal to a multiple of 150 kbit $\cdot\ \text{s}^{-1}$. Some CD-ROM drives use CAV rather than CLV, or a combination of both, in order to achieve faster seek times. This sometimes leads to confusion about the speed of a CD-ROM. For example, a 32-speed CAV drive has a data transfer rate of $32 \cdot 150\text{kbit} \cdot \text{s}^{-1} = 4.8\text{Mbit} \cdot \text{s}^{-1}$ on its outside track and only 2.1 Mbit $\cdot$ s^{-1} on its inside track, whereas a 16-speed CLV drive has a transfer rate of $16 \cdot 150$ kbit $\cdot$ $\text{s}^{-1} = 2.4$ Mbit $\cdot$ s^{-1} on all tracks.

A simple experiment is presented in this section which can be used to measure the velocity and the mode of rotation of the CD. The duty cycle of the signal which drives the CD player's spindle motor is measured at several different radial positions, r, of the optical pickup. The signal's duty cycle is proportional to the angular velocity of the CD. The hypothesis is that the duty cycle will not change for CAV and should be linear with r^{-1} for CLV.

The velocity experiment (and all subsequent experiments presented in this contribution) were performed using an Emerson model CD230 CD player. The duty cycle of the spindle-motor drive signal was measured at 12 different radial positions of the optical head. The measurements were made such that their corresponding times were equally distributed over the entire duration of the disc. The duty cycle of the pulse width modulated (PWM) signal driving the spindle motor was converted to a time-varying voltage using a simple low-pass filter ($R = 10\text{k}\Omega$ and $C = 100\mu\text{F}$).

Spindle motor voltage is plotted versus inverse disc radius in Fig. 2. The disc radii r were determined from the elapsed time displayed by the CD player when the velocity measurements were recorded. If CLV is assumed, the fraction of the total time elapsed during a particular interval must be equal to the fraction of the spiral track read during that interval, i.e.,

$$\frac{t}{t_{\max}} = \frac{L(r_1, r)}{L(r_1, r_2)}, \quad 0 \le t \le t_{\max} \tag{7}$$

where r is the radial position on the disc corresponding to time t and $t_{\max}$ is the maximum recording time (nominally 75 min). The spiral track length function $L(r_1, r_2)$ was defined previously by (5). Using (7) it can be shown that the radial position at any time t is simply

$$r(t) = \sqrt{\frac{t}{t_{\max}} \cdot (r_2^2 - r_1^2) + r_1^2}, \quad r_1 \le r \le r_2. \tag{8}$$

The linear relationship between the voltage and the inverse disc radius illustrated in Fig. 2 indicates that this particular optical disc system uses CLV.

The CLV of the disc may be determined by measuring the duration of the minimum run-length symbol in the CD's eye pattern. An oscilloscope connected to the CD player's EFM test point is typically used to display its eye pattern. The duration of the minimum run-length symbol in the eye pattern corresponds to a length 0.833 μm pit or land on the disc surface (a complete discussion of the eye pattern and its component EFM symbols is presented in Part D of this section). It is easy to measure a symbol duration correctly to within a few percent of its nominal value of 694 ns. The CLV of the disc is simply the minimum run length divided by its duration observed in the eye pattern, or $1.2\text{m} \cdot \text{s}^{-1}$.

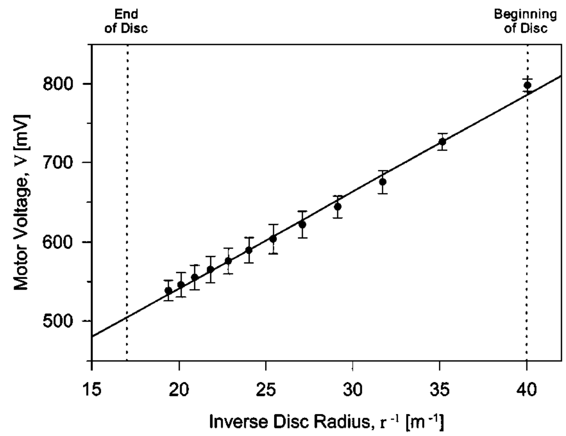

Fig. 2. Spindle motor voltage versus inverse radius. Measurements were taken at equal time intervals for the duration of the CD play time.

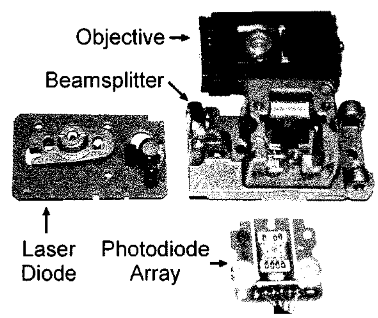

Fig. 3. Photograph of a disassembled optical pickup showing the laser diode beamsplitter, objective lens, and photodiode array. Not shown is the diffraction grating which fits directly over the laser diode.

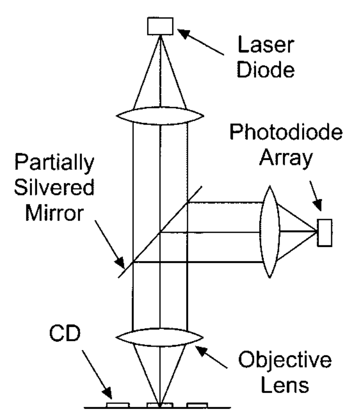

Fig. 4. The basic operating principle of the optical pickup.

C. Optical Pick-Up

The optical pickup is central to a CD player's operation. This hardware assembly is responsible not only for reading the data from the disc, but also for generating focus and tracking correction signals. The disassembled pickup from the Emerson CD player is illustrated in Fig. 3. The laser diode, diffraction grating, beamsplitter (partially silvered mirror), objective lens, and photodiode array are identified. Disassembling and examining the pickup gives one a very good appreciation of its compact form and clever design. Fig. 4 illustrates how the different components of the optical pickup work as a unit. Other CD players

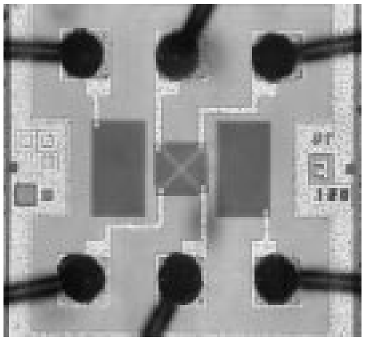

Fig. 5. Optical microscope image of the photodiode array used in the laboratory CD player. The information signal and focus-correction signal are generated by the quadrant detector in the center of the array. The tracking-correction signal is generated by the two outer detectors. The quadrant detector is square.

may use a polarizing prism and quarter-wave plate combination instead of the beamsplitter [4],[6],[9].

The photodiode array may be further examined using an optical microscope. A microscope image of the photodiode array from the Emerson CD player is illustrated in Fig. 5. Four optical detectors are visible in the center of the photograph, as well as two outer, larger detectors. The four central detectors are collectively called the quadrant detector. They are responsible for detecting the optical channel bit stream and are also part of the focusing subsystem. The outer detectors are employed by the tracking subsystem.

When a CD player begins to read a new disc, it begins by trying to focus the laser on the information layer inside the CD. The Emerson CD player uses astigmatic focusing, however, in general, various techniques may be employed. Astigmatic focusing distorts the laser beam such that it has two focal planes. At these focal planes the beam is elliptical in shape and the long axes of the two focal-plane-ellipses are perpendicular. At some plane between these two focal planes, the beam will form a circular spot. The circular beam produces an equal signal on the four detectors of the quadrant detector, as shown in Fig. 6, indicating that the system is focused on the CD [4], [6], [9], [15]. When the system is out of focus, the opposite pairs of detectors produce dissimilar photocurrents, which are subtracted to produce a focus correction signal. The correction signal is used in a feedback loop to control the distance between the objective lens and the CD. It was observed in the disassembled optical pickup that the objective was mounted in a small electromagnet. The focus correction signal varies the current through the electromagnet causing the objective to move up and down, as required, to maintain focus.

Astigmatic focusing is easily demonstrated on a larger scale using a HE–NE laser, a circular lens, and a cylindrical lens. The components should be mounted on an optical rail so that the lenses can be moved along the optical axis, and the optical output can be projected onto a white screen. By changing the distance between the two lenses, the elliptical and circular beams used for astigmatic focusing are reproduced so that they are easily viewable.

In addition to being part of the focusing subsystem, the quadrant detector also converts the channel bit stream from an optical signal to an electrical signal by summing the output of all four quadrants. As the CD spins, the focused laser spot scans along the track of pits and lands. When the spot is over a land, the light is reflected and the received optical signal is large. When the spot is over a pit, however, it reflects from both the bottom of the pit and the land on either side of the pit (between adjacent tracks). The pit depth is designed to be $\lambda/4$ such that the pit and land reflections are $\lambda/2$ out of phase. In this way, light reflected from the two areas interferes destructively, and the received optical signal is small.

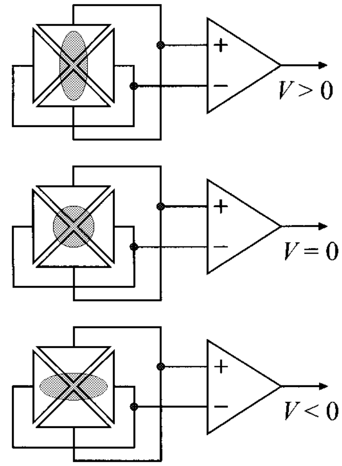

Fig. 6. Astigmatic focusing creates an elliptical light distribution on the quadrant detector when the system is not in focus. The focus correction signal is generated by subtracting the signals generated by opposite pairs of detectors.

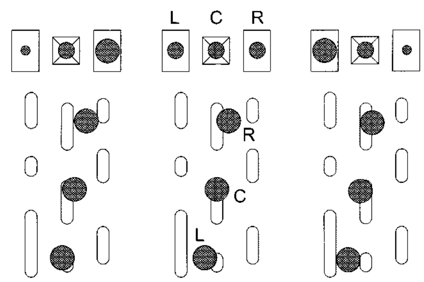

Fig. 7. Tracking in a three-beam type optical pickup. The relative intensity of the two tracking beams generates the tracking-correction signal.

While the quadrant detector detects the main laser beam, the two larger outer detectors of the photodiode array use two additional beams as part of the tracking subsystem. In this three-beam type pick-up, the two tracking beams are generated by a transmission diffraction grating positioned immediately in front of the laser diode [9]. The tracking beams are positioned so as to precede and follow the main readout beam as it reads the data. They are also offset from the track by roughly half the spot width. The two outer photodiodes detect the two tracking beams as shown in Fig. 7. If the three beams drift off of the track being read, then one of the reflected tracking beams experiences more destructive interference than the other beam. Subtracting the signals produced by the two outer photodiodes generates a tracking correction signal. This signal modifies the position of the optical pickup assembly on its carriage.

The diffraction grating is manufactured by ruling, scratching, or etching parallel notches into the surface of a glass plate (the grating in a CD player is really a plastic replica of a master grating made in glass). The parallel notches introduce a regular variation in optical thickness across the grating. The period of this variation, called the grating's ruling, α, was measured experimentally using the setup illustrated in Fig. 8. The grating equation can again be employed, where α replaces Δr. In the Emerson CD player, the ruling was determined to be 42 grooves $\cdot\ \mathrm{mm}^{-1}$.

D. The Eye Pattern

The bit stream which is ultimately recorded on a CD is composed of parity bits, control and display (C&D) bits, and audio bits. This composite bit stream, called the data bit stream, is modulated using a technique called EFM before it is written to the disc. The data bit stream is modulated for two reasons. First, more information may be stored on the disc if the data stream is modulated (as shown earlier in Part A of this section). Second, it is much easier to regenerate a clocking signal from the modulated bit stream. A CD player's EFM signal is easily recovered from the output of its photodetector and displayed on an oscilloscope to produce the very characteristic CD-player eye pattern.

During the CD mastering process, the audio bit stream, additional parity bits, and the C&D bits, are combined to form the data bit stream. Data bytes, taken from the data bit stream eight-bits at a time, are eight-to-fourteen modulated (eight-bit data bytes from the data stream are uniquely mapped into 14-bit EFM symbols) and then interleaved with groups of 3 merging bits. A group of 462 EFM bits and 99 merging bits constitute a frame of 24 audio samples. A unique 27-bit synchronization sequence is added to the beginning of each frame to identify the start. This final sequence of bits, which is ultimately written to the disc, is called the channel bit stream.

The EFM mapping and additional merging bits ensure that the channel bit stream is run-length coded such that there are at least two, but no more than ten, consecutive binary zeros between any pair of binary ones [16]. Thus, the run-length limits are represented by the binary sequences 100 and 10000000000. These are often called the $3T$ to $11T$, signals where $T = 231$ ns is the period of one channel bit. The lower limit is dictated by the spot size of the reading laser, and the upper limit is necessary to maintain tracking and clock signals. The frequency of the CD's EFM code ranges from 196 kHz $(11T)$ to 720 kHz $(3T)$.

An optical micrograph of a CD showing its channel bit stream is illustrated in Fig. 9. The EFM codes annotated in the figure are decoded in Fig. 10. The first 27 bits designate the start of a frame. The two consecutive $11T$ codes are reserved for this purpose. Proper selection of the merging bits ensures that this sequence is not duplicated by the data stored within the frame. The remainder of the frame is composed of 33 pairs of three merging bits and 14 EFM bits, however, only the first two pairs are shown in the figure.

This channel bit stream can be used as an inexpensive source for an eye pattern. Eye patterns reveal information about the noise margin, timing sensitivity, and expected performance of a digital communication system. Typically an eye pattern is observed and studied in the laboratory environment by driving a communication system with a pseudo-random number generator. However, the CD player provides an excellent source of a real-world eye pattern, at a much lower cost than the pseudo-random number generator.

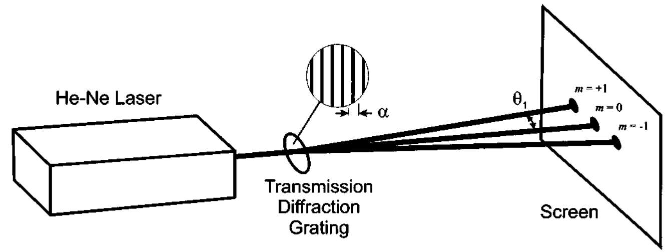

Fig. 8. Generation of multiple beams with a transmission grating for a three-beam type optical pickup. The ruling is determined by illuminating the grating with He-Ne laser light and applying the grating equation.

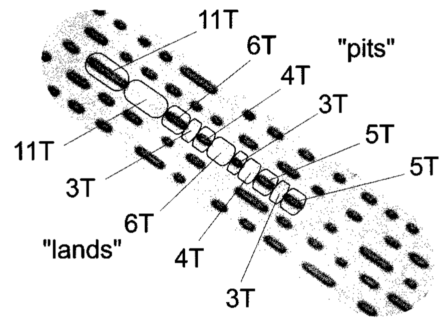

Fig. 9. Optical microscope micrograph showing a portion of a CD. The lengths of the pits and lands are labeled according to how many channel bits they represent. The track spacing is 1.6μm.

The channel bit stream is extracted from the CD player at the output of the transimpedance amplifier and observed on an oscilloscope. The eye pattern represents all possible transitions of the channel bit stream. The characteristic channel eye pattern generated by a CD player is shown in Fig. 11. A fully open eye characterizes a good quality communication system while a partially closed eye indicates inter-symbol interference. Horizontal broadening of the lines in the eye diagram indicates timing jitter, while vertical broadening indicates noise in the system.

The amplitudes of the minimum and maximum run-length signals in the channel eye pattern are indicated as V_3 and V_{11}, respectively. The quality of the optical elements used in a pick-up, particularly the objective lens, determine the amplitude ratio V_3/V_{11} observed in the eye pattern. A pick-up that uses a good quality objective lens (large numerical aperture) is characterized by an amplitude ratio that approaches unity. The high spatial frequency pit patterns, specifically the minimum run-length patterns, are attenuated by the modulation transfer function (MTF) of the optical pickup [5], [9], [16].

III. Error Detection and Correction

The detection and correction of errors is unique to the digital transmission and storage of information. It is the digital representation of the information that both necessitates coding and also makes error correction possible. An error in the least significant bit of a 16-bit audio sample makes very little difference to the reconstructed audio signal, however, the same error in the most significant bit of the sample will result in a very large

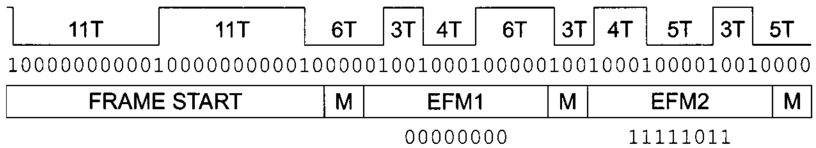

Fig. 10. Manual demodulation of the EFM pattern illustrated in Fig. 9. From top to bottom in the figure: the pit and land pattern on the CD, the channel bit stream, the EFM data structure, and the data bit stream. The data bit stream is passed to the CIRC decoder.

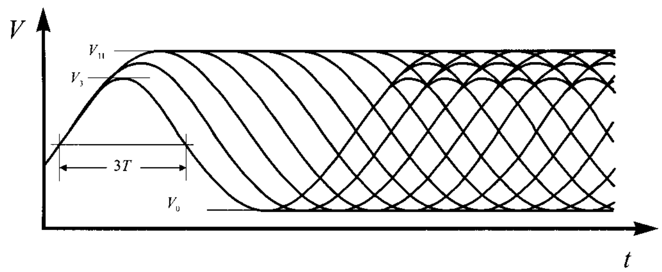

Fig. 11. Typical EFM eye pattern generated by a CD. The minimum run length of two successive zeros, represented by the binary sequence 100, requires three channel bit periods where.

voltage spike in the analog audio signal and an audible click in the musical passage. Digital audio data is relatively forgiving compared to numerical data where an incorrect bit may mean the difference between adding or subtracting values from a bank account. The CD system employs a very advanced error detection and correction system which approaches the specification for data reliability demanded by the computer industry — a bit error rate of 10^{-12} – less than one uncorrectable bit error in one trillion.

Error detection and correction is possible because additional or redundant data is added to the original data stream. In serial alphanumeric communications for example, a single parity bit is typically added to each 7-bit ASCII code to force the entire 8-bit byte to have either even or odd parity. Using this strategy it is possible to detect single bit errors, however, error correction is impossible. In the CD audio system, a total of eight parity bytes are added to each frame of twenty-four data bytes in two separate encoding stages. The CD decoder is capable of *detecting* a maximum of four erroneous bytes if error correction is not attempted. The decoder is capable of *correcting* a maximum of two erroneous bytes, or a maximum of four erasures (an incorrect byte is called an erasure if it is known *a priori* to be unreliable), however, the error correction decreases the detection capability of the decoder.

Two types of errors, namely random errors and burst errors, are common to both optical and magnetic storage media. The error control systems in these devices must be capable of detecting and correcting both types of errors. Errors that are randomly distributed in the data stream are called random errors and are usually introduced into the data stream by intersymbol interference, detector and electrical noise, and small imperfections in the polycarbonate substrate. Errors that occur in groups that cover hundreds or even thousands of bits are called burst errors. Burst errors are typically caused by dust particles or fingerprints on the CD surface, large defects or scratches in the disc substrate, and incorrect tracking or focusing by the CD player. The manner in which an error control system deals with a particular error depends on its severity. Error detection using redundant data is attempted first to check the validity of the channel data stream. Incorrect bytes that can be recovered using the redundant data are corrected and those that can not be corrected are flagged for concealment at a later stage. Incorrect audio samples are interpolated from valid samples if possible, or in the worst case when concealment is not possible, most systems choose to mute the audio output.

A. CIRC Primer

The CD digital audio system employs an error control system based on a Cross-Interleaved Reed–Solomon Code (CIRC). Reed–Solomon codes were invented at the MIT Lincoln Laboratories by Irving Reed and Gustave Solomon in 1960. The codes are based on polynomials whose coefficients are members of a Galois Field $GF(q^m)$ of order q^m. In CIRC, the coefficients are selected from $GF(2^8)$ in order to yield 8-bit symbols (there are a total of $2^8 - 1 = 255$-bit symbols). This symbol length was selected to facilitate the representation of 8-bit digital data as well as 16-bit audio samples. The discovery of an efficient decoding algorithm for the Reed-Solomon codes transformed what was initially just a mathematical curiosity into one of the most powerful and popular error control systems. The CD digital audio system is generally considered to be the first consumer product to employ Reed–Solomon codes for error control. A comprehensive review of cross-interleaving and Reed–Solomon coding is well outside the scope of this paper. A good introduction may be found in [17] and [18].

The presentation of an error control system usually starts with the encoding process, however, in the present situation, only a description of the decoder is necessary. A simplified block diagram of the CIRC decoder is illustrated in Fig. 12. The CIRC architecture consists of two Reed–Solomon decoders C1 and C2 separated by a set of delay lines of unequal length. A frame of 32 eight-bit symbols (24 audio and eight parity) is input in parallel to decoder C1. The decoder uses the four P-parity symbols to correct random errors in the input frame, and in addition, to detect burst errors. In order to achieve optimum detection ability, decoder C1 usually attempts to correct only one erroneous symbol in each frame. If more than one incorrect symbol is detected in the frame, all 28 output symbols (24 audio and four parity) are marked with erasure flags and passed through the set of delay lines to the C2 decoder. Symbols that appear to be correct are not processed by the decoder and passed through directly to the delay lines. The delay imposed by each line is a multiple of $D = 4$ frame periods such that the top symbol is delayed $27 \cdot 4 = 108$ frame periods and the bottom symbol is not delayed at all.

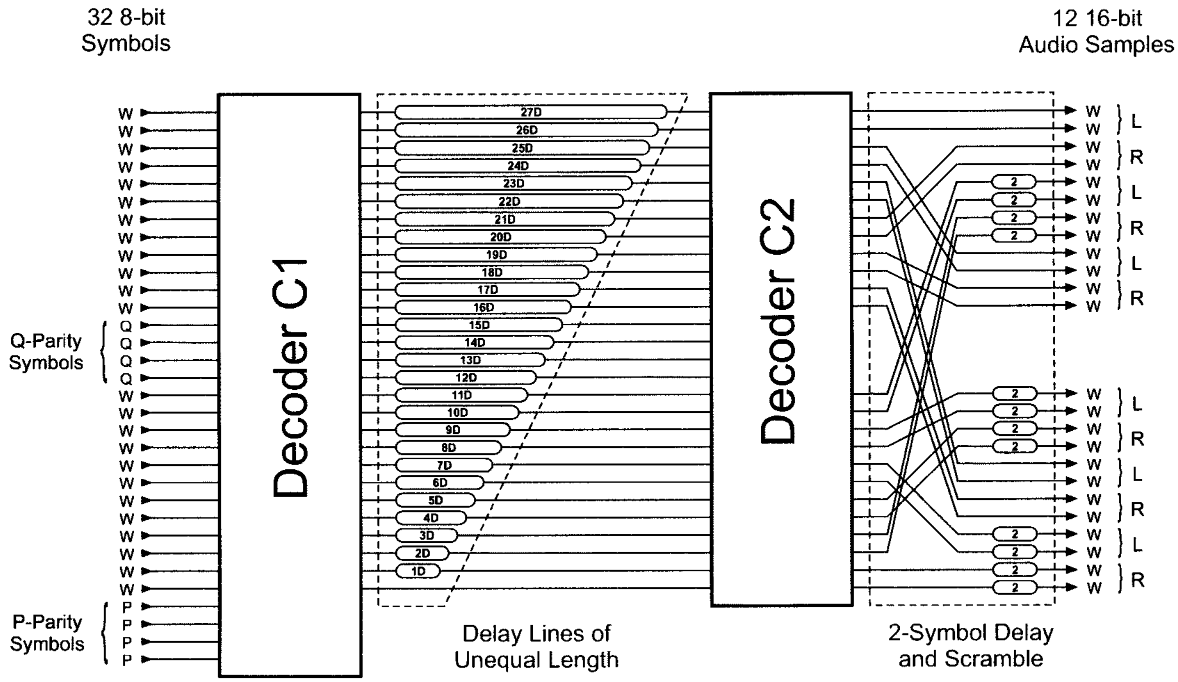

Fig. 12. Simplified block diagram of the CIRC error control system.

The de-interleaving implemented by the delay lines enables the C2 decoder to correct long burst errors. Consider a burst error that contaminates the entire 32 symbol frame input to decoder C1. The burst error is detected by C1 and each symbol leaving C1 is marked with an erasure flag. The 28 erasure symbols will be spread out in time over a total duration of 108 frames by the time the top erasure symbol reaches C2. In this way, the 24 symbol frames input to decoder C2 will have a maximum of one erasure symbol per frame, and will be separated by three frames with zero erasures, assuming the initial burst error contaminated only one full frame at decoder C1. A burst error of four consecutive frames at decoder C1 would result in a 109 consecutive frames each containing a single erasure symbol. Decoder C2 is capable of correcting frames with up to four erasure symbols per frame which corresponds to almost 16 contaminated frames input consecutively at decoder C1. This corresponds to a maximum burst-error-correcting capability of approximately $16 \cdot 32 \cdot 8 \approx 4000$ data bits or 2.5 mm of track length on the disc [19].

A frame of 28 symbols (24 audio and four parity) is input in parallel to decoder C2. The decoder uses the four Q-parity symbols and any erasure flags passed from C1 to correct burst errors, and in addition, decoder C2 may also attempt to correct any single symbol errors it detects. The CIRC decoder strategy has not been standardized and each manufacturer is free to choose their own optimum strategy (various strategies and performance analysis have been published in the literature [20]). Some CD players perform only double-erasure decoding at decoder C2 while more advanced systems attempt to correct quadruple errors. If decoder C2 cannot correct all of the errors in a frame, for example, when more than four symbols are flagged, all 24 audio symbols are flagged and passed on for interpolation or concealment. The two-symbol delay shown in Fig. 12 between the even and odd audio samples ensures that interpolation is possible even when two uncorrectable blocks occur consecutively at the input to decoder C2.

B. Measurement of CIRC Error Statistics

The two Reed–Solomon decoders in the CIRC architecture generate error flags that are passed on to the next processing block. Decoder C1 attaches flags to symbols in its output frame when a burst error is detected; the flags are used by decoder C2 for erasure decoding. Similarly, decoder C2 attaches flags to symbols in its output frame when correction is not possible; these flags are employed by a concealment algorithm to either interpolate or mute the incorrect samples. CIRC decoder chips employed by most CD players make these status flags available for external diagnostics and statistical testing. Most chips provide additional CIRC status information. The Philips SAA7376 chip, which attempts double-error correction at decoder C1 and quadruple-erasure correction at decoder C2, reports the number of errors detected at decoder C1 (either 0, 1, 2, or > 2), the number of errors detected at decoder C2 (either 0, 1, 2, 3, 4, > 4), and whether or not sample interpolation was required for error concealment. An experimental system is presented in this section which allows the student to access the error-correction status flags in a consumer grade CD player and count the number of errors which are detected by each of the Reed–Solomon decoders. The system is used in the following sections to measure the symbol error rate of a typical CD, the corresponding symbol interpolation rate achieved by the CIRC system, and the maximum correctable burst error length.

The Emerson CD230 CD player employed for the experiments in this paper is based on a chipset developed by Yamaha. The CIRC decoding algorithm implemented in the YM3805

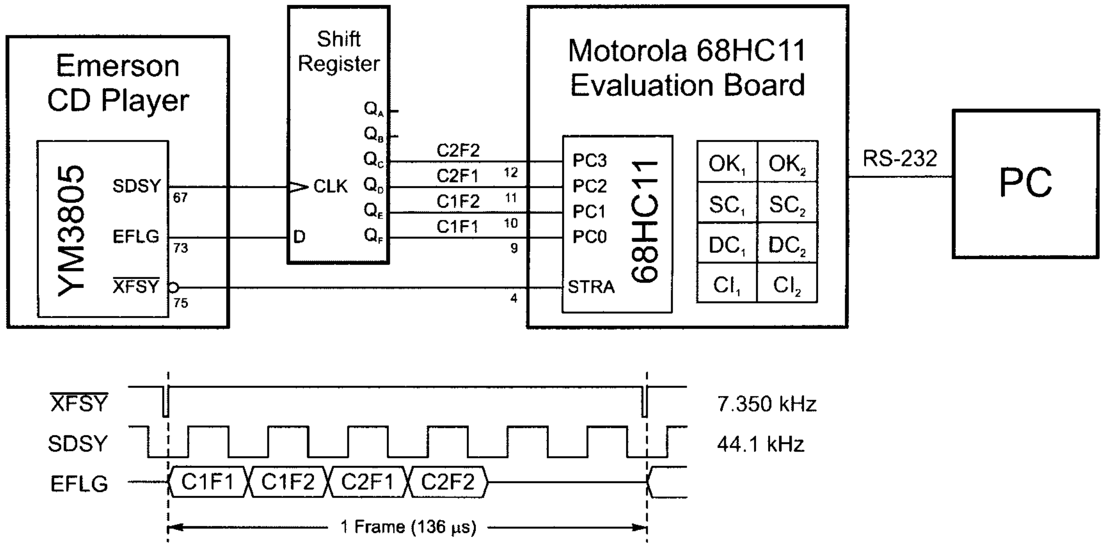

Fig. 13. Experimental setup employed to collect CIRC statistics and the Yamaha YM3805 status flag timing diagram.

signal processor chip attempts double-error correction at decoder C2 and double-erasure correction at decoder C2. The error correction status for decoders C1 and C2 is output every frame as a sequence of four bits at pin 73 labeled EFLG. The serial four-bit status pattern and a timing diagram are illustrated in Fig. 13. The first two bits in the sequence describe the status of decoder C1 and the last two bits describe the status of decoder C2. The two-bit status is identical for both decoders and is shown in Table I. The status flags are output sequentially by the Yamaha YM3805 signal processor necessitating a shift register to convert the four-bit status pattern into a parallel format. In general, the CD signal processors developed by Philips also output their status bits serially, however, the signal processors developed by Sony provide a parallel output.

A Motorola M68HC11 evaluation board and PC were employed to count the status events output by the CIRC decoder and display the error-correction statistics. The experimental setup is illustrated in Fig. 13. The four-bit status sequence output from the YM3805 signal processor at EFLG is clocked into a six-bit shift register using the 44.1 kHz clock signal SDSY provided at pin 67 of the YM3805. The four-bit status nibble is latched into the lower four bits of port C in the 68HC11 microcontroller on the rising edge of strobe signal $\overline{\text{XFSY}}$ provided at pin 67. The microcontroller was programmed to count the number of error free, successfully corrected, and uncorrectable frames reported by the two CIRC decoders and periodically upload the accumulated counts to a host PC for statistical processing and display. As shown in Fig. 13, a set of eight 16-bit registers was employed to count the number of frames in which zero, single, double, and multiple-symbol errors were detected by decoders C1 and C2. An interrupt service routine, initiated by strobe signal $\overline{\text{XFSY}}$ once per frame (the frame rate is 7.350kHz), latches the current status nibble in the shift register, determines the number of errors present in the frames most recently processed by decoders C1 and C2, and increments the appropriate counters. The registers OK_i, SC_i, DC_i, and CI_i, accumulate the number of frames processed by decoder i which contains, respectively, zero symbol errors, one symbol error, two symbol errors, and more than two symbol errors which are impossible to correct. The counts are uploaded to a host PC every few seconds in order to avoid register overflow.

TABLE I
DECODER C1 AND C2 STATUS FLAGS
PROVIDED BY THE YM38

CxF2	CxF1	Decoder Status
0	0	Cx frame contained no errors
0	1	Cx frame contained one error
1	0	Cx frame contained two errors
1	1	Cx frame contains more than two uncorrectable errors

C. Symbol Error Rate

Random errors are introduced into the channel bit stream by small imperfections embedded in the disc substrate, intersymbol interference, and noise introduced during optical detection. An experimental method, which employs the status flag counting hardware discussed in the previous section, is presented in this section to measure the number of symbol errors in the data stream due to random errors introduced into the channel bit stream. The channel bit stream is the sequence of bits read directly from the disc (14-bit EFM symbols separated by three merging bits) while the data stream refers to the sequence of eight-bit symbols output by the EFM demodulator. Each frame of the data stream is composed of 32 data bytes and one control and display byte. The 32 data bytes are input in parallel to CIRC decoder C1 as illustrated previously in Fig. 12. The symbol error rate represents the probability of an incorrect symbol, or alternatively, the fraction of erroneous symbols, entering the CIRC error control system. It is measured by counting the number of incorrect frames that are detected by decoder C1 and then converting this frame error rate to a symbol error rate. The conversion is tractable if the data channel is assumed to be memoryless, i.e., if it is assumed that the noise processes affecting a given symbol are independent of those affecting preceding or succeeding symbols.

The probability of an incorrect frame entering decoder C1, due to one or more erroneous symbols in the frame, is measured by counting the total number of frames processed by the decoder and the number of those which are detected to have at least a single erroneous symbol. The frame counts are measured by the experimental system described in the previous section. The probability of a frame error is estimated by calculating one minus the probability of a correct frame, or in terms of the measured frame counts

$$P_{C1} = 1 - \frac{OK_1}{OK_1 + SC_1 + DC_1 + CI_1}. \qquad (9)$$

A single frame input to decoder C1 consists of 32 symbols. Assuming a memoryless channel, that is, assuming that the noise process affecting a given symbol is independent of those affecting preceding or succeeding symbols[18], Chapter 10, the probability of a symbol error (or equivalently the symbol error rate) is given by

$$\begin{aligned} P_{\text{symbol}} &= 1 - (1 - P_{C1})^{1/32} \\ &= 1 - \left[\frac{OK_1}{OK_1 + SC_1 + DC_1 + CI_1}\right]^{1/32}. \end{aligned} \qquad (10)$$

The status flags generated by the Emerson CD player while playing seven different CD's where counted using the system presented in Section B and the symbol error rate was calculated by (10). Each disc was cleaned with alcohol before each experiment to minimize burst errors caused by finger prints and dust particles. The CD that had the lowest symbol error rate had no visible scratches while that with the highest symbol error rate had minor scratches. The measured symbol error rate ranged from 6×10^{-5} to 4×10^{-4}. The average symbol rate has also been measured by others to range from 1×10^{-4} to 2×10^{-4}[1].

D. Sample Interpolation Rate

The symbol error rate represents the probability of an incorrect eight-bit data-stream symbol entering the error control system, while the sample interpolation rate represents the probability of an incorrect 16-bit audio-stream sample leaving the error control system. In other words, the symbol error rate is the probability of an error being input to the CIRC while the sample interpolation rate is the probability of an error leaving the CIRC.

The error control system was designed to minimize the sample interpolation rate for a given symbol error rate. The sample interpolation rate characterizes the performance of the CIRC system to random errors at a specific symbol error rate, and the symbol error rate is determined by the condition of the CD and the quality of the optical readout and the detection system. The sample interpolation rate is measured by counting the number of incorrect frames which are detected by decoder C2 and then converting this frame error rate to a sample interpolation rate assuming a memoryless channel.

The derivation of an expression for the experimentally determined sample interpolation rate closely follows that of the symbol error rate. The probability of an incorrect frame entering decoder C2, due to one or more erroneous symbols in the frame, is measured by counting the total number of frames processed by the decoder and the number of those which are detected to have at least a single erroneous symbol. The frame counts are measured by the experimental system described in Section B. The probability of a frame error is estimated by calculating one minus the probability of a correct frame, or in terms of the measured frame counts

$$P_{C2} = 1 - \frac{OK_2}{OK_2 + SC_2 + DC_2 + CI_2}. \qquad (11)$$

A single frame output from decoder C2 consists of 24 eight-bit audio bytes or, equivalently, 12 audio samples (six left and six right channel samples). Assuming that the noise process affecting a given audio sample is independent of those affecting preceding or succeeding samples[18, Ch. 10], the probability of a sample error (or equivalently the sample interpolation rate) is given by

$$\begin{aligned} P_{\text{interpolation}} &= 1 - (1 - P_{C2})^{1/12} \\ &= 1 - \left[\frac{OK_2}{OK_2 + SC_2 + DC_2 + CI_2}\right]^{1/12}. \end{aligned} \qquad (12)$$

The sample-interpolation rate was measured using the Emerson CD player for the same seven CD's used in the symbol error rate experiment. The sample interpolation rate depends on the symbol error rate (quality of the disc and optical readout system) and the error correction strategy employed by the CD player. One of the discs produced no interpolation errors over its entire length about 50% of the time and had a symbol error rate less than 10^{-4}. The average sample interpolation rate for the seven disc ranged from 4×10^{-9} to 2×10^{-5} or, equivalently, 1.3 samples per hour to 1.8 samples per second (left and right channels each sampled at 44.1 kHz). The CIRC specification defines a sample interpolation rate for two representative input bit error rates [19]. At a low input error rate ($\text{BER} = 10^{-4}$), the sample interpolation rate must be less than 3×10^{-10} or less than 1 sample every 10 h. When the input error rate is high ($\text{BER} = 10^{-3}$), the sample interpolation rate must be less than 2×10^{-4} or no more than 1000 samples every minute.

E. Maximum Correctable Burst Error Length

Errors of extended duration which occur in groups that cover hundreds or even thousands of bits are called burst errors. They tend to occur more frequently than random errors and are usually caused by dust particles or fingerprints on the CD surface, large defects or scratches in the disc substrate, and incorrect tracking or focusing by the CD player. An important characteristic of any error control system is its maximum correctable burst error length (MCBEL). This is the length of the longest burst error, expressed in terms of bits or its physical track length on the disc, which can be fully corrected by the error control system. The specification for CIRC defines a MCBEL of 4000 data bits [19] which is equivalent to 2.5 mm of track length (a channel bit has an effective track length of approximately $[(0.833\,\mu\text{m})/3]\cdot[(14+3)/8] = 0.6\,\mu\text{m}$). The standard CIRC encoding algorithm guarantees, at least in theory, that the MCBEL

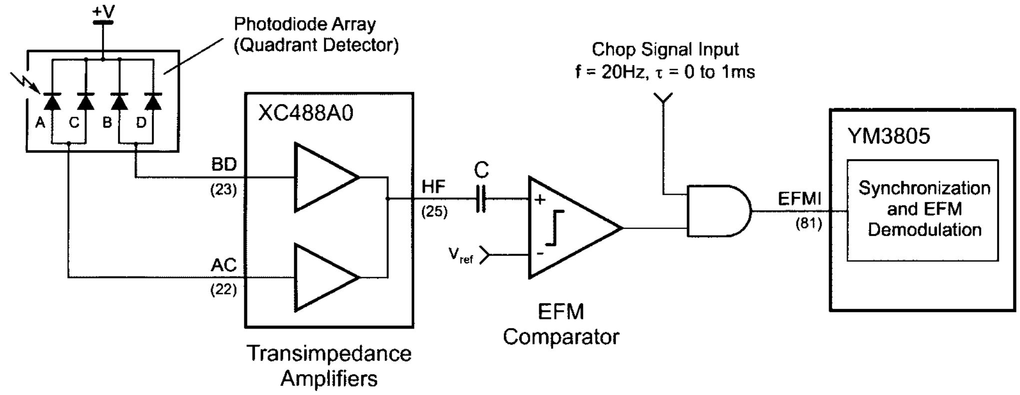

Fig. 14. Burst error simulation circuit. Burst errors were simulated by chopping the EFM signal between the comparator and EFM demodulator.

specification is achievable, however, the actual MCBEL realized on a given CD player depends on its particular CIRC decoding strategy.

An experimental technique, which employs the status flag counting hardware discussed previously, is presented in this section to measure a CD player's MCBEL. A series of burst errors, simulated by chopping the EFM signal, was introduced into the channel bit stream. The quality of the audio was observed and the performance of the error control system was measured as the duration of the simulated burst errors was increased. The longest burst which can be introduced into the channel bit stream without significantly increasing the probability of an uncorrectable symbol error at decoder C2 represents the CD player's MCBEL.

Burst errors were simulated in the channel bit stream by chopping the EFM signal between the EFM comparator and the EFM demodulator using an AND gate as illustrated in Fig. 14. The chop signal was a negative-going TTL pulse train with a frequency of $f = $ 20Hz and a pulse width equal to the duration of the desired burst error (the chopping frequency must be less than 68 Hz such that adjacent burst errors do not collide at the input of decoder C2). As the error duration was increased, the impact of the burst errors was observed by listening to the quality of the audio track and by counting the average number of corrections attempted by decoder C2. The status-flag counting hardware was employed to count the average number of single corrections, double corrections, and the average number of frames where correction was impossible, at several burst error durations. The MCBEL was estimated by analyzing the measured data set and locating the error duration at which the average number of frames, where error correction was impossible, started to increase quickly.

The duration of the chop pulse was increased from $\tau = 0$ μs to $\tau = 1000$ μs in small steps and the average number of error-free, singly-corrected, doubly-corrected, and correction-impossible frames were counted for each different chop duration. The average single-correction, double-correction, and correction-impossible rates, for the Emerson CD player, are shown in Fig. 15. The counts were converted to a correction rate by multiplying them by (7.350 kHz)$/(N \cdot 20$ Hz), where $N = OK_2 + SC_2 + DC_2 + CI_2$ is the total number frames processed, and (7.350 kHz/(20 Hz) is the ratio of the frame rate to the burst-error frequency. The correction rates illustrated in

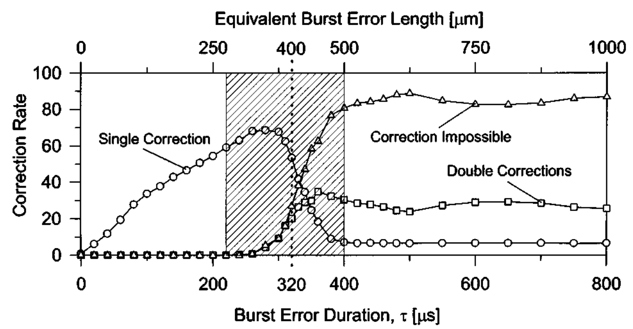

Fig. 15. Average single correction, double correction, and correction-impossible rates for a single simulated burst error. A burst error of duration $\tau = 400 \mu$m could be corrected by the Emerson CD player 50% of the time.

Fig. 15 represent the average number of frames per burst error that required a single-correction, or a double-correction, or that were impossible to correct.

The average single-correction rate increased linearly with chop duration while the correction-impossible rate remained zero for chop durations less than 220 μs, thus a burst error of duration less than 220 μs (275 μm of disc surface at 1.25 $\mathrm{m} \cdot \mathrm{s}^{-1}$) could be fully corrected by CIRC with only a single correction required per frame. Additional measurements showed that the maximum correctable burst error lengths that could be corrected between 1 and 99 times out of 100 had durations between 220 μs $(275\mu$ m and 400 μs $(500\mu$ m. They are illustrated in Fig. 15 by the cross-hatched region. A burst error of duration 320 μs or 400 μm of disc surface could be corrected by the CD player 50% of the time. In theory, a CD player which attempts double-error correction at decoder C2, such as the Emerson model used in this work, should be able to correct a burst error of eight consecutive frames corresponding to a duration of 1088 μs or 1.36 mm of disc surface [1]. A burst error introduced into the channel bit stream, however, results in a much longer burst error after EFM demodulation. When longer bursts are introduced, the clock and frame synchronization signals required for EFM demodulation may be lost and, consequently, demodulation and error correction will not be possible again until a bit and frame lock can be reestablished. The Emerson CD player did not meet the burst error specification because synchronization was lost before the CIRC error control system had a chance to correct the error.

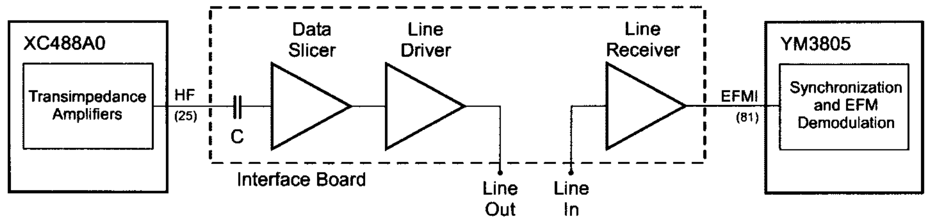

Fig. 16. Block diagram of the CD player interface board. The channel bit stream is rerouted between the output of the transimpedance amplifier and the input of the DSP chip (YM3805). The interface board allows an external fiber transmission system to be easily connected.

IV. Optical Fiber Communication

Compact discs are a nearly ubiquitous source of modulated data. The CD player is an inexpensive piece of equipment containing the optics and electronics necessary for reading, demodulating, correcting, and presenting this data in audio format. With minor modifications, the CD player is converted into an excellent tool for teaching optical fiber communications. When properly modified, the CD player performs not only as a data source, but also as a way to qualitatively and quantitatively evaluate a fiber link in the laboratory. Traditionally this would require several pieces of expensive test equipment that are usually not available in an undergraduate teaching laboratory. In addition, the audio signal is much more captivating than the traditional repetitive or random signal.

A. Optical Fiber Communication Link

The audio CD is a convenient source of a coded and modulated signal for either observation on an oscilloscope or transmission over an optical fiber. The complex signal can easily be recovered and extracted from an inexpensive CD player with only minor adjustments to the hardware.

Prior to experimentation, the Emerson CD player was modified to gain easy access to the channel bit stream as shown in Fig. 16. The channel bit stream path was broken between the output of the transimpedance amplifier and the input of the digital-signal processing (DSP) chip. This point is accessible in most CD players. From this break in the signal path the channel bit stream was diverted through a custom interface board. The interface board performed thresholding on the channel bit stream to convert the bandwidth-limited signal observed in the eye diagram, into a sharp square wave. A line driver was used to supply the thresholded signal to a BNC connector. Another BNC connector and a line receiver were used to reinsert the bit stream into the CD player at the input of the DSP chip. For normal CD player operation, the output of the line driver and the input of the line receiver can be jumpered. Alternatively, the signal can be further diverted through a fiber link using the BNC connectors.

A block diagram of a fiber link connected to the interface board and the CD player is shown in Fig. 17. The goal of the exercise was to design and build transmitter and receiver circuits that would successfully transmit the signal over a given length of fiber at a predetermined BER of 10^{-5}. The components that were used included 60 m of a 1 mm plastic optical fiber (ESKA model SH4001), an LED transmitter (HP model HFBR-1527), a matched PIN receiver (HP model HFBR-2526), and Motorola emitter-coupled-logic (MECL) logic chips. The HFBR-2526 package includes both a PIN detector and a preamplifier. The transmitter and receiver circuitry used for this paper is presented in the design notes for the HFBR-2X2X pair.

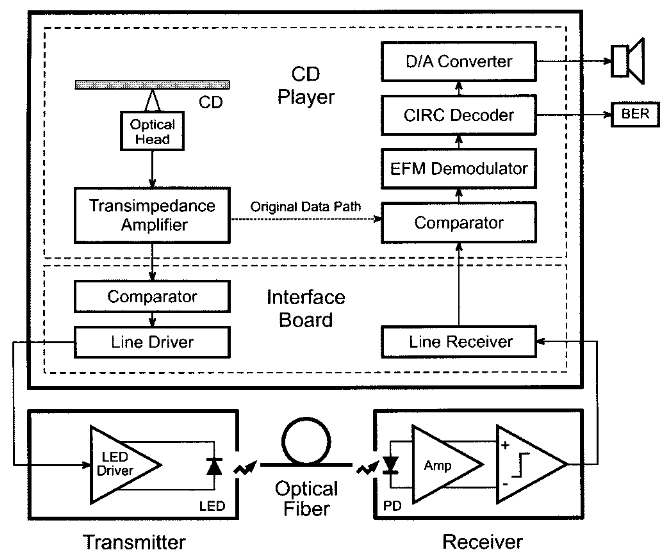

Fig. 17. Overall diagram of the optical fiber communication link. The channel bit stream is removed from the CD player and sent through the fiber link via an interface board. The bit stream received is returned into the CD player where it is demodulated errors corrected, and the original analog audio signal reconstructed. The channel bit rate is 4.32 Mbits/s^{-1}.

Plastic fiber was chosen over silica fiber for reduced cost and ease of use. The core diameter of plastic fiber is much larger than for silica fiber. A larger core reduces connector tolerances, thus reducing cost, and also makes adding connectors to the fiber much easier. Finally, the larger fiber core means more light is coupled into the fiber, allowing LEDs to be used as optical sources instead of laser diodes. LEDs are safer and cheaper than laser diodes, and require only simple circuitry to be used as transmitters.

Two conditions must be met for an optical link to work. The bandwidth of the link must be high enough to preserve the general shape of the bit stream, and the receiver must be sensitive enough to regenerate the bit stream at an acceptable probability of error. To ensure that these conditions are met and to determine which is the limiting factor, bandwidth (or rise time) and power budgets are calculated for the link. A bandwidth budget considers the rise times of the various components including the optical emitter, the fiber, and the detector. A power budget includes the LED power launched onto the fiber, fiber loss, coupling losses, and the receiver's sensitivity. Coupling losses include Fresnel (reflection) losses at the fiber exit

(0.2 dB) and the detector (0.2 dB), and the detector misalignment losses (1.2 dB), where the listed values are estimates for the experimental system. The power budget must also consider the signal-to-noise ratio (SNR) necessary to achieve the desired BER. A PIN detector suggests a thermal-noise-limited system, and thus a BER of 10^{-5} corresponds to a SNR of approximately 19 dB.

Plastic fiber has much higher signal attenuation than silica fiber, in our case 0.2 $\text{dB} \cdot \text{m}^{-1}$ at the LED operating wavelength of 660 nm, compared to a minimum of 0.2 $\text{dB} \cdot \text{km}^{-1}$ for silica fiber at 1.55 μm. Modal dispersion for the SH4001 fiber is 140 $\text{ps} \cdot \text{m}^{-1}$. Power and bandwidth budgets performed on the experimental system reveal that the system is severely attenuation or power limited. When building the circuitry, it becomes evident that fiber attenuation is very important. As very little optical signal remains after 60m, it becomes necessary to identify and control noise in the receiver to maintain the desired SNR. This is especially important when building the circuit on a proto-board where amplified signals can easily be coupled back to the small detected signal. The importance of the circuit layout and a neat wiring job become very apparent.

B. Evaluating the Communication Link

The completed fiber link successfully transmitted the channel bit stream over the fiber. The receiver detected, amplified, and quantized the bits. After being reinserted into the CD player, the signal was demodulated, decoded, and reconstructed into the original audio signal. The fiber link was evaluated qualitatively by simply listening to the audio output and by examining the eye pattern of the received signal. An eye pattern measured at the output of the receiver preamplifier is shown in Fig. 18. The bit rate was 4.32 $\text{Mbit} \cdot \text{s}^{-1}$ and the channel was 30 m long. Quantitative evaluation of the link was achieved by interfacing the CD player's error correction DSP chip and a personal computer. In this way the BER of the link was measured.

As previously described in Section III, the BER of the communication link can be evaluated using the error correction status flags from the CD player's DSP chip. Eight bit data symbols are represented on a CD as strings of $14 + 3 = 17$ channel bits according to the EFM channel code. Because the code is run-length-limited, the assumption of a memoryless channel no longer applies and consequently one can only calculate the upper and lower bounds on the channel BER. An upper bound on the channel BER, assuming 8 channel bits per symbol and 32 symbols per code word, is given by

$$\begin{aligned} \text{BER}_{\text{CHAN}} &\leq 1 - (1 - P_{C2})^{1/8 \cdot 32} \\ &= 1 - \left[\frac{OK_2}{OK_2 + SC_2 + DC_2 + CI_2} \right]^{1/8 \cdot 32} \end{aligned} \tag{13}$$

where P_{C2} is the probability of a frame error and is defined by (11). A lower bound on the channel bit error rate would assume 17 rather than eight bits per symbol.

The channel BER for a single CD player with no optical fiber link is compared to 30 m and 60 m optical fiber links in Table II. As the length of fiber increases, the optical power at the PIN detector decreases. This reduces the SNR of the signal leading to an increase in the BER of the system.

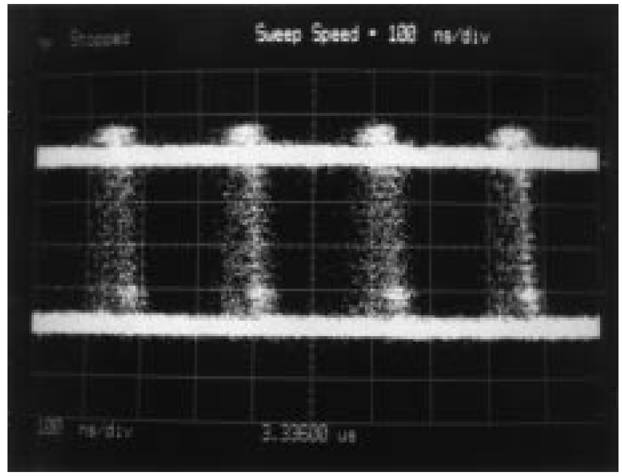

Fig. 18. Eye diagram measured at the receiver of the optical fiber link. The NRZI channel bit stream (EFM signal) recovered from the CD is transmitted across 30 m of plastic fiber at 4.32 Mbit/s^{-1}.

TABLE II
CHANNEL BIT ERROR RATES (BER) FOR AN OPTICAL FIBER LINK

BER	No Fiber Link	30 m	60 m
Upper Bound	4.6×10^{-6}	5.0×10^{-6}	2.2×10^{-5}
Lower Bound	1.2×10^{-6}	1.3×10^{-6}	5.6×10^{-6}

V. CONCLUSION

The common CD player employs some of the most impressive engineering technology to be marketed as a consumer product. It is a synergy of optics, communication theory, digital signal processing, and control engineering. A series of simple experiments, based on the familiar CD player and suitable for implementation in an undergraduate EE laboratory, have been presented in this contribution. The CD player is ideal for teaching digital communication and optical storage concepts because it was originally designed as a transmission system. The CD player is generally very familiar to most undergraduate students as an entertainment product. Employing it to teach quite complicated ideas in the laboratory has significant pedagogical value and can be much less intimidating for the students. The sophistication of the CD player, its familiar and nonintimidating character, and its ease of availability make it a very attractive alternative to the complicated and expensive laboratory instruments traditionally required.

The laboratory sessions based on the CD player are now entering their sixth successful year of operation in the Electrical and Computer Engineering Department at Dalhousie University. The courses are currently offered to students in their senior year, however, students in the junior years are aware of the CD-player based laboratories and look forward to the time when they are able to participate in the experiments. The authors have found the approach of employing a familiar device to teach complicated ideas to be very effective. The experiments based on the CD player have great educational value and are enjoyable for the students.

The cost of CD players has dropped considerably since they were first introduced. Home players can be purchased for less than $100 and portable battery operated versions are even less expensive. Only minor modifications to the CD player itself are required to perform most of the experiments presented here. Most of the interesting signals are made available to the outside world as test points on the main printed circuit board. Additional circuitry and software are required to perform the error detection and correction experiments. Requests for more information can be sent to Michael.Cada@dal.ca.

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