

- 2.5 Conduct exploratory investigations and analysis of operational parameters required for each of the control technologies (occupancy sensors, photosensors, dimming electronic ballasts) in common commercial and industrial applications, such as private and open offices and warehouses.**

### ***Exploratory Analysis of Operational Parameters of Controls***

A convenient way of analyzing control devices is to consider a device as a system of inputs and outputs. Inputs to control devices are usually sensors and commissioning set points, and the outputs are control signals that govern the operation of the controlled equipment. Once the inputs and outputs are identified, then the operation of the control device is described by how the inputs affect the outputs. The input/output relationships can either be logical relationships, continuous functional relationships, or a combination of the two. This type of analysis is effective for both small, local control systems such as an occupancy sensor in a room, and for large, distributed control systems where the outputs of devices such as occupancy and photosensors are used as inputs to higher-level building automation control systems. In fact, communication protocols for building automation systems, such as BACnet and LonWorks, are specified in terms of inputs and outputs. This report focuses on occupancy sensors, photosensors, and dimming ballasts, describing them in terms of inputs and outputs.

The information for this report was gathered from the publications cited as well as those listed in the bibliographies, and from manufacturers' web sites, conference seminars, product briefs and interviews with manufacturers.

### ***Occupancy sensors***

Available sensor inputs:

- Passive infrared (PIR)
- Ultrasonic
- Acoustic

Other inputs:

- Sensitivity adjustments (for PIR and ultrasonic)
- Time delay

Outputs:

- On/off power relay
- Bi-level switching on/off power
- Low voltage logic signal (to be used as an input for another controller)

### **Input sensing technologies**

Three sensing technologies are used in occupancy sensors for commercial and industrial lighting applications: PIR, ultrasonic, and acoustic. Products are available

that use either PIR or ultrasonic, or a combination of ultrasonic or acoustic with PIR sensing. The latter are referred to as “dual technology” products.

### ***Passive Infrared***

PIR sensors respond to movement of infrared sources, such as human bodies in motion. A patterned IR transmitting lens is placed in front of a pyroelectric detector that is sensitive to the infrared blackbody radiation emitted by objects at a temperature near and around human body temperature. The patterned lens, typically of Fresnel design, focuses radiation from adjacent wedge-shaped areas of the room onto the detector. As an IR radiating object moves in and out of each segment of coverage, the signal strength received by the detector changes, signaling the detection of movement. Newer designs use a dual-element pyroelectric detector with the elements connected in series with opposite polarity. Changes in the room temperature then do not affect detection, because for static objects, both elements receive the same signal and cancel one another due to the opposite polarities of their electrical connections. The coverage area and sensitivity of a PIR sensor is greatly affected by the type of patterned lens used. Different lens designs are suited for different applications. An overall wide field of view combined with many narrow field of view segments is used for room occupancy sensors, while fewer, larger segments with an overall narrower field of view are used for corridors to maximize to length of the coverage area.

### ***Advantages***

Passive detection does not emit any potentially harmful or interfering signals. It offers the possibility of consuming very little energy to operate (potential for battery operation).

### ***Limitations***

Historically, PIR sensors have had trouble detecting small hand movements. The size of movement for reliable detection depends on the number and size of each wedge-shaped field of view segment that is focused onto the detector. The smaller the segments, the smaller the differential signal strength as an object moves. This places a limitation on how small the segments can get for a detector of a particular sensitivity. PIR sensors must have an unblocked line of sight to detect motion. Room partitions and furniture can prevent PIR sensors from detecting motion. PIR sensors are most sensitive to movement perpendicular to the direction of the sensor, as this type of movement cuts across the wedge-shaped segments. Sensitivity is lowest for objects moving directly towards and away from the sensor.

### ***Ultrasonic sensors***

Ultrasonic occupancy sensors are active devices that must emit ultrasonic sound energy at a frequency typically in the range from 25 to 40 kHz, at sound pressure levels in excess of 90 dB (0.63 Pa). Motion is detected by sensing the Doppler shift in the frequency of reflected sound waves when reflected off moving objects.

### ***Advantages***

Ultrasonic sensors cover the whole volume of the space. A direct line of sight is not required for motion detection, and motion can be detected around partitions such as inside office cubicles and lavatory stalls. Ultrasonic sensors are more sensitive to small movements than PIR sensors.

#### *Limitations*

Emission of relatively high levels of ultrasonic sound energy raises health concerns for long-term exposure, even though most sensor companies claim that their products emit less energy than the safe exposure limits set by organizations such as OSHA and the World Health Organization (WHO). Ultrasonic devices require up to 0.5 watts to generate the ultrasonic signal, so battery operation is not practical. They are also sensitive to air movement as well as body movement; therefore, HVAC system operation can cause false triggering.

#### *Acoustic sensors*

Acoustic sensors are passive devices that respond to sound pressure levels in a space; i.e., a microphone. In commercial and industrial products, these sensors are not used for primary detecting, but rather are used in combination with PIR sensors to reduce the occurrence of false off-triggers. That is, a PIR occupancy detector equipped with an acoustic sensor will only switch off the lights after a period of time during which both the PIR sensor and the acoustic sensor do not indicate occupancy.

#### *Advantages*

Simple passive device.

#### *Limitations*

Since ambient noise levels in buildings vary greatly, and acoustic sounds can travel quite far, acoustic sensors cannot differentiate sounds generated inside a space from sounds generated elsewhere. Also, occupancy does not necessarily generate sound which would lead to annoying false off-triggers in a quiet space. These facts limit the application of this technology to a secondary role in occupancy detection.

#### **Other inputs of occupancy sensors**

To help reduce the occurrence of false triggers, occupancy sensors usually have sensitivity adjustments to fine-tune operation for specific room conditions. Recent designs are incorporating more sophisticated logic for automatically adjusting sensitivity. The incorporation of microprocessors in the devices makes these new features possible at competitive prices. Sensitivity adjustments can be triggered by at least three different inputs: ambient signal strength, time of day, and on/off state of the output.

*Ambient signal strength:* Having sensors automatically compensate for ambient signal strength helps the device distinguish between background “noise” and the more erratic signals generated by occupant movement. Instead of having one sensitivity setting that is a compromise between adequate sensitivity for detection and background

“noise” rejection, certain sensors can dynamically adjust the signal level that causes a trigger. For example, the steady signal caused by HVAC air movement would cause the device to set a higher trigger threshold to avoid a false trigger. In the absence of a steady signal, when the HVAC system cycles off, the trigger threshold would lower, thereby increasing the likelihood of detecting occupancy.

*Time of day:* Sensors with microprocessors are also incorporating real-time clocks that provide a time-of-day and calendar-day input to the device. This information can be used to alter the sensitivity or trigger level of the sensor. Real-time clocks and sophisticated logic are now being combined in a form of artificial intelligence through which the sensor “learns” the daily and weekly routines of motion in the space and uses this information to dynamically adjust sensitivity and/or trigger levels.

*On/off state of the output:* A simpler kind of logic added to occupancy sensors permits different trigger levels to be assigned under different conditions. For example, a false trigger that turns off the lights when the room is occupied is a worse mistake than keeping the light on a few minutes longer when the room is unoccupied. Therefore, when the lights are on, a lower trigger level might be used to insure that the smallest of movements will keep the light on. On the other hand, when the lights are off, the trigger level might be set higher so that only a large movement, like someone entering the room, will trigger the lights to turn on.

Variable time delays for turning off the lights are another method used to avoid false off signals. Under one scenario, if the occupancy sensor erroneously switches the lights off while the room is occupied, the occupant will immediately make a large movement to switch the lights back on. The sensor could be programmed so that if a large signal is detected immediately after switching off the lights, the following time delay for switching off the lights for a second time might be extended. Similarly, the sensitivity could be increased, or the trigger level lowered to avoid future false off conditions.

The extent to which these different types of logic are used and how successfully they are implemented undoubtedly varies for different manufacturers. The above information was distilled from the claims manufacturers make in promoting their products and was not further verified. Nevertheless, the claims demonstrate that occupancy sensor technology for lighting products continues to be refined and developed.

### **Occupancy Sensor Outputs**

The output from an occupancy sensor is a two-state binary signal: occupied or unoccupied. Such a signal can be directly connected to a power relay to switch lights on and off. Occupancy sensors for local control most often incorporate a power-switching relay right into the device, while others provide a logic-level signal that is connected to some other lighting controller.

While the signals from occupancy sensors are two-state, the output does not necessarily have to completely switch the light on and off. In many applications where a certain low level of illumination is always required, occupancy sensors are used for bi-level switching of the lighting. For example, occupancy sensors are used in warehouses to switch on the lights over individual aisles to provide high visibility for tasks such as reading labels, while the unoccupied part of the warehouse can remain at lower illumination levels.

## Photosensors

Available sensor inputs:

- Illuminance (wide field of view)
- Luminance (narrow field of view)

Other inputs:

- Sensitivity (gain)
- Light level set point
- Hysteresis (dead band)

Outputs:

- On/off power relay
- Bi-level switching on/off power
- Continuous dimming level (e.g. 0-10V)

## Background

The input to a photosensor is optical radiation. Loosely speaking, the input is light, but because some photosensors respond to infrared (IR) and ultraviolet (UV) radiation as well, it is necessary to make a distinction between optical radiation that is visible light and other kinds of optical radiation. The response of a photosensor to optical radiation is fully described by the *spatial response* and the *spectral response*.

The spatial response describes the sensitivity of the photosensor to incident radiation from different directions—in other words, what the photosensor “sees” at different locations. Spatial response is analogous to a luminaire intensity distribution, but describes sensitivity instead of output.

The spectral response describes the sensitivity of the photosensor to optical radiation of different wavelengths. This is important because only a small part of the optical radiation spectrum is visible. Daylight and fluorescent lighting differ substantially in spectral composition. Daylight has a comparatively uniform distribution of energy over the near-UV, visible, and near-IR regions of the spectrum. Fluorescent lamps, on the other hand, have most of their output concentrated in the region of the spectrum where visual sensitivity is high. This is one reason fluorescent lighting is so efficient. Even though the exact spectrum of daylight changes depending on weather conditions, times of the day and season, as well as being affected by surrounding buildings and foliage, these differences are small compared to the relative differences in UV and IR

content between daylight and fluorescent light sources. The greater UV and IR content of daylight, combined with the broader than ideal spectral response of most photosensors, makes most photosensors much more sensitive to daylight than to light from fluorescent lamps. A greater sensitivity means that a photosensor will respond as if more daylight were present than actually exists. This can lead to problems where precise switching or dimming levels need to be realized.

### ***Illuminance sensors (wide field of view)***

The signal produced from illuminance type sensors is useful for detecting ambient light levels. A wide spatial response corresponds closely to what an illuminance meter would measure.

#### ***Advantages***

The advantage of a wide spatial response is that the optical signal sensed by the photosensor is representative of the illumination on the whole workplane, or over the entire room, when the sensor is located on ceiling. The optical signal is also less affected by normal activity in the room than for a narrow response sensor.

#### ***Limitations***

The difficulty with a wide spatial response is that the ceiling illuminance does not usually correspond to the workplane illuminance as the balance between daylight and electric light changes. In fact, the ratio of ceiling to workplane illuminance typically changes by a factor of five or more in offices with vertical windows as the proportions of electric light and daylight change. However this non-correspondence in illuminance levels can be largely overcome by the photosensor control algorithm and the above advantages can be realized.

### ***Luminance sensors (narrow field of view)***

Not as common as illuminance type sensors, luminance sensors detect light from a particular direction and over a small field of view. They are used to detect brightness from a distant location; for example, to detect desktop luminance from a mounting position in the ceiling.

#### ***Advantages***

The narrower the photosensor's spatial response, the more closely it responds to the luminance (brightness) of the surface at which it is aimed. The luminance of a surface, in turn, is directly proportional to the illuminance falling on the surface provided that the reflectance factor of the surface is constant. Therefore, provided that the reflectance properties of the surface do not change, a narrow spatial response can effectively track illuminance changes; the narrower the response, the better the tracking for a particular location.

#### ***Limitations***

The narrower the spatial response, the smaller the sensor's field of view, so what the sensor "sees" may not be representative of the whole surface or workplane. Therefore,

a narrow response makes the sensor very sensitive to changes in the reflectance properties of what it is viewing. In practice, the reflectance of the workplane is not constant, but changes depending on the activities going on in the room. Examples include a dark desktop that is sometimes covered with white papers, the colors of peoples' clothing, such as a white shirt versus a dark suit, and even rearrangement of the room's furniture.

Another limitation of a narrow spatial response is increased sensitivity to mirror-like, specular reflections off shiny surfaces. Illuminance on a surface is directly proportional to luminance only for diffusely reflecting surfaces. Most surfaces in a room are diffuse, but some, like a glass table top, can reflect overhead light directly back into the photosensor's field of view causing erratic performance. Specular reflections have proportionally less effect on photosensors with a wider spatial response.

### **Other Photosensor Inputs**

The following inputs are set during the commissioning of photosensors. Depending on the type of output (on/off or continuous dimming), as well as the type of control algorithm employed in the particular device, one or more of these inputs will be available to the user. On some photosensor products, the sensitivity and certain set points are combined into one input that controls both together according to some programmed relationship.

### ***Sensitivity (gain)***

The spatial sensitivity and the spectral sensitivity of the photosensor characterize the optical gain. Electronic gain amplifies the weak signals from the photocell to practical signal levels. These two gain mechanisms (optical and electronic) determine the sensitivity of the photosensor. Sensitivity adjustments are required for open-loop sensors where the sensitivity adjustment determines the relationship between electric light levels and the sensed signal. For photosensors that do not have a sensitivity adjustment, or those that combine sensitivity with other set-point adjustments, the sensitivity alone can always be adjusted optically by the positioning of the photosensor. While positioning the photosensor differently for different sensitivities is an option, it not very practical and it certainly is not a systematic way of commissioning photosensors.

### ***Set-points***

The signal level that must be attained before an action occurs is known as a set-point. For photosensors, set-points determine the signal level at which lights will be switched, or at what light level dimming will start and/or end. The type and number of set-points that are employed in a photosensor depends on the type of control algorithm used. Simple, open-loop photosensors that switch lights on and off only need to have one set-point that determines the level at which the lights will switch. Often, two set-points are used, however, to give the switch some hysteresis, or a deadband, whereby the light switches on at a higher signal level than that which turns them off. This is to prevent unstable frequent switching when signal levels are near the set-point.

More complicated closed-loop control algorithms may employ several set-points, which might be measurements that determine sensor and task illuminance ratios used in the algorithm to determine the electric light level.

### **Photosensor Outputs**

Photosensors fall into two main categories depending on the output. The most familiar and the most prevalent use of photosensor control is on/off control output which is used to turn lights on, or off, based on the light level detected. Far less prevalent is the continuous level output photosensor, which is used with dimming systems to dim the electric lighting level based on some dimming function or control algorithm.

The light-sensing element within a photosensor might be a photodiode, a phototransistor, or a photo-resistive cell. It is important to make a distinction between this, the photocell, and a complete photosensor device that includes additional circuitry to produce the desired output signal(s).

### ***Photosensors for on/off control***

Photosensors for on/off control work most effectively in applications where a large difference in light level exists between the on condition and the off condition. Photosensors for outdoor street lighting is such an example. The set-point at which the output is switched does not have to be precise due to the large difference in illumination levels between night and day. Photo-resistive sensing elements are commonly used in this application because of low cost and relatively simple circuit design. Photo-resistive sensors do not have a linear response with light, part-to-part consistency is poor, and they have a large temperature dependency. Taken together, these characteristics make precise action at specified set-points difficult. A further disadvantage of photo-resistive devices is that many common types use cadmium, a heavy metal that is considered harmful to the environment.

When switching at precise light levels is needed, silicon photodiode detectors are commonly used. Used in conjunction with an amplifier circuit, these devices offer very predictable and linear output that is stable with time and temperature. This allows switching at precise set-point levels. These types of detectors are useful for indoor applications where the overall range of acceptable light levels is orders of magnitude less than that encountered outdoors.

The output from an on/off sensor is a two-state binary signal. Such a signal can be connected directly to a power relay to switch lights on and off, or used as a low level logic-level signal that is connected to some other lighting controller.

### ***Photosensors for dimming***

Photosensor control for dimming is divided into two main types: open loop and closed loop:

*Open loop* - the photosensor does not respond to, or “see” the electric light that it controls. An example of an open-loop system is a photosensor mounted on the outside of a building that controls the electric light level inside the building. In such a case the photosensor is exposed only to daylight. The electric light level is determined from the daylight signal alone. In the case of on/off control, such systems can be designed to simply turn electric lights off when outside daylight reaches a predetermined level. In the case of a dimming system, a signal proportional to the outside daylight instructs the system to dim the electric light by an amount proportional to the amount of available daylight sensed by the photosensor. No feedback control is used for an open loop system.

The drawback of open-loop feedback control is that the system cannot compensate or correct for any changes in the light distribution that affects the constant of proportionality between interior light levels and outside daylight levels. For example, the system will not respond to the use of window blinds, so if the occupant draws the blinds to block direct sunlight, the system will not increase the electric light to compensate for the decreased daylight levels inside the room.

*Closed loop* - the photosensor senses and responds to the electric light that it controls. An example of a closed-loop system is a photosensor mounted on the ceiling of the room where the electric lighting is being controlled. In this case the photosensor is exposed to both the daylight and the electric light in the room. The sensing of the electric light forms a feedback loop.

Closed-loop systems use negative feedback to respond to changing conditions. Negative feedback is a means of error correcting or compensating whereby an increase in an input signal level causes a decrease in the output signal. Conversely, a decrease in input signal causes an increase in output signal. This is the desired action of photosensor control; an increase in the amount of light in the room causes a decrease in the electric light intensity, and a decrease of daylight causes an increase of electric light. The overall feedback loop of a photosensor system must be negative for proper operation. The control algorithm characterizes the negative feedback of a photosensor.

The amount of feedback can vary for different systems and different locations of the system components. In systems where the photosensor is mounted near a window, the feedback is proportionally less than in systems where the photosensor is mounted deep within the room. This is because near the window the proportion of daylight is greater than electric light and the photosensor “sees” proportionally less of the electric light that it is controlling. The opposite is true for a photosensor mounted deep within a room. The amount of feedback is also governed by room geometry and surface reflectances. A room with light-colored finishes will have a greater feedback gain than a room with dark-colored finishes. The gain caused by room geometry and surface reflectances combines with the optical and electrical gain of the photosensor to determine the actual signal level received by the photosensor.

**Effect of photosensor output on light level:** For dimming systems, the dimming ballast controls the electric light level based on input from the photosensor. The amount of dimming as a function of input signal is characterized by the dimming response function. For many dimming ballasts, the dimming response function is linear, meaning that it reduces the electric light level in proportion to the input signal. However, the active input dimming range is usually less than the specified range of input control voltage. For example, for a ballast with an input signal specification of zero to 10 V, dimming may actually take place over a more limited range from about 1.5 V (minimum light output) to 8.5 V (maximum light output).

## Dimming Ballasts

Available inputs:

- 1-10V analog signal
- <0.5 volt standby signal
- Phase chop angle power line signal
- Digital control interfaces (DALI and SuperDim)

Outputs:

- Lamp power level
- Ballast status (e.g., lamp failure for DALI equipped ballasts)

## Dimming Ballast Inputs

Control inputs to ballasts are divided into analog and digital categories. Within each of these categories, different signaling protocols and/or conventions are used. Digital control inputs to ballasts have only recently been introduced on the market and currently comprise a very small market share. There is, however, considerable interest in and backing by different ballast manufacturers for the DALI communication protocol for ballasts. (For a detailed listing of the strengths and weaknesses of the different ballast control interfaces see Task 2.9 below)

Currently, analog control interfaces for ballasts are the most widely available with 0-10V control interfaces being most common. The 0-10V interface was the first to be used when dimming electronic ballasts appeared on the market in the early 1990s. The control scheme itself dates back to the early 1970s where it originated in the theatrical lighting controls industry. In fact ANSI has recently approved a 0-10V standard for entertainment technology (Standard E1.3-2000). However, the implementation of 0-10V control in ballasts is different than that used in theatrical controls. ANSI Standard E 1.3-2000 even specifically states that the standard does not apply to fluorescent dimming ballasts. Ballast manufacturers themselves have not adopted a standard for commercial use at this time and it seems likely at this time that none will ever come about. As a result, consistent behavior across different ballasts types or manufacturers is not assured.

The main difference between the implementation of 0-10V control for ballasts and that used in the entertainment industry is that the ballast is capable of providing its own signaling voltage while other 0-10V devices require the signaling voltage to be provided by a separate controller. The benefit of having a device that provides its own signaling voltage is that it allows the use of very simple control devices that do not require their own power sources. For example, a 0-10V ballast can be dimmed by a simple variable resistor connected across the control wires. Compatibility problems arise when a ballast is connected to a controller that also supplies a signaling voltage. To work properly the controller must be able to conduct current from the higher voltage control wire to the lower voltage wire (sink current). If a controller cannot conduct current in this reverse direction, from the viewpoint of the controller, the ballast will keep the signal high and no dimming will take place.

A deficiency of 0-10V control for both ballasts and products covered by the Entertainment Industry standard is that the relationship between dim level and control voltage is not defined. As a consequence, consistent dimming behavior among different ballast types and ballasts made by different manufacturers is not assured. For example, a 5-volt signal for one ballast might result in a 30% dim level, while the same 5-volt signal might result in a 50% dim level for another manufacturer's ballast. This is problematic for at least two reasons. First, it prevents the mixing of different ballast types within one control area, and second, it complicates the commissioning of dimming systems because each system must be individually calibrated for dimming response. Some manufacturers also provide for analog command regions within the 0 to 10V signal range. For example, a control voltage less than 0.3 volts might signal the ballast to shut-down. While these extensions might provide desirable features, they can also lead to compatibility problems with controllers not designed with these features in mind.

Another problem with the 0-10V conventions used by ballast manufacturers is that the signal levels are low and thus suspect to interference. Little, if any guidance is given by ballast manufacturers on proper cabling techniques to avoid interference, but anecdotal evidence suggests that control wires must be kept away from power lines and lamp leads, and that the total cable length is a concern.

As an alternative to 0-10V control, two-wire, or ac phase chop dimming is available. This analog approach uses the power lines for signaling. In this control scheme, the rise of the ac signal after each zero-crossing is delayed an amount of time (zero to 8.3 ms or one-half of the wave form period) which is related to the dim level. Delaying the rise of the ac voltage after each zero-crossing results in a lower rms ac voltage signal whose shape looks as if part of the waveform has been removed, or chopped. This chopping is inexpensively performed by solid-state switching devices such as triacs or silicon controlled rectifiers (SCRs). This technique is used for controlling certain electrical loads such as heater coils and incandescent lamps. Operating a non-dimming electronic ballast on a phase-chopped voltage could be damaging to the

device, but electronic ballasts designed to accept such signals use the phase-chopped signal to set the output power to the lamps.

The major benefit of using power line phase-chop signals for dimming is that no additional wiring is needed to control dimming. For retrofit applications, dimming controllers can replace existing switches and the existing power lines carry both the power and the signal. A secondary benefit is that the signals are less sensitive to interference than low voltage analog signals.

An alternate way of using the existing power lines to carry control signals is by using a power line carrier signal (PLC) at a frequency much higher than the 60 Hz power frequency. While somewhat successful for carrying digitally encoded signals, such a scheme has not been used for analog control.

For digital control PLC communications have been around for many years, although they have not been very successful in commercial and industrial environments. From the start such systems have been plagued with interference problems and are now considered to be unreliable, except for residential use. Ironically, many of the interference problems are the result of electronic power equipment, such as electronic ballasts, on the same, or nearby circuits. The X-10 protocol for digital control using PLC signals is supported by some lighting equipment manufacturers although no ballast manufacturers are known to have incorporated this directly into their ballast designs.

Another digital communication protocol not supported by ballast manufacturers, but used for lighting equipment is the DMX-512 protocol. DMX-512 is used extensively in theatrical lighting control systems. It is a high-speed, wide bandwidth (250 kbytes/s) method of communication allowing up to 512 points of control per control loop. DMX-512 has not been incorporated directly into ballast designs, most likely because of the relatively high cost of adding such a high-speed communication interface. Also, the existing commands do not lend themselves well to architectural and energy saving applications.

The two digital interface control protocols that are directly incorporated into ballasts are the SuperDim protocol by Energy Savings, Inc. and the Digital Addressable Lighting Interface (DALI), originally conceived by Tridonic, a European lighting equipment manufacturer. Without going into all the details of the protocols, there are some important features that make these protocols useful for commercial lighting control.

Both protocols use two, isolated, low voltage control wires to carry control signals. Twisted pair wiring such as what is used for computer networking is commonly used for cabling. Both use a form of serial communication similar to the common and widely used RS232 method. Data rates are low, 2400 baud for SuperDim and 1200 baud for DALI. The use of relatively low signal rates indicates the need for a robust, low cost

network over a higher speed network. Both protocols emphasize the need for both low cost and simple implementation.

The main barrier to overcome when setting up a ballast control network is finding an easy way of commissioning the system. To commission such a system the interconnected ballasts must be logically grouped together to realize different lighting scenes and energy saving strategies. With analog control, the grouping of ballasts is “hard-wired” when the ballasts and control gear are installed. This hard-wired approach could also be done with digital controls, but it would not take advantage of one of the main benefits of digital controls which is the increased flexibility that they offer. Realizing this increased flexibility means that the burden of commissioning has largely been shifted from the installer to a later user of the system. Having a system that can be easily reconfigured seems to be an important selling point of digital control systems over existing analog control systems.

SuperDim and DALI protocols make use of each ballast in a network having a unique address. With the SuperDim protocol a permanent, unique 28-bit address is assigned to every ballast at the time of manufacture. Part of the commissioning process is then having the addresses of all the connected ballasts input to the controller. Though not mentioned in the communication protocol, ballasts by Energy Savings, Inc., make use of an optical sensing commissioning tool that is used to retrieve the addresses of ballasts by receiving a high frequency modulated light signal from the fluorescent lamps being operated by the particular ballasts. When so instructed, ballasts will output their addresses via high frequency light output modulation. The commissioning tool receives this information when aimed at the ballast of interest and relays the address information to the main controller. In this manner installed ballasts within luminaires can be identified and grouped into logical zones for control without dismantling fixtures.

The DALI protocol handles addressing in a different manner. When so instructed, all DALI ballasts on a network will assign each one a randomly generated 24-bit address. The controller then determines each ballast’s address through an iterative trial-and-error process of trying different addresses until it gets a response. Once the addresses are all known, individual ballast locations can be identified by having the controller send signals to a particular ballast instructing the ballast to flash the lamps on and off, for example. If by chance more than one ballast has the same address, provisions are made for just those ballasts with identical addresses to repeat the randomization process.

## **Dimming Ballast Outputs**

### *Lamp power level*

Reducing the power delivered to a fluorescent lamp reduces the light output and effectively dims the lamp. Due to the operational characteristics of fluorescent lamps,

power reduction must be done with at least two major provisions to keep the lamp from extinguishing and to preserve long lamp life.

- Maintain a sufficiently high voltage across the lamp to sustain the arc.
- Keep the electrodes properly heated so that they can supply sufficient free electrons to the discharge without being severely damaged.

For these reasons, a specially designed dimming ballast is required to effectively dim fluorescent lamps to levels less than about 70% of full light output.

The requirements of maintaining lamp voltage and electrode heating prohibit magnetic ballasts from being used successfully as dimming ballasts. While products are on the market that dim magnetic ballasts (e.g., panel-level dimmers), the dimming range is limited to about 50% of full light output. In addition, long operation times at a low dim level are likely to reduce lamp life.

High-frequency electronic ballasts have been successfully developed to dim fluorescent lamps to light output levels as low as 1% of full light output through the use of active electronic components that can dynamically change ballast-operating characteristics as the lamp is dimmed. Lamp voltage can be maintained even at low currents and supplementary electrode heating can be increased to maintain proper electrode heating as the lamp is dimmed.

Even though electronic ballasts are capable of dimming lamps to low power levels while preserving life, the supplemental electrode heating requirements, as well as the power requirements of the additional circuit components, reduce the overall system efficacy of dimming systems compared to non-dimming systems. This is clear from an analysis of the different electronic ballast types currently on the market.

Table 1 lists manufacturer-reported and National Lighting Product Information Program (NLPPIP) test data on ballast factor and ballast efficiency factor for instant start, rapid start, and dimming ballasts. For each group of similar ballast type, the average ballast factor and average ballast efficiency factor is calculated. In the case of dimming ballasts, the ballast efficiency factor is for the full light output condition. For the same lamp type, and the same number of lamps operated per ballast, ballast efficiency factors can be directly compared to show relative system efficacy. All the ballasts in this analysis are two-lamp ballasts operating T8 lamps. To aid in comparing relative system efficacy, the group averages are shown as a percentage of the highest BEF group, in this case the instant start ballast group. Relative efficacies are also shown for the dimming ballast group at 40% and minimum light output levels calculated directly from NLPPIP reported light output and system power measurements.

Table 1 shows that, on average, instant start ballast systems are about 5% more efficacious than electronic rapid start systems. This efficacy difference, combined with lower costs and similar lamp life performance, can explain why instant start electronic ballasts constitute about 80% of electronic ballast sales based on U.S. census data.

When instant start systems are compared to dimming ballasts, the discrepancy in efficacy increases to about 9%. Consequently, from an energy point of view, the average power reduction from dimming would have to be nearly 10% just to break even on energy consumption if dimming ballasts were used in place of instant start electronic ballasts. In other words, the user would get 10% less light from a dimming system than from an instant start system for the same energy usage.

Most dimming ballasts show a linear relationship between light output and dim level. (See Figure 1 from NLRIP Dimming Ballast Specifier report.) It is important to note that the curve showing this relationship does not intersect the origin, but rather it is offset to the right. This offset is due to a combination of lower lamp efficacies when operated at low power, and energy that is consumed by the ballast, which represents an increasing percentage of the total power consumed by the system as the lamp is dimmed. Therefore, though linear with power, light output is not proportional to power, but shows diminishing returns as the light output is reduced. The data in Table 1 reveal this by showing the relative efficacies for dimming systems at 40% and at minimum light output levels. The relative efficacies for these conditions are 66% and 37%, respectively. The reduced efficacy at 40% light output gives only a 43% energy savings when the light are dimmed 60%. When compared to non-dimming instant start systems, the energy savings are only 40% for a 60% reduction in light output.

Because of the diminishing energy savings with dimming, dimming below about 20% of full light output is ineffective when dimming for energy savings. Below this level, the only way to get further substantial energy savings is to switch off the ballast.

### **Other dimming ballast outputs**

In addition to lamp power output, digital addressable ballasts using the DALI protocol are capable of a limited form of two-way communication. While at present there doesn't appear to be any clear energy-saving argument for two-way ballast communication, there are instances where feedback from the ballast could improve lighting quality. For example, failed lamps could be automatically reported to facility personnel.

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**Table 1. Relative Efficacies of 2-lamp, T8 Electronic Ballasts by Type**

Gray indicates NLPIP test results, otherwise manufacturer data

**Instant Start**

BF	BEF	BF	BEF	BF	BEF
1.23	1.57	0.87	1.49	1.17	1.53
0.87	1.50	0.78	1.52	0.91	1.54
0.89	1.55	0.77	1.48	0.78	1.53
0.87	1.55	0.79	1.52	0.79	1.56
0.86	1.53	0.88	1.52	0.88	1.50
0.87	1.47	0.90	1.49	0.87	1.54
0.89	1.55	0.89	1.50	0.88	1.49
0.87	1.50	0.88	1.52	0.77	1.51
0.87	1.54	0.89	1.56	0.77	1.55
0.90	1.53	0.88	1.52	0.88	1.51
0.90	1.54	0.89	1.53	1.18	1.55
1.18	1.55	0.88	1.49	1.16	1.57
1.08	1.41	0.88	1.53	0.88	1.49
0.80	1.51	1.18	1.49	0.91	1.54

Averages	BF	BEF	Relative Efficacy
	0.91	1.52	1.00

**Electronic Rapid Start**

BF	BEF
0.88	1.40
0.92	1.46
0.92	1.42
0.94	1.53
0.86	1.50
0.89	1.49
0.88	1.45
0.88	1.40
0.78	1.44
1.21	1.39

Averages	BF	BEF	Relative Efficacy
	0.91	1.45	0.95

**Dimming Ballasts**

BF	BEF
0.88	1.36
1.00	1.43
0.86	1.41
0.86	1.43
0.86	1.43
0.74	1.29
0.85	1.33
0.91	1.34
0.91	1.34
0.88	1.40
0.88	1.36
1.00	1.43

NLPIP Data Relative Efficacy		
100%	40%min	
99	76	26
99	75	25
98	73	73
96	70	70
85	58	17
93	42	40
96	78	24
99	77	58
92	66	31
100	76	24

Averages	BF	BEF	Relative Efficacy	Relative efficacy at dim levels	
				100%	40%min. Level

0.89    1.38    0.91                    0.91    0.65    0.37

Figure 1. Gray area shows range of relative light output (RLO) plotted against power demand for dimming ballasts tested for NLRIP Specifier Report: Dimming Electronic Ballasts (1999).

