Intelligent Wireless Lighting Control using Wireless Sensor and Actuator Networks: A Survey

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ABSTRACT: Minimizing energy usage and increasing occupant comfort are the two primary objectives of intelligent and eco-friendly buildings. Energy savings of up to 70%, combined with significant occupant productivity gains are possible via the application of wireless sensor and actuator networks (WSAN). Despite the increasing interests in WSAN-based wireless intelligent lighting control, no prior survey work exists. In the paper, we aim to provide a holistic survey of various WSAN-based schemes for intelligent lighting control so that researchers interested in the field can gain up to date knowledge and inspiration for future research. Specifically, an overview of various sensor data collection and management techniques relevant to lighting control is provided; taxonomy of various intelligent decision making schemes for lighting control is detailed; moreover, open issues within this field are identified and future research directions are proposed.

1 INTRODUCTION

Buildings consume 29% of all electricity generated in the US, while lighting systems are among the largest energy consumers within buildings, constituting between 30 to 40% of all building electricity usage [1]. Therefore, the implementation of intelligent lighting control for buildings will have significant impact on national energy usage.

Lighting system research over the past two decades has been driven by the need to improve energy efficiency in order to reduce energy costs. This has resulted in schemes such as occupancy sensing, day lighting and dimmable ballasts, which have been proven to be capable of generating up to 50% savings in energy usage [2]. In spite of the widespread availability of such energy–saving schemes, these technologies have not been widely adopted due to the high-cost of retrofitting them into existing buildings.

The improvement of building occupant comfort via climate and lighting control is another recent development. It has been demonstrated that lighting is a major determinant of occupant comfort and productivity [2,3]. The productivity gains in the US from improved indoor work environments could range between $20 - $50 billion [4]. As a result, significant amounts of research have been conducted on providing personalized lighting and climate zones for building occupants.

As a result, intelligent buildings seek to minimize total energy usage while improving occupant comfort. Unfortunately the attainment of the twin goals has been hampered by the following problems:

– Retrofitting existing lighting systems to provide intelligent lighting control is a complex and costly endeavor, with cabling costs representing a significant portion of this expenditure [5].

– Granular lighting control is essential to improving lighting efficiency, but the fixed wiring of legacy lighting systems prohibits such control of lighting fixtures. This makes it difficult to vary lighting levels at specific locations in a building or workspace in order to satisfy individual occupant preferences.

– Current lighting system architectures cannot provide the detailed workspace level lighting measurements required to determine user lighting conditions or verify that occupant preferences are met.

The integration of Wireless sensor and actuator networks (WSANs) into lighting control systems promises to overcome these issues while providing additional functionality. WSANs consist of large

Table 1. Comparison of Intelligent Lighting Control Schemes

numbers of small sensor or actuator-equipped, power-constrained wireless devices with limited amount of memory and processing power. These networks typically run over the IEEE 802.15.4 Physical and MAC layers and use protocols such as Zigbee [6] or 6LoWPAN [7]. WSANs have found significant application within Home and Building Automation networks, due to their flexibility, low cost, and the easy deployment of wireless nodes [8,9].

The ability of WSANs to sense and interact with their environment enables them to extend the embedded computing paradigm to include computation, control and communication. The computational capabilities of WSAN nodes provide the intelligence required to satisfy conflicting user lighting level requirements, while their wireless communications capabilities permit individual ballast control and networking. These capabilities enable the lighting systems to respond to demand response commands from utilities during peak load conditions, for example, dimming individual ballasts to reduce the loads. To our best knowledge, no prior survey exists on the use of WSANs for intelligent lighting control applications. In this paper, we aim to summarize significant work done to date to provide a holistic overview of the various sensing, actuation and decision-making schemes utilized for WSAN-based intelligent lighting control. We also examine the challenges faced by WSAN-based lighting and highlight the open areas and future research directions.

The paper is structured as follows: Section 2 provides an overview of lighting control systems, followed by a discussion of WSANs in Section 3. Section 4 discusses sensor data collection and management and examines data validation and aggregation for sensor networks along with open issues within this area. Various lighting control schemes are classified and discussed in Section 5, along with future research directions proposed. Finally, the paper is concluded in Section 6.

2 LIGHTING CONTROL SYSTEM OVERVIEW

Lighting control systems provide workspace illumination, ambience and security, shown in Figure 1. They directly influence workplace productivity and occupant safety, but are often one of the largest consumers of electricity in a building. These systems utilize fluorescent, incandescent and Light Emitting Diode (LED) lamps, but we will focus only on fluorescent lamp based systems.
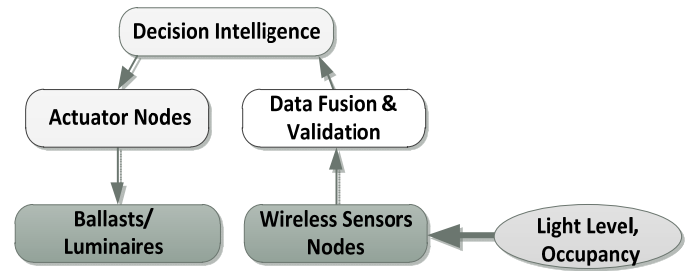

Figure 1. An Intelligent Lighting Control System

2.1 Lighting Control System Components

Lighting control systems consist of luminaries, sensors and controls.

2.1.1 Ballasts/Luminaries

Luminaries are complete lighting fixtures comprising of a lamp, ballast, reflectors and an enclosure for all the lighting unit components. Ballasts are used to provide the starting voltages required for lamp ignition and to regulate the current flow within the lamp in order to guarantee optimal operation. They can be either magnetic or electronic (solid state) types, with newer installations tending towards electronic ballasts due to their superior performance in terms of noise and flicker. Newer ballasts also enable fluorescent fixture dimming between 1-100%, utilizing either analog or digital dimming. Analog dimming utilizes a control voltage ranging between 0-10V to signal the percentage of dimming required. Due to its low cost and simplicity, analog dimming is the most widely deployed dimming scheme. Digital dimming [10] offers greater control granularity, as well as the ability to individually address and network ballasts, and is therefore gaining more acceptance.

2.1.2 Sensors

Sensors serving as the eyes and ears of the intelligent lighting control system allow the system to detect and respond to events in its environment. The most commonly used sensors are occupancy and photo sensors, although some systems incorporate the use of smart tags to detect and track occupants.

These smart tag based schemes are yet to gain widespread acceptance due to privacy concerns.

Occupancy sensors are used in detecting room occupancy. They are utilized in locations with irregular or unpredictable usage patterns such as conference rooms, toilets, hallways or storage areas [1]. The primary technologies used in occupancy sensors are ultrasonic and Passive Infra-red (PIR) sensors. Newer sensors incorporate both technologies to provide improved detection, at the expense of increased cost.

Photo sensors detect the amount of ambient light, which can be used to determine the amount of artificial lighting required to maintain total ambient lighting at a defined value. Therefore, photo sensors are an integral component of daylight harvesting systems.

2.1.3 Lighting Controls

These are the various mechanisms used for lamp actuation. They can be simple devices such as basic on/off wall switches, time clock switches for scheduled lighting actuation, or dimmer switches. More complex lighting controls include lighting automation panels and Building Automation Systems.

2.2 Lighting Tasks

A variety of control strategies are available for lighting control, depending on the function of the room or location in question. The simplest and most basic form of lighting control is on/off control, which is often achieved by means of a wall switch. It can be combined with scheduling, occupancy detection or demand response to achieve greater energy savings. Another basic control is dimming, where the level of lamp luminance is altered to compensate for user preferences, achieve energy savings, or in response to demand response signals from the utility. More complex controls are discussed below.

2.2.1 Scheduling

This is the most prevalent control scheme after on/off control. Lights are turned on/off according to a predetermined schedule, and this control method is most appropriate in buildings and areas such as shops or large offices, which have predictable usage patterns.

2.2.2 Daylight Harvesting

Also known as day lighting, this technique involves harnessing available daylight to minimize the amount of artificial lighting generated. Photo sensors are utilized to detect ambient light levels and dimmers are used to dim fixtures to maintain defined lighting levels.

2.2.3 Demand Response

Demand Response is the ability to respond to signals from the power utility company to reduce power usage due to high system loads. This is primarily achieved by dimming or switching off non-essential loads. Demand responsive dimming is usually unnoticeable to building occupants due to the limited sensitivity of the eye to minor variations in lighting intensity [11].

2.3 Task Tuning

The amount of light output is adjusted to suit the task being performed or the current function of the workspace. This allows occupants to personalize their workspace lighting in accordance with their current work task or optimal comfort level. It is also used for aesthetic purposes such as the adjustment of lighting in order to accentuate items on display, or to create additional ambience in lobby areas. Task tuning prevents energy waste from over lighting and can be achieved via on/off control or dimming.

3 OVERVIEW OF WIRELESS SENSOR AND ACTUATOR NETWORKS

Wireless sensor and actuator networks (WSAN) consist of a group of sensors and actuators connected by wireless medium to perform distributed sensing and actuation tasks [12]. Sensors are battery powered, low-cost, low-energy devices with limited sensing, computation and wireless communication capabilities. Actuators tend to have greater capabilities than sensing nodes, along with longer battery lifetimes. For example, they can be wall powered or possess abundant renewable energy resources [13].

WSANs have the ability to observe their physical environment, process sensed data, make decisions based on observations, and perform appropriate actions. Real-time response and coordination are two unique characteristics of WSANs. A WSAN can provide rapid response to sensor input. After receiv-

Table 1. Comparison of Intelligent Lighting Control Schemes

ing event information, actuators can coordinate with each other in order to determine the most appropriate manner to perform an action [14].

Due to these characteristics of WSANs, WSANs have been widely used in battlefield surveillance, nuclear, biological and chemical attack detection, and environmental monitoring [14]. And they are the perfect choice for lighting control system and home automation. They can react rapidly within given delay bounds as the environment changes, while their energy efficient operation enables the wide adoption and easy implementation due to the low system cost and infrequent battery changes.

4 SENSOR DATA COLLECTION AND MANAGEMENT

Intelligent systems are able to operate without human intervention and respond to random changes in their environment. They interact with their environment via sensors, and utilize sensor data as input for their decision making algorithms. It is therefore essential that the collected data be an accurate representation of the current system state. Unfortunately, due to the low cost of WSAN nodes and their often hostile operating environments, the fidelity of sensed data is often poor [15] or the nodes are prone to failure. This problem can be addressed by means of multi-sensor fusion.
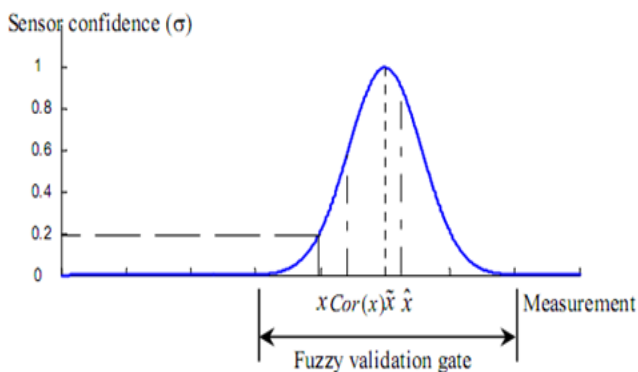

Figure 2. Fuzzy-centered Validation curve [23]

Multi-sensor fusion combines data from multiple sensors or sources to obtain inferences which would not be available if a single source was utilized, or to obtain data of higher quality compared to with a single source [16]. The accuracy and efficiency of an intelligent system is determined by efficacy of the

data collection techniques utilized in the WSAN [17]. As a result, data validation and fusion techniques are essential to improve the accuracy and reliability of the data collected from WSANs. They also enable the system to remain stable in the event of sensor failures or erroneous input, providing accurate sensor data for actuation and decision-making.

4.1 Sensor Data Validation and Fusion

Sensor data needs to be validated and integrated before it can be utilized. Data validation determines the accuracy of sensor output based on measures such as sensor characteristics or the correlation of data among multiple sensors. The first step in validating sensor data is modeling the sensor output. This provides a measure of the quality of the sensor data by characterizing the uncertainty and error in sensor output [18]. Data fusion is the combination of data from various sources in order to gain a more complete and accurate picture than what would be obtainable with only one sensor [16]. The primary data fusion schemes include estimation, feature maps, aggregation, and inference methods [19].

Inference schemes utilizing fuzzy logic have found wide-spread application in wireless sensor networks due to their proven performance in the presence of imprecise inputs and their ability to approximate non-linear system models. Their low computational complexity also makes them very attractive for use in resource constrained sensor networks [20]. Abdel-rahman *et al* [21] and Phanishankar *et al* [22] developed a data fusion scheme for quasi-redundant sensors and generated a Gaussian probability density function to provide a best estimate of the sensed data. Their work was applied and extended by Wen *et al* to develop a Fuzzy logic based data validation and fusion scheme for lighting applications [17,23,24]. This system consists of three steps – data validation, fusion and prediction.

Data validation is initiated by discarding sensor readings outside the measurement capabilities of the sensors and then assigning confidence values to each of the remaining sensor readings. The confidence value is obtained by means of a validation curve, which can be seen in Figure 2. This curve is produced from the sensor characteristics, predicted sensor values, correlation among all sensor readings, and the physical limitations of the sensors. The cen-

ter of the curve is adjusted by means of a fuzzy logic function which takes the predicted sensor value $\hat{x}$ and the correlation of all sensor data *cor(x)* as inputs. The correlation among the filtered sensor values is obtained using a majority rule scheme based on either the median sensed value or a Gaussian correlation curve scheme. The advantage of these schemes is their immunity to outlier values which might escape the filtering process of the validation procedure.

Validated sensor readings are weighted with their corresponding confidence values and averaged along with predicted sensor values and weighting functions which indicate system state. The fused value also incorporates a scaling factor to ensure system stability in the absence of valid sensor input [17].

4.2 Adaptive Sensing

Continuous sensing of ambient lighting conditions is essential to intelligent lighting systems, as it enables the rapid detection and compensation for changes in the physical environment or the different occupant requirements. Unfortunately, WSAN nodes, especially those devoted to pure sensing tasks, are often power limited. This leads to a trade-off between sensing frequency and device lifetime. High sensing rate enables rapid system response with more energy consumption, while low sensing rate increases sensor network lifetime but results in significant system lag. The trade-off needs to be balanced.

Singhvi *et al's* [25] scheme schedules light sensor reads for periods which maximize the expected system utilization. They harness the spatial and temporal distribution of daylight to provide coordinated sensing across multiple sensors thereby reducing the sensing and data transmission frequency per node. They developed a predictive model for sunlight distribution during the day, and utilized this model, in conjunction with Markov chains and dynamic programming, to develop an adaptive sensing scheme. This scheme was deployed on a WSAN test bed using MICA2 motes, demonstrating that active sensing frequencies as low as 1-3 reads per day could provide energy savings and user satisfaction close to a system making 10 equally spaced readings per day.

Wen [26] utilized a predictive model combined with fuzzy logic to create the algorithm in Figure 3, which adaptively varies the sensing rate according to changes in the physical environment. Various filtering methods were utilized for the prediction engine,

but Wiener filters were found to provide the smallest prediction error and lowest amount of tuning effort. Large prediction errors indicate significant changes in the environment and hence need higher sensing rates. Low prediction errors indicate steady system state and low sensing frequency requirements. Fuzzy logic was used to convert the imprecise system state terms of "High, medium, low" change rates to weighting parameters which are used to vary the sensing rate.
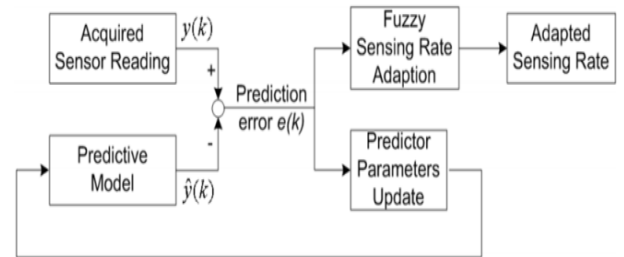

Figure 3. Adaptive Sensing Rate Algorithm[26]

4.3 Future Research

Additional research is required in the areas of reducing energy consumption and improving individual occupant sensing. Energy usage is always a critical issue in WSAN applications, and a potential avenue for additional power savings is the extension of the earlier discussed active sensing schemes with event-based/ self-triggering sensing and actuation. Mazo *et al* [27, 28] introduce self-triggering and event-based sensing and actuation as a means of extending sensor lifetime while guaranteeing system robustness and stability, and their framework can be readily extended to lighting applications.

Individual occupant sensing is still an open issue as currently available occupancy sensors cannot accurately detect the number of occupants in a room or determine their precise locations. Several schemes propose the use of smart tags or RFID badges to uniquely identify users in order to determine user preferences and location [29-31] but this raises the issue of occupant privacy. As a result, the development of user detection and identification schemes which guarantee privacy and anonymity will enable the enhancement of occupant comfort in a non-obtrusive and user-friendly manner.

Table 1. Comparison of Intelligent Lighting Control Schemes

	Prioritization	Influence Diagrams	Linear Programming	Multi-agent Systems
Overview	Conflicts resolved by deferring to the highest priority user present	Complex interrelationships formulated using simple graphs. Non-deterministic decision-making	Effective optimization scheme for modeling and satisfying competing objectives	Ideal for environments where learning and prediction are essential while interrelationships between system parameters are either unknown or not well-defined
Approach	Node prioritization	Bayesian probabilities	Linear optimization, scalarization,	Artificial Intelligence - Neural networks, expert systems
Response time	Fastest	Rapid response	Rapid response	Medium
Scalability	Centralized architecture which limits scalability and produces single-point failures			Highly scalable due to distributed architecture
Weaknesses	Can only guarantee comfort for a single occupant	Probabilities must be determined via experimentation	Optimization problem formulation is a non-trivial task	No wireless scheme currently deployed due to complexity of the problem

5 INTELLIGENT LIGHTING CONTROL SCHEMES

Intelligent lighting control systems combine digital control with computation and communications capabilities. The result is a lighting system with low costs and high levels of flexibility. A survey of published work on intelligent wireless lighting control indicates that intelligent lighting control schemes can be broadly classified into centralized and decentralized schemes as seen in Figure 4.
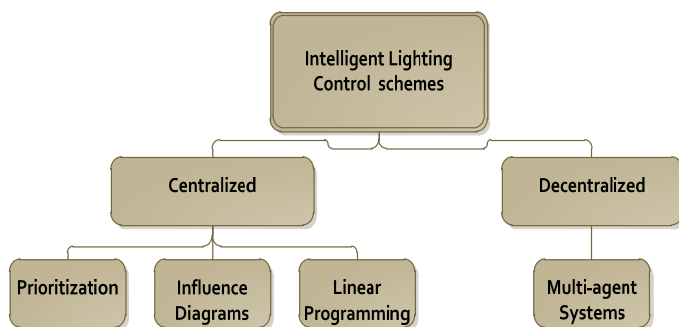

Figure 4. Taxonomy of intelligent wireless lighting control

Centralized schemes provide faster performance and lower convergence time than de-centralized schemes, but suffer from scalability issues and single-point failure problem. Table 1 provides an overview of various schemes, while an in-depth discussion is provided below.

5.1 Prioritization

This is simple model which decides between conflicting user lighting preferences on the basis of occupant priority. Li [13] developed a WSAN-based lighting monitoring and control prototype in which pre-assigned user priority determines which occupant's preference dominates in conflict situations. The unique contribution of this work is a two-tier heterogeneous WSAN in which actuation control signaling is separated from sensing traffic via an overlay network. This separation enables the provision of delay and service guarantees for time sensitive actuation commands.

5.2 Influence Diagrams

Influence Diagrams provide a mathematical and graphical framework for visually describing a decision problem and the inter-relationships between de-

cision variables [32]. They are based on Bayesian networks and succinctly describe the system variables, decision nodes and objective functions in a simple graphical manner [24]. Decision variables are interrelated via conditional and marginal probabilities enabling the use of Bayes' rule for non-deterministic decision making and inference [33].

An Influence diagram is a directed acyclic graph consisting of state, decision and value nodes. State nodes are uncertain events over which we have no control. As seen in Figure 5, they are represented by ellipses, symbolizing the various states in the system.
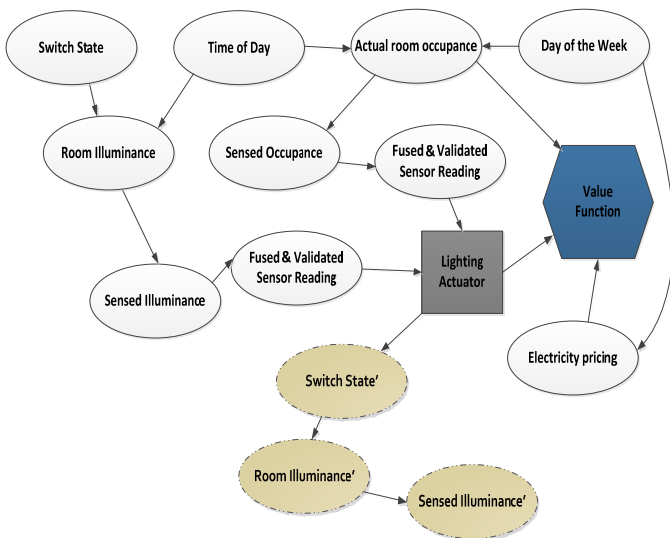

Figure 5. Inference Diagram for Intelligent Lighting Control

Decision nodes denote the available control actions and, in this context, represent the decisions available to the controllers/actuators in the system. They are typically represented by rectangles. Value nodes represent the cost function which we seek to maximize (or minimize) and are denoted using hexagons. A value node ranks the various decisions available to the system controller in response to current system state, with the optimal decision being that which maximizes the expected value of the cost value function [34]. Arcs represent interrelationships between system nodes. An arc from a state node into a decision node represents information available to the controller at decision time, while an arc from a decision node to a state node indicates a causal relationship.

Granderson *et* al [24,33] utilize Inference diagrams to provide intelligent decision-making for a dimmable ballast WSAN-controlled lighting system. Their

system provides demand response capabilities to enable the reduction of building lighting energy usage while also satisfying conflicting occupant preferences for shared workspaces. Shared workspaces are those in which multiple occupants are served by the same ballast.

They modeled all the various system states, variables and their dependencies in order to define a regional value function which identifies the optimal decisions amidst conflicting occupant lighting preferences and current lighting sensor readings. Their work was validated using a sensor test bed consisting of 3 WSAN light sensor nodes and 4 WSAN nodes for lighting ballast actuation [33].

This work was extended by Wen *et al* [23] to vary not only the amount of dimming per ballast but also the rate of dimming. High dimming rates result in occupant discomfort, so in order to maximize occupant comfort, dimming should be performed at slow rates. It has also been discovered that the human eye does not notice dimming of lights by as much as 20% as long as the dimming is performed slowly enough. This provides the ability to make significant power savings by slow-rate dimming in response to demand response requests from the power utility company. Their system was able to maintain work surface illuminances within 5% of user specified levels even though one third of the six light sensor nodes used for the test failed, demonstrating the resilience of their system to sensor failures.

5.3 Linear Optimization

The goal of linear optimization is to maximize (or minimize) an objective function subject to constraints [35]. It is one of the most widely used schemes for minimizing energy consumption subject to satisfying user preferences [25,29,30, 36-41].

Singhvi *et al* [25] developed a WSAN system to optimize the tradeoffs between satisfying occupant lighting preferences and reducing building energy usage by means of utility functions which capture occupant preferences. Their optimization problem formulation utilizes scalarization [35] to solve this multiple criterion optimization problem. The formulation of the problem is provided in equation (1):

$$U(a, x) = \sum_{i=1}^{n} \Phi_i(a, x_i) + \gamma \Psi(x) \qquad (1)$$

Where $\Phi(a, x_i)$ is the utility function for occupant *i* at location x_i, **a** is the vector of all the lighting levels

Table 1. Comparison of Intelligent Lighting Control Schemes

for each of the luminaires in the room, ψ is the building energy utility function which is monotonically increasing with energy usage, and γ is the scalarization or tradeoff factor which penalizes high energy usage. Their system control strategy is to maximize $U(a,x)$. The efficacy of their system was demonstrated using a test bed consisting of 12 MICA2 WSAN nodes and 10 desk lamps. Their system provided significantly better performance than a greedy heuristic algorithm which seeks to maximize each user's utility function.

Wen *et al* [34] addressed the same issue by creating an illuminance model of the room which captured the effect of each individual luminaire on work surface lighting. Their objective is the minimization of work surface illuminance levels subject to the satisfaction of lighting preferences of current room occupants. Their system calculates the optimal linear combination of individual illuminance models and lighting levels which minimizes energy usage. The lighting framework is shown in Figure 6.
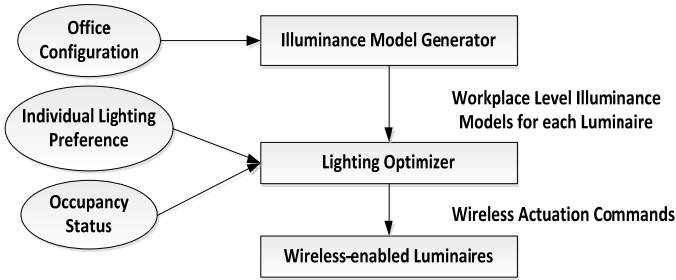

Figure 6. Intelligent Lighting Control Framework [34]

Their optimization problem is formulated as:

$$\min \ \|d\| \ , \text{subject to}$$
$$Ld = \tilde{E} \tag{2}$$
$$minDimLevel \le d \le maxDimLevel$$

where d is the vector of light output levels of all luminaires in the room, L is the vector of all workspace illuminance level models, $\tilde{E}$ is the illuminance of the work surface due to the linear combination of all the luminaires, and $minDimLevel$ and $maxDimLevel$ represent the physical limitations of the amount of dimming the ballasts are capable of providing, respectively. This optimization problem may not be feasible and this is addressed by the discovery

that the human eye is insensitive to illuminance variations of up to 20% [11]. This knowledge enables the optimization constraints to be relaxed to inequality constraints, converting the optimization problem to equation (3):

$$\min \ \|d\| \ . \text{subject to}$$
$$\tilde{E} - \varepsilon_{tol} \le Ld \le \tilde{E} + \varepsilon_{tol} \tag{3}$$
$$minDimLevel \le d \le maxDimLevel$$

Their system was tested in a large workspace with 12 luminaires and was able to maintain work surface illuminance within 15% of user specified settings in environments where multiple users are served by the same luminaire. Energy savings between 68-70% were achieved based on the number of occupants present.

In [29], Meng *et al* propose a WSN-based intelligent light control system which utilizes linear and nonlinear programming for indoor environments. For the binary satisfaction model, the goal is to minimize the power consumption, and the constraints are the upper bound and lower bound of background and concentrated illumination requirements for each user. In their continuous satisfaction model, each user's satisfaction level is a function of lighting intensity. The decision algorithm seeks to maximize the users' satisfaction level while the constraints are the satisfaction threshold for various users present.

They divided area into grids and install fixed sensors to measure the background light intensity. Each user wears a badge which is used to measure the concentrated light intensity that the user experiences. The authors assume that each user's satisfaction range or function is known in advance and that each light's effect coefficient in each grid is known by detection. Their work was extended by Yeh *et al* [30] who proposed a mathematical model for obtaining the effect coefficient. Based on the user's light requirement, the light adjustment value can be obtained via optimization.

Miki *et al* [39], Tomishima *et al* [40] and Kaku *et al* [41] developed distributed, autonomous intelligent lighting control schemes to provide user-defined illuminance at specific locations. Even though the proposed systems are not wireless, they enable individual lighting actuation and control independently of the luminaires wiring scheme. Tomishima and

Kaku's work is based on Miki's 2004 paper, with Tomishima extending Miki's work with the addition of color temperature control, as this has been found to improve user comfort [42]. Kaku's work details the implementation of this system in 240 square meter workspace with 26 lighting fixtures and 22 illuminance sensors.

5.4 Multi-Agent Systems

Multi-agent systems consist of large number of autonomous intelligent agents which cooperate to accomplish complex tasks in a decentralized manner. Sandhu *et al* [31] proposed a lighting management system which incorporates the advantages of the Influence diagram-based scheme developed by Granderson *et al* [24], but operates in a decentralized manner. The advantages of such a scheme include scalability, self-configuration and adaptation via machine-learning capabilities. Two user satisfaction models are proposed − a workspace-based scheme and a user-centric scheme. The former utilizes occupancy sensors to detect room occupancy but is unable to uniquely identify occupants, while the latter provides a means of identifying individual room occupants via RFID tags or similar schemes, obviating the need for occupancy sensors. Their proposed system is capable of distributed learning via supervised learning or reinforcement learning schemes [43]. Unfortunately they only provided a theoretical framework for their system, precluding a performance evaluation of their system.

5.5 Future Research

Decentralized intelligent lighting control promises highly scalable systems without single point failure, but they require more complex protocols and suffer from longer convergence times compared to centralized schemes. The convergence time of Miki's scheme is 3-5 minutes compared to a few seconds in Yeh's and Wen's centralized schemes. Distributed data validation and fusion requires the optimal distribution of computational tasks and communication energy among sensor nodes which is a non-trivial task [23].

All the reviewed schemes which were actually deployed utilized centralized schemes. The only decentralized schemes were Miki *et al* (which is wired scheme) and Sandhu's work (which was not implemented). Almost all the centralized schemes have

proposed decentralized versions of their work but none have been implemented to date. As a result actual deployment of a distributed WSAN based lighting control system is still an open issue.

The primary inhibitor is the problem of the computation of a global optimum on the basis of local data obtained at each sensor. This requires the implementation of a robust information exchange system to enable each node to share data in order to provide each actuator with a view of global conditions, which is a non-trivial task.

This open issue can be addressed by the use of distributed inference architecture for WSANs such as proposed by Paskin *et al* [44]. This scheme enables global decision-making for sensing and control tasks via message passing. The demonstrated utilization of this work for distributed control applications, along with its rapid convergence times, make it an ideal platform for extending the intelligent lighting control schemes to distributed environments.

6 CONCLUSIONS

Advancements in the application of WSANs for intelligent lighting control promise significant benefits in both energy saving and user comfort. In order to further research in this field, we have provided an overview and taxonomy of the various intelligent lighting control strategies using wireless sensor and actuator networks, along with the various data collection and management strategies required for guaranteeing accurate input for decision–making. Open research issues regarding energy usage for data collection, individual user detection and distributed lighting control were identified and solutions proffered.

7 ACKNOWLEDGEMENT

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