Università degli Studi di Padova

Facoltà di Ingegneria.

Corso di Laurea in Ingegneria dell'Automazione.

Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation

Laureando

Peruffo Andrea

Relatore

Schenato Luca

Supervisor

Pandharipande Ashish

Anno Accademico 2014/2015

A tutti quelli che ho incontrato.

Forse un mattino andando in un'aria di vetro,
arida,rivolgendomi vedró compirsi il miracolo:
il nulla alle mie spalle, il vuoto dietro
di me, con un terrore di ubriaco.

Poi come s'uno schermo, s'accamperanno di gitto
alberi case colli per l'inganno consueto.
Ma sarà troppo tardi; ed io me n'andró zitto
tra gli uomini che non si voltano, col mio segreto.

Eugenio Montale, Ossi di Seppia

Contents

1 Introduction **7**

1.1 Lighting systems in today's buildings 8

1.1.1 Commercial Products 9

1.1.2 Research 10

1.2 Previous works on Lighting Control Systems 11

1.3 Networked Control System 12

1.4 Contribution 14

1.5 Thesis Outline 15

2 System model **17**

2.1 Analytical model 17

2.2 Communication network 22

3 Digital PID **25**

3.1 The standard PID control 25

3.2 Digital Controllers 26

3.2.1 Digital PID 29

3.3 Generalized Controller 29

3.4 Wireless Reference Controller 30

3.5 PI parameters: Dead Beat Case 31

3.6 PI parameters: *PI with offset* Case 32

3.7 Stability of the Controllers 33

3.8 Sending Schedule of the Reference Controller 34

3.9 Imperfect Communication 34

3.9.1 Input Communication Lost 36

3.9.2 Output Communication Lost 36

3.9.3 Input and Output packet loss 37

4 Proposed wireless control design **41**

5 Simulation results **45**
5.1 Effects of Packet Loss 46
5.2 Starting from Zero state 46
5.3 Overshoot with occupancy change 48
5.4 Network load 49

6 Conclusions **53**

A TrueTime toolbox **55**
A.1 Wired Network Parameters 56
A.2 Wireless Network parameters 56

Chapter 1

Introduction

This thesis was written based on an internship project developed from March till September 2014 in Philips Research & Development, High Tech Campus, Eindhoven, The Netherlands, located in the department formerly called *Lighting Control Systems*, now named *Smart Professional Spaces*, under the supervision of Senior Scientist Ashish Pandharipande and Ph.D. David Caicedo. The project's results are depicted and explained briefly in a paper that has been submitted and accepted for the publication to *Energy and Buildings* [32], an international journal devoted to investigations of energy use and efficiency in buildings [30].

Royal Philips is a diversified health and well-being company, focused on improving people's lives through meaningful innovation in the areas of Healthcare, Consumer Lifestyle and Lighting. Headquartered in the Netherlands, Philips posted 2013 sales of EUR 23.3 billion and employs approximately 115,000 employees with sales and services in more than 100 countries.

The company is a leader in cardiac care, acute care and home healthcare, energy efficient lighting solutions and new lighting applications, as well as male shaving, grooming and oral healthcare [29].

Philips Lighting is a global market leader with recognized expertise in the development, manufacturing and application of innovative lighting solutions. Philips has pioneered many of the key breakthroughs in lighting over the past 123 years, laying the basis for the current strength and ensuring that the company is well-placed to be a leader in the digital transformation. The aim is to further strengthen the position in the digital market through added investment in LED leadership while at the same time capitalizing its broad portfolio, distribution and brand in conventional lighting.

Philips addresses people's lighting needs across a full range of market segments. Indoors, they offer lighting solutions for homes, shops, offices, schools, hotels, factories and hospitals. Outdoors, they offer solutions for roads (street lighting and car lights) and for public spaces, residential areas and sports arenas. In addition, it addresses the desire for light-inspired experiences through architectural projects. Finally, it offers specific applications of lighting in specialized areas, such as horticulture and water purification.

Philips Lighting spans the entire lighting value chain – from light sources, luminaires, electronics and controls to full applications and solutions – through the following businesses:

- Light Sources & Electronics;
- Consumer Luminaires;
- Professional Lighting Solutions;
- Automotive Lighting;
- Lumileds.

The Department of Philips *Research & Development* is located in High Tech Campus, Eindhoven, The Netherlands. High Tech Campus Eindhoven is the smartest km^2 in The Netherlands with more than 125 companies and institutes, and some 10,000 researchers, developers and entrepreneurs working on developing future technologies and products. The Campus helps accelerate innovation by offering easy access to high tech facilities and international networks. Campus companies (a.o. Philips, NXP, IBM, Intel) strategically decide what knowledge, skills and R&D facilities they share in order to achieve faster, better and more customer-oriented innovation in the application fields Health, Energy and Smart Environments. Located at the heart of Brainport Campus companies are responsible for nearly 40% of all Dutch patent applications [31].

1.1 Lighting systems in today's buildings

According to several researches [1], [2], buildings consume a great part of the total available energy, one-third of those is utilized for lighting needs: one of the next years' goals is to achieve important energy savings. Even though many systems in real world are becoming smart, artificial intelligence has not been applied to lighting systems, which are essential in everyday life.

Lighting control integrates in this direction. Control of artificial lighting to save energy has thus received significant attention, in particular by adapting to daylight and occupancy [2], [3], [4], [5]. It has been demonstrated [3] ,

[7] that it is possible to achieve 40% or 50% of energy savings with an intelligent lighting control system with respect to a classical system with on/off switches. The aim of this research field is to reduce energy consumption while still keeping high level of users' satisfaction. The pursuit of both these goals at the same time is not possible: the problem must be handled as a tradeoff, where an intelligent lighting control system must manage energy savings and occupants' preferences.

In addiction, to implement these systems in current buildings, a huge problem will be encountered: the need of re-cabling, because current wiring systems do not allow individual lamp control.

1.1.1 Commercial Products

Philips became worldwide famous thanks to its lighting bulbs. Nowadays, the products is much wider and evolved in many different fields, but still the lighting is a great interest. Tradition and innovation mix in the LED lights among Philips' products: they provide a soft white light, energy savings, a higher quality of light and they are dimmable.

Philips has a wide range of dimmable LED products, making it easy to adjust the light intensity. LED dimming technologies are the ideal replacement for incandescent and halogen solutions, in terms of performance, compatibility and light output. Philips LED bulbs are able to create the same deep, warm tones as a dimmed incandescent. Lighting is an unobtrusive, yet very practical way to enhance the atmosphere in your home.

LEDs are able to provide a wide range of white colors, each one linked to a color temperature. Color temperature is indicated in Kelvin (K). A low color temperature creates a warm, cozy light effect, while a high color temperature creates a cool, more energizing effect. The majority of Philips LED lighting products provides from 2200 Kelvin, which is soft white light, to 6500 Kelvin, which is a cool white light.

In order to understand the energy use of a light source, lumens and wattage are important concepts. In simple words, a LED light uses far less energy (watts) to produce the same light output (lumens). An example: a LED bulb uses only 10.5 watts to produce a light output of 800 lumens, while a traditional light bulb uses 60 watts (or 6 times more energy) to product the same lumen output.

LED lighting is very energy efficient compared to traditional lights, because it uses less energy to produce the same light output. Plus, the lifetime of a LED bulb or fixture is up to 20 times longer with respect to a traditional bulb. There are 2 things that make LED lighting the most energy efficient lighting; very low energy usage and a very long lifetime. LED lighting means sustainable lighting in many ways. First, LED lights save up to 85% energy compared to a traditional bulb with the same light output. LED light sources last longer, avoiding the hassle of frequent changing of light bulbs. This significantly reduces waste but also saves money in the long term. The lifetime of a LED light source can be up to 20 times longer than that of traditional light sources. A traditional incandescent light bulb has a lifetime of about 1,000 hours, while Philips LED lighting has a lifetime up to 25,000 hours, which is more than 22 years.

1.1.2 Research

To overcome the issue of re-cabling, wireless technology is a promising approach, easier to deploy in comparison to a wired system, allowing integration of a lighting control system and is attractive for retrofitting new lighting controls with minimal disruption. However, wireless networks suffer from unreliable communications leading to high packet-loss rates and large random delays. We consider the effect of wireless channel impairments on the performance of the considered lighting control system. In particular, our goal is to design a wireless lighting control system, in a multi-hop environment, that results in an illumination performance similar to the wired counterpart. This then ensures lighting experience to a user agnostic of the communication interface.

The advent of light emitting diode (LED) based luminaires has made possible to easily and flexibly control artificial lighting. Thanks to key-features as energy efficient, durable and environmental-friendly, LEDs are the prevailing trend in lighting control systems. Thus it is possible to adapt LED based luminaires to daylight and occupancy at a fairly granular spatio-temporal level. In particular, systems with sensor-equipped luminaires offer high sensing granularity and have been recently considered [3], [6], [7], [8].

An emerging communication protocol [22] is ZigBee, that provides low-power two-way wireless communications. Other key features are real-time response (rapid response to an input) and coordination.

In the lighting system evaluated in this work, we consider a wireless mesh networked lighting system with multiple sensor-equipped luminaires and a central controller. The topology of a wireless lighting control system in an open office is illustrated in Fig. 2.4. In the system, each luminaire has a co-located light sensor and occupancy sensor. The light sensor determines the average illuminance from daylight and artificial light incident within its field-of-view. The occupancy sensor results in a binary value - one, under occupant presence within the field-of-view and zero otherwise. The sensor results are transmitted to the central controller, and fed to a respective PI control law. The output of the control law is a dimming level for the corresponding luminaire and this value is transmitted to the luminaire.

The dimming levels of each luminaire are to be determined by corresponding PI control laws such that the total artificial light output contribution, in combination with daylight contribution, results in net illuminance above desired levels at the workspace plane. Let W_o and W_u denote the respective target average illuminance values in an occupied and unoccupied zone at the workspace; a zone being a logical partitioning, for instance that defines a region around work desks, of the physical horizontal workspace plane. As an example, European norms for office lighting recommend minimum average illuminance values of $W_o = 500$ lux and $W_u = 300$ lux [9]. The target average illuminance values at the workspace plane are specified in terms of sensor set-points at corresponding light sensors. These set-points are determined in a night-time calibration step. In the absence of daylight, the luminaires are dimmed to a level so that the desired illuminance, say W_o, is achieved and the corresponding light sensor measurements $\{r_{o,m}\}$ are stored as the associated set-points. Let $r_{o,m}$ and $r_{u,m}$ be respectively the set-points of the m-th light sensor corresponding to occupancy and non-occupancy. Then the control objective is to at least achieve this set-point, while limiting overshoot and oscillations in dimming (i.e. system should achieve steady-state), and achieving power savings. The controller considered is a so called *PI with offset*, which is a PI controller that seeks to achieve a positively biased set-point. This choice was made thanks to the observations found in [7] regarding the daylight effect in a lighting control system. Overshoot is the peak value compared to the final steady-state value.

The wireless system had been implemented with TrueTime, a Matlab / Simulink - based simulator for real-time control systems. TrueTime facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics [21]. The aim was to simulate the system in a wireless communication network and compare the performances with an ideal wired network, analyse potential problems that arise and propose a solution to eliminate them.

1.2 Previous works on Lighting Control Systems

A centralized lighting control system was considered in [10] for occupancy adaptive lighting resulting in a linear optimization problem. This system was extended in [4] to take into account spatio-temporal daylight variations.

Knowledge of light distribution at the workspace plane was assumed in both formulations. Distributed optimization algorithms for lighting control with daylight and occupancy adaptation were proposed in [3], [6], [11], under networking and information exchange constraints. Under different system settings, and wherein users carried light sensors, linear programming and sequential quadratic programming approaches were proposed for centralized lighting control [12], [13]. A wireless networked lighting system with light sensors at work desks was considered in [14], [15]. In [16], a distributed lighting system was proposed with light sensors at desks, and equipped with a controller, which control luminaires in a neighborhood using infra-red communication. Measurements of light sensors in a desk-placed or portable configuration can however be sensitive to environmental changes such as occupant movements and shadowing of objects, thus affecting illumination performance of the lighting system. It is thus common practice to use ceiling-mounted sensor configurations [3], [7], [17], [18]. Stand-alone as well as networked controllers for distributed lighting systems were considered in [7], under the assumption of perfect communication channel. Herein, a PI control law with offset was considered. The positive offset in the control law was introduced to deal with the problem of under-illumination that occurs due to different contributions of daylight over the workspace and light sensors over time. This observation was made early in [18], [19], for a singe light sensor-driven lighting system.

1.3 Networked Control System

A great challenge for the future is to find a performing method to extend the current control systems into networked control systems. Networked control systems (NCSs) are distributed control systems in which the communication occurs through a band-limited communication network, shared among sensors, controllers and actuators [26]. Many advantages are brought by this approach, such as flexible architectures and reduced cost for installation and maintenance. On the other hand, many issues are introduced: a NCS project must deal with band-limited channel, sampling, random delays and packet loss.

Murray *et al.* [27] identify *control over networks* as one of the *key directions for controls.*

NCSs' design clearly lie between control and communication theories. Usually, control theory deals with the interconnection of dynamical systems linked through ideal channels, where perfect communication is considered; communication theory otherwise studies the transmission of information over imperfect channels. The combination of both these aspects is needed to model a NCS; in order to fulfil this aim it is useful to highlight some key issues that distinct NCS from traditional control systems.

1. *Band-limited channels*: any communication link can carry a limited amount of information per unit of time. Recalling Shannon's work on the maximum bit rate that a network can carry in order to have a reliable communication, many efforts have been spent to find the minimum bit rate needed in order to stabilize a dynamical system over a band-limited network. It is easy to imagine that the performance and the stability of the closed loop system is strongly influenced by the performance and reliability of the communication network.

2. *Sampling and Delay*: as well known from the communication theory, in order to be sent over a digital network, continuous data must be sampled and quantized, often coded or even encrypted. All these procedures lead to a difficultly predictable delay which accounts of network access delays and transmission delays, depending on the network traffic and quality; usually in control theory the delay accounted is only limited to a period sampling process. Many researches have been done in order to characterize an upper bound on the sampling interval for which the stability can be guaranteed.

3. *Packet Loss*: another great difference between NCSs and traditional control systems lies on the fact that packets can be dropped during the communication over the network. Many reasons can be given to justify this situation: network unreliability can result from, e.g., congestion, buffer overflows, transmission errors. While it is true that a retransmission mechanism is implementable over the communication network, it is also true that generally old data is not useful.

4. *System Architecture*: a typical architecture of a NCS is shown in Figure 1.1: it captures the main features of a NCS, as random delays, packet loss and band-limited channels. The plant represents the process to be controlled, sensors sample the physical quantity of interest. A sending module takes care of sending the coded value through the network, which is received by the controller and decoded. The controller then computes the control signal according to a control law and sends through the network the control signal. The message is received by the actuator thanks to a receiving module, then acts according to the control signal. Commonly, a single feedback loop is considered, as in figure.

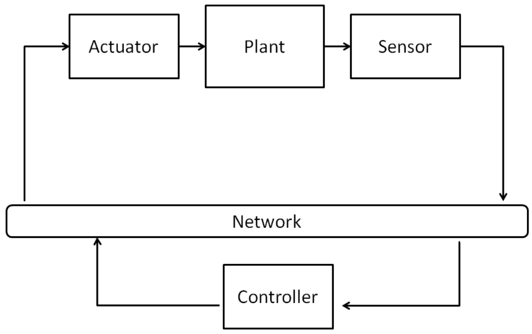


Figure 1.1: A single loop networked control system.

1.4 Contribution

As said in the previous section, the connection between control theory and communication theory is not so straightforward.

The contribution of this thesis is to analyse which issues arise from the transition from a wired to a wireless network, in the specific environment of a lighting system. PID controls usually do not consider packet losses but this is, in real applications, a situation which always occurs. A PID control that does not take into account these issues was demonstrated in this thesis not to work properly and not to achieve the desired requirements. So, the main object of this work was to find a new kind of controller able to face high packet loss rate and deal with large delays. To fulfil this achievement, an estimation of the sensor measurement and a failure detection method was implemented.

In particular, three issues were identified: sensor to controller communication failure, controller to actuator communication failure, network overload. To solve these problems, the proposed controller integrates three features:

- an *estimation centralized algorithm*, to obtain an estimation of the lost measurement value;

- a dimming levels' *reception detection*: the controller performs an indirect check if the dimming level sent was effectively received by the actuator;

- a *new sending mechanism*, that permits to send a dimming level only if the difference from the previous one is greater than a threshold.

The last feature of the proposed algorithm allowed to reduce the network traffic, leading to a minor messages loss; this helped the control to be more effective. The estimation mechanism permitted to avoid delays due to a defective communication and to compute the necessary dimming level even in a busy network. The estimation of the received message by the actuator permitted to avoid a wrong dimming level calculus.

Thanks to these characteristics, the proposed controller outperformed the reference one, both in terms of settling time needed to obtain a steady configuration of all the luminaires and packet loss.

1.5 Thesis Outline

The remainder of the content in the thesis is organized as follows. In Section 2, we present an analytical model of the lighting control system. The performance of the stand-alone PI controller under wired and wireless communications, assuming a ZigBee wireless mesh network, is studied in Section 3.4. We use the PI control law with offset [7] as a reference controller due to its simplicity in implementation. An adversely longer settling time is observed under a ZigBee wireless lighting system in comparison to a wired system. We then consider control and networking strategies in Section 4 to address this problem. Specifically, we consider interpolation at the controller and a modified control law, along with retransmissions with message acknowledgement. In Section 5, the performance of the proposed design is compared with the reference controller, with the evaluation done using an example open-plan office lighting model implemented in DIALux [20], and control simulation done in Simulink/TrueTime [21]. Conclusions are drawn in Section 6.

Chapter 2

System model

The system studied in this thesis is a lighting system, located in a office-type room. The system to be controlled is composed by several luminaires placed at the ceiling, equipped with sensors, while the control aim is to reach a desired illuminance at the workspace plan: from this archicteture derives the first issue of the controller, i.e. there is no direct measurement of the control objective since it is located in another plan with respect to the sensors. The luminaires considered are composed by Light Emitting Diodes (LEDs) which permit to model the lighting system as a linear model.

As seen in [3] and shown in Figure 2.1, if the illuminance is taken as the output and the dimming level as the input, the function is well approximated by a linear model.

LEDs luminaires allow to set the illuminance at a desired level, differently from the traditional luminaires which can be switched on or off. This level, considered from 0 to 1, is called *dimming level*.

In the following sections, it is considered that the sensors sample the illuminance at the ceiling, while it seems natural now to consider the output of the controller, i.e. the input of the plant, as the dimming level of the luminaire. A system composed by M luminaires and N workstations is studied and modelled in the following section.

2.1 Analytical model

Consider a lighting system with M ceiling-based luminaires. Each luminaire has a co-located light sensor and occupancy sensor, and that can communicate with a central controller using a wireless radio. Let the luminaire be dimmed using pulse width modulation (PWM). Let the n-th luminaire be

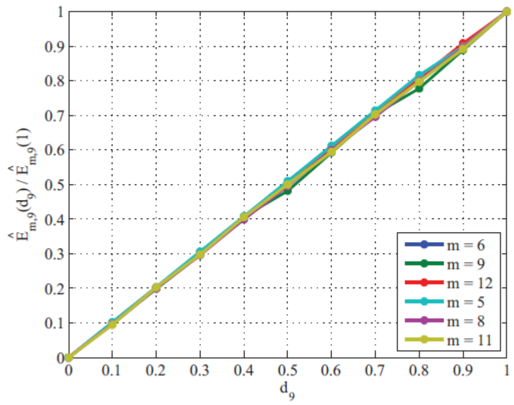


Figure 2.1: Linearity of LEDs with respect to the dimming level (image taken from [3]).

dimmed linearly with duty cycle $u_n(t)$ at time instant t, where

$$0 \leq u_n(t) \leq 1.$$

The illumination value at the m-th sensor, in lux, at (continuous) time t can be expressed as

$$y_m(t) = \sum_{n=1}^{M} G_{m,n} u_n(t) + d_m(t), \quad m = 1, \ldots, M \tag{2.1}$$

where $G_{m,n}$ is the illuminance value at the m-th light sensor when the n-th luminaire is dimmed at its maximum, while all the other luminaires are off and there is no other source of lighht; $d_m(t)$ is the illumination contribution at the m-th light sensor in lux given by the daylight at time t.

Let the workspace plane be divided into N logical zones (where typically N $<$ M), i.e. workstations. The illuminance value at zone j may be written as

$$w_j(t) = \sum_{n=1}^{N} H_{j,n} u_n(t) + p_j(t), \quad j = 1, \ldots, N \tag{2.2}$$

where $H_{j,n}$ is the illuminance value at the j-th zone in lux when the n-th luminaire is dimmed at its maximum, all the others luminaires are off and no other light source is considered; $p_j(t)$ is the illuminance contribution in lux at the j-th zone due to the daylight at time t.

In matrix form, the model can be written as

$$\begin{cases} \mathbf{y}(t) = G\mathbf{u}(t) + \mathbf{d}(t) \\ \mathbf{w}(t) = H\mathbf{u}(t) + \mathbf{p}(t) \end{cases} \tag{2.3}$$

where

$$\mathbf{y}(t) = [y_1(t), \ldots, y_M(t)]^T,$$

$$\mathbf{u}(t) = [u_1(t), \ldots, u_M(t)]^T,$$

$$G = \begin{bmatrix} G_{1,1} & G_{1,2} & \ldots & G_{1,M} \\ G_{2,1} & G_{2,2} & \ldots & G_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ G_{M,1} & G_{M,2} & \ldots & G_{M,M} \end{bmatrix},$$

$$\mathbf{d}(t) = [d_1(t), \ldots, d_M(t)]^T,$$

$$\mathbf{w}(t) = [w_1(t), \ldots, w_N(t)]^T,$$

$$H = \begin{bmatrix} H_{1,1} & H_{1,2} & \ldots & H_{1,M} \\ H_{2,1} & H_{2,2} & \ldots & H_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ H_{N,1} & H_{N,2} & \ldots & H_{N,M} \end{bmatrix},$$

$$\mathbf{p}(t) = [p_1(t), \ldots, p_N(t)]^T.$$

Denote G, as above, to be the $M \times M$ matrix with (m, n)-th element $G_{m,n}$. The elements $G_{m,n}$ may be obtained in a night-time calibration step and are known.

Each light sensor samples with a sampling period T_s. Given that sensing is distributed, the sampling is not synchronous across sensors; in Figure 2.2 it is shown the structure of the described situation.

The illuminance value at light sensor m can be written as in [7]

$$\begin{aligned} \hat{y}_m(kT_s + \tau_m) = & G_{m,m} u_m((k-1)T_s + \tau_m + \tau_c) + d_m(kT_s + \tau_m) + \\ & + \sum_{n \neq m} G_{m,n} u_n(kT_s + \tau_m) \end{aligned} \tag{2.4}$$

where τ_m is a constant random delay, $-\frac{T_s}{2} \leq \tau_m \leq \frac{T_s}{2}$, for each instance of the controller, τ_c is the delay between sampling and updating a zero-order-hold (ZOH) filter and $k \in \mathbb{N}$. The constant delay between controllers reflects the asynchronous nature of the system. The last term represents the coupling between the m-th sensor and the other luminaires/sensors.

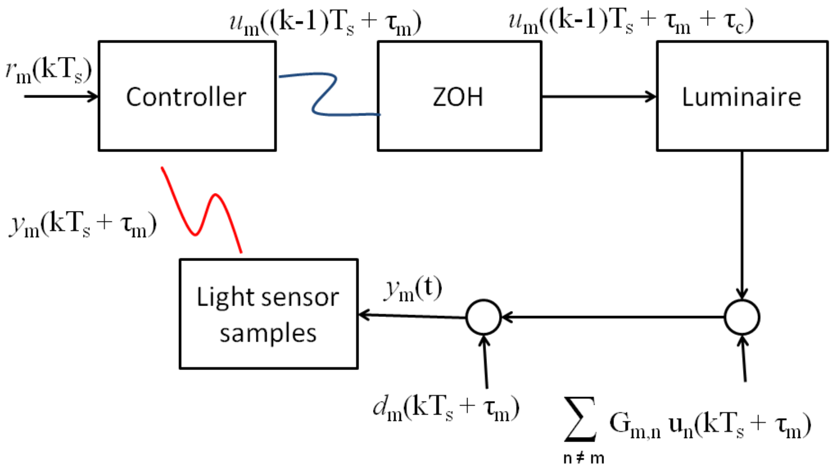


Figure 2.2: Structure of the complete system, with random delays τ_m and by the zero order hold τ_c. The wireless connection are denoted in red, for the sensor-to-controller one, and in blue for the controller-to-luminaire one.

To evaluate stability, steady-state behaviour of the system and furthermore of the controllers, we consider a model for the whole system. Consider now that the light sensors are ordered by the order of their execution. With this ordering, let $\hat{G}$ be the sorted matrix representing the relation between the luminaire dimming level and the sensor measurement, in the absence of daylight. The first row of $\hat{G}$ thus represents the illuminance contributed from the luminaires to the first sensor which is sampled in the system. Then

$$\hat{y}_m(k) = \hat{G}_{m,m}u_m(k-1) + \sum_{n=m+1}^{M} \hat{G}_{m,n}u_n(k-1) + \sum_{n=1}^{m-1} \hat{G}_{m,n}u_n(k) + \hat{d}_m(k), \quad (2.5)$$

in matrix form, the model is written as

$$\hat{\mathbf{y}}(k) = (\hat{G}_d + \hat{G}_u)\mathbf{u}(k-1) + \hat{G}_l\mathbf{u}(k) + \mathbf{d}(k), \quad (2.6)$$

where $\mathbf{y}(k)$ and $\mathbf{d}(k)$ are $M \times 1$ vectors containing components $\hat{y}_m(k)$ and $d_m(k)$ respectively. $\mathbf{u}(k)$ and $\mathbf{u}(k-1)$ are $M \times 1$ vectors containing the components $u_m(k)$ and $u_m(k-1)$ respectively. $\hat{G}_d$ is the diagonal part of $\hat{G}$, $\hat{G}_u$ the strictly upper triangular part of $\hat{G}$ and $\hat{G}_l$ the strictly lower triangular part of $\hat{G}$, so that

$$\hat{G} = \hat{G}_d + \hat{G}_u + \hat{G}_l. \tag{2.7}$$

We consider stand-alone single-input, single-output (SISO) control laws for simplicity of implementation, i.e. the controller deals with a multiple SISO system. In Fig. 2.3, one such SISO PI controller is illustrated. The controller calculates the dimming level of the luminaire so as to achieve the light sensor reference value $\{r_{o,m}\}$ in case of local occupancy, or $\{r_{u,m}\}$ in case of local unoccupancy and global occupancy. A zero order hold (ZOH) filter is used at the luminaire to obtain the continuous dimming level, $u_m(t)$. Every T_s, each light sensor sends its measurement to the controller according to a communication protocol. The sampled sensor values $\hat{y}_m(k)$ are given by (2.4). If the message is correctly received by the controller, it calculates the required dimming level and sends it to the corresponding luminaire, that will set it as the new dimming level. From the controller point of view, the system is composed only by the diagonal part of G, G_d; this is another issue of the distributed control approach.

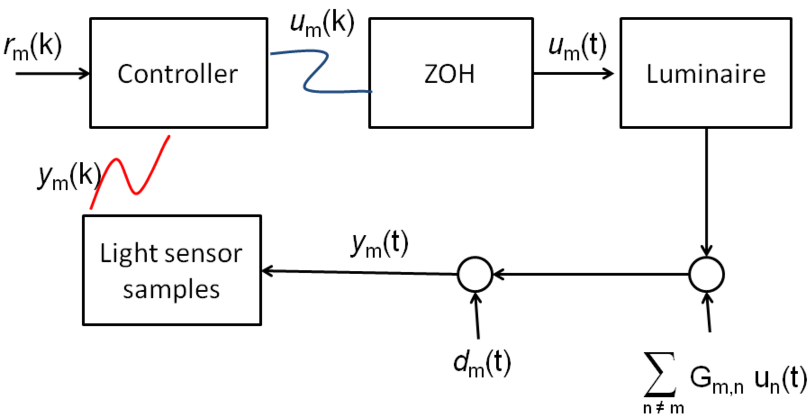


Figure 2.3: Simplified structure of a stand-alone controller, without delays.

2.2 Communication network

We now describe how the communication network responds to delivering information from the light sensors to the central controller, and from the central controller to the luminaires. Two main settings have been tested: the wired configuration and the wireless configuration. The first is the most common setting when considering a theoretical controlled system because it brings no issue of communication, and the assumption that the messages are sent and received instantly is close to be satisfied. The latter is, as said above, an intriguing communication setting since it brings fascinating features - as the retrofitting for old buildings - together with a list of issues rarely mentioned in theoretical studies: packet loss, fixed and random delays among all.

Wired Network

In the wired network, a direct link is present between sender and receiver, and communication is assumed to be perfect.

This network is the usual environment taken into account when studying the performances of controllers in control theory. Delays due to coding the datas, communication protocol or sensing the network is assumed to be negligible, so it is possible to approximate the communication as instantaneous. Packet losses, a great issue of the wireless network is not possible in the architecture. The wired network is used as a benchmark, against which the performance of the lighting system in a wireless network is compared.

After having built the wired network with perfect communication, to test which issues could have arose from a wireless communication protocol, a wireless network was built.

Wireless Network

The network under consideration is a mesh network, where several luminaires act as a bridge and carry sensor/control messages, as depicted in Fig. 2.4. It was built as a multi-hop network, where there are several nodes which act as bridge nodes. The controller can be considered the root of the network, placed in one corner of the room. 19 nodes can be reached in one hop: among these, there are 6 nodes that act as bridge, i.e. nodes 39, 48, 57, 66 and 76. In two hops the controller can reach 38 nodes; nodes 6, 25, 34, 43, 52, 62 and 72 act as bridges for the remaining 23 nodes, reachable in three hops.

This peculiar topology was chosen mainly for two reasons:

1. in many buildings is not uncommon to have a centralized controller that deals with the signals coming from every room in the entire building. This archicteture comes from, for example, old HVAC systems, where there was only one place where all the heating came from. In a similar way, it is possible to imagine that the controller in the room in not the actual place where the needed calculation are run but it is a module where all the measurements arrive, then they are sent through a wired (or generally another) network towards a centralized controller which computes the control signals and then sends them back. The centralized controller can be the controller for an entire floor, a group of floors or for the entire building as previously said.

2. it was useful, from a didactic point of view, to study the behaviour of a network under a considerably high rate of traffic. Of course, if a different position of the controller was chosen, or a single-hop structure instead of a multi-hop one was built, the traffic of the network and consequently the performances of the system would have been different: in this case however, the interesting behaviour shown by the transition from wired to wireless network would not appear so clearly.

This network structure has more communication traffic and larger delays than a classical star network. A ZigBee mesh network which is based on the IEEE 802.15.4 standard is assumed, given its prevalence in lighting applications [22].

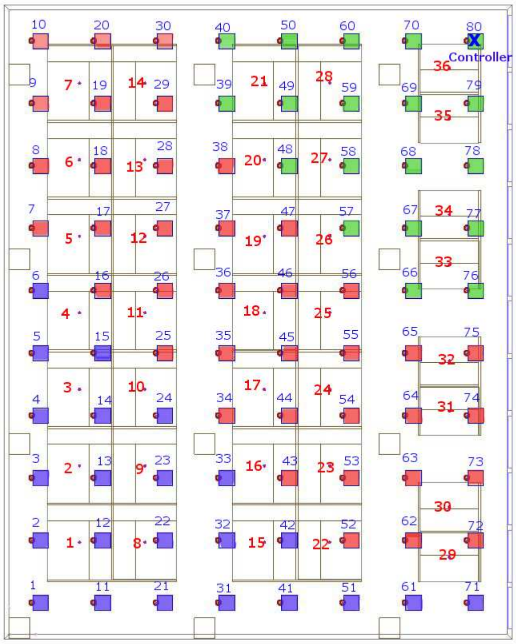


Figure 2.4: The mesh topology depicted: the controller is placed at the right top corner of the office, the luminaires equipped with occupancy and light sensors distributed at the ceiling. Green sensor/actuators reach the controller in one hop, red sensor/ actuators reach the controller in two hops, blue sensor/actuators reach the controller in three hops. Many sensor/actuators act as bridge nodes: number 16, 25, 34, 43, 52, 62 and 72 for the three-to-two-hop communication; number 40, 39, 48, 57, 66 and 76 for the two-to-one-hop communication.

Chapter 3

Digital PID

The most common controller is without doubt the Proportional, Integral, Derivative controller, better known as PID. Its strength lies on the simplicity of tuning and the good performance which can be achieved. In this work, a digital PI controller is considered. In the following sections, we recall the basics of the PID control, starting from an overview with continuous time and then specifying it in the digital world.

3.1 The standard PID control

The most common PID control compares the sampled value with a reference set-point. The error is utilized as input of the control block which calculates the output to fed the actuator. The PID control is the sum of three elements, the proportional, integral and derivative action. All these components are based on the input error; written in equation results

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t)dt + K_d \cdot \frac{d}{dt}e(t) \tag{3.1}$$

where the controller tuning parameters are K_p, the proportional gain, K_i the integral gain and K_d the derivative gain. The error $e(t) = r(t) - y(t)$ is the difference of reference set-point and the sampled signal at continuous time t. There exist many forms and structures tuned for different applications, e.g. in *parallel* and in *series*, but the focus will remain on the configuration 3.1, representing the parallel one, which is useful enough for our study. It is not uncommon to find it written as

$$u(t) = K_p \left(e(t) + \frac{1}{T_I} \int_0^t e(t)dt + T_D \frac{d}{dt}e(t) \right)$$

known as the *standard form*; T_I is called *integral time* while T_D the *derivative time*.

3.2 Digital Controllers

In the digital era, it is necessary to project a digital controller. When in presence of a continuous process to control, a natural approach for building such a controller is made by two steps:

1. Design a continuous controller according to given requirements;
2. "Translate it" into a digital one, through the *emulation* technique.

We assume now that the procedures needed to project and tune a PID (or a more general controller) in continuous time are known. We will now discuss how to *emulate* it in order to obtain a digital controller, with particular focus on PID controller. In general this process will need some approximation, that will be discussed when presenting the methods.

The emulation technique can be divided into three main groups:

a. By substitution of variables;

b. Matched Pole-Zero (MPZ);

c. Step Response Invariance.

We will now analyse each type of emulation.

a). Substitution of Variables
The key idea of this method is to find a reasonable way to approximate the s variable, traditionally linked to the Laplace transform of a differential equation, and to translate this approximation into the z domain, traditionally linked to the Zeta transform. Clearly, the issue lies on how to translate the time derivative operational into some discrete relation. There exist three main possibilities:

- Forward Euler
$$\frac{d}{dt}x(t) \sim \frac{x(t+T)-x(t)}{T}$$
where T is the sampling time. This equation is translated into the transform domain as
$$s \sim \frac{z-1}{T}. \tag{3.2}$$

Furthermore, with this method the equality $z = e^{sT}$ is approximated by

$$e^{sT} \sim 1 + sT.$$

- Backward Euler

$$\frac{d}{dt}x(t) \sim \frac{x(t) - x(t-T)}{T}.$$

This equation is translated into the transform domain as

$$s \sim \frac{1 - z^{-1}}{T}. \tag{3.3}$$

Furthermore, with this method the equality $z = e^{sT}$ is approximated by

$$e^{sT} \sim \frac{1}{1 - sT}.$$

- Tustin

$$\frac{d}{dt}\left(\frac{x(t+T) + x(t)}{2}\right) \sim \frac{x(t+T) - x(t)}{T}.$$

This equation is translated into the transform domain as

$$s \sim \frac{2}{T}\frac{z-1}{z+1}. \tag{3.4}$$

This approximation leads to

$$e^{sT} \sim \frac{1 + \frac{sT}{2}}{1 - \frac{sT}{2}}.$$

Once designed the continuous controller then, the digital controller is calculated simply substituting the s variable following 3.2, 3.3 or 3.4.

Note that particular attention must be put in the stability study of this "translation". The left half-plane, the *stable* one when considering the Laplace transform, is mapped in the z plane into the unit circle if the Tustin emulation is considered, into a circle of 0.5 as radius and center in 0.5 if Backward Euler is chosen and into the plane on the left of $z = 1$ if Forward Euler is taken. Clearly, Forward Euler is very likely to be unstable, unless very small sampling time T is considered.

b). Matched Pole-Zero This method deals with the need of an *exact* mapping of poles and zeros of the original controller (or transfer function in general) from the s plane into the z plane. In order to obtain such a translation it is useful to follow these simple steps:

1. Write the controller $C(s)$ in Evans form, highlighting poles and zeros

$$C(s) = k\,\frac{\prod_i (s - z_i^c)}{\prod_i (s - p_i^c)}$$

2. Using the mapping $z = e^{sT}$ find a first controller as

$$C_1(z) = k\,\frac{\prod (z - e^{z_i^c T})}{\prod (z - e^{p_i^c T})}$$

3. If there are requirements about the relative degree (or delay) of the controller it is possible to add m zeros in -1

$$C_2(z) = C_1(z)(z+1)^m$$

4. Finally add the gain k_0 in order to assure the same asymptotic gain for $C(s)$ and $C(z)$

$$C(z) = k_0 C_2(z)$$

   where k_0 is calculated as

$$\lim_{s\to 0} s\; C(s)\frac{1}{s} = \lim_{z\to 1} \frac{z-1}{z} C(z) \frac{z}{z-1}.$$

c). Step Response Invariance This method is quite famous and it is based on the idea that the continuous controller's step response (or process) must be compared with the step response of the digital controller and from this equivalence building the digital controller. In formulas, the following equivalence results

$$C(z) = (1 - z^{-1})\mathcal{Z}\left\{\mathcal{S}\left\{\mathcal{L}^{-1}\left\{\frac{C(s)}{s}\right\};T\right\}\right\}$$

where $\mathcal{L}^{-1}$ is the inverse Laplace transform, $\mathcal{S}$ is the sample operational with sampling time T and $\mathcal{Z}$ is the Zeta transform operational.

It is worth to say that this technique in general offers poor performances with respect to the Tustin or MPZ.

The three emulation methods can be applied to a general transfer function and, as the case of interest, more specifically for a PID controller. In the following section the translation from a continuous PID into a digital PID is analysed.

3.2.1 Digital PID

Recalling Section 3.1, PID controllers are composed by three actions, which give the name, *proportional*, *integral*, *derivative*. Mainly there are two ways to implement such a controller, *in parallel* and *in series*. Let us focus on the *parallel* configuration.

Consider separately the three component and their digital version:

- *Proportional:*

$$u_p = K_p^d e(k)$$

- *Integral:* using Backward Euler the integral action results

$$u_I(k) = u_I(k-1) + \frac{T}{T_I} e(k)$$

- *Derivative:* again using Backward Euler

$$u_D(k) = \frac{T_L}{T + T_L} u_D(k-1) + \frac{T_D}{T + T_L} \left(e(k) - e(k-1)\right)$$

Clearly, the example given above for Backward Euler can be simply derived also for Forward Euler and Tustin.

Once analysed the digital transformation from a continuous to a digital controller, let us move the focus on the controller utilized in the lighting system of interest.

3.3 Generalized Controller

Let us focus on a wired network where the communication is assumed to be perfect. The controller considered in this work is a multiple SISO that can be seen as M single controllers that work jointly. Controller m seeks to determine the dimming level u_m so to achieve the light sensor reference set-point $r_{o,m}$ in case of occupancy of the corresponding zone or $r_{u,m}$ in case of unoccupancy of the zone but there is global presence.

As showed in 2.5, the sampling among the sensors is not synchronous.

The general form of the controller can be described as follows

$$u_m(k) = \alpha_m u_m(k-1) + \beta_m e_m(k) + \zeta_m \tag{3.5}$$

where α_m, β_m and ζ_m are constants in $\mathbb{R}$. The input of the controller is

$$e_m(k) = r_m(k) - \hat{y}_m(k) \tag{3.6}$$

where r_m represents the reference set-point and can assume the value $r_{o,m}$ in case of occupancy or $r_{u,m}$ in case of unoccupancy.

We can describe the controller equation in a state space representation as

$$\begin{cases} x_m(k+1) = \alpha_m x_m(k) + \beta_m e_m(k) + \zeta_m \\ u_m(k) = \alpha_m x_m(k) + \beta_m e_m(k) + \zeta_m \end{cases} \tag{3.7}$$

where $x_m(k)$ represents the state which is equal to $u_m(k-1)$.

In the previous equation 3.7, physical limits of the luminaire dimming levels were not taken into account. Since the luminaires are dimmed according to a PWM, the duty cycle is limited between 0 and 1, i.e. $0 \leq u_m(k) \leq 1$. A saturation function is applied to the controller output to make sure the the output is within these bounds. The saturation function $\mathcal{Q}$ is defined by

$$\mathcal{Q}(x_m) = \begin{cases} 1, & if\ x_m > 1 \\ x_m, & if\ 0 \leq x_m \leq 1 \\ 0, & if\ x_m < 0. \end{cases} \tag{3.8}$$

The saturated output of the controller is stored in memory and used to calculate the next dimming level; the state space representation with saturation of the generalized controller results

$$\begin{cases} x_m(k+1) = \mathcal{Q}(\alpha_m x_m(k) + \beta_m e_m(k) + \zeta_m) \\ u_m(k) = \mathcal{Q}(\alpha_m x_m(k) + \beta_m e_m(k) + \zeta_m) \end{cases} \tag{3.9}$$

In the following sections, the PI controller are analysed ignoring the effect of saturation for simplicity.

3.4 Wireless Reference Controller

The final form of the controller used as the reference one in this work is not so straightforward to obtain. In order to give a clear explanation about all the steps that led to such a final form, we will give a little general overview of a controller in this section; then, in the following section, we will study a dead beat controller, which assures that the error fades to zero in just one step. This kind of controller does not give satisfying performances in terms of illuminance at the workspace (as we discuss later) so it was necessary to introduce, in a further section, a new type of controller, called *PI with offset*.

Recalling equation (3.9), the control law to compute the dimming level $u_m(k)$ for luminaire m at instant k can be described as follows:

$$u_m(k) = \mathcal{Q}\{\alpha_m u_m(k-1) + \beta_m e_m(k) + \zeta_m\} \tag{3.10}$$

where $\alpha_m, \beta_m, \zeta_m$ are control parameters chosen so as to maintain stability of the control loop. The function $\mathcal{Q}\{\cdot\}$ ensures that the dimming level is within the valid range $[0, 1]$. Again, the input to the controller is the error term given by the difference between the reference set-point, r_m, and the light sensor measurement,

$$e_m(k) = r_m(k) - y_m(k). \tag{3.11}$$

The reference set-point r_m assume the value $r_{o,m}$ if the corresponding occupancy sensor has local occupancy and a value $r_{u,m}$ if the corresponding occupancy sensor has local unoccupancy, but there is global occupancy.

3.5 PI parameters: Dead Beat Case

As one can expect, the best controller in terms of achieving the reference is the dead beat one, i.e. the one which guarantees that the measure achieves the reference just after one step.

We assume that the daylight changes slowly compared to the sample time and neglecting the coupling term, the estimate of the illuminance value at the sensor $\tilde{y}_m(k+1)$ of $\hat{y}_m(k+1)$ can be written as

$$\tilde{y}_m(k+1) = G_{m,m}u_m(k) + d_m(k+1). \tag{3.12}$$

Looking back to (2.5), we now write $(kT_s + \tau_m)$ as (k) and τ_c is neglected for simplicity. The controller seeks to achieve $r_m(k)$, so when it reaches the reference set-point we must have

$$r_m(k) = \tilde{y}_m(k+1) = G_{m,m}u_m(k) + d_m(k+1) \tag{3.13}$$

Now we can calculate $u_m(k)$ from 3.13, which gives

$$u_m(k) = \frac{r_m(k) - d_m(k+1)}{G_{m,m}}. \tag{3.14}$$

We assumed the daylight to change slowly, so that $d_m(k) \simeq d_m(k+1)$; so 3.14 becomes

$$u_m(k) \simeq \frac{r_m(k) - d_m(k)}{G_{m,m}}. \tag{3.15}$$

The missing term $d_m(k)$ can be obtained from (3.13) as

$$d_m(k) = \tilde{y}_m(k) - G_{m,m}u_m(k-1). \tag{3.16}$$

Substituting (3.16) into (3.15), the final expression for the controller is obtained

$$u_m(k) = \frac{e_m(k)}{G_{m,m}} + u_m(k-1). \tag{3.17}$$

Equation (3.17) is a classical PI controller equation, which can be though as the generalized form in (3.5) where

$$\alpha_m = 1, \quad \beta_m = \frac{1}{G_{m,m}}, \quad \zeta_m = 0. \tag{3.18}$$

As said, with constant daylight and without coupling, this controller will achieve the reference set-point in one step.

In several studies, [7], [18], [19] it has been demonstrated that this approach is not sufficient to ensure the achievement of the reference set-point at the workspace plane in presence of daylight. This effect is due to many reasons, one among all, the different contribution of daylight at the ceiling and at the workspace that prevents the good behaviour of the controllers. This considerations lead to a different PI control law, called *PI with offset* that will be discussed in the following section.

3.6 PI parameters: *PI with offset* Case

This new class of controllers seek to achieve a positively biased reference set-point. A similar class of controllers was considered in [19] for a lighting system controlled by a single light sensor with all the light sources set to the same dimming level. In [18], [19], it was observed that under certain situations where the daylight is present and increases, the controller which is designed to achieve the reference set-point at the ceiling results in lower illuminance value at the workspace plane than desired.

To face this, a daytime calibration step was utilized and a new term, the ratio between the daylight contribution at the workspace plane and the contribution at the light sensor at the ceiling, was introduced in the controller design.

In Laplace domain we can write the controller in [18] as

$$U(s) = \frac{\rho}{1+s\tau} E(s) + 1, \tag{3.19}$$

where $U(s)$ and $E(s)$ are the Laplace transforms of $u(t)$ and $e(t) = r(t) - y(t)$ respectively; τ is a time constant and ρ is a parameter calibrated such that the illuminance at the workspace plane equals (or exceeds) the required illumination for a given daylight contribution.

In time domain 3.19 may be written as

$$\dot{u}(t) = \frac{\rho e(t) - u(t) + 1}{\tau}. \tag{3.20}$$

Now, it is possible to find the discrete form using the Forward Euler method, that gives

$$\frac{u(k) - u(k-1)}{T_s} = \frac{\rho e(k) - u(k) + 1}{\tau}. \tag{3.21}$$

So we obtain

$$u(k) = \frac{\tau u(k-1) + \rho T_s e(k) + T_s}{\tau + T_s}. \tag{3.22}$$

This controller can be expressed in the generalized form 3.5, where

$$\begin{cases} \alpha_m = \frac{\tau}{\tau+T_s}, \\ \beta_m = \frac{\rho T_s}{\tau+T_s}, \\ \zeta_m = \frac{T_s}{\tau+T_s}. \end{cases} \tag{3.23}$$

3.7 Stability of the Controllers

If the coupling among the luminaires and the saturation are ignored, the closed loop transfer from the reference input of the system to the output of the system can be described in the discrete Laplace domain as

$$\frac{Y_m(z)}{R_m(z)} = \frac{G_{m,m}\beta_m}{z - \alpha_m + G_{m,m}\beta_m}. \tag{3.24}$$

The system has one pole at

$$p_m = \alpha_m - G_{m,m}\beta_m. \tag{3.25}$$

For stability

$$|p_m| < 1 \tag{3.26}$$

should hold.

For the classical PI controller, using 3.18 we have $p_m = 0$.

For the PI controller with offset, the pole equals

$$p_m = \frac{\tau - G_{m,m}\rho T_s}{\tau + T_s}. \tag{3.27}$$

When the stability requirement (3.26) is applied to 3.27, we obtain

$$-\frac{1}{G_{m,m}} < \rho < \frac{2\tau}{G_{m,m}T_s} + \frac{1}{G_{m,m}}. \tag{3.28}$$

3.8 Sending Schedule of the Reference Controller

When the dimming level is calculated, the controller sends the control message to the luminaire, which sets the new dimming level. The reference controller is activated only when it receives a message coming from sensors and thus cannot deal with a lost packet that was sent from the sensor.

In general, packet loss leads to different effects depending on whether the lost message was from the light sensor or from the controller to the luminaire. A lost sensor message will create a delay of at least one sampling time T_s because the controller does not have enough information to calculate the dimming level. On the other hand, a lost dimming level creates a more complicated situation. If we observe the structure of the PI law we notice that the integral part is composed of the previous dimming level; usually PI controllers assume perfect communication and when a dimming level is lost an ambiguous situation appears [24]. Consider the control law in (3.10). Assume that $u_m(k-1)$ was not received at the corresponding luminaire. The controller would assume, since it has no means to detect whether a packet was lost or not, that the sent dimming level was received; so $u_m(k)$ is calculated using a wrong information. If $u_m(k-1)$ was not received, the real last dimming level is $u_m(k-2)$, assuming that this message was actually received. As a consequence, the controller receives two (or more) similar sensor measurements which increases the integral part till it saturates.

The main effect of packet losses is an increased settling time, i.e. the time needed to reach a steady-state value is increased, as illustrated in Fig. 3.1 where we show the average illuminance value over zone 4 vs time. We assume that the office becomes occupied at time $t = 0$ and there is daylight. The average illuminance in zone 4 with the reference controller in a wireless network under packet losses is compared with the reference controller in a wired network. It can be observed that the wireless network has the adverse impact of significantly increasing the settling time. Note that the difference in the steady-state illuminance value and the target illuminance value is due to the stand-alone control law employed,i.e. the *offset* in the PI control law and constraints in dimming levels.

3.9 Imperfect Communication

In standard industrial systems, three main blocks are usually considered: sensor, controller and actuator. The control loop is executed periodically, i.e. at a fixed rate the sampled data arrive at the controller that computes the designed control law and send to the actuator the desired output signal.

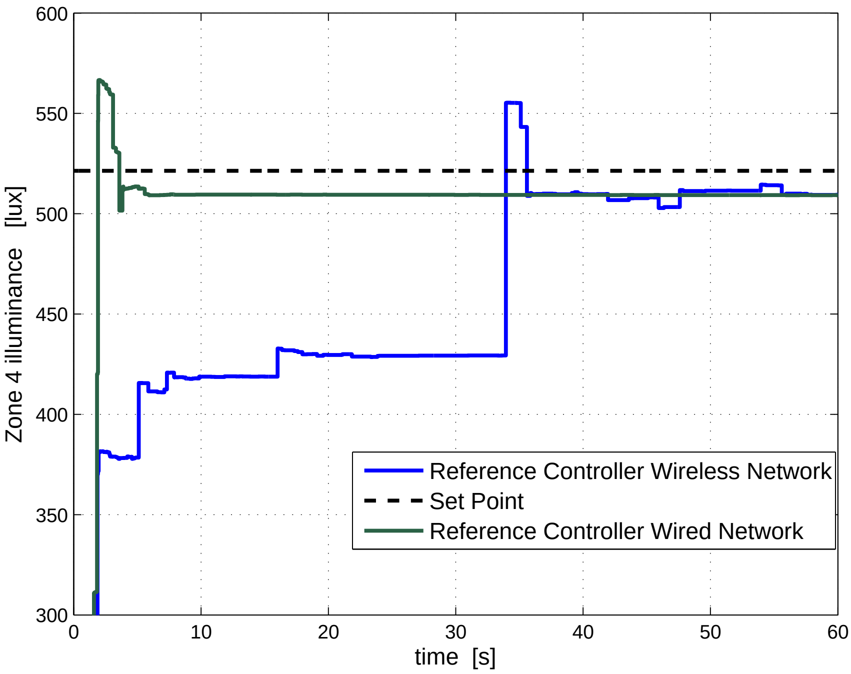


Figure 3.1: Zone 4 illuminance after a step input. At $t = 0$ local presence is detected, sensors send their measurement and the controller calculates and send back the dimming level to the corresponding luminaire. Simulations run with Retry Limit set to 3, Loss Probability set to 1% and with daylight.

This control paradigm works well with wired and reliable systems which utilise robust communication protocols, such as ProfiBus or FieldBus; nowadays nevertheless it is interesting and a reasonable assumption that wireless communication will replace wired ones. This may happen in order to obtain a more flexible installation and an easier management, saving cabling cost, achieving power savings and many more reason mentioned above.

Introducing wireless communication protocol we expect to deal with random packet loss and communication delays which result in a very challenging control design. Nowadays there exist many wireless automation standards, such as WirelessHART and ISA 100.11a, recently developed and already on the market. Despite many researches, a global agreement on which control procedure should be employed in automation systems is missing. As a fact, the majority of control control strategies are based on the assumption of reliable communications.

In the following section, we will discuss the behaviour of a PID controller in a high packet loss situation, considering the different contribution of the single terms, proportional, integral and derivative.

In the typical case of no communication loss, the PID keeps the process in a steady state after a transient. In the case studied in this work, the objective was to control a process, modelled with a constant matrix, with a discrete controller. The output was sampled and sent to the controller, which computed the dimming level to be sent to the actuator.

In order to show some plot evidences of what will happen in case of non perfect wireless communication, a reduced system with only one sensor/actuator and one controller was tested. A step is used as a reference, with step time 1 second. Every second, the sensor samples and sends the signal to the controller through a wireless network with ZigBee as communication protocol. Once received the measurement signal, the controller computes the respective control PID law and sends it to the actuator which will set it as the new dimming level. As said, the controller is triggered: if it does not receive any signal, it does not calculate the dimming level.

First, as a benchmark, a perfect communication run was simulated, shown in Figs. 3.2(b) and 3.2(a). After three steps, the PID law brings the output to the reference and it fades to zero.

3.9.1 Input Communication Lost

We now consider what would happen to the three components of the output if the communication from sensor to controller is lost in a time interval $[t_1, t_2]$.

As said before, if the packet from the sensor to the controller is lost, the controller simply does not activate its computations: the output clearly remains as it was in t_1.

A simulation with the test system is shown in Fig. 3. In that simulation, the communication was blocked from $t_1 = 0s$ to $t_2 = 2s$, so three samples were lost. This situation (see Fig.3.3(a)) is translated in a delay of three steps for the output, which achieves the reference 3 seconds after the case of perfect communication. The proportional, integral and derivative part (see Fig. 3.3(b)) remain zero until the first measurement is received and then they behave as the perfect communication case.

3.9.2 Output Communication Lost

We now consider the situation where the communication from the sensor to the controller is perfect but the communication from the controller to the actuator is blocked during the time interval $[t_1, t_2]$.

In such a condition, the proportional component will remain the same, since the set-point and the measured value remain constant; the integral component, on the other hand, will linearly increase from t_1 till t_2 since the error is constant; the derivative part will stay at zero because the error is constant. As a consequence, the output of the controller linearly increase its value: this destabilizes the process; the longer is the time interval the bigger will be the drift from the set-point. Moreover, when the communication is restored (at t_2) the derivative contribution will give a spike, because of the great output value given by the PID control at t_2.

A simulation with the test system is shown in Fig. 4. The communication from controller to the actuator was blocked from $t_1 = 0s$ to $t_2 = 0s$, so three messages were not received. This situation depicts, as shown in Fig.3.4(b),the proportional part that stays at the same value in the time interval $[t_1, t_2]$ while the integral increases its value till t_2 and the derivative component stays at zero since the error does not change. When the first dimming level is received by the actuator, the dimming level is saturated, which is translated in the overshoot shown in Fig.3.4(a). The derivative part cannot give a spike because of the limited gain, but it achieves its maximum possible value as the following iteration.

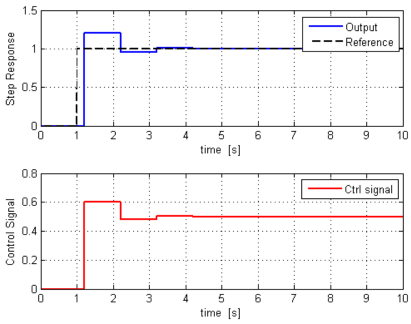
3.9.3 Input and Output packet loss

Let us now consider the situation where both sensor and controller messages are lost in random time instants.

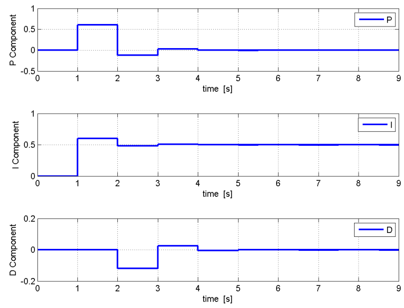
The result is the superposition of effects of the two previously described aspects: delays (from the input messages lost) and wrong dimming level received (from the controller messages lost).

A simulation with the test system was simulated with three messages lost for each communication channel: sensor messages were lost in $t = 1, 5, 7s$ while controller messages were lost in $t = 2, 4, 7s$, shown in Figs.3.5(a), 3.5(b).

The combined action of messages lost is the most dangerous for the system: the controller signal is saturated at 1 because of the measurement message lost at $t = 1$ and the controller message $t = 2s$, which is translated in the overshoot at $t = 3s$. Then, at $t = 4s$, another controller message was lost, so the output remains at the same value and so the saturated dimming level. At $t = 5s$ a sensor message was lost, so the controller did not calculate the dimming level, as a result the output did not change its value. Finally at $t = 6s$, the measurement was received and the controller signal was received by the actuator but the dimming level was saturated at zero for the same reasons as above; the output then went to zero. At $t = 7s$ both messages were lost, so the output and the dimming level remained at zero. At the end, from $t = 8s$, the controller could compute the control law to make the output achieve the reference signal.

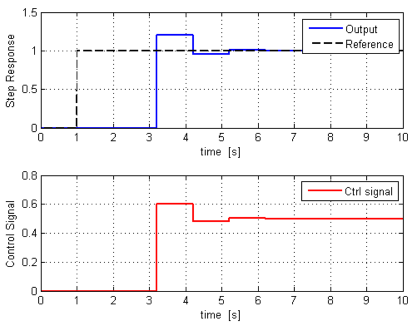


(a) Step Response for the system (above) and the respective dimming level (below).

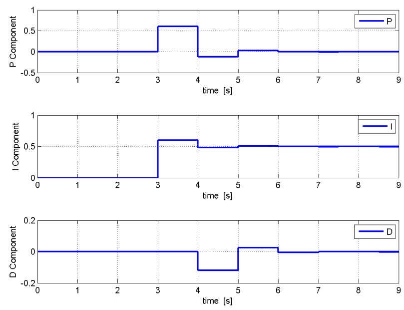


(b) The three components of PID controller.

Figure 3.2: Step response, dimming level (on the left) and the P, I, D component for a test system in case of perfect communication. In three iterations, the output achieve the steady state.

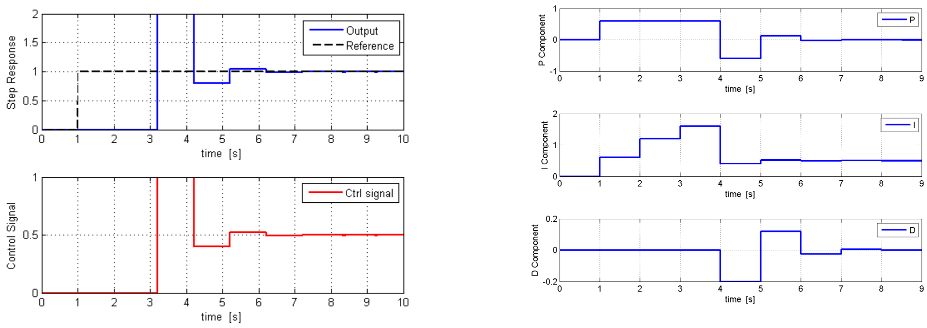


(a) Step Response for the system (above) and the respective dimming level (below).



(b) The three components of PID controller.

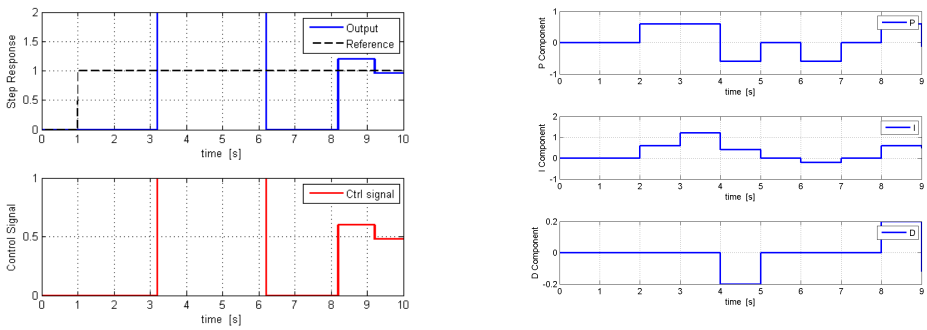
Figure 3.3: Step response, dimming level (on the left) and the P, I, D component for a test system in case of the first three measurement packets lost.



(a) Step Response for the system (above) and the respective dimming level (below).

(b) The three components of PID controller.

Figure 3.4: Step response, dimming level (on the left) and the P, I, D component for a test system in case of the first three controller messages lost. This case is much different with respect to a simple measurement packet lost, because it implies a saturation of the dimming level together with the delay. The integral and proportional components saturate the control signal at 1, while the derivative part stays at zero. When finally the dimming level is received, the output shows a great overshoot. The controller is able to make the output reach the reference in 3 seconds even in this case.



(a) Step Response for the system (above) and the respective dimming level (below).

(b) The three components of PID controller.

Figure 3.5: Step response, dimming level (on the left) and the P, I, D component for a test system in case of packets lost in different and non sequentially time instants. The measurement packets are lost at $t = 1, 5, 7\ s$ and the controller messages are lost at $t = 2, 4, 7\ s$.

Chapter 4

Proposed wireless control design

Packet losses due to the wireless medium may occur in the link between the light sensors and the central controller, as well as the link between the controller and luminaires. We consider enhancements to the PI control with offset law to cope with packet losses, while ensuring that any design changes do not increase network load adversely.

We assume that the controller knows the expected arrival times of every sensor message; this information can be obtained after an initialization step, since the sensors send measurements periodically. As such, the controller can wait for the sensor message and if this is not received after a reasonable transmission delay, it can assume that the message was lost.

In order to resolve the issue of the lost sensor message $\hat{y}_m$, the controller will perform an estimation *at each time step*, denoted as $\tilde{y}_m$. If the sensor message was actually lost during the transmission, the controller will utilize the estimate as the true value and will compute the dimming level as the transmission was successful. Otherwise, if the message is correctly received, the estimate is used to decide whether the previous dimming level was effectively received by the luminaire at the previous time step. This mechanism is important because according to this decision will change the control law and so the way to compute the dimming level. How the estimate is calculated and how the decision about the dimming level reception is made will now be explained.

We now make the assumption that the dimming level is always successfully received by the actuator; we will use it only for clarity of explanation of the estimation procedure.

At time instant $k > 0$, the controller estimates the expected measurement $\tilde{y}_m(k)$ at light sensor m as

$$\tilde{y}_m(k) = \hat{G}_m \mathbf{u}_c(k, k-1) + \hat{d}_m(k-1) \tag{4.1}$$

where $\hat{G}_m$ is the m-th row of the sorted process matrix, $\hat{d}_m(k-1)$ the daylight contribution at the previous time instant and $\mathbf{u}_c(k, k-1)$ is a vector containing the dimming levels at two different time instants. We now analyse what stands behind these two quantities.

Looking back to Section 2.1, recall equation (2.6)

$$\hat{\mathbf{y}}(k) = (\hat{G}_d + \hat{G}_u)\mathbf{u}(k-1) + \hat{G}_l\mathbf{u}(k) + \mathbf{d}(k).$$

Neglecting the daylight, it is easy to state that the illuminance measurement at time instant k is given by two terms, one depending on $u(k-1)$ and the other depending on $u(k)$, according to the ordering of the sensors' sending schedule. Given the nature of the component of $\hat{G}$, every u_i can contribute only in one of the two parts, i.e. only as $u_i(k-1)$ or $u_i(k)$, again according to the ordering. In this situation it is possible to build a vector, denoted $\mathbf{u}_c(k, k-1)$, which contains all the dimming level that give a contribution in the illuminance at the m-th sensor: if $\hat{G}$ is multiplied by $\mathbf{u}_c(k, k-1)$ the result is the same as equation (2.6); the equivalence holds

$$\hat{\mathbf{y}}(k) = (\hat{G}_d + \hat{G}_u)\mathbf{u}(k-1) + \hat{G}_l\mathbf{u}(k) + \mathbf{d}(k) = \hat{G}\mathbf{u}_c(k, k-1) + \mathbf{d}(k),$$

or, in more formal terms

$$\hat{G}_m\mathbf{u}_c(k, k-1) = \sum_n \left(\left[(\hat{\boldsymbol{G}}_d + \hat{\boldsymbol{G}}_u) \right]_{m,n} u_n(k-1) + \left[\hat{\boldsymbol{G}}_l \right]_{m,n} u_n(k) \right),$$

where $[\boldsymbol{A}]_{m,n}$ is the (m,n)-th element of matrix $\boldsymbol{A}$. The daylight component $\hat{d}_m(k)$ is calculated as follows. At instant time $k > 0$, the controller estimates the daylight contribution, $\hat{d}_m(k)$, at light sensor m as

$$\hat{d}_m(k) = \begin{cases} \hat{y}_m(k) - \hat{G}\mathbf{u}_c(k, k-1), & \text{if } \hat{y}_m(k) \text{ is successfully received,} \\ \hat{d}_m(k-1), & \text{otherwise.} \end{cases} \tag{4.2}$$

In (4.1) and (4.2), we assume, as said in Section 2.1, that daylight changes slowly between consecutive periods T_s, i.e. $\hat{d}_m(k) \approx \hat{d}_m(k-1)$.

Let now drop the assumption of successful reception of dimming level at each time instant and call $u_n^{(A)}$ be the last known dimming level successfully received by luminaire (and so by the actuator) n.

Without loss of generality, we assume that at time instant $k = 0$ all luminaires are off and there is no daylight contribution, i.e. $\{u_n(0) = 0\}$, $\{u_n^{(A)} = 0\}$ and $\hat{d}_m(0) = 0$.

The m-th controller determines that the corresponding m-th luminaire has successfully received the dimming command transmitted at time instant $(k-1)$ using the following rule

if $|\hat{y}_m(k) - \tilde{y}_m(k)| < \delta$ **then**
$u_m^{(A)} \leftarrow u_m(k-1)$ *%Last dimming command sucessfully received*
end if

where $\delta \geq 0$ is a pre-defined threshold. This threshold mechanism can only be used when the m-th controller successfully receives a measurement, $\hat{y}_m(k)$, from the m-th light sensor at time instant k. If the measurement $\hat{y}_m(k)$ from the m-th light sensor is lost, then the m-th controller assumes that the dimming level $u_m(k-1)$ was successfully received by the luminaire. Instead of the threshold mechanism for the detection of the received dimming level, the controller could use application-level acknowledgment information to know exactly whether a packet has been received or not. However, these additional messages will increase the network load, introducing the risk of a higher packet loss due to collisions and network congestion.

The control law is modified as follows:

$$u_m(k) = \mathcal{Q}\{\alpha_m u_m^{(A)} + \beta_m \hat{e}_m(k) + \zeta_m\} \tag{4.3}$$

where

$$\hat{e}_m(k) = \begin{cases} r_m(k) - \hat{y}_m(k) & \text{, if } \hat{y}_m(k) \text{ is successfully received,} \\ r_m(k) - \tilde{y}_m(k) & \text{, otherwise.} \end{cases} \tag{4.4}$$

Furthermore, we also consider a scheduling scheme at the controller to reduce the network traffic. The controller sends a dimming level to the luminaire only if this differs from the previous dimming level by more than a specified threshold, ε:

if $|u_m(k) - u_m^{(A)}| > \varepsilon$ **then**
Transmit dimming command
end if

where $\varepsilon \geq 0$ is a pre-defined threshold. If at time instant k, the controller decides not to send a dimming command to the m-th luminaire, then at time instant $(k+1)$ the m-th controller does not check whether the m-th luminaire receives a dimming command. In Figure 4.1 it is shown a scheme of the wireless system with the signals u_m, u_m^A, $\hat{y}_m$ involved.

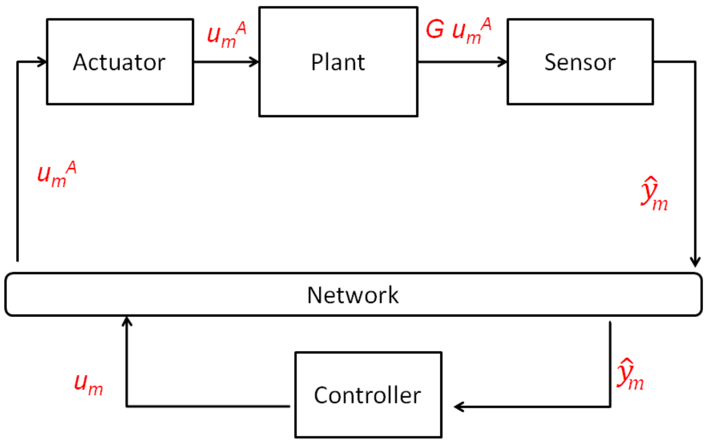


Figure 4.1: Scheme of the wireless system with the signals involved.

Chapter 5

Simulation results

Simulations were used to evaluate the performance of the wireless reference and proposed controllers. The performance was evaluated in terms of transient and steady-state control response, in particular overshoot and settling time, as well as network load. The office lighting model was created in DIALux [20]; for a detailed description of the example model, please refer to [7]. The office lighting plan is depicted in Fig. 2.4 where the 80 blue rectangles represent locations of the luminaires, with the light and occupancy sensors depicted by a red circle, and are indexed by blue numbers. The half opening angle of the occupancy sensors is approximately 45°; when a zone is occupied, the occupancy sensors within whose fields-of-view a user falls detect presence. The workspace plan is divided into 36 zones, indexed by red numbers, representing the office work areas. The room is oriented 110° North.

For the wireless communication system, the ZigBee mesh network was assumed. The data rate is assumed to be 250 kbits/s, frame size is 400 bits, transmit power is 20 dBm, and the receiver signal threshold is taken to be -20 dBm. A free-space path loss propagation model with path loss exponent of 3.5 was used. The communication range was assumed to be 10 meters, which is typical in such a lighting application. Given the dimensions of the considered office space (see Fig. 2.4), the maximum number of hops needed to reach every sensor/actuator was 3. Packets routes were statically chosen based on the shortest path based on Euclidean distance; in practice, common routing algorithms such as the Ad hoc On-Demand Distance Vector (AODV) routing algorithm [25] may be employed. Communication among sensor/actuators is possible only via bridge nodes to carry on the sensor (or controller) messages. Message retransmissions are controlled using the Retry Limit (RL) parameter which represents the maximum number of times a node will try to re-transmit a message before giving up. The unreliability of the wireless channel is captured by the Loss Probability (LP) parameter, which represents the probability that a message is lost during a transmission owing to the wireless medium, and not for instance due to packet collisions.

The networked lighting control system was implemented in Matlab/ Simulink using the TrueTime toolbox [21]. TrueTime facilitates co-simulation of controllers in real-time kernels with network transmissions and continuous dynamics of the controlled system [23]. Every network node is implemented so that it either sends or receives a packet at a given time. The controller parameters were given as $\alpha_m = \frac{\tau}{\tau+T_s}$, $\beta_m = \frac{\rho T_s}{\tau+T_s}$ and $\zeta_m = \frac{1}{\tau+T_s}$ as in [7],where τ is a time constant and the parameter ρ is calibrated such that the illuminance at the workspace plane equals the required illuminance for a given daylight distribution. A sensor sampling time of $T_s = 2$ seconds is chosen.

5.1 Effects of Packet Loss

In Chapter 4 and Chapter 5, we discussed the effect of packet losses on the performance of the wireless reference controller as evidenced by the increased settling times shown in Fig. 3.1. For the same settings, we now include the performance of the proposed controller, as shown in Fig. 5.1. For the proposed controller, two values of RL, 0 and 3, are chosen, corresponding to no retransmission and three retransmissions respectively. For the proposed controller, we can specifically observe the effect of the estimation procedure performed at the central controller to account for lost light sensor messages. With RL= 0, the settling time is already considerably smaller and close to the performance of the reference controller under a wired network. With RL= 3, the wireless proposed controller and the wired reference controller show similar behavior.

In Fig. 5.2, we consider the response of the wireless reference and proposed controllers under an occupancy change from occupied to unoccupied in zone 14. For both controllers, simulations are performed with the same sensor ordering and timing. For the wireless network, a packet loss probability of 1% and RL= 3 was assumed. An increased settling time of the wireless reference controller is observed, while the wireless proposed controller has a behavior similar to the reference controller under wired network.

5.2 Starting from Zero state

We now consider the effect of packet loss probability (LP) on settling time and the impact of message retries in conjunction with the wireless proposed

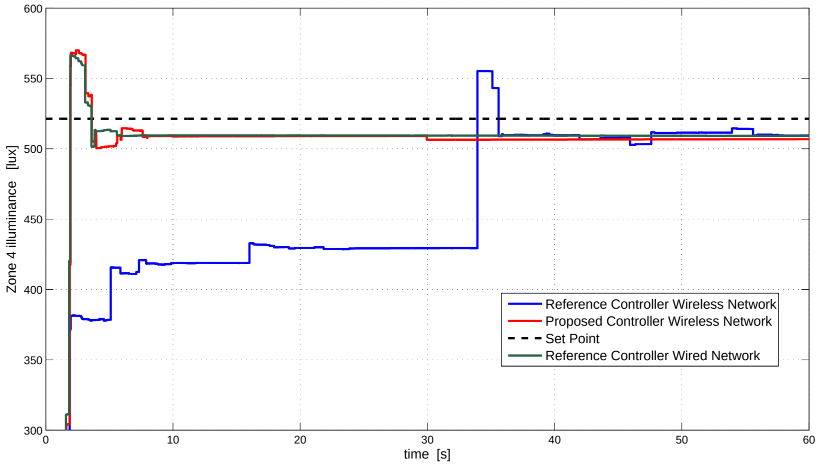


Figure 5.1: Comparison of the reference and proposed controller under the same sensor sampling ordering and timing. The high number of lost messages prevents the reference controller to work properly for more than 30 seconds, while the proposed controller performs the illuminance estimation and has a behavior similar to the wired network. Simulations run with Retry Limit set to 3, Loss Probability set to 1% and with daylight.

controller. In Figs. 5.3 and 5.4, we respectively show the cumulative distribution of the settling time for different values of LP and RL. To test the response of the lighting system, simulations run starting from zero state, when all luminaires are off. At $t = 0$, an occupancy step is simulated for each zone, so that $r_m = r_{o,m} \quad \forall\ m$, and the time needed to achieve the steady-state is collected for each zone. The settling time, defined as the time needed for the illuminance to reach and stay inside a 5% band of the achieved steady-state value, is collected and shown in Figs. 5.3 and 5.4.

We see from Figs. 5.3 and 5.4 that the wireless proposed controller outperforms the wireless reference controller for the same parameter configuration. From Fig. 5.3, we see that after about 20 seconds from the beginning of the simulations, with 1% LP, the proposed controller achieves illuminance inside the 5% error band for 99.94% of the zones, while the reference controller achieves 97.8%; with LP set to 10%, the proposed controller achieves 98.7% against the 97.8% of the reference controller. Thus, with larger message retries, the proposed controller shows small improvement in settling times in comparison to the reference controller since there is already sufficient system robustness. In Fig. 5.4, we observe that with RL = 0 (blue lines), there is a longer settling time compared to case with RL = 3 (red lines). With

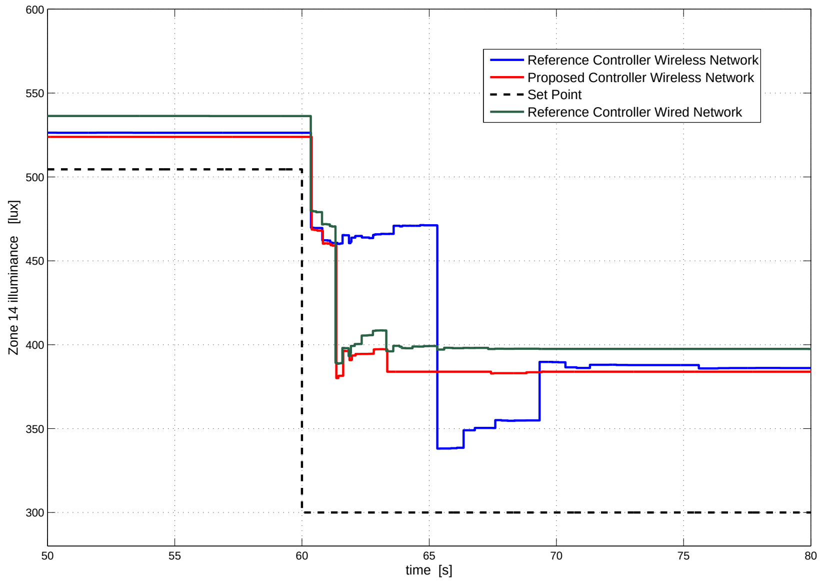


Figure 5.2: At $t = 60$ seconds, zone 14 changes its occupancy from occupied to unoccupied, while all the other zones remain occupied. The behavior of the reference and proposed controller are compared with the same sensor sampling ordering and timing. All the simulations have been run with Retry Limit set to 3, Loss Probability set to 1% and with daylight.

RL=0, after 20 seconds from the beginning of the simulations, the proposed controller achieves illuminance inside the 5% error band for 93.7% of zones against 74.4% for the reference controller, showing considerable improvement. Thus, one can conclude that with network redundancy in the wireless proposed controller, the performance gets close to the wired reference controller. The number of retries however cannot be made too high since this would lead to a larger load on the network, potentially leading to higher packet loss and network congestion.

5.3 Overshoot with occupancy change

To analyse overshoot under the two controllers, we consider the scenario where a zone gets an occupancy step while all the other zones are not occupied. For each zone, an occupancy step was simulated 200 times with different ordering of light sensor sampling, with daylight contribution. The overshoot results over every zone are depicted in Fig. 5.5. The box plot shows the median as the red line, the 75-th and 25-th percentile values as the box boundaries, and points outside 1.5 times the size of the box are displayed individually by red crosses [28]. The overshoot has been calculated taking the achieved illuminance of each zone as reference value.

From Fig. 5.5(a), we can observe that for the reference controller, the overshoot in zones 18, 26 and 27 is above the 20% limit; in particular, in zone 27 the overshoot percentage reaches 33.9% in an extreme case. We notice in Fig. 5.5(b) that with the proposed controller, only in one case the overshoot is over the 20% limit; it appears in zone 18 and it is 21.3%, above the limit but only in one of the simulation instances. Note from Figs. 5.5(a) and 5.5(b) that the overshoot is smaller in zones 29-34 compared to other zones. This is because the target illuminance in these zones may be easily achieved with the luminaires dimming down since these zones receive significant daylight contribution due to being close to the window.

5.4 Network load

We analyze the load on the network to ensure that the enhancements in the wireless proposed controller do not adversely increase the number of messages in the network in comparison with the wireless reference controller. In Fig. 5.6, we depict the percentages of sensor messages received at the controller for both the reference and proposed methods, assuming a packet loss probability of 1% and RL= 3. In Fig. 5.6(a), we can see that the amount of sensor messages received by the wireless reference controller has a large variance, while it decreases notably regarding the wireless proposed controller as shown in Fig. 5.6(b).

While the amount of outliers for both controllers is comparable by quantity and distribution, the variance and the average differs, indicating that it is more likely to have a situation where a large amount of sensor messages are correctly received with the wireless proposed controller. We notice also some outliers indicating a situation where only 20 or 30% of the sensor messages are received; these circumstances are due to the periodic nature of sensor sampling.

It can happen that a light sensor finds the wireless medium occupied when it is trying to send its packet and after an amount of retries specified by the communication protocol, it is forced to drop the packet. This situation can happen periodically every time interval, with little variations that randomly permit to the sensor message to reach the controller. This kind of condition is barely resolvable in the presence of a high-traffic network, as in our case.

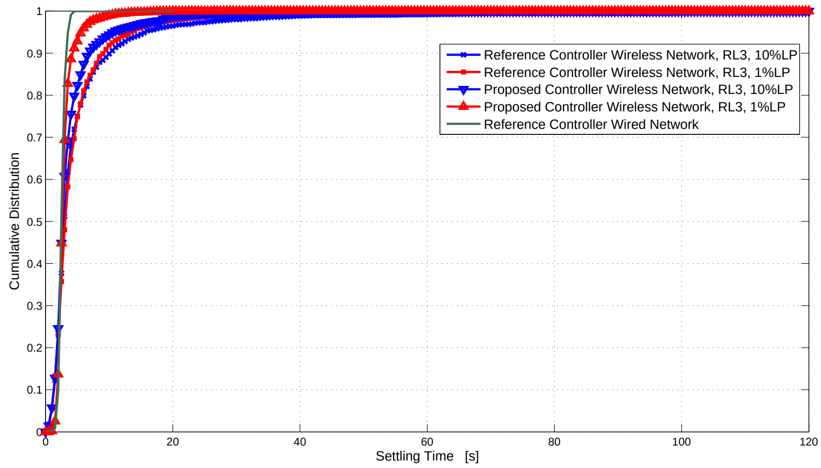


Figure 5.3: Settling time performance with Retry Limit = 3 and different values of Loss Probability.

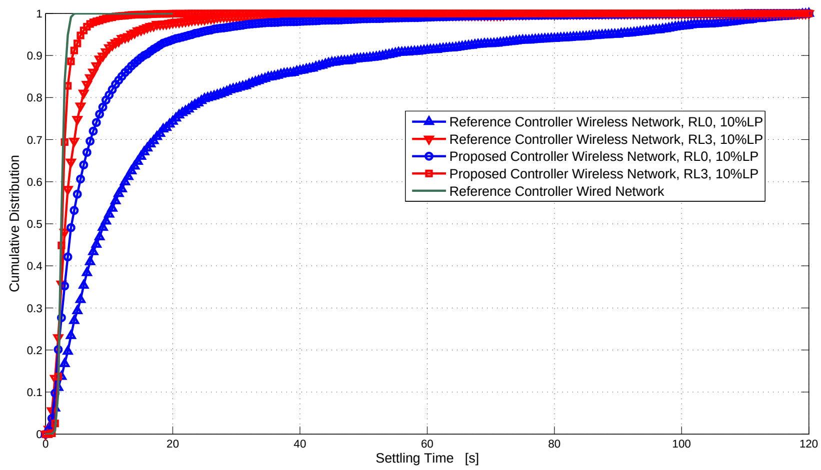
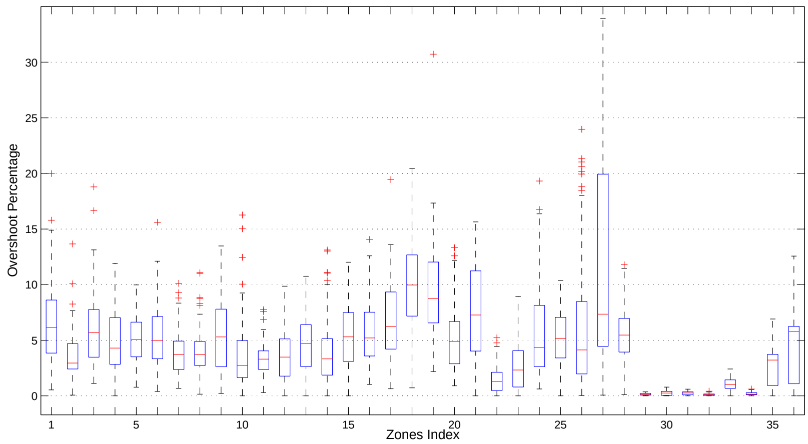
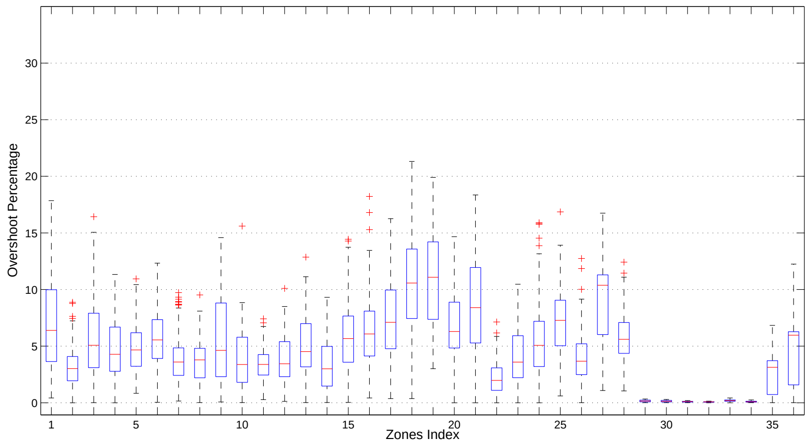


Figure 5.4: Settling time performance with 10% Loss Probability and different Retry Limits.

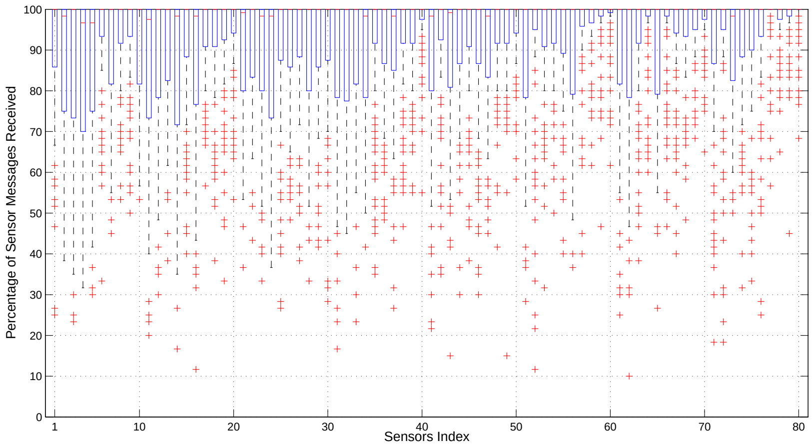


(a)

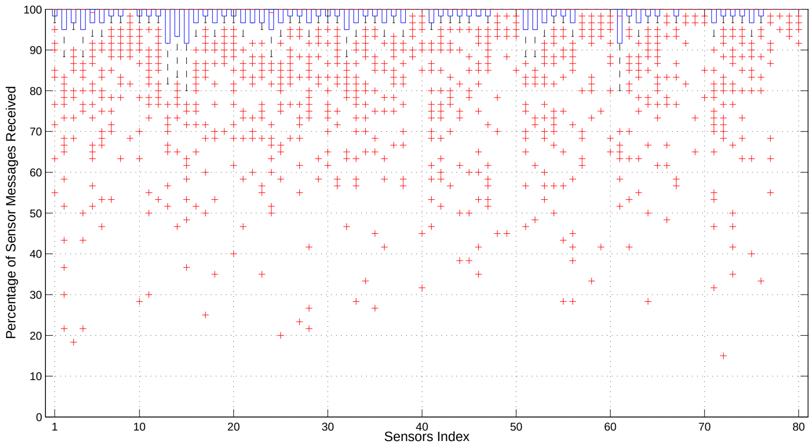


(b)

Figure 5.5: Comparison of overshoot percentage with (a) the reference and (b) the proposed wireless control systems. Simulations run with Retry Limit set to 3, Loss Probability set to 1% and with daylight.



(a)



(b)

Figure 5.6: Comparison of percentage of sensor messages received under (a) the reference and (b) proposed wireless control systems. Simulations run with Retry Limit set to 3, Loss Probability set to 1% and with daylight.

Chapter 6

Conclusions

Wireless lighting control in a system of multiple luminaires, with co-located light and occupancy sensors, and a central controller using stand-alone PI control laws is considered for daylight and occupancy adaptation. Wireless impairments were found to lead to a degradation in illumination performance, specifically resulting in an increase in settling time of luminaires due to packet losses. An enhanced PI control law along with transmission redundancy via message acknowledgements and retries were proposed to alleviate the effects of packet losses and shown to have a lighting behavior close to a wired reference controller system.

We presented a distributed wireless lighting control system in two different communication systems. The wired network was taken as a benchmark to underline the challenges in the transition from the wired to the wireless communication. The Reference Controller, which performances are shown in [7] in a wired network, loses its effectiveness in case of high amount of lost messages with the wireless network under consideration. The Proposed Controller was built to deal with this through an estimation and a threshold mechanism: it resulted in shorter settling times and overshoot under the 20% limit in 99.99% of simulations. Further improvements can be taken: maintaining the multiple SISO structure for the controllers, an application ACK can be built to have the exact information about the arrival of the dimming levels; moreover a MIMO controller can be designed to capitalize on the whole vector of illuminance measurements, not only to calculate dimming levels in a more complete way but also to use the periodical sensor sampling time to send messages during the gap when the medium is free.

Appendix A

TrueTime toolbox

An important tool used throughout this work is TrueTime [21]. TrueTime is a Matlab/Simulink-based simulator for real-time control systems. It facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics. It includes several features, as

- Written in C++ MEX, event-based simulation;
- External interrupts;
- Possibility to write tasks as M-files or C++ functions. It is also possible to call Simulink block diagrams from within the code functions;
- Network block (Ethernet, CAN, TDMA, FDMA, Round Robin, Switched Ethernet, FlexRay and PROFINET);
- Wireless network block (802.11b WLAN and 802.15.4 ZigBee);
- Battery-powered devices, Dynamic Voltage Scaling, and local clocks;
- Stand-alone network interface blocks;

It was developed mainly by Martin Hast, Martin Ohlin, Dan Henriksson, Anton Cervin and Johan Eker from Lund University in Lund, Sweden. All the networks, communication systems and simulation were run employing TrueTime.

Many parameters are tunable in every communication system. This appendix will analyse briefly the utilized parameters in the wired and wireless networks.

A.1 Wired Network Parameters

The wired network has been developed and designed first of all to test the controller behaviour and performances and to be a benchmark which refers to when discussing about the wireless network. The wired network was assumed to perform perfect communication, i.e. without any packet loss or random delay; communication among nodes was surely predictable.

The randomness was given only by the decision of the sensor sampling time, obtained thanks to the Matlab function `rand`. Assume that the sensor sampling is periodical with period T_s; assume also the controller divides the (continuous) time in intervals which length is T_s. The controller division of time was taken as the reference division of time.

Now there is still a degree of freedom in choosing when, inside each period $[k \cdot T_s, (k+1) \cdot T_s]$, the sensor i will sample the illuminance at the ceiling. That instant is the sensor sampling time; it is sufficient to choose it in the first time interval since the sensors are periodical.

This procedure was used to simulate a real initialization of the network, when sensors are activated randomly, in a non predictable order and with non predictable effective gap among them. Each simulation had a different array of sensor starting times, to test the network behaviour under several network configurations.

The wired network was built so that the whole process of sensing the illuminance, sending the measurement to the controller, receiving the sensor message, compute the PI law, sending the dimming level to the corresponding luminaire and setting it as the new dimming value will last 2 ms. This is the standard value already set in TrueTime and was found to be realistic.

A.2 Wireless Network parameters

The wireless network is the main object of the study. The communication protocol chosen is ZigBee, as explained briefly in 2.2. TrueTime offers a wide range of parameters to tune:

- **Network number:** the number of the network block. The networks must be numbered from 1 and upwards. Wired and wireless networks are not allowed to use the same number;
- **Number of nodes:** the number of nodes that are connected to the network;
- **Data rate (bits/s):** the speed of the network;

- **Minimum frame size (bits):** a message or frame shorter than this will be padded to give the minimum length. Denotes the minimum frame size, including any overhead introduced by the protocol;
- **Transmit power:** determines how strong the radio signal will be, and thereby how long it will reach;
- **Receiver signal threshold:** if the received energy is above this threshold, then the medium is accounted as busy;
- **Path-loss exponent:** the path loss of the radio signal is modeled as $1/d^a$ where d is the distance in meters and a is a parameter to model the environment;
- **ACK timeout:** the time a sending node will wait for an ACK;
- **Retry Limit:** the maximum number of times a node will try to retransmit a message before giving up.
- **Error coding threshold:** a number in the interval [0, 1] which defines the percentage of block errors in a message that the coding can handle. E.g., certain coding schemes can reconstruct a message if it has less than 3% block errors. The number of block errors are calculated using the SNR ratio, where the noise is all other ongoing transmissions.
- **Loss Probability:** the probability that a packet is lost during a transmission, due to the non perfect reliability of the wireless network;
- **Initial Seed:** the starting seed for the random number generator used to calculate the loss probability.

The ZigBee packet transmission model is specified in Fig. **??**.

The topology of the network is shown in Fig **??**. The controller is placed in the right top corner of the office, in the same plane of the sensor/actuators,i.e. at the ceiling. In this setting, the controller can reach in one hop 19 luminaires, in two hops 38 luminaires and in three hops 23 luminaires; to ensure the communication, 14 nodes act as bridge nodes: they carry on sensor messages and dimming levels for the more distant nodes but they represent also the bottle necks of the network. As an example, node 66 is loaded with X messages every T_s, this number must be multiplied by 2 (the number of sensor messages equals the number of dimming levels) to obtain the total number of messages that depends on this single node.

Chosen 10 meters as the maximum range of communication, which is a possible value for indoor applications, the topology was designed as follows:

each node inside the ten-meters-range from the controller was included in the one-hop section; from each node included in the one-hop section a new ten-meters-range was taken into account and the two-hops section was built as the union of all the nodes not included in the previous section but inside this new ten-meters-range. The remaining nodes constitute the three-hops section.

The communication path was designed following this rule: every node that can directly reach the controller will communicate in one-hop with it; otherwise, a node should communicate with the closest (in Euclidean norm) node with a lower number of hops. This intentionally led to a topology with bottle necks: the purpose was in fact to explore the impact of high packet loss rate on a PI wireless control.

The implementation of this network with TrueTime provides also the feature of adding random delays to every action taken by the nodes. The analysis of a period for a one-hop node provides this schedule:

- sensing the illuminance: 500 μs + δ_1;
- sending the measurement: 400 μs + δ_2;
- receiving the sensor message, calculating the dimming level and sending it: 500 μs + δ_3;
- receiving the dimming level and setting it as the new dimming level: 500 μs + δ_4

This leads to a total time for a single hop node of 1.9 ms + δ, where $\delta = \sum_{i=1}^{4} \delta_i$. These values were found as examples values and kept as close to reality. Obviously, if the node belongs to the two-hops or three-hops section, the total time increases with the number of hops.

Bibliography

[1] Energy Information Administration, *Commercial Buildings Energy Consumption Survey*, 2003.

[2] B. Roisin, M. Bodart, A. Deneyer and P. D. Herdt, "Lighting energy savings in offices using different control systems and their real consumption", *Energy & Buildings*, vol. 40, no. 4, pp. 514-523, 2008.

[3] D. Caicedo and A. Pandharipande, "Distributed illumination control with local sensing and actuation in networked lighting systems," *IEEE Sensors Journal*, pp. 1092-1104, Mar 2013.

[4] A. Pandharipande and D. Caicedo, "Daylight integrated illumination control of LED systems based on enhanced presence sensing," *Energy & Buildings*, pp. 944-950, April 2011.

[5] P. K. Soori and M. Vishwas, "Lighting control strategy for energy efficient office lighting system design," *Energy & Buildings*, pp. 329-337, Nov 2013.

[6] H. Wang, A. Pandharipande, D. Caicedo and P. P.J. van den Bosch, "Distributed lighting control of locally intelligent luminaire systems", *IEEE International Conference on Systems, Man and Cybernetics*, pp. 3167-3172, 2012.

[7] N. van de Meugheuvel, A. Pandharipande, D. Caicedo and P. P. J. van den Hof, "Distributed lighting control with daylight and occupancy adaptation", *Energy & Buildings*, pp. 321-329, June 2014.

[8] S. Afshari and S. Mishra, "Decentralized feedback control of smart lighting systems", *ASME Dynamic Systems and Control Conference*, 2013.

[9] EN 12464-1, Light and lighting - Lighting of work places - Part 1: Indoor work places, European Committee for Standardization, June 2011.

[10] D. Caicedo, A. Pandharipande and G. Leus, "Occupancy based illumination control of LED lighting systems", *Lighting Research and Technology*, vol. 38, no. 4, pp. 358-376, 2010.

[11] S.-H. Lee and J.-K. Kwon, "Distributed dimming control for LED lighting", *Optics Express*, pp. 917-932, 2013.

[12] M.-S. Pan, L.-W. Yeh, Y.-A. Chen, Y.-H. Lin and Y.-C. Tseng, “A WSN-based intelligent light control system considering user activities and profiles”, *IEEE Sensors Journal*, pp. 1710-1721, 2008.

[13] L.-W. Yeh, C.-Y. Lu, C.-W. Kou, Y.-C. Tseng and C.-W. Yi, “Autonomous light control by wireless sensor and actuator networks”, *IEEE Sensors Journal*, pp. 1029-1041, 2010.

[14] Y-J. Wen and A. M. Agogino, “Personalized dynamic design of networked lighting for energy-efficiency in open-plan offices", *Energy & Buildings*, vol. 43, no. 8, pp. 1919-1924, 2011.

[15] Y-J. and A. M. Agogino, “Control of wireless-networked lighting in open-plan offices", *Lighting Research and Technology*, vol. 43, no. 2, pp. 235-248, 2011.

[16] M. Miki, A. Amamiya and T. Hiroyasu, “Distributed optimal control of lighting based on stochastic hill climbing method with variable neighborhood", *IEEE International Conference on Systems, Man and Cybernetics*, pp. 1676-1680, 2007.

[17] D. Caicedo, A. Pandharipande, and F. M. J. Willems, “Daylight-adaptive lighting control using light sensor calibration prior-information", *Energy & Buildings*, pp. 104-113, Apr 2014.

[18] F. Rubinstein, “Photo-electric control of equi-illumination lighting systems," *Energy & Buildings*, vol. 6, pp. 141-150, 1984.

[19] F. Rubinstein, G. Ward and R. Verderber, “Improving the performance of photo-electrically controlled lighting systems,"*Journal of the Illuminating Engineering Society*, 1989.

[20] DIAL Gmbh, DIALux 4.11, Online: http://www.dial.de/DIAL/en/dialux/download.html.

[21] TrueTime 2.0 beta 7, Online: http://www.control.lth.se/truetime.

[22] Online: http://www.zigbee.org/Products/ByFunction/Lighting.aspx.

[23] A. Cervin, D. Henriksson, B. Lincoln, J. Eker and K.-E. Årzén, “How does control timing affect performance? Analysis and simulation of timing using Jitterbug and TrueTime", *IEEE Control Systems Magazine*, vol. 23, no. 3, pp. 16-30, 2003.

[24] J. Song, A. K. Mok, D. Chen, M. Nixon, T. Blevins and W. Wojsznis, “Improving PID control with unreliable communications", *ISA EXPO 2006*, Houston, TX, 2006.

[25] C. E. Perkins and E. M. Royer, “Ad-hoc on-demand distance vector routing", *IEEE Workshop on Mobile Computing Systems and Applications*, pp. 90-100, 1999.

[26] J.P. Hespanha, P. Naghshtabrizi, Y. Xu, "A Survey of Recent Result in Networked Control Systems", *IEEE Contr. Syst. Mag.*, vol. 95, no. 1, pp. 138-161, Jan. 2007.

[27] R.M.Murray, K.J.Astrom, S.P.Boyd, R.W.Brockett, G.Stein, "Control in an information rich world", *IEEE Contr. Syst. Mag.*, vol. 23, no. 2, pp. 20-33, Apr. 2003.

[28] Online: http://www.mathworks.nl/help/stats/boxplot.html

[29] Online: http://www.philips.com/about/company/

[30] Online: http://www.journals.elsevier.com/energy-and-buildings/

[31] Online: http://www.hightechcampus.com/

[32] Online: http://www.journals.elsevier.com/energy-and-buildings/