Wireless Networked Lighting Systems for Optimizing Energy Savings and User Satisfaction

Yao-Jung Wen, Alice M. Agogino, Member, IEEE

Abstract — Energy savings and user satisfaction are two major design considerations for modern lighting systems. While some new commercial lighting systems for shared-space office buildings have been able to achieve significant savings via various lighting control strategies, the occupants’ diverse lighting preferences and visual comfort have been generally overlooked or even compromised. Moreover, retrofitting legacy buildings with modern lighting systems is still economically unattractive due to the high cost of global rewiring.

Leveraging the versatility of wireless sensor and actuator network technologies, this paper describes a wireless networked lighting system that fulfills both design criteria for modern lighting systems – energy efficiency and user satisfaction. The intelligent lighting optimization algorithm formulates lighting control as a linear programming problem to minimize energy usage and meet occupants’ lighting preferences at the same time. The hardware of the lighting system is designed with minimizing retrofitting efforts and costs in mind, and an implementation of the developed system in a multiperson office shows substantial energy savings while meeting users’ lighting preferences.

Index Terms — actuation, energy efficiency, lighting control, lighting system, optimization, wireless sensor network, wireless actuator network, user satisfaction.

I. INTRODUCTION

Buildings consume more than one-third of the total primary energy in the US, and about two-thirds of the building primary energy use attributed to electricity [1]. Lighting accounts for 30% of the primary energy use in office buildings, and hence dominates the possibility of energy savings among all the electrical systems [2]. Although 25-40% potential savings may be achieved by daylight harvesting, load shedding, scheduling, etc. [3], modern lighting control technologies are still considered too luxurious for legacy buildings due to exorbitant retrofitting costs [4]. The emergence of wireless sensor network technologies promises an economic lighting system circumventing costly rewiring by taking wires out of the equation. Not only the installation of typical photosensors and occupancy sensors benefit by wireless sensor network technologies, but also the light switches or dimmers may be wirelessly enabled to form actuator networks for more sophisticated lighting control.

Shared-space offices are the most common room configuration in office buildings, where the illuminances on each of the workplanes result from the combined light contribution from multiple overhead luminaires. This research is targeted at developing intelligent lighting control systems for shared-space offices in commercial buildings with the following two objectives: (1) minimize the overall lighting energy usage and (2) provide a satisfactory lighting condition that meets the occupants’ individual lighting preferences. Leveraging the ease of incorporating wireless network technologies with the existing lighting hardware, the lighting fixtures were interfaced with a wireless module for enabling individual switching and dimming. An intelligent control algorithm was developed by formulating lighting control as a linear programming problem, which minimizes the overall energy consumption while constrained by possibly conflicting lighting preferences of the occupants. The developed system was then implemented in a build-to-scale office for verification.

II. ENERGY SAVINGS VS. PERSONAL LIGHTING PREFERENCES

Up to 40% of the lighting electricity could be saved by adopting a combination of modern control strategies such as daylight harvesting, occupancy sensing, scheduling and load shedding [3]. However, individual visual comfort currently receives much less attention than energy conservation in the energy-efficient lighting technologies. Studies conducted in typical office environments have shown the positive correlation between lighting satisfaction and productivity of the occupants [5]. Researchers have also identified the significantly diverse preferences and requirements on lighting among individuals as well as by the same person for different tasks [6], [7]. This poses a huge challenge for current advanced lighting control systems as the light fixtures are typically wired and grouped into zones in which identical lighting is enforced.

As a result, current energy-efficient lighting technologies are designed according to the standard recommended by authoritative organizations such as Illuminating Engineering Society of North America (IESNA). Although the suggested standard is derived from well-studied conditions acceptable to...
most users, it never guarantees satisfaction nor accounts for the diversity of individual lighting preferences. In fact, satisfying personal visual comfort is generally considered as a counterbalance to energy savings. Nonetheless, recent studies have revealed that it could be energy efficient on average if occupants are granted the option of working under their ideal light settings [8], [9]. In other words, it is totally possible to increase users’ lighting satisfaction and energy savings at the same time. Morel has specifically pointed out that an automatic lighting control system must optimize user’s comfort in the Daylight and Electric Lighting Control Systems Design Guide of the International Energy Agency [10]. Leveraging the versatility of wireless sensor and actuator network technologies, we have developed an intelligent wireless networked lighting control system that simultaneously maximizes user satisfaction as well as energy conservation in shared-space offices.

III. RELATED WORK

Park et al. have developed a lighting system utilizing carefully designed high fidelity wireless light sensor modules for creating high quality stage lighting in theaters to satisfy user-specified illumination profiles [11]. Since the system was exclusively for entertainment and media applications, energy conservation was not in the scope of their development. Teasdale et al. developed wireless enabled dimmable ballasts for dimming fluorescent lights that showed promise for easy retrofitting and wireless control [12]. However, they did not report how the ballasts could be integrated into a lighting control system. Singhvi et al. proposed and demonstrated a lighting control system with wireless sensors and a combination of incandescent desk lamps and wall lamps actuated by the X10 system [13]. The system satisfied occupants’ lighting preference and energy savings by maximizing the modeled personal lighting utility function and building operator’s utility function. The efficiency of this approach heavily relied on the simplification of the maximization problem assuming each light only affects a small zone, and hence, a limited number of occupants.

IV. INTELLIGENT LIGHTING OPTIMIZATION

The core of the proposed system is an intelligent lighting optimization algorithm that builds on the fact that each of the luminaires is wireless-enabled through wireless network technologies, and can be dimmed or toggled on/off individually. The hardware realization will be depicted in the following section while this section focuses on the theoretical and algorithmic development.

A. Framework

Fig. 1 shows the framework of the lighting system. The overall lighting in an office is considered as a linear combination of the light contributions from each of the luminaires. The office is first discretized into a grid of squares in the system. In the illuminance model generator, a model of the workplane level illuminance for the entire room is generated from the RADIANCE Synthetic Imaging System [14] for each of the luminaires. This requires the basic knowledge of the office configuration including room dimension, luminaire locations, surface reflectance, etc., and only has to be done once as long as there is no change to the office configuration. The generation of the illuminance model is inspired by SPOT™ [15], and Fig. 2 shows an example of one such model for a single luminaire, where the x and y axes are the room dimensions. The lighting optimizer calculates the optimal linear combination of the individual illuminance models that minimizes the entire lighting output, and hence the energy consumption, while meeting the present occupants’ lighting preferences even under possible conflicts. The optimal settings of each luminaire are wrapped into actuation command packets and sent to the luminaires wirelessly. The wireless-enabled luminaires subsequently translate actuation commands to corresponding signals to dim/lighten the lights or toggle the lights on/off.

![Fig. 1. Framework of the lighting system.](image)

![Fig. 2. Workplane level illuminance model.](image)

B. Energy usage and preferences optimization

The light setting control implemented in the lighting optimizer is formulated as a linear programming problem. The objective is to minimize the resulting illuminances at the workplane level, and the constraints are the lighting preferences of the present occupants. Since the power consumption is proportional to the light output from the luminaires, the formulation of the optimization problem can be expressed as:

\[
\text{Minimize} \quad \sum_{i=1}^{N} \sum_{j=1}^{M} \text{illuminance}_i \times \text{power}_j
\]

Subject to:

\[
\sum_{j=1}^{M} \text{illuminance}_i \times \text{power}_j \leq \text{maxlluminance}
\]

Where:

- \( \text{illuminance}_i \) is the illuminance at location \( i \) for each luminaire.
- \( \text{maxlluminance} \) is the maximum recommended illuminance for the workplane.
- \( \text{power}_j \) is the power consumption at location \( j \) for each luminaire.

The lighting optimizer solves this problem to find the optimal combination of power output from each luminaire that satisfies the lighting preferences of the occupants while minimizing energy consumption.
luminaire [16], minimizing the illuminances is equivalent to minimizing energy usage.

The room is first geometrically discretized into a grid of squares with predefined resolution, and the illuminance at the center of each small square at the workplane level is calculated with respect to each luminaire. The generated model is represented in a matrix where each of the elements is the workplane level illuminance corresponding to each square. Take an office with K luminaires, for example, and suppose it is discretized into a grid of m x n squares. The generated illuminance models are K m-by-n matrices, \( \mathbf{t}^1, \mathbf{t}^2, \ldots, \mathbf{t}^K \), associated with each of the K luminaires indicated by the superscript number. The illuminance of the room at the workplane level (\( \mathbf{E} \)) can then be represented as the linear combination of each model as shown in equation (1), where \( d_i \) is the output light level of each luminaire.

\[
\mathbf{E} = \sum_{i=1}^{K} d_i \cdot \mathbf{t}^i = \sum_{i=1}^{K} d_i \cdot \begin{bmatrix} t_{11} & \cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots & t_{mn} \end{bmatrix} 
\]

(1)

For mathematical manipulation, each matrix is rearranged into a column vector by concatenating the columns, denoted \( \mathbf{\tilde{t}}^1, \mathbf{\tilde{t}}^2, \ldots, \mathbf{\tilde{t}}^K \), and equation (1) can be rewritten as a simple matrix operation (2). The operator \( \mathbf{L} \) with the rearranged vectors of the models as its columns defines the transformation from a vector of light output level \( \mathbf{d} \) into the resulting workplane level illuminance \( \mathbf{\tilde{E}} \) of the room. \( \mathbf{\tilde{E}} \) is the vector of the concatenated columns of \( \mathbf{E} \) due to the rearrangement of the illuminance models.

\[
\mathbf{\tilde{E}} = \begin{bmatrix} \mathbf{\tilde{t}}^1 & \mathbf{\tilde{t}}^2 & \cdots & \mathbf{\tilde{t}}^K \end{bmatrix} \mathbf{d} \triangleq \mathbf{Ld} 
\]

(2)

The objective is to find an optimal set of light output levels \( \mathbf{d} \) so as to result in a properly illuminated room \( \mathbf{\tilde{E}} \) that satisfies each occupant’s lighting preference. The occupants’ preferred light settings are also specified corresponding to the small squares in the grid of discretized room, which are the preferred light settings are also specified corresponding to the points of interest are most likely confined to small area rather than the entire room, it is unrealistic and unnecessary to artificially generate the entire \( \mathbf{\tilde{E}} \) for finding the optimal light setting. Therefore, the reduced-order vector \( \mathbf{\tilde{E}}_{\text{sub}} \) that contains only the specified illuminances at the points of interest is considered. Likewise, the order of the operator \( \mathbf{L} \) is reduced to obtain the corresponding matrix \( \mathbf{L}_{\text{sub}} \), and equation (2) is then condensed to equation (3), where \( e_{p_1}, e_{r_1}, \ldots, e_{s_y} \) are the illuminances at the specified locations. The goal then becomes finding the optimal set of light output levels \( \mathbf{d} \) that satisfy the occupants’ lighting preference \( \mathbf{\tilde{E}}_{\text{sub}} \).

\[
\mathbf{\tilde{E}}_{\text{sub}} = \begin{bmatrix} e_{p_1} \\ e_{r_1} \\ \vdots \\ e_{s_y} \end{bmatrix} = \mathbf{L}_{\text{sub}} \mathbf{d} = \begin{bmatrix} l_{p_1}^1 & l_{p_1}^2 & \cdots & l_{p_1}^K \\ l_{r_1}^1 & l_{r_1}^2 & \cdots & l_{r_1}^K \\ \vdots & \vdots & \ddots & \vdots \\ l_{s_y}^1 & l_{s_y}^2 & \cdots & l_{s_y}^K \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_K \end{bmatrix} 
\]

(3)

This problem is formulated into a linear programming problem as shown in (4). By minimizing the 1-norm of the vector \( \mathbf{d} \), the summation of the output levels from each luminaire is minimized, which translates into minimizing the energy usage of the resulting light settings. The lighting preferences of the occupants are posed as the constraints to the linear programming problem. The physical dimming capabilities of each luminaire, \( \text{DimLevel}_{\text{min}} \) and \( \text{DimLevel}_{\text{max}} \), are also considered as constraints.

\[
\begin{aligned}
\min & \| \mathbf{d} \|_1, \text{ subject to } \\
& L_{\text{sub}} \mathbf{d} \leq \mathbf{\tilde{E}}_{\text{sub}}, \\
& \text{DimLevel}_{\text{min}} \leq \mathbf{d} \leq \text{DimLevel}_{\text{max}}
\end{aligned}
\]

(4)

However, this optimization problem may not have a feasible solution, depending on how each of the points of interest is specified in the equality constraint. Infeasible problems are most likely caused by the occupants’ conflicting lighting preferences. In case of infeasibility, the equality constraints are relieved to inequality constraints, thus allowing some tolerances. The relief of the equality constraints makes sense in that the physical meaning of this is to allow the lights at the points of interest to be regulated in certain tolerable ranges (\( \varepsilon_{\text{tol}} \)) instead of demanding the exact illuminances. Studies have shown that people are insensitive to 20% of illuminance changes and are willing to accept an illuminance change up to 30% [17]. In summary, the algorithm starts with the original linear programming problem with equality constraints and gradually expands the tolerable range by relaxing the equality constraints into inequality constraints as shown in equation (5).

\[
\begin{aligned}
\min & \| \mathbf{d} \|_1, \text{ subject to } \\
& L_{\text{sub}} \mathbf{d} \leq \mathbf{\tilde{E}}_{\text{sub}} + \varepsilon_{\text{tol}}, \\
& L_{\text{sub}} \mathbf{d} \geq \mathbf{\tilde{E}}_{\text{sub}} - \varepsilon_{\text{tol}}, \\
& \text{DimLevel}_{\text{min}} \leq \mathbf{d} \leq \text{DimLevel}_{\text{max}}
\end{aligned}
\]

(5)

V. WIRELESS NETWORKED LIGHTING SYSTEM

In order to deliver different light outputs for energy savings and user satisfaction, it is necessary to enable individual dimming control of each luminaire. The obstacle of enabling individual lighting control in legacy buildings with the current technologies is the exorbitant cost of rewiring, including the addition of the large number of switches required to achieve the desired level of control.

Wireless technologies have been considered a promising solution for advanced building operation systems to circumvent costly installation and rewiring, particularly in legacy buildings [18], [19]. Recently, some researchers are focusing on applying wireless sensor and actuator technologies to the next generation of advanced lighting systems [12], [13]. Building on our previous work [20], [21], we developed a prototype of a wireless lighting system that includes wireless actuation modules and a base server utilizing the popular wireless network platform known as a “mote” [22]. The system architecture is shown in Fig. 3.
The actuation module was developed with two objectives in mind: to enable the self-configuring wireless communication capability of the luminaires and to minimize the retrofitting cost and complexity. Fig. 4 shows the resulting actuation module prototype, which is installed between the dimming ballast and the mains via five short local wires, eliminating any need for out-of-fixture or global rewiring. The line power is stepped down, rectified, and regulated to the voltages that are required to power the mote and dim or toggle the lights on/off. Since the mote is always powered, the limited-energy issue typical with other wireless sensor networks is nonexistent.

The mote platform sitting on the actuation module is programmed to listen to the network for actuation commands, report back its current actuation status to the base server, and coordinate with other motes to form a multi-hop network. Upon receiving an actuation command addressed to it, the mote translates the specified level to a voltage signal through the onboard digital-to-analog converter. This signal is then amplified to 0-10VDC dimming signal to set the level of the dimmable ballast. If the command is to switch the lights on or off, the mote will instead toggle the relay on the module with its general I/O port. The mote also periodically generates packets containing its current status and sends them back to the base station. The purpose for the status feedback is twofold: to monitor the actuation status, and hence energy usage of the entire system, and to reinforce the wireless network links and compensate for lost or corrupted actuation packets during wireless transmission. In addition, the motes will autonomously configure themselves into a network by identifying their parent mote in the route to the base station as soon as they are powered up. The network is dynamic and periodically updated to avoid bad or interrupted communication links.

The base server is an integration of three components: a database, a control application program, and a mote base station. Each of the elements was implemented with free open source software in view of zero-overhead, compatibility, and scalability. The database is implemented with MySQL® to store the actuation and status feedback histories. The mote base station is composed of a mote plugged into the USB port of the computer that “listens” to the wireless network. TinyOS is the operating system running on the base mote as well as all the actuation motes.

The control application program, a Java® program, is the core of the system, where the intelligent lighting optimization algorithm resides and actuation commands are issued. The program translates the optimal light settings from the optimization algorithm into actuation command packets for wireless transmission. Each time an actuation command is generated, a corresponding entry will be logged into the associated table in the database. In order to account for possible interruption or corruption of the wireless network communication, the program also listens to the status feedback from the actuation motes, compares the status to the most recent actuation history, and resends the actuation packet if any inconsistency is detected.

VI. SYSTEM SIMULATION AND VERIFICATION

The intelligent lighting optimization algorithm depicted in section 3 was simulated and verified with a pilot implementation. A 30′-by-19′-by-14′3″ office was realized in both the simulation and the verifying implementation with 10 personal workstations and some shared worksurfaces as illustrated in Fig. 5. The workplanes were 29.25″ above the floor. There were 12 2-lamp troffers hanging 4′ from the ceiling evenly mounted in the office as the 12 equally spaced rectangles illustrates in Fig. 5. The reflectance of the floor, walls and ceiling were measured to be 10%, 50% and 30% respectively. As the illuminance model generator in the lighting optimization algorithm requires a wall as a boundary, our model placed an artificial wall on the north side of the part of the room under study, whereas the actual room was connected to a meeting area with no physical separator in between. No window was considered at this point as the there was no window in this inner office. The incorporation with windows and daylight will be discussed in the next section.
practical factors were also taken into account: (1) the resulting optimal light settings were represented in the percentage of the maximum output of the luminaires and rounded to integers as the dimming resolution of the actuation module is discrete (256 distinct levels); (2) the light levels were set to 5% whenever the optimized output was less than 5% but greater than 0 since the effective output range of typical dimming ballasts is 5-100%. The lights would be turned off if the optimized light setting was 0.

The first scenario considered a sparsely occupied office where only four occupants were present with diverse lighting preferences. The purpose of this simulation was to show that the optimized lighting not only managed to meet each occupant’s preference but also efficiently conserved energy by not illuminating unoccupied areas. The resulting illuminance at the workplane level is shown in Fig. 6, and the optimal light settings for each of the 12 luminaires are \{74\%, 31\%, 79\%, 0\%, 100\%, 5\%, 0\%, 0\%, 0\%, 100\%, 0\%, 0\%\}. Compared to the original lighting configuration of the office where the luminaires were wired to be turned on altogether, only 32.4% of the light, and hence the energy, was used to achieve the occupants’ lighting requirements. To verify the simulation, a light meter was placed at the desktop where preferred illuminances were specified. The numbers at the bottom of each group of three stacked numbers in the luminance contour plot in Fig. 6 are the specified preferred illuminance (in lux), those in the middle are the light level resulting from the optimization algorithm, and those at the top are the actual illuminances measured by the light meter.

The second scenario assumed a more densely occupied office with seven occupants present, and the lighting preferences of some occupants sitting adjacent to each other varied drastically. This simulation demonstrated the capability of the system to balance diverse and conflicting lighting preferences while delivering reasonable lighting to all occupants. The resulting workplane level illuminance is shown in Fig. 7, and the corresponding optimal settings for each luminaire are \{76\%, 27\%, 100\%, 100\%, 100\%, 60\%, 96\%, 0\%, 21\%, 0\%, 44\%, 0\%\}. Only 52.0% of the light was used compared to the original all-on lighting configuration. The optimized light setting, the numbers in the middle of each group of three stacked numbers in Fig. 7, diverged from the specified values (the number at the bottom) due to the necessary compromise of diversely specified preferences between adjacent occupants. Nonetheless, the optimized lighting stays within 15% of the specified illuminances as are the actual measurements.

It is obvious from Fig. 6 and Fig. 7 that the measured illuminances differed from the calculated optimal illuminances more significantly towards the north side of the office (right side) where an artificial wall was placed in the simulated room to simulate an interior room where the original software module assumed a north facing external wall. The additional absorption and reflection introduced by the virtual wall might have rendered the illuminance model near the north side of the office less accurate. Since the illuminance models were generated with respect to an empty room, the furniture in the real office could have also contributed to the inaccuracies in the models. Moreover, the lighting hardware, namely the dimming ballasts and fluorescent light tubes, might not guarantee a consistent mapping from the dimming signals to the actual output luminous due to manufacturing tolerances.

These uncertainties in the model motivate the future research of incorporating the wireless sensors as discussed in the next section.

VII. CONCLUSION AND FUTURE RESEARCH

This paper presents a wirelessly networked intelligent lighting actuation system that efficiently minimizes the energy consumption and satisfies users’ diverse lighting preferences in shared-space office buildings. The lighting optimization algorithm generates results in seconds and is capable of being implemented in real time. The developed system showed promising results, as well as opportunities for future research.

The proposed algorithm uses a centralized control strategy, a common practice in building management systems; however, autonomous and decentralized lighting control could be realized by deploying the algorithm to the actuation nodes. Although the generation of illuminance models demands complicated and specialized computation, the models will remain the same as long as there is no change in the room configuration. Therefore, the illuminance model generation could be integrated into centralized scheduled maintenance by transmitting and storing the models in their corresponding wireless actuators. On the other hand, the lighting optimizer
could reside in the actuation nodes, and be executed in a cyclic manner. Given the occupants’ lighting preferences, only a small portion of the elements in each illuminance model will be involved in the lighting optimization process, and hence, with minimal exchange of the model information, the optimal lighting can be calculated and delivered by the actuators themselves. It may also be possible to further parallelize the optimization process by performing the linear programming collaboratively among the actuators.

To account for the uncertainties of the models generated from the illuminance model generator, photosensors measuring desktop illuminance could be effective components to be integrated into the system. These miniature-sized wireless sensors are predicted to be economically affordable in the near future and could be deployed on the desktops to form a sensor network that interact real-time with the actuator network to better regulate the desktop illuminance in accordance with the optimized settings. The sensor fusion algorithm presented in [23] could extract pertinent light readings from redundant sensors while rejecting possibly faulty or disturbed sensor readings. Once integrated with photosensors, the system could save more energy by reducing artificial light in response to daylight. It would also be possible to pose the load shedding request as another constraint in the lighting optimizing algorithm as part of a larger energy management system.

In the developed system, the occupants’ lighting preferences are assumed to be known for simplicity. It is otherwise non-trivial to acquire users’ lighting preferences since they may vary over time as well as depend on the nuances of the current tasks being performed [7]. Allowing overriding the optimized light settings could serve as an effective way for the system to learn and update the users’ preferences. Studies have also shown that users always demand a certain degree of control no matter how intelligent the system may be [24], [25]. Thus, an overriding mechanism that can help learn and update user’s lighting preferences and interact with the automatic lighting optimization algorithm should be incorporated into the system.

ACKNOWLEDGMENT
The authors would like to acknowledge Raul Abesamis, Elaine Ito, Medardo Largoza, and Sal Castro of the Physical Plant-Campus Service of UC Berkeley for their retrofitting and consulting services. We also wish to thank Dr. Jessica Granderson, James Bunnell and Alireza Lahijanian for their research support on the implementation.

REFERENCES