Pacific Gas and Electric Company

Emerging Technologies Program
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Street Lighting Network Controls
Market Assessment Report

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Preface

Energy Solutions developed this market assessment report under contract to the Emerging Technologies Program of the Pacific Gas and Electric Company (PG&E).

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Introduction

This report provides a technology and market assessment of emerging network control and monitoring systems in street lighting applications. Presently, streetlights through the U.S., including California, are generally controlled with photocontrols that sense ambient light in order to turn streetlights on at dusk and off at dawn.

Using network control and monitoring systems with streetlights has the potential to save a significant amount of energy. These systems offer the ability to more precisely control on/off schedules at dusk and dawn and represent a major shift from the traditional model of lights controlled only by photocontrols, with no operator feedback. Network systems provide citywide management and monitoring of streetlight assets from a remote location, including the potential to meter actual street lighting energy use for billing purposes. Network controls that offer dimming capability can also provide energy savings through adaptive street lighting control, such as reducing lighting power as conditions change (i.e. lower traffic or pedestrian volume). Additional benefits from network controls can include reduced runtimes and detection of outages and "day-burners." At this point in time, network-controlled streetlights are very rare in the U.S., although a few products discussed in this report have begun to make inroads in the U.S. market

Streetlight network controls options rely on various communication strategies to interconnect network assets, from local radio frequency (RF) mesh networks to wide area networking with cellular technology and power-line carrier (PLC) communication through existing infrastructure. All systems reviewed here also include means to connect streetlight networks to internet servers for system data storage and remote web access for network monitoring and control. The various communication options carry inherent advantages and drawbacks, which are examined here.

This report provides an overview and comparison of network controls technology from the following five manufacturers: Echelon Corporation, ROAM / Acuity Brand Controls, Streetlight Intelligence, Tyco Electronics, Ltd., and Relume Technologies, Inc.

For each manufacturer, the report presents background information on the company, a description of the current and future product offering and how it functions, along with information and discussion on its capabilities, and any potential limitations. The report presents pricing information, discusses the installation process, and provides information on prior demonstrations and installations of each network control product. The report also provides estimates on the potential energy savings in California and in the PG&E territory from implementing network controls, and also discusses current market barriers and risks that this technology faces. Finally, the report provides a brief review of existing information on adaptive and mesopic street lighting.

Overview of Network Control Technology

Background

This report provides a technology and market assessment of emerging network control and monitoring systems in street lighting applications. Streetlights are a significant end-use of electricity in the U.S., as well as in California and the Pacific Gas and Electric Company (PG&E) service territory. Over 90% of U.S. streetlights are high intensity discharge (HID).[1] Presently, streetlights are generally controlled with photocontrols that sense ambient light in order to turn streetlights on at dusk and off at dawn.

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Through desk research, industry contacts, and previous experience, five of the leading manufacturers of streetlight network controls for the U.S. were identified and selected for thorough review. Information on the controls technologies presented in this report was collected through on-line literature and product research, as well as through interviews and meetings with network controls manufacturers.[2] While these are currently the leading manufacturers of streetlight network controls, it is also important to note that since this is an expanding market, additional manufacturers are continually entering the market.[3]

In addition to this market assessment, PG&E has carried out two field assessment projects in 2009 to study the performance of light emitting diode (LED) fixtures with network controls in street lighting applications. The experience gained with the technologies deployed in these

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[1] Navigant Consulting, Inc. (2002). "US Lighting Market Characterization, Volume I." Available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/lmc_vol1.pdf

[2] Presentation and other materials collected through interviews and meetings with manufacturers are available in a separate file, upon request.

[3] Additional manufacturers identified, which have not been reviewed in this report include: Phillips ("Starsense"); Ripley Lighting Controls ("Aladdin") and Brown Betty ("Sunrise").

complementary assessment projects (Echelon's LonWorks PLC platform in San Jose CA, and ROAM Acuity's system in San Francisco CA) has also been integrated into this report. The detailed field assessment reports can be found at www.etcc-ca.com.

CONTROL CAPABILITIES AND LIMITATIONS

While the control capabilities of streetlight network control and monitoring systems vary from product-to-product, all of these products represent a significant advancement over standard on-off control with photocontrols.

All of the products reviewed allow the streetlight operator to remotely control individual streetlights, groups of streetlights, or the entire network of streetlights, by turning them on and off manually or with scheduling features, normally relative to astronomical time clock-based calendars. Streetlight operators are able to remotely control streetlights in their network from their desktop, after logging in to a secure website.

Among the five products reviewed, there is currently significant variability with respect to their dimming capabilities. Three of the five products featured dimming functions that enable the systems to implement more dynamic control strategies that adapt to changing environmental conditions to adjust light level output. Those systems that currently offer dimming include Echelon's managed streetlight network technology, Streetlight Intelligence's Lumen IQ technology, and Relume's Sentinel technology. ROAM Acuity's next generation product also will be compatible with dimmable streetlights. The advanced ROAM dimming capability is scheduled to be available in production volume in early summer 2010, though prototype ROAM dimming controls have reportedly already shipped to several customers.

Echelon's technology allows dimming schedules based on known variations in traffic, weather, and/or available light conditions. Adaptive dimming schedules can be established remotely by the operator through the web-based interface to increase energy savings in lower conflict zones or over certain days/times. The technology can be continuously dimmed. Settings in the system dashboard, a web-interface software provided by third-party company Streetlight.vision, allows dimming to specific pre-set levels which can be customized per installation. A challenge of the Echelon system approach however, is that it relies on existing distribution infrastructure to transmit PLC information and commands; infrastructure that is often not suited for easily networking large numbers of streetlights.

Streetlight Intelligence's Lumen IQ technology can be remotely programmed to dim streetlights during non-peak periods. The Lumen IQ dimming technology allows for 60 steps of dimming, at intervals of approximately 1%. The current version of the Lumen IQ system is designed primarily for HID fixtures; compatibility with LED streetlights is still an issue although the company is currently working with LED fixture manufacturers on an LED solution for Lumen IQ. The current system is designed to capture energy savings by adjusting streetlight power over time to maintain a constant target lamp output, rather than initial over-lighting typical of HID systems due to expected lumen depreciation. Electronic ballasts for the HID system are not required. The technology currently relies on light sensors integral to each fixture, introducing additional equipment and complexity which could drive up system cost and maintenance challenges.

Relume's Sentinel is the third streetlight monitoring and control system that was reviewed that provides dimming capability. The Sentinel system operates using RF transmissions on a dedicated licensed public-safety band that leverages a city's existing infrastructure. Sentinel can dim LED fixtures from 100 to 0% intensity, at 16 dimming levels including full on and full-off. These dimming levels are pre-defined and stored in the system's transceivers, but pre-defined levels can be customized and specified by the municipality. In addition to the remote on/off control and dimming capabilities, the Sentinel system has several features that could improve safety and response, such as LED lamp flashing, evacuation route designation with chasing LED lamps, and emergency reporting through optional call buttons. As Relume is also an LED luminaire manufacturer, the Sentinel system is primarily designed for interoperability with Relume's own streetlights, potentially limiting its applicability to other installations.

Acuity's ROAM streetlight monitoring system provides a simple RF-enabled photocontrol solution to build local mesh networks of streetlights that communicate with each other and back to central gateways for internet connectivity. ROAM is compatible with any fixture that has a locking type receptacle, including HID, LED, CFL, induction, and incandescent. The ROAM system can be used to turn streetlights on/off as needed by the operator, or by issuing a scheduled operation, including virtual astronomical time clock dusk/dawn timing. Although ROAM does not currently allow for dimming, the company is currently working to incorporate dimming capabilities into its next generation product (expected to be available in summer, 2010).

Tyco Electronics' Lumawise technology also uses RF-enabled devices that communicate with one another and back through one or more central gateways, to connect to the internet. The Lumawise system allows for remote manual on/off control and remote on/off scheduling, of individual or groups of lights. Fixtures can also be set to operate in on-off based on a local photocontroller, with automatic back-up to a time-based schedule if the event of a photocontroller failure. Similar to the current ROAM technology, Tyco Electronics' Lumawise technology does not currently provide dimming capability.

ENERGY SAVINGS POTENTIAL

At the present, streetlights are generally operated at full output and are controlled with photocells that sense ambient light, to simply turn fixtures on at dusk and off at dawn. Network controls technologies can provide enhanced energy benefits by providing more precise control of on/off schedules and detection of streetlights that are operating at unnecessary times. Much higher savings potential is possible with dimmable streetlights and controls that allow operators to set lighting power to meet efficiency and performance goals and even adjust lighting power adaptively based on agreed to criteria. Energy savings can be achieved with advanced network controls through a number of different scenarios, discussed below.

Enhanced Flexibility in Designing and Operating Streetlight System

Dimming provides streetlight engineers and operators an unprecedented level of flexibility around designing and operating streetlights. For instance, the ability to dim can allow streetlight operators to experiment with different light outputs, before deciding on a default setting that maximizes energy savings while maintaining acceptable light levels. In a recently completed San Jose pilot of LED streetlights with advanced network controls, energy savings were enabled by advanced network controls that allowed operators to experiment with different light outputs before settling on a 50% power setting default.

Dimming in Areas Traditionally Over Lighted

Since traditional (mainly HID) streetlight lamp wattages are fixed and fixtures are not dimmable, streets are often over lighted initially in anticipation of lumen depreciation and in order to meet uniformity criteria, which are typically written for "maintained" performance.[4] Over-lighting may also result from using a higher wattage lamp when the streetlight design criteria call for a lower wattage that is not available, or is not used because the streetlight owner has standardized on a system combination for maintenance purposes. Network controls with dimming could be used to tailor a streetlight's light output to the design criteria, reducing or eliminating over lighting and saving energy.

Dimming capabilities offered by some network controls products, can also be harnessed to reduce the over lighting that is required to compensate for lamp lumen depreciation. Streetlight systems are designed to provide some minimum light level to meet local lighting requirements. Since the light output from all lighting sources declines, or depreciates over its lifetime (while power remains constant), lamps may be selected to meet minimum lighting requirements at the end of its lifetime. Most commonly however, lamps are not selected according to the lumen output at the end of their life, but rather, according to their mean lumens (i.e., the average rated lumens over the lifetime of the lamp). In either case, these lamps will provide lighting that exceeds the minimum lighting requirements over much of their life, wasting energy.

Some network control products (Streetlight Intelligence's Lumen IQ technology) compensate for this lumen depreciation by adjusting the power and light output over the lifetime of the lamp, reducing the wasted lumens and as a result, saving energy.

Adaptive Control of Streetlights

Adaptive control of streetlights is a key feature of dimmable network controls systems that can provide significant energy savings. A variety of factors are considered when selecting the appropriate light levels for a street; including pavement reflectance, traffic and pedestrian density, source lumen depreciation, and intersection type. Some of these parameters are fixed while other can vary considerably throughout the day and season. Yet, existing streetlight control strategies are very static. Control is limited to on/off scheduling based on the detection of daylight with a photocontrol. The existing design practice considers all parameters and then designs around a "worse case" condition. Fixtures are selected to provide the light level for this scenario, and as a result, they waste energy by lighting exterior spaces regardless of actual lighting requirements at a particular time and under particular environmental conditions.

Roadways are classified according to levels of traffic volume and pedestrian conflict in standards such as Illuminating Engineering Society of North America (IESNA) RP-8-00. These standards do not (yet) address adaptive strategies directly. However, traffic and pedestrian conflict levels are not necessarily constant throughout the night; in most cases the number of pedestrians will be far less late at night and in the early morning, when businesses are closed. Pedestrian conflict levels may also vary between weekday and weekends, with seasonal factors, and due to local events.

With network controls and dimmable lights, streetlights can be scheduled to adjust light output level during non-peak times of the night (e.g., periods with low pedestrian conflict levels). Light output levels can also be adjusted based on the day of the week (weekend vs. weekday), seasonal factors, local events such as festivals or sporting games, or changes in weather conditions. As an example of how an adaptive schedule might be implemented, consider the following abridged version of the RP-8-00 standard, showing recommended illuminance levels for collector roadways

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[4] DMD and Associates, LTD. (2007). *Final Report. Centralized Street lighting Control and Monitoring Demonstration Project.* Prince George, British Columbia. Accessible at: http://dmdeng.com/pdf/Prince_George_Report.pdf

based on pedestrian conflict levels. From high to low pedestrian conflict in the collector roadway classification, the recommended illuminance drops 50%, from 1.2 to 0.6 fc.

Table 1. Hypothetical Use of RP-8-00 Classifications to Implement Adaptive Lighting Strategies

Road and Pedestrian Conflict Area		Pavement Classification			Uniformity E_{avg}/E_{min}
Road	Pedestrian Conflict Area	R1 fc	R2 & R3 fc	R4 fc	
Collector	High	0.8	1.2	1.0	4.0
	Medium	0.6	0.9	0.8	4.0
	Low	0.4	0.6	0.5	4.0

Roadway lighting systems are typically designed for the conditions of highest anticipated traffic volume and highest anticipated pedestrian activity, but an adaptive lighting strategy would recognize that for many hours of the evening and early morning, the actual traffic and pedestrian activity is much lower. Recommended light levels under these lower activity conditions would also be lower per RP-8-00. The savings implications are significant, but are predicated on controls options that allow dimming schedules. Future standards guidelines would help clarify acceptable adaptive street lighting strategies by directly addressing this point.

However, throughout most of the U.S., streetlights operate as un-metered load and are billed at flat monthly rates. For customers to use network controls for adaptive dimming purposes, cost savings can only be realized if appropriate utility rate schedules are available. Network control products with energy metering functions must provide metered energy data in a useful format and at a level of accuracy acceptable to utilities for adaptive rate schedules to be feasible.

In addition to the energy-saving benefit available in all of these scenarios, reductions in light output from street lighting will also lead to reductions in obtrusive light (e.g., spill light, sky glow and glare). Astronomers, for example, who are particularly sensitive to sky glow, would be able to take advantage of adaptive dimming by scheduling observations during times when street lights are dimmed.[5]

Shortening Nightly Runtime

Additional energy savings can also be captured with network controls by shortening a streetlight's nightly and annual runtime based on astronomical dusk/dawn calendars. This more precise scheduling would switch lights on later and off earlier than would occur with photocontrols. It may even be determined that certain areas do not require street lighting after a given hour, in which case network controls enable a shortened run schedule.

Eliminating Day Burning Lamps

Day burning lights are streetlights that erroneously remain on during daylight hours. Day burners result when a streetlight's traditional photocontrol fails; for public safety, the failure mode of a photocontrol is often to switch the streetlight on. Since photocontrol failure can normally only be

[5] *Ibid.*

detected by observation, a day burner can operate for days, weeks, or longer before it is reported to the city or utility, and a maintenance crew is dispatched to replace the photocontrol. Meanwhile energy is wasted as the streetlights needlessly operate in full daylight hours. The monitoring feature of streetlight network control systems can save energy by immediately registering the failure of a photocontrol (if the system uses a photocontrol) or other control feature, and transmitting it to the central system, allowing the operator to create a work order for replacement. With a monitoring and reporting system provided by the network control system, the number of daylight hours that day burners run could be significantly reduced, saving energy.

INTEROPERABILITY WITH EFFICIENT STREETLIGHTS

Three out of the five streetlight network control products (ROAM Acuity, Echelon, and Relume Sentinel) that were reviewed for this report are interoperable with LED streetlights. In addition, while Tyco Electronics' Lumawise specification sheets do not list LED as a compatible light source, the company reports successfully testing its product with several LED fixtures in its lab.[6] However, LED options must currently be sent in to its lab for compatibility testing prior to deployment. Streetlight Intelligence's Lumen IQ product was designed for, and has been deployed with HID fixtures but the company is currently working with several LED fixture manufacturers on an LED solution. Products from several manufacturers are also compatible with induction fixtures; ROAM Acuity, Tyco Electronics specifically report compatibility with induction fixtures in product literature.

MONITORING AND METERING CAPABILITIES

All of the products reviewed are designed to serve as remote monitoring systems, connecting and reporting real-time performance data for each network streetlight. Equipment failures are tracked, logged and synchronized with the operator's maintenance work orders.

One key point of interest, and a highly touted feature of network controls, is the ability to monitor streetlight energy usage. This is an improvement from the city and utility perspective because currently streetlights operate as un-metered load and it is not always known when they are not operating properly; i.e. lamp failures or day burning lights. How the energy data from these systems is going to be collected and shared is another question. Ideally, some form of communication with utility information systems would be available to transfer data collected by the streetlight network for monitoring and billing purposes. As mentioned previously, to realize cost savings associated with schedule changes, appropriate utility rate schedules must be available that bill streetlights based on actual, rather than assumed, energy use. This will be especially important for adaptive lighting scenarios, where the fixture wattage is not a fixed point.

Similarly, there will need to be some standardization in terms of the frequency and accuracy of power measurements recorded by network controls systems. Utilities such as PG&E maintain strict requirements for revenue-grade metering, such as accuracy of ±2.0%, compliance with ANSI C12.1, programmability for rolling interval demand calculations, etc. Some of these standards may not apply to streetlight control systems, but key elements like accuracy may not be met by the current generations of the network controls technology reviewed in this report. Future versions need to be more robust in their energy measurements.

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[6] Communications with Tyco Electronics.

As a first step, utilities need to determine minimum energy monitoring requirements for measurement of street lighting energy use with network controls and develop a specification to provide to control manufacturers. Also, a clear pathway for data transfer should be developed between cities, controls designers, and utilities.

Four out of the 5 systems reviewed currently have on-board power measurement circuitry: ROAM, Tyco, Streetlight Intelligence and Relume. Echelon's next generation streetlight controls will also reportedly include this feature.

The ROAM system relies on a diagnostic photocontrol installed on each fixture, which collects and reports data on the average power draw over one hour intervals. The software can also provide energy consumption reports based on measured power draw and run time information; data can be customized for daily, weekly, or monthly aggregation. The hourly power report accuracy is reportedly -10% to +5%, over a load range of 40 to 1,000W. At a load of 100W, the company reports an accuracy of 2.7%; at 400W, the accuracy is reportedly 0.5%. Next generation ROAM controls will reportedly improve on power metering accuracy. Tyco Electronics' Lumawise technology also records power measurements at the fixture level, although the accuracy of on-board readings was not provided for this report. Streetlight Intelligence's Lumen IQ technology includes on-board power measurement circuitry in each fixture and power measurements are reportedly accurate to within 1% of revenue grade utility meters, though the overall accuracy based on this description is unclear, as utility accuracy requirements may vary. Similarly, Relume anticipates revenue grade certification for the Sentinel system's metering method, with reported accuracy to 1%.

Echelon's technology used in the recent San Jose pilot demonstration was not capable of real-time power monitoring; instead, the technology reported calibrated power levels for dimmed or full-power settings based on pre-installation measurements. Future versions of the technology will reportedly include actual luminaire-level power monitoring devices.

Controls manufacturers should be contacted for more technical details on the power measurements, energy metering, and data handling characteristics of each controls technology.

MARKET READINESS

At this point in time, network-controlled streetlights are very rare in the U.S., although a few of the products mentioned in this report have begun to make inroads in the U.S. market. Many of the installation and demonstrations projects that have occurred over the last 3-4 years are summarized in this section below.

Network controls for streetlights have also gained traction in the European market (in particular, Echelon's technology) and the Canadian market (where Streetlight Intelligence appears to have the strongest presence at this time).

The E-Street project[7] in Europe has raised the prominence of this technology in many European countries. The project is a partnership between manufactures, utilities, and city and country governments and its main objective is to expand the market for energy efficient street lighting. The project is working towards this objective with active procurement by streetlight owners who are part of the project, participation in pertinent standards and legislation, and by communicating customer needs to market players. The E-Street project has asserted it also wants to test the

[7] E-Street project website: http://www.e-streetlight.com/

application of new financial instruments (e.g., energy performance contracting, third party contracting) with street lighting projects.

Glendale, Arizona (*ROAM*): In 2007, 18,500 ROAM wireless transceiver-equipped diagnostic photocontrols, or "nodes," were installed throughout the City of Glendale, over a four-month period. [8] This was ROAM's largest deployment to date. In addition, the city partnered with ROAM to replace 8,500 LPS fixtures with HPS fixtures. In the four months following installation and training/education for system users and service crews, the City of Glendale reduced their system-wide outages and malfunction from 20% of fixtures to less than 4%. The audit, fixture replacement, and ROAM installation also revealed additional conditions that had been previously unknown, including: a much higher rate of outages and malfunctions (20%, as opposed to the expected 5%) and fixtures on group control, which the City had previously been assured no longer existed. The city reached a new outage performance benchmark of less than 1% in 2008 and reduced the volume of citizen calls regarding malfunctioning streetlights, from 20% to about 3%.

San Francisco, California (*ROAM*): In 2009, the San Francisco Public Utilities Commission installed a pilot network of 50 ROAM-controlled LED streetlights to assess the benefits of wireless streetlight network management and the energy and lighting performance of LED streetlights. The PG&E Emerging Technologies report documenting the results from this pilot will be available in January 2010 at www.etcc-ca.com.

Los Angeles, California (*GE Smartlights, now Tyco Lumawise*): The City of Los Angeles has also previously demonstrated wireless network controls benefits for its street lighting system, deploying nearly 5,000 network-controlled streetlights several years ago as part of a system trail for GE StreetSmarts,[9] now Tyco Lumawise. In conjunction with a new plan announced in 2009 to replace 140,000 HID streetlights with LED streetlights, the City is planning to install network controls on all new streetlights. The control and monitoring system will allow the LA Bureau of Street Lighting to monitor system performance in real time, verifying LED energy savings and optimizing maintenance.[10]

San Jose, California (*Echelon, and ROAM demonstrations*): In 2009 the City of San Jose, as part of an LED streetlight and network controls pilot demonstration, replaced 118 55W nominal LPS streetlights with fully dimmable LED luminaires of 75W at full output and dimmed to 50% power as the default setting. Echelon network controls were integrated into the demonstration luminaires and network segment controllers, WiFi antennas, and an internet gateway were installed and commissioned to allow for advanced control options such as remote scheduling, dimming and

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[8] ROAM Case Study – City of Glendale:
http://www.naesco.org/resources/casestudies/documents/Final_City%20of%20Glendale%20Insert.pdf

[9] See press release at:
www.geconsumerproducts.com/pressroom/press_releases/lighting/commercial_lighting/streetsmarts.htm

[10] City of Los Angeles Led Street Lighting Case Study. CCI, Feb, 2009.
http://www.mwcog.org/environment/streetlights/downloads/CCI%20Case%20Study%20Los%20Angeles%20LED%20Retrofit.pdf

outage identification and energy metering. The PG&E Emerging Technologies report documenting the results from this pilot is available at www.etcc-ca.com.

The City also issued an RFP for another demonstration project to replace approximately 160 higher wattage LPS streetlights (135 and 180W nominal) in an industrial setting with LED streetlights and integrated wireless monitoring and control system, and has selected ROAM Acuity to be the provider of network controls. The project's intent is "to evaluate LED streetlight technology and optimization of energy consumption through wireless automated monitoring and control."

City of Oslo, Norway (*Echelon*): In 2006 the City of Oslo, Norway used Echelon's LonWorks technology in its fleet of streetlights.[11] The project was implemented by Hafslund ASA, Norway's largest generator and supplier of electric power and security products. The city replaced its older, less efficient magnetic ballasts in 15,000 HPS streetlights with electronic ballasts from SELC Ireland Ltd. Streetlights were networked using Echelon's LonWorks power line technology, and the system was integrated by Kingsberg Analogic AS (a specialist in LonWorks based energy management solutions) and Philips Lighting. Streetlight.vision's enterprise monitoring software was used to control lamps, analyze their behavior, and identify failures. In addition, Philips StarSense software and Streetlight.vision's Streetlight Suite software was used to measure and display energy use.

Reported benefits from the installation included reduced lamp downtime and significant energy savings. The City of Oslo reduced energy use for streetlights by 62%. About two-thirds of the savings was due to the installation of efficient electronic ballasts and the rest was due to reduced lamp burning hours. An estimated five year payback was reported.[12] In future years, as public acceptance to changing light levels, Oslo expects to realize an additional 10 to 15% savings in energy use.

Brittany France (*Echelon*): Another pilot of the LonWorks technology was carried out in Brittany, France. In the pilot phase that was completed in November 2005, the city deployed network controls on 44 streetlights and used electronic ballasts (SELC Ireland Ltd.) and Echelon's LonWorks node. One supply cabinet was equipped with Echelon's *i*.LON SmartServer, which communicated through GPRS with the central streetlight monitoring software from Streetlight.vision. The server used its internal astronomical clock to automatically turn the lights on and off at dusk/dawn, and to dim the ballasts to 60% between 11 pm and 5am. Electricity use was reduced by 46%, which resulted in a 30% savings in electricity costs. Projected electricity savings are about $80,000 per year. Among the other benefits, lamp downtime was reduced by 90%.[13] Following the pilot, the City decided to extend the network to 3,100 additional fixtures over the next 18 months.

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[11] Oslo Street lighting System Slashes Energy Use with LonWorks® Technology: http://www.echelon.com/solutions/unique/appstories/Oslo.htm

[12] http://blog.norway.com/2009/04/27/oslo-street-lighting-system-slashes-energy-use-with-echelon/

[13] See Echelon (2007) for discussion of other benefits from this installation: Echelon (2007). *Monitored Outdoor Lighting: Market, Challenges, Solutions, and Next Steps.* September 2007. Available: http://www.echelon.com/solutions/streetlight/documents/Echelon_StreetlightWhitepaper_FINAL.pdf

City of Prince George, Canada (*Streetlight Intelligence*): Streetlight Intelligence Lumen IQ system was piloted in the City of Prince George in British Columbia in 2006; the project networked 170 existing HPS fixtures along a main arterial (meeting IESNA "Major" roadway classification, as defined in RP-08).[14] The project employed various dimming levels. Streetlights that were dimmed by 50% light output achieved a 40% power savings, reportedly with no impact on the safety of motorists or pedestrians. Overall, the energy reduction was 25%, compared with standard streetlights. Annual energy savings (from pedestrian conflict dimming only) realized in the City of Prince George pilot amounted to C$3,098[15] which, when considered with the total cost of the retrofit project (C$22,950), implies a 7.5 year simple payback. Note that these savings do not take into account the savings from dimming for lumen maintenance, nor do they account for the benefits from the system's maintenance management features.

CURRENT COSTS

The current cost of network control technology for streetlights varies widely between the technologies that were examined in this report. Pricing per streetlight (in 2009$) range from around $70 to almost $300. Generally, the products with the lowest price per streetlight were the least technically complex. The lower cost options were also the more mature network control products reviewed with the highest number of number of actual installations to-date. In general, dimming capabilities were found to correspond to higher upfront costs. Most systems also carried some ongoing monthly or annual costs for services such as area network maintenance, internet connection and service, software licensing, data storage fees and technical support plans. Annual ongoing costs per streetlight varied widely amongst technology options, ranging from less than $1 to over $6.

All of the technologies reviewed are relatively new and are still emerging in the street lighting marketplace; costs are expected to reduce as the technologies mature and production scales increase.

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[14] DMD and Associates, LTD. (2007). *Final Report. Centralized Street lighting Control and Monitoring Demonstration Project.* Prince George, British Columbia. Accessible at: http://dmdeng.com/pdf/Prince_George_Report.pdf

[15] This is based on British Columbia's rate of C$0.066 per kWh; rates in California and in other regions of the U.S. are much higher.

Product Descriptions

ECHELON / STREETLIGHT VISION

COMPANY BACKGROUND

Echelon Corporation is a public company and leading supplier of control networking hardware and software, and a developer of "smart metering" solutions. Echelon, headquartered in San Jose California, offers two main product lines: the NES System for advanced metering infrastructure, and the LonWorks® infrastructure products for control networking. Echelon's streetlight network controls system is part of the LonWorks family of products.

SYSTEM OVERVIEW

Echelon's managed street lighting network technology uses the company's LonWorks platform and dimmable streetlights and ballasts (HID) or drivers (LED) supplied by a third party. The streetlight is controlled by a LonWorks node installed inside the fixture. Echelon's technology uses PLC technology for communication between streetlights and the network. Fixtures communicate with the Echelon's *i*.LON® SmartServer as a segment controller that links to the internet and centralized streetlight monitoring software through a system gateway. An overview of Echelon's system configuration is shown in Figure 1.

Echelon's managed street lighting network system is designed to provide a more robust operations strategy than a typical on/off photocell control, including capabilities such as streetlight scheduling, dimming (based on traffic, weather, and/or available light), failure detection, and asset management. Key system features include:

- Astronomical time-clock based on/off scheduling; photocells not required
- Different dimming level options available
- Individual streetlight and system-wide average power and energy reporting (based on assumed wattage)
- Outage detection and maintenance tracking
- Adaptive dimming schedules available to increase energy savings in lower conflict zones or over certain days/times

Echelon's system relies on existing power lines to carry the communication signals, which in theory can lower up-front costs associated with a network control system, by lowering material and installation costs. However, one of the biggest challenges for the Echelon system used in the recently completed San Jose street lighting controls assessment project was the layout of the local distribution circuits with only a small number of streetlights wired to a single circuit downstream of the residential transformers that step down the voltage to a standard 120 volts. Echelon technology uses a PLC communication signal that is issued by segment controllers located downstream of these transformers. As a result, many more segment controllers were required than was originally expected, in order to propagate the PLC signals to all streetlights in the network.

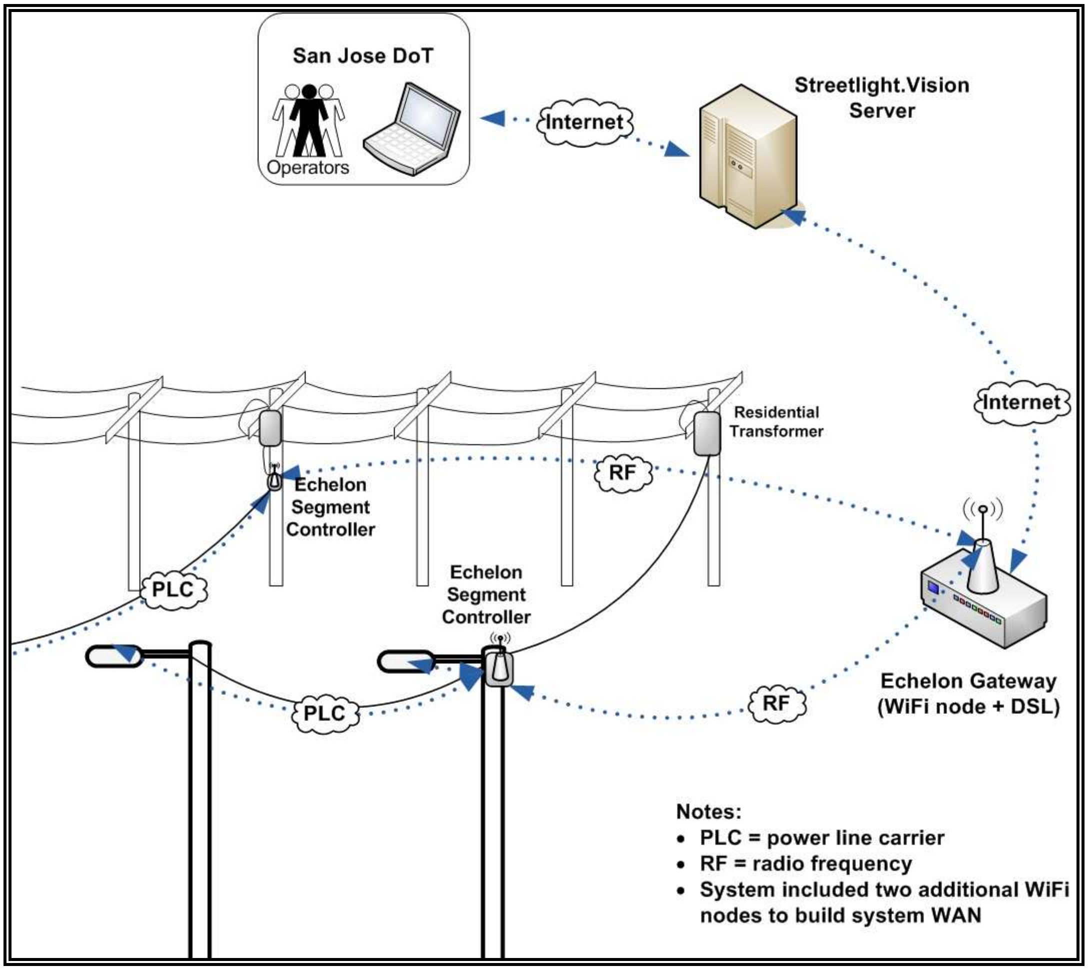

Figure 1. Basic System Architecture Diagram of Echelon Pilot System in San Jose Demonstration

HARDWARE AND CONTROLS DETAILS

The LonWorks platform was introduced in the 1990s, and today, is a well-established technology. Millions of LonWorks power line devices have been deployed around the world in applications including commercial buildings, public transportation systems, industrial plants, and electricity metering infrastructure.

For streetlight applications, a LonWorks Node is installed in each fixture and works in conjunction with a dimmable electronic ballast for HID or driver for LED. Echelon specifies that to be compatible with the system, ballasts/drivers must be: 1) dimmable; 2) capable of out-detecting lamp and electrical failures; 3) able to measure and set data such as lamp status, lamp level, accumulated energy use of the streetlight, voltage, current and power factor, and send data over lower line networks using LonWorks protocol; and 4) able to receive switch and dimming commands from a streetlight segment controller over power lines using LonWorks protocol.[16] The success of several large-scale monitored streetlight projects in Europe has helped spur ballast

[16] Echelon (2007). *Monitored Outdoor Lighting: Market, Challenges, Solutions, and Next Steps.* September 2007. http://www.echelon.com/solutions/streetlight/documents/Echelon_StreetlightWhitepaper_FINAL.pdf

manufactures to develop electronic dimmable ballasts that can communicate on the open (not proprietary) LonWorks protocol.[17]

Echelon's *i*.LON® SmartServer (Figure 2) is the streetlight network segment controller, designed to manage and command up to 200 streetlights on a single circuit through PLC communications and typically installed in a feeder pillar (e.g., power supply cabinet) or in a weatherproof enclosure on distribution and streetlight poles. As the connection point between a central system gateway and the fixtures, the segment controllers are responsible for monitoring and controlling the streetlights. They record lamp status, energy use and running hours, and calculate the availability of natural light using an internal astronomical clock to set on/off schedules. Other reported options include collection of data from traffic and weather signals to automatically dim some or all streetlights. The segment controllers are equipped with WiFi antennas (802.11G wireless local area network protocol) to communicate to the system gateway that connects the streetlight network to the internet for remote monitoring, control, and data storage purposes.

Figure 2. Echelon *i*LON SmartServer

The demonstration technology piloted in San Jose was not capable of true power measurements in the field. Instead, the manufacturer measured power with a lab grade power analyzer for the set of fixture equipment (LED fixture, 0-10v continuous dimming ballast, power line carrier transceiver) at full power and dimmed states and programmed results so that the system reports power levels for each power setting. The fully developed Echelon system is expected to include power measurement circuitry for real-time power logging with accuracy of better than 2% in their next deployment.

The power consumption of the i.LON SmartServer (segment controller) is less than 15W according to the technical data sheets,[18] and was measured to be about 10W through the San Jose pilot demonstration project. Echelon also reported system gateway wattage for the San Jose project as 41.3W. In addition, for the luminaire-level smart driver device necessary to maintain communication between the streetlight and the segment controller, the California Lighting Technology Center (CLTC) measured continuous power draw of 1.3W in its lab.

Echelon provides a standard warranty of one year on system components, though extended warranty options are also available.

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[17] *ibid.*

[18] Echelon i.LON SmartServer Technical Data Sheet: http://www.echelon.com/support/documentation/datashts/721xx.pdf

NETWORK DESIGN

PLC communication is accomplished using transceivers that send a signal on the power line. Echelon uses the ANSI 709.2 (LonWorks) standard for power line communication. LonWorks is an open, extensible architecture that allows control devices from multiple manufacturers, to communicate with each other. This underlying protocol has been used in thousands of control applications throughout the world.

For projects using Echelon's technology, a third-party company, Streetlight.vision has been the software provider.[19] The Streelight.vision M2M Data Collect software is used to collect, aggregate, transform, filter and store data from all controllers in a central, open database that is installed at the SPEI IT center in Paris. While Streetlight.vision acts in a supervisory role to collect system-wide data and provide real-time control for service purposes, the Echelon segment controllers perform scheduling and data logging functions on-board and can operate independently.

NETWORK MANAGEMENT INTERFACE

Streetlight managers access the system using centralized streetlight monitoring software and a web interface. The information from this software can be used by work-order management applications as well as by energy billing applications. Screenshots from the Streetlight.vision software are shown in Figure 3. In the San Jose assessment project, the operator found that the method for saving new schedule settings and verifying that new schedules are active was not intuitive and in fact, it appeared that the test schedules did not take effect.

The control system schedules fixture on and off commands by an astronomical time clock. In the San Jose assessment project, the LED luminaries were continually dimmable with the Echelon smart controller and dimmable driver integrated into each fixture. The settings in the system dashboard allowed for dimming to 100, 75, 50, and 25% of the maximum power level (see Figure 3), although different levels could be specified or set up by the operator.

The system can identify and track fixture outages, and report these to operators through text or email messages. Alarms are sent to Echelon support when they are triggered. For example, the system reports that a fixture has lost communication to Echelon support, which then troubleshoots and resolves the issue.

Fixture runtime and on/off reporting, lamp burn hours and total energy consumption are recorded in the system for each fixture. In addition, system-wide power and energy reporting is also available. As noted earlier in this report, the pilot system did not have the capability to take true power measurements; power values reported by the system were assumed wattages and not real-time measurements.

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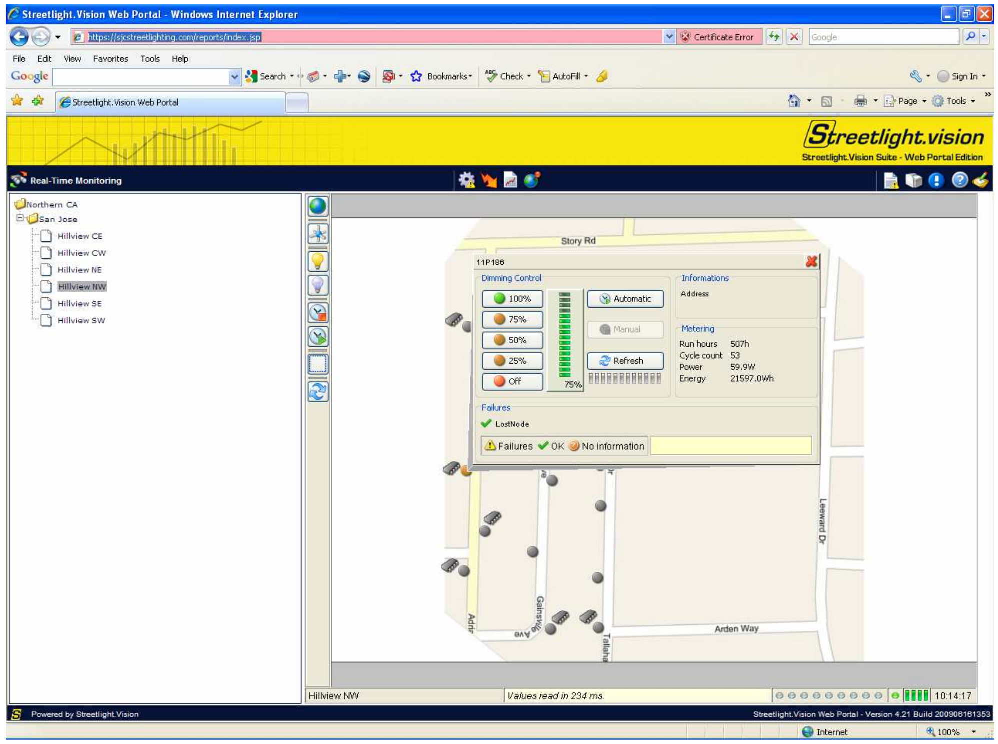
[19] Streetlight.vision is an independent "Streetlight Monitoring" and "City Monitoring" software solution provider, and is headquartered in Paris, France. http://www.streetlight-vision.com/content/solutions.htm



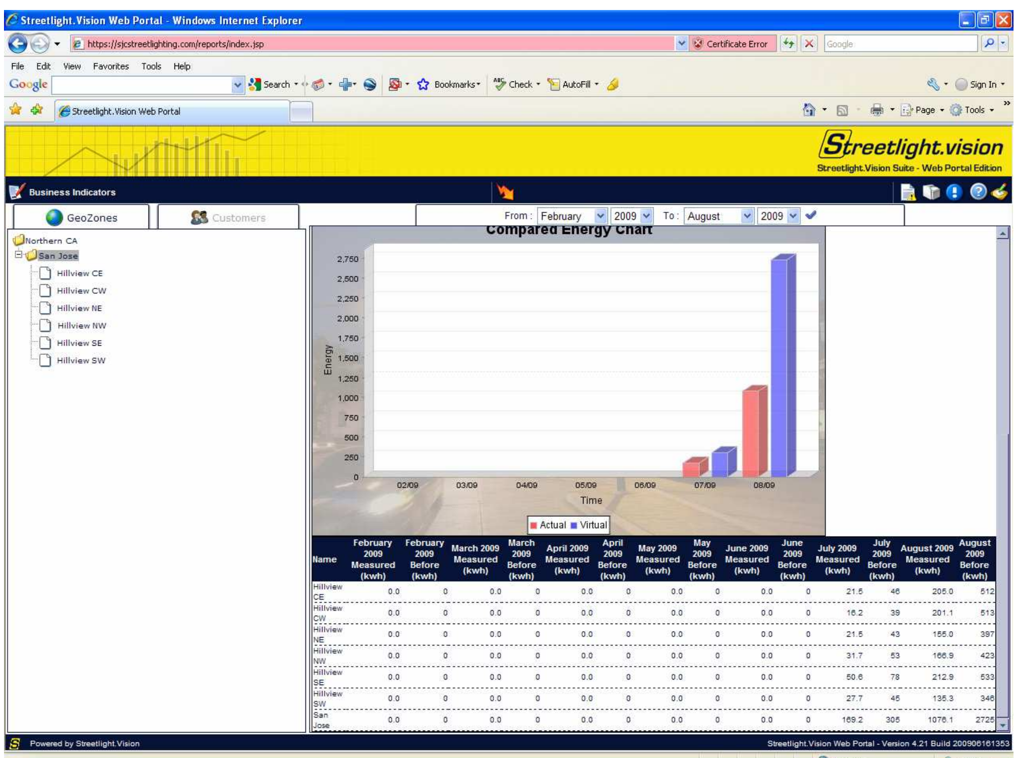


Figure 3. Screen Shots from Streetlight.vision
Dimming controls interface (upper) and energy system comparison interface (lower).

Installations & Demonstrations

The LonWorks technology has been extensively piloted throughout Europe (more than 30 sites alone, in 2006). In 2006, the City of Oslo, Norway began to install a system of "smart streetlights" for 15,000 unit inventory with Echelon power line carrier controls. The city achieved a reported 62% energy savings on retrofitted lights; two thirds due to changing over to electronic ballasts and the balance due to the controls to reduce lamp burn hours.

The San Jose PG&E pilot demonstration project carried out in 2009 marks the first significant installation of Echelon's technology with streetlights in the U.S.

ROAM ACUITY

Company Background

ROAM, a remote streetlight monitor solution, is a subsidiary of Acuity Brand Controls, wholly owned and operated by Acuity Brands, Inc., headquartered in Atlanta, George. Acuity Brands, Inc. together with its subsidiaries is one of the world's leading providers of lighting fixture equipment and services. The ROAM division was established in 2004 and is headquartered outside Atlanta in Convers, Georgia.

System Overview

ROAM stands for Remote Operation Asset Management. The ROAM system (Figure 4) networks individual streetlights within a municipal area into a streetlight monitoring system. Through the network, system owners and operators can view, monitor, and control streetlights from a secure remote location. This system of management can minimize the life cycle costs of street lighting, while also improving safety, sustainability and service levels.

The ROAM system consists of: 1) ROAM communicating photocontrols, compatible with any NEMA twist lock receptacle, which serve as the communications node; 2) one or more ROAM gateways – each gateway manages up to 2,000 nodes through a wireless mesh network; 3) a remote Network Operation Center (NOC) which manages communications, safeguards and communicates data, and conducts high-level diagnostics; and 4) a secure ROAM internet portal which provides the ability for full work order management and offers the ability to schedule and control lights.

ROAM is compatible with any fixture that has a locking type receptacle. The ROAM photocontrol, with diagnostic and wireless technology, locks on top of the fixture and replaces a traditional on/off photocontrol. ROAM can be used with any light source from 45 to 1,000W, and is compatible with a wide variety of light sources including HID, LED, CFL, induction, and incandescent.

The ROAM system can be used to turn streetlights on/off manually, or by issuing a scheduled operation, including virtual astronomical time clock dusk/dawn timing. Benefits from ROAM's remote streetlight monitoring and management system include improved lighting safety and security and enhanced service level by reducing streetlight outages/malfunctions and minimizing life cycle costs of the system. The ROAM system as demonstrated to-date has not allowed for dimming, limiting the energy-savings opportunities. However, the company is currently working to incorporate dimming capabilities, discussed further in next section of the report.

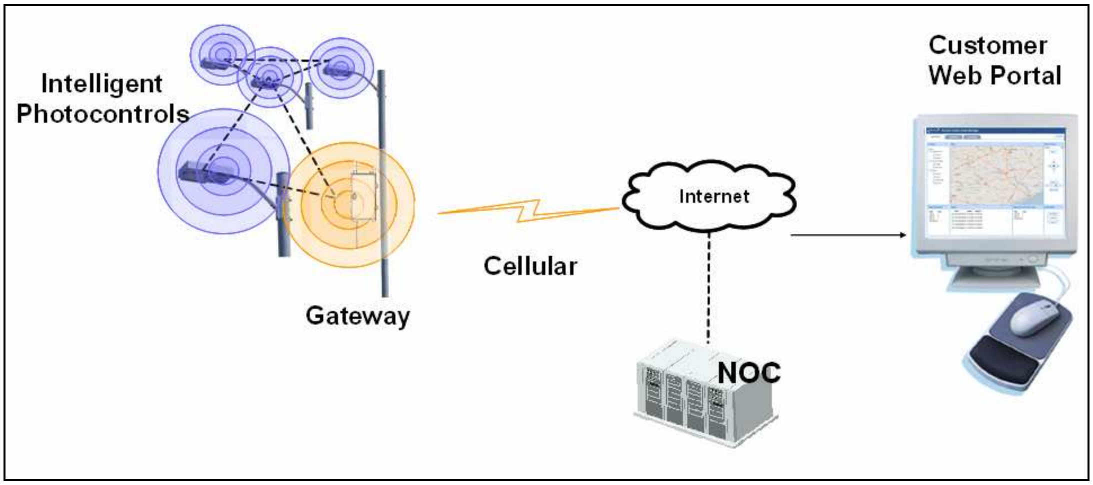


Figure 4. Basic System Architecture Diagram for ROAM System

HARDWARE AND CONTROLS DETAILS

ROAM uses a patented "smart" diagnostic photocontrol (Figure 5), which looks nearly identical to a standard photocontrol, serves as the node to collect operational information from the fixture and transmit the information wirelessly first to the gateway and then the NOC. The ROAM photocontrol can detect and report on the following conditions: Fully Operational; Fixture Malfunction, No Communication; Unspecified Malfunction; Partial Report; Unregistered; No Power at Activation; Low Wattage; Operational with Issues (Cycling, Dayburner, Group Control, Excessive Power, Low Voltage High Voltage, High V Delta, High Current, Node 120, Fixture 240V).

Figure 5. A ROAM diagnostic photocontrol[20]

The ROAM diagnostic photocontrol uses a filtered silicon light sensor. Each photocontrol collects and reports data on the following each hour: average power draw over the hour, average, maximum and minimum line voltage every hour. The hourly power report accuracy is about -10% to +5% over a load range of 40 to 1,000W. At a typical load of 400W, the reported accuracy is about 0.5%. Next generation ROAM controls will reportedly improve on power metering accuracy.

The ROAM gateway serves as the central collection point for multiple ROAM photocontrols in the vicinity and transmits information between the photocontrols within the network and the NOC through internet connection. Depending on network topology, one gateway can manage up to 2,000 photocontrols.

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[20] Source: ROAM 2.0 User Guide Version 1.2

Optional ROAM equipment includes hand-held devices, GPS locators, and rugged Toughbook laptop computers, but they are not required for ROAM to function.

While the current ROAM technology does not allow for dimming, ROAM's system provides the needed architecture to convey dimming commands to ROAM enabled fixtures. ROAM is currently working with several fixture manufacturers to develop solutions that will allow the fixture to execute dimming commands.[21] This would involve having an integrated dimmable electronic ballast/driver and a ROAM dimming control module (ROAM DCM) in the fixture. The ROAM DCM would be compatible with any fixture that has a 0-10V enabled dimmable driver available from a ballast manufacturer. According to ROAM, the ROAM DCM and dimmable ballast/driver will need to be integrated into the fixture when the fixture is manufactured. The company expects the DCM to be available in volume production in early summer 2010, although demonstration samples are already available. The ROAM DMC will be a standard package size, so it will require some effort for each fixture manufacture to integrate it into their product line.

ROAM system components currently come with a 3 year product warranty and have a reported 8-year design life. ROAM's predictive FIT analysis projects a 0.76% annual failure rate for photocontrols and field experience to date (> two years, 25,000 devices), suggests an approximate 1% annual failure rate.

The load from each ROAM photocontrol is on average 1.6W, with a maximum of 2.2W.[22] The ROAM enabled gateway has an average power draw of 5.5W, with a maximum of 12W.[23] The average hourly power draw that is reported from each node to the NOC does not account for these loads. In addition, the DCM will likely require some small additional power draw; data on this is not currently available.

NETWORK DESIGN

The gateway serves as the central collection point for multiple ROAM photocontrols in the vicinity. ROAM nodes communicate at 2.4 GHz using IEEE 802.15.4 standard protocols, at a Baud rate of 250 Kbit per sec, and have a range of 1,000 feet with a clear line of sight. The nodes and gateway form a WAN; each node communicates with other nodes in order to deliver data to the gateway. Routing decisions are made at the node level, which improves the robustness of the network.

The gateway communicates with the NOC either by cellular uplink or direct Internet connection (Ethernet) if cellular service is weak or not available in the area. Alternatively, a local Wi-Fi network can also be used, if available. The customer can choose the uplink choice that makes the most sense based on locally available access and cost of service. For example, if free public wireless is available in the area, this may be the lowest-cost option. Cost of cellular, Ethernet, or other local wireless connection options will vary based on location. Communications between the gateway and ROAM NOC are encrypted using the Advanced Encryption Standard (AES) algorithm.

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[21] ROAM FAQs: http://www.roamservices.net/pdf/ROAM_FAQs.pdf

[22] ROAM Enabled Node Spec Sheet.

[23] ROAM Enabled Gateway Spec Sheet.

The company reports that while RF interference can occur, it is typically temporary. In cases where chronic RF interference occurs, this problem can be overcome with a higher power ratio or other measures, depending on the situation.[24]

In the event of a cellular network problem or if the ROAM network goes down, the streetlights' ROAM photocontrols will revert to default standard photocontrol dusk/down operation. Should a power outage occur, the company reports that the network could be brought back up within one minute after power is restored. To date, ROAM reports the longest period of service disruption was less than one day (location of disruption was not given), in a situation where the system was taken down for server maintenance (no data loss was encountered).

Lighting data is stored at the ROAM NOC., located in Conyers, Georgia. The NOC is protected by power back-up and disaster recovery procedures. Historical data is kept on the portal for one to three years; older data is stored on an alternative media. The ROAM NOC can store 15 years of scheduled node operation.

Network Management Interface

The ROAM package also includes software licenses for users to access lighting data from the secure customer portal. A user ID and password are required to access lighting data from the web portal. From the web portable, available views include: a Main Dashboard, Map, Reporting, Historical, Scheduling, Work Order, and Grouping.

The ROAM system can provide diagnostics and reporting on:

- Fixtures which are fully functional;
- Fixture malfunctions;
- Fixtures which are functioning but that have an operational issue such as: Cycling lamps; day-burner lamps; and wiring problems.
- Fixtures without power or that are not communicating with the ROAM system;
- Voltage measurement and reporting, including high current alerts;
- Wattage reporting including excessive power draw;
- Burn hour reporting (Hourly and Cumulative kWh);

From the web portal, system owners and operators are able to command and schedule the streetlights to turn on/off; capture historical data on repairs, maintenance and equipment replacements which will be facilitated through an integrated work order module, and can generate reports on malfunctions repair and repair data, also facilitated by work order management module. The average latency is 2 to 4 minutes, and depends on the number of streetlights being commanded or scheduled, the distance, and lamp type. Screenshots from ROAM's web portal are shown in Figure 6.

In the San Francisco pilot project, successful luminaire control, grouping, and outage detection from the user interface was observed during testing. However, some difficulties arose with luminaire scheduling features, as actual activation of saved schedules appeared to lag by one day from settings. Customer support was easily available during system testing to address those types of questions.

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[24] ROAM FAQs: http://www.roamservices.net/pdf/ROAM_FAQs.pdf

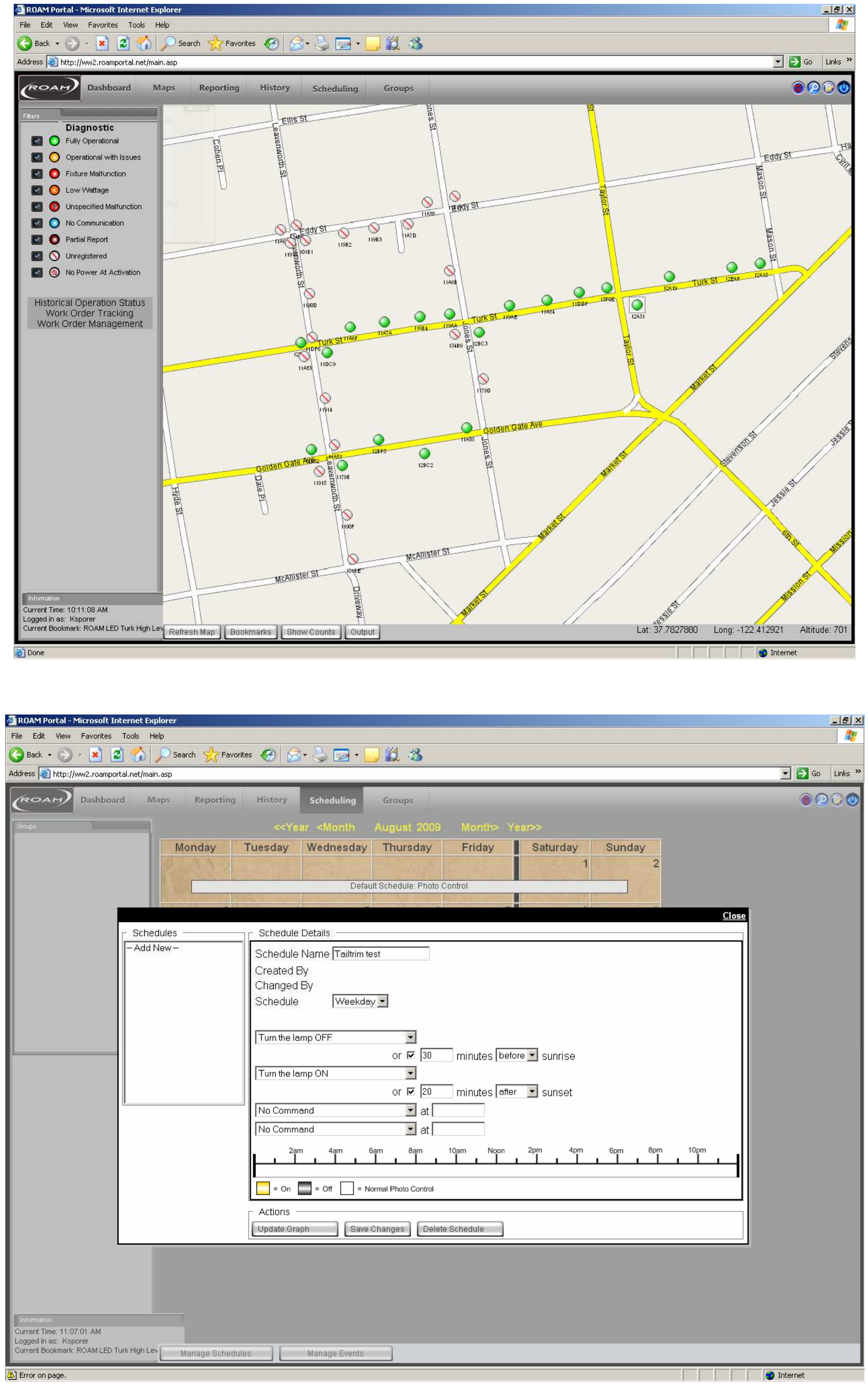

Figure 6. Screen Shots from the ROAM web portal

Main dashboard showing overview of network streetlights and summary diagnostics (top); and a scheduling interface (bottom).

INSTALLATIONS & DEMONSTRATIONS

With approximately 30,000 total network streetlights in deployment, the company reports that it currently has more wireless network streetlights deployed than any other manufacturer in North America. This system was recently piloted in San Francisco, through the joint SF PUC/PG&E pilot installation and assessment project.

In 2007, the City of New Orleans Department of Public Works installed 1,000 ROAM units in a pilot project throughout the French Quarter area of the city, to evaluate the technology's effectiveness.[25] The company's largest deployment to date has been in the City of Glendale, Arizona.[26] In 2007, 18,500 ROAM photocontrols were installed throughout the City of Glendale, over a four-month period. The city reduced their rate of system-wide outages and malfunction from 20% of fixtures to less than 4%.

Additional customers of ROAM technology include: Los Angeles Bureau of Streetlights; College Station, Texas; Chapel Hill, North Carolina; Greenville, South Carolina; BrandsMart; Gwinnett Arena; the Maryland Transit Administration; and McConnell Air Force Base.

STREETLIGHT INTELLIGENCE

COMPANY BACKGROUND

Streetlight Intelligence, Inc., incorporated in March 2003, is a public company headquartered in Victoria, British Columbia, Canada. The company is the developer and provider of proprietary intelligent streetlight optimization technologies, trademarked and marketed as Lumen IQ™.

SYSTEM OVERVIEW

Lumen IQ™ streetlight technology has been designed to allow streetlight operators to significantly reduce their energy consumption, maintenance costs and environmental impact. The Lumen IQ Streetlight Optimization System[27] provides an integrated network lamp control system. The system (Figure 7) includes (1) one or more Lumen IQ C200 lamp controllers; (2) one or more Lumen IQ Stations, which serve as the communication hubs; (3) the Lumen IQ Commander for in-field set-up and programming; and (4) Lumen IQ Central, the internet-based software system for streetlight management from a central location.

The Lumen IQ Station and the local lamp controllers in the network communicate over a 900 MHz RF mesh network. The Lumen IQ Station connects to the Internet and Lumen IQ Central through a wide area 1X cellular data link. The Lumen IQ system allows users to remotely program the output of the entire streetlight network, a subgroup of fixtures, or individual fixtures from any

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[25] News Release dated 6 December 2007:
http://www.roamservices.net/pdf/ROAM%20New%20Orleans%20Insert.pdf

[26] ROAM Case Study – City of Glendale:
http://www.naesco.org/resources/casestudies/documents/Final_City%20of%20Glendale%20Insert.pdf

[27] Lumen IQ technology is available as either a standalone streetlight controller (Lumen IQ™ Stand Alone Streetlight Controllers) or as part of network streetlight infrastructure (Lumen IQ™ Streetlight Optimization System). This report only discusses the network controls option.

computer with an internet connection. Streetlights can be turned on or off at user-defined times as well as dimmed during non-peak periods, when traffic is low. In addition to potential energy savings from dimming during non-peak periods, the Lumen IQ system also carries a proprietary technology that provides the capability to capture energy savings from adjusting the lamp output (using an on-board sensor) in response to lumen depreciation. However, relying on sensors integral to each fixture, introduces additional equipment and complexity which could drive up system cost and maintenance challenges.

The system is scalable and can be rolled out in phases, linking additional fixtures to an existing network already in place. One drawback of Lumen IQ technology is that it has not yet been applied to LED light sources and was designed for magnetic HID ballasts, but the company reports the system's architecture is flexible enough to accommodate future light sources (e.g., LEDs) and electronic ballasts. Currently, the company is working with several LED fixture manufacturers (Ruud, Leotek, Philips-Lumec, and LED Roadway Lighting) to tailor the Lumen IQ technology to LED fixtures.

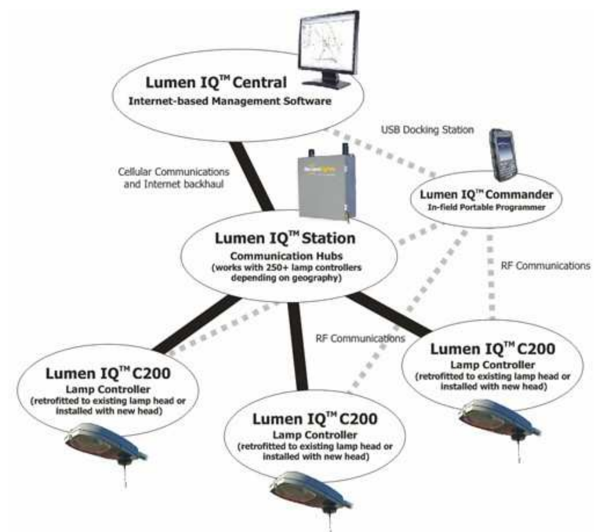

Figure 7. Overview of the Lumen IQ Streetlight Optimization System[28]

HARDWARE AND CONTROL DETAILS

The Lumen IQ C200 Lamp Controller (Figure 8), installed with every fixture, has three main components: (1) a microprocessor with a 900 MHz RF radio that wirelessly interfaces with the Lumen IQ Station communication hub and other lamp controllers in the local network; (2) a real-time lamp sensor; and (3) an "intelligent" photocell.

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[28] *Source: http://www.streetlightiq.com/Products/Overview/NetworkLampControl/tabid/174/Default.aspx*

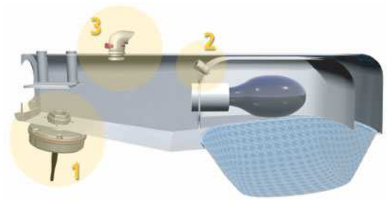

Figure 8. Lumen IQ C200 Lamp Controller[29]

The microprocessor uses data from the lamp sensor to continually monitor and adjust the lamp performance so that it meets the adaptive lighting protocol set by the clients using the Lumen IQ Central software application. Photocells are not required with every controller; however, two or more photocells are required for each local network of 250 controllers. The photocell includes several proprietary technologies that improve accuracy and make the photocell easier to orient for optimal performance and it is also programmable to enable minor adjustments for localized ambient lighting.[30] A new feature will be available beginning second quarter of 2010, where the system will also be able to be programmed to use calculated dawn-dusk time based on GPS locations, to maximize savings potential by shortening nightly runtime.

The wireless network uses one or more Lumen IQ Stations, mounted in an external enclosure within 300 meters (1,000 ft.) of its group of lamps (range will depend on local geography), to distribute programming instructions from Lumen IQ Central to the Lumen IQ C200 lamp controllers that are in the local network. One Lumen IQ station is required for every 250-500 controllers. The Lumen IQ Station collects data from each controller that is relayed to the Internet and Lumen IQ Central. Lumen IQ Central is a computer application that uses the Internet to interface between the database for the user's streetlight network and one ore more Lumen IQ Stations, providing access to the streetlight network from desktop PC with an internet connection.

The Lumen IQ Commander is a hand held PC programmer that can communicate with the Lumen IQ C200 Lamp controllers via 900 MHz RF radio during initial commissioning when lamp controllers are installed in the field. During installation the operating parameters can be loaded to the lamp controller (alternatively, this can be preset at the factory per client's request), the system associates the Lumen IQ Lamp Controller ID with a unique pole ID, assigns a GPS location to the pole, sets a real-time clock inside the microprocessor, and captures all the asset inventory data for the lamp fixture, including manufacturer/model of fixture, ballast, capacitor and igniter. Field personnel can upload commissioning information back to Lumen IQ Central using a docking station. The Commander also serves as a field-servicing device, to locate faulty lamp fixtures for repair or replacement, to check inventory in or out during repair or maintenance, and provides be used to track services of field crews.

Lumen IQ dimming technology allows for 60 steps of dimming, at approximately 1% intervals.[31] This is achieved with Streetlight Intelligence's custom multi-tap capacitor that varies capacitance

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[29] http://www.streetlightiq.com/Products/Overview/NetworkLampControl/LampControllers/tabid/175/Default.aspx

[30] DMD and Associates, LTD. (2007). *Final Report. Centralized Street lighting Control and Monitoring Demonstration Project*. Prince George, British Columbia. Accessible at: http://dmdeng.com/pdf/Prince_George_Report.pdf

[31] DMD and Associates, LTD. (2007). *Final Report. Centralized Street lighting Control and Monitoring Demonstration Project*. Prince George, British Columbia.

levels to achieve the 60 steps of dimming. The fixture can be dimmed from 100% of output down to 31% of output. With HID, the system dims down to 50% power (based on the HID lamp manufacturer's specifications and limitations). When Lumen IQ is used with LED fixtures, up to 100% dimming is possible. Streetlight Intelligence reports that the dimming technology is compatible with nearly any LED fixture and the company is currently working with several LED suppliers (Ruud, Leotek, Philips-Lumec, and LED Roadway Lighting).

In addition to potential energy savings from dimming during non-peak periods, the Lumen IQ system also carries a proprietary technology that provides the capability to capture energy savings from adjusting the lamp output to adjust for lumen depreciation. The company reports associated energy savings range from 17% (150W HPS lamp) to 22% (400W HPS lamp). This function is compatible with all common HID ballasts; electronic ballasts are not required. In addition, the Controller has a proprietary anti-cycling feature that detects and reports when the bulb begins to cycle incorrectly, also cutting power to the fixture to protect the fixture's electronics and save energy.

On board power measurement circuitry is included in each fixture and is accurate to within 1% of revenue grade utility meters. Power measurements are taken every ten minutes. The Lumen IQ power measurement circuitry has not yet been approved as a revenue grade utility meter for billing purposes. Streetlight Intelligence reports the Lumen IQ has reported a 20-year mean time between failures (MTBF), and currently a 2-year product warranty. However, Streetlight Intelligence indicated in January 2010 that is currently reviewing this warranty and expects it will change in the next 3-6 months; no indication was given whether the standard warranty period is likely to increase or decrease.

The load of the Lumen IQ Controller ranges from 1 to 4W, as a function of input voltage (120V to 480V, respectively). The Lumen IQ Station segment controller's load ranges from 20 to 40W, as a function of input voltage and configuration.

NETWORK DESIGN

The Lumen IQ Controllers, Station(s), and Commander(s) communicate wirelessly through a mesh network on the 900 MHz RF band. The 900 MHz band is unlicensed and requires no special permits. The system uses a 900 MHz frequency hopping spread spectrum with "Data Encryption Standard" (DES). Redundancy is provided in the system since each Controller can communicate with its adjacent neighboring lamp, providing a self healing data path if one or more modules in the local network fails. The system uses 128-bit security encryption for all communications. The Lumen IQ Station is connected to the server and the Internet using a wide area 1x cellular data communications (GSM or CDMA), or a community's existing wireless network infrastructure.

Lumen IQs retain data for up to 7 days, while the stations retain data for months and poll IQs nightly for data. IQs also have a back-up battery that allows the fixture to save the last even prior to power down. Along with Lumen IQ Central application discussed earlier, Streetlight Intelligence offers two options for data collection and storage: Streetlight's fully managed central database involves a secure Tier One data facility as a repository for all information pertaining to the client's Lumen IQ Streetlight Optimization Systems, which is offered on a per lamp fixture/per month basis and includes the Lumen IQ Central software package, maintenance and upgrades at no additional cost. Alternatively, users can chose to use Lumen IQ Central software with a database that is housed and maintained by the organization. For this latter option, purchasers pay an annual software license for the Lumen IQ Central software and database.

NETWORK MANAGEMENT INTERFACE

Lumen IQ Central application interface allows users create and implement adaptive light protocols based on energy usage analysis, and easily generates reports and analysis of the streetlight network's performance and energy savings. The Lumen Central Smart Client software can be installed on any Internet-enabled computer. Lumen Central is driven by a SQL database with row versioning and change tracking. Streetlight operators log in with a username and encrypted password. Current reporting includes: power consumption; power saved due to over lighting; power saved due to scheduled dimming; and fixture component anomaly/failure reporting. The application also offers a variety of maintenance and inventory tracking features including the ability to create and maintain inventory records for all streetlight network(s); the option of creating and managing pro-active streetlight maintenance schedules based on roadway type and GPS location; and the ability to interface with asset management systems to provide accurate routing and location information. Screenshots from the application, illustrating some of these features are shown in Figure 9.

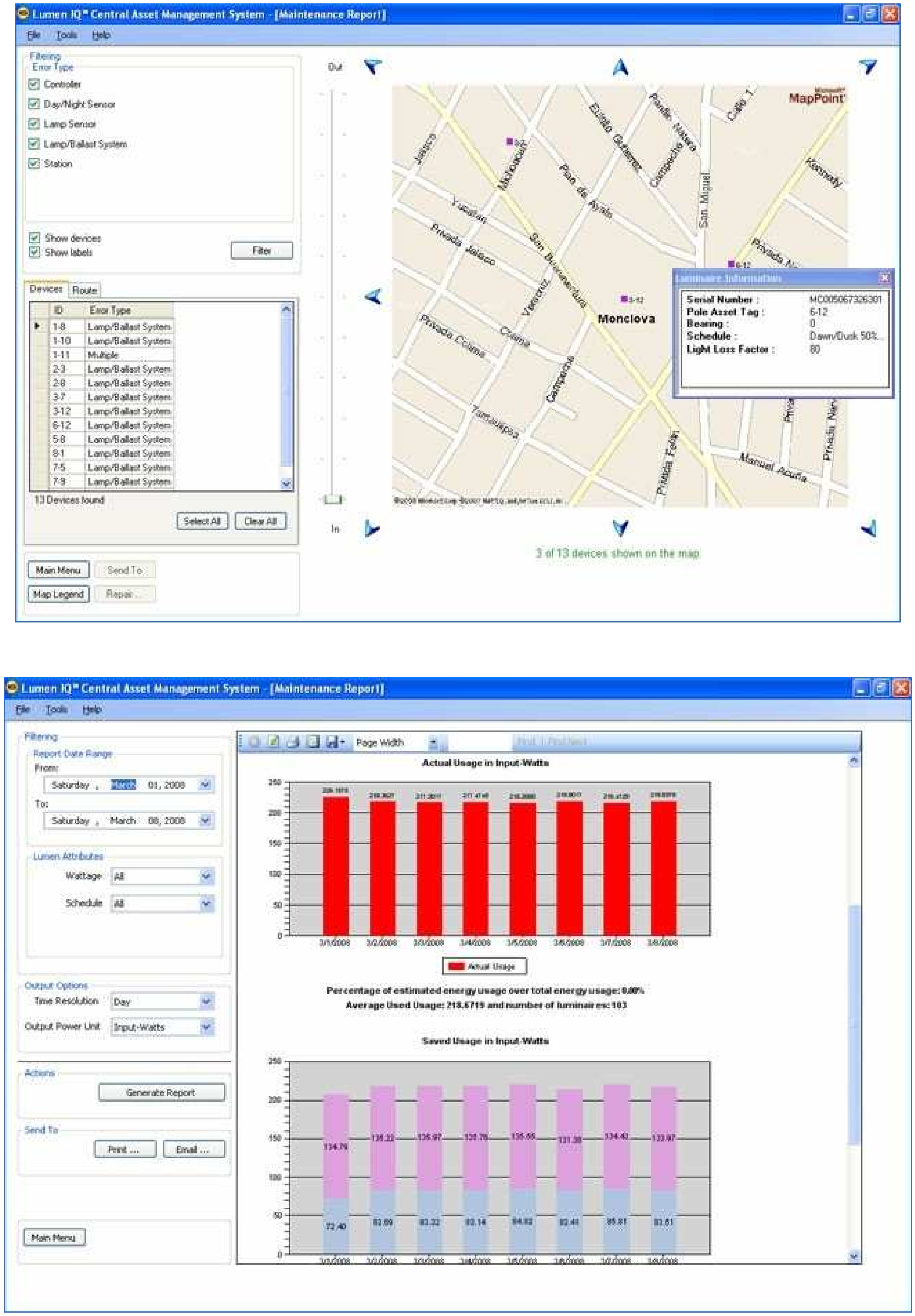

Figure 9. Screen Shots from the Lumen IQ Central
User interface upon login (top); and reporting for energy and performance analysis (bottom).

INSTALLATIONS & DEMONSTRATIONS

Streetlight Intelligence Lumen IQ system was piloted in the City of Prince George in British Columbia in 2006; the project installed networked controls for 170 existing HPS fixtures along a main arterial.[32] The project employed various dimming levels. Streetlights that were dimmed by 50% achieved a 40% power savings, with no impact on the safety of motorists or pedestrians. Overall, energy savings were reported to be 25%, compared to traditional streetlights.

In addition to other pilot projects throughout Canada, the company's first commercial sale was in 2007, for the Lake Okanagan bride in Kelowna, British Columbia, Canada.[33] The Lumen IQ system has also been deployed on about 2,000 streetlights in the City of Monclova Mexico.

TYCO ELECTRONICS

COMPANY BACKGROUND

Tyco Electronics, Ltd., formally a segment of Tyco International Ltd., is a public company based in Switzerland. The company is a global provider of engineered electronic components, network solutions, undersea telecommunication systems and specialty products. In 2006, Tyco acquired Telemics Inc. and incorporated their wireless streetlight control management system into their offerings. The company has continued the development of the proprietary product trademarked "Verics" and markets it under the name "Lumawise™". The product allows wireless monitoring and management of streetlight assets via a self configuring network, through retrofits of existing streetlights.

SYSTEM OVERVIEW

Lumawise technology allows for a reduced total life cost of owning street and outdoor lights, lower energy consumption, improved quality of lighting service, enhanced asset management, and better risk management. The technology is available as a retrofit system and installs into the standard NEMA photocell sockets found on most streetlight fixtures.

The system consist of several components: (1) "CheckPoints" which are the nodes of the wireless network, are used to monitor, diagnose, and control streetlights (one CheckPoint per lamp/ballast system), and communicate with one another over a proprietary mesh network (900 MHz/2.4 GHz ISM bands); and (2) "AccessPoints" which mediate communication between up to 500 CheckPoints on the wireless mesh network, and also connect to the internet via Wireless GPRS, Wi-Fi, or Ethernet connections. Information is exchanged between AccessPoints and the central "DataCenter," run by Tyco, which can be accessed and managed from any internet enabled device via a web-application.

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[32] The final report from this study, DMD and Associates, LTD. (2007), is posted on DMD's website at: http://dmdeng.com/learning/

[33] See New Release at: http://www.streetlightiq.com/About/NewsReleases/NewsReleaseDetail/tabid/164/Default.aspx

The system has reportedly been deployed on over 13,000 streetlights in the U.S., and has been used to monitor/control HPS, LPS, metal halide, mercury vapor, and induction fixtures with a large variety of differing lamp and ballast types.[34] Although Tyco Electronics' Lumawise specification sheets do not list LED as a compatible light source, the company reports that it has successfully testing its product with several LED fixtures in its lab.[35] However, LED options currently must still be sent in to its lab for compatibility testing prior to deployment. The Lumawise technology also currently does not offer any dimming capability.

HARDWARE AND CONTROL DETAILS

The Lumawise system consists of two field deployed hardware components: CheckPoints and AccessPoints (Figure 10), as well as a DataCenter (Tyco Electronics' server and database system) and a Web Application interface.

A CheckPoint is installed in the twistlock photocontroller receptacle of an individual fixture, and monitors and controls the operation of that fixture. An AccessPoint is also installed into a fixture through the same twistlock photocontroller receptacle and provides the same functionality as a CheckPoint, as well as local wireless mesh cluster management. The AccessPoints connect the local cluster of CheckPoints (approximately 500 or fewer) to the DataCenter server through an internet connection.

Figure 10. Tyco's CheckPoint (left) and AccessPoint (right)[36]

The DataCenter consists of the Tyco Electronics' server and database system, which is hosted in a secure Tier 1 facility. The DataCenter services the deployed AccessPoint and CheckPoint clusters, collects data, monitors network operations, implements customer specified operational asset conditions, and provides customer asset management system data feeds.

The Web Application is an Internet browser-based secure individual login interface, for users to analyze and control their lighting asset network, generate operational reports, and for geographical network representations.

Each CheckPoint and AccessPoint module is capable of turning the fixture on and off, either according to a preprogrammed schedule, by manual command or by the input of a photocell. Data

[34] Tyco data sheets for AccessPoints and CheckPoints indicate the system is compatible with the following luminaire types: LPS, HPS, metal halide, induction, as well as the following ballast types: CWA, Reactor, Regulated, and Auto ballasts.

[35] Communications with Tyco Electronics.

[36] Source: http://www.telemics.com/products_architecture.php

characterizing each fixtures performance is sent to a central web server. This report includes hours of burn time and ignitions faults.

Power measurements at the fixture level are taken using analog sampling at 3 kHz, with on-going accumulation and periodic upload to the DataCenter. The periodicity of DataCenter records is generally set to a three hour interval, but can be adjusted to affect dataload costs. In addition, the following information is measured and logged:

- Vrms of the AC power line
- Arms, total current drain on the line of fixture, CheckPoint, and devices connected to the PC twistlock
- Watts, of the total load
- Whrs, of the total load
- Power Factor, of the total load
- Burn hours
- Ignitions
- Control regime

Fault messages are sent as priority messages, upon occurrence, and are independent of the standard periodic messaging.

All Lumawise components carry a warranty of one year against any manufacturer defect,[37] though Tyco reports that the expected lifetime of the system is greater than 10 years. The MTBF calculations suggest a lifetime of greater than 40 years.

A CheckPoint consumes on average, less than 1.5W, and an AccessPoint consumes on average less than 2.5W. The load of these devices, one of which will be plugged into the photocontrol receptacle in each fixture, is included in the report data.

NETWORK DESIGN

Lumawise's existing platform utilizes 902-928 MHz frequencies that do not require customer licensing. The company is developing a 2.4 GHz-based platform, which will take advantage of cost reduction opportunities although the functional capabilities will be mostly the same. The company reports this new platform will be available for deployment in Q4 2009. The monitoring devices communicate with each other, to form a self-configuring and self-healing mesh network consisting of CheckPoints clustered around AccessPoints. The AccessPoints in turn, communicate with a secure server via the Internet (through Wireless GPRS, Wi-Fi, or an Ethernet connection).

Lumawise has a scalable design, that allows CheckPoints and AccessPoint clusters to be deployed at any desired rate of deployment, without a large upfront infrastructure investment. As clusters expand and "grow together" as a result of new, adjacent installations, Tyco Electronics' patented auto-redundancy mechanism across AccessPoints continues to gain communications robustness.

Tyco's web services are hosted by a world-class Internet data center (earthquake resistant construction, extensive security systems, dry-chemical fire-suppressant system, and controlled temperature and humidity environment), and consequently, requires no new IT infrastructure

[37] As defined in the Tyco Electrics Standard Terms and Conditions of sale at: http://www.tycoelectronics.com/tc.pdf

investment on the streetlight operator's end. Tyco's Network Operation Center is open 24x7, 365 days a year.

NETWORK MANAGEMENT INTERFACE

The dedicated web site is password protected. The Web Application is used to set and retain operational control modes, for one or more fixtures, or a group of fixtures. Several screenshots from this Web Application are show in Figure 11. Using this Web Application, although dimming is not currently a standard option with Lumawise; fixtures can be set to operate in any of the following:

- On-off based on the local photocontroller, with automatic backup to a time-based schedule in the event of photocontroller failure
- Continuous on
- Continuous off
- On-off based on a defined time schedule

The system reports on the following operating conditions:

- Operating normally
- Photocontroller not functioning
- Photocontroller oscillating
- Line voltage out of range
- Cycling lamp
- Fixture malfunction (lamp unable to operate properly)
- Device self diagnostic fault
- No Communications (power, network, or device failure).

Using these conditions, reports can be generated for analysis by group, status, location, control mode, etc. These reports can be charted, tabulated, geographically represented (if GPS information was originally uploaded), and exported in various formats including xml for import into the customer's work assignment system.

Figure 11. Screenshots from Tyco's Web Application

Fault report screen (top); and lighting homepage, demonstrating the system's monitoring capability by showing fixture status as well as fixture properties (bottom)

Installations & Demonstrations

Tyco Electronics reports that multiple customers throughout the U.S. are currently using the Lumawise Street lighting System, with over 13,000 CheckPoints delivered.

RELUME TECHNOLOGIES

Company Background

Relume Technologies, Inc. was incorporated in 1994 as an LED research and development company and is headquartered in Oxford, Michigan. Relume manufacturers LED lighting products, using its patented Silver Circuitry™ thermal management technology. Relume Sentinel™ is the company's streetlight monitoring and control system.

System Overview

Relume Sentinel is a streetlight monitoring and control system that relies on a city's existing public safety communication infrastructure to send and receive information from each fixture. Sentinel can accommodate up to 16 million streetlights on the network. The system functions through high-powered RF transmissions to and from fixtures, across secure, FCC licensed communication channels in dedicated public safety bands. Using dedicated licensed public-safety bands allows the system to avoid possible uncontrolled radio emissions and resulting interference issues that may arise with mesh networking systems which operate in widely used unlicensed RF bands.

Sentinel provides on-off control of individual streetlights or any zone/group of streetlights, and offers either LED lamp dimming or flashing for individual lamps or by zone. In addition to the remote on/off control and dimming capabilities, the Sentinel system has several features that could improve safety and response, such as LED lamp flashing, evacuation route designation with chasing LED lamps, and emergency reporting through optional call buttons.

Sentinel is composed of three main hardware components: (1) the Wireless Lighting Control Module, which is enclosed within or connected to, each fixture; (2) a Master Network Interface Module at the municipal communication point; and (3) the city's already installed ultra high-frequency (UHF) repeaters that extend the range of the system to all nodes.

One of the reported advantages of the Sentinel system over other streetlight networking and control systems is that it leverages existing infrastructure and communication channels, thus reducing the initial infrastructure investment and avoiding the monthly communication/data charges.

As Relume is also an LED luminaire manufacturer, the Sentinel system is primarily designed for interoperability with Relume's own streetlights. This may potentially limit its applicability to other installations. The company reports that Sentinel can be used with competitive LED fixtures, although since the control module currently comes in a standard size, there may be form factor issues with fitting the module inside different fixture. Although designed for LEDs, Sentinel technology is also adaptable to traditional streetlights and can be used to network existing or new MH or HPS street lights.

HARDWARE AND CONTROLS DETAILS

The Sentinel system is comprised of three hardware components: (1) the Wireless Lighting Control Module, which is enclosed within or connected to, each fixture; (2) a Master Network Interface Module at the municipal communication point; and (3) the city's already installed ultra high-frequency (UHF) repeaters that extend the range of the system to all nodes. This system is summarized in Figure 12.

The Wireless Lighting Control Module (Figure 13) is enclosed within the Relume LED fixture, or can be connected to a competitor's LED fixture. The Wireless Lighting Control Module can also be used with a city's existing HID streetlights, in which case the module is attached through the photoelectric cell port. The module permits bi-directional communication between the Master Network Interface Module and the individual streetlights. Commands for dimming, flashing, and on-off can be received and implemented. The module also senses current, ambient temperature, and interfaces with up to two external switches for emergency call features (e.g., see emergency call buttons in Figure 12).

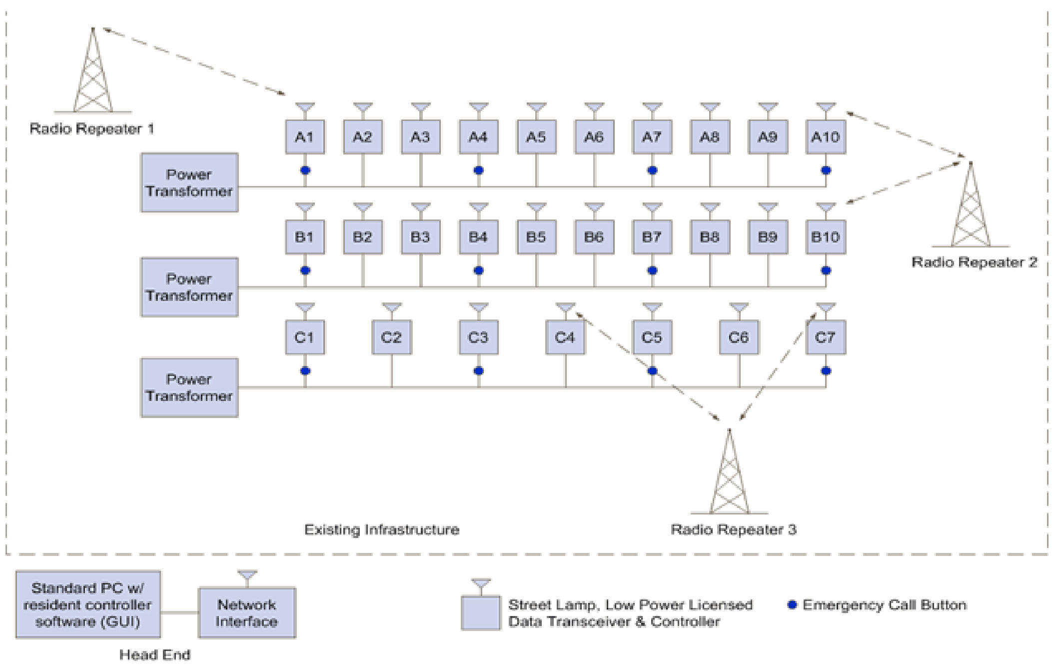

Figure 12. Overview of Sentinel System[38]

[38] Source: http://www.relume.com/htm/products_sentinel_schematics.htm

Figure 13. Sentinel Lighting Control Module

Each fixture also has a built-in photocell for sensing ambient light. At dusk, if the module does not receive a network command, the fixture will activate to its last known intensity level. At dawn, each fixture will remain at its present intensity level if a network command is not received. This default operating mode can be disabled.

Each fixture's transceiver can operate at up to 5W of RF output power to ensure adequate signal strength across the coverage area. Fixtures can also be fitted with high gain antennas, if desired, to improve performance in areas with low signal strength. The transceivers use flashed based microprocessors architecture and are designed for field software upgrades.

The Master Network Interface Module, located at the municipal communication point, serves as the interface between the central computer and the municipal RF system. Data is exchanged between each fixture's Wireless Control Module and the Master Network Interface Module, through the existing repeater channels in the licensed and regulated UHF 450 to 470 MHz band (or another assigned band).

The Sentinel system relies on a city's existing UHF repeaters to extend the range of the system to all nodes. Since Sentinel operates on a channel within the licensed 450 to 470 MHz band, each end user is licensed specific channels in this band to minimize interference with nearly cities.

Sentinel's Streetlight Monitoring and Control Software is hosted locally on a server included with the Sentinel system. In addition to this software, the system comes with a rack mount server, a rack mount monitor and keyboard, a rack mount Municipal Base Station, and the required antennas. The management system can be run locally on the host computer, or can be accessed remotely with an internet connection, via a secure location.

Each fixture continuously monitors its energy usage. The Sentinel system can support revenue grade metering with calibration to 1% accuracy, and Relume is seeking revenue grade certification (IEC 60253).

The Sentinel system can dim LED fixtures from 100% to 0% intensity. The system can operate at 16 dimming levels, including full off and full on. These dimming levels are pre-defined and stored in the Sentinel transceivers, but the pre-defined levels can be customized and specified by the municipality. Sentinel also allows for control of many types of HID lights (either new or retrofit) using single step dimming to 50-60% of full intensity.

The Sentinel system carries a 5 year warranty. Each fixture control module has a standby power consumption of less than 0.5W.

Network Design

Relume Sentinel system uses a point- to multi-point network topology that operates in the 450 to 470 MHz UHF band. Although the Sentinel system follows the intent of NCTIP 1213 (Object Definitions for Electric and Lighting Management Systems) for its general control scheme and configurability, it uses a customer protocol and is therefore not compliant with NCTIP 1213.

All network communications use a 128 bit encryption for system security. Communications between the rack mounted PC local host and the rack mount municipal base station is encrypted using a similar scheme, but with a separate unique key to ensure the base station can only be controlled by the dedicated host PC. The system uses packet error detection and a redundant pack structure to provide a robust communications.

The management system supports Network Time Protocol (NTP). NTP access time can be varied as needed to meet system requirements.

The Sentinel Streetlight Monitoring and Control Software stores key information in a SQL Server data base that resides on the local host computer. Parameters that are stored in this data base include lamp operating status, energy usage, and fixture run times.

Network Management Interface

The Sentinel Streetlight Monitor and Control system relies on a graphical user interface software. The software is hosted locally on a server that is included with the Sentinel system. The management system provides five levels of access:

1. Network Administrator – full access with ability to perform non-routine system upgrades
2. Administrator – full access to operate and maintain the system
3. Operator – individual access rights to operate the system
4. Report Generation – read only access rights plus report creation
5. Read Only – view status of devices and reports

The software allows configuration of various network operating parameters, allows for control of individual lamps or groups of lamps, and the status of every device on the network. The software has the option to alert the operation to device issues including lamp outages, excessive energy use, abnormal fixture temperatures, photo detector failure, and RF performance degradation. With the report generator feature, issues can be sorted and prioritized for the maintenance department.

The control system can operate individual lamps, any groups of lamps, or all lamps in the network. Up to 255 groups can be assigned in the system. Any lamp can be assigned to any group, enabling sequential, zone based, or map based control. Individual lamps or groups of lamps can be controlled manually through the graphical user interface, or they can be automatically sequenced using the Sentinel scheduling feature. The Sentinel system allows for 16 dimming levels, including full off and full on. These dimming levels are pre-defined and stored in the Sentinel transceivers, but the pre-defined levels can be customized for a municipality. A single network command can implement a specific dim level for either individual lamps, any group of lamps, or all lamps in the network. A Network Administrator can disable a pre-defined schedule and/or the default operating mode, to meet specific lighting requirements.

The Sentinel report generator can be used to access lamp operating conditions and status, and information on individual lamps. The Sentinel SQL Server data base stores the following information: lamp identification code, lamp name, pole number, lamp physical address, lamp geographical coordinates, and lamp manufacturer and model number. The report generator can be used to create maintenance and repair schedules. Relume is also investigating compatibility with ESRI and Arc GIS as a future option.

Installations & Demonstrations

Relume's Sentinel system has been installed in small, proof-of-concept demonstrations in Ann Arbor, Michigan; Anchorage, Alaska; as well as in San Jose, California. Relume reports that the Sentinel system will be available in production volume, in early 2010.

Summary of Product Information and Features

Table 2 provides a summary of the key features and information for each of the 5 products that have been reviewed in this report.

Table 2. Summary of Network Control Product Characteristics, Features and Cost

Product	**Echelon**	**ROAM**	**Lumen IQ**	**Lumawise**	**Sentinel**
Company	Echelon http://www.echelon.com/	Roam Acuity http://www.roamservices.net	Streetlight Intelligence http://www.streetlightiq.com/	Tyco Electronics http://www.tycoelectronics.com	Relume Technologies http://www.relume.com/
Communications					
Communication Type	PLC	Mesh RF	Mesh RF	RF	RF
Frequency	*NA*	2.4 GHz (802.15.4)	900 MHz	900 MHz, 2.4 GHz	450-470 MHz
Range	*NA*	1,000 ft clear line of sight	1,000 ft	1,000 ft	Unknown
Backhaul Communications	Ethernet, Cellular, or Wi-Fi	Ethernet, Cellular, or Wi-Fi	Ethernet, Cellular, or Wi-Fi	Ethernet, Cellular, or Wi-Fi	Local Municipal UHF Radio
Controls and Components					
Fixture Level	LonWorks Node	Intelligent Photocontrol / Node	IQ C200 Lamp Controller	CheckPoints	Wireless Lighting Control Module
Gateway (ratio to streetlights)	Gateway (1: 1,000)	Gateway (1: 2,000)	IQ Station (1: 250-500)	AccessPoint (1: 500)	Master Network Module (1)
Other Interface Components (ratio)	Segment Controller (1:100)	*NA*	*NA*	*NA*	City's existing UHF repeaters
System and Fixture Compatibilities					
Lamp Type(s) Compatibility	HID, LED, possibly others	HID, LED, CFL, Induction, Incandescent.	HID (1)	HID, MV, Induction. LED (limited)	HID (2), LED
Ballast/Driver Min. Requirements	Dimmable elec. ballast or driver	*NA*	*NA*	*NA*	*NA*
Capabilities, Functions and Features					
Dimmability	Yes	No (3)	Yes	No	Yes
Remote On/Off	Yes	Yes	Yes	Yes	Yes
Power Metering (Accuracy)	No (4)	Yes (0.5%)	Yes (1.0%)	Yes (Unknown)	Yes (1%)
Monitoring and Reporting	Yes	Yes	Yes	Yes	Yes
Failure Detection	Yes	Yes	Yes	Yes	Yes
Network Management, User Interface					
Web Interface	Yes	Yes	Yes	Yes	Yes
Load from Network Control Components					
Node	1.3W	1.6W	1 - 4W	1.5W	0.5W
Gateway	41.3W	5.5W	20 - 40W	2.5W	*NA*
Other	Segment Controller: 10W	*NA*	*NA*		*NA*
Additional load per streetlight (5)	3.1W	3.4W	2.3 - 8.9W	3.2W	1.1W

([1]) Currently, the company is working with several LED fixture manufacturers to tailor the Lumen IQ technology to LED fixtures.

([2]) Although designed for LEDs, Relume reports that their Sentinel technology is also adaptable to traditional MH and HID streetlights.

([3]) ROAM Acuity's next generation product (expected to be available in summer 2010, in production volume) also will be compatible with dimmable streetlights

([4]) Future versions of Echelon's technology will reportedly include actual luminaire-level power monitoring devices.

([5]) Since controls components run continuously, to represent controls load on a per-streetlight basis for the period of time during which the streetlights are on, controls power must be multiplied by a factor of 24 hours (controls runtime) / 11.23 hours (average nightly streetlight runtime) = 2.14. The total controls power load per streetlight was calculated by dividing the number of controls components by the number of streetlights and multiplying this by the load per controls component times the runtime factor of 2.14.

Technology Potential

Energy Use of Streetlights

Streetlights are a significant end-use of electricity in the U.S. A study prepared by Navigant Consulting for the U.S. Department of Energy (DOE) estimated that street lighting in the U.S. requires about 31 terawatt hours (TWh) of electricity each year (Navigant Consulting, Inc. 2002). To put this in perspective, the report found that lighting consumes about 22% of all electricity generated in the U.S., or about 765 TWh. Street lighting therefore uses about 4% of all electricity for lighting, or approximately 1% of all U.S. electricity generated.

Over 90% of the country's current base of streetlights is HID. The most common types of HID sources within the current stock are HPS (59% of all roadway lamps) and mercury vapor (20% of all roadway lamps). LPS and metal halide constitute a smaller proportion of roadway lamps (10 and 5%, respectively). LED technology, while currently more expensive than HID in street lighting applications, can provide significant energy savings compared to current HID streetlights and continue to make inroads in the streetlight market as costs decline and customers become more familiar with the technology and confident in its performance and energy savings benefits.

Data on PG&E's current inventory of streetlights[39] and estimates on the number of streetlights in other CA IOU territories[40] were used to estimate the energy use of street lightings in the IOU territories of California (Table 11). The weighted-average wattage across the PG&E's inventory of streetlights is 132W; this same wattage was also applied to estimate the energy use of streetlights in the Southern California Edison (SCE) and San Diego Gas and Electric Company (SDG&E) territories.

Annual electricity use was calculated assuming annual operating hours of 4,100 hours (or about 11.2 hours per day) that is specified in the PG&E LS-2 rate sheet. According to PG&E inventory of streetlights, non-HID streetlights constituted about 0.8% of the connected load of all PG&E streetlights; this estimate was used to refine the estimates for annual electricity use and connected load across all streetlights, to only HID streetlights. These calculations suggest the total annual electricity use by HID streetlights in PG&E territory is about 398 GWh and the connected load is about 97 MW. Across the CA IOUs, the annual electricity use of HID streetlights is estimated to be roughly 882 GWh, with a connected load of 215 MW. Throughout California, HID streetlights are estimated to consume about 1,070 GWh and have a connected load of approximately 261 MW. This is a conservative estimate when compared to the California Energy Commission's demand forecast, which predicts "all electricity used for traffic control, street, and highway illumination" to be 1,848 GWh.[41]

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[39] Data on PG&E's inventory of streetlights obtained through communication PG&E's Street and Outdoor Lighting Manager.

[40] Estimates for the inventory of streetlights in SCE and SDG&E provided by PG&E's Senior Project Manager for the Emerging Technologies Lighting Portfolio

[41] California Energy Demand2010-2020 Staff Revised Forecast, Second Edition. California Energy Commission, Staff Final Report, November 2009, CEC-200-2009-012-SF-REV. Available at http://www.energy.ca.gov/2009publications/CEC-200-2009-012/CEC-200-2009-012-SF-REV.PDF

Table 3. Annual Electricity Use and Connected Load for Streetlights in California IOU Territories

		All Streetlights		HID Streetlights	
Utility	Number of Streetlights	Annual Electricity Use (GWh/yr)	Connected Load (MW)	Annual Electricity Use (GWh/yr)	Connected Load (MW)
PG&E	742,000	402	98	398	97
SCE	800,000	433	106	429	105
SDG&E	100,000	54	13	54	13
Total IOU	**1,642,000**	**889**	**217**	**882**	**215**
Total CA[1]	**1,994,000**	**1,079**	**263**	**1,070**	**261**

[1] Estimated using a scaling factor of 1.2; this factor was developed by taking a ratio of the 2008 historical electricity demand of California (286,771 GWh) to the 2008 historical electricity demand of the CA IOUs (236,135 GWh), found in the California Energy Demand 2010-2020 Forecast.[42]

Streetlight Network Controls: Technical Potential

There is no known technical barrier to adoption, so the technical potential for energy savings is equivalent to the savings if all HID streetlights in PG&E and/or IOU territory implemented network controls. To calculate the technical potential throughout the PG&E as well as the broader IOU territory, the percent annual energy savings per streetlight was first estimated, under four separate scenarios (Table 12). The baseline was assumed to be a HPS fixture with a 100W lamp and ballast with ballast factor (BF) of 0.2878,[43] for total fixture wattage of 128W. Accordingly, the estimated annual energy use per streetlight, assuming 4,100 operating hours, is approximately 528 kWh.

Seven scenarios, described below, were developed and analyzed, to estimate the potential range of potential energy savings (per fixture) from using network controls. These estimates are only intended to provide an order-of magnitude estimate for the technical potential savings associated with network controls and LED streetlights.

- **Scenario H1:** Network controls are used with HPS streetlight and energy is saved through nightly adaptive dimming. Assumptions for a potential adaptive dimming scenario have been bee used: it has been assumed that streetlights will operate at full power (129W) for 60% of operating hours and reduced power (50%, or 64W), for 40% of operating hours.

[42] California Energy Commission (CEC). California Energy Demand 2010-2020 Staff Revised Forecast, Second Edition. November 2009. Available at: http://www.energy.ca.gov/2009publications/CEC-200-2009-012/CEC-200-2009-012-SF-REV.PDF

[43] PG&E schedule LS-2, calculated by taking an average BF of 0.20 (for 120 V) and 0.3756 (for 240 V).

With this scenario, energy savings of 20% are achieved, relative to the HPS streetlight baseline.

- **Scenario H2:** Network controls are used with HPS streetlight, and energy is saved through nightly adaptive dimming and through dimming that compensates for initial over-lighting due lumen depreciation. In this scenario, the estimate of savings due to lumen depreciation was based on a 150W General Electric (GE) Deluxe Lucalox® HPS lamp, with initial lumens of 10,500, mean lumens of 9,135 (13% less than initial lumens), and a lifetime of 15,000 hours.[44] If streetlight's HID lamp is specified according to its mean lumens as is best practice, this lamp could be operated at a reduced wattage until depreciation would result in this specified output level. Assuming that lumen depreciation is approximately linear, the lamp could be dimmed from 13% to 0% over the first half of its expected lifetime.[45] With this scenario, annual energy savings of 23% are achieved relative to the HPS streetlight baseline.

- **Scenario H3:** Network controls are used with HPS streetlight, and energy is saved through nightly adaptive dimming, through dimming that compensates for initial over-lighting due lumen depreciation, and through reducing the fixture's operating hours at night by one hour (from 11.2 to 10.2 hours). This shortened nightly runtime could be achieved by moving back the time the fixture turns on at dusk, moving up the time the fixture turns off at dawn, or some combination of the two. While technical feasible, it is important to note that in practice, cities may be reluctant to reduce nightly runtime due to real or perceived safety and liability issues. However, given the assumptions outlines, under this scenario energy savings of 29% relative to the HPS streetlight baseline could be achieved.

- **Scenario L0:** LED streetlights are used with no network controls. Energy is saved due to the reduced wattage of LED fixtures (58.3W), as compared to the baseline HID fixture (129W). With this scenario, energy savings of 55% are achieved, relative to the HPS streetlight baseline. This scenario was included in order to enable a separate evaluation of network controls when used with LED streetlights, apart from the savings that are due only to switching from HID to a LED streetlight.

  Scenario L1: Network controls are used with LED streetlights and energy is saved both through the reduced wattage of the LED fixture (58.3W) and through nightly adaptive dimming as in Scenario H1. For this scenario, the same adaptive dimming assumptions have been applied as were used in Scenario H1. With this scenario, energy savings of 64% are achieved, relative to the HPS streetlight baseline. The incremental savings when compared with Scenario L0 (LED streetlights, no network controls) are about 20%.

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[44] 2008 GE HID lighting catalogue: http://www.gelighting.com/na/business_lighting/education_resources/literature_library/catalogs/downloads/2008_hid.pdf

[45] Assumptions of linear depreciation and linear decrease in light output with power usage were made for simplification. In practice, lumen depreciation can follow various trends, and light output is generally reduced further than wattage reduction.

Scenario L2: Network controls are used with LED streetlights, and energy is saved through the reduced wattage of the LED fixture, through nightly adaptive dimming, and through dimming that compensates for initial over-lighting due lumen depreciation. The current convention is that the lifetime of a LED fixture is determined by when the fixture reaches 70% of its initial lumens (i.e., L70). In this scenario, savings estimates were developed assuming the LED streetlight would be dimmed from 15% to 0% (linearly) over the first half of its lifetime, to compensate for lumen depreciation. With this scenario, energy savings of 65% are achieved, relative to the HPS streetlight baseline. The savings when compared with Scenario L0 (LED streetlights, no network controls) are about 23%.

- **Scenario L3:** In this scenario, network controls are use with LED streetlights, and energy is saved through: (1) the reduced wattage of the LED fixture compared with the baseline HPS fixture; (2) nightly adaptive dimming; (3) dimming that compensates for initial over-lighting due lumen depreciation; and (4) shortening nightly runtime using the assumptions outlined in Scenario H3. Under Scenario L3, energy savings of 68% are achieved relative to the HPS streetlight baseline. Additional energy savings of about 30% are realized relative to Scenario L0, suggesting LED streetlights with network controls can provide significant savings when compared with LED streetlights that do not use network controls.

Network controls used with an HPS streetlight can save energy by reducing the runtime of day burners. However, in practice, network controls will also lead to some increase in energy use since they will be able to identify in real-time, lamps that have failed which will facilitate quicker lamp replacement (and therefore, shorter outages).[46] It may take, on average, a month for a dayburner to be detected and fixed, and two weeks for a failed lamp to be detected and replaced. Since lamps have about half the expected lifetime of a photocontrol, this implies there would be about 1 dayburners for every 2 lamp outages. As a result, the net savings from the combined effect of reduced dayburners and shorter duration of lamp outages would be approximately zero. Consequently, the potential energy savings from reduced runtime of dayburners has not been considered in these scenarios.

[46] Despite this increase in energy use, the ability to more quickly fix streetlight outages has important public safety benefits.

Table 4. Scenarios for Potential Annual Energy Savings from Network Controls

Scenario	Lamp Type	Type of Savings	Annual Energy Use per Streetlight (KWh/yr)	Savings (% from Baseline)
	Baseline (HPS)	***NA***	**528**	***NA***
H1	HPS	-Adaptive dimming	422	20%
H2	HPS	-Adaptive dimming -Depreciation compensation	409	23%
H3	HPS	-Adaptive dimming -Depreciation compensation -Shorten runtime	372	29%
L0	LED	-HID-to-LED savings *(No network controls)*	239	55%
L1	LED	-HID-to-LED saving - Adaptive dimming	191	64%
L2	LED	-HID-to-LED saving -Adaptive dimming -Depreciation compensation	185	65%
L3	LED	-HID-to-LED saving -Adaptive dimming -Depreciation compensation -Shorten runtime	168	68%

Current market penetration of streetlight network controls in the U.S. is still extremely low at this point in time; for the purposes of technical potential calculations, it can been assumed to be zero.

Applying Scenario L3, the technical potential energy savings across all IOU territories from implementing LED streetlights and network controls is about 601 GWh/yr. About 482 GWh/yr (or about 80%) of this total technical potential, is from replacing traditional HPS streetlights with a LED streetlights. About 118 GWh/yr (or about 20%) of the total technical potential results from applying network controls.

In PG&E territory, the technical potential of LED streetlights and network controls is about 272 GWh, where about 218 GWh are from LED streetlights alone and 54 GWh are from the network controls.

Table 5. Potential PG&E, IOU, and Statewide Annual Energy Savings from Scenario L3

	All Streetlights		HID Streetlights	
Utility	**Annual Electricity Savings (GWh/yr)**	**Connected Load Savings (MW)**	**Annual Electricity Savings (GWh/yr)**	**Connected Load Savings (MW)**
PG&E	274	54	272	53
Total IOU	601	217	882	215
Total CA[1]	1,079	263	1,070	261

[1] Estimated using a scaling factor of 1.2; this factor was developed by taking a ratio of the 2008 historical electricity demand of California (286,771 GWh) to the 2008 historical electricity demand of the CA IOUs (236,135 GWh), found in the California Energy Demand 2010-2020 Forecast.[47]

[47] California Energy Commission (CEC). California Energy Demand 2010-2020 Staff Revised Forecast, Second Edition. November 2009. Available at: http://www.energy.ca.gov/2009publications/CEC-200-2009-012/CEC-200-2009-012-SF-REV.PDF

Market Barriers and Risks

Market adoption of network LED streetlights on a larger scale will hinge not only on lighting and energy performance, but also on economic competitiveness. The initial investment in LED streetlights and network controls will only be made if system savings warrant the extra upfront cost. Currently, the initial hardware costs for network controls will range considerably from $70/streetlight to nearly $300/streetlight. Some network controls also carry an annual cost, ranging from less than $1 to $6 /streetlight.

Several qualities will be expected of advanced controls options if they are to become more prevalent also. Compatibility with the grid as well as emerging street lighting options, durability, reliability, and performance all need to be guaranteed before large and costly street lighting networks are rolled out. Experiences in early adopter locations like Glendale, Los Angeles, and San Jose should help planners understand the potential and limitations of network options and designs.

The features that network controls systems offer streetlight managers currently vary, but all represent some improvement over basic photocell control. It is important that the functions promised by the technology, such as flexible scheduling, system energy reporting, outage detection, and maintenance tracking deliver once systems are installed. Testing and verification of system operation such as the pilots carried out in San Francisco and San Jose will be critical, especially given that these systems are much more complex than the controls technology they are replacing. Pilots demonstrating these technologies in real world applications, and underscoring challenges that manufacturers need to address, will help cities understand the value of controls for street lighting inventories and project their benefits for future installations.

Network controls technologies can provide some energy benefits by providing tighter control of on/off schedules and detection of streetlights on at unnecessary times. However, higher savings potential is possible with dimmable streetlights and controls that allow operators to set lighting power to meet efficiency and performance goals and even adjust lighting power adaptively based on needs. Some, but not all, products on the market that were reviewed in this report currently offer dimming capabilities. Dimmability would likely be a key requirement for utilities looking to offer rebates or other financial assistance for network control streetlights.

Industry standards such as IESNA RP-8-00, which classifies roadways according to levels of traffic volume and pedestrian conflict, must also evolve to reflect the new technologies and dimming capabilities. These standards do not (yet) address adaptive strategies directly.

In addition, to realize cost savings associated with schedule changes, appropriate utility rate schedules must be available that bill streetlights based on actual, rather than assumed, energy use. This will be especially important for adaptive lighting scenarios, where the fixture wattage is not a fixed point. Similarly, there will need to be some standardization in terms of the frequency and accuracy of power measurements recorded by network controls systems. Utilities such as PG&E maintain strict requirements for revenue-grade metering, such as accuracy of ±2.0%, compliance with ANSI C12.1, programmability for rolling interval demand calculations, etc. Some of these standards may not apply to streetlight controls system, but key elements like accuracy may not be met by the current generations of the network controls technology reviewed in this report. Future versions need to be more robust in their energy measurements and a clear pathway for data transfer should be developed between cities, controls designers, and utilities.

Review of Adaptive and Mesopic Street Lighting Information

The energy savings identified in the "Technology Potential" section of this paper result from both network controls and from the replacement of conventional HID luminaires with new LED luminaires. In turn, two important methods of achieving savings from these measures are (1) the reductions in overall light output from the use of nightly adaptive dimming and (2) the improved visibility provided through the use of broad spectrum lighting. This section provides a brief background into broad spectrum lighting, as well as a review of the existing literature on both broad spectrum lighting and adaptive dimming.

Broad Spectrum Lighting

In conjunction with network controls, an understanding of the human response to light in dim conditions can allow for increased energy savings by utilizing broad-spectrum ("white") light sources. Outdoor lighting standards have traditionally been based on models corresponding to visual perception in bright light conditions, which is not identical to visual perception in low light conditions. These changes in visual perception at different light levels may result in white light sources may being able to provide the same level of visibility with decreased total light output compared to conventional sources.

Instead of being uniform across the color spectrum, the efficiency of visual perception changes depending on the wavelength of light. This behavior follows two distinct spectral response curves depending on the light level: the photopic response curve and the scotopic response curve. The photopic response curve is a function that weights the visual effectiveness of wavelengths in the electromagnetic spectrum according to the human eye's response in levels of adaption over 3 cd/m^2 (e.g., daylight conditions), which are dominated by the eye's cone photoreceptors. Commercial photometry traditionally measures light levels based on this function. However, under the lowest light conditions (adaption less than 0.001 cd/m^2), when the eye's rods are the active photoreceptors, human perception of light follows the scotopic luminous efficiency function. At intermediate levels between daylight and darkness (ambient photopic luminance in the 0.001 to 3 cd/m^2 range) typical of nighttime roadway lighting levels, rods and cones both provide levels of spectral sensitivity, with rods' importance diminishing and cones' increasing as light levels increase. In these intermediate levels, the photopic response curve and the scotopic response curve are both important. This is known as the mesopic range.

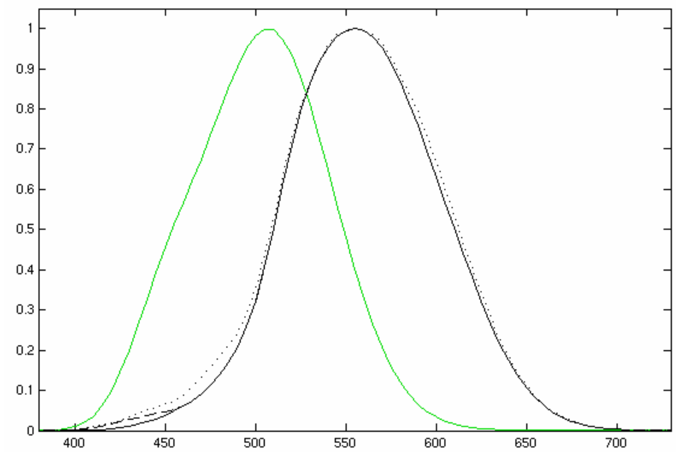

Figure 14: Plot of Photopic and Scotopic Luminosity Functions

"Photopic (black) and scotopic (green) luminosity functions. The photopic includes the CIE 1931 standard (solid), the Judd-Vos 1978 modified data (dashed), and the Sharpe, Stockman, Jagla & Jägle 2005 data (dotted). The horizontal axis is wavelength in nm." http://en.wikipedia.org/wiki/Photometry_(optics)
Accessed: November, 2009

Since light sources differ in their spectral power distribution, they also differ in their effectiveness at different light levels. Light sources considered "white" (e.g., metal halide, LED, induction) emit energy broadly across the visible spectrum. These broad spectrum sources excite multiple photoreceptors (e.g., short, medium, and long-wavelength cones and rods depending on the adaptation state) in contrast, to narrow spectrum sources (e.g., HPS, LPS, and color-specific LEDs), which may only excite a specific type of photoreceptor. Narrow spectrum sources may provide little or no energy at wavelengths sensed by the rods or short or medium-wavelength cones. Visual performance and apparent brightness at mesopic light levels can therefore be enhanced by light sources emitting light in the low to mid section of the visible light spectrum.

However, since mesopic vision results from the combination of both photopic and scotopic luminous efficiency functions, any increased visual performance based on broad-spectrum lighting relies on the use of both rod and cone photoreceptors. The concentration of rods and cones is not uniform in the eye however, which results in unequal contributions depending on the area of concern within in the field of view. Cones, and as a result the photopic response curve, are the cells responsible for vision in the direct line of sight (central/ on-axis). Rods, and the associated scotopic response curve, increase in importance as the area of interest becomes further from the line of sight (peripheral/ off-axis). As a result, studies have come to differing conclusions regarding the benefit of broad spectrum lighting based on the different types of tasks they have used for evaluation. Since cones dominate on-axis vision, studies that have utilized in line of sight and object recognition tasks to determine low-light performance have found minimal benefit to broad spectrum lighting. Conversely, studies that utilize full-field vision (e.g. brightness perception) or off-axis vision (e.g. peripheral target detection) have found significant benefit. While the importance of each of these tasks varies depending on the activity undertaken, it is generally agreed that all of these tasks are necessary to a degree for nighttime driving. Research is under way to determine the relative importance of each however, and by extension the relative importance of photopic and scotopic vision.

As current IES roadway lighting standards rely only on photopic performance and do not account for the scotopic or mesopic characteristics of a light source, savings may be possible through revision of these standards to account for visibility differences provided by sources of different spectral power distributions. However, the proper methods for determining visibility in the mesopic range and for use in outdoor lighting analyses are under debate in the lighting community.

Based on the current state of research, IESNA indicates in a November 2009 Position Statement reluctance to consider mesopic conditions in conjunction with existing recommendations, but acknowledges that future recommendations may account for them:

> Research into the suitability of using weighting functions other than the photopic luminous efficiency function is ongoing. At present the research is not considered sufficient to support the application of any alternative to photopic luminous efficiency function. Accordingly, it is the policy of the IES that for compliance with all IES recommendations, photometric quantities shall be calculated using the photopic luminous efficiency function as defined in the IES Lighting Handbook, unless specifically stated in the IES document that contains the recommendations.[48]

MESOPIC RESEARCH

Both the IESNA and CIE have formed technical committees to define and investigate mesopic performance, underscoring its increasing importance in the lighting discussion.[49] The IESNA has published a technical memorandum on the subject, TM-12-06, Spectral Effects of Lighting on Visual Performance at Mesopic Light Levels. This technical memorandum is currently undergoing revision to provide more specific recommendations for incorporating lamp spectral distribution effects under mesopic conditions into street lighting design.

MESOPIC MODELS

Two principle models have been generated which attempt to define equivalent mesopic light levels based on information about the lighting spectral distribution and level. These models are the X-model, also called the Unified System of Photometry, and the Mesopic Optimization of Visual Efficiency (MOVE) model. These models are explained below, along with the Lumen Effectiveness Multiplier paradigm, which is based on the Unified System of Photometry.

There are two principle differences between these two models: the type of experiments/ tasks that were used to develop the initial data on which they are based, and the upper limits of the range in which they will calculate mesopic levels. To devise the X-model, experiments were performed measuring reaction time and brightness-matching in the mesopic range. On the other hand the MOVE model was based on reaction time, contrast threshold, and recognition threshold experiments. This results in differing calculations of equivalent illuminance in the mesopic range.

[48] IES Position Statement: Use of Spectral Weighting Functions for Compliance with IES Recommendations (PS-02-09). Approved by the IES Board of Directors, 11/15/09.

[49] CIE Technical Committee 1-58: "Visual Performance in the Mesopic Range" http://www.lightinglab.fi/CIETC1-58/index.html#

IESNA Mesopic Technical / Research Committee: http://www.ies.org/about/committees/committees_view_action.cfm?committeeid=306

Additionally, when calculating mesopic levels, the X-model applies only to luminances up to 0.6 cd/m^2, whereas the MOVE model considers levels up to 10 cd/m^2. According to a comparison paper published in 2006,

> The differences between the models became clearer with decreasing visibility conditions, i.e. lower luminance, lower contrast… The comparison of the two mesopic models indicated that there are differences in the models' predictions and the MOVE model is stated to perform better in predicting mesopic luminances.[50]

However, the 10 cd/m^2 cut-off for the MOVE model has been criticized by some as being too high. It is claimed that at the upper limits of the MOVE model the difference between mesopic and photopic levels are negligible, so the MOVE model serves only to add unnecessary complexity calculations of luminance levels. Recently, a modified version of the MOVE model has been proposed which reduces the upper-limit of the mesopic region to 5 cd/m^2, which the authors claim to be the "practical upper limit for [the] mesopic region."

UNIFIED SYSTEM OF PHOTOMETRY (X-MODEL)

The Unified System of Photometry is a model proposed by Rea et al in 2004, [51] based on the reaction time studies of He et al. It is described by the Lighting Research Center at Rennselaer Polytechnic Institute in a recently published article on outdoor lighting visual efficacy through its ASSIST program (Alliance for Solid-State Illumination Systems and Technologies):

> "The unified system of photometry integrates both the scotopic and photopic luminous efficiency functions into a complete system that can be used across the entire range of light levels available to the human visual system. The system differentially weighs the scotopic and photopic luminous efficiency functions depending upon light level."[52]

Rea's closed-form expression for combining photopic and scotopic luminance levels to calculate unified (mesopic) luminance, as published in the ASSIST article referenced in the text, is:

$$L_{mesopic}\ (cd/m^2) = 0.834P - 0.335S - 0.2 + \sqrt{(0.696P^2\ - 0.333P\ \ 0.56PS + 0.113S^2 + 0.537S + 0.04)}$$

P = photopic luminance (cd/m^2)
S = scotopic luminance (cd/m^2)

[50] Viikari M, Chen W, Eloholma M, Halonen L, Chen D. 2006. Comparative study of two visual performance based mesopic models based on reaction time and contrast threshold data. Light & Engineering, 14 (4): 2132.

[51] Rea et al. 2004. A proposed unified system of photometry. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, USA. Lighting Research and Technology, 362: 85-111

[52] Outdoor Lighting: Visual Efficacy. ASSIST Recommends… Vol 6, Issue 2. Jan. 2009. Lighting Research Center.

MESOPIC OPTIMIZATION OF VISUAL EFFICIENCY (MOVE) MODEL

The MOVE model is a performance-based model developed for the European Community by the Lighting Laboratory of Helsinki University of Technology.[53] The model is based on the results of vision experiments which evaluated subjects' ability to complete various tasks deemed to be necessary for night-time driving. The MOVE model uses photopic and scotopic luminance values to calculate mesopic luminance values, based on the following iteratively calculated mesopic spectral luminous efficiency function:

$$L_{mesopic} = ((X_i * P + (1 - X_i) * S * 683/1699)) / (X_i + (1 - X_i) * (683/1699))$$

X_i converges to a single value after several iterations, and is the weighting factor between the photopic and scotopic spectral luminous efficiency functions, defined as:

$$X_{i+1} = 1.49 + 0.282 * Log ((X_i * P/683 + (1 - X_i) * S/1699) / (1 - 0.65 * X_i + 0.65 * X_i * X_i))$$

$X_1 = 0.5$
P = photopic luminance (cd/m^2)
S = scotopic luminance (cd/m^2)

The modified MOVE model developed in 2008 to reduce the upper limit of the mesopic range to 5 cd/m^2 has the following modification:

$$X_{i+1} = 0.7670 + 0.3334 * Log (L_{mesopic}) \qquad 0 \leq X_{n+1} \leq 1$$

$X_1 = 0.5$
X and $L_{mesopic}$ as a function of photopic luminance and light source S/P-ratio are presented numerically in paper.

The creators of the modified MOVE model found that:

> The modified MOVE-model described the data best in nine situations out of 17. The MOVE-model was in seven situations and X-model in one. The differences between the MOVE- and modified MOVE-model were small while X-model differed considerably from both the MOVE and modified MOVE-models.[54]

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[53] Mesopic Optimisation for Visual Efficacy. Performance Based Model for Mesopic Photometry. Helsinki University of Technology Lighting Laboratory. Report 35. Espoo, Finland. 2005

[54] Viikari M, Ekrias A, Eloholma M, Halonen L. 2008. Modeling spectral sensitivity at low light levels based on mesopic visual performance. Clinical Ophthalmology, 2 (1): 113.

LUMEN EFFECTIVENESS MULTIPLIERS (LEMS)

The LEM model was proposed by Ian Lewin in 2001 as different approach for quantifying the effectiveness of white light sources under low light conditions.[55] As opposed to other models which provide formulations for any combination of photopic and scotopic luminance levels, LEMs are light source specific multipliers.

> The subject is complex, and many variables are involved. If, however, better vision is achievable through judicious selection of the light source type, then it may be reasonable to treat lighting achieved with white sources as having a higher "effectiveness" than HPS lighting. The concept of "Lumen Effectiveness Multipliers", LEM, has been developed, whereby a luminance level computed using the normal photopic response curve of the eye and lamp manufacturer's rated lumens can be multiplied by the LEM to represent an effective increase in lighting level resulting from use of an improved lamp spectrum.[56]

The light sources originally examined were HPS, LPS, Mercury, and Metal Halide, and the resulting LEMS were normalized to 1.0 based on the performance of an HPS source. More recently, Lewin has developed multipliers for four additional light sources (warm and cool-white LEDs, warm and cool-white Induction).

While the LEMs are based on the specific spectral distribution of the light sources used, they can be assumed to be close enough to similar LEDs and induction lamps to be informative. They trend toward higher values as the spectral distribution of the light source shifts to blue/green wavelengths and as luminance levels decrease.

Two sets of LEMs were developed, one based on Adrian's brightness matching mesopic functions,[57] and the other on He and Rea's reaction time mesopic functions, as shown below.[58, 59]

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[55] Lewin, Ian. "Lumen Effectiveness Multipliers for Outdoor Lighting Design." Journal of the Illuminating Engineering Society, JIES, Summer 2001. Illuminating Engineering Society of North America, New York, NY.

[56] Lewin, Ian. "Lumen Effectiveness Multipliers for Outdoor Lighting Design." Journal of the Illuminating Engineering Society, JIES, Summer 2001. Illuminating Engineering Society of North America, New York, NY.

[57] Adrian, Werner. "The Influence of Spectral Power Distribution for Equal Visual Performance in Roadway Lighting Levels." Proceedings: Vision at Low Light Levels. EPRI/LRO Fourth International Lighting Research Symposium. TR-110738. Lighting Research Office of the Electrical Producers' Research Institute, Palo Alto, California. 1999

[58] He, Junjian; Bierman, Andrew; Rea, Mark. "A System of Mesopic Photometry." International Journal of Lighting Research and Technology. Vol. 30, no. 4. Chartered Institution of Building Services Engineers, London, UK. 1998

[59] Rea, Mark. "A Unified System of Photometry for Lighting Applications." Proceedings of the CIE Symposium: 75 years of CIE Photometry, Budapest, 1999

Table 6: Lumen Effectiveness Multipliers from Brightness Matching Mesopic Functions.[60]

Luminance (cd/sq.m.)	.001	.01	.1	1	3	10
Metal Halide	2.25	2.11	1.82	1.35	1.13	1.00
High Pressure Sodium	1.00	1.00	1.00	1.00	1.00	1.00
Clear Mercury	1.48	1.43	1.38	1.22	1.09	1.00
Low Pressure Sodium	0.47	0.51	0.61	0.82	0.95	1.00
Cool White LED	2.75	2.57	2.09	1.47	1.22	1.00
Warm White LED	1.71	1.67	1.50	1.23	1.10	1.00
Cool White Induction	2.24	2.14	1.83	1.36	1.17	1.00
Warm White Induction	1.83	1.77	1.56	1.24	1.11	1.00

Table 7: Lumen Effectiveness Multipliers from Reaction Time Mesopic Functions.[61]

Luminance (cd/sq.m.)	Scotopic	0.03	0.1	0.3	Photopic
Metal Halide	2.58	2.30	1.88	1.40	1.00
High Pressure Sodium	1.00	1.00	1.00	1.00	1.00
Clear Mercury	1.98	1.79	1.53	1.22	1.00
Low Pressure Sodium	0.35	0.46	0.64	0.83	1.00
Cool White LED	3.11	2.45	1.98	1.51	1.00
Warm White LED	1.86	1.64	1.45	1.24	1.00
Cool White Induction	2.47	2.05	1.72	1.38	1.00
Warm White Induction	1.97	1.72	1.51	1.27	1.00

[60] Lewin I, O'Farrell J. "Extension of the Concept of Lumen Effectiveness Multipliers to LED's and Induction Lamps." Report to Sacramento Municipal Utility District, May 2009. Lighting Sciences Inc, Scottsdale, AZ

[61] Ibid.

Adaptive Street Lighting

The amount of light required needed for a given outdoor area can vary significantly according to activity level, and is influenced by a variety of factors including time of day, day of week, weather, season, and local events. However, existing streetlight control strategies are very static; control generally is limited to on/off scheduling based on the detection of daylight with a photocontrol. In the "Technical Potential" section, the potential energy savings based on an assumed nightly adaptive lighting schedule is calculated. This calculation shows the dimming control of streetlights to key savings feature of network controls systems.

As a result of the generally limited amount of control allowed over streetlight power levels at this time, existing design practices recommend designing to a "worst case" condition. Luminaires are specified to provide the amount of light required for this scenario, and as a result provide more lighting than is required in other circumstances. While network controls and dimmable lights would allow for reduced energy usage by lowering levels to those required when not in the worst case condition, most U.S. streetlights operate as un-metered load and are billed at flat monthly rates. For customers to use network controls for adaptive dimming purposes, cost savings can only be realized if appropriate utility rate schedules are available. Network controls products with energy metering functions must provide metered energy data in a useful format and at a level of accuracy acceptable to utilities for adaptive rate schedules to be feasible.

Standards such as RP-8-00 do not currently specifically address adaptive strategies, which have only recently become possible with the advent of easily dimmable light sources like LEDs. As an example of how an adaptive schedule might be implemented, consider the following abridged version of the RP-8-00 standard, showing recommended illuminance levels for collector roadways based on pedestrian conflict levels. From high to low pedestrian conflict in the collector roadway classification, the recommended illuminance drops 50%, from 1.2 to 0.6 fc.

Table 1. Hypothetical Use of RP-8-00 Classifications to Implement Adaptive Lighting Strategies

Road and Pedestrian Conflict Area		Pavement Classification			Uniformity E_{avg}/E_{min}
Road	Pedestrian Conflict Area	R1 fc	R2 & R3 fc	R4 fc	
	High	0.8	1.2	1.0	4.0
	Medium	0.6	0.9	0.8	4.0
Collector	Low	0.4	0.6	0.5	4.0

Roadway lighting systems are typically designed for the conditions of highest anticipated traffic volume and highest anticipated pedestrian activity, but an adaptive lighting strategy would recognize that for many hours of the evening and early morning, the actual traffic and pedestrian activity is much lower. Recommended light levels under these lower activity conditions would also be lower per RP-8-00. The savings implications are significant, but are predicated on controls options that allow dimming schedules. Future standards guidelines would help clarify acceptable adaptive street lighting strategies by directly addressing this point

Street Lighting Standards

In the United States, the most common basis for roadway lighting design is the ANSI/IESNA RP-8-2000 Recommended Practice for Roadway Lighting. While the standards in that document are not meant to be mandatory and specific standards vary between different agencies and municipalities, most do not have the motivation or levels of funding and expertise to set scientifically and legally defensible standards on their own. As a result, a large majority adopt a variation on the recommendations from other organizations, with RP-8 being the most common. Other standards include the American Association of State Highway and Transportation Officials GL-6 Roadway Lighting Design Guide and the International Committee on Illumination (CIE) 115 – 1995 Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic.

It should be noted however that in practice, roadway lighting standards are often not met in existing installations. This is because street lighting parameters are highly variable; factors that affect the lighting include pole spacing, pole height, roadway geometry, obstructions (such as trees), and ambient light. Fully accounting for all of these factors would result in significant expense in both design and maintenance costs, as a large mix of different streetlights would be required in any given area.

The recommendations in RP-8 are based on levels of traffic volume and pedestrian conflict, and take the form of average photopic levels, uniformity ratios (maximum-to-minimum and average-to-minimum), veiling luminance, and small-target-visibility.

These recommendations are based on broad assumptions about the luminaires used to light the roadway – predominantly cobrahead-type HID luminaires. While these assumptions are generally valid, they do not necessarily apply to newer technologies. For example, as discussed above, utilizing broad-spectrum sources can provide equivalent performance under mesopic lighting conditions with reduced photopic light output. Additionally, while HID luminaires traditionally have lighting distributions characterized by "hot spots" directly under the pole, improved optics can provide a more even distribution that provides equivalent or improved visibility with decreased average illuminance. This will be an especially important consideration as LED streetlights become more common, because the discrete and directional nature of LEDs can allow for much greater optical control that was possible with HID sources.

Additionally, partly due to the small market penetration of dimming technology for HID luminaires, RP-8 does not yet address adaptive strategies directly. Since proper lighting design accounts for the worst-case-scenario, luminaires are chosen based on the highest activity levels. However, traffic and pedestrian conflict levels are not necessarily constant throughout the night; in most cases activity will be far less late at night and in the early morning, when businesses are closed. These levels may also vary between weekday and weekends, with seasonal factors, and due to local events, and the amount of lighting required may vary accordingly. As a result, there is a potential for energy savings if network controls and dimmable technologies are used to change lighting levels to match necessity.

While RP-8 does not directly address either broad spectrum or adaptive lighting, discussions are currently ongoing regarding potential changes which may address these issues. Additionally, there are already a number of standards and demonstration studies that addressed them either explicitly or implicitly. A few of these are discussed below

Adaptive/ Mesopic Street Lighting Activities

While adoption of adaptive dimming strategies and mesopic lighting considerations is still limited, there are numerous instances of agencies beginning to utilize them or explore their potential. This section provides a brief background on some of these ongoing activities.

BC HYDRO

From 2004-2006, BC Hydro completed a "Power Smart" demonstration which implemented dimming strategies on the street lighting system in Prince George, British Columbia. This project applied dimming to 170, 250 watt HPS luminaires, with an estimated 276 kWh annual savings per luminaire. No negative impacts or comments were noted as of the time of the final report.

After this demonstration, BC Hydro developed a "Power Smart Partner – Adaptive Street Lighting Initiative" program for 2008-2010. To be eligible to participate in this program, projects must have an energy assessment conducted by an approved consultant that demonstrates the potential for a minimum savings of 100,000 kWh/yr. This assessment includes inventory of luminaires, existing lighting levels and dimming recommendations, and costs repaid by the utility for completed projects. The incentive program then provides incentives of up to 60% of capital costs for approved projects, as well as 100% of required energy assessment costs for completed projects. Additionally, while flat-rate billing is retained, all power savings are discounted off customer invoices based on the energy assessment report.

CITY OF CALGARY

The City of Calgary is currently engaging in the Streetlight Adaptive Lighting Pilot Project. This project consists initially of an engineering study beginning in August 2008, subsequent to which a pilot retrofit 500 streetlights to use network controls is planned. This pilot will allow for varying light levels in accordance with levels of vehicular and pedestrian traffic, and is planned to last for approximately one year.

GROTON UTILITIES

In 2008, the LRC published a paper for Groton Utilities which studied the effects of utilizing street lighting technologies with increased mesopic performance. The study replaced HPS streetlights with various broad spectrum alternatives which were designed to have equivalent lighting performance to that recommended in RP-8 when using the Unified Photometry System. Despite reduced photopic lighting levels, the study found that "residents perceptions of visibility, safety, security, brightness, and color rendering improved considerably"[62]. This study concluded by recommended using the Unified Photometry System to determine wattages of streetlights equivalent to those required to meet RP-8.

[62] Morante, Peter. "Mesopic street lighting demonstration and evaluation final report". Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, USA Prepared for Groton Utilities, Groton, Connecticut.

INTERNATIONAL COMMITTEE ON ILLUMINATION (CIE)

The CIE E-Streetlight Partnership program is an international effort begun in 2006 to "expand the market for energy efficient street lighting" in Europe. The program goal is to have installed 20,000 – 30,000 "intelligent streetlights," which are estimated to provide up to 63.7% energy savings based on the use of situational dimming depending on parameters including weather conditions, traffic patterns, and street layout. In addition, complimentary reports, specifications, and other documents have been created based on the project. As of June 2008, the program had recorded nearly 80,000 installed intelligent streetlights in various projects across Europe:

> The realized or assessed energy savings are between 20% and 50% depending of scope of the system renovation, country place of the new installations and other specific factors. The payback period varies from 3 to 5 years by the moment. The products from more than 22 firms are put into the realized projects. About 40 municipality and/or road administrations of 14 countries[63]

TORONTO HYDRO

In 2007, Toronto Hydro Energy's Street Light Division began a project to reduce energy consumption of the street lighting in the city of Toronto. This Adaptive Lighting Asset Management Program began with technology review and small-scale testing, the results of which are currently being assessed. The goal is to implement efficient streetlights with adaptive dimming technologies throughout the city of Toronto starting in 2010.

U.S. DEPARTMENT OF DEFENSE (DOD)

In 2006, the US Department of Defense published the Unified Facilities Criteria – Design: Interior and Exterior Lighting and Controls, which "provides planning, design, construction, sustainment, restoration, and modernization criteria, and applies to the Military Departments, the Defense Agencies, and the DoD Field Activities." This document provides explicit demonstration of the use of brightness-matching LEMs, and discusses benefits from broad spectrum sources in a street lighting application as follows:

> Research shows that peripheral vision and detection are enhanced under white light. White light (as opposed to more orange light produced by high-pressure sodium) renders objects sharper and provides excellent peripheral detection compared to high-pressure sodium. This peripheral detection is critical at points where other vehicles may be entering a roadway and pedestrians may be crossing the street.
>
> In addition to providing better visibility, this has an energy impact as well. The same visibility can be provided with a lower level of white light that would require a higher level of HPS light [64]

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[63] Black Sea Regional Energy Centre. 2008. Intelligent Road and Street Lighting in Europe, WP 3: Market penetration and procurement activities, D 3.4: Procurement evaluation report.

[64] US Department of Defense. 2006. Unified Facilities Criteria - Design: Interior and Exterior Lighting and Controls. UFC 3-530-01

OTHER STANDARDS

As of this report, other standards that consider light quality in establishing guidelines include those for the United Kingdom and for Australia and New Zealand. The United Kingdom standards allow for limited light level reduction on residential roads when using high CRI light sources, and the standards for Australia and New Zealand de-rates HPS and LPS lamp lumens on low-traffic residential roads.

Conclusions and Recommendations

When utilized to their full potential, it is estimated that dimming network controls can provide up to 30% energy savings. Combined with an upgrade to LED lighting technology, it is estimated that nearly 70% savings could be achieved from a non-networked HPS baseline. While the cost premium is significant for networked street lighting systems, the energy and maintenance savings are substantial. Combined with the potential for increased performance, and based on the results of existing case studies, dimming LED streetlights are recommended as current best practice for new street lighting installations.

As with any new or emerging technology, there is significant variation in technology design and performance between products on the market. The benefits and drawbacks of the competing approaches and product offerings are not yet completely understood, though this report demonstrates some of the differences in currently available technologies. Since the market is still evolving and expanding rapidly, it is advised that due research is performed with products available at the time of any implementation effort.

There area a number of steps that remain to be taken before the savings potential from networked dimming LED luminaires can be realized on a wide scale.

- Technological advances are needed for some network controls technologies to reduce upfront cost, ensure compatibility with the grid and emerging street lighting options, and allow revenue-grade metering and provide data transfer for billing purposes.
- Some, but not all, products on the market offer dimming capabilities. Dimmability will likely be a key requirement for utilities looking to offer rebates or other financial assistance for network control streetlights.
- Policy changes may also need to be made to allow the use of emerging street lighting options, and dimming strategies. For instance, clarification on the use of existing IES recommended practices for implementation of adaptive energy savings strategies will be needed. Also, metered rate structures for streetlights will be needed to allow customers to see the financial benefits of reduced energy usage.
- Guidance and standards should be developed between municipalities, controls manufacturers, and utilities, regarding the specific requirements for controls-based power measurement and energy metering accuracy and data management and transfer so that the full potential of adaptive streetlight metering through streetlight network controls can be realized.

To accelerate adoption, market drivers can be put in place such as informational programs, energy efficiency incentives, adaptive controls “readiness” policies, and eventually codes or standards:

- Informational programs can take the form of case studies and demonstrations, which are critical to vet products and help cities understand the value of controls for street lighting inventories and project their benefits from future installations.
- Incentives can provide assistance overcoming upfront cost hurdles, and associated specification criteria requirements can ensure savings as well as customer satisfaction. They do this by allowing only well-performing products, and requirements could include electrical performance/ efficiency, metering accuracy/ precision, and interoperability criteria. Additionally, coupled criteria across incentive programs can provide further market pull – for example, advanced streetlight incentives could require installed technologies to be compatible with dimming or network control technologies.

- Adaptive controls readiness policies can be considered for new street lighting installations, so that at a minimum newly installed equipment is compatible with and ready for networked dimming controls technologies, even if not equipped with advanced controls in every case. For example, a policy could be adopted requiring that all new streetlights, whether HID, LED, induction, or other, be equipped with electronic, 0-10v dimmable ballasts or drivers, so that if / when dimming controls are deployed, new streetlights will be compatible.
- Codes or standards can push the marketplace either by setting technology-neutral performance targets or by requiring specific technological advancements, when the technology has been sufficiently vetted through widespread installation.

Appendix A: Contact Information for Network Controls Manufacturers

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