Visible light communications for sensing and lighting control

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Abstract— **Indoor lighting systems need to be designed to balance energy consumption and the visual comfort of occupants. Achieving this goal with multiple luminaires and sensors is however not a simple problem. Lighting control systems need to adjust the dimming levels of luminaires in real-time based on occupancy conditions and external daylight changes. We propose a system based on visible light communication to monitor and control artificial lighting in a robust manner. In our system, luminaires modulate the emitted light to broadcast basic control information while fulfilling their main purpose of illumination. Based on the broadcasted information, luminaires use collocated light sensors to estimate the optical channel gains and daylight contributions. This information is then used in a control algorithm to determine the dimming levels of luminaires under specified illumination constraints. We provide an analytical framework, simulations and an empirical evaluation of our approach in an office space. We compare our method with a state-of-art lighting control system that uses radio transceivers to communicate information, and thus, cannot monitor optical channels in real time. Our results show that while the radio-based system may under-illuminate and even oscillate around the desired illumination due to large reflectance changes in the environment, our method provides stable illumination close to desired levels.**

Index Terms— **Visible light communication, Light sensors, Lighting control systems, Daylight and occupancy adaptation.**

I. INTRODUCTION

Artificial lighting accounts for a major portion of the total electrical energy consumption in commercial buildings [7]. Lighting control systems designed to save energy have thus received considerable attention. Control of artificial lighting also needs to meet the illumination requirements of occupants in the office space. Emerging smart lighting control systems offer energy savings by incorporating knowledge about the environment. These new systems have the following main components: *monitoring* changes in environment conditions, *communicating* this information to a controller, *computing* the appropriate dimming levels at the controller, and *actuating* the luminaires with the computed dimming levels. With advances in sensing, communication and control technologies as well as the growing adoption of LEDs, it is possible to incorporate these technologies at the luminaire level and control individual luminaires at a granular level to realize deep energy savings.

A. Research challenges

State-of-art networked lighting control systems use LED luminaires that can be dimmed flexibly to provide variable light output, occupancy sensors to detect the presence of occupants, light sensors to monitor changes in illuminance conditions and a wireless radio such as ZigBee to provide connectivity among luminaires [1], [11], [12]. The sensors and radio may be collocated at every luminaire in the lighting system. Consider an indoor space such as an office where the goal is to provide high illuminance over workspaces that are occupied, and a lower illuminance otherwise, as long as there is some workspace occupied in the entire area. The desired illuminance values over the workspace zones are estimated by the ceiling-based light sensors indirectly. This estimation requires a calibration phase. In practice, a simple procedure is used where luminaires are turned on and the average workspace illuminance is measured with a light meter along with the corresponding light sensor values at the ceiling [12]. This mapping is used to establish a scaling factor between the light sensor and workspace illuminance values.

The main problem with this calibration approach is that it is performed in the absence of external light sources and considering only the reflectance of objects present during calibration. However, during operational use, the surface beneath the light sensors may change. For instance, the desk positions may be altered, or a shiny (or dark) surface may be placed at the desk. This causes the amount of illumination measured at the light sensors to be different, while the illumination at the workspace remains the same. That is, the initial calibration becomes invalid. Since radio-based lighting systems cannot monitor the optical channel, they are not able to suitably adapt to reflectance changes. This leads to outdated calibrations that can result in either under-illumination or over-illumination [4], [5].

B. Contributions and organization of our work

To counter the above described problem, we propose a lighting control system that estimates the optical channel gains using visible light communication (VLC). In the proposed VLC-networked lighting system, the communication among luminaires is piggybacked over the illumination itself. As such, our system does not need the extra wireless radio module used in radio-based lighting systems to provide connectivity among luminaires.

Overall, our work makes the following contributions:

- Sections IV and V: *A real time estimation of dynamic illuminance conditions.* Based on a simple Time Divi-

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sion Multiple Access (TDMA) mechanism, luminaires exchange information via VLC without collisions. The signals received at the light sensors are disaggregated to estimate (i) the illuminance contributions of each luminaire to every light sensor (optical channel gains) and (ii) the contributions of daylight at the light sensors.
- Section VI: *An algorithm that uses the estimated control variables to compute dimming levels.* The values estimated in the prior step are then used in an optimization algorithm to compute the dimming levels of the luminaires. The optimization enables luminaires to adapt artificial light output to sudden changes in reflectance that may occur in the environment.
- Section VII: *An evaluation of our approach via simulations and testbed experiments.* The performance of our approach is compared with a radio-based system under dynamic settings. Our evaluation, based on simulation data from a large open-office lighting model and experimental results with an 8-luminaire setup, shows that our system provides stable illumination close to the desired level. In comparison, the radio-based lighting system may under-illuminate or over-illuminate the workspace and even result in oscillations under specific environment conditions.

II. RELATED WORK ON LIGHTING CONTROLS

We divide related work to this paper into three main areas.

Networked lighting control and light sensor configuration. Lighting control systems that adapt the dimming of luminaires to occupancy conditions and daylight changes have been considered under different sensor configurations, communication and control topologies. A lighting control system wherein users carried light sensors was considered in [10], [15], [21], and linear programming and sequential quadratic programming approaches were proposed. A wireless networked lighting system with light sensors at work desks was considered in [18], [19]. Measurements of light sensors in a desk-placed or portable configuration can however be sensitive to occupant movements and shadowing of objects. Also, wireless communications for realizing sensor feedback to the controller may be lossy. These aspects may adversely impact illumination performance of the lighting system. It is thus common practice in lighting controls to have ceiling-mounted sensor configurations [1], [3], [14], [16], [12]. Distributed control methods using luminaire-level sensing information were considered in [1], [3], [16]. Stand-alone as well as networked controllers for distributed lighting systems were considered in [16], assuming ideal communication conditions. Networked lighting control systems were considered to ensure that control decisions are taken by accounting for sensor information across the entire system. Wireless radios, e.g. based on ZigBee, have typically been used in networked lighting systems to provide connectivity across luminaires. While connectivity across luminaires in radio-based networked lighting control systems improves system performance when compared to stand-alone lighting systems, such systems still cannot react to environment changes due to lack of ability to sense environmental optical channel gains.

Lighting control methods. In [10], [18], [19], [21], centralized lighting control approaches based on optimization methods were considered. These methods assumed perfect knowledge of the optical channel gains and daylight. These methods cannot deal with environment changes that affect the input feedback measurements to the controller [5]. Furthermore, small dimming steps and a large dead-band needs to be employed to make these methods robust to small environment changes [11]. Sub-optimum controllers such as variations of proportional-integral-derivative (PID) may be employed that do not use knowledge of the optical gains [16]. The controller set-point in these methods is determined in a calibration phase and any subsequent environment changes lead to user dissatisfaction due to under-illumination or energy wastage due to over-illumination [4].

VLC-based system. Visible light communications was used in [9] to detect the ID of a luminaire above an illuminance sensor placed at workspaces. The possibility of using VLC for providing luminaire connectivity, sensing and control adaptation was not explored. Applications of VLC have been used considered for sensing for lighting control applications in [20]. Specifically, in [20] the disaggregated estimation of daylight at light sensors placed at workspace was considered using a VLC system employing a carrier sense multiple access with collision avoidance (CSMA-CA) protocol.

Our contributions however advance these prior studies in the following aspects. We consider a smart lighting control system with ceiling-based light sensors and TDMA VLC for networking the luminaires. We estimate the optical channel gains between every luminaire-light sensor pair and the daylight contributions at each light sensor, and incorporate this information into the control algorithm in order to determine new dimming levels of the luminaires. Prior works either considered sub-optimal control schemes [16] or assumed complete knowledge of system parameters [21].

III. VLC-BASED SMART LIGHTING SYSTEM

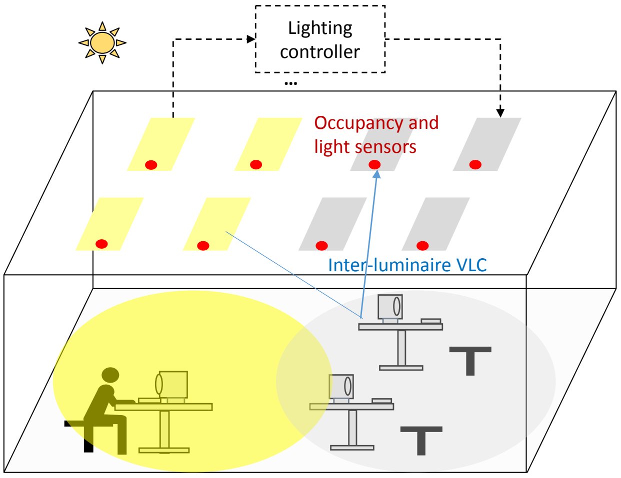


Fig. 1: VLC-based smart lighting system.

In this section we describe our scenario of interest and the basic architecture of our lighting control system. We consider an indoor office lighting system with N ceiling-mounted luminaires as depicted in Fig. 1. Each luminaire has a light sensor and an occupancy sensor. Both sensors have similar fields-of-views pointing towards the workspace plane directly below them. The luminaires may be dimmed individually and communicate among themselves using VLC. The desired level of illumination at the workplane may vary based on occupancy conditions. For instance, European norms recommend an average illuminance of 500 lux for occupied zones in office environments, and 300 lux for unoccupied zones [8].

Monitoring. The sensors at each luminaire constantly monitor two pieces of information: occupancy and illuminance. Local occupancy is measured with passive infrared (PIR) sensors typically used in lighting control systems. Light sensors monitor illuminance levels and have two set-points: one used when the workspace zone is occupied and another when it is unoccupied. A set-point is the amount of light required at the light sensor to satisfy the illumination requirements at the corresponding workspace zone. The set-points are obtained using a pre-operational calibration step. The occupancy information at each luminaire is later used by the controller to set the dimming levels required to achieve the appropriate set-point.

Communication. Luminaires communicate directly with each other by modulating their light intensity. We assume TDMA scheduling. In one time slot, a specific luminaire is modulated to transmit data, while other luminaires do not transmit but may be illuminating. The transmitted data is received at the other luminaires via their associated light sensors. The transmission slots are coordinated by a master luminaire that serves as a central controller. Our system assumes that all luminaires are within range of each other.

Controller. The controller seeks to provide the desired illumination at the workplane level with low power consumption. The TDMA scheduling enables the central controller to gather knowledge from each luminaire about occupancy states as well as light sensor measurements. Based on this information, the controller uses a centralized algorithm to compute new dimming levels for the luminaires so that the light sensor measurements are above the respective set-points. The controller then communicates back to all the luminaires the dimming levels to be adopted.

IV. VISIBLE LIGHT COMMUNICATION LINKS

The primary function of a LED luminaire is to generate light output to provide illumination. Without VLC, it is sufficient for a luminaire driver circuit to simply generate a direct-component (DC) electrical signal $x(t) = u$. The value u can be adapted for a dimmable luminaire, proportionally to the required dimming level.

To enable VLC transmission on top of the light output, an amplitude modulation scheme is considered. In amplitude modulation, data is embedded in the fluctuation of $x(t)$. This kind of data modulation is easy to implement in practice. An important issue to consider is that there should be no visible flicker or illumination level variation in the presence of VLC.

To achieve flicker-free VLC, it is important to have a DC-free signal so that the average light output does not change. To achieve DC-free properties, DC-free modulation codes can be employed. A simple and commonly used modulation code is the binary Manchester code [13], that we shall employ. Herein, bit 1 is converted into symbols $[+1, -1]$ and bit -1 is converted into symbols $[-1, +1]$.

In an environment with N VLC luminaires, the illuminance measured at the light sensor has three main components: the daylight contribution, the noise contribution and the aggregated illuminance contribution from all luminaires. Denoting T as the symbol period ($2T$ is the bit period) and L as the message length in bits, the sensed signal at light sensor m within the scope of one received packet $0 \leq t < 2TL$ is [17], [20]

$$\begin{aligned} y_m(t) &= d_m(t) + v_m(t) \\ &+ \sum_{n=1}^{N} (\alpha_{m,n} \beta_{m,n} (u_n + \Delta_n b_n(t))) * h_{m,n}(t), \end{aligned} \tag{1}$$

where $d_m(t)$ is the daylight contribution at light sensor m at time t, $v_m(t)$ is the modeled additive white Gaussian noise (AWGN) contribution with $v_m(t) \sim \mathcal{N}(0, \sigma_m^2)$, and the sum term is the aggregated contribution of modulated light output from all luminaires. In (1), $\alpha_{m,n}$ is the optical channel gain and $\beta_{m,n}$ the maximum illuminance contribution from luminaire n to light sensor m. Further, u_n is the dimming level and Δ_n is the modulation depth around the dimming level to transmit '0' and '1'. Note that $0 \leq u_n + \Delta_n b_n \leq 1$, i.e. the modulated dimming has to be within physical limits.

Denoting Δ_{min} as the minimum modulation depth for reliable communication, Δ_n could take values in the range $[\Delta_{min}, 1]$ and the dimming level u_n at luminaire n could take values in the range $[\frac{\Delta_{min}}{2}, 1 - \frac{\Delta_{min}}{2}]$. The final impact of modulation on the light intensity is determined by the message contribution $b_n(t)$, which is defined by

$$b_n(t) = \begin{cases} \sum\limits_{j=1}^{2L} M_j \Pi(\frac{t}{T} - j + \frac{1}{2}) & \text{if luminaire } n \text{ is transmitting} \\ 0 & \text{otherwise,} \end{cases}$$

where $M_j \in \{-\frac{1}{2}, \frac{1}{2}\}$ is the jth symbol of the bit sequence corresponding to the message modulated using Manchester coding, and $\Pi(t)$ is the rectangular function

$$\Pi(t) = \begin{cases} 1 & \text{if } |t| \leq \frac{1}{2} \\ 0 & \text{if } |t| > \frac{1}{2}. \end{cases}$$

Denoting the normalized impulse response of the channel between luminaire n and light sensor m to be $h_{m,n}(t)$, the overall illuminance contribution from luminaire n to light sensor m is given by $\alpha_{m,n}\beta_{m,n}(u_n + \Delta_n b_n(t)) * h_{m,n}(t)$.

For the following analysis of recovering the bit sequence from the modulated signal, the assumption is made that $h_{m,n}(t) = \delta(t)$, where $\delta(t)$ is the Dirac delta function. This assumption is only made to simplify the theoretical analysis. In this case, (1) may be rewritten as

$$y_m(t) = d_m(t) + v_m(t) + \sum_{n=1}^{N} \alpha_{m,n}\beta_{m,n}(u_n + \Delta_n b_n(t)). \tag{2}$$

At light sensor m, the signal $y_m(t)$ is sampled at a frequency f (being an integer multiple of $1/T$) and processed using a matched filter which computes for each sample $s = 0, 1, \ldots 2T(L-1)f$,

$$\rho_m[s] = \frac{1}{2Tf} \sum_{k=0}^{2Tf} y_m\left(\frac{s+k}{f}\right) g\left(\frac{k}{f}\right), \tag{3}$$

where $g(t)$ is the template signal defined by

$$g(t) = \begin{cases} 1 & \text{if } t \leq T \\ -1 & \text{if } t > T, \end{cases}$$

corresponding to the Manchester coding of a '1' bit.

In the noiseless case, assuming u_n and d_m are constant in the scope of a bit period, the time average sensed illuminance in (2) during a '1' Manchester symbol from luminaire p is

$$y^+ = d_m + \alpha_{m,p}\beta_{m,p}\Delta_p(\frac{1}{2}) + \sum_{n=1}^{N} \alpha_{m,n}\beta_{m,n}u_n \tag{4}$$

and the average sensed illuminance during a '0' Manchester symbol is

$$y^- = d_m + \alpha_{m,p}\beta_{m,p}\Delta_p(-\frac{1}{2}) + \sum_{n=1}^{N} \alpha_{m,n}\beta_{m,n}u_n. \tag{5}$$

Using (4) and (5), in the case of a transmission of a '1' bit at matching sample $s^\star$ from luminaire p, the sampled output of the matched filter is

$$\rho_m[s^\star] = \frac{1}{2}(y^+ - y^-) + \tilde{v}_m = \frac{1}{2}\alpha_{m,p}\beta_{m,p}\Delta_p + \tilde{v}_m, \tag{6}$$

where $\tilde{v}_m$ represents the reduced noise due to the matched filter: $\tilde{v}_m \sim \mathcal{N}(0, \frac{1}{2Tf}\sigma_m^2)$. Equivalently, a '0' bit would result in the value $-\rho_m[s^\star]$.

The matched filter output is downsampled at the bit rate $\frac{1}{2T}$ to obtain

$$\mu_m[i] = \rho_m[2Tf(i-1)] \quad \text{for } i = 1, 2, ..., L. \tag{7}$$

The values of $\mu_m[i]$ are compared with a zero-level threshold slicer. Thus, all positive values are interpreted as '1' bits and all negative values are interpreted as '0' bits. These values are later used to make an estimation of $\alpha_{m,p}$, and obtain an estimation of the daylight contributions at the luminaires as explained in the following section.

V. ESTIMATION OF CONTROL VARIABLES

A high-level flow of the considered estimation of optical gains and daylight values is presented in Fig. 2. The analytical models underlying the *Light sensor, Matched filter, Slicer* and *Interpreter* blocks depicted in this figure were covered in the earlier section. In this section, we will first describe the *Gain extraction* step which pertains to the estimation of the optical channel gains. We will then describe the estimation of daylight values done at the area controller, shown by the *Daylight estimation* step in Fig. 2.

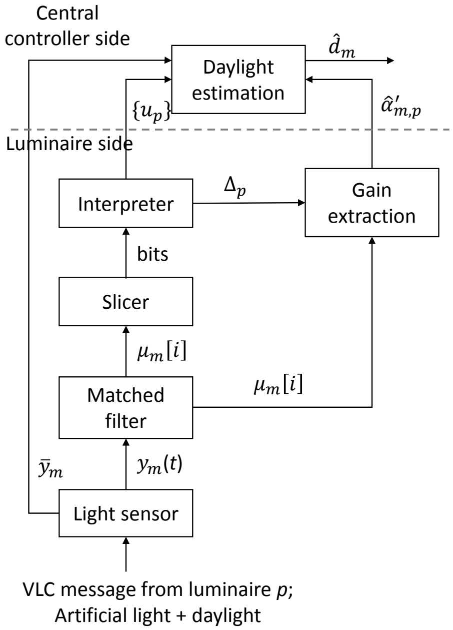


Fig. 2: Overview of estimation method of control variables.

Every message sent by the p-th luminaire contains the modulation depth Δ_p. Any light sensor m within VLC range may decode this information. Assuming that the dimming levels u_n and the daylight contributions d_m for all luminaires are constant within a message and that no bit errors occur in detection, an estimation $\hat{\alpha}'_{m,p}$ of the optical gain can be made from the i-th downsampled matched filter output in (7) by averaging over all the bits in the packet as

$$\hat{\alpha}'_{m,p} = \frac{2}{\beta_{m,p}\Delta_p L} \sum_{i=1}^{L} \text{bit}[i]\mu_m[i], \tag{8}$$

where

$$\text{bit}[i] = \begin{cases} 1 & \text{if bit } i \text{ is '1'} \\ -1 & \text{otherwise.} \end{cases}$$

Note that $\beta_{m,p}$ is a function of the maximum luminous power P_n and the sensor area A_m, which are fixed parameters, thus, $\beta_{m,p}$ is a known constant. Besides sending the modulation depth Δ_m in every message, luminaires also send the most recent estimations of $\hat{\alpha}'_{m,n}$ for all n and a measurement of the average illuminance $\bar{y}_m$ corresponding to the current control cycle. The average illuminance $\bar{y}_m$ is the sample average of $y_m(t)$ obtained in a time slot in the beginning of the control cycle, where no VLC message is transmitted. This implies that after each luminaire has transmitted its VLC message in a TDMA round, the area controller has knowledge of the constant parameter $\beta_{m,n}$ and the optical channel gains for all light sensors m and all luminaires n. Also given that the controller determines the dimming levels for all luminaires, it has all the dimming level values u_n associated with the current control cycle. Thus, an estimation of the daylight contribution $\hat{d}_m$ can be made by

$$\hat{d}_m = \bar{y}_m - \sum_{n=1}^{N} \hat{\alpha}'_{m,n}\beta_{m,n}u_n, \tag{9}$$

where

$$\bar{y}_m = \frac{1}{2TLf} \sum_{k=0}^{2TLf} y_m\left(\frac{k}{f}\right)$$

is the sample average of $y_m(t)$ at sampling frequency f.

With the estimated daylight contributions and the optical channel gains, the area controller has the necessary information to compute the dimming levels to be adopted in the next control cycle.

VI. LIGHTING CONTROL

The controller seeks to determine the dimming levels of the luminaires required to satisfy the desired illumination requirements with low power consumption. Denote $\boldsymbol{A}$ to be the $N \times N$ matrix with elements $[\boldsymbol{A}]_{m,n} = \alpha_{m,n}\beta_{m,n}$. Also, let $\boldsymbol{u} = [u_1, u_2, \ldots, u_N]^T$ be the vector containing dimming levels, $\boldsymbol{d} = [d_1, d_2, \ldots, d_N]^T$ be the vector containing daylight components, and $\boldsymbol{l} = [l_1, l_2, \ldots, l_N]^T$ be the vector containing the reference illuminance set-points at the light sensors.

In order to achieve the target levels of average workplane illumination of 300 lux for unoccupied zones and 500 lux for occupied zones (this choice of desired illumination values follow European office workspace recommended norms [8]), the system is calibrated prior to operation. All luminaires are turned on and a light meter is placed at a few points over the workspace plane. Then, luminaires are dimmed to two dimming levels, u^{300} and u^{500}, to achieve an average illumination of 300 lux and 500 lux respectively. For these two configurations, we measure the resulting light sensor values and store these values as the target set-points l_m. This calibration process is simple and thus widely used.

In the VLC system the reference set-points l_m are updated each control cycle as follows

$$l_m = \begin{cases} \sum_{n=1}^{N} \alpha_{m,n}\beta_{m,n} u^{500}, \\ \quad \text{if sensor } m \text{ is triggered by occupancy,} \\ \sum_{n=1}^{N} \alpha_{m,n}\beta_{m,n} u^{300}, \\ \quad \text{if sensor } m \text{ is not triggered under area occupancy.} \end{cases} \tag{10}$$

This set-point adaptation allows the system to handle environment changes affecting the workplane illumination.

The controller seeks to solve the following optimization problem to determine the dimming levels,

$$\begin{aligned} &\text{minimize} \quad ||\boldsymbol{A}\boldsymbol{u} + \boldsymbol{d} - \boldsymbol{l}||_2^2 \\ &\text{subject to} \begin{cases} \boldsymbol{A}\boldsymbol{u} + \boldsymbol{d} \geq \boldsymbol{l} \\ \frac{\Delta_{min}}{2} \leq u_n \leq (1 - \frac{\Delta_{min}}{2}), \end{cases} \end{aligned} \tag{11}$$

where the inequality constraints above should be interpreted as component-wise inequalities. The cost function $||\boldsymbol{A}\boldsymbol{u}+\boldsymbol{d}-\boldsymbol{l}||_2$ is the 2-norm of the difference between the illuminance value at the light sensors and the reference illuminance set-points. Minimizing this cost also would reduce power consumption. The first constraint in the optimization problem states that a minimum illumination must be achieved that is above the set-point. The last constraint related to the dimming levels u_n being within the permissible range $[\frac{\Delta_{min}}{2}, 1 - \frac{\Delta_{min}}{2}]$.

The above optimization problem is a convex quadratic minimization problem with linear inequality constraints and can be solved efficiently using algorithms like the interior point or barrier method [2].

VII. PERFORMANCE EVALUATION

In this section we evaluate the performance of our system under dynamic settings. We perform simulation and testbed experiments where changes are made to the environment at different control cycles. To quantify the benefits of our approach we consider two system setups.

- The first setup implements our proposed method. Luminaires exchange information via VLC links and estimate their optical channel gains $\hat{\alpha}'_{m,n}$ and daylight contributions $\hat{d}_m$ as described in Section V.
- The second setup employs dedicated radio communication hardware. In this case, a continuous estimation of the optical channel gains is not possible. Instead, an initial measurement of the optical gains is used.

For both of these setups we solve the optimization problem detailed in Section VI to obtain dimming levels $\boldsymbol{u}$ based on the set-point information provided by each system.

A. Simulation results

We first evaluate the performance of the two control systems via simulations using an indoor open-plan office lighting model. The model was created in DIALux [6], which is a software that may be used for professional light planning and for obtaining realistic 3D illumination visuals. The lighting model consists of $N = 80$ ceiling-mounted luminaires in an 8-by-10 grid. A total of 36 desks were considered at the workspace plane level where each desk defines a zone. Daylight entered from one side of the room, as depicted in Fig. 3. Mixed sky conditions were used from 8:00 a.m. onward to emulate daylight. Lighting data is extracted from DIALux and used in a control simulator implemented in Matlab. While the simulator assumes that the communication is perfect in both control systems, it is well suited to capture changes in optical channel gains $\boldsymbol{A}$ and daylight contributions $\boldsymbol{d}$.

Further environmental changes are introduced by changing the desks' reflectance in the underlying DIALux model. The reflectance parameter is a value between 0% and 100%. A surface with a reflectance value 60% means that it reflects 60% of the light that falls on it. In general, low values represent a surface with a dark color and high values represent one with a light color. Changing the reflectance parameter results in different values for $\boldsymbol{A}$ and $\boldsymbol{d}$.

In the simulations, the input of the light sensor is modeled using (2). To quantify clearly the effects of environmental changes, we consider a noiseless system, i.e. $v_m(t) = 0$. All zones are considered occupied, making the desired workplane illuminance 500 lux. The underlying model is changed twice during control operations, first after 12 control cycles, and again after 24 control cycles, resulting in three distinct environment situations for each simulation. The radio-based system uses values for $\boldsymbol{A}$ calibrated for the first part of the evaluation and maintains these values for its entire run, while the VLC system obtains a new estimation of $\boldsymbol{A}$ every control cycle. For both cases, daylight levels are estimated at each control operation using the corresponding matrix $\boldsymbol{A}$.

We present results for one of the zones and its associated luminaire: zone 20 and luminaire 48, as indicated in Fig. 3.

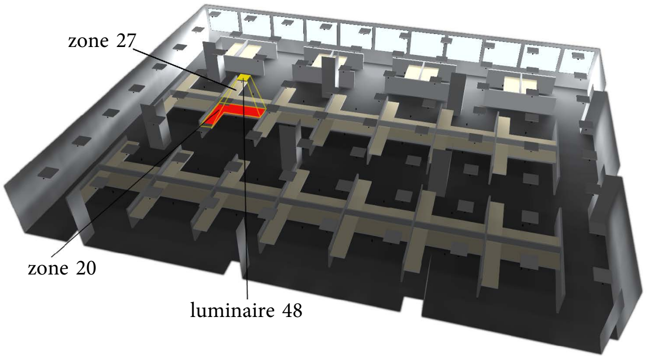


Fig. 3: Office lighting model used in simulation.

This zone is a representative sample point affected by daylight conditions at low intensity. Zones that are next to the windows get almost all of the necessary light from the sun, leading the controller to select the lowest possible dimming values (not much control needed); and zones that are the farthest from the window are not exposed to daylight effects.

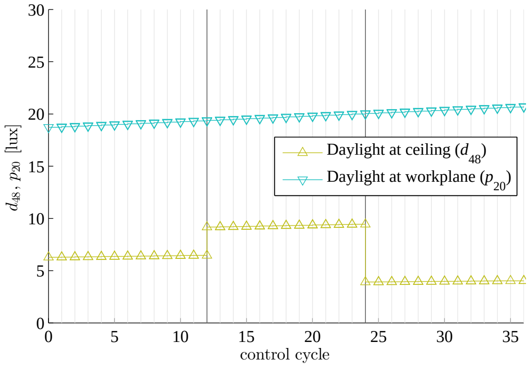
We consider the influence of daylight on three components of the lighting control system: (1) the input measurement, which is the average illuminance $\bar{y}_{48}$ at the ceiling-based light sensor, (2) the actuator, which is the dimming level u_{48}, and (3) the output, which is the average workplace illuminance $\bar{w}_{20}$. All these metrics are measured per control cycle. The external uncontrollable part of the system, the daylight, is shown as: (i) the ground truth daylight illumination at the workplane p_{20} and (ii) the daylight contribution at the ceiling d_{48}.

1) Local under-illumination and over-illumination: In the first simulation, we evaluate three different environments. Originally, all desks have a reflectance of 60% (reflectance of wooden desk in cream color). After 12 control cycles, only the desks corresponding to zones 20 and 27 have their reflectance changed to 90%. This change of reflectance may represent the effect of covering the desks with white paper. Lastly after 24 control cycles, the same desks have their reflectance changed to 30%. This may represent dark objects being placed on the desks, such as coats, bags or laptops.

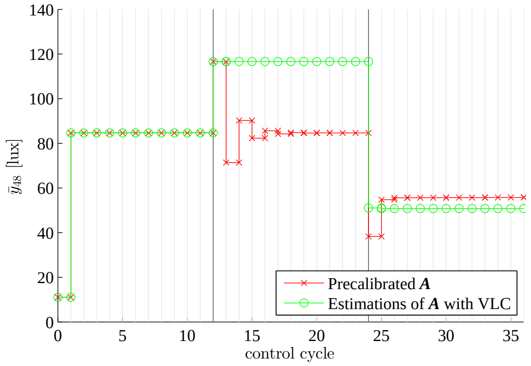
Figure 4 depicts the resulting control behavior. First let us look at the phenomena of under-illumination, which affects user comfort. In Fig. 4(a) we can observe that the ground truth daylight p_{20} increases gradually by a small amount through the experiment. Thus, in principle, the illuminance received at the workplane $\bar{w}_{20}$ should still remain within the values expected by the standard (500 lux) and only a small change would be expected on the dimming level u_{48}. However, when the reflectance value increases, more light reflects back at the light sensor. This phenomena increases the ground-truth daylight contribution at the ceiling $\hat{d}_{48}$ and the overall illuminance $\bar{y}_{48}$, by 3 and 35 lux in Fig. 4(a) and 4(b) respectively. The radio-based system can not update $\boldsymbol{A}$ and maintains the same set point, i.e. it tries to bring back the illuminance level at the ceiling to the original value of 82 lux, Fig. 4(b). This leads to a reduction of the dimming level, Fig. 4(c), and consequently to under-illumination of the workplane, around 100 lux less than the desired value, Fig. 4(d). Our VLC-based approach on the other hand estimates the changes in the channel gain $\boldsymbol{A}$ and adapts the set-point accordingly to 120 lux, Fig. 4(b). This change maintains the dimming level unmodified, Fig. 4(c), and provides the expected illumination at the workplane, Fig. 4(d). The phenomena of over-illumination, which occurs from the reduction in the reflectance of desks, follows a similar but reversed pattern. The overall illuminance at the light sensor decreases, prompting the controller in the radio-based system to increase the dimming level to reach the outdated set point. This leads to an over-illumination of 30 lux at the workplane, causing an unnecessary use of energy resources. Our VLC-method on the other hand remains stable across all three scenarios.

2) Oscillation under local reflectance changes: Lacking the ability to monitor optical channel gains and daylight contributions not only leads to the under- and over-illumination problems described above, but this limitation can also lead to uncomfortable oscillations in illuminance levels. These oscillations can already be observed in Fig. 4, but we perform a different simulation to illustrate this problem in a better manner. In this simulation we also consider three different phases, but the order in which we change the reflectance parameters is different. All desks start with a reflectance of 30%. After 12 control cycles, only the desks corresponding to zones 20 and 27 have their reflectance changed to 90%, and after 24 control cycles, these desks have their reflectance changed to 60%.

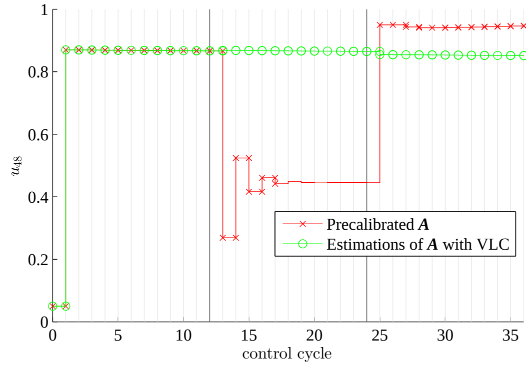
Now consider Fig. 5. When the reflectance changes from 30% to 90%, the perceived illumination for both systems jumps dramatically from 50 to 120 lux, Fig. 5(b). The radio based system reacts to this change by reducing the dimming level to the lowest possible value, leading to significant under-illumination at the work plane. When the reflectance changes to 60%, we observe oscillations. We will now explain the reason for this phenomena. The stored values for $\boldsymbol{A}$ in the radio networked lighting setup correspond to desk surface reflectance of 30% in this simulation. In this case, when the reflectance increases after 12 control cycles, there is more light reflected back at the light sensor, Fig. 5(b). This then translates to an overestimation of daylight contribution, and a reduction in computed dimming level, Fig. 5(c). The reduction in dimming level in turn reduces the illuminance value at the light sensor. This cycle continues, leading to oscillations in dimming level values and in illumination values at the workspace zone, Fig. 5(d). More generally, the oscillations arise due to a mismatch between the expected and actual illuminance levels at light sensors. This mismatch results in either an over-estimation or an under-estimation of daylight levels. As a result, the controller determines correspondingly either lower or higher dimming levels at the next control cycle, impacting the light sensor illumination values. This behavior subsequently leads to oscillations in illumination and dimming levels. In comparison, the setup implementing VLC can adapt suitably to these changes and the workplane illumination value is held constant.



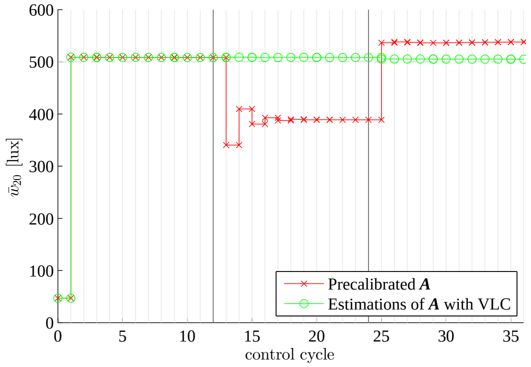
(a) Daylight levels.



(b) Illuminance value at the light sensor.

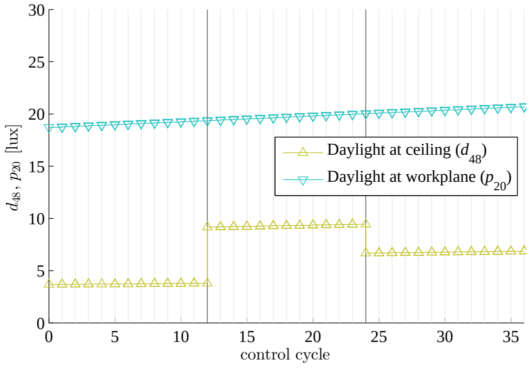


(c) Dimming levels.

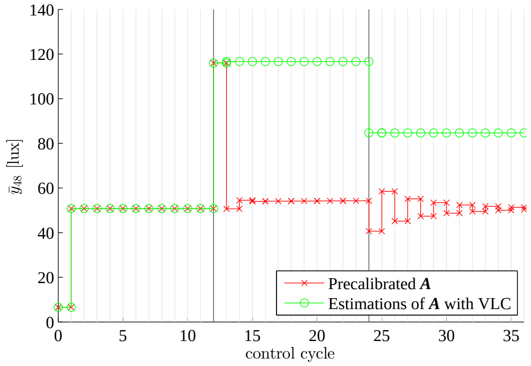


(d) Illuminance value at the zone.

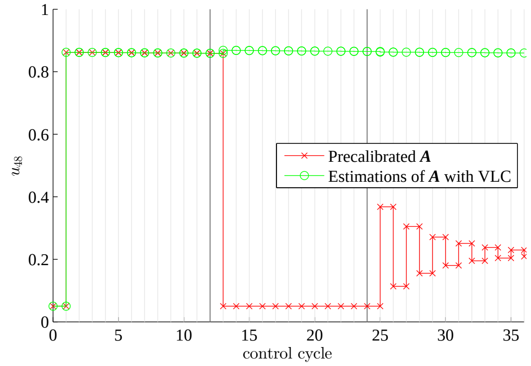
Fig. 4: Simulated control behavior through localized changes in desk reflectance (60%, 90%, then 30%) under changing daylight conditions, showing that illumination close to the target is achieved by the proposed VLC system.



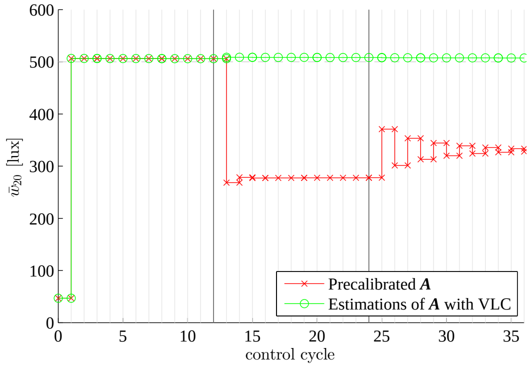
(a) Daylight levels.



(b) Illuminance value at the light sensor.



(c) Dimming levels.



(d) Illuminance value at the zone.

Fig. 5: Simulated control behavior through localized changes in desk reflectance (30%, 90%, then 60%) under changing daylight conditions, showing stable behavior in the proposed VLC system.

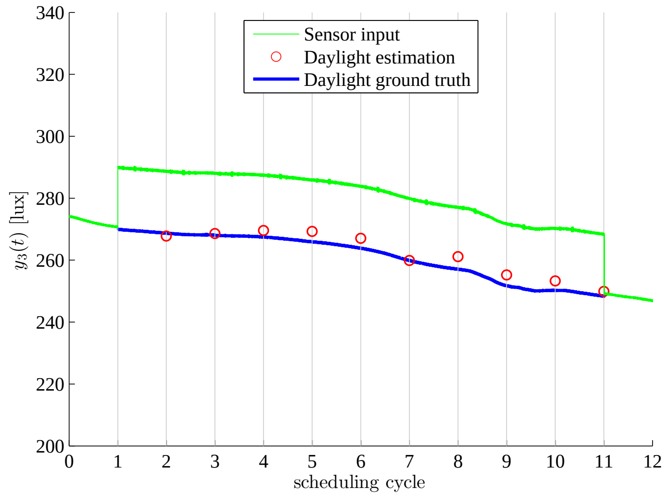


Fig. 6: Experimental daylight extraction at luminaire 3 over 10 scheduling cycles

B. *Experimental results*

The proposed VLC-based system was implemented on an experimental testbed with $N = 8$ LED luminaires mounted at the ceiling as a 2-by-4 grid in an office room. The distance between the centers of any two neighboring luminaires on the grid is 2.1 meters. The north side of the room has windows along its length with blinds.

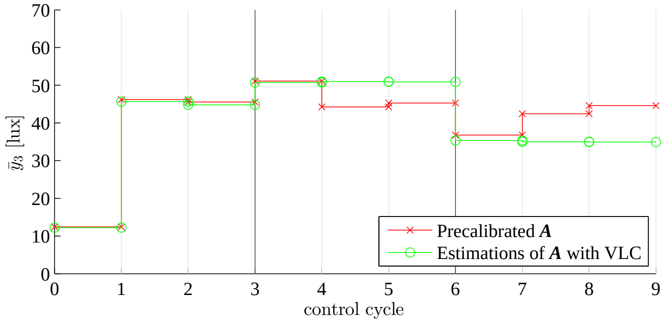
For simplicity, we implement the control algorithm at a dedicated central computer instead of a master luminaire. Data from the sensors at the luminaires is read out with a data acquisition (DAQ) device and made availale at the central computer. The computed dimming levels are then sent to the luminaires. For any current dimming level, the largest modulation depth is used so that the average luminous power output is not compromised or exceeds the limitations of the light source.

1) Daylight estimation: We first evaluate daylight estimation using the testbed. By doing so, the underlying optical channel gain extractions on which the daylight estimation depends are also tested. For this result, all luminaires communicate with each other via a TDMA scheduling. Each luminaire communicates once in a cycle in the order of their identifiers.

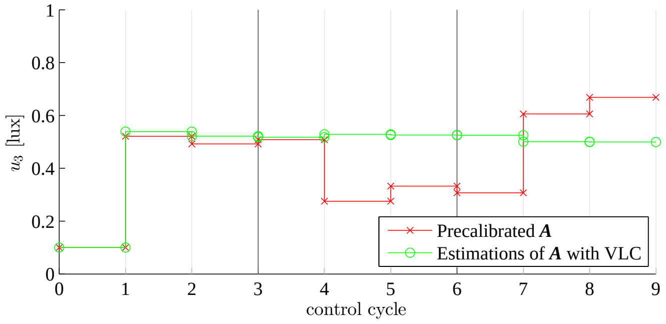
The results are shown in Fig. 6. For the duration of the first scheduling cycle, the sensed illuminance at luminaire 3 equals the ground truth of daylight. All luminaires in the room are then turned on to a dimming level of 0.5 (half the maximum power output) for ten cycles of scheduling. For each cycle, after all optical channel gains are extracted from the transmitted messages, daylight estimation is performed. The occurrence of these messages can be seen in the received signal of each cycle. After the ten cycles, the luminaires are switched off again. From the figure, we can observe that the daylight estimation is close to the ground truth.

2) Local under-illumination and over-illumination: To benchmark the performance of our approach, a radio-based lighting system setup was also implemented on the experimental testbed. In order to preserve similar external light contributions for both measurements, the blinds are closed. Reflectance changes in the office were made over nine control cycles. Over the first three control cycles, a plain brown cardboard is placed on the desk. Subsequently, a white paper of similar size is placed on the desk. Lastly, after 6 control cycles, a black fabric is placed.

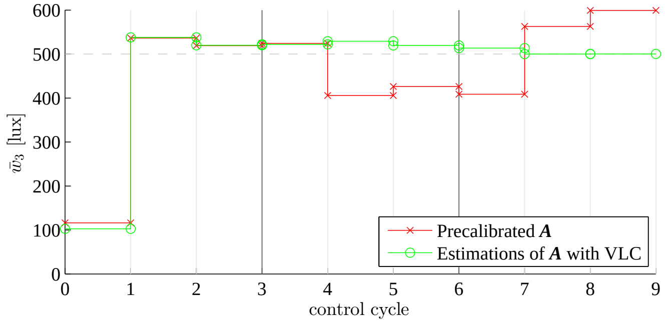
We show the illumination behavior corresponding to luminaire 3 and the workplane area, denoted as zone 3, below it in Fig. 7. In the control cycles following either environment change, the difference in ceiling illuminance caused by the different reflective materials is evident, Fig. 7(a). The proposed VLC setup is shown to be able to adapt to these changes in practice, providing the desired constant workplane illumination. The wireless lighting setup has varying workplane illumination, where under-illumination is evident after the first environment change, and over-illumination is present after the second change, Fig. 7(c).



(a) Illuminance value at the light sensor.



(b) Dimming levels.



(c) Illuminance value at the zone.

Fig. 7: Control performance in experimental testbed through changes in objects placed on desk (plain cardboard, white paper, then black fabric), showing under-illumination is prevented in the proposed VLC system.

VIII. CONCLUSIONS AND DISCUSSION

We proposed a networked lighting control system based on VLC that adapts to daylight and occupancy changes by estimating optical channel gains and daylight contributions using VLC transmissions. The estimated values were used by a controller to optimize the dimming levels of the luminaires. Using simulations and an experimental testbed, we show that the proposed VLC system achieves more stable illuminance (closer to desired levels in the presence of environmental reflectance changes) compared to a radio-based networked lighting system under an optimization based approach. More generally, the proposed VLC-networked lighting system can inherently track optical channel gains and achieve light levels closer to the desired level at the light sensors, in comparison to lighting systems that do not perform continuous calibration. To deal with potential oscillations in dimming due to factors like reflectance changes, state-of-art lighting systems use carefully designed control steps and a large deadband [11].

Our work contributes towards the goal of designing efficient lighting systems but there are still important issues to tackle. We assumed single-hop VLC in the paper. For large office spaces, the limited range of VLC would mean multiple hops are needed. The impact of multiple hops in VLC on lighting control performance needs to be considered. We did not consider the effect of clock drifts at luminaires on TDMA scheduling of the VLC transmissions. In practice, a protocol for time synchronization would need to be considered. An analytical framework was employed to evaluate the impact of reflectance changes on the lighting control system. These results need to be further evaluated by user field tests to study the impact of environment changes on rendered illumination and user perception.

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