Cost Analysis of Smart Lighting Solutions for Smart Cities

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***Abstract*—Street lighting is an essential community service, but current implementations are not energy efficient and and require municipalities to spend up to 40% of their allocated budget. In this paper, we propose heuristics and devise a comparison methodology for new smart lighting solutions in next generation smart cities. The proposed smart lighting techniques make use of Internet of Things (IoT) augmented lampposts, which save energy by turning off or dimming the light in the absence of citizens nearby. Assessing costs and benefits in adopting the new smart lighting solutions is a pillar step for municipalities to foster real implementation. For evaluation purposes, we have developed a custom simulator which allows the deployment of lampposts in realistic urban environments. The citizens travel on foot along the streets and trigger activation of the lampposts according to the proposed heuristics. For the city of Luxembourg, the results highlight that replacing all existing lamps with LEDs and dimming light intensity in the absence of users in the vicinity of the lampposts is convenient and provides an economical return already after the first year of deployment.**

I. Introduction

World population living in cities has experienced an unprecedented growth over the past century. While only 10% of the population lived in cities during 1900, nowadays this percentage corresponds to 50% and is projected to increase in upcoming years [1]. Sustainable development plays therefore a crucial role in city development. While nearly 2% of the world's surface is occupied by urban environments, cities contribute to 80% of global gas emission, 75% of global energy consumption [2] and 60% of residential water use [1].

With the aim of improving citizens' quality of life, significant research efforts are undergoing to provision citizens innovative and sustainable solutions for public services such as healthcare and wellbeing, safety and smart transportation among the others [3]. To achieve these objectives, smart cities rely on Information and Communication Technology (ICT) solutions [4], [3]. The application of the Internet of Things (IoT) paradigm to urban scenarios is of special interest to support the smart city vision [3], [5]. IoT is indeed envisioned as the candidate building block to develop sustainable ICT platforms. In IoT, everyday life objects are "smart", i.e., they are uniquely identifiable and are equipped with computing, storage and sensing capabilities and can communicate one with each other and with the users to enable pervasive and ubiquitous computing [6], [7]. Proper exploitation of the variety and the potentially enormous volume of the data generated by these devices will foster the development of innovative applications in a broad range of domains. Including citizens in the loop with crowdsensing approaches augments capabilities of existing infrastructures without additional costs and is proved to be a win-win strategy for smart city applications [8], [9], [10], [11].

Public street lighting[1] is a traditional service provided by lampposts distributed on streets and roads. Equipping lampposts with sensors and communication technologies, thus making them IoT-based, enables a number of new services. Lampposts can be employed to monitor traffic, noise and air pollution, increase coverage of cellular and WiFi networks and enable Visible Light Communications (VLC) [12], [13]. Unfortunately, the cost of deploying new IoT-based lighting infrastructure is high, while the benefits are often unclear and need to be quantified. For this reason, in this paper we provide an analysis on costs and benefits in deploying an IoT-based infrastructure for the *sole* service of public lighting. We infer that assessing the effectiveness IoT-augmented lampposts for their primary service is essential to motivate municipalities in investing into the development of new infrastructure.

In this paper, we develop three new heuristics for smart lighting that are that are designed to reflect technology used in lamps. For example, lamps that are based on Light-Emitting Diode lamps (LEDs) can light up/dim the light intensity, while High Pressure Sodium (HPS) cannot. As a result, LEDs combined with sensing of presence can be used to dim the light intensity when people are passing in the lampposts' vicinity. On the other hand, HPS-based lampposts can only turn on or off the lamp. This makes each smart lighting solution to bring in different level of energy saving. For performance evaluation, we exploit a custom-built simulator, where lampposts are deployed in realistic urban environments. Users walking on streets trigger activation of the lampposts according to different smart lighting solutions. The results show that in a pedestrian area with nearly 500 lampposts, replacing all existing lamps with LEDs becomes beneficial already after the first year of deployment. Adopting HPS lamps and turning them on in the presence of users and off otherwise reduces annual operational expenditures by nearly

Dr. Claudio Fiandrino developed this work as a Ph.D. student at the University of Luxembourg.

[1] In this paper we use the terms street lighting, public lighting and smart lighting interchangeably.

Table I
COMPARISON OF LAMP FEATURES AND TECHNOLOGIES

TYPE OF LAMPS	NOMINAL WATTAGE (W)	LAMP EFFICACY (LM/W)	ENERGY CONSUMPTION (KWH/1000 H)	AVERAGE LIFE (H)
HPS-97241	150.0	110.0	172.7	24 000
HPS-93010296	250.0	129.0	283.4	24 000
MH-NaSc	100.0	90.0	165.0	10 000
LED-GRN60	46.8	131.0	51.8	100 000
LED-GRN100	73.3	138.0	82.7	100 000

60% with respect to current implementations.

The rest of the paper is organized as follows. Section II presents background on smart lighting, including comparison of the available technologies and current trends. Section III proposes the three new heuristics. Section IV details the comparison methodology used in Section V for performance evaluation. Section VI concludes the work outlining future research directions.

II. BACKGROUND ON SMART LIGHTING

The Europe 2020 Strategy defines three targets for climate change and energy: (i) 20% reduction of greenhouse gas emission, (ii) 20% increase in energy production from renewable sources, and (iii) at least 20% increase of the energy efficiency [14]. Street lighting attributes nearly 19% of the worldwide use of electrical energy and entails 6% of global emissions of greenhouse gases. A decrease of 40% of energy spent for lighting purposes is equivalent to eliminating a half of the emissions from the production of electricity and heat generation in the US [15]. In this context, public street lightning, which is an essential community service, plays an important role, as it impacts for around 40% on the cities' energy budget. Consequently, in preparation of the EU commitments, optimizing the lighting service is a primary objective for the municipalities [16].

The street lighting solutions currently implemented in cities are not energy efficient. Typically, every lamp operates at full intensity 12 hours a day on average: 8 hours during summer and 14 hours during winter period [16]. As a result, the costs the municipalities sustain are high [15]. A number of different types of lamps are applicable for public street lighting, including High Pressure Sodium (HPS), Metal-halide (MH) lamps, Compact Fluorescent lamps (CFL) and Light-emitting diode (LED). The list does not comprise all possible technologies. For example, the use of mercury-vapor lamps for lighting purposes was banned in the EU in 2015 [17]. HPS is the most common technology currently implemented in EU streets [18]. Nevertheless, in terms of average lifetime, maintenance, electrical performances and energy savings, LED technology appears to be the most convenient solution [19].

Table I compares different types of lamps. LEDs have an average lifetime 4 times longer than HPS lamps and 10 times longer if compared to MH lamps. Installing LEDs is effective to reduce hardware, installation and maintenance costs. Low wattage provides significant energy savings and allows increasing the lamp efficiency [20], [21]. LED lamps can dim the light intensity by more than 50% modifying therefore the output level of light according to the circumstances. For example, when traffic is low or in rarely visited areas of the city, like the parks at night. The city of Brittany in France, dims street lights by 60% between 11 PM and 5 AM to decrease waste energy [16].

III. SMART LIGHTING SOLUTIONS

This section presents three new heuristics proposed for smart lighting and explains the employed underlying technologies and control mechanisms in detail. In the context of energy-aware lighting, a number of control mechanisms was proposed [22]. The most important strategy is *occupancy*, which makes lamps to switch on/off or to dim the light intensity according to the presence of users or vehicles. In this paper, we adopt the occupancy control strategy suitable for pedestrian zones in smart cities.

The control of street lighting can be performed in distributed or centralized manner. With the latter method, a coordinator unit is responsible to control a cluster of lampposts on the basis of their feedback on users presence [23]. With the former method, each lamppost operates independently. Distributed control systems require significant changes in the existing infrastructure, while centralized solutions can be deployed with minor intervention. However, as the employed control policy is occupancy-based, distributed systems have the potential to achieve higher energy savings because they react to the change of user presence faster. In this work, we adopt a completely distributed system.

Table II briefly summarizes properties of the three different smart lighting solutions proposed in comparison with current adopted approach. For each method, its efficiency is denoted as low (LO), medium (ME) and high (HI).

Current Implementation (CUR): The most widely implemented methodology for street lighting makes lampposts to operate at full light intensity for a predefined period of time. Typically lampposts operate continuously for an average of 10 or 12 hours a day [16]. This solution does not account at all for the presence of users passing nearby the lampposts, and as a result, it is expected to be the lowest in terms of efficiency (see Table II).

Unlike CUR the heuristics we propose take into account the presence of users nearby the lampposts to save energy, which is achieved by installing a presence sensor like the SE-10 PIR motion sensor [24]. With presence sensors, every lamppost is able to recognize the presence of citizens within a certain radius R, as illustrated in Fig. 1.

Table II
SMART LIGHTING SOLUTIONS

METHOD	ACRONYM	DESCRIPTION	EFFICACY
Current	CUR	Lampposts remain continuously active emitting maximum light intensity.	LO
Delay-based	DEL	Lampposts are switched on when users pass nearby. If nobody is present within the coverage radius R, the lampposts remain active for time window W and then are switched off.	HI
Encounter-based	ENC	Lampposts are switched upon the first encounter with at least one user and remain active the whole night.	ME
Dimming	DIM	Lampposts operate at 60% light intensity in absence of users within the coverage radius R. Lampposts light up/dim the light intensity in proportion to the number of users passing nearby.	HI

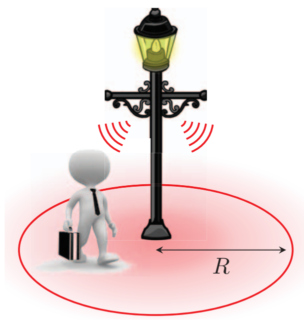


Figure 1. Coverage radius R

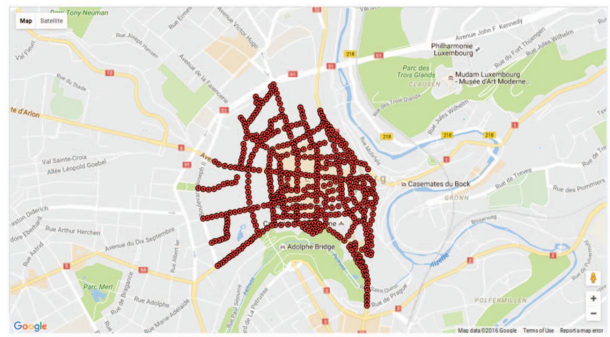


Figure 2. Position of lampposts in Luxembourg city center

Delay-based (DEL): The lampposts remain active and operate at full intensity as long as the motion sensor detects presence of users. The lamp is turned off if no users are sensed in the vicinity and during a time window W nobody passes nearby. Then, whenever a pedestrian approaches the lamppost closer than the distance R, it triggers re-activation of the lamp. This methodology can employ both LEDs and HPSs lamps. For HPSs lamps, that are currently the most widely adopted in our cities [25], it might take around 15 minutes to the lamp to reach the maximum brightness after turning on, because the sodium inside the bulb needs to be fully heated [26]. As a result, DEL should be a preferred method for LED lamps.

Encounter-based (ENC): This method is a modification of DEL. The lampposts turn on after the first user passes nearby and remain active until the end of the predefined activity period in the morning. Although being simple, the method improves CUR. Moreover, as lamps do not need to be switched on and off frequently, HPS technology and not LEDs can be employed lowering the capital expenditures significantly. For this reason, Table II rates ENC to be medium efficient.

Dimming (DIM): The last proposed method dims the light of lampposts in proportion to the number of users in the vicinity. Similarly to the solution adopted in Brittany, i.e., the minimum light intensity level is 60% if no users are within the coverage radius R. Lampposts then light up or dim the intensity level in proportion to the number of users passing in the vicinity. In more details, if the number of users within R is increasing, the light intensity increases up to 100% or remains at that level. On the contrary, if the number of users within R reduces, so does the light intensity until it reaches the minimum level. Having a minimum level of light intensity fixed at 60% ensures sufficient luminosity to detect obstacles, animals passing by while providing at the same time considerable energy savings in under utilized scenarios. The HPS lamps do not support dimming [19] and only LEDs can be employed to perform dimming properly. The use of LEDs is gradually gaining popularity due to its photo metric characteristics, such as low weighted energy consumption (kW/1000hrs), high luminous efficacy (lm / W), high mechanical strength, long lifespan and reduction of light pollution [18], [19]. This solution is expected to be highly efficient (see Table II).

IV. COMPARISON METHODOLOGY

This section presents the methodology adopted to evaluate and compare the performance of the proposed smart lighting solutions. For the purpose, we have built a custom discrete-event simulator, which follows the design criteria illustrated in [27], [28] supports realistic urban environments for the deployment of lampposts on the streets and pedestrian mobility.

The center of Luxembourg city was selected for simulations. It covers an area of 1.11 km^2 and is the home of many national and international institutional buildings. To obtain information about the streets of the city, the simulator exploits a crowdsourced application which provides free access to street-level maps[2]. The information is given in the form of coordinates $\mathcal{C}$ that contain $<$*latitude, longitude, altitude*$>$. The set of 537 lampposts has been deployed according to their physical location in the streets and squares (see Fig. 2).

The users move along the streets of the city, with their original locations randomly assigned from the set of coordinates $\mathcal{C}$. The number of users is set to 5 000, which corresponds to nearly one twentieth of the population of Luxembourg (110 499 inhabitants as of the end of 2015). Each user walks for a period

[2]DigiPoint: http://www.zonums.com/gmaps/digipoint.php

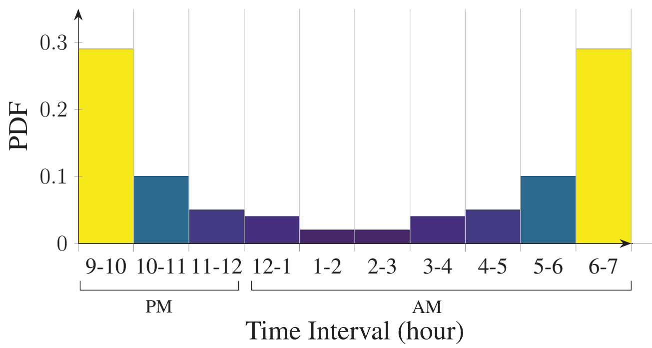


Figure 3. PDF of user mobility during the evaluation period

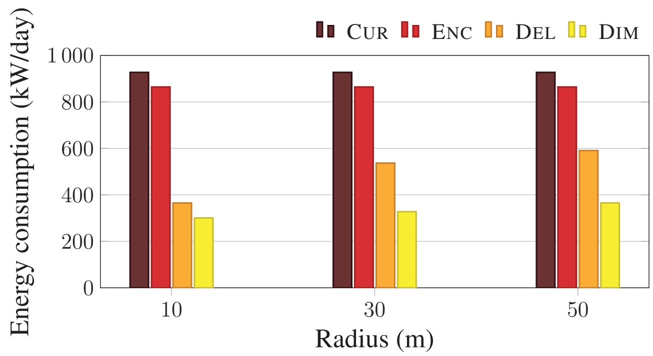


Figure 4. Comparison of smart lighting solutions

of time uniformly distributed between $[10, 20]$ minutes with an average speed uniformly distributed between $[1, 1.5]$ m/s. The users begin walking according to a specific arrival pattern. During the evaluation period, set between 9 PM and 7 AM, each user has a probability to start traveling that is defined by the probability density function (PDF) defined in Fig. 3. To illustrate with an example, during 9 PM and 10 PM nearly one third of the total number of users starts walking and at 7 AM all 5 000 users end traveling.

V. Performance Evaluation

For performance evaluation, the experiments are carried on varying the coverage radius R and the time window W. In more details, R assumes values equal to $\{10, 30, 50\}$ m, while W assumes values equal to $\{2, 5, 10, 20\}$ minutes only for the DIM method.

Fig. 4 compares the smart lighting solutions proposed in terms of energy consumed per 10 hours activity, which corresponds to a day. As expected, the current implemented methodology (CUR) is the least efficient if compared to the proposed heuristics. The ENC method improves CUR by nearly 7%. As the lampposts turn on only upon detection of users nearby, some of the lampposts remains initially idle while in CUR all the lampposts are active starting from 9 PM. The most energy efficient techniques are DEL and DIM. For the DIM method, Fig. 4 shows the results for a time window $W = 5$ minutes. Both methodologies are most effective for short values of R because the probability of having users nearby the lamppost is lower. However, different values of R impact differently on the performance of DEL and DIM. For the former method, the energy consumption augments of nearly

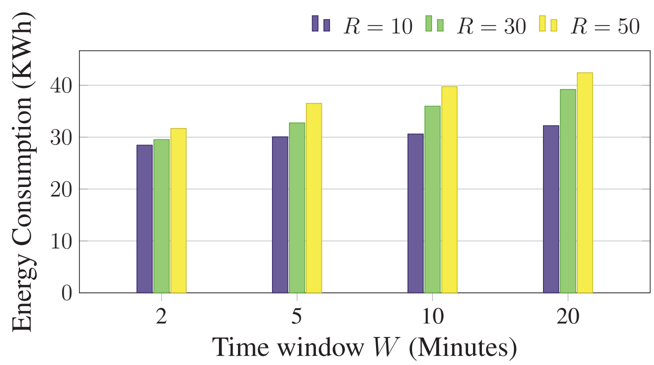


Figure 5. Impact of W on performance of DIM for different values of R

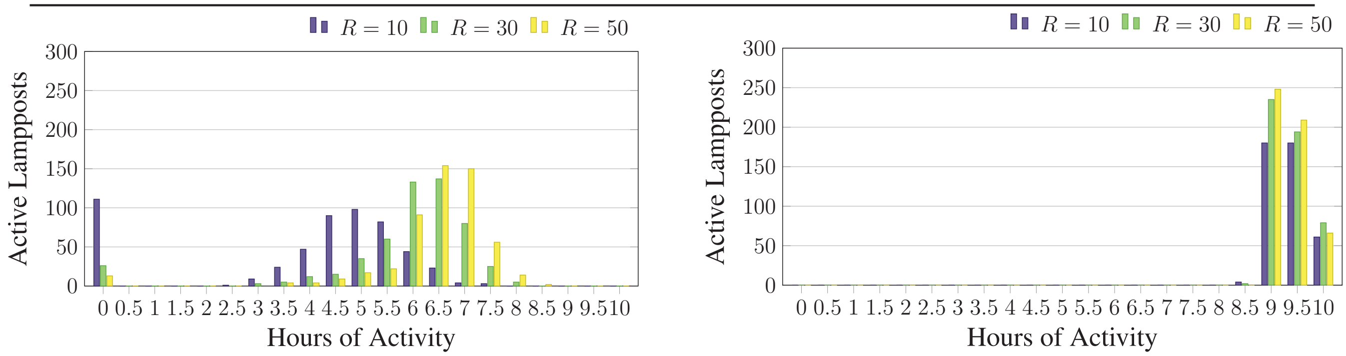
38% while for the latter the increase is *only* 17%. Two are the main reasons: i) the LEDs used in DIM are more efficient than HPS lamps used for DEL, ii) the DIM checks presence of nearby users every more often than DEL.

Having determined the energy costs per kWh in different countries according to [29], [30], [31], Table III compares the daily cost to operate for a 10 hours long period the proposed smart lighting solutions. The values of energy consumption of each method are determined as the average over 100 simulation runs of the energy consumption of all the 537 lampposts. Table III compares capital and operational expenditures (CAPEX and OPEX respectively). The OPEX costs are determined for 537 lampposts for a time period of 1 year without considering salary costs of workman for installation and maintenance. Consequently, the analysis focus completely on energy costs that directly originate by operating the platform. CAPEX costs are determined considering the additional sensor components necessary to make operational the methods. In CUR and in ENC methods, every lamppost is equipped with an HPS-97241 lamp [21]. In order to implement ENC, it is essential to add a micro-controller (model PIC12F635 [32]) and a presence sensor (model SE-10 [33]) per lamppost. For DEL and DIM in addition to the previous components, the lamp is not an HPS, but a LED lamp (model GRN100 [20]) described in Table I. Interestingly, with a focus on Luxembourg, Table IV shows that DIM would be beneficial in providing an economical return already in his first year of implementation. The ENC method does not bring considerable advantages over CUR. However, it is worth mentioning that the simple operation of not turning on all the lampposts simultaneously saves operational expenditures for 6.7%. Implementing ENC is nearly $8\times$ cheaper than implementing DEL and DIM, but the latter methods significantly lower the yearly OPEX costs.

Fig. 5 analyzes the impact of the time window W used to check the presence of users nearby on the energy performance the DIM solution provides. The analysis is carried on with different values of the coverage radius R. As expected, the energy consumption increases with the increase of W and R. Interestingly, the contribution given by R in the increase of energy consumption is higher for high values of time window W. For $W = 2$ and $W = 20$, the increase of energy consumption from values of $R = 10$ to $R = 50$ is respectively 10% and 24%.

Table III
COST COMPARISON OF SMART LIGHTING SOLUTIONS FOR DIFFERENT COUNTRIES

COUNTRY	ENERGY COST (€ / KWH)	METHOD (€)			
		CUR (927.4 kWh per day)	ENC (865.1 kWh per day)	DEL (384.0 kWh per day)	DIM (298.5 kWh per day)
Luxembourg	0.18	166.9	155.7	69.1	53.7
Italy	0.24	222.6	207.6	92.1	71.6
Germany	0.29	268.9	250.9	111.3	86.6
France	0.17	157.6	147.1	65.3	50.7
China	0.07	64.9	60.5	26.9	20.9
USA	0.10	92.7	86.5	38.4	29.8



(a) DEL method

(b) ENC method

Figure 6. Distribution of lamppost activity

Table IV
COST ANALYSIS IN LUXEMBOURG

METHOD	COST EXPENDITURE (€)		
	CAPEX	OPEX	TOTAL
CUR	–	60 930	60 930
ENC	4 779	56 835	61 614
DEL	36 999	25 227	62 226
DIM	36 999	19 611	56 610

Having compared the performance of the proposed smart lighting solutions in terms of energy consumption, we now investigate the distribution of hours of activity for the DEL and ENC. The results are displayed with the granularity of 30 minutes. Unlike the other smart lighting solutions, these methodologies turn off the lampposts if nobody is passing nearby. The DEL method, being more energy friendly than ENC, reduces the hours of activity of the lampposts in proportion to the coverage radius R. Fig. 6(a) clearly highlights that the distribution of the number active lampposts follows a normal distribution whose center changes for different values of R. The higher the values R assumes, the higher is the average number of hours the lampposts remains active. The lower the values R assumes, the more energy efficient the DEL policy becomes. The number of lampposts that remain switched off is higher and on average, the lampposts are active for shorter time periods. Fig. 6(b) shows the distribution of the hours of activity for the ENC method. As the lampposts remain active until the end of the period once turned on, the distribution is significantly different than the one obtained for the DEL method and the impact of R is almost negligible. Having fixed $R = 10$, Fig. 7 compares with a heatmap the hours of activity of the lampposts for both DEL and ENC methods. The results are obtained with Google Heatmap tool[3].

VI. CONCLUSION

Smart lighting solutions can significantly decrease energy costs of street lightning municipalities. In this paper, we propose three new heuristics for smart lighting based on the peculiar characteristics of the employed technology. LEDs allows to dim the light intensity while HPS lamps are turned off if nobody is passing nearby the lampposts. We developed a custom simulator to evaluate the proposed smart lighting solutions in a real city environment.[4] The results highlight that LED technology combined with dimming of light intensity provides higher energy savings than other evaluated solutions. In Luxembourg city center, replacing all existing lamps with LEDs is beneficial financially already after the first year of deployment, while in other countries like China and USA economic returns will come after the second year of installation.

For future work, we plan to investigate more advanced solutions, such as how to coordinate light dimming of lampposts of each street according to the prediction of user mobility patters.

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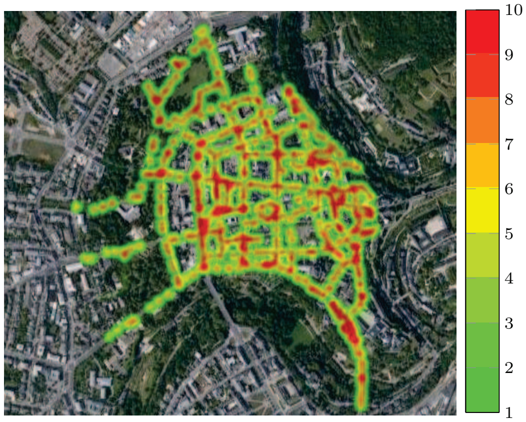

(a) DEL method

(b) ENC method

Figure 7. Heatmap of lampposts activity (values in hours of activity)

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