NLPIP :: Lighting Answers
Volume 13 Issue 1 July 2015

Comparison of Wired and Wireless Lighting Controls for Single Rooms

Glossary terms are shown in **boldface**; terms are defined in the Glossary section, beginning on p. 29.

Abstract

The National Lighting Product Information Program (NLPIP) investigated the performance of wireless occupancy sensors and **photosensors**, focusing on control systems designed for a single room in a commercial building such as an office, classroom, or conference room. NLPIP tested wireless and wired control systems from Lutron, Leviton, and WattStopper because these are the brands of controls most frequently selected by specifiers according to an NLPIP survey. The investigation included:

- Occupancy sensor and photosensor features and performance
- Wireless communication performance
- Compatibility with lighting products
- Energy harvesting and storage capabilities
- Capital costs of control systems

NLPIP found that:

- Wireless occupancy sensors from the evaluated brands were available with only passive infrared detection technology. The lack of wireless ultrasonic and dual technology occupancy detectors should be taken into consideration where furniture may block line-of-sight motion detection.
- The wireless occupancy sensors and photosensors tested had similar performance as equivalent wired sensors from the same manufacturer.
- NLPIP found little difference in the occupancy sensors' and photosensors' performance compared to that seen in previous NLPIP studies of these types of products.
- The wireless communication was robust in a typical office environment.
- Operation of **electronic ballasts** or **drivers** could be compromised for controllers that don't make use of a neutral wire and/or are installed in a switchbox without a neutral wire.
- **Photovoltaic** energy harvesting by the tested occupancy sensors is likely to be insufficient at some ceiling locations. Installing a battery in the sensor will circumvent this problem.
- The tested wireless occupancy sensor systems had 54 to 128% higher capital costs than the equivalent wired systems from the same brand.

Introduction

Automated lighting controls such as occupancy sensors and photosensors can be an effective way of reducing energy use. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Energy Standard for Buildings 90.1-2010 and the National Energy Code of Canada for Buildings 2011 (NECB) require automated lighting control sensors in more rooms than earlier building codes. Specifiers evaluating lighting control products to meet these needs may consider wireless lighting control options, which are often claimed to reduce installation costs compared with wired options.

The National Lighting Product Information Program (NLPIP) compared the performance and the features of wireless lighting controls with equivalent wired controls, focusing on systems designed for a single room in a commercial building, such as an office, classroom, or conference room. NLPIP did not investigate more complex control systems that store pre-programmed lighting scenes, control a whole building, or communicate with one another on mesh networks.

Figure 1 illustrates the components of wired and wireless control systems for single rooms. Components include a sensor, controller (which may be called an actuator, relay, or **power** pack), and wall-mounted switch or dimmer. The wireless controller is sometimes integrated with the switch or dimmer into one component that replaces an existing light switch.

The sensor is usually mounted on a ceiling or **luminaire** or high on a wall. Because a wireless sensor lacks a wired connection, it must be self-powered with a battery and/or by energy harvesting (by using a photovoltaic module).

In wired systems, the sensor device is physically connected to the controller and light switch. In wireless systems, the controller communicates with the sensor (and possibly the light switch) via radio **frequency** (RF) signals. Because the controller is always connected by wires, an electrician is needed for installation, whether it uses wired or wireless communication.

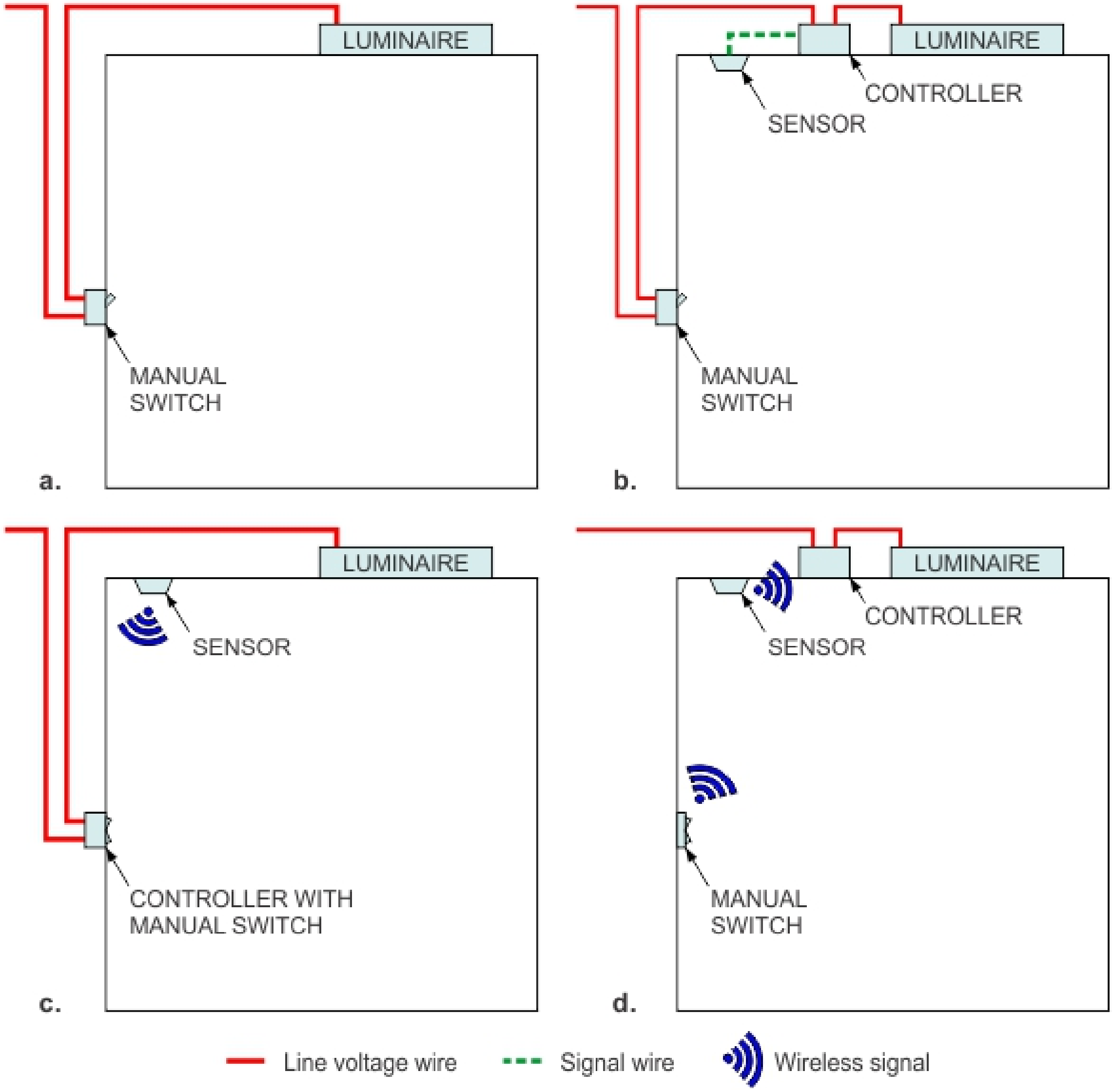

Figure 1: Wiring schematic diagrams. (a) shows the lighting system without automated controls; (b) shows an example of a wired control system, representative of the wired control systems tested by NLPIP; (c) shows an example of a wireless control system with the manual switch and controller integrated into one device, representative of the Leviton and WattStopper systems tested by NLPIP; (d) shows a wireless control system with a separate manual switch and controller, representative of the Lutron system tested by NLPIP. (The manual switch was not tested.) .

NLPIP identified some potential advantages of wireless lighting controls, compared with wired versions:

- decreased installation labor for wiring
- increased ability to add controls in spaces that don't have easy access to ceiling or wall cavities and surface conduit isn't desired
- increased ability to reposition sensors or add more sensors for improved coverage if needed

NLPIP identified some potential disadvantages of wireless lighting controls, compared with wired versions:

- lack of availability of ultrasound or dual technology occupancy sensors
- higher capital cost
- potential for wireless communication problems, such as **electromagnetic interference (EMI)**
- potential for sensor to stop operating due to lack of energy

NLPIP first identified manufacturers of wireless lighting controls and found that products were available in the U.S. from more than 40 companies at the time of the study. NLPIP then surveyed lighting specifiers not identified with manufacturers to identify three brands to test. The results showed that the three brands of wireless lighting controls most frequently evaluated or selected by the 152 specifiers who responded were Leviton, Lutron, and WattStopper.

NLPIP then consulted these three brands' marketing literature and sales representatives to determine the equipment to purchase. NLPIP purchased products suitable for automatically controlling the lighting within a single room in order to meet energy codes. Equipment was not sought to provide whole-building control, programmable scenes, or other features. For each brand, NLPIP attempted to purchase four sets of equipment: wired and wireless occupancy sensors and photosensors. WattStopper did not offer a wireless photosensor at the time of purchasing, so no WattStopper photosensors were tested. Because the wireless occupancy sensors were exclusively passive infrared (PIR) rather than ultrasound or dual technology, NLPIP specified PIR wired sensors for comparison purposes. The products that NLPIP tested are shown in Table 1.

Table 1: Equipment tested by NLPIP

Brand	Sensor connection	Occupancy sensor	Photosensor
Leviton	Wired	 Sensor: OSC04-RIW	 Sensor: ODC0P-00W
		 Controller: OSP20-ND0	 Controller: MZD20-102
	Wireless	 Sensor: WSC04-IRW	 Sensor: WSCPC-W
		 Controller: WSS10-GUZ	 Controller: RF WST05-010
Lutron	Wired	 Sensor: LOS-CIR-450-WH	 Sensor: EC-DIR-WH
		 Controller: PP-120H	 Controller: QSN-4T16-S
	Wireless	 Sensor: LRF2-OCR2B-P-WH	 Sensor: LRF2-DCRB-WH
		 Controller: RMJ-ECO32-DV-B	 Controller: RMJ-ECO32-DV-B
WattStopper	Wired	 Sensor: CI-200-1	WattStopper photosensors were not tested because, at the time of purchase, WattStopper did not sell a wireless photosensor.
		 Controller: BZ-150	
	Wireless	 Sensor: EOPC-100	
		 Controller: EOSW-101	

NLPIP performed tests to investigate the following characteristics of wireless lighting controls:

- occupancy sensor performance
- photosensor performance
- wireless communication performance
- compatibility with lighting products
- energy harvesting and storage capabilities

The lighting controls were purchased in January and February 2014 and were tested in March through June 2014. NLPIP's results are based on tests of one sample of each product. Variation between samples was not investigated.

How well do wireless occupancy sensors perform compared with wired occupancy sensors?

NLPIP last published a report on occupancy[1] sensors in 1998 (NLPIP 1998). Despite the number of years that has passed since that report, the technologies used in these sensors and their performance have remained unchanged. Therefore, the reader is referred to that report for a more detailed understanding of these devices.

NLPIP used the procedure described in *Appendix: Detailed Methodology* to investigate the geometry of the sectors that are sensitive to motion and their sensitivity. As noted in the appendix, NLPIP investigated the location of sensitive sectors in a zone from the central axis of the sensor out to 30° away from the axis, even though the sensors are sensitive to motion beyond this zone.

The results of the investigation are shown in Figure 2. NLPIP found that there was little difference between the tested wired and wireless occupancy sensors from Leviton and Lutron. The WattStopper wireless sensor had fewer sensitive sectors than its wired sensor. The sensors primarily detect occupancy when a person moves into or out of a sensitive sector, so the WattStopper wireless sensor has less ability to detect small motion than its wired sensor in portions of the tested zone.

The tested Leviton and Lutron wireless occupancy sensors had lower sensitivity than the wired sensors from the same brand. NLPIP expects this lower sensitivity could result in a smaller coverage area and diminished ability to detect small motion, but because the decrease in sensitivity is relatively small, it is not likely to have a noticeable effect on occupancy detection.

[1] This publication refers to these products as occupancy sensors. They can be configured as either vacancy sensors, whereby the lights must be turned on manually but can be turned off automatically, or as occupancy sensors, whereby the lights are turned on and off automatically.

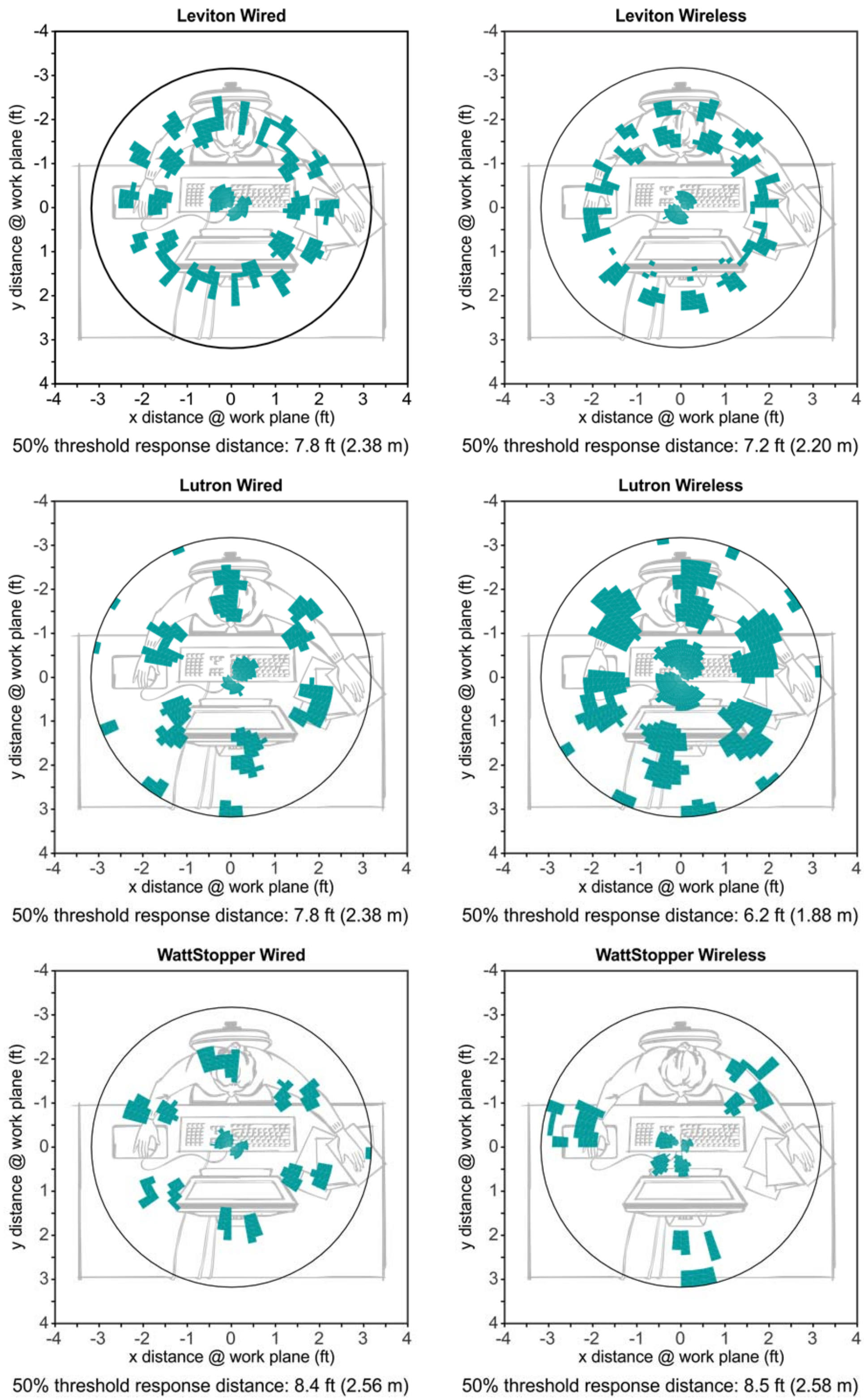

Figure 2: Occupancy sensor results. The color-shaded areas in each illustration show the thermally sensitive sectors if the sensor were mounted on an 8 ft (2.4 m) ceiling over a person sitting at a desk. NLPIP tested to only 30° from nadir; the sensor is able to detect motion across a wider field than shown. For each sensor, the distance is noted at which only 50% of thermal stimulus was detected; the greater this distance, the more sensitive the sensor is, as discussed in *Appendix: Detailed Methodology*.

Dual-technology sensors (employing both ultrasonic and PIR technology in one device) can detect small motion better than PIR alone and do not require a line-of-sight to detect motion. However, ultrasound detection requires more **power** than PIR detection. Presumably because of the limited energy available in wireless sensors (which rely on batteries and/or **photovoltaic**, or PV, modules), only PIR detection technology was offered in wireless sensors at the time of this study. The lack of ultrasonic and dual technology motion detection can be a drawback to wireless occupancy sensors at this time, especially for spaces where furniture such as cubicle partitions may block detection. The increased ability to add and reposition wireless occupancy sensors compared with wired sensors may mitigate issues encountered from decreased detection due to the lack of ultrasound technology or decreased sensitivity.

How well do wireless photosensors perform compared with wired photosensors?

NLPIP last published a report on photosensors in 2007 (NLPIP 2007). The technologies used in the sensors tested for this study and their exhibited limitations have remained unchanged since the earlier report. Therefore, the reader is referred to that report for a more detailed understanding of these devices.

NLPIP used the procedure described in *Appendix: Detailed Methodology* to investigate the performance of wired and wireless photosensors from Leviton and Lutron by having them control the electric lighting in an empty scale-model room while exposing them to simulated daylight. (At the time of the study, WattStopper did not offer a wireless **photosensor**, so this brand was omitted from photosensor testing.)

NLPIP found that both the wired and wireless photosensors from Leviton use an "integral" control algorithm, which is designed to maintain a constant **illuminance** on the photocell rather than the work plane. As discussed in the 2007 photosensor report, integral control may not work well for spaces where the daylight enters through windows because it doesn't allow for the changing task-to-ceiling illuminance ratio that occurs throughout the day. (For example, when only electric lighting is present, the ratio is typically 5:1, but when daylight comes in from the side it can be 1:1.) The use of this control algorithm contributed to the 400 lux variation in work plane illuminance that the wired photosensor allowed as the simulated conditions transitioned from pre-dawn to noon, as shown in Figure 3. Another contributor to the large variation in work plane illuminance was the limited dimming capability of the controller-**ballast** combination that was used.

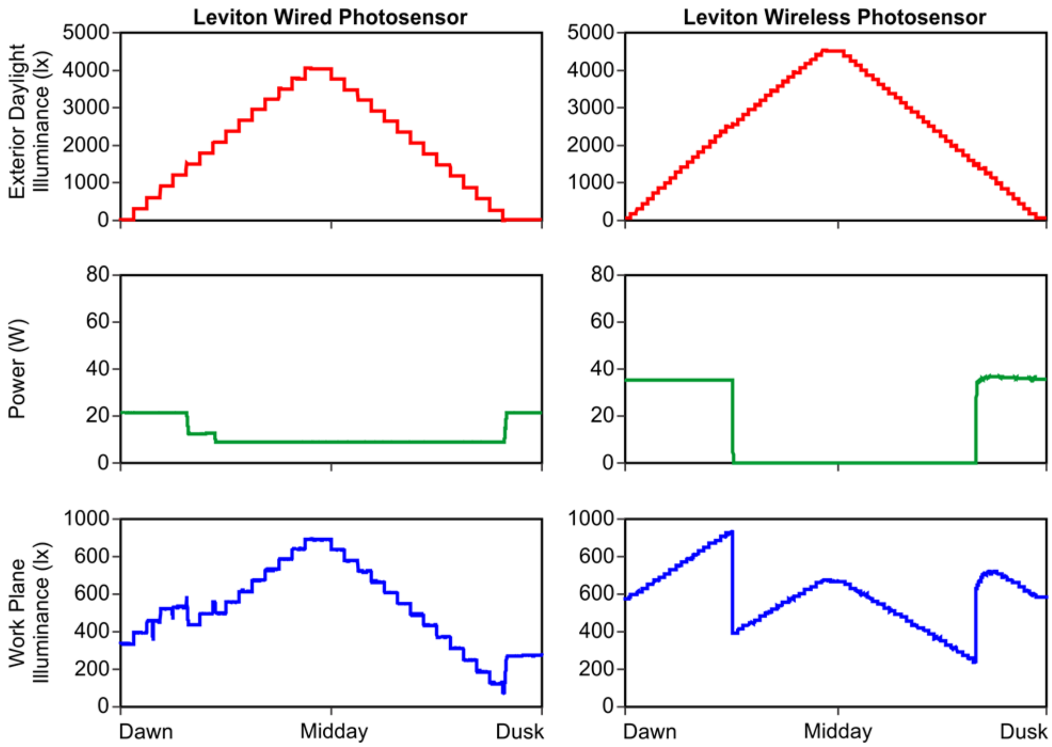

Figure 3: Leviton photosensor daylight simulation results. In this test, the work plane illuminance level in a scale model room is measured as the simulated daylight increases then decreases to mimic the diurnal pattern. The work plane illuminance includes the contribution from both daylight and electric light. The wired controller was set to "AutoCAL" mode for this test.

The wired and wireless Lutron photosensors, in contrast, use a "proportional response" control algorithm, whereby the control voltage sent to the **luminaire** is proportional to the sensor illuminance, which provides tighter control over the work plane illuminance than the integral algorithm. However, the Lutron photosensors exhibited another issue discussed in the 2007 photosensor report: a lack of independent control over the offset (the daylight level at which dimming starts) and the gain (the amount of dimming for a given amount of daylight), making it difficult to tune the photosensor to the room in which it is installed. The wired photosensor offers only one adjustment, called the "setpoint." As shown in Figure 4, decreasing the setpoint decreases the work plane illuminance in the absence of daylight, but it also changes the gain, allowing the illuminance to dip below the desired level when low daylight levels are introduced. Having independent offset and gain settings would eliminate this issue. The wireless sensor system does have two independent adjustments, the photosensor "sensitivity" and a "high-end trim" adjustment on the controller for the maximum electric lighting level, but they are not as effective as independent offset and gain controls. As shown in Figure 4, changing the photosensor sensitivity only changes the size of the steps when it is dimmed. The target illuminance level on the work plane can be changed up to 50% by adjusting the high-end trim, which was not tested.

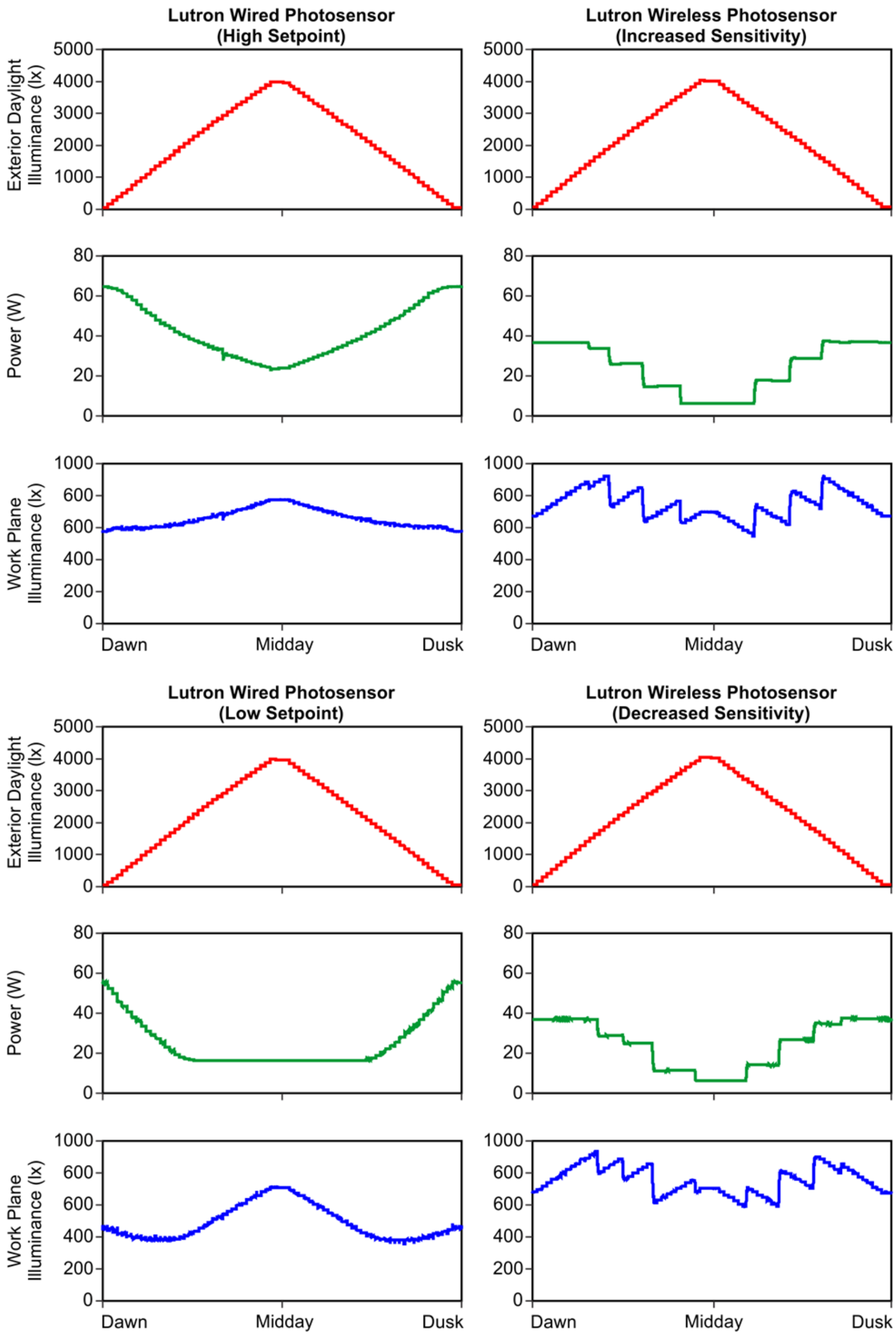
Lutron Wired Photosensor
(High Setpoint)
Lutron Wireless Photosensor
(Increased Sensitivity)
Lutron Wired Photosensor
(Low Setpoint)
Lutron Wireless Photosensor
(Decreased Sensitivity)
Exterior Daylight Illuminance (lx)
Power (W)
Work Plane Illuminance (lx)
5000
4000
3000
2000
1000
0
80
60
40
20
1000
800
600
400
200
Dawn
Midday
Dusk

Figure 4: Lutron photosensor daylight simulation results. In this test, the work plane illuminance level in a scale model room is measured as the simulated daylight increases then decreases to mimic the diurnal pattern. The work plane illuminance includes the contribution from both daylight and electric light.

Other notable testing results include:

- Both the Leviton wired and wireless photosensor systems exhibited too much **hysteresis**. Some hysteresis is desirable to prevent excessive switching of electric lighting when daylight levels fluctuate, but the amount of hysteresis exhibited by these sensors left the simulated room with light levels lower than the Illuminating Engineering Society recommends (DiLaura et al. 2011) for a typical commercial environment when the daylight was decreasing at the end of the simulated day. The hysteresis was more pronounced in the wired system, which allowed the work plane illuminance to fall to 100 lux before the lights switched back on.
- The wireless Leviton photosensor has a mode that allows for dimming, but at the time of NLPIP's testing, Leviton did not offer a dimming controller that works with this photosensor. Therefore, the photosensor system operates only as a switching system, which resulted in over 500 lux variation in work plane illuminance over the course of the simulated day.
- The Lutron wireless photosensor system showed a step dimming response rather than a **continuous dimming** response, so it can provide only discrete electric light levels in steps of about 50-250 lux, and may not achieve the target illuminance level exactly. The step dimming occurred over a one-minute period, long enough that the change between the illuminance levels was not noticeable to NLPIP researchers.

How robust are the wireless communications?

NLPIP investigated two aspects of wireless communication of occupancy sensor systems: **EMI** and the maximum communication distance between the sensor and the controller.[2] Detailed test procedures can be found in *Appendix: Detailed Methodology*.

As shown in Table 2, NLPIP found that the unobstructed transmission distance was 92 ft (28 m) for the Leviton system and at least 110 ft (34 m) for the Lutron and WattStopper systems (the maximum indoor distance available for testing). These transmission distances are adequate for typical installations in commercial buildings and are within the manufacturers' specifications.

Likewise, NLPIP found that EMI did not present a problem in the commercial building where testing was conducted. However, there may be some rare cases of EMI in other commercial buildings, and potential sources of RF at each system's transmission **frequency** are noted in Table 2. This table also shows the interfering signal strength that was required to prevent the controller from receiving the signal from the occupancy sensor. The greater the interfering **signal** power that can be tolerated by the system, the more resistant the wireless communication is to EMI. (The RF generator that NLPIP used allows the radiated power to be set only in discrete steps, so only a range of interfering signal power could be determined.) As shown, the Lutron system was able to overcome a higher-power interfering signal than the Leviton and WattStopper systems. Even though NLPIP was able to intentionally jam the signal of each occupancy sensor system, and NLPIP did detect background RF energy at the transmission frequencies, the background RF was so weak that it did not interfere with the communication of the wireless systems. The background RF was typically between -100 decibel-milliwatts (dBm) and -94 dBm, which is at least an order of magnitude less than the power of EMI needed to jam the communication.

[2] A third potential issue with wireless communication, interference from building materials, was not studied because it is not likely to be encountered within a single room, the focus of this study. The control manufacturers provide guidance on the amount the communication range is decreased based on the presence of building materials.

Table 2: Wireless communication results. When determining the power of signal that prevented communication, the distance between the sensor and controller was 15 ft (4.6 m). The power of electromagnetic energy is in the units of decibel-milliwatts (dBm). The greater the value, the greater the power. For example, -40 dBm is a higher power than – 50 dBm. The accuracy of the power measurements is ± 5 dBm.

Brand	Transmission frequency	Maximum line-of-sight distance	Potential sources of EMI at transmission frequency	Power of signal at receiver that prevented communication
Leviton	313.4 - 315.2 MHz	92 ft (28 m)	garage door openers, security systems, car remote keyless entry, military aviation communications	Between -73.5 dBm and -68 dBm
Lutron	433.6 MHz	Undetermined, but greater than 110 ft (34 m)	hobby transceivers, wireless alarm systems, wireless presentation remotes, wireless home weather stations, military radar, RFID	Between -50 dBm and -46 dBm
WattStopper	902.8 - 902.9 MHz	Undetermined, but greater than 110 ft (34 m)	cordless phones, baby monitors, walkie talkies	Between -77 dBm and -74 dBm

The consequences of the loss of wireless communication depend on the control scheme in use and whether the EMI is intermittent or continuous. For example, in vacancy sensor mode (manual on, automatic off), a lack of communication will result in a reduction in energy savings. In occupancy sensor mode, it is unlikely but conceivable that an occupant could be left in the dark if a manual switch is not accessible.

If an installed lighting control system's wireless communications are not reliable, potential issues can be explored by:

- Using a handheld spectrum analyzer to determine if there is EMI (RF energy at the transmission frequency).
- Making sure that the sensor is sufficiently charged; NLPIP found that the Leviton occupancy sensor was able to transmit a signal only half the distance shown in Table 2 when it was not fully charged (no battery was installed and the integrated PV received inadequate **illuminance**). Installing a battery will overcome this problem.
- Noting if any objects obstruct the line between the sensor and controller.
- Checking that the distance between the sensor and controller is less than the maximum distance specified by the manufacturer.

What considerations are there for electrical compatibility with lighting products?

One electrical compatibility consideration is the maximum controllable load. The manufacturer specifications for the tested products are shown in Table 3.

A second consideration for controllers with no neutral wire connection is whether the controller (whether wired or wireless) will be sufficiently powered when the load is in the off state. If the controller is connected to three wires (hot, neutral, and ground) and the manufacturer does not specify a minimum controllable load, then the type of connected load is not a concern. If the controller cannot be connected to a neutral wire or a minimum controllable load is specified, NLPIP suggests contacting the manufacturer or testing the operation of a controller with the **lamps** or **luminaires** that it will control in order to determine if the controller will operate properly when the load is off. The reason for this is that the controller may need to draw leakage current through the luminaire in order to operate. NLPIP found that some **ballasts** and **drivers** limit the leakage current flowing through them, which may leave the controller with insufficient **power**.

Table 3: Manufacturer maximum and minimum controllable loads. MLV = magnetic low voltage transformer, ELV = electronic low voltage transformer.

Brand	Controller/ Receiver Model	Rated Maximum Controllable Load	Rated Minimum Controllable Load
Leviton	WSS10-GUZ	@120V: 800 W tungsten, 1200VA ballast, ¼ HP @277V: 2700 VA ballast	25 W minimum load
Lutron	RMJ-ECO32-DV-B	Not applicable (sends only low voltage signals for controlling **compatible ballasts**)	
WattStopper	EOSW-101	@120V: 800W tungsten, ELV, MLV, ballast, LED driver, 1/6 HP @277V: 1200 W ballast, LED driver, MLV	15 W minimum load @120V 30 W minimum load @277V
Leviton	OSP20-0D0	20 A fluorescent and incandescent 1 HP @120V, 2 HP @ 240V	Not specified
Lutron	PP-20	16 A (not to exceed 60 ballasts)	Not specified
WattStopper	BZ-150	20 A, 1 HP	Not specified

Do wireless occupancy sensors have sufficient energy to operate?

NLPIP evaluated the battery life of three wireless occupancy sensors and the PV energy harvesting characteristics of the two of these sensors equipped with PV modules.

As shown in Table 4, the Lutron occupancy sensor was not equipped with PV and was powered solely by a replaceable battery. Both the Leviton and WattStopper occupancy sensors employed PV with an electric double layer super **capacitor** for energy storage, and both of these devices had an option of using a non-rechargeable replaceable battery as well.

Table 4: Wireless occupancy sensor battery specifications and presence of PV modules.

Wireless Sensor	PV modules present?	Battery (3V lithium)		
		Type/size	Required or optional	Capacity
Leviton WSC04-IRW	Yes	½ AA	optional	950 mAHr
Lutron LRF2-OCR2B-P-WH	No	CR123A	required	1500 mAHr
WattStopper EOPC-100	Yes	CR2032	optional	240 mAHr

NLPIP estimated the battery life of each occupancy sensor by measuring the steady-state power and RF transmission energy and then using the equations and assumptions shown in *Appendix: Detailed Methodology.* The results show that the Lutron sensor battery is projected to last for 16 years, the Leviton battery for 22 years, and the WattStopper battery for 8 years. The estimated battery life of the WattStopper device is shorter than the other two devices because of its smaller, coin cell battery.

NLPIP also characterized the energy generation by the PV modules incorporated into the Leviton and WattStopper occupancy sensors. The PV modules were illuminated with a phosphor-converted white LED module and the current flowing into the super capacitor was measured. NLPIP found that the PV cells on both the Leviton and WattStopper products produce approximately 100 nA of current per **lux**.

Based on this PV current generation and the sensors' average power demand measured by NLPIP, both sensors require 1200 to 1700 lux-hours per 24-hour period (e.g. 100 to 140 lux for 12 hours) to maintain operation without a battery. However, assuming an average work plane **illuminance** of 300 lux, a 5:1 task:ceiling illuminance ratio (NLPIP 2007) and 12 hours per day of lighting, the sensor would receive only 720 lux-hours per 24 hours, which would not be sufficient to maintain operation. Therefore, some commercial ceiling locations receive too little illuminance to keep the tested Leviton and WattStopper occupancy sensors operational without a battery.

NLPIP's calculated illuminance requirement is higher than Leviton's specification for its wireless occupancy sensor of 645 lux-hours per 24 hours (specified as 20 foot candles for 3 hours every 24 hours) and WattStopper's specification of 860 lux-hours (specified as 20 foot candles for 4 hours to operate 24 hours). A possible reason for the difference between

NLPIP’s calculations and the manufacturers’ specifications is that NLPIP measured PV electricity generation with a white LED, whereas the manufacturers may have measured with daylight, which provides higher electricity production per lumen. If this is the case, NLPIP suggests that the white LED is more representative of an office environment.

NLPIP also estimated the duration of the capacitor charge for the two tested sensors when PV is first used to fully charge the internal capacitor and then the sensor is left in the dark without a battery installed. The same battery-depletion calculation methodology mentioned earlier was used for this analysis, except motion detection was excluded. The capacitor used in the Leviton device is estimated to power the sensor for two days in the dark without a battery. NLPIP’s estimate is consistent with Leviton’s specification that the sensor has an operating life of 48 hours when starting at full charge. This imposes a limitation on using this device in places that might not be illuminated by daylight or electric lighting for several days in a row, such as any interior space left unlit over a long weekend. NLPIP estimates that the WattStopper sensor would operate for eight days in the dark, which is longer than WattStopper’s specification of 72 hours. If the sensor is located in a space not illuminated by daylight or electric lighting for a longer period of time (extended darkness), then the sensor could become inoperable.

As discussed above, NLPIP identified two concerns about wireless sensors that rely on only PV for their energy: the potential to receive inadequate illuminance for PV charging and the possibility of energy depletion due to extended darkness when relying on PV. Therefore, NLPIP recommends installing batteries in wireless sensors and properly disposing of the batteries when they are depleted. Building maintenance staff should replace all of the wireless sensor batteries on a defined schedule.

Are wireless controls economically advantageous?

Manufacturers suggest in marketing materials that one of the primary benefits of wireless lighting controls is reduced installation labor costs due to the avoidance of wiring the sensor to the controller. However, NLPIP found that wireless control equipment is more expensive than equivalent wired equipment from the same brand, as shown in Table 5. Whether or not reduced wiring labor costs outweigh the increased capital costs depends on several factors including:

- how easily wire can be run through the ceiling and wall
- the size of the room
- the acceptability of the surface conduit
- how familiar the installer is with setting up the wireless control equipment

Because of the uncertainty in the installed cost introduced by these factors, NLPIP recommends obtaining a cost quotation from an electrical contractor to determine if the reduced labor will outweigh the increased capital cost.

Table 5: Online retail prices for retrofit occupancy sensor systems. Occupancy sensor system cost includes one sensor and one controller. Prices are current as of March 2015 and are for a quantity of one for each component purchased separately (i.e. not in a bundle) excluding shipping and tax. Lutron prices are from Pro Lighting Group at http://www.prolighting.com. Leviton prices are from Gordon Electric Supply at http://www.gordonelectricsupply.com. WattStopper prices are from Ready Wholesale Electric Supply at http://www.readywholesaleelectric.com.

Brand	Sensor connection	Motion sensor system				Incremental price of wireless compared to wired occupancy system	
		Hardware function	Model	Price per component ($)	Price per system ($)	($)	(%)
Leviton	Wired	Sensor	OSC04-RIW	$76	$111	$89	80%
		Controller	OSP20-ND0	$35			
	Wireless	Sensor	WSC04-IRW	$108	$200		
		Controller	WSS10-GUZ	$92			
Lutron	Wired	Sensor	LOS-CIR-450-WH	$80	$110	$59	54%
		Controller	PP-120H	$30			
	Wireless	Sensor	LRF2-OCR2B-P-WH	$60	$169		
		Controller	RMJ-ECO32-DV-B	$109			
WattStopper	Wired	Sensor	CI-200-1	$84	$114	$146	128%
		Controller	BZ-150	$30			
	Wireless	Sensor	EOPC-100	$125	$260		
		Controller	EOSW-101	$135			

The time needed to pair wireless sensors with controllers should also be included in cost estimates. All of the wireless systems required NLPIP staff to follow detailed written instructions to accomplish this pairing for the first time. The time needed to pair the equipment will typically decrease for subsequent installations as the installer becomes familiar with the procedure. However, NLPIP found that with the Leviton **photosensor** system, the pairing didn’t occur the first time following the manufacturer’s instructions, and the procedure, consisting of several steps, had to be repeated several times before compatible devices would communicate with each other.

Appendix: Detailed Methodology

Occupancy Sensors

The performance of a PIR sensor can largely be captured through two characterizations: the spatial sensitivity pattern and the absolute sensitivity of the infrared detector. The testing used a Peltier cooler device, which had a 24°C temperature difference between its front and back sides; flipping it from one side to the other simulated human movement in a room-temperature environment. For this test all sensors were set to their maximum sensitivity settings. As shown in Figure 5, NLPIP tested spatial sensitivity to only 30° from **nadir**, but the sensors are able to detect motion across a wider field.

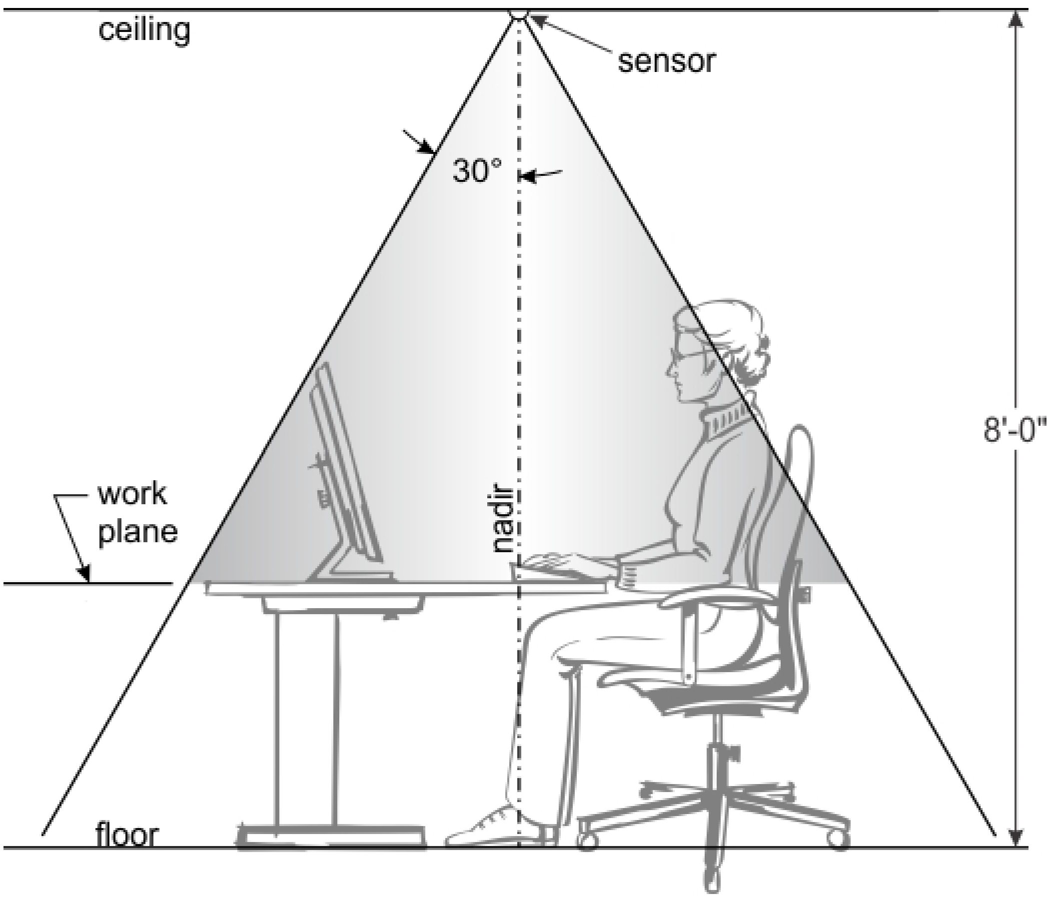

Figure 5: NLPIP tested occupancy sensors to 30° from nadir. The sensors are able to detect motion outside of the tested sectors.

The spatial and absolute sensitivity testing was conducted by mounting the sensor on a bar goniophotometer and oriented so that the nadir direction was aligned along the length of the bar. A 5 cm × 5 cm Peltier cooler device was mounted 2.5 m away from the sensor. The hot side of the Peltier cooler device was approximately 37°C and the cool side was approximately 24°C, which corresponds to the temperatures of a human body and room-temperature surroundings, respectively. A stepper motor flipped the Peltier device by 180° (taking ~300 ms to do so), then paused for 0.5 seconds, and then flipped it back. During the flip and for 2 seconds after the flip the state of the PIR signal was monitored for a detection response. If the sensor registered motion, it was allowed to reset before the

Peltier device was flipped again. This test setup allowed NLPIP to make sensitivity measurements more cost effectively than by following the National Electrical Manufacturers Association (NEMA) Occupancy Motion Sensors Standard NEMA WD 7-2011. In order to measure the spatial sensitivity pattern, the goniometer was set to scan elevation angles from 0 to 30° in 1° increments and azimuthal angles from 0 to 355° in 5° increments.

To measure the 50% sensitivity threshold, the Peltier cooler device was moved farther from the occupancy sensor until only half of the flips were detected. Since detection of low-level signals is determined probabilistically, three to six trials were conducted at each distance to determine the detection percentage. The threshold distance corresponding to a 50% detection rate was calculated. Threshold distance was calculated for two angles of view: nadir, and at the approximate center of one of the sensitivity sectors next in elevation angle from nadir (typically 16° elevation angle). For this test, all products were set to their maximum sensitivity settings.

Photosensors

To compare the performance of wired and wireless **photosensor** systems, NLPIP purchased Lutron and Leviton wired and wireless photosensors that were appropriate for controlling the lighting in one room. Three of the systems (excluding the Leviton wireless photosensor system) could control multiple lighting zones separately, but NLPIP did not test this capability. While WattStopper occupancy sensors were investigated, their photosensor products were not tested because they did not offer a wireless photosensor at the time of the study, and the goal of the testing was to compare wireless photosensors with wired photosensors from the same brand.

The Lutron wired controller was connected to a Lutron ECO10 0-10V **dimming ballast**. The Lutron wireless controller was connected to a Lutron digital Ecosystem H-Series dimming ballast, one of the Lutron products it was designed to work with. Both the wired and wireless Leviton systems were connected to a Universal Triad dimming ballast.

The Leviton photosensor can be powered by either its integrated PV module or a replaceable battery, and NLPIP installed a battery for this testing. The Lutron photosensor can be powered with only a replaceable battery.

The photosensors were tested in the Lighting Research Center (LRC) Daylighting Controls Simulator per the methods described in the NLPIP Scale Model Bench Test (NLPIP 2007). This is a box with two openings that simulates an empty room that has a rectangular floor plan and a window. A high-power white LED is used to simulate daylight entering through the opening. It can provide over 6600 lux at the opening. This apparatus has a controller that measures the analog voltage (0-10V) from the photosensor, ballast power, **illuminance** in the simulator and relative light output in the LED box outside the opening. A custom software program changed the LED light output to mimic changing daylight levels over one day. The lighting from pre-dawn to post-dusk was simulated over a two-hour period. The LRC modified the simulator from that described in the NLPIP Specifier Reports[3] in the following ways.

1. A shielded high-power LED was used to simulate daylight in the sun box. It provided 0 to >6600 lux at the window aperture between the sun box and the scale model.

The LED was controlled by a custom software program that allowed the LED current to be changed to mimic the time course of daylight over one day. The rate of increasing daylight provided by the LED was approximately 100 lux per minute to allow for **time delays** and response times. (NLPIP did not attempt to replicate the spectrum of daylight with either the metal halide or LED light sources. The LED allowed better control over light levels than the MH.)

Wireless Communications

NLPIP tested the maximum distance the sensors and controllers could be separated and still communicate reliably. The sensors were powered with new batteries and moved progressively further from the controllers. The testing was done in an office environment. Line-of-sight was maintained between the sensors and controllers.

To test the maximum communication distance, the following procedure was used:

1. The receiver with its load was placed at one end of a hallway in a commercial building.
2. The background electromagnetic energy level at the receiver was measured.
3. The transmitter was moved progressively farther from the receiver. At various distances, a signal was sent from the transmitter to turn the lamp on or off. The test ended when the system could not communicate or the longest possible line-of-sight distance was reached.
4. The maximum distance at which the sensor could successfully communicate to the controller was measured.

To test **EMI**, the sensors (powered with batteries) were placed 15 ft (4.6 m) from the controllers. A signal generator (TPI Synthesizer Version 5.0; RF-Consultant, Austin, Texas) was used to generate electromagnetic energy. The generator was uncalibrated, but the signal **frequency** and strength was measured using a handheld spectrum analyzer (RF Explorer ISM Combo; Nuts About Nets, Bellevue, WA). The power of the emissions was increased in steps until the receiver no longer acted on signals sent by the transmitter. The signal generator was set to the same frequency as the wireless communication signal for each system, shown in Table 2. Testing was done in a laboratory and office environment, without protection from EMI. Background RF energy was measured at the transmission frequencies used by the three systems and found to be between -100 dBm and -94 dBm.

To measure the presence of electromagnetic energy, the RF Explorer spectrum analyzer was used. The frequency accuracy is ±10ppm and the absolute power accuracy is ± 5dBm (RF Explorer 2015).

The signal generator (TPI Synthesizer) was also used to generate electromagnetic energy to test for interference with communication. The device is uncalibrated. However, the testing did not rely on the generator to determine the RF power. Instead, the electromagnetic power and frequency were measured with the RF Explorer spectrum analyzer.

To test EMI, the following procedure was used:

1. Each controller was wired to an incandescent lamp and to line power. The controller is part of one circuit that also includes the load and line power.
2. Each sensor/transmitter was powered with a battery. The Lutron sensor can be powered only by a replaceable battery. The WattStopper sensor is intended to operate using its integrated PV, but a battery is supplied for setup, and this was used during the testing. The Leviton sensor was powered with the optional battery specified in the instructions.
3. The sensors and controllers were paired so they could communicate with one another.
4. The sensor was set on a wood counter and the controller and load were set on a plastic cart 15 ft (4.6 m) away.
5. The front of the controller and the side of the sensor with the PIR detector lens were faced directly toward one another. Under the assumption that the RF emitters are close to omnidirectional, this orientation should give similar results as an actual installation.
6. The background electromagnetic energy level at the receiver was noted.
7. The frequency at which the sensor sends its signal and the signal power at the receiver were measured with the spectrum analyzer.
8. Electromagnetic emissions at the frequency or frequencies used by the transmitter were generated by the signal generator. The power of the emissions was increased in steps until the receiver no longer acted on signals sent by the transmitter.

Energy Generation and Storage

To calculate battery life, NLPIP made the following assumptions:

- Self-discharge rates were 2% per year for lithium replaceable batteries (Jacobs 2013) and 2.4% per day for the internal super capacitors (electric double layer capacitors) built into each occupancy sensor (Panasonic 2012).
- Occupancy was assumed to be 4 hours per day (50% of an 8-hour work day), 365 days per year. NLPIP found that occupancy rates have a small effect on battery life.
- The working voltage range of the capacitor is from 4.5 (fully charged) to 2.7 volts.
- The occupancy sensor will continue operating until the battery is fully discharged.
- Energy from photovoltaic modules was not included, even if a module was built into the occupancy sensor. This worst-case scenario would be appropriate for dim or infrequently-lighted locations.

The initial capacity level of each sensor's battery is as shown in Table 4.

The battery run time was calculated using the following discharge rate equation:

$$\frac{dQ}{dt} = -k - rQ$$

Where Q is the charge (in coulombs) available in the battery or capacitor, k is the rate at which charge is used by the device (coulombs/day) and r is the self-discharge rate (%/day). The discharge rate due to the load consists of three parts: 1) the steady state, non-transmitting operating current (I_{op}), 2) transmitting charge/day during unoccupied time periods (I_{vacant}), and 3) transmitting charge/day during occupied time periods ($I_{occupied}$). In equation form:

$$k = Iop \quad + I_{vacant} + I_{occupied}$$

$$I_{occupied} = (Q \text{ per transmission})(n \text{ transmissions per day})\eta$$

$$I_{vacant} = (Q \text{ per transmission})(n \text{ transmissions per day})(1 - \eta)$$

Where η is the fraction of time the space is occupied. For these calculations occupancy was assumed to be 50% of an 8-hour work day: η = 0.50*(8h/24h) = 0.165.

The solution to the first-order differential equation describing the remaining charge is:

$$Q(t) = \left(Q_0 + \frac{k}{r}\right)e^{-rt} - \frac{k}{r}$$

Q_0 is the initial battery or capacitor charge (in coulombs) at time = 0. Life is given by solving this equation for time when $Q(t)=0$ (i.e., no charge left).

To measure PV electricity generation, the super capacitor voltage was set to 3.0 volts.

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Credits

Lighting Answers: Comparison of Wired and Wireless Lighting Controls for Single Rooms
Volume 13, Issue 1 June 2015

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Acknowledgements

The Lighting Research Center would like to thank the following people for providing review of this project: Sam Fankhauser of Eversource and Pierre Gallant and Andrew Giallonardo of Natural Resources Canada. Reviewers are listed to acknowledge their contributions to the final publication. Their approval or endorsement of this report is not necessarily implied. The authors also gratefully acknowledge the contributions of: Russell Leslie, N. Narendran, Howard Ohlhous, Martin Overington, and Mark Rea of the Lighting Research Center.

Glossary

Sources of term definitions: National Lighting Product Information Program (NLPIP), Lighting Research Center's Lighting Education Online, the IEEE Standard Dictionary of Electrical and Electronics Terms (IEEE Std 100-1996).

ballast	A device required by electric-discharge light sources such as fluorescent or HID lamps to regulate voltage and current supplied to the lamp during start and throughout operation.
capacitor	A device used in electric circuitry to temporarily store electrical charge in the form of an electrostatic field. In lighting, a capacitor is used to smooth out alternating current from the power supply.
compatible ballasts	An abbreviated list of common ballasts that will provide the necessary circuitry for a photosensor to operate correctly. Other ballasts may also be compatible; contact the photosensor manufacturer for details.
continuous dimming	Control of a light source's intensity to practically any value within a given operating range.
dimming ballast	A device that provides the ability to adjust light levels by reducing the lamp current. Most dimming ballasts are electronic.
driver	For light emitting diodes, a device that regulates the voltage and current powering the source.
electromagnetic interference (EMI)	The interference of unwanted electromagnetic signals with desirable signals. Electromagnetic interference may be transmitted in two ways: radiated through space or conducted by wiring. The Federal Communications Commission (FCC) sets electromagnetic interference limits on radio frequency (RF) lighting devices in FCC Part 18.
electronic ballast	A ballast that uses electronic components instead of a magnetic core and coil to operate fluorescent lamps. Electronic ballasts operate lamps at 20 to 60 kHz, which results in reduced flicker and noise and increased efficacy compared with ballasts that operate lamps at 60 Hz.
frequency	The number of cycles completed by a periodic wave in a given unit of time. Frequency is commonly reported in cycles per second, or hertz (Hz).
hysteresis	The dependence of the output of a system not only on its current input, but also on its history of past inputs. The electric light level set by a photosensor with hysteresis, for a certain photocell input signal, depends on whether that photocell signal is increasing or decreasing. Hysteresis provides stable operation in switching photosensors but is undesirable in dimming photosensors.
illuminance	The amount of light (luminous flux) incident on a surface area. Illuminance is measured in footcandles (lumens/square foot) or lux (lumens/square meter). One footcandle equals 10.76 lux, although for convenience 10 lux commonly is used as the equivalent.
lamp	A radiant light source.
luminaire	A complete lighting unit consisting of a lamp or lamps and the parts designed to distribute the light, to position and protect the lamp(s), and to connect the lamp(s) to the power supply. (Also referred to as fixture.)

lux (lx)	A measure of illuminance in lumens per square meter. One lux equals 0.093 footcandle.
nadir	In the lighting discipline, nadir is the angle pointing directly downward from the luminaire, or 0°. Nadir is opposite the zenith.
photosensor	A device used to integrate an electric lighting system with a daylighting system so lights operate only when daylighting is insufficient.
photovoltaic (PV)	Photovoltaic (PV) cells produce electric current from light energy (photons). PV cells are joined to make PV panels.
power	The power used by a device to produce useful work (also called input power or active power). In lighting, it is the system input power for a lamp and ballast or driver combination. Power is typically reported in the SI units of watts.
time delay range	For motion sensors, the range of time that may be set for the interval between the last detected motion and the turning off of the lamps.

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