Report Title: Final Report: “Adapting Wireless Technology to Lighting Control and Environmental Sensing”

Type of Report: Final Report

Reporting Period Start Date: August 01, 2004

Reporting Period End Date: April 30, 2006

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Reporting Date: July 2006

Award Number: DE-FC26-04NT41944

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Final Report: “Adapting Wireless Technology to Lighting Control and Environmental Sensing”

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Abstract

Although advanced lighting control systems offer significant energy savings, the high cost of retrofitting buildings with advanced lighting control systems is a barrier to adoption of this energy-saving technology. Wireless technology, however, offers a solution to mounting installation costs since it requires no additional wiring to implement. To demonstrate the feasibility of such a system, a prototype wirelessly-controlled advanced lighting system was designed and built. The system includes the following components: a wirelessly-controllable analog circuit module (ACM), a wirelessly-controllable electronic dimmable ballast, a T8 3-lamp fixture, an environmental multi-sensor, a current transducer, and control software. The ACM, dimmable ballast, multi-sensor, and current transducer were all integrated with SmartMesh™ wireless mesh networking nodes, called motes, enabling wireless communication, sensor monitoring, and actuator control. Each mote-enabled device has a reliable communication path to the SmartMesh Manager, a single board computer that controls network functions and connects the wireless network to a PC running lighting control software. The ACM is capable of locally driving one or more standard 0-10 Volt electronic dimmable ballasts through relay control and a 0-10 Volt controllable output, in addition to 0-24 Volt and 0-10 Volt inputs. The mote-integrated electronic dimmable ballast is designed to drive a standard 3-lamp T8 light fixture. The environmental multi-sensor measures occupancy, light level and temperature. The current transducer is used to measure the power consumed by the fixture. Control software was developed to implement advanced lighting algorithms, including open and closed-loop daylight ramping, occupancy control, and demand response. Engineering prototypes of each component were fabricated and tested in a bench-scale system. Based on standard industry practices, a cost analysis was conducted. It is estimated that the installation cost of a wireless advanced lighting control system for a retrofit application is at least 20% lower than a comparable wired system for a typical 16,000 square-foot office building, with a payback period of less than 3 years. At 30% market penetration saturation, a cumulative 695 Billion kWh of energy could be saved through 2025, a cost savings of $52 Billion.

Table of Contents

List of Figures

Introduction

This report summarizes the work performed under the project titled "Adapting Wireless Technology to Lighting Control and Environmental Sensing" during the period of performance from August 1, 2004 through April 30, 2006.

Executive Summary

Advanced lighting control systems can improve energy efficiency in buildings by using dimmable ballasts to adjust light level based on user comfort and available sunlight, shedding load during peak price periods, and turning lights off when areas are unoccupied. By implementing intelligent controls, over 50% energy savings on lighting can be realized in a typical office environment. To date, system components and installation have been prohibitively expensive for wide-scale adoption. Installation and commissioning can also be destructive and intrusive due to the need for running additional control wiring. Wireless technology, however, offers a convenient way to control lighting components and report sensed environmental data in a manner that can be cost-effectively retrofit.

The work performed under the project "Adapting Wireless Technology to Lighting Control and Environmental Sensing" has successfully demonstrated advanced lighting control using Dust Networks' SmartMesh™ wireless networking products for communications. The feasibility of cost reduction through advancing single-chip wireless technologies and volume production is also shown.

Integrated wireless Dimmable Ballast and Analog circuit module prototypes were designed, built, tested, and refined. Environmental multi-sensors and current transducers were also equipped with wireless communication capability. Control Logic Software was designed to implement open and closed loop daylighting algorithms, load shedding, occupancy control, and manual control.

In bench-top testing, the full, integrated lighting system was deployed and tested. Results showed open-loop daylighting capabilities, accurate closed-loop setpoint control, timely occupancy function, and load shedding. A novel aspect to the control implementation is the ability to maintain load shed levels while simultaneously adjusting light levels based on daylighting.

A volume-based cost analysis shows that a wireless system provides an installation cost savings of more than 20%, including over 45% savings on installation labor over a wired system. With energy savings of 50%, the wireless retrofit system can pay for itself in less than 3 years.

With supplier commitment to cost reduction and demonstrated system feasibility, the project team recommends further promotion of wireless lighting control through engagement with committed stakeholders, including utilities and state energy agencies. This would encourage bulk production, decreased cost of wireless lighting components, and accelerated market penetration resulting in nearly 700 BkWh in cumulative energy savings by 2025.

Project Objectives

1. Demonstrate that wireless technology can be cost-effectively applied to the problem of retrofitting integrated lighting controls into existing buildings. The outcome of the program will be an advanced lighting control system capable of implementing all lighting control strategies in existing buildings without the need to run additional wires.
2. Demonstrate that wireless technology can be cost-effectively embedded into controllable fluorescent lamp ballasts allowing independent control of individual ballasts from and intelligent, wireless environmental sensor.

Background

The energy-saving and occupant comfort benefits of advanced lighting control, while well known within the lighting community, have not been realized on a large scale due to the cost and difficulty of installing and commissioning electronic dimmable ballasts and supporting hardware. Retrofitting existing buildings with dimmable ballasts and appropriate sensors requires running new control wires, which makes the cost and complexity of installing such systems prohibitive.

A new class of low power, low data rate wireless mesh networking devices promises to reduce the barriers to implementing advanced lighting control systems by eliminating the need for control wires. These wireless mesh networks offer the user a reliable means of transmitting sensor data and control commands to and from remote monitoring and control points by means of a self-forming, self-healing, and multihopping network architecture. Dust Networks has developed a very low power, reliable wireless mesh network product called SmartMesh™. Each node in the SmartMesh network is called a Mote and can be embedded into monitoring and control devices. The Dust Networks system uses a central network access point called the SmartMesh Manager (Manager). Application specific software running on a PC or building management system can communicate directly with the Manager, providing the user with monitoring and control capabilities.

The purpose of this project is to apply wireless technology to lighting controls in order to develop a system capable of advanced lighting strategies that is also cost effective for commercial retrofit applications. Occupants will benefit from improved workplace comfort, building owners will benefit from improved energy efficiency and flexible lighting control, and utilities will benefit from energy savings that are responsive to peak demand periods.

Commercial lighting consumes approximately 3.7 quads per year. At 30% long-term market penetration and an average of 50% energy savings resulting from advanced lighting strategies, well over one half quad of energy could be saved annually.

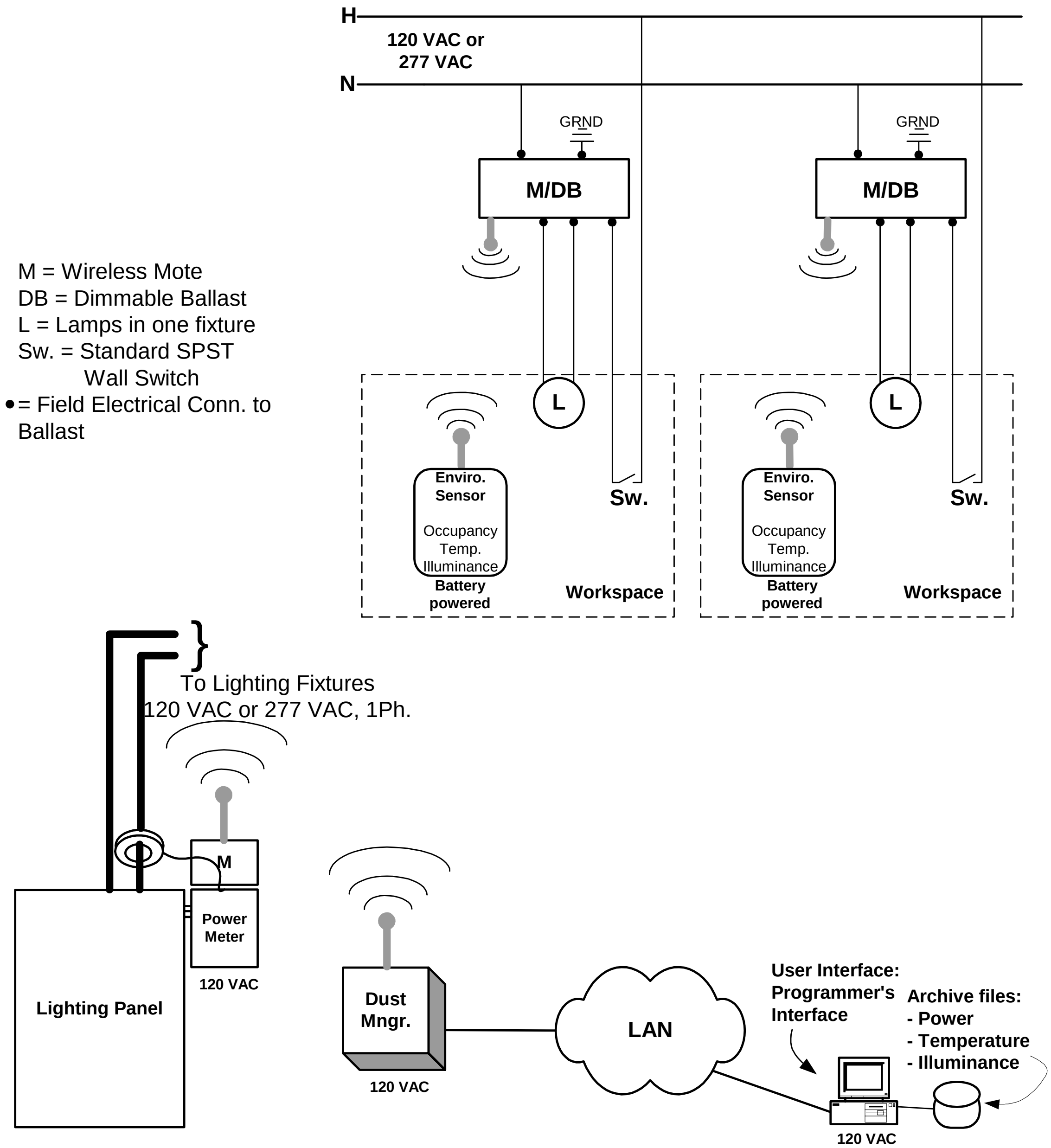


Figure 1. Concept Drawing of Adapted Wireless Lighting Control System.

Wireless-Enabled Dimmable Ballast and Analog circuit module

The development of the Mote-integrated Dimmable Ballast was performed in three parallel efforts: analog circuit module development, electronic dimming ballast design, and mote-ballast integration. This parallel approach has enabled a complete product development assessment within a shortened development cycle. The design and testing portion of the integrated dimming ballast was segmented to allow design consultants to build their respective elements independently and to avoid delays due to serial work load, learning curves and design implementation.

The development activity has been completed as follows:

1) Mote-Integrated Analog circuit module (ACM)
2) Dimming ballast platform
3) Mote-Integrated Dimming Ballast (MDB)

Mote-integrated Analog circuit module (ACM)

Overview

The ACM responds to commands delivered wirelessly through the integrated on-board Dust Networks Mote. Commands received by the embedded Mote via wireless transmission are passed serially to a micro controller in the ACM, which controls ACM function. Using commands from a custom command set, the ACM has the ability to open or close a 20 Amp control relay contact in addition to providing a 0-10V analog output signal. The ACM also has a 0-10V input and 24V input for monitoring capabilities. The ACM is intended to be a “bridge” product that provides wireless control of lighting and non-lighting loads of up to 20 Amp loading at 120 or 277VAC. The 0-10V output can be used to control existing 0-10 VDC dimming ballasts or other voltage-controlled components. By providing the ability to control fade rates and set levels for demand reduction, the device can be used in load shed or daylighting applications where additional energy savings can be obtained.

Figure 2 illustrates a potential implementation of the ACM to control electronic dimmable ballasts. With a 20 Amp relay, each ACM can control a switchleg powering up to 16 T8 lamps at 120VAC or 47 T8 lamps at 277VAC.

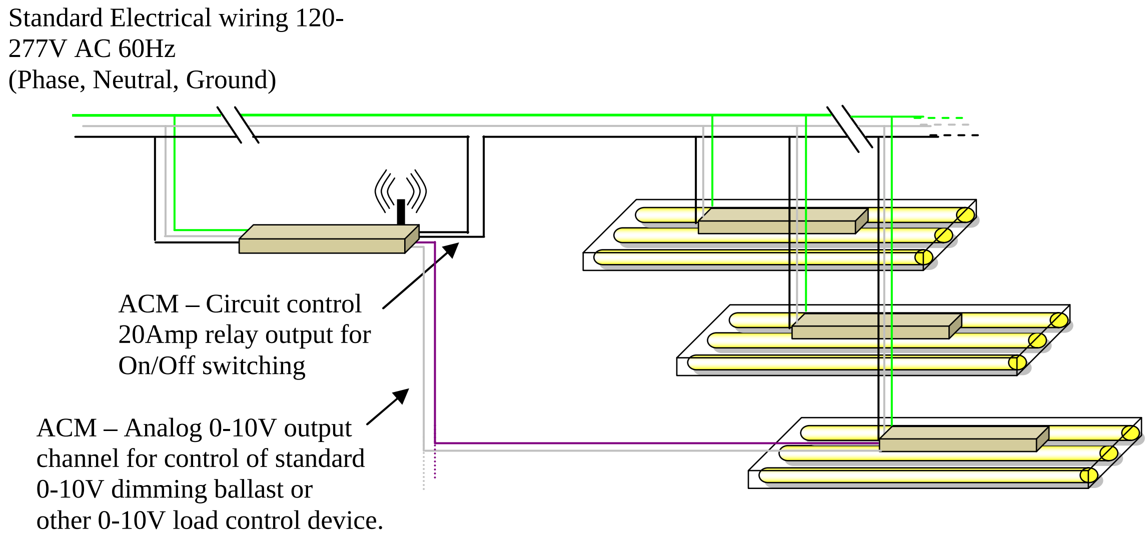


Figure 2. Diagram showing the connection of a wirelessly controlled ACM to dimmable ballasts

The ACM is comprised of the Dust wireless mesh networks communication module, a microcontroller for protocol handling, and control logic to support the 0-10V output and 20 Amp relay. A block diagram is shown in Figure 3. Packaged into a standard ballast enclosure, the ACM device can be installed in a standard lighting fixture, as shown in Figure 4, or wall mounted in an electrical enclosure. Care must be taken to allow the ACM antenna to be mounted outside the metal enclosure.

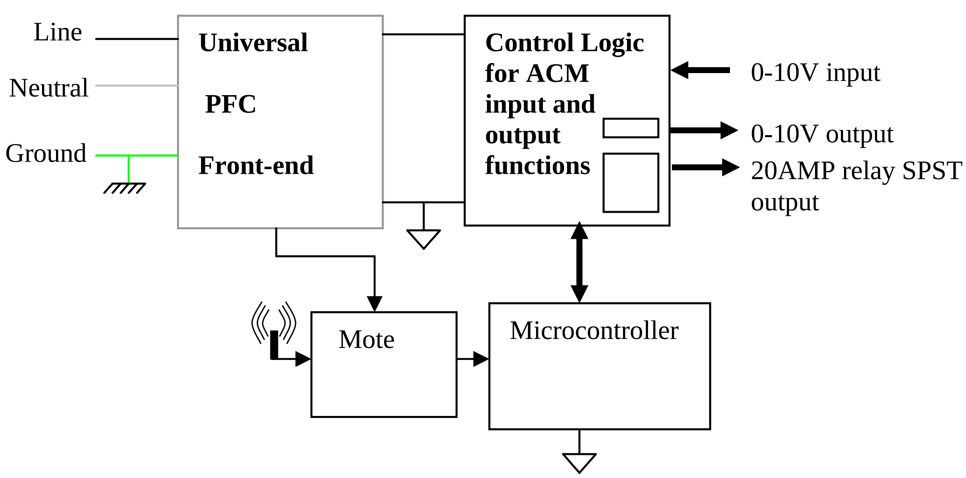


Figure 3. ACM block diagram. The line-powered mote passes control messages to an embedded microcontroller that controls the output voltage and relay state.

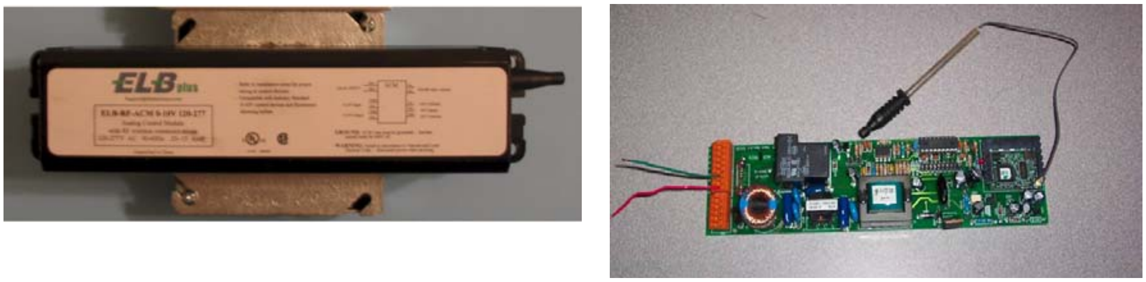


Figure 4. Finished ACM package (left) and ACM circuit board (right) as submitted by SVA Lighting

The command set for the ACM (Appendix A) was implemented to mirror the custom command set that will be used for the Mote-integrated Dimming ballast (MDB). As an example the ON/OFF command when sent to an ACM address will open or close the 20 Amp relay and when sent to the ballast will turn the fluorescent lamps on and off. In this way, installed ACM devices can be used in similar applications as the MDB while retaining the flexibility to function in other control applications. Ballast development and testing time is also reduced, as the software will port from the ACM to the ballast design.

Testing

ACM functional testing was completed by sending commands over the wireless link between the Dust Networks' SmartMesh™ Manager (Manager) and the ACM, as depicted in Figure 5. Operation was confirmed for the commands listed in Appendix A.

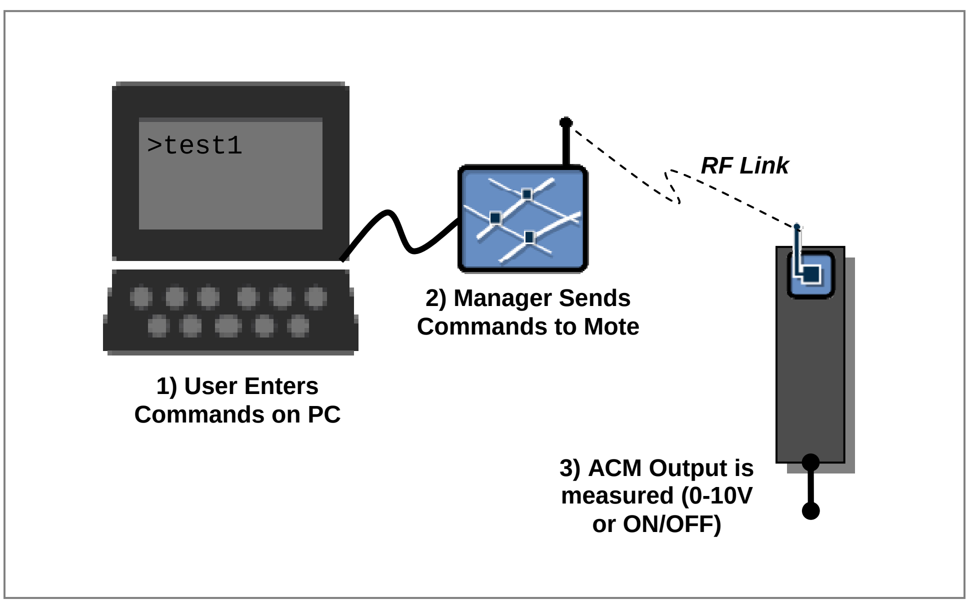


Figure 5. ACM Test Set-up

To meet quality and field reliability requirements of the commercial buildings market, all products will be rigorously tested. SVA Lighting subjects its designs to the tests listed in Appendix B before release. In addition to the listed quality and reliability tests, performance testing is also completed.

Mote-integrated Dimming Ballast (MDB)

Overview

The MDB has been developed for compatibility with fluorescent, 3-lamp T8 120-277V fixtures. The dimming range is from 100% of maximum light output to 5%. Commands are implemented to allow full range dimming in addition to load reduction commands that will limit the light output of the ballast during a load shedding period or when adequate daylight is available. Figure 6 is a conceptual illustration showing MDB installation with lighting fixtures and standard wiring. The MDB is designed to be a “drop-in” replacement for any standard ballast allowing it to be installed by standard lighting maintenance personnel. Because the MDB would ordinarily be mounted within a fixture’s metal body, the MDB’s antenna must extend outside of the fixture. Because the MDB communicates wirelessly, low-voltage control wiring is not required.

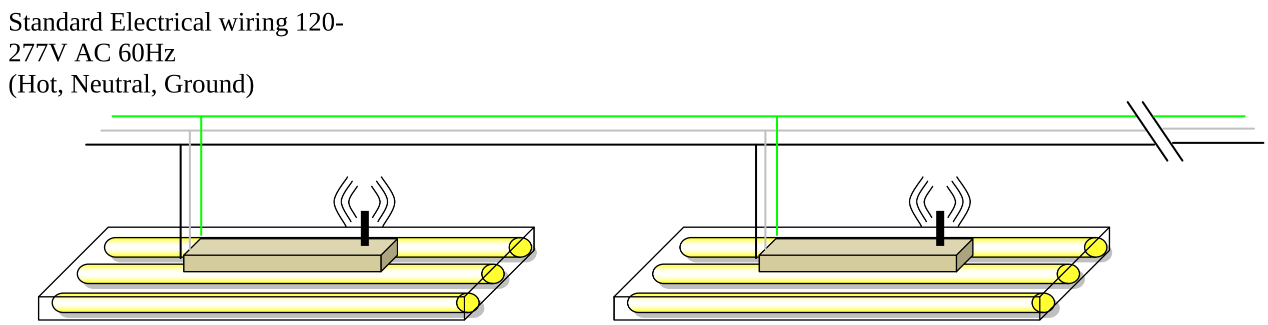


Figure 6. Diagram of installed Mote-integrated dimmable ballasts

The MDB provides a cost effective solution to lighting retrofit applications. Replacing the existing fluorescent lighting ballast with the MDB in addition to installing basic control components provides load management, occupancy light level tuning and reporting functions for the building manager.

Using current market proven ballast design techniques assures that the MDB offers a reliable product solution. The resonant half bridge inverter combined with the dimming controller allows full lamp control while meeting ANSI requirements for lamp operating performance. The embedded microcontroller provides the interface control and protocol conversion between the Dust mote and the ballast control and monitoring components. A block diagram of the MDB components is shown in Figure 7.

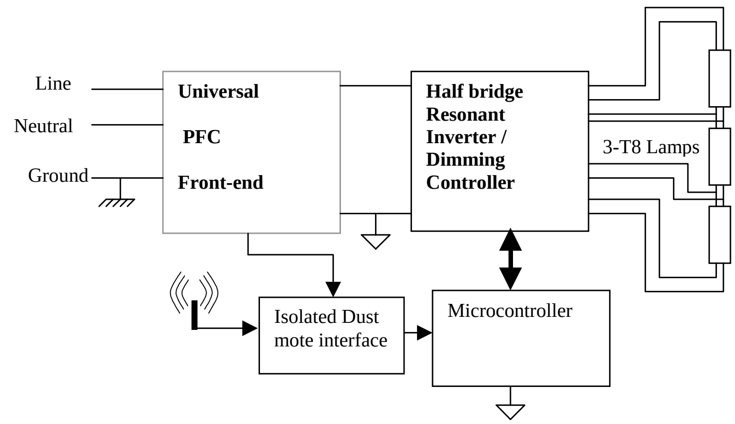


Figure 7. Block diagram of the Mote-integrated Dimmable Ballast. The wireless Mote connects to a microcontroller that controls ballast functions.

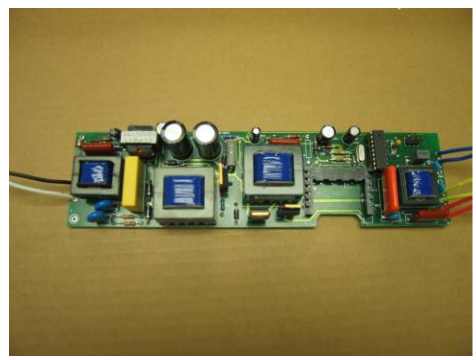


Figure 8. SVA Lighting Electronic Ballast Packaging (left), MDB circuit board (right)

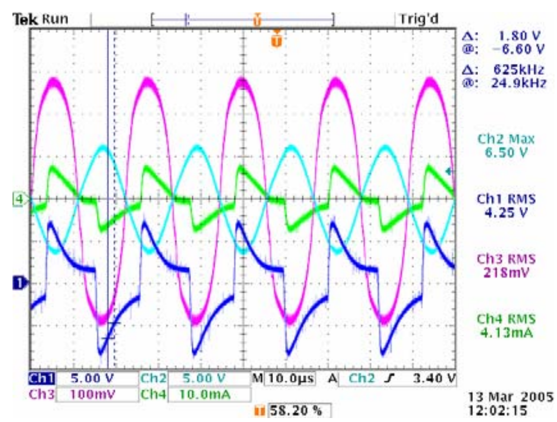
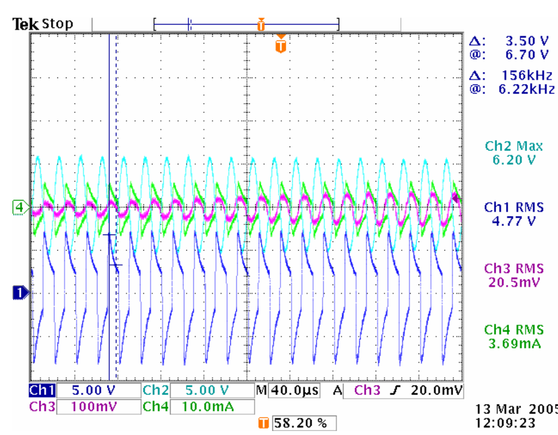
Testing

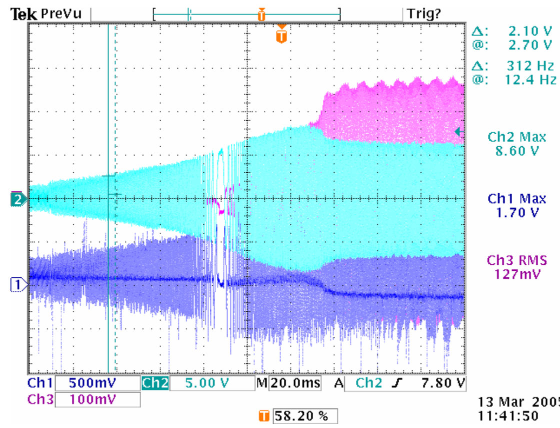
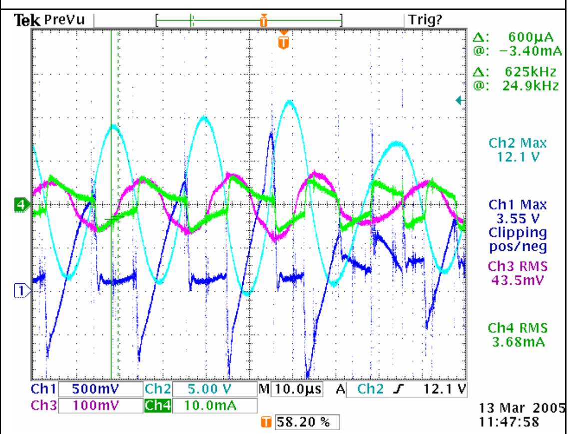
A number of tests were conducted on the ballasts to insure that they meet industry operational requirements. To qualify a product for the USA commercial lighting market, rigorous testing is required to assure the design result is a high quality product meeting market performance (ANSII) and safety (UL) standards. Although testing for the ability of a product to pass the required UL safety tests is necessary, it is also important that a ballast design operates the lamp appropriately to ensure proper light output and acceptable lamp operating life. The lamp operating performance, starting and end of life operation guidelines are documented within the ANSII standards for electronic ballasts. SVA Lighting will complete approximately 24 different tests related to product and design reliability and specification verification. Upon completion of the tests the products will be submitted to UL for safety testing and approval. Products will be available for market introduction at that time.

Lamp starting and removal tests, end of lamp life tests, and product comparison tests are described in this section.

Lamp Starting and Removal

Lamp life is determined by the ballast lamp current starting method, filament voltages, lamp operating current and overall smoothness of the energy supplied. The first 3 waveforms displayed below were taken from the T8-32W 3 lamp-dimming platform used for the integration of the Dust module. The waveforms show the correct operation for lamp starting characteristics. The scope photos show the lamp starting and filament voltage needed to fall within the ANSII parameters. Waveform 4 shows the lamp fault test condition.

1) Normal full light lamp voltage, current and filament voltage and current: Ch1: Blue filament voltage (5V/div. RMS = 4.25V). Ch2: Lamp voltage (3 lamps in series, 100X probe, 500V/div. Peak= 650V) Ch3: Lamp current (toroid at blue side, 100mA/div. RMS = 218mA) Ch4: Blue filament current, (100mA/div. RMS = 413mA) The significant point of this test is to assure that at full light output the filament, lamp current and lamp voltage parameters fall within the recommended lamp operation guidelines provided by ANSII. The design meets requirements.	
2) Prior to strike, lamp voltage, current filament voltage and current: Ch1: Blue filament voltage (5V/div. RMS = 4.77V). Ch2: Lamp voltage (3 lamps in series, 100X probe, 500V/div. Peak= 620V) Ch3: Lamp current (toroid at blue side, 100mA/div. RMS = 20.5mA) Ch4: blue filament current, (100mA/div. RMS = 369mA). The filament resistance at 25C is 2.7 Ohm. Prior to strike, filament resistance is 4.77/0.369=12.9 Ohm**. Rh/Rc = 4.787**. This test shows the current and voltage levels prior to the actual starting of the lamp. Lamp stress and damage occur during the transition stage from off to on and the way the lamp is treated prior to starting is critical to obtaining the required lamp life. Design	

meets requirements.	
3) During strike, lamp voltage, current and fault monitoring voltage: Ch1: Fault monitoring voltage (0.5V/div). Ch2: Lamp voltage (3 lamps in series, 100X probe, 500V/div. Peak= 860V) Ch3: Lamp current (toroid at blue side, 100mA/div.) Perhaps the most critical point of the lamp operation is when the lamp actually begins to strike. This is the period of time that the lamp cathodes are spitting of material. A controlled start assures that minimum damage occurs. The design is a program start operation, which is the preferred starting method to achieve the longest lamp life. Results of this test are positive and meet requirements.	
4) During middle lamp removed fault, lamp voltage, current and fault monitoring voltage: Ch1: Fault monitoring voltage (0.5V/div). Ch2: Lamp voltage (3 lamps in series, 100X probe, 500V/div. Peak= 1210V) Ch3: Lamp current (toroid at blue side, 100mA/div.) It is important to understand how the ballast design functions during lamp failure. Fault testing is performed to assure that the lamp operating conditions are maintained within specifications for the remaining lamps and a hazardous condition does not develop. Results are positive and within recommended operating parameters.	

End of Lamp Life test:

When a fluorescent lamp fails there is a period of time in which the lamp looks like a short circuit to the ballast circuit. During this time arcing is present in the lamp and it is important that the ballast can support the high currents generated. An end of lamp life test is important to assure that the ballast design is capable of supporting this event. An Arc tester can be used to simulate the arcing created during a lamp end of life period. The photo below shows the simulated arc test being performed on the SVA Dust integrated ballast. The ballast under test did not fail and went into the proper shutdown mode therefore passing the test requirements.

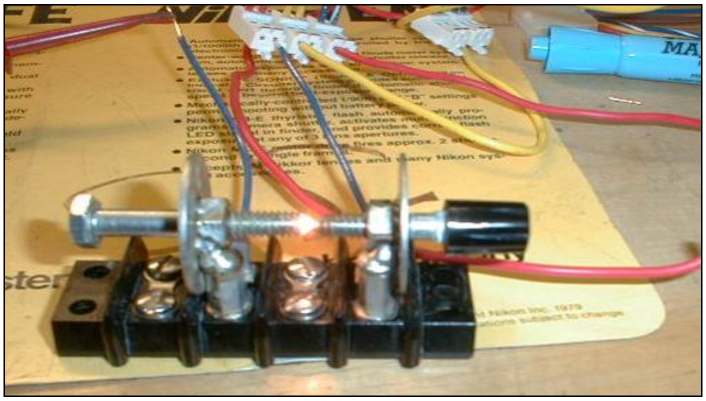


Figure 9. Photograph of arc test set-up

Product Comparison

To assure that the SVA Lighting ballast design measures up to the performance of the dimming ballasts currently in the market place, the performance of existing products needs to be understood. The response curve below shows the lamp output to control level input profile of the Advance 3 lamp 0-10V dimming ballast. This product was picked since it is a leading product in the market. Other manufacture products will also be tested prior to the final release of the SVA product. SVA Lighting's ballast will provide similar tracking between the control input parameters and the lamp output levels.

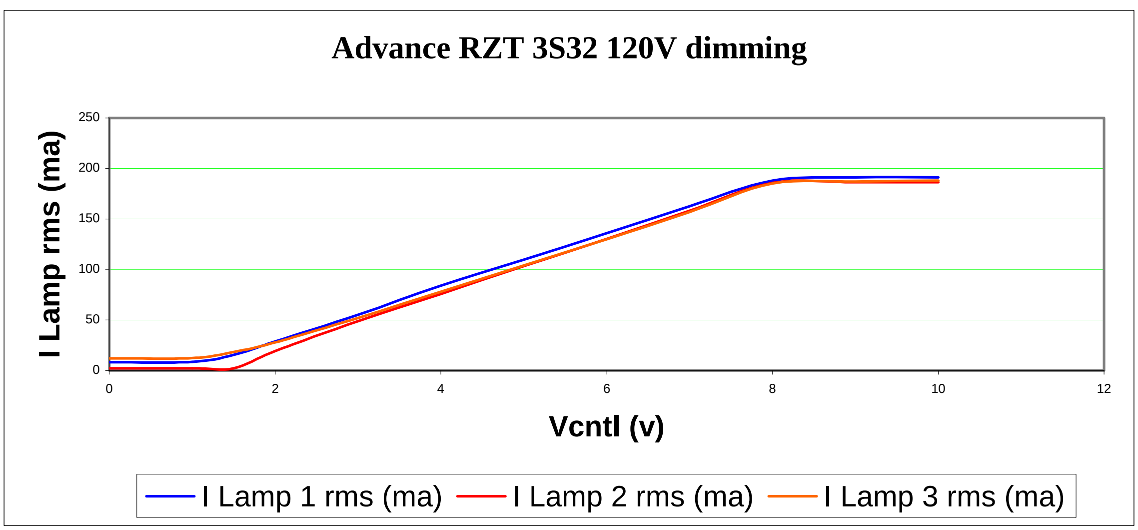


Figure 10. Plot of the control input vs lamp output current

Wireless-enabled Environmental Sensor

The environmental multi-sensor developed by LBNL is capable of measuring illuminance and occupancy (and vacancy). For this project, the environmental sensor was integrated with a Dust Networks' Mote to allow wireless communication. The on-Mote temperature sensor adds temperature monitoring function to the multi-sensor.

The wireless lighting control solution employs a control design scheme that requires environmental sensor inputs for automatic on, off and daylight control functions. The system will automatically turn the light ON upon occupancy detection and OFF after a preset time upon the departure of the occupant from the zone. For the daylight control function, illuminance, as measured by the light-sensing portion of the environmental sensor, will provide an input to the control logic software, which will adjust ballast output accordingly. This strategy saves energy by reducing lighting power when daylight is available.

Two daylighting control modes are envisioned: open-loop and closed-loop. In open-loop mode, the daylighting control algorithm establishes a one-to-one correspondence (essentially a lookup table) between light level as detected by the light detector and the ballast's light output. As the detected light level goes up, the ballast output goes down. This is the simplest control algorithm to implement. In closed-loop mode, the algorithm will drive down the light level as the light detected by the light detector increases. But unlike the open-loop case, the light detector is able to "see" the light that it controls. Using closed-loop feedback, the system continuously senses the light level and continuously adjusts the electric light output so that the signal from the light detector remains at a preset value (the setpoint). In both open and closed-loop mode, the user is able to set the light level setpoint (in lux or footcandles) from the GUI running on the Control Logic Computer.

The control logic for the closed-loop daylighting algorithm is as follows: when the illuminance sensor measures a value greater than the setpoint, the control logic will gradually reduce the output of the fluorescent lamps operated by connected dimming ballasts. The control logic will then resample the light level from the environmental sensor and do one of three things: If the newly sampled light level is close to the setpoint level, the ballast output will be unchanged. If the sampled light level is (still) higher than the setpoint, then the control logic will decrease the ballast output by a small amount and repeat the above step by resampling the environmental sensor. If the sampled light level is lower than the setpoint, then the control logic will slightly increase the ballast output and repeat the above step by resampling the environmental sensor.

LBNL environmental sensors built previously around the 1-wire™ networking protocol were modified to provide occupancy sensor status and light level output to the Dust Networks' Evaluation Kit Motes (Figure 11). Each Mote receives analog data from the environmental sensor via a 6' RJ-11 cable connected from the environmental sensor to the Mote's terminal block, designated as P1, and shown in Figure 12. Mote terminal block pin A1 monitors the Multi-Sensor light level, which is indicated by a voltage in the range of 0 (no light) to 5V (maximum light). Mote terminal block pin A2 monitors the environmental sensor's occupancy status: 0V (unoccupied) or 0.6V (occupied). The environmental sensor is powered by three AA batteries located at the Mote end of the RJ-11 cable.

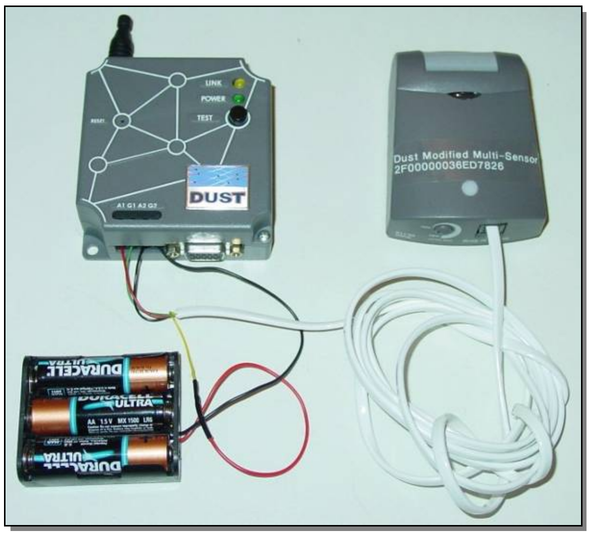


Figure 11. Modified environmental sensor connected to Dust Networks' Mote and powered by 3 AA batteries

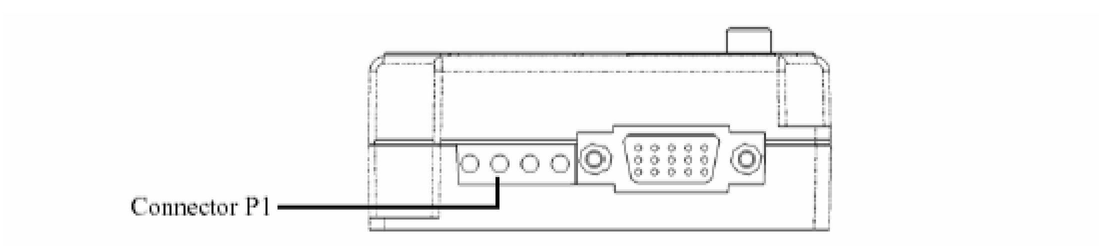


Figure 12. Dust Networks' Packaged Evaluation Kit Mote - view showing connectors. Environmental Sensor inputs are wired to terminal block connector (P1).

The terminal block of the mote was used for voltage input because it allows two 0 to 5V analog inputs. Connector P1 is a 4-position terminal block and contains internal filter circuitry for reducing 60 Hz noise.

Previously developed environmental sensors were modified to expose the analog light level and occupancy signals that formerly were multiplexed through a Smart Battery Monitor (Dallas Semiconductor/MAXIM part number DS2438) and outputted onto the 1-Wire digital LAN. We bypassed the DS2438 and wired the light level and occupancy sensor outputs directly to the modular jack on the environmental sensor. Then a simple 4 wire cable with RJ-11 connectors was used to route the signals from the environmental sensor to the Dust Mote.

The original environmental sensor developed by LBNL also measured temperature by virtue of the fact that the DS2438 in the environmental sensor contained an internal thermistor. However, since the DS2438 was bypassed in our wireless implementation, the measurement of temperature must be done elsewhere. The Dust sensor board already contains a temperature sensor; therefore, the same basic functionality is provided.

It is important to realize that the environmental sensor that was modified for wireless operation in this contract was originally designed as a wired (tethered) sensor connected to an always-on 12 VDC power supply. Because of budget and scheduling constraints, we did not have the luxury of designing a low-power consumption environmental sensor from scratch that might have been more suited to wireless (untethered) operation. While the light detecting portion of the environmental sensor has relatively low power requirements, the occupancy sensor portion should be replaced with a low-power consumption detector as well.

The TSLG257 photodiode was used for light sensing. When combined with a Hoya CM500 color correcting filter the spectral response of this particular photodiode is reasonably close to the desired photopic response. This results in low errors due to mismatch between the detector response and the photopic curve.

One of the environmental sensors modified for the contract was tested at LBNL. The results are below.

Occupancy Sensing

The tested environmental sensor detected occupancy with a power supply voltage greater than 3.8V. The particular occupancy sensor used by LBNL contains an LED that blinks on briefly (about 1 second) when it detects occupancy. When the occupancy is sensed, the sensor sends 0.6 V to the A2 terminal of the mote. In early prototypes, the signal duration was short (in the range of seconds). LBNL increased the duration to detect occupancy and relay the information for the control logic software. The angular range of the sensor has been confirmed to be 120 degrees.

Light Level Sensing

The maximum voltage output of the environmental sensor's illuminance sensor is limited by the battery supply voltage, with a further unknown reduction due to losses in internal circuitry. Therefore, as supply voltage decreases with increasing battery drain, the output voltage indicating maximum light level will also decrease. This means that readings at the high end of the voltage range should be used carefully since the maximum light level measured decreases as the batteries age.

LBNL tested the light sensor for maximum illuminance level, resolution and level of accuracy. Initially, we found that the light sensor was far too sensitive for the desired range of iluminance (0-1000 lux). We determined that the gain of the light detector's photo amplifier could not be easily changed. Unable to reduce the gain electrically, we elected to accomplish the same objective by using a pin hole filter over the detector. This is an inelegant, if expedient, solution since it is not easily reproducible across different sensors.

After adding the pin hole filter, the maximum illuminance measured was 3.84V and 1090 lux. The 3.84V value is highly dependent on the battery power as stated above. A plot of the measured illuminance versus the sensor output voltage is shown below. Applying a linear fit to the measured data, we determined that the calibration of the light sensor was 260 lux per volt. Accuracy of this linear fit was not further analyzed, but from the plotted data it is clear that at certain illuminances, the accuracy is only about 30%. The accuracy could obviously be increased by using a non-linear fit but this was not necessary for our initial purposes.

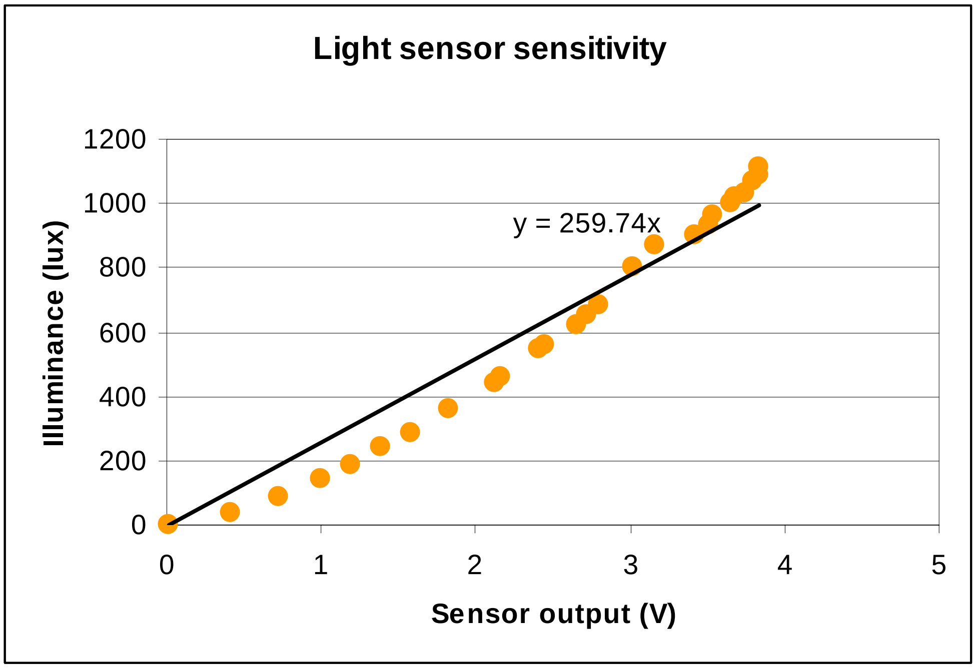


Figure 13. Plot of illuminance vs. sensor voltage for light sensor

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Power Meter

Lighting energy usage was monitored using current transducers (CTs) wired to Dust Networks' Evaluation Motes. This monitoring approach can be extended to sub-metering loads throughout a building by installing CTs at power sub panels. The CTs selected for this application are the Hawkeye® 822 model from Veris Industries. This model is a solid-core 0-10 Amp current transducer with a 0-5 Volt output. Integration with Dust Networks' Evaluation Mote (EVM) module is straightforward. The CT can be wired directly to the 0-5 Volt input of the EVM. The selected CTs require no power source since the voltage output is generated electromagnetically from the current flowing through the measured wire. Figure 14 shows an example of EVMs wired to CTs located inside power sub panels.

Figure 14. Motes connected to current transducers monitoring energy loads in building sub panels.

Control Logic Software – Phase 1

The control software was designed to allow the sophisticated user (either the installer and/or commissioning agent) to set up different control algorithms to implement 1) a simple occupancy sensor, 2) an open-loop daylight control algorithm and 3) a simple demand response control algorithm. In addition, the software allows the user to monitor a channel using a virtual strip chart recorder and to make "advanced" changes in the operation of the software.

Software Control Logic Diagram

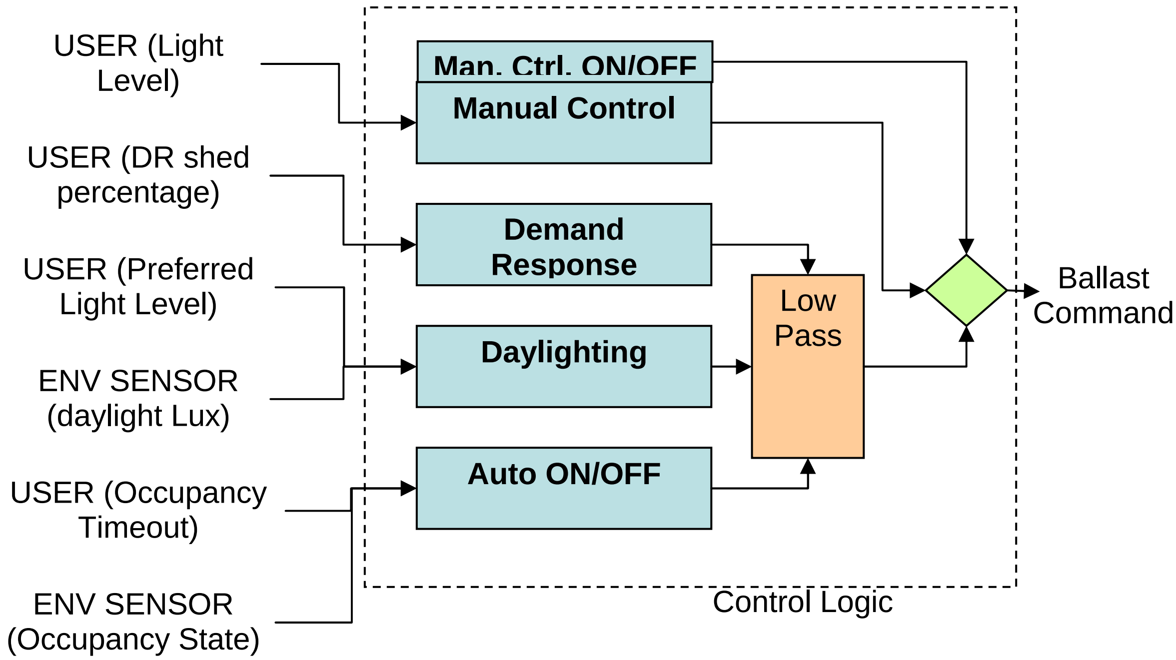

Figure 15. Control Logic Software Flow Chart

Inputs to the Control Logic Software include:

1. User defined light level (% Brightness): Light level for ballast when manual control mode is selected
2. User-entered demand response setting (% of existing): Light level will be reduced by an amount defined by operator.
3. User preferred light level setpoint: value (in Lux) will be used in daylighting mode to adjust ballast light level based on the environmental sensor illuminance measurement. The
4. Environmental Sensor illuminance: measured light level (in Lux) will be used to adjust ballast light level in daylighting mode. The sensor is mounted so as to measure only the external daylight. Since light from

the dimmable lamp (ballast) is not measured, this strategy is known as open-loop daylighting control.

5. User Occupancy timeout: desired amount of time (in minutes) after the occupancy sensor indicates no occupancy in a room before the CLS reduces the room light level to 0%
6. Environmental Sensor occupancy: sensed occupancy in zone of sensor

Outputs of the Control Logic Software include:

1. Ballast commands

Feature Description

The control logic software maintains control of commercial lighting systems in a manner that provides occupants with the following convenient, energy efficient features:

- **On/Off Control -** The light turns ON and OFF through use of the occupancy sensor in the environmental sensor.
- **Manual Dimming Control** - When the system is in “Manual” mode, the value of the dimming level signal to the ballast is set by the user through the Graphical User Interface (GUI).
- **Automatic Control** - When the system is in “Automatic” mode the lowest signal (up to and including OFF) of the following three sources is sent to the ballast:
  1. **Demand Response (DR)** – The GUI to the Demand Response mode allows the user to enter a desired “Shed” value as a percentage of the existing ballast light level output (from the mote’s perspective). After the shed percentage is entered, a mode control switch in the GUI allows the operator to initiate and later exit the DR mode. Upon initiation of the DR mode, the existing ballast light level output is checked. Next, the DR ballast light level output is calculated and sent to the ballast. The DR ballast light level output is a percentage of the existing level (e.g., if the existing level was 80% and the DR mode called for a 50% shed, the DR ballast light level output would be 40%).
  2. **Automatic ON and OFF Function (Auto-OFF)** – Upon detecting occupants, the system will automatically turn lights ON. Lights automatically turn OFF 5 minutes (adjustable) after the occupant has left the zone.

3. **Daylighting Mode** - Light level automatically adjusts to maintain predetermined user-defined illuminance levels during daylighting control mode. Saves energy by reducing lighting power when daylight is available. In daylighting control mode, the user can adjust the curve used to determine open-loop light level settings. The control logic will adjust the light output to correspond to the measured light level. For example, when the illuminance measurement increases, the control logic will reduce the ballast light level output. The control algorithm for this functionality is a linear (ramp) function. The characteristics of the ramp are set-up manually through a calibration procedure.

Display – Power level, although not directly used to determine actuation commands, is viewable through the software GUI.

Control Logic Software – Phase 2

In the second phase of control software development, a set of features based on closed-loop control of light level were added. Although the Phase 1 functions remain usable, only the new features are described in the following section.

For the vast majority of control applications, closed-loop control is considered more advanced in terms of performance and efficiency than open-loop control. In closed-loop control systems, the desired setpoint or target value is set by the user of the system. The system uses sensor(s) to measure the parameter of interest, (e.g., light level) and compares this to the setpoint target. If the measured value is less than setpoint, the closed-loop control algorithm will increase the output signal to the final control element (e.g., dimmable ballast) until setpoint is achieved. The inverse occurs if the measured value exceeds setpoint.

The following analogy contrasts the differences between open and closed-loop control. An automobile “cruise-control” system is a type of closed-loop control. As the car goes over a hill, the system will increase the throttle going up and decrease it going down the hill as necessary to maintain a fixed setpoint (e.g., 55 mph). By contrast, if a car had open-loop control, the throttle could be set at a fixed position. While a constant speed could be maintained on a flat road, the car would slow down going uphill and exceed the speed limit going down.

Software Control Logic – Phase 2 Diagram

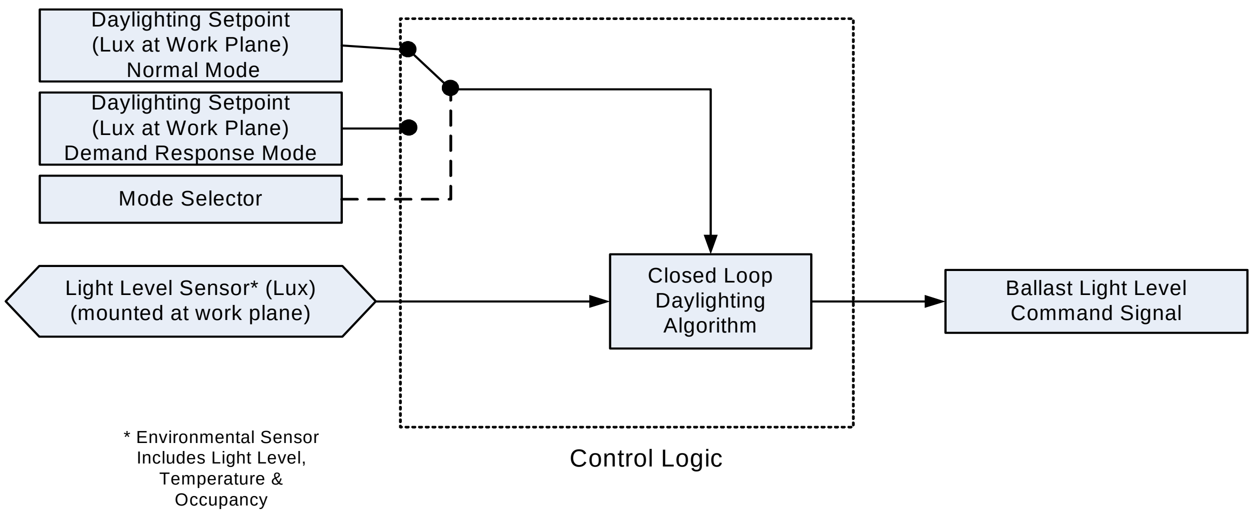

Figure 16. Control Logic Software – Phase 2 Flow Chart

Inputs to the Control Logic Software include:

1. User defined light level setpoint: Light level (in Lux) at the work plane (i.e., desktop). This value is entered via the graphical user interface.
2. User defined light level setpoint Demand Response mode: Light level (in Lux) at the work plane (i.e., desktop) during DR events. This value is entered via the graphical user interface.
3. Light Level (Environmental) Sensor illuminance: measured light level (in Lux) will be used to adjust ballast light level in daylighting modes. The sensor is mounted at the work plane (desktop) and measures the sum of daylight and light from the dimmable lamp (ballast). This strategy is known as closed-loop daylighting control.

Outputs of the Control Logic Software include:

1. Ballast commands

Feature Description – Closed-Loop Daylighting Control

Closed-loop daylighting control was designed, implemented, and tested in Phase 2 of the project. This energy saving feature was used for both "normal" daylighting as well as demand response mode (figure BBB).

- **Daylighting Mode** - Light level automatically adjusts to maintain predetermined user-defined illuminance levels at the work plane (desktop). Saves energy by reducing lighting power when daylight is available. In daylighting control mode, the user can adjust the light level setpoint that will be maintained by the closed-loop control algorithm. The characteristics of the closed-loop control algorithm were optimized by researchers (figure CCC). This simplifies the user experience by removing the need for a ramp calibration procedure required by the Phase 1 software.
- **Demand Response (DR)** – Demand Response mode allows the user to enter a desired "DR" value as a reduced light level that will be maintained at the work plane (desktop) during DR events. Under some conditions, this innovative strategy can ensure the desired DR light level from daylight alone and turn off the dimmable ballast completely (figure DDD).

Graphical User Interface Screens

Operators/commissioners of the wireless lighting system use a computer based Graphical User Interface (GUI) to monitor and set up the system. It is not necessary for a user or occupant of a facility illuminated by the system to use a computer to operate their lights. However, the Main tab was created as an example of the kind of interface that would be useful for both operators and occupants. The other tabs are designed for operators only.

Main Tab

The Main tab (Figure 17), provides the operator with an overview of the system. The current ballast command signal level is shown (lamp level %). The lamp % shown on the Main tab is the actual value of the signal sent to the ballast, regardless of the current mode of operation. The occupancy status and Demand Response (Utility Status) are also shown.
The mode of lamp operation is selected by clicking either the "Auto" or "Manual" buttons. When in Manual mode, the lamp percentage is set from this screen. When in Auto mode, the lamp percentage is set by values generated by the Daylighting, Demand Response, or Occupancy algorithms.

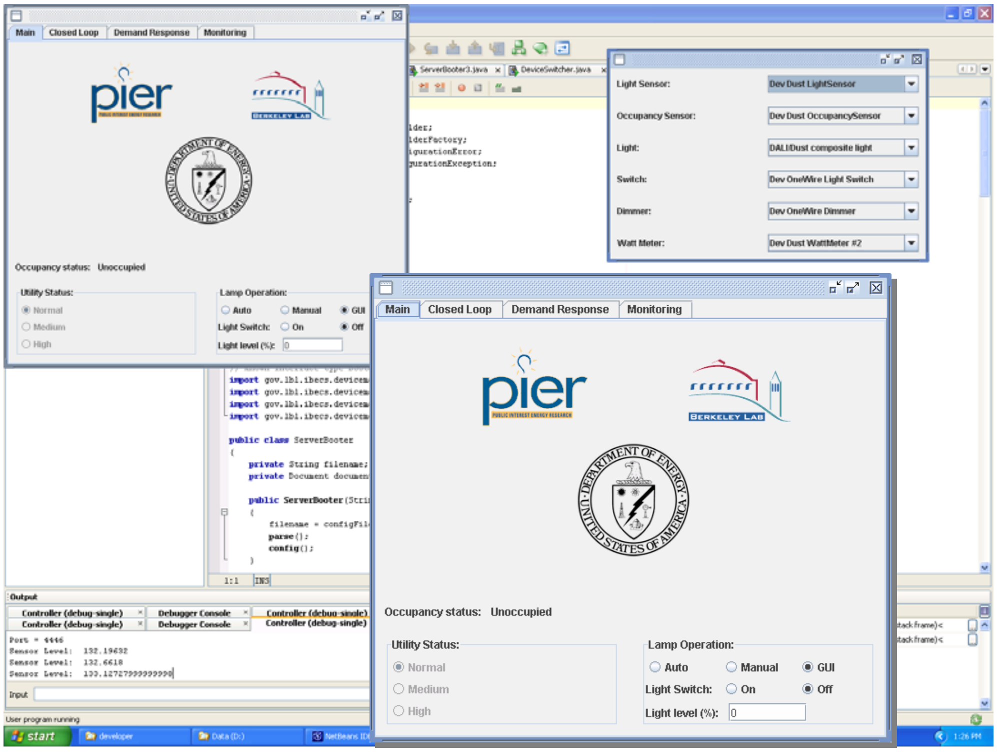

Figure 17. Control Software Graphical User Interface: Main Tab

Daylight Ramp

The Daylight Ramp (Figure 18), allows the operator to fine-tune the daylighting algorithm so that it provides the proper ballast light output in response to various daylight conditions measured at the site. This feature enables the lighting system to minimize use of electric lighting when natural daylight from the windows is available. By adjusting the slope of the ramp, the system can be set up to be very responsive to minor changes in the measured daylight or to be comparatively insensitive. The slope of the ramp is defined by entering end-points of the slope. The program automatically adds the “ceiling” and “floor” so as to give bounds to the control range. In the example shown, the Light Level % will vary inversely and proportionally with the measured day light sensor value. As the measured daylight level goes up, the Light Level output to the ballast will go down. The light level will never drop below the 20% “floor” or rise above 80% “ceiling” due to the values programmed in this example. Note: The sensitivity or “gain” of the system described above is independent of the fade rate. The fade rate is the rate at which the ballast goes from one light level value to another. This value is set using the Advanced tab of the GUI. The fade rate value is stored in the ballast.

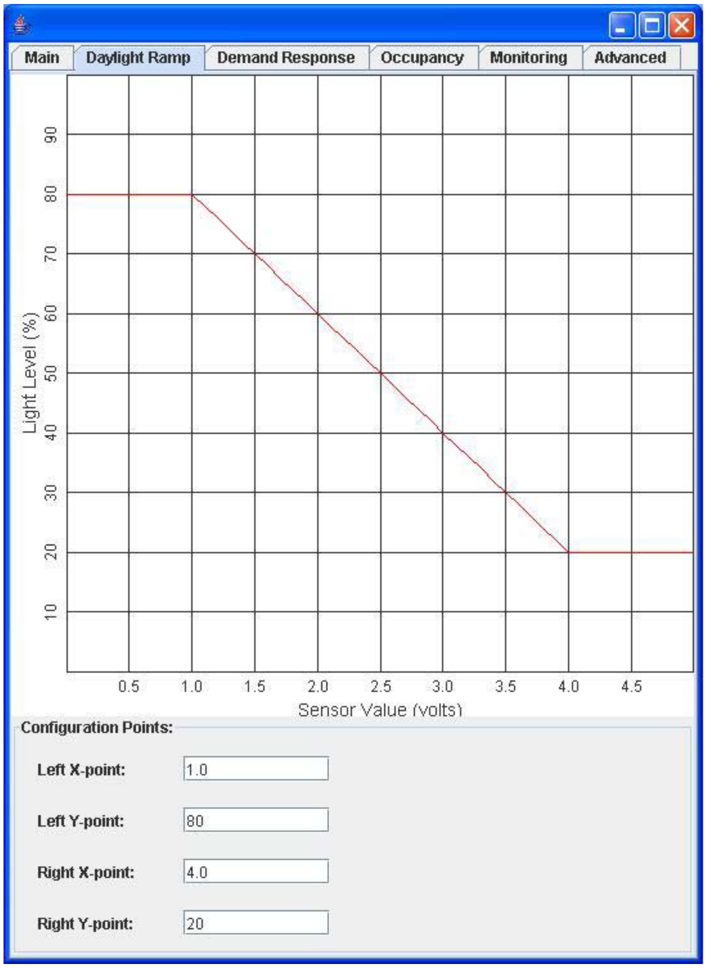

Figure 18. Control Software Graphical User Interface: Daylight Ramp

Demand Response

The Demand Response tab (Figure 19), allows the operator to set up the behavior of the system during demand response events. The values entered under Normal, Medium and High data entry fields show the percentages that the light level will be reduced when the system enters each of those modes. The mode level can be set by the operator. This interface gives operators the ability to configure pre-determined behaviors for various levels of demand response. The existing software is designed for “operator in the loop” demand response programs. A utility or other entity would announce upcoming demand response events to the building operator via phone, e-mail, pager etc. At the agreed time, the operator changes the Demand Response mode from Normal to Medium or High reduction levels. This action would cause the system to enter a pre-determined level of demand response. Note: the control logic software is designed so as to allow future upgrades that would allow a utility or other entity to initiate the demand response event automatically, without operator in the loop.

Figure 19. Control Software Graphical User Interface: Demand Response

Occupancy

The Occupancy tab (Figure 20), allows the operator to set up the time delay until the system shuts off the lights in an unoccupied space. It also shows whether the space is currently occupied. The time delay shown in figure 5 is 30 seconds, which is useful for system demonstration purposes. In a system set up for normal use in an occupied facility, time delays between 300 and 600 seconds are more practical values.

Figure 20. Control Software Graphical User Interface: Occupancy

Monitoring

The Monitoring tab (Figure 21), allows operators to monitor the power used by the lights in the system. As the light level varies, the measured power varies accordingly. The measured power is plotted against time (seconds) in a strip chart recorder type indicator shown.

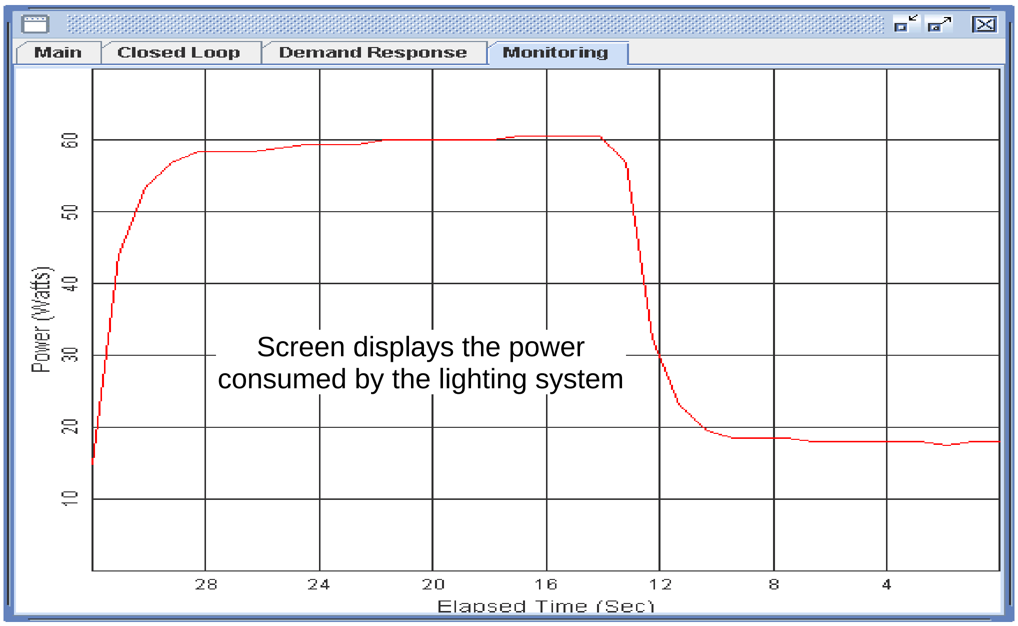

Figure 21. Control Software Graphical User Interface: Monitoring

Advanced

The Advanced tab (Figure 22), allows operators to set-up and calibrate two advanced, seldom used functions:

1. Occupancy Sensor trigger voltage: The trigger voltage defines the threshold for which the occupancy sensor defines the occupied state.
2. ACM Fade rate: The fade rate is the rate at which the ballast goes from one light level value to another. This value (0-255) is set using the Advanced tab of the GUI. The fade rate value is stored in the ballast.

Figure 22. Control Software Graphical user Interface: Advanced

Commissioning

The Control Logic Software gives the operator tools to perform the following tasks:

- Identification: Each network component is identified as a ballast, environmental sensor, or power meter
- Grouping: Corresponding environmental sensors, ballasts, and current sensors are grouped to determine control links (i.e. light level from sensor A drives ballasts X & Y).

System Testing

Test Set-up – Phase 1

The functionality of each ballast, ACM & environmental sensor component was tested by a contractor prior to shipment to LBNL. At LBNL, system level tests were conducted. Both environmental sensors were placed within range of the SmartMesh Manager inside a cubicle. One sensor was placed on the work surface and the other on top of the monitor in the space. As the input parameters were changed, the sensors' readings were observed through the SmartMesh software.

After resetting the Dust Mote, it took the usual amount of time for the motes to join the network (~90 seconds). Once visible to the network, the environmental sensor profile is downloaded to the motes. From the SmartMesh Console software the voltage values for the light sensor and the occupancy sensor are both accessible. The slope and cross-over points for the trend line are entered using the tool provided by the Smart Mesh software so as to view the approximate values for the light sensor.

The system testing efforts concentrated on fixture and ACM integration. Figure 23 shows the fixture and ACM test set up.

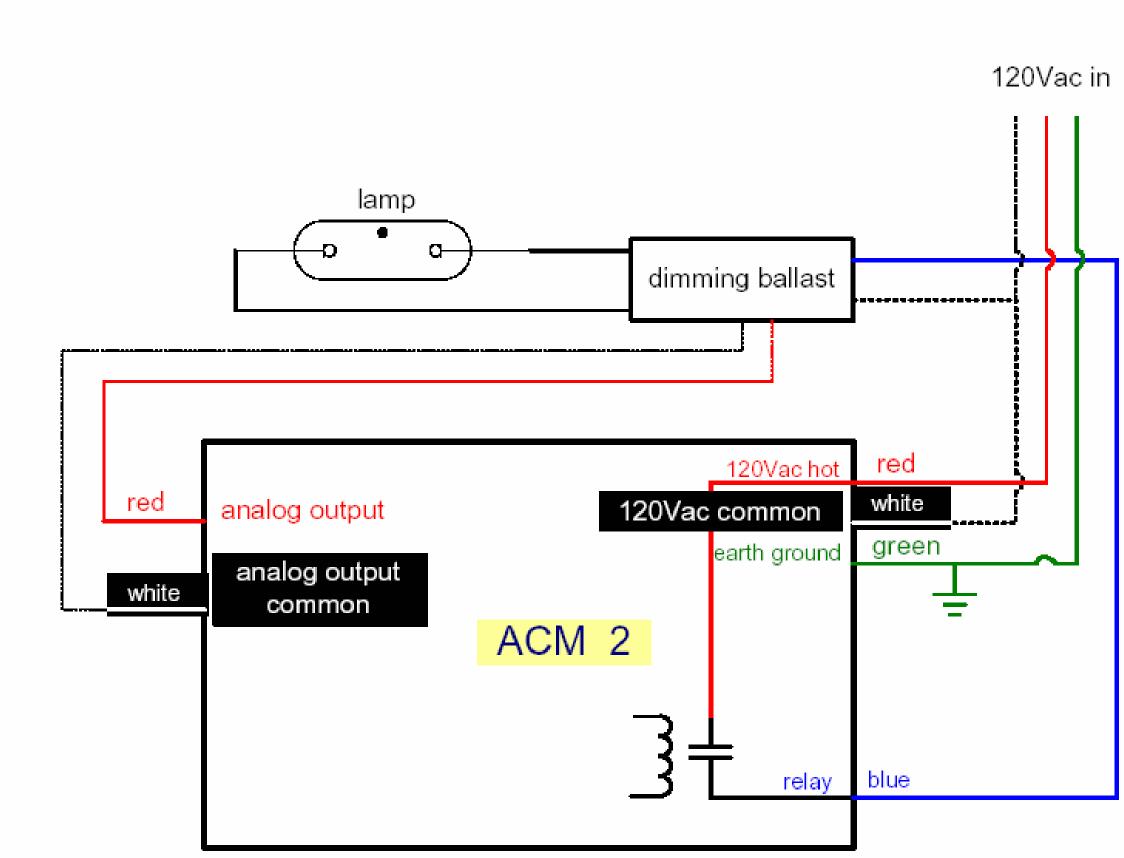

Figure 23. Fixture/ACM set-up for system testing

Test Set-up – Phase 2

The test set-up for phase 2 is shown in Figure 24.

The set-up includes:

- Wireless lighting control system
  - Wireless dimmable ballast
  - Wireless light sensor
  - Wireless Dust Manager and associated PC hosted control logic software.
- Measurement, verification and other test equipment used to test functionality and performance of the wireless system
  - Simulated daylight lamp controlled by (wired) data control and acquisition system (DCAS).
  - (Wired) light sensor (scientific grade sensor used to verify functionality and performance of wireless light sensor.

- (Wired) power meter used to verify functionality and performance of wireless lighting control system.

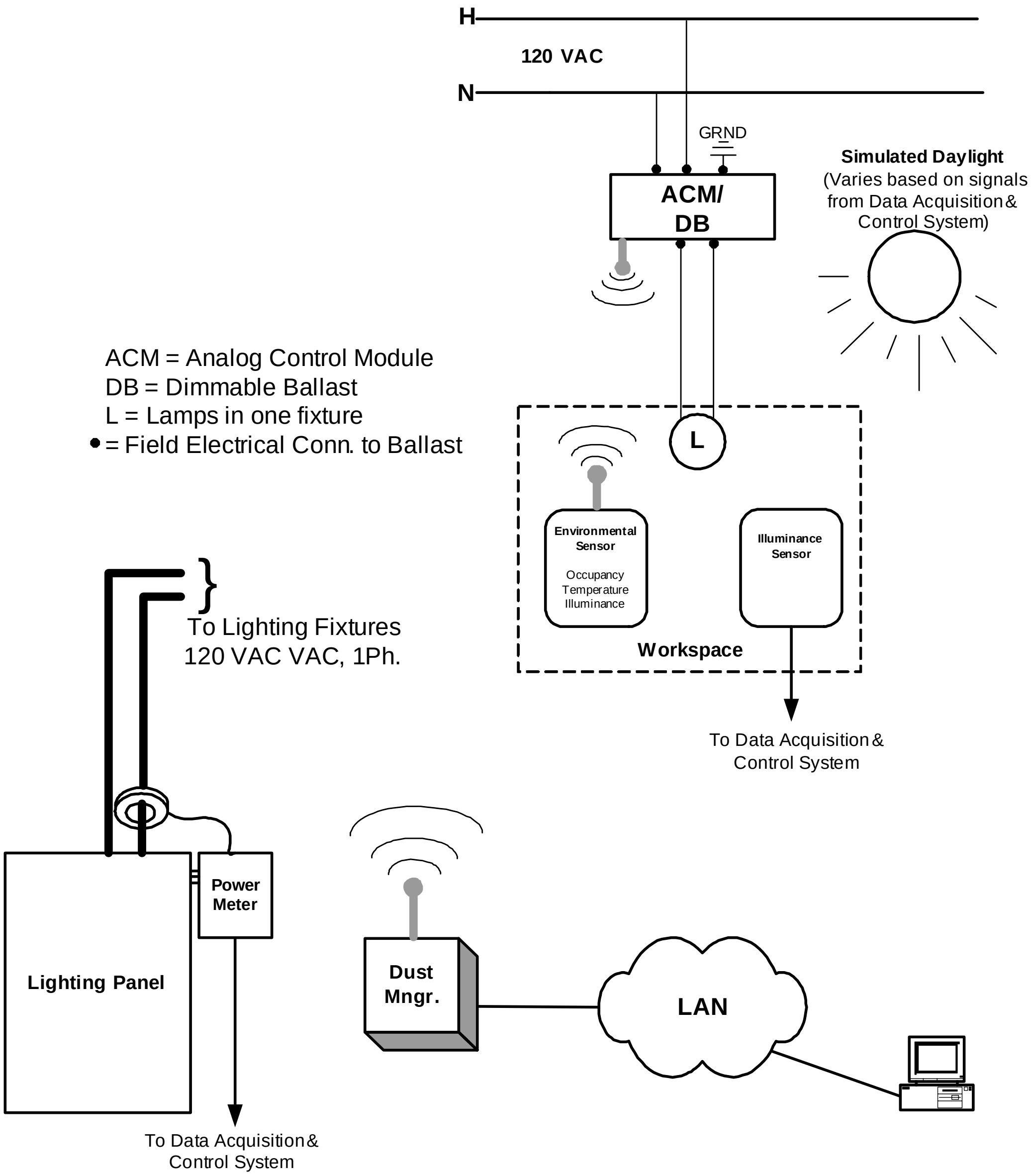

Figure 24. Phase 2 Test Set-up

Test Results

Closed-loop daylighting control test (see Figure 25).

The simulated external daylight level was varied by the DCAS so as to simulate changes in external light level that occur naturally due to outside ambient light conditions. The rate of change was greatly accelerated for test purposes.

The light level setpoint at the work plane (desktop) was set to 250 Lux. The wireless sensor was placed on the work plane.

As the simulated external daylight level varied, the wireless system (sensor, Dust Manager, ballast) varied the light output of the lamp so as to maintain a constant light level of 250 Lux on the work plane. Although some undershoot and overshoot was measured during transitions of the external light source between light at dark, the wireless system was able to regain stable control with 25-30 seconds. Since naturally occurring ambient light varies much more slowly then the simulated light source used in this test, we are confident that the wireless system is well suited to provide stable light level control in real-world conditions.

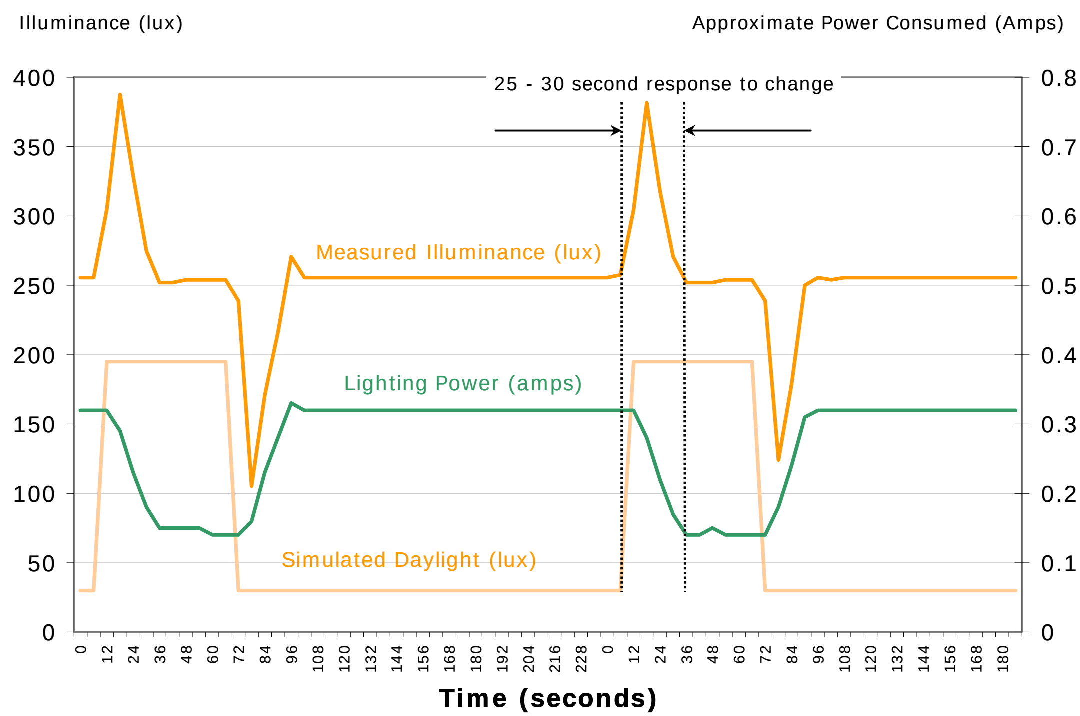

Figure 25. Phase 2 – Closed-loop lighting control –measured values

Closed-loop daylighting control test – Demand Response Mode (see Figure 26)

In the Closed-loop daylighting control test – Demand Response Mode, the wireless control systems maintained work plane light level setpoint similar to the previous test. However as the Lux level setpoint was reduced from 360 to 290, the power used by the lamps reduced accordingly. As the Lux level setpoint was reduced from 290 to 205, the power level dropped to zero. Under these conditions, the light level setpoint on the work plane was maintained using external daylight alone. As the daylight reduced, the system caused the ballast and lamp to re-energize and add light as necessary to maintain setpoint.

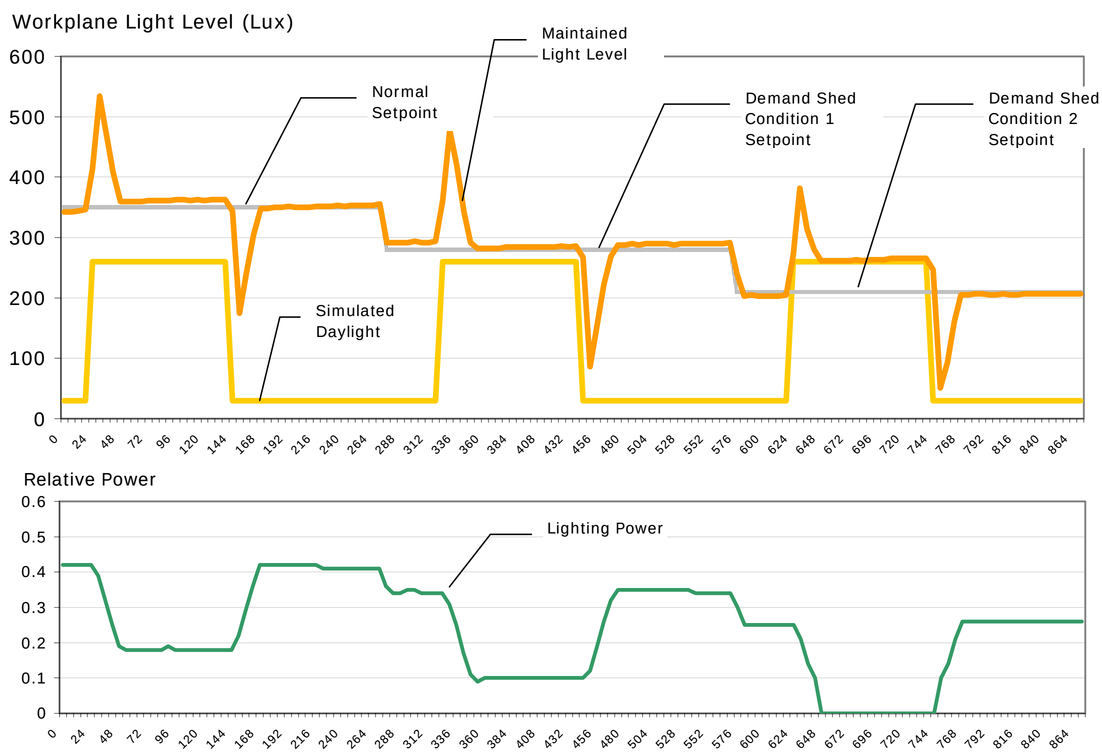

Figure 26. Phase 2 – Closed-loop lighting control – demand response mode measured values

Single-Chip Mote Feasibility

The embedded SmartMesh wireless Motes used for this project were primarily multi-chip modules consisting of a radio, microprocessor, and associated circuitry. In order to demonstrate feasibility for further cost reduction, single-chip wireless devices were tested. The chips were attached to boards with a similar form factor to the multi-chip Motes for ease of testing in ballasts and ACMs.

These devices were tested in bench-scale systems, and shown to respond to commands from the Control Logic Software.

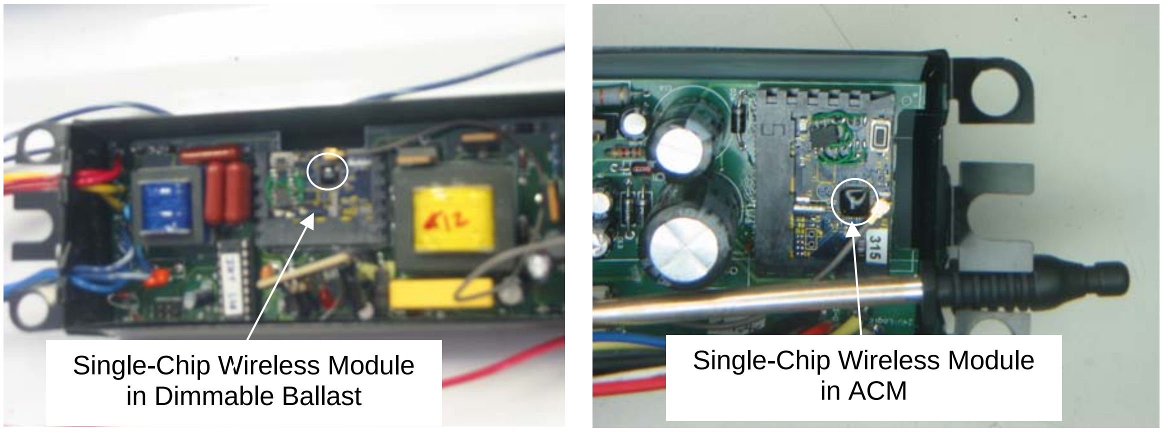

Figure 27. Single chip mote mounted on board and installed in Dimmable Ballast (left) and ACM (right)

In volume, single chip wireless devices could also be programmed specifically for lighting control applications, thereby eliminating the need for additional processor components in the ballast, and contributing to further cost and layout space savings.

Cost & Energy Savings Analysis

A cost analysis was conducted by examining market penetration, component cost, and system payback for advanced wireless lighting control systems. Starting with estimates of market penetration based on a growing demand for energy-saving systems, annual ballast sales can be used to drive ballast cost estimates, which in turn provide input for system-level analysis.

Market Penetration

The penetration of advanced wireless lighting controls into the commercial lighting market over the next 20 years is likely to increase in a standard S-curve fashion, with early adopters in the first years of product availability followed by a wide scale adoption of the technology about 6 years after introduction. By understanding the total market size, the number of ballasts shipped can be calculated. Figure 28 shows the estimated total commercial building floor space, broken down by existing floor space and cumulative new floor space since the beginning of the period. In 2004, approximately 70 billion sqft of commercial floor space existed. By 2030, commercial floor space will increase to over 100 billion sqft, over half of which will be built after 2004.

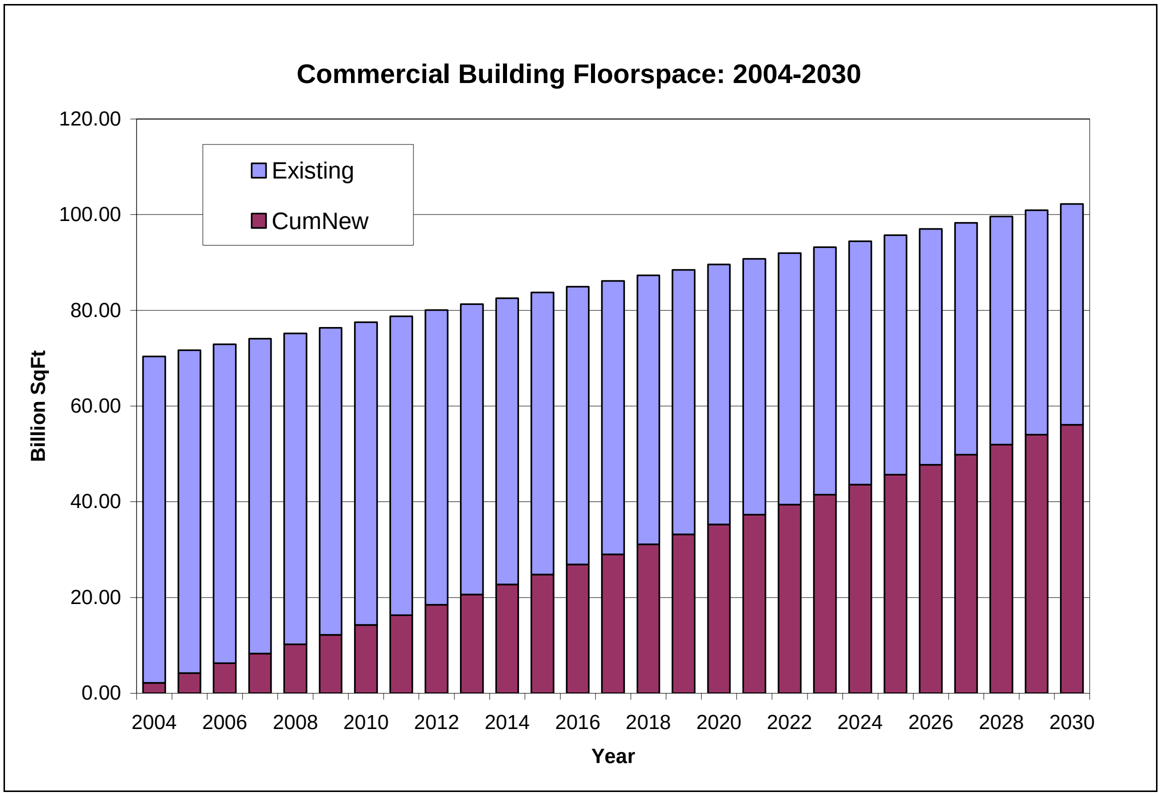

Figure 28. U.S. Commercial Floorspace, 2004-2030.

Three market penetration scenarios are considered: 15%, 30% and 60%. In each case, market penetration is ramped in an S-curve over 20 years, ending at these penetration scenario levels in 2025. Cumulative energy savings and the total number of ballast units sold with respect to market penetration are shown in the table below.

	60%	**30%**	**15%**
Cumulative Energy Savings (quads)	16.90	8.45	4.23
Cumulative Ballasts Sold (millions)	782	277	195

Cumulative Energy Savings and Wireless Dimmable Ballasts Sold through 2025 for 60%, 30%, and 15% Market Penetration.

A breakdown by year for the 30% saturation scenario in Figure 29 illustrates the ramp of ballasts sold and the significant annual impact on energy used for commercial lighting (nearly 75 BkWh/yr by 2025). According to a modest climb in the early years of market penetration, annual ballast sales will exceed 2 million units annually from initial usage through 2009. Annual shipments will climb to over 16 million units in 2010 and over 45 million units in 2011.

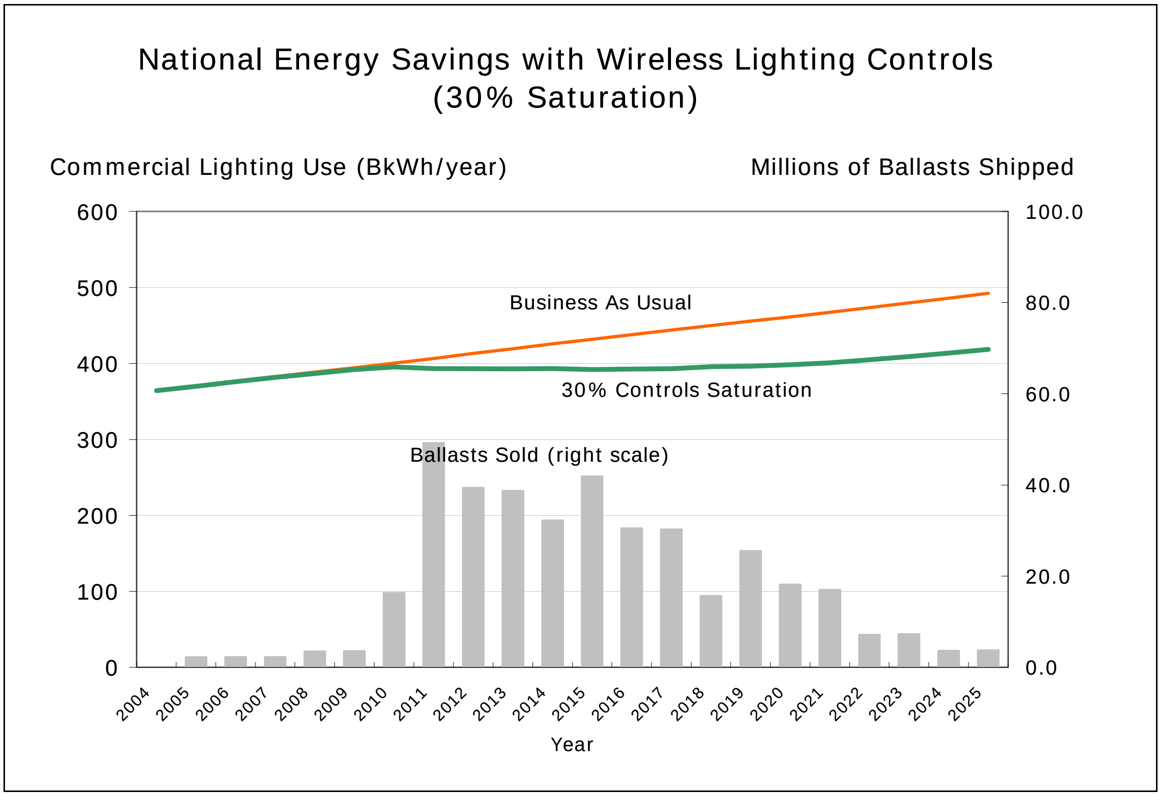

Figure 29. National Energy Savings with Wireless Lighting Controls at 30% Market Saturation.

Component Costs

The potential market for hundreds of millions of wireless dimmable ballast shipments will drive manufacturers of ballasts and of wireless products to competitive high-volume component pricing. We estimate standard commercial dimmable ballasts costs of $20 are achievable with the 30% market penetration scenario.

In high volume, adding wireless function to commercial ballasts requires integration of only two additional components per ballast: 1) a wireless chip with embedded lighting application and networking code and 2) an antenna. Because of the relatively close spacing of ballasts, forming a mesh network with inexpensive wire whip antennas is straightforward.

Wireless mesh networking products are already being produced as single chips, with volumes being driven by a variety of industries, including building automation, industrial process monitoring, and security. Industry analysts expect a compound annual growth rate of 200% between 2004 and 2009 for 802.15.4

chipsets, and over 150 million units shipped annually by 2009[1]. Commercial vendors of wireless networking chips are currently advertising pricing of $2.30 for million-unit quantities[2], which makes feasible the target $3 adder for the total integrated wireless ballast.

System Installation & Payback

Based on a $20 ballast cost and $3 wireless adder, system installation costs and payback of a wireless control system can be computed and compared to traditional alternatives.

Wireless control offers many benefits over wired control, like system flexibility and ease of installation. Reduced wiring translates directly into reduced installation costs. And so we compare the installation cost of a wireless retrofit system with a wired version capable of the same advanced lighting control. The following retrofit cost breakdown applies to a 16,000 sqft. commercial building area, assuming the same number of ballasts, fixtures and sensors are installed for each scenario.

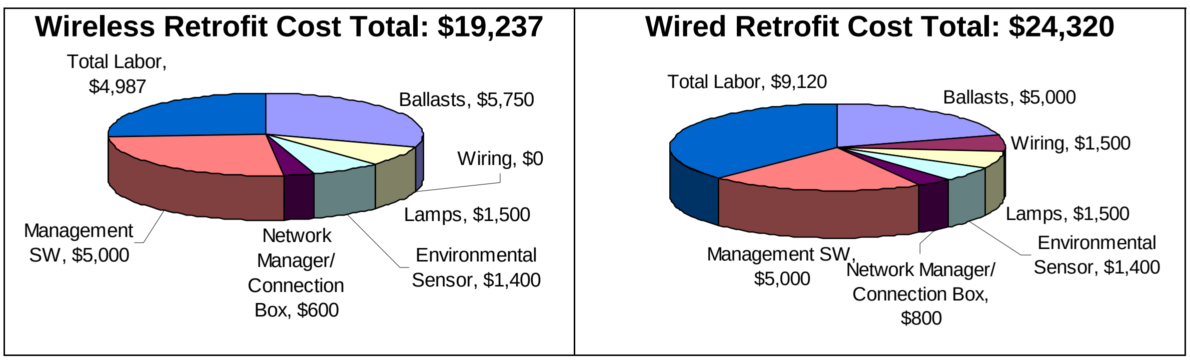

Figure 30. Breakdown of Retrofit Costs: Wireless vs. Wired

The cost breakdown in Figure 30 shows that the wireless retrofit offers more than a 20% total savings with respect to the wired retrofit cost. This analysis assumes ballasts prices of $20 for wired dimmable ballasts and $23 for wireless dimmable ballasts. Although the wireless ballasts are slightly more expensive than the wired version, this is more than compensated for by the 45% reduction in labor costs, elimination of wiring costs, and reduction in network management costs.

The labor required to install a wired retrofit system includes ballast and lamp replacement, control wiring installation, and commissioning. A wireless system retrofit necessitates ballast and lamp replacement, but eliminates wiring

[1] In-Stat, June 8, 2005, "802.15.4 Market Could grow 200% by 2009 Reports In-Stat," http://www.instat.com/press.asp?ID=1356&sku=IN0501836MI

[2] November 21, 2005 Press release, "Chipcon Launches a high-performance and low-cost 2.4 GHz true SoC with radio, Flash, and MCU," http://www.chipcon.com/index.cfm?dok_id=257&kat_id=6

completely, and decreases commissioning labor by about half. For a typical wired installation, a significant portion of the commissioning process is dedicated to troubleshooting and testing wiring connections. By eliminating this time consuming operation, commissioning can be completed much more rapidly. Additionally, network management of a wired system requires costly gateways and signal conversions to tie the lighting controls to building control programs. A Dust Networks' Manager can be connected directly to a building LAN. Network monitoring and control can be performed directly over this link.

Payback for lighting control systems comes in the form of energy savings. Energy is saved by implementing advanced controls, and also by adopting more efficient components, like changing from 120 Watt to 80 Watt lamps. In the payback analysis shown, half of the energy is saved through improved lamp efficiency, and the other half is due to control algorithms. Figure 31 shows how the time required for system payback decreases as energy costs escalate. Because of the initial costs associated with system management & software, the payback period also decreases as building area increases, as shown in Figure 32.

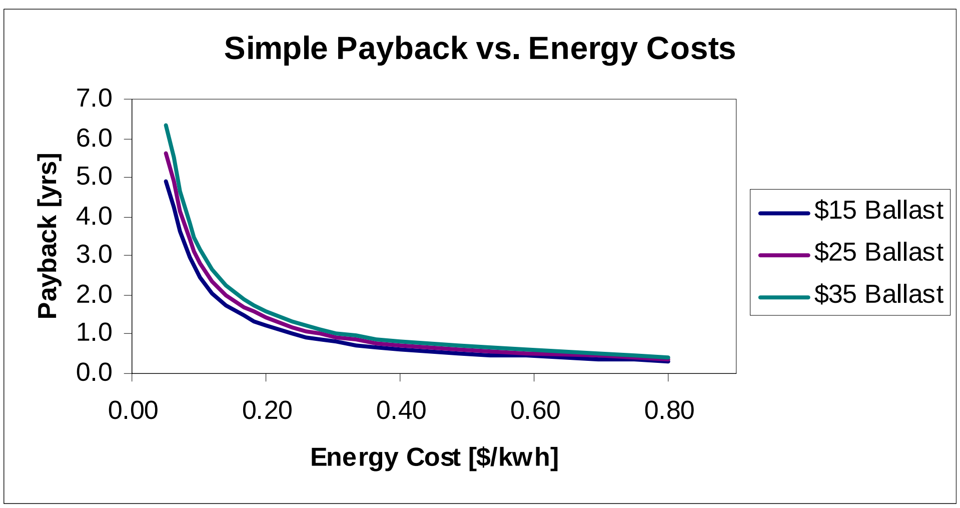

Figure 31. System payback versus energy costs for $15-$35 integrated ballasts. Assumes 16,000 sqft building and 50% energy savings through advanced controls.

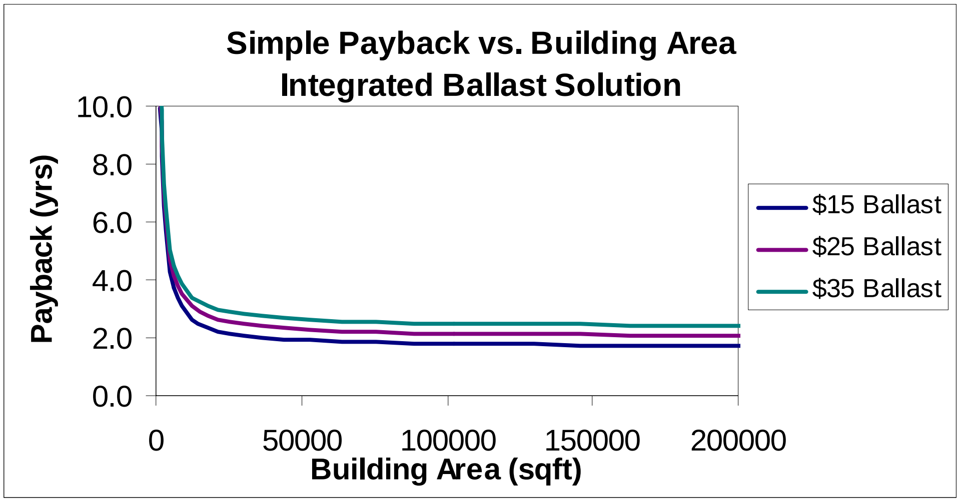

Figure 32. System payback versus building area for $15-$35 integrated ballasts. Assumes 0.10 $/kwh energy cost and 50% energy savings through advanced controls.

This work has demonstrated an alternative to total wireless ballast retrofit. For the case where dimmable ballasts are already installed, or intelligent on/off control is desired with existing standard ballasts, an Analog circuit module (ACM) can be used to drive multiple ballasts. This option represents a bridge product that allows advanced lighting control with low total installation costs, but may sacrifice some of the performance and flexibility that is achieved with individually-addressable ballasts. Figure 33 shows installation costs for the fully-integrated wireless and wired ballast solutions and for the ACM solution (no new ballasts needed).

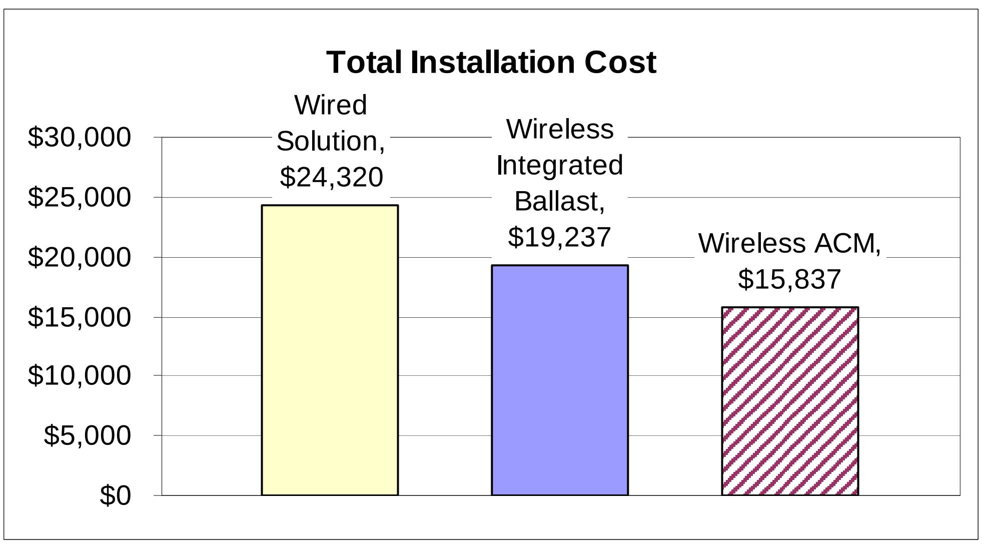

Figure 33. Total Installed Cost of wired, wireless and ACM solutions.

Conclusions & Recommendations

The potential for over 50% lighting energy savings using advanced lighting control systems make them an attractive alternative to traditional lighting control. Wireless mesh networking technology lowers the installation costs for such lighting systems by eliminating the need to run and troubleshoot control wiring. On a national scale, the tremendous environmental impact of 30% market penetration saturation is summarized in Figure 34.

Estimated National Energy Savings from Wireless Lighting Controls Installed in U.S. Commercial Buildings

Years	Cumulative Energy Savings (Billion kWh)	Value of Accumulated Savings ($ Billion)	Avoided Carbon Emissions (MM TCe)	Millions of Cars Removed, Equivalent
Present thru 2025	695	52	139	93
Present thru 2015	104	8	21	14

Figure 34. Estimated National Energy Savings from Wireless Lighting Controls Installed in U.S. Commercial Buildings

By engaging with committed stakeholders such as utilities and state energy agencies, the DOE can promote wireless lighting control use through incentive programs and bulk procurement in the Federal market sector. Additionally, the DOE can work side-by-side with industry and research organizations to accelerate the implementation and adoption of variable output lighting systems.

Using a wireless system, installation costs for a lighting system retrofit are reduced by more than 20% over wired systems. Although technical feasibility has been demonstrated and low-cost components are becoming available, market adoption will largely be a function of the aggressiveness of regulatory agencies to mandate energy saving technologies for both existing and new commercial buildings.

Appendix A – ACM and MDB Functions

The following functions list is made up of 3 sections:

1) Commands sent to the ACM/MDB – these are commands that are transmitted wirelessly to the embedded mote in the ACM/MBD and result in a function performed by the ACM or ballast
2) Operating conditions – these describe functions performed by the ACM/MDB in response to changes in operating conditions
3) Status commands – the ACM/MDB responds to these commands with status messages that are sent wirelessly to the SmartMesh Manager, where they can be read by the control logic software.

Commands sent to the ACM/MDB:

BC1) On/OFF
{Used in conjunction with "Lamps Set Level" command}
Ballast: Turns on/off lamps – {power to ballast is not switched off}. When turned ON lamps goto "Lamps set Level" without fade. An OFF would set the lamps to off (0).
Analog Controller: Opens and closes relay contact. Intended to control ballast power. When turned ON 0-10 volt output is at "Lamps Set Level"

BC2) Set Level (Low level - Full level)
{Used in conjunction with "Lamps On/OFF" command}
Ballast: Sets lamp output level value between 0% and 100%. Low level is determined by actual ballast design, 5%, 10%, etc.
Analog Controller: Sets Analog output level value between 0V and 10V. Low level of lamps is determined by actual 0-10V ballast design, 5%, 10%, etc.

BC3) Fade rate set point (0-10min) {0=no fade time ... 255 = 10 min} (Default to '0')
{Used in conjunction with "GOTO set level with fade" command}
Ballast: Provides option to adjust the light output over time.
Analog Controller: SAME

BC4) GOTO level (Low level - Full level) with fade;
{Used in conjunction with "Ballast fade rate set point command}
Ballast: Sets lamp output level value between 0% and 100% using fade rate set point value. Transitions the lamps from current level to the new level.
Analog Controller: Sets Analog output level value between 0V and 10V using fade rate set point value. Low level of lamps is determined by actual 0-10V ballast design, 5%, 10%, etc.

BC5) Clear lamp runtime counter (Default to '000000')
{Used to clear the runtime counter to "000000"} Hours of operation

BC6) Demand Reduction Level 1 {0% - 100%} (Default to '100')
Ballast: Sets Maximum light output level and transitions lamps to level specified if lower then current level and if level is higher then current set point no action. (using stored rate in device)
Analog Controller: Sets Maximum 0-10V level and transitions 0-10V output to level specified if currently above Level 1 set point.

BC7) Demand Reduction Level 2 {0% - 100%} (Default to '100')
Ballast: Sets Maximum light output level and transitions lamps to level specified if currently above Level 2 set point.
Analog Controller: Sets Maximum 0-10V level and transitions 0-10V output to level specified if currently above Level 2 set point.

BC8) Demand Reduction Reset for Level 1 and Level 2
Command resets max level to 100% for level 1 and level 2 and lamp set level is know set to demand reduction {last level command is changed}.
Ballast: Resets Maximum level to 100% and does no action with output.
Analog Controller: SAME

BC9) Lamp Warning (also known as blink or flash) Warning is done quickly < 1 sec.
Ballast: Lamps go from current level to Max Level – then to 10% - and back to initial level
Analog Controller: 0-10V output goes from current level to Max Level – then to 2V - and back to initial current level.

BC10) GOTO previous Level
Ballast: Device retains the previous level of the lights prior to a change of state. When command is received the lamps are changed to the previous level with fade.
Analog Controller: Device retains the previous level of the 0-10V output prior to a change of state. When command is received output is changed to the previous level.

Operating conditions:
- Power ON level (Default to '0')

Commands for information returned back to the System:

** BR1) Lamp status On/Off
Ballast: Returns the status of the Lamps (0=lamps off , value > 0 equals percent level
Analog Controller: Sends back the status of the 0-10V output

** BR2) Ballast operating status (to be defined)
Ballast: Returns key information of ballast (operating voltage, lamp failure Status, ?)
Analog: ?

** BR3) Ballast Power level (to be confirmed for capability and defined)
Ballast: Returns the power level of the ballast -
Analog Controller: ?

** BR4) Diagnostic info (to be confirmed for capability and defined)
Ballast: ?
Analog: ?

** BR5) Lamp run time counter (to be confirmed for capability and defined)
Ballast: Returns the value of the counter internal "0000" Used to identify time lamps have been ON.
Analog Controller: Returns the value of the counter "0000" Used to identify time 0-10V has been above "0" level.

**These commands have not yet been implemented.

Appendix B – Ballast Testing and Qualification

LAMP FAULT TESTING	Test for Ballast Only (x)	**LINE DISTURBANCE TESTING**	Test for Ballast Only (x)
Diode Mode Lamp		Brown Out(80%)	
Single Lamp Short	X	Line Drop Out(0%)	
One Lamp Removed	X	Line Surge(150%)	
Red/Blue Short	X	Line Transients(IEEE 587)	
ARC Test	X	Inrush Test	
Wrong Lamp	X	Freq Shifts	
Degassed Lamp	X		
Open Filament	X	**AGENCY TESTS**	
Filament Shorts	X	EMI Conductive	
Potentiometer Test	X	EMI Radiated	
		UL/Leakage	X
MARGIN TESTING		UL/Hipot	
One Lamp out Voltage		UL/Foil Test	X
30sec/30sec Lamp Life Test			
Filament Temp Rise	X	**RELIABILITY TESTING**	
Line Regulation		Multi Thermal Couple	
Voltage Step Stress		Thermal Camera	
Dim Mode % Light vs Power		Temp Step/Stress	
		Cold Strike Time	
COMPONENT EVALUATION		Low Line 2' Lamp Strike 0C	
Capacitive Jar Test		FMEA	
Magnetic Saturation		ESD	
FET SOA		ESS	
DOE		ALT	
50 piece CP,CPK,PPK		Altitude	
Monte Carlo Simulation		Humidity	
		Acoustic Noise	

The following testing requirements are added to the qualification of the product over and above the standard testing for the ACM and MDB.

1. Input Response testing,
   i. Power line variations (regulation, transient noise, line drop out, surge, ESD, etc)--- ACM & MDB
   ii. DUST transmission testing (Multiple sequential commands, transmission distance, lamp arcing/striking interference, Lamp faults, etc) ----ACM & MDB

iii. Wiring faults (power line connections to 10 Volt output, Missing case ground, 10 V output shorts, Lamp current thru relay contacts, reverse +10 VIN)----- ACM
iv. Injected Noise (ground noise, 10 V sparking, Relay contact arcing, DIode mode lamps, missing lamps)-- ACM & MDB

2. Output Response testing
   i. Reverse transmission of faults in the presence of interference (Lamp arcing, diode mode lamps, missing lamps) ---MDB
   ii. Latent time in response to many ballast commanded to change state simultaneously. --- ACM & MDB
   iii. Power line interruption in the middle of a MOTE command ---- ACM & MDB
   iv. Simultaneous transmission of different commands from two mote kits. ACM & MDB
   v. Initialization and Last State recovery from line interruption.

3. Software validation.
   i. Automatic tester for RS232 stacked Vector command injection with various sequences and time intervals. Needed to test
   ii. The command set since the MOTE doesn't allow stacked commands. ACM and MDB
4. Micro interrupt structure analysis during simultaneous fault occurrences and MOTE Transmissions---MDB

5. Fault Tree analysis testing. (Resonator off frequency. low battery, stuck bit, etc) ACM & MDB

6. d. Environmental testing.
   i. Excessive Cold or heat.
   ii. Thermal Shock
   iii. Excessive humidity (Condensing)
   iv. Vibration pseudo-random