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Retrofit Fluorescent Dimming with Integrated Lighting Control

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Retrofit Fluorescent Dimming - Interim Report

Introduction

This report presents the results of work performed to date by Lawrence Berkeley National Laboratory (LBNL) related to Project 3.1: Retrofit Fluorescent Dimming with Integrated Lighting Control. The first section of the report describes the scope of work for the project, which consists of eight tasks. The second section presents the status of the first six tasks and the research work completed for each, including adjustments made to the original work plan. The final section makes recommendations for completing the research project underway.

Scope of Work

The goal of the *Retrofit Fluorescent Dimming with Integrated Lighting Control* Project is to develop and test a dimmable, fluorescent lighting control system that is suited for easy retrofit into existing commercial buildings and to demonstrate the benefits to the lighting community. The system will dim 0-10 Volt DC fluorescent dimming ballasts down to 20 percent light output without the need for additional control wiring and without negatively affecting power quality.

The system will provide control of the lighting system using the following manual and automatic means:

1. Manual dimming from a wallbox.
2. Automatic lighting control using PC-connected “multi-sensor”.
3. Manual dimming from PC control panel.
4. Utility-triggered load shedding via Intranet-connected PC.
5. “Auto-pilot” mode, automatically enabled when PC, multi-sensor or IP connection are not in service.

Combining a dimmable fluorescent lighting system with the above control options will result in an integrated, yet highly flexible lighting control system (see Figure 1.). This unique lighting solution is particularly suited to retrofit applications since the installation requires no added wiring.

A key objective is the development and testing of an intelligent junction box (IJB) that will contain a novel encoder to dim 0-10 volt controllable ballasts down to 20 light output percent without the need to run additional control wiring. A second key objective is the coupling of the IJB with a multi-function environmental sensor (“multi-sensor”), which will allow user-friendly implementation of two key lighting control strategies (specifically, daylighting and occupancy detection). A third key objective is the adaptation of a Bluetooth communications link that will allow wireless communication between the PC and the IJB, as well as providing a simple communications link to the Internet or local Intranet. A fourth objective is to work with ballast and control manufacturers to embed the resultant control technologies into their lighting control products.

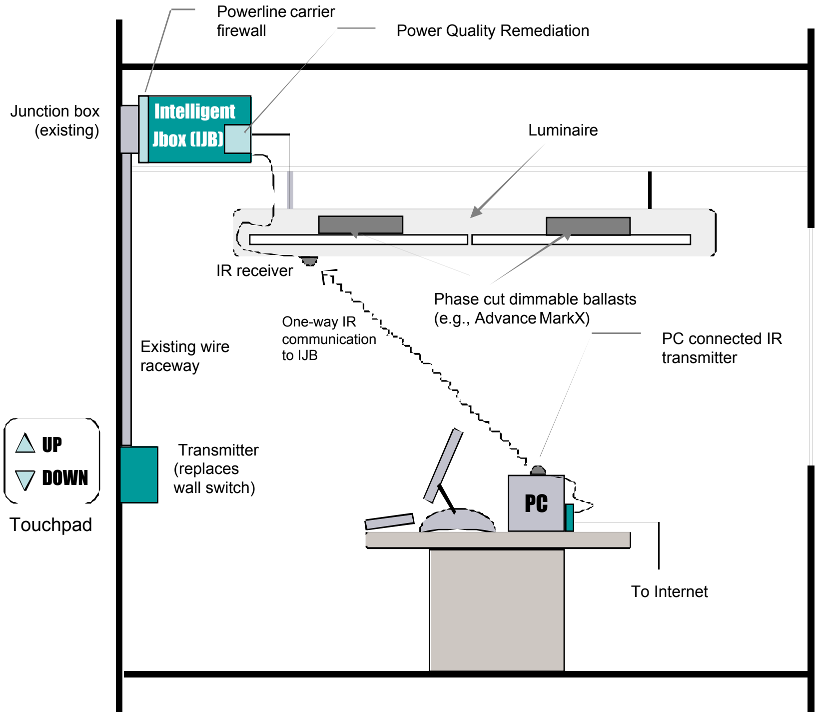


Figure 1. Conceptual diagram of the proposed new lighting control system. As originally conceived, an intelligent junction box would be used to dim downstream "in-line" ballasts.

This project has seven key technical objectives:

1. Intelligent junction box: Prototype and lab test an IJB that can operate commercially available 0-10 VDC dimming fluorescent ballasts over the entire useful dimming range.
2. Verify harmonic remediation: Verify in the laboratory that most of the electrical harmonic distortion caused by the IJB and dimming ballast system can be mitigated over the dimming range and that any residual harmonics are contained within the controlled lighting circuit.
3. Wall dimmer controls: Develop and demonstrate two alternative means for controlling the output of the IJB from a wallbox. A power line carrier transmitter will form one alternative. A lower cost, non-PLC option will also be demonstrated.
4. Multi-sensor: Adapt the multi-purpose environmental sensor from the ongoing PIER High Performance Commercial Buildings R&D Program to interface the "multi-sensor" with a personal computer via the serial communications or USB port. The addition of the multi-sensor will allow user-friendly implementation of daylighting and occupancy sensing.
5. Bluetooth communications link: Demonstrate a Bluetooth communications link between the personal computer and IJB. A Bluetooth link between PC and IJB will allow the intelligence resident in the PC to operate and re-program the IJB thus providing a "future-proof" solution.
6. Control software: Enhance control software developed by LBNL to allow data collection from the multi-sensor and Bluetooth communication between PC and IJB.
7. Manufacturer participation: Obtain the participation of ballast and controls manufacturers in the development program.

Status of Work Completed to Date

Task 1. Develop, Test, and Demonstrate IJB

The objective of this task is to adapt and modify an existing dimmer to control commercially available "inline controlled" style fluorescent ballasts (e.g., Advance Mark X) while maintaining power quality over entire dimming range.

Summary

Measurements were performed on commercially available dimmable ballasts (both "in-line" and "0-10 VDC" types) to qualitatively ascertain the amount of current harmonics generated by these ballasts under different dimming conditions. A commercially available harmonic reduction device was tested to determine whether the third harmonic from the "in-line" ballast type could be significantly reduced using this method. The results were described in the Electrical Test report.

A detailed diagram of the overall lighting control system to be developed for the project was created that delineated each of the component parts in the overall system and their relationships to one another. A communications technology called Phase Cut Carrier that had been demonstrated earlier by Vistron was identified as being most appropriate for meeting the technical project objectives. An Invention Disclosure on the technology was prepared and submitted to the LBNL Patents Office for consideration for application for patent. The Patent Office determined that the technology was of sufficient merit to justify the preparation and submission of a Provisional Patent on the technology.

The main components of the proposed system, which consists of the intelligent junction box (IJB) and as many ballast-connected decoders as are needed for each ballast to be controlled from the IJB, were designed and prototypes fabricated for testing and evaluation. LBNL arranged with PG&E engineers to test the reliability and performance of the IJB and decoders at PG&E's Thermal Testing Facility in San Ramon.

Details

When LBNL proposed the "Retrofit Fluorescent Dimming with Integrated Lighting Controls" project, researchers had assumed that dimming commands could be sent to commercially-available "in-line" ballasts over the existing branch power lines without producing an objectionable level of line current harmonics. It was anticipated that this objective could be met using commercial "in-line" dimming ballasts – a type of dimmable ballast that are controlled over the existing power lines using incandescent-type dimmers (that utilize silicon-controlled rectifiers (SCR) or TRIAC switching devices). Ballast manufacturers' product literature for "in-line" ballasts elides the Total Harmonic Distortion (THD) issues and presents little harmonic performance data on in-line ballasts under dimmed conditions. LBNL originally anticipated that even if the current harmonics from dimming the "in-line" ballasts was higher than desirable, the poor THD performance could be mitigated under dimmed conditions by employing harmonic filtering at each branch circuit to form a "firewall" for harmonic pollution.

Given these questions about the possible increase in harmonics from "in-line" ballasts, LBNL elected to explore the potential harmonic problem from "in-line" ballasts at the outset of the project, and performed cursory testing on a small sample of commercially-available ballasts representing the major ballast types. Vistron ran initial baseline power quality measurements on two types of "in-line" ballasts and one type of 0-10 VDC controllable ballast at several different dimming levels. Researchers also investigated commercially available means to mitigate harmonics from "in-line" electronic dimming ballasts. A photo of one such ballast product is shown below in Figure 2.

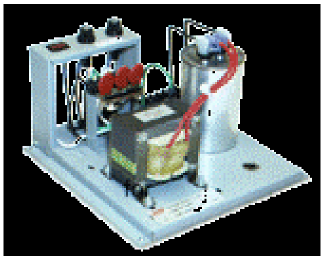


Figure 2. A passive harmonic filter from the MTE Corporation. It is designed to significantly reduce the total harmonics, especially the third harmonic, in dimmed power circuits. The unit shown is rated at 5 amperes.

Measurements indicated that the harmonics of "in-line" (also sometimes designated as "2-wire") style ballasts increased under dimmed operation as compared to the 0-10 VDC dimming ballast tested. However, researchers only measured a few ballasts and the scope of work did not allow for a more thorough testing program. The key question the researchers sought to answer was whether the increased harmonics from a heavily dimmed "in-line" ballast would be higher than the harmonics from a standard (undimmed) ballast. The reasoning was that the absolute value of the current harmonics from a dimmed ballast should not exceed that of a ballast that would be replaced. This is essentially the equivalent of the Hippocratic Oath "Do no harm."

Cursory measurements indicated that, even with affordable filtering, the two samples of "in-line" ballasts have significantly higher total current harmonic than a 0-10 VDC controllable ballast at all dimming levels. However, the small sample size did not allow LBNL to quantify these differences to an adequate degree.

In order to get a better handle on the current harmonic issues for different types of ballasts, the researchers examined publicly available technical performance data from Advance Transformer - a leading manufacturer of electronic and magnetic ballasts. According to Dr. Oliver Morse [ref Advance Atlas], it is the Total Harmonic Current (THC), not Total Harmonic Distortion (THD), that is the key attribute when analyzing the effects of harmonic distortion on building electrical systems. Using the total harmonic current data given on page 2-14 of the Advance Atlas, the total harmonic content for four types of commercially-available ballasts can be plotted (see Figure 3. below). Because of the many differences between various manufacturers products, LBNL thought it best to limit this comparison to ballasts from one major manufacturer[1]. These comparisons, using manufacturers' data for four different ballasts, show that the 0-10 VDC ballasts (Mark VII) have superior performance with regard to total harmonic current (THC) as compared to the "in-line" ballasts (Mark X), the standard electronic ballast, and the magnetic ballasts.

In Project 3.1, it is assumed that an existing ballast will be replaced in the ceiling with an improved ballast (and other components). In California, with its rich tradition of energy efficiency, it is likely that a standard electronic ballast exists in place or possibly an energy efficient magnetic ballast, if the building is old enough. According to Advance's data, the standard electronic and magnetic ballasts have THCs of 0.1 and 0.12 A, respectively. The Mark X ballast with matched dimmer has a THC of 0.09A at full light output, which is a 10 percent improvement over the standard electronic ballast.

[1] Other ballast manufacturers make products with similar performance. Inclusion of data from one company does not imply endorsement of the company or its products.

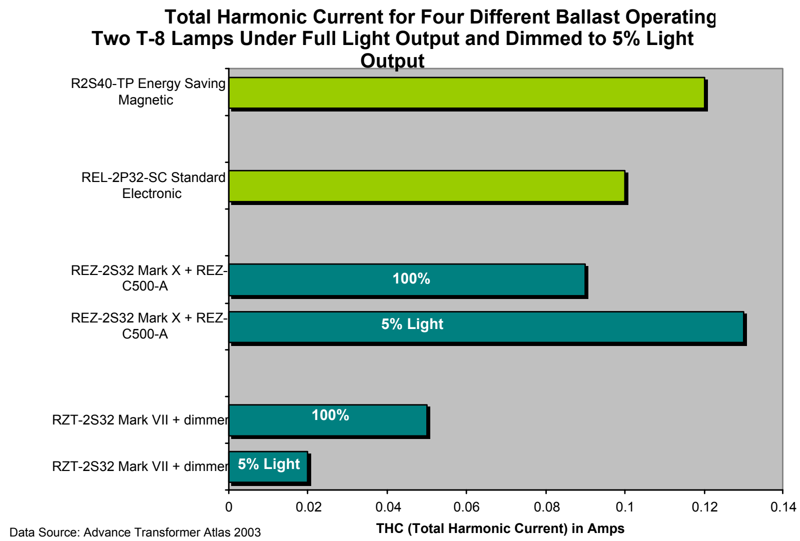


Figure 3. Total harmonic current for four different ballasts operating two T-8 lamps under full light output and dimmed to 5 percent light output. Data from Advance Transformer Atlas 2002-2003

But at five percent light output, the THC increases to 0.13A. Although this is not remarkably high, it is significantly higher than the standard electronic ballast (the most likely base case ballast) and somewhat higher than the energy efficient magnetic ballast that might be in the ceiling. Furthermore, Advance's data is for a matched dimmer and ballast, both manufactured by Advance. A different in-line ballast that is technically inferior to Advance's Mark X coupled with an unmatched dimmer could result in even higher levels.

By contrast, the Mark VII ballast at full light output has 44 percent less THC than an equivalent Mark X at full light output. At 5 percent light output, the differences between the THC from the Mark VII and Mark X is more extreme. At this level, the Mark X produces 0.13 A THC while the THC from the Mark VII is only 0.02 A -- more than six times lower.

For this project, dimming ballasts will be used to capture significant energy savings. Based on these results, LBNL determined that the in-line ballast is not recommended as a solution, given the potential to increase total harmonic content when compared to the system it would replace.

Finalizing the Component Arrangement for the Proposed System

Based on the results of the above-described measurements, LBNL detailed all the different components that the proposed system would require to meet the proposed project objectives. The proposed system is shown in diagrammatic form in Figure 4.

Development and Application of Phase Cut Carrier

An inexpensive and robust technique called the "Phase Cut Carrier" (PCC) has been perfected, which will allow 0-10 VDC ballasts to be controlled over existing power lines in essentially the same manner as the "in-line" ballasts. The PCC technology permits researchers to realize the best characteristics of both ballast types. LBNL successfully completed engineering feasibility models demonstrating this PCC communications technique in December 2002. Pete Pettler of Vistron demonstrated an early prototype of the intelligent junction box (IJB) and two different types of decoders (one for a 0-10 VDC controllable ballast and the other for a multi-level switching system). The devices worked well (after some minor electrical adjustments) and researchers documented the demonstration with digital photography (Figure 5. and Figure 6.) and video.

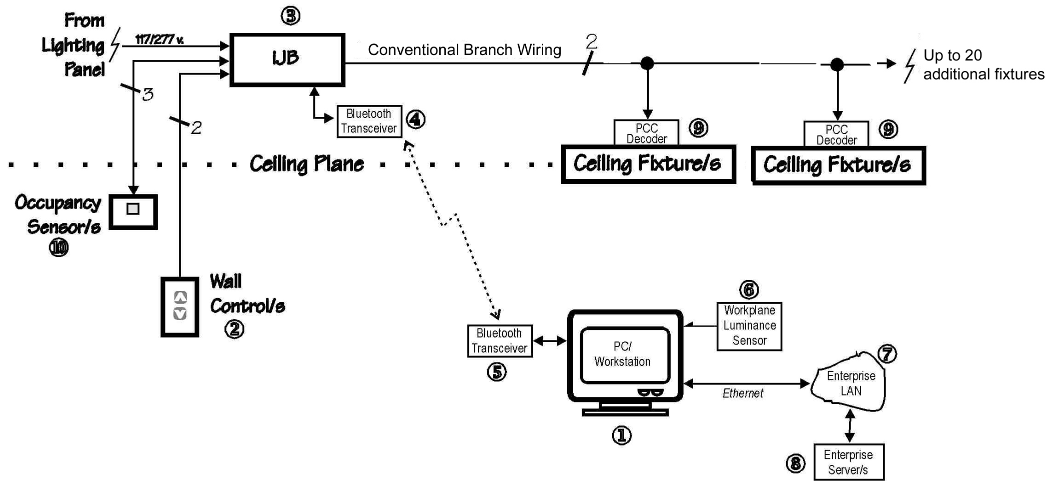


Figure 4. Proposed Retrofit Fluorescent Dimming System

PCC permits the transmission of digitally coded signals on the branch circuit power lines in a way that is ideally matched to the inherent operating characteristics of electronic ballasts. Since PCC eliminates the one drawback to the 0-10 VDC ballast relative to the in-line ballasts (i.e. the need for extra control wiring) and since there is little or no difference in cost of the two ballast types, no generality is lost with this solution.

After making this adjustment, LBNL built multiple PCC units for testing of the system at PG&E Thermal Testing Facility and filed a provisional patent application to cover this new technology. The feasibility model versions of the eight decoders and single encoders shipped to PG&E are shown in Figure 7. , Figure 8. , and Figure 9.

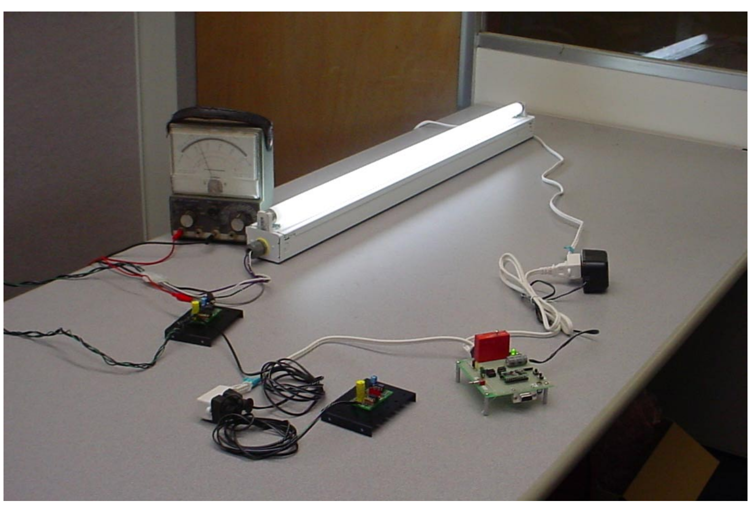


Figure 5. Demonstration of an encoder (part with large red block) and two decoders as setup at LBNL on December 16, 2002. The encoder is shown with the dimming decoder module controlling the light fixture to its lowest light level. The voltmeter shown, which was connected to the output of the decoder module, was reading about 2 VDC (minimum intensity).

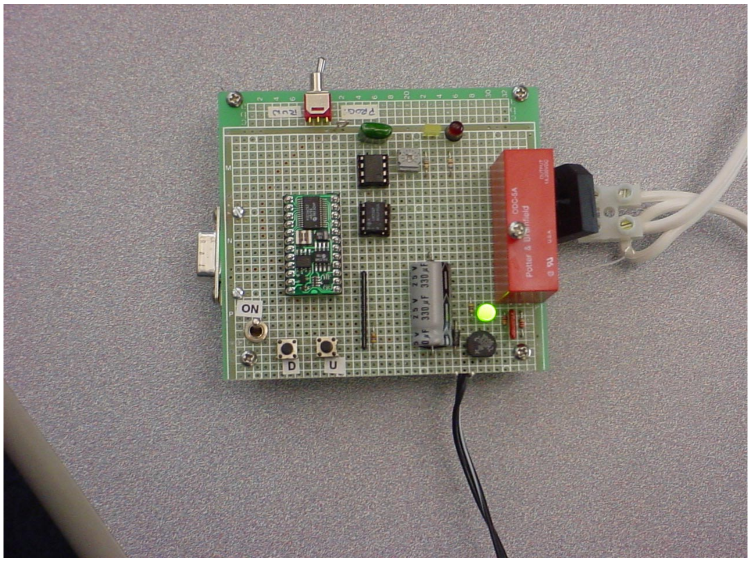


Figure 6. Engineering prototype of the encoder with callouts showing key components. The light level is varied by pressing the pushbuttons shown. In the production version, the encoder would be the main component of the intelligent junction box while the pushbuttons would be removed to the wall switch.

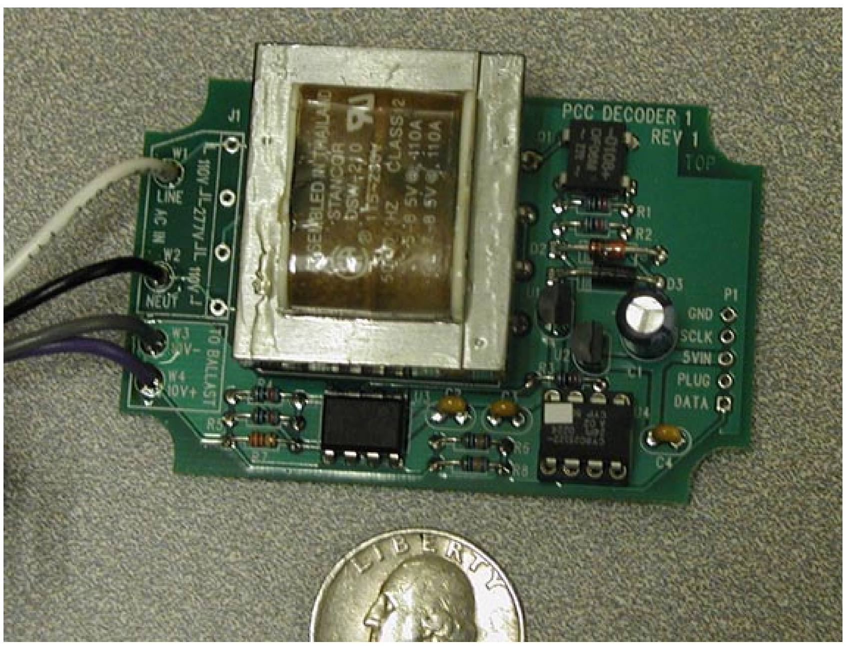


Figure 7. Photo of the Phase Cut Carrier Decoder 1 (Field trial version). The two upper wires on the left go to the hot lead and neutral. The lower two wires go to the 0-10 VDC control input on a controllable ballast.

Figure 8. Field trial version of Phase Cut Carrier Encoder mounted on the cover of a dual gang junction box.

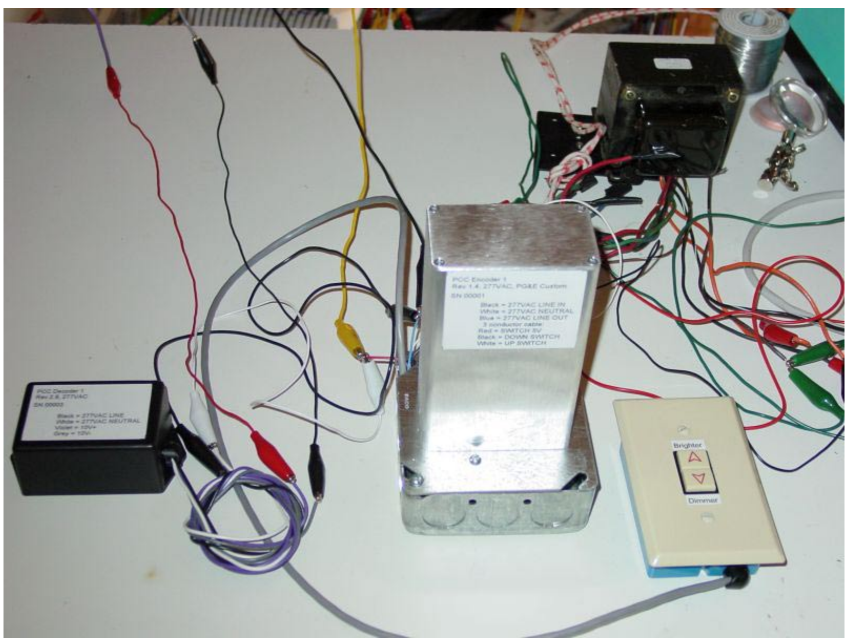


Figure 9. Photo of the Phase Cut Carrier Decoder, Encoder and wallbox control unit (shown from left to right) before shipping to PG&E's Thermal Testing Facility for reliability testing.

As part of the development work on the PCC units, LBNL modified the PCC encoder software and hardware design to interface with an external commercial occupancy sensor. The PCC encoder hardware design and software code was also modified to operate with single or multiple station pushbutton wall controls interfaced to the IJB via a two-wire connection. A scheme was devised that permits adding a three LED visual annunciator to each wall switch for indication of the state of tri-level dimming. The scheme does not require additional wiring to the wall controls. A MOSFET-based modulator was also designed and tested for the PCC encoder. Discussion of the firmware to operate the encoder and related software development issues is reported in Task 6.

The design of the hardware has been completed for a new feature for the PCC Encoder 1 that will support real-time measurements of the current being consumed by the lighting branch that it controls. Researchers intend to report the branch current to a nominal accuracy of approximately ± 10 percent, with consumption averaged over five-minute intervals. The encoder firmware routines to implement this function are not yet completed.

Task 2. Adapt Multi-Sensor from PIER High Performance Commercial Buildings Program

Objective is to adapt a multi-purpose environmental sensor developed as part of the ongoing PIER/LBNL High Performance Commercial Buildings Program (HPCBS) so the available light, occupancy state and temperature in the controlled space can be measured from a small wired sensor.

Summary

LBNL performed optical and electrical measurements on the multi-sensor developed during the HPCBS Program and determined that numerous modifications would be necessary to adapt the sensor for this project. To allow better accuracy in measuring workplane illuminance and occupancy, the original multi-sensor was split into two parts: one for light and temperature, and the other for occupancy detection. The silicon photodiode used for measuring illuminance was upgraded for better accuracy with respect to spectral response. Then, both portions of the sensor were modified so no external power was required with both sensor elements taking power directly from the two network wires (a technique called "using parasitic power"). This simplified the cabling between the sensor elements and the PC-connected port adaptor, since only two wires are required in the cable rather than four. This also reduces the requirements for the port adaptor, since unlike earlier systems, the port adaptor needs only handle the one-wire network connection and does not have to supply power over additional wires.

Detail

The measured performance of the environmental sensor for the HPCBS program indicates that the multi-sensor, as it currently stands, cannot be used for this project without extensive modification. The multi-sensor (Figure 10.) was intended to be a "proof-of-concept" rather than a finished product and the photocell and occupancy built into the multisensor are not commercial grade.

There were two key factors that had to be considered in making this determination:

1. Could an "all-in-one" multi-sensor collect reasonably accurate data on workplane illuminance and workstation occupancy?
2. Could the sensor be modified to operate parasitically off the network wiring?

The Problem with an "All-in-one" Environmental Sensor

The "all-in-one" sensor prototyped for the HPCBS program used the same lensing element for light as well as for detecting the occupant's "heat signature". Unfortunately, measuring horizontal illuminance requires that the sensor be oriented horizontally at a practical location in the workstation. If oriented correctly for illuminance measurement, the sensor was detecting occupancy in the upper hemisphere. In this orientation, the PIR detector will not properly detect the presence and absence of the room's occupant. If, on the other hand, the sensor was oriented vertically, facing the occupant as is appropriate for best detecting occupancy, it would measure vertical illuminance away from the eye.[2]

Figure 10. Image of multi-sensor prototype developed during the HPCBS research work. Note the white plastic hemisphere serves primarily as a lens for the infrared radiation that detects the occupant's heat signature. The plastic dome also plays the role of diffusing the light that falls on an internally mounted silicon photodiode.

These observations led to the development of a two-part environmental sensor: one part optimized to measure horizontal workplace illuminance, and the second part optimized to detect the workstation's occupancy. This two-part solution is similar in concept to an advanced control product (Isole) from The Watt Stopper.

Parasitically powered sensors

In previous work under the HPCBS Program, researchers questioned the practicality of requiring separate low-voltage power to operate sensors and actuators. It would seem that requiring four wires in a low voltage cable should not be much more expensive or difficult to install than a two wire cable system. After all, the linear cost of two-conductor cable is not significantly less than that of four-conductors. However, after many conversations with industry experts, LBNL determined that the lighting industry's experience has generally been that every cable connection is an opportunity to introduce a wiring error[3]. Wiring errors committed by cable installers are the hobgoblin for wired building control systems.

Because of these considerations, LBNL elected to redesign both elements of the new multi-sensor to operate without the external power that had been available with the former four-wire network infrastructure. This necessitated the use of a parasitic powering scheme that stores snippets of usable energy from the network during the null intervals between the message packets that are being transmitted. To accommodate this scheme, a new 50-microampere maximum current (~235 microwatts) guideline was established for the general-purpose designs of IBECS sensor and actuator nodes. This will require challenging micropower techniques be incorporated in such future designs.

Engineering prototypes for the occupancy detector and the combined illuminance and temperature sensor were fabricated for the project. The illuminance and temperature sensor

[2] It can be argued that vertical illuminance at the eye is more useful than horizontal illuminance as an indicator of occupant performance and comfort. However, in this case, the vertical illuminance measurement would be in the wrong orientation – vertical illuminance *away* from the eye. This latter measurement has no predictive power and is not useful.

portion uses a blue-enhanced photodiode with integrated amplifier (Panasonic PNA4603H) to measure illuminance and an embedded battery monitor chip (Dallas/Maxim DS2438). The occupancy portion of the sensor uses a modified PIR detector and embeds a single addressable switch (DS2405). In order to be able to read these devices, the software must be able to communicate with both Dallas/MAXIM devices. This has ramifications for the software selection (see next two tasks).

Considerable work was performed in selecting the particular photodiode to use in the illuminance sensor. Of particular concern was the need to use a photodiode with a spectral response curve reasonably close to that of the human eye. The spectral response of several different photodiodes was evaluated and the relative error calculated from each under a range of lighting conditions. The results of this analysis will be presented as a separate research note and should be of interest to lighting control device manufacturers.

Task 3. Interface Multi-Sensor to PC

The goal of this task is to produce and test the serial port interface between the multi-sensor and personal computer.

Summary

Using a standard PC and a port adaptor, LBNL verified the two-part environmental sensor prototype developed in Task 2 could be read using software running on the PC.

Detail

This task required researchers to verify whether the values from the two-part environmental sensor developed in Task 2 could be successfully read from a personal computer. As a first step, a port adaptor was installed on a personal computer running Windows XP Professional and software was installed that would allow the two-part sensor connected to the port adaptor to be read.

There are several methods available for reading the environmental sensor from the PC equipped with a port adaptor:

- TMEX software from Dallas Semiconductor/MAXIM. TMEX is available free and is capable of querying and operating devices that embed DS microchips. The software is supported and frequently updated by Maxim. TMEX can serve as a “template” for producing application specific control software. However, at this time no control algorithms have been written for this platform
- “Home-grown” Java scripts. In previous work in the HPCBS program, several simple “control panels” written in Java were produced that allow the end-user to read the values from the environmental sensors.
- Data acquisition software. Several firms make software that can serve as a “front-end” to a generalized data acquisition and control system. Two examples of this software are GeniDAQ by Advantech and LabView from National Instruments.

Although being able to read the connected environmental sensor with minimal software is a necessary objective for the Project, unnecessary resources were not spent on this piece of the problem since much of the task of creating truly useful software is developing the user interface for the control software. In the lighting control applications area, there are several key users of the software, each with different requirements and each requiring a different user interface. A less ambitious route has been taken of identifying the advantages and disadvantages of the above three approaches and reporting on these findings.

Task 4. Demonstrate Wireless Link between PC and IJB

The goal of this task is to demonstrate an infrared (IR) communications link between the PC and IJB.

Summary

After exploring the use of IR as a means to communicate between the PC and the intelligent junction box, LBNL elected to use Bluetooth as a communications technique. This was indicated because of the increasing use of Bluetooth on modern personal computers as well as the elimination of distance and interference limitations.

Detail

Task 4 of the original scope of work anticipated the use of an IR data link between the PC and the IJB. The IJB is typically located in the ceiling plenum in commercial buildings. Consequently, it would be necessary to pierce the ceiling plane for the mounting of an optical transceiver in order to have an unobstructed optical path for this data link. Also, the most widely accepted standard for bi-directional IR data communications is IrDA, which is now widely integrated in most Personal Digital Assistants (PDAs). Unfortunately, as it is commonly implemented this scheme only has an effective distance range of several meters. This range limitation was felt to be marginally acceptable for this application.

To overcome these problems, alternate types of data links were examined. The recent emergence of Bluetooth as a more widely available peripheral communications infrastructure indicated that it would be a desirable replacement for IR. Its indoor range is at least an order of magnitude longer, and, because it uses a radio frequency link, it will easily penetrate the materials commonly used for suspended ceilings. Also, many new PCs now offer with Bluetooth options. Pricing for these options is rapidly declining in step with the wider usage of this technology.

Based on the reasoning summarized above, LBNL concluded that the design would proceed on the basis of employing a Bluetooth data link. A vendor of suitable Bluetooth modules has been selected and demonstration units have been procured. Preliminary testing of a sample module contained within a metallic mock-up of the IJB enclosure with an external 4’’ whip antenna showed error-free performance over distances well in excess of 100 feet.

Commercial "Bluewave" modules will be utilized by the system to conduct two-way Bluetooth data communications between the PCC Type 1 Encoder and the host PC. The modules appear to operate without problems over indoor distances well in excess of 100 feet in the presence of drill motors and similar noise sources.

The hardware and software for the PCC Encoder interface to the bi-directional Blue Tooth data link was implemented and debugged. The communications protocol for the data link between the PCC Encoder 1 to the PC host was developed and mostly debugged.

A scheme was implemented to permit the manual initiation of a simulated load shedding command from the keyboard of the PC host. Upon recognition of this command, the system initiates a rudimentary load shedding routine.

Task 5. Demonstrate Multi-Channel Wireless Dimming Control

The goal of this task is to demonstrate ability to wirelessly control more than one type of light using a multi-address IR link (now Bluetooth).

Summary

The work originally proposed for this task is not necessary to the completion of a system meeting the project's technical objectives. The Phase Cut Carrier technology can be modified to allow addressing of different downstream loads (i.e., other lights on the same circuit). However, it adds considerably to the cost and complexity of the decoders and since there are potentially several decoders for each encoder, the added cost of addressability would be high with relatively little added benefit. Consequently, it is suggested not to further pursue addressability for the moment.

Task 6. Develop Control Software

The goals of this task are to develop control software resident on the PC that will read data from the multi-sensor and commit this data to hard disk, produce software capable of driving an IR transmitter and communicating with the IR receiver connected to the IJB, and produce user-friendly software capable of dimming the overhead lighting both from a local PC and from the Web. Software will be written in C++ and Python.

Summary

Researchers used a programmable System-on-a-Chip (PsoC) to embed the intelligent control into the encoder. Flowcharting of the firmware control routines has begun for the encoder.

Detail

Firmware

The PsoC that researchers used has associated firmware that defines the PsoC responses to all combinations of control conditions. This firmware has been written in the industry-standard C programming language. Researchers have created firmware program modules which configure the various PsoC peripheral hardware functions, synchronize the processor time base to the AC line waveform, and encode the phase cuts precisely at the AC waveform's zero crossing for minimum harmonic distortion. Routines have also been included to monitor the status of the occupancy sensor and to then issue a "courtesy wink" prior to extinguishing the lights after a period of sustained no occupancy. The wall control pushbuttons are monitored with routines that permit button depressions to vary the dim level with an auto-repeat function and provisions to override the occupancy sensor if it is reporting an unoccupied status while the user is depressing the push buttons. Additional firmware routines were written to implement full-duplex Bluetooth communications between the IJB and a "Blue Wire" adaptor, which plugs into a serial port of the PC. The Bluetooth link carries commands from the PC to the IJB and returns status information, including dim level, instantaneous/averaged current consumption on the controlled lighting branch, etc. The IJB control code includes a provision to limit the maximum dim level that is permitted under load shedding conditions.

Flowcharting of the firmware control routines has begun for the encoder that is at the heart of the IJB. The PCC code protocol was expanded to improve noise immunity and to enhance the speed/integrity of decoder synchronization during system initialization. Firmware revisions for Encoder 2 were written. The firmware routines have been expanded for the IJB to modulate the lighting branch voltage waveforms to convey either Phase Cut Carrier or Phase Cut dimming commands. This feature has the prospect of substantially broadening the utility of the IJB control architecture. Provisions have been added in the firmware to permit the selection between the two types of in-line dimming control (0-10 VDC or in-line) as a commissioning option. The same basic encoder can be used to communicate with either ballast. Obviously, the details of the communications scheme would not be the same. Nonetheless, there are significant advantages to having these different ballast types controlled by a similar architecture. Although, for this project the 0-10 VDC control will be the only one pursued to completion.

A preliminary (crude) RF noise survey using a handheld AM radio indicates that Radio Frequency Interference (RFI) that caused interference on an earlier pulse-width modulation control scheme tested by PG&E will not be present with the new PCC system.

The firmware for both the PCC Type 1 Decoder and Type 1 Encoder was revised to incorporate an expanded, unambiguous synchronization code format. System testing was performed to validate the stability of the revised decoding firmware to operate under noise and line voltage extremes. A design change was devised to add an electro-mechanical relay to the PCC Encoder. This revision will minimize power dissipation and heating in the encoder package during the long intervals when PCC codes are not being transmitted.

LBNL added a new protocol command to the PCC encoder repertoire for a “slow fade” mode in order to have an inconspicuous transition between dimming levels. The associated changes to the PCC Decoder 1 firmware have, however, not yet been implemented.

Preliminary documentation of the firmware and related software for operation of the Phase Cut Carrier Encoder are given in Appendix C.

Recommendations for Completing Work

Overall

Overall, the work progress for the project is on schedule. Early enhancements to the original scope of work (especially focusing the research on the operation of 0-10 VDC ballasts rather than “in-line” ballasts) led to unavoidable delays in completing the most ambitious first task. As indicated below, the research in the remaining tasks is on track. LBNL has requested and received approval for a no-cost extension on the overall project until May 2004 in order to adequately complete the deliverables.

Researchers have determined that the Phase Cut Carrier technique appears to fully meet the objectives set for power line transmission of dimming commands without causing unacceptable power quality deprecation. More comprehensive testing and some refinement of the prototype encoder and decoder designs will be performed in the months ahead using the invaluable engineering services from Pacific Gas & Electric. When completed, researchers are confident that a reasonably polished system will exist that is suitable for demonstrating the basic functionality and characteristics of Phase Cut Carrier dimming control.

The project work yet to be completed is listed below by task:

Task 1:

To complete this task, which is the most challenging of the tasks, LBNL needs to complete the measurements of the reliability and performance of the prototype encoders and decoders operating a typical lighting system. LBNL has made arrangements for PG&E engineers at the San Ramon Thermal Testing Facility to test the encoders and decoders. PG&E has received the equipment and has set up a measurement facility to measure the prototype system performance. This represents a significant engineering effort on the part of PG&E. As of this writing, PG&E had completed the first set of pilot measurements on the system and the results are very encouraging.

Vistron is tasked with assembling of two additional IJB encoders (one for delivery to LBNL and one to be retained by Vistron) incorporating the latest design enhancements. The encoder and decoders delivered to LBNL will form the desktop demonstration that is one of the deliverables for this task.

Finally, Vistron will complete the detailed documentation of the circuitry and the annotation of the firmware code for both the decoder and encoder. Appendix C presents an early version of the documentation.

Task 2:

This task will be complete once the performance of the submitted prototypes has been verified by testing at LBNL. The results of the analysis conducted to identify the best commercially available photodiode that will serve as the heart of the illuminance portion of the environmental sensor will be presented in the Final Report for the project. This analysis used the manufacturer-supplied data on the photodiodes spectral response to calculate the error incurred using the tested photodiode measuring different standardized spectral distributions. This information will be of interest to photocell manufacturers who want to build photocells with improved spectral performance.

Task 3:

To complete this task, researchers need to finish the comparison of the advantages and disadvantages of different types of software for interfacing between the multi-sensor and the personal computer. This software comparative matrix will be a component of the Final Report.

Task 4:

This task involves devising an elementary demonstration of daylighting functionality using measurements performed by the multi-sensor and devising a rudimentary demonstration of a load-shedding routine.

Task 5:

This task is complete and the results will be reported in the Final Report.

Task 6:

Since the objective of this task requires reading the attached environmental sensors from the PC and then commanding the IJB via Bluetooth to activate different light levels as appropriate, it is the most challenging of the remaining technical tasks and involves the development of software.

The key technical objectives of this task were originally planned to:

1. Develop control software resident on the PC that will read data from the multi-sensor and commit this data to hard disk.
2. Produce software capable of driving an IR transmitter and communicating with the IR receiver connected to the IJB.
3. Produce user-friendly software capable of dimming the overhead lighting both from a local PC and from the Internet. Software will be written in C++ and Python.

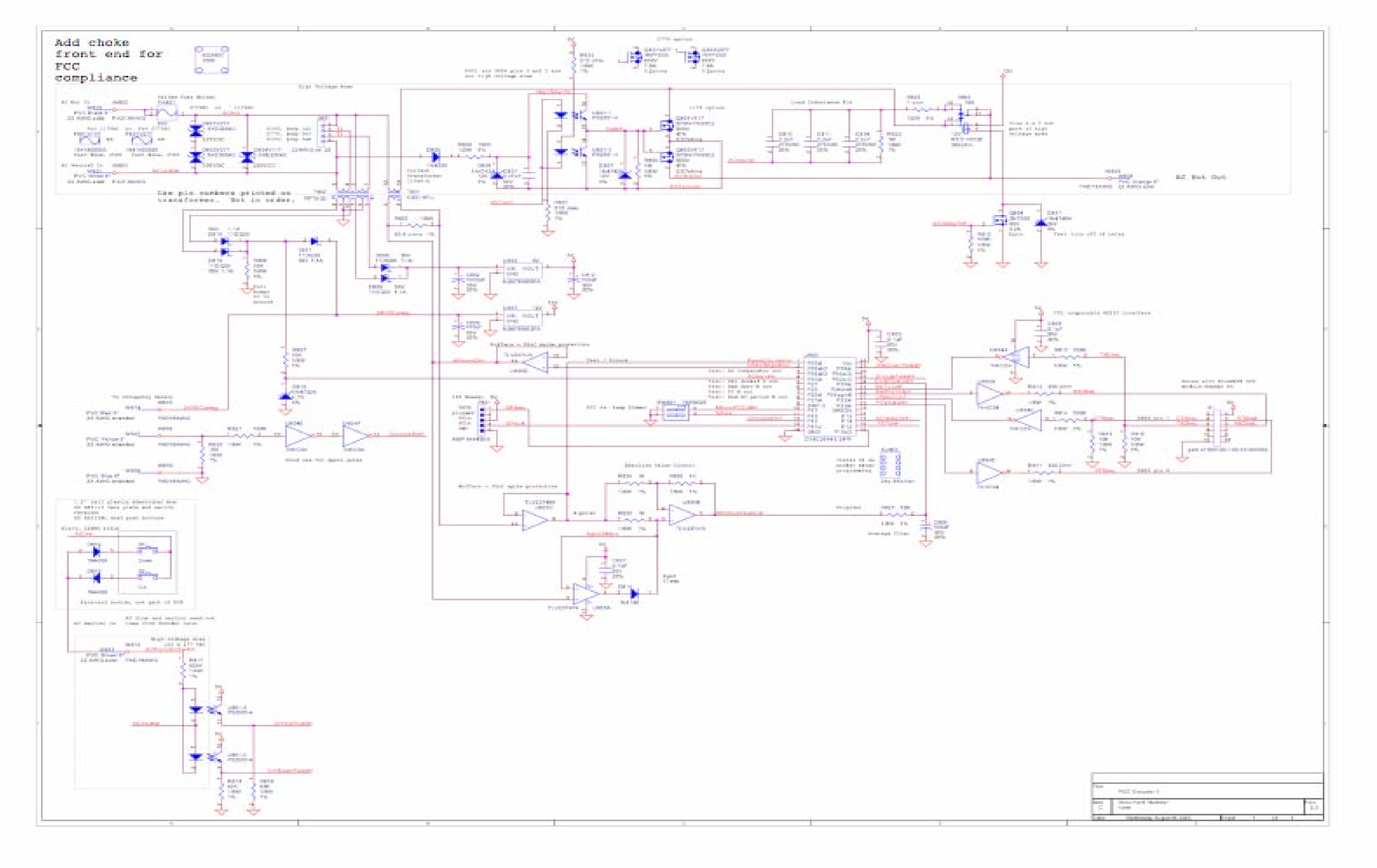
Except for the substitution of Bluetooth for IR, LBNL will meet objectives 1 and 2, which require:

- Completing the testing of the bi-directional Bluetooth communication pathway between the PC and the plenum-located IJB.
- Writing PC software routines with a simplified operator interface to demonstrate wireless control of the IJB from the Bluetooth-enabled PC.

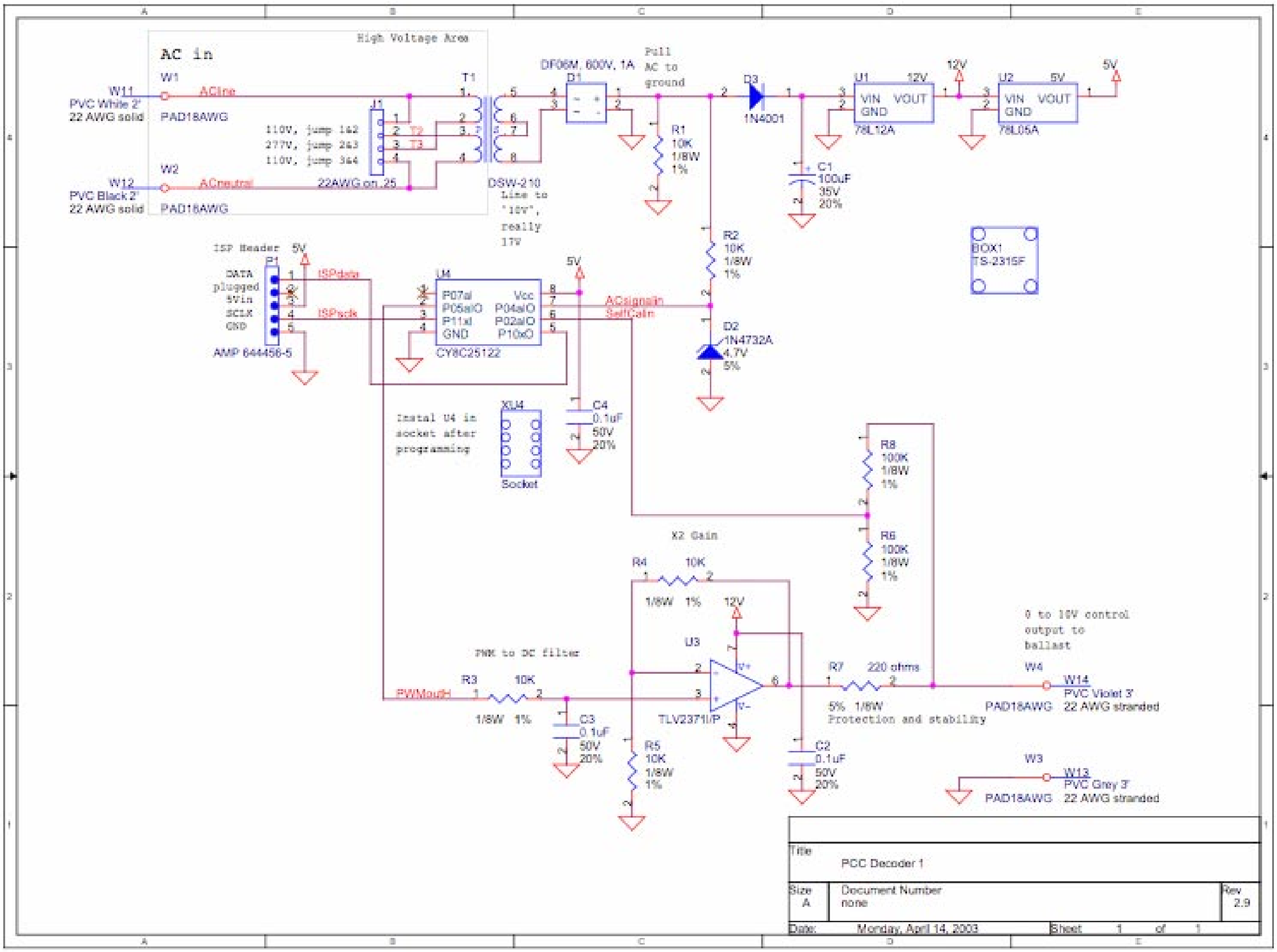
Successful completion of the above will complete the task.

Since the project budget does not allow for significant software development work, minimal software will be developed that is necessary to achieve the project objectives and a user-friendly interface for the developed software will not be created.

Appendix A Circuit Diagram for Phase Cut Carrier Encoder



Appendix B Circuit Diagram for Phase Cut Carrier Decoder



Appendix C Firmware Documentation for Phase Cut Carrier Encoder

System Communications Overview

The office PC and the local PCC Encoder 1 communicates by RS232 that is transmitted via BlueWAVE RS232 to Blue Tooth adapters. The PC sends commands to the PCC Encoder 1, which returns status to the PC. The status returned will allow verifying that the PC's commands have been received. The PCC Encoder 1 will spontaneously send status about once every 15 minutes when it has new average current values to report. The PC must initiate a connection between the BlueWAVE module it is hooked to and the BlueWAVE module in the PCC Encoder 1 before it will be able to send commands or receive status.

RS232

RS232 settings are 115,200 Bits per Second, 8 Data Bits, No Parity, 1 Stop Bit, and Hardware Flow Control.

ASCII

The data is ASCII. The left most character in commands or status is sent first. Null, 00 hex, must never be sent as it is interpreted as no character received by the PCC Encoder 1's firmware. The characters are case sensitive.

Blue Wire

The PC must initialize the BlueWAVE DTE unit that is connected to the PC's RS232 port to establish a wireless connection to the BlueWAVE DCE unit in the PCC Encoder 1. No other Blue Tooth master devices may connect to the PCC Encoder 1's DCE while the PC's DTE unit is connected. The PIN # of the BlueWAVE DCE module is 1111. The address of the local PCC Encoder 1 must be discovered after installation while no other unknown Blue Wire devices are within RF range of the PC's DTE unit.

DATA Mode: On power up the BlueWAVE RS232 Wireless Cable units will be in DATA mode. In this mode, all data passed from one BlueWAVE module will be sent through the other BlueWAVE module to the RS232 port and vice versa once it has been connected. The power up condition is that the BlueWAVE module is not connected to any other BlueWAVE modules. Once connected, the BlueWAVE units act as a cable, but only if the specified RS232 settings are used.

COMMAND Mode: COMMAND mode is used to configure and control the PC's BlueWAVE module. COMMAND mode can be entered by sending three consecutive ASCII '+' characters which are more than 100ms apart over the RS232 interface. In command mode, no data is received from the remote Bluetooth device. Data entered on the local RS232 interface is passed to the local BlueWAVE unit. This implementation is consistent with most modem interfaces. The Configuration commands are listed below. The configuration, other than establishing the connection, is stored in the BlueWAVE DTE's non-volatile memory and will only require setup once. The factory default configuration of the BlueWAVE DTE units are 115200 baud, no parity, 1 stop bit and 8 data bits.

Configuration Commands: The following commands can be used to connect with or configure the BlueWAVE DTE device. Simply send the command as shown, then a carriage return, and an 'OK' or 'ERROR' string will be returned to indicate success.

Commands required to connect to the PCC Encoder 1 after each power up of the PCC Encoder 1 or the PC.	
Command	Function
+++	Place local BlueWAVE DTE in command mode. No status or echo returned. Separate +s by 0.1 second or more.
AT+BWI	Discover available Blue Tooth devices to connect to. Status returns the ID of available devices, followed by "OK" on the next line. The local PCC Encoder 1's expected address will be discovered if it is operating correctly. Other PCC Encoder 1's within RF range will also be discovered, but should not be connected to.
AT+BWC=*address,PIN#*	Connect to the PCC Encoder 1's DCE. The *address* is the value returned by the AT+BWI status for the desired PCC Encoder 1's DCE, followed by a "," and then the PCC Encoder 1's DCE *PIN#* which is a default of 1111. There will be a status of "CONNECT" returned after a significant delay, when the PCC Encoder 1's DCE has connected.
AT+BWE	Exit COMMAND mode – return to DATA mode. Required to send data to the PCC Encoder 1 after connecting. Status of "OK" will be returned.
Configuration Commands, not required for connection.	
ATE0	Turn local echo Off
ATE1	Turn local echo On
AT+BWB=0	Set baud rate to 1200 baud
AT+BWB=1	Set baud rate to 2400 baud
AT+BWB=2	Set baud rate to 4800 baud
AT+BWB=3	Set baud rate to 9600 baud
AT+BWB=4	Set baud rate to 19200 baud
AT+BWB=5	Set baud rate to 38400 baud
AT+BWB=6	Set baud rate to 57600 baud
AT+BWB=7	Set baud rate to 115200 baud
AT+BWB=8	Set baud rate to 230400 baud
AT+BWP=N	Set Parity to None
AT+BWP=O	Set Parity to Odd
AT+BWP=E	Set Parity to Even
AT+BWS=1	Set Stop Bits to 1
AT+BWS=2	Set Stop Bits to 2
Information Commands, not required for connection.	
Command	Function
ATI3	Display the BlueWAVE Model
ATI6	Display the firmware version
ATI8	Display the date of software build
ATI9	Display the country of manufacture
Control Commands, not required for connection.	
AT+BWN=nnnn	Set Bluetooth™ PIN to nnnn. Pin should consist of between 4

	and 8 characters
AT+BWZ	Allow the unit to go into sleep mode.
AT+BWM=xxxx	Set the Bluetooth™ unit name. The name is the identity by which the device is seen by other Bluetooth™ systems. This does not effect the Bluetooth™ address.

PCC Encoder 1 command set

Dim levels: fx, sx, and mx commands and the dx and cx status refer to dim levels. The dim level relates to light output as follows for PCC Decoder 1s (4 wire, 0 to 10V) and Phase Cut (2 wire) ballasts:

dim f, 0% of rating, ballast receives no AC power, is off.
dim 0, 25% of rating, least illumination
dim 1, 36% of rating
dim 2, 46% of rating
dim 3, 57% of rating
dim 4, 68% of rating
dim 5, 79% of rating
dim 6, 89% of rating
dim 7, 100% of rating, full illumination

PCC Decoder 2s (step dim) will use dim 0 as their least bright setting that is on, plus as many higher dim settings as are available from the ballasts. The upper limit may be set by the PC with the mx command in the general case, or can be hard coded in the PCC Encoder 1 in custom systems.

Commands from PC	**Characters**
fast dim	f0 … f7, ff
slow dim	s0 .. s7, sf
maximum dim	m0 … m7
encoder status bad	eb

The PC must not over run the PCC Encoder 1's RS232 receiver. Hardware flow control is used to tell the PC to stop sending characters after each character received by the PCC Encoder 1. The flow control will enable to the PC to send more characters when the PCC Encoder 1 has room to receive them and has finished any status report in progress. The PCC Encoder 1 will honor hardware flow control commands sent by the PC. Each PC command is two ASCII bytes with no carriage return or line feed. The PCC Encoder 1 will respond to each received command with a status string.

fx PC command will cause the PCC Encoder 1 to command the PCC Decoders or Ballasts to go to the specified dim level or turn off. The response will not be deliberately delayed beyond the fraction of a second required for noise filtering and the time to send the message by PCC to the PCC Decoders if any. fx will over ride a previous dim level set by the user's wall switch or the PC. If the PCC Encoder 1 detects that the room is unoccupied a fx and will cause the same occupancy sensor over ride as if the user had pressed a wall switch button. Each command re-starts the occupancy over ride timer. The lights will be turned back on for one hour if they had been turned off due to an unoccupied room. Turning off the lights with a ff or by the wall switch will abort any occupancy sensor over ride in process. No action other than issuing a pb status will occur if the PC attempts to command a dim level higher than the maximum allowed as reported by the cx bytes of the status report.

sx PC command will cause the PCC Encoder 1 to command the PCC Decoders to slowly slew to the newly specified dim level. Used to command new dim levels as part of a light regulation or daylight harvesting control system. The rate of change is about 10 seconds per dim level change for ballasts controlled by PCC Decoder 1s. This rate of change is not easily noticed by the room's occupant. Phase Cut (2 wire) ballasts and PCC Decoder 2s (step dim) will respond to this command without delay, as if it were a fx command. sx will over ride a previous dim level set by the user's wall switch or PC, and it is the PC's responsibility to restore the user's dim level if light regulation is turned off, and to notice if the user increments or decrements this level. Light regulation is over ridden by the room being unoccupied. The sx command will be illegal if the lights are off due to the PCC Encoder 1's occupancy sensor indicating that the room is unoccupied. The sf command will not abort the occupancy sensor over ride time as the ff command does. The sx commands do not restart the occupancy over ride timer if in process. Because 0 is the minimum dim level that can be commanded, the sf command causes the PCC Encoder 1 to turn off the ballasts without delay. The PCC Decoder 1s slew between their present 0 to 10V output and the target 0 to 10V output at the slew rate. They will pass through light levels between the defined dim levels while slewing; but the target dim level will be a defined dim level. Changing the dim level with a new sx command while slewing will update the target to the last commanded value and can change the direction of the slew. Sending an fx command will cancel any slewing in process and cause the new fx command to be applied without delay. Changes due to an mx command can over ride the target of a slew in process, but will not cancel slewing. No action other than issuing a pb status will occur if the PC attempts to command a dim level higher than the maximum allowed as reported by the cx bytes of the status report.

mx PC command limits the dim level set by the user's wall switch and PC commands. The PCC Encoder 1's present dim level will be reduced to this value if it was set to a higher light output. This can be used to achieve load shedding. The PCC Encoder 1 will forget this value if it loses power. The PCC Encoder 1 will not remember the previous dim level setting if it is reduced by the mx command so PC should remember and restore the user's dim level after the end of the load shedding when the PC raises the mx limit. The mx commands do not affect the occupancy over ride timer if in process. If the PC is turned off while in load shedding, the PCC Encoder 1 may still have a dim limit imposed by the mx command when the PC is turned back on after load shedding is over. The status bxx and cx allow detecting this condition so that it can be corrected by sending the maximum allowed mx command. mx commands greater than the default maximum dim level as reported by the bxx status will not be allowed.

eb PC command will cause the PCC Encoder 1 to send its present status. The PCC Encoder 1 has no further error recovery behavior in response to this command, so it may be used to request status.

Status from Encoder	Characters
dim level	d0 … d7, df
occupancy sensor on, off, over ride	on , of, oo

Ballast is Phase Cut, PCC	bp*x* , bc*x* where *x* is the maximum dim level, not
changed by mx limit.	
instant mA	i*xxxx* , where *xxxx* is current in mA
15min average mA	a*xxxx*t*x* , where *xxxx* is current in mA, and *x* is relative
time counter 0 to 7.	
cap on dim level	c0 … c7 where x is the maximum dim level that can be
commanded.	
PC command bad	pb sent instead of above status lines if a bad command
has been received.	
delimiter	<space> separates symbols.
end of message	<cr lf> terminates status.

All status messages in response to a valid PC message will contain "dx ox bxx ixxxx axxxxtx cx <cr lf>".

dx status reports the dim level presently in force. This dim level will be the final dim level while the PCC Decoder 1s are slewing to a final dim level in response to an sx command. The PC can figure out the approximate light output while the PCC Decoder 1s are slewing by reading the instantaneous current or calculating that the rate of change in response to sx commands is about 10 seconds per dim level. User light level input from the wall switch will act as if an fx command has been sent. It is expected that light level regulation will not send changes in dimming of more than one dim level, or faster than the PCC Decoder 1s can slew to the new level. Failure to follow these constraints could result in confusion if the user changes dim level based on the target dim level, not the instantaneous dim level, should they be more than one dim level apart. The PCC Encoder 1 will default to ballasts off after power up. When the occupancy sensor has turned off the light, as indicated by status "of", the dim level reported is the one that will be in effect if the occupancy sensor turns the lights back on. The dim level not equal to "df" does not indicate that the light is on if the occupancy status is "of".

ox status reports the PCC Encoder 1's occupancy sensor state. "on" will be returned while the occupancy sensor is detected to be on or has not been debounced for more than 10 seconds in the off state. The occupancy sensor is assumed to be "on" after the PCC Encoder 1 has been powered up till after the debounce period has expired. If the occupancy sensor state is "of", or a courtesy wink in process, the status will be "of". If the occupancy sensor has been over ridden by f0 .. 7 commands from the PC or user dim 0 .. 7 commands from the wall switch, the status will be occupancy sensor over ride, "oo". Occupancy over ride state lasts about 1 hour after the last over ride.

bxx status reports the type of power line communication in use and the maximum dim level allowed by the PCC Encoder 1's firmware. The type of power line communication is selected by the PCC vs. Lamp Dimmer dip switch in the PCC Encoder 1. bpx indicates that the PCC Encoder 1 is in Phase Cut, 2 wire, continuous dimming mode. This selection is tuned for use with Advance Mark X ballasts and does not require PCC Decoders. bcx indicates that the PCC Encoder 1 is in Phase Cut Carrier, PCC, 4 wire, 0 – 10V mode. Phase cuts are sent only during commands from the PCC Encoder 1 to the PCC Decoders. The type and tuning of PCC Decoder must match the ballast it controls. The standard maximum dim level reported is 7.

Customization of the PCC Encoder 1's firm ware is required to change this. This value is the maximum allowable dim level that can be set by the mx command.

ixxxx status reports the last reading of the instantaneous current consumed by the ballasts under the control of the PCC Encoder 1. New readings are taken approximately once per second and are averaged over about a second before being digitized. This represents the average of the current waveform after it has been full wave rectified, not the RMS value. The PC can calculate the RMS value from this average if the load draws sinusoidal current as is typical of 4 wire, 0 – 10V ballasts above the lower dim levels. For sine waves: Vrms = Vave * Pi / (2 * sqrt(2)). Power consumption in Watts is the RMS line voltage times the RMS current. Good accuracy converting average to RMS when controlling 2 Wire ballasts and all ballasts at low light level will require calibration software in the PC. The PCC Encoder 1 does not presently do any calibration of the current readings for zero current offset, gain or linearity to improve the accuracy of the average value it measures. Better accuracy of the current reading can be obtained by calibrating the zero current offset with the load off (can be done without user assistance), and the gain / linearity at each dim level with the aid of a RMS current meter. The current reading accuracy is good enough to assure that it is monotonic, and the best accuracy is achieved at the higher dim levels. The current is reported in 2s complement with the least significant bit equal to 1mA. Zero current offsets can result in negative current values being reported, but ideally only positive current values should be reported due to the absolute value process in the PCC Encoder 1 hardware. Treat negative current values as being the result of an offset error. Changing their polarity is not a correct way to calibrate negative values; clipping them to zero would be preferred if they can not be calibrated out. It is expected that negative current values will not occur when at least one ballast is turned on and commanded to a dim level above off. Only the lower 13 bits of the current value are used for magnitude. The sign is extended across the remaining bits 13 .. 15. The current is digitized by a 12 bit A/D, with ideally no values in the negative half of the range. The ideally 11 bits are scaled to the desired 1mA LSB which requires 13 bits to represent. The current value is hexadecimal ASCII, not BCD or true binary. Possible current values that will be reported are +/- 6.649A if no calibration occurs in the PCC Decoder 1. The maximum possible current values that can be represented in 13 bits are -8.192A to 8.191A, E000 to 1FFF.

axxxxtx status reports an average of the ixxxx current values. The average is updated about every 15 minutes, with new samples added to the average about every second, 1024 samples total. This averaging process significantly improves the accuracy and resolution of the axxxx value above the ixxxx value if the load is constant during the averaging period. The value reported by axxxx is the last 15-minute average that has been completed, so it could be out of date by up to 15 minutes. The value reported before the first average has been accumulated after power up is 0. This is not a running average, the average starts over each 15 minute period. The tx portion of axxxxtx identifies which 15 minute period is being reported. The x in tx can be 0 to 7, starting at 1 after power up, incrementing after each average has been accumulated, and rolling over to 0 after 7. The axxxxtx value will be reported every 15 minutes. It is possible for the report requirement to be satisfied through a status report in response to a command from the PC. The tx value allows detecting this condition. The tx value can be used to tell when a new average has been completed if the PC polls for 15 minute average current status rather than relying on spontaneous reporting of this value. If the PC is off, or tells the PCC Encoder 1 to stop sending data, for more than about 2 hours there is potential for confusion as the tx number may be the same as that sent before communication was stopped, but will represent a different sample. An unsent average is replaced by the most recent one, not qued for sending.

cx status reports the maximum allowed dim level in force. This is the default maximum dim level reported by the bxx status unless changed by the mx command. The PC must use the mx command to raise the maximum allowed dim before commanding dim levels above the cx dim level.

pb status reports that the last two characters received by the PCC Encoder 1 were not interpreted as a valid command and no additional action has been taken. The PC should re-send the last command. Improper command syntax, illegal commands or communication errors will cause a status of “pb <cr lf>”. If this condition persists, it may be due to an extra character being received, or a missed character. Noting that the pb response occurs after what the PC considers to be the first character of a two byte command detects this out of synch condition. The out of synch condition can be corrected by sending any illegal character, such as $, which will cause the pb status and ready the PCC Encoder 1 for the next valid command.