Agent-based modeling and radio frequency energy harvesting: a proposal for smart street lighting

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Abstract

This paper proposes a solution to one of the most relevant problems in the field of energy saving and environment preservation: light pollution, which hides the natural brightness of the night sky and afflicts in many ways the circadian cycle of both humans and animals.

The suggested solution starts from already existing considerations and experimentations on the viability of an intelligent system to control street lights, so that it is possible to avoid unnecessary lighting - meaning more energy will be saved - when streets are empty.

In order to do that, a suitable network should be prepared to allow communications. To complete the eco-friendliness of the project, such a network of transmitting and receiveng devices should be able to self-sustain; this is finally achieved with energy harvesting from the ambient, implementing some of the newest technology developed in the field of rectennas for RF energy harvesting, which means recycling unused energy dispersed on the most crowded frequency of wifi, 3G and digital TV.

1. Introduction

Light pollution is a serious threat to the environment and an important cause of energy wasting through over-illumination.

Reducing light pollution is a compelling necessity not only for wildlife and human health, but also for the economy (nearly 60% of the electricity produced is used for street lighting due to its continuous operation during night time)[1][2]. In such a critical time for what regards energy resources, it is essential to implement new technologies for saving and recycling.

During the past few years, a step toward a greener lighting system has been made by substituting traditional bulbs with LED arrays. Nevertheless a part of the old problems persists, while newer are being unveiled by recent studies.

2. Background

2.1. The problems of LED street lighting

As shown in [3], LED street lighting has many advantages when compared to HPS (High Pressure Sodium bulbs[1]); with nearly the same level of illuminance, it shows higher scotopic luminous efficacy (lm/W) and Color Rendering Index (CRI), thus being the most suitable choice to light streets at night.

[1] The most common traditional street lightning

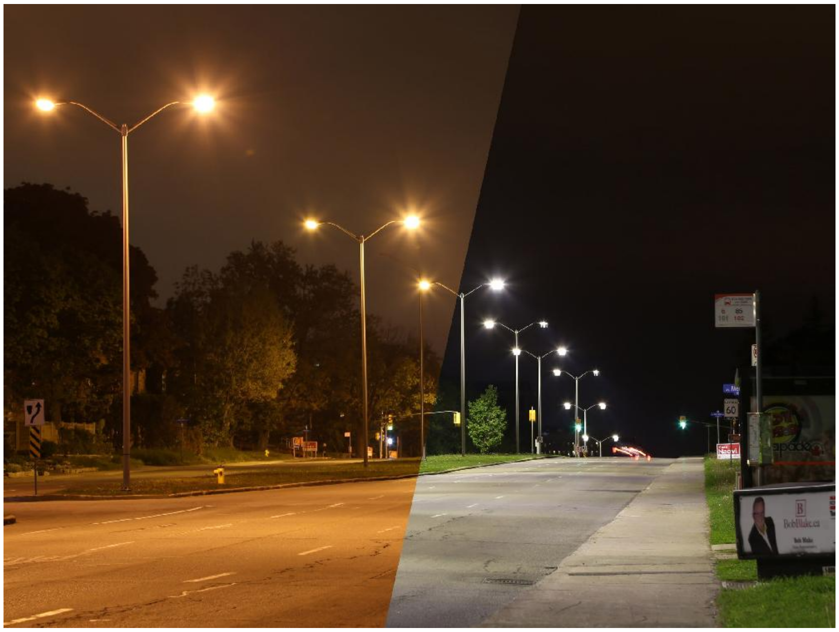

Figure 1: Comparison between HPS (left) and LED (right) lighting.

But if it's true that LEDs prove to be an efficient energy saving technology (especially when coupled with renewable energies[4]), on the other hand they increase light pollution[5] and interfere with the night activity and life cycles of various animals[6]. Furthermore, studies have also highlighted evidence of potential harm to citizens, as prolonged exposure to radiation in the blue band (for example from windows facing the street) alters melatonin production and circadian cycle[7].

2.2. Already proposed solutions

The simplest solution may be the deployment of smart street lighting which could reduce light-time to the bare minimum, hence cutting down light pollution and electrical costs.

The concerns in the development of such a project would be many; firstly the sensor network, the communication between nodes and the overall topology of the graph. Secondly, a pivotal factor would certainly be the efficience of the algorithm that establishes the brightness of each street lamp, not to mention its scalability and resilience to faults.

In [8] it was studied the possibility to exploit already existing powerlines as hardware support to connect each sensor unit with a common central controller, while in [9] it is suggested to use wireless transmission with the Zigbee specification - chosen among others for its very promising low-power requirements.

3. Proposal

3.1. Infrastructure

As exposed in the works cited before, the cheapest and less invasive options available are PLC and wireless communication (such as Zigbee or Bluetooth LE). Each has its own advantages and disadvantages; in terms of security, it should be noted that PLC guarantees better protection towards hacking, while wireless communication is generally more vulnerable to jamming. However, wireless offers a better deal in terms of costs and flexibility, while security problems could be significant only in domotic technologies and relatively contained in street lighting.

Indeed, these two technologies are quite on a par if we only consider the problem of converting old poles into smart ones; however, when it comes to deploy new lights or build new network paths, PLC involves the placement of new powerlines - an expensive task that could easily be avoided by new LED light posts fed with renewables[4] and connected to a wireless and self-sustained network, as shown in picture 2.

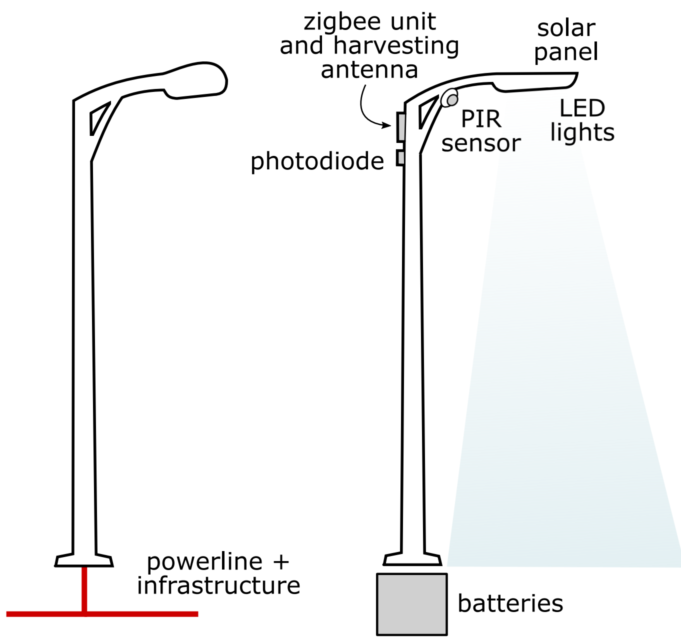

Figure 2: Left: a traditional street light fed by powerline that could also be adapted for communication. Right: design proposed in this paper. It is interesting to observe that this would need no physical connections to the grid.

Furthermore, a wireless network could more smartly rearrange itself after sudden changes or faults in the communication path.

3.2. Sensors

Each pole, or signpost light, should be provided with two sensors: a 360^o pyroelectric PIR[2], triggered by vehicles and pedestrians passing by, and a photodiode for the

[2] Passive Infrared Sensor

detection of natural brightness level, which should be appropriately calibrated in terms of perceived lumen.

3.3. Communication module and harvesting antenna

The sensor unit should be coupled with a zigbee node capable of receiving and transmitting. A microstrip antenna would also be included, which would be optimized to harvest ambient RF[3] energy.

3.4. Network organization and algorithm for brightness management

This paper suggests the implementation of a locally distributed network where each light acts like an autonomous agent, communicating with the outside through sensors and a zigbee transmitter/receiver.

Following the algorithm exposed in figure 4 lights are oblivious to the general structure of the network and, relying on the fact that the range of a zigbee low-power signal is $\sim 20m$, have an actual knowledge limited to their neighbours. They are absolutely independent and can elaborate with no need to receive orders from the outside, thus making the network more resilient.

Besides, a decentralized network would be implemented with the aid of central controllers (from now on, CCs) to manage accidents and defects. Indeed, when a light detects any problem it sends a message that jumps from one pole to another - in respect to zigbee radius - until it reaches its reference CC which, in turn, evaluates the priority of the problem and arranges technical fixing.

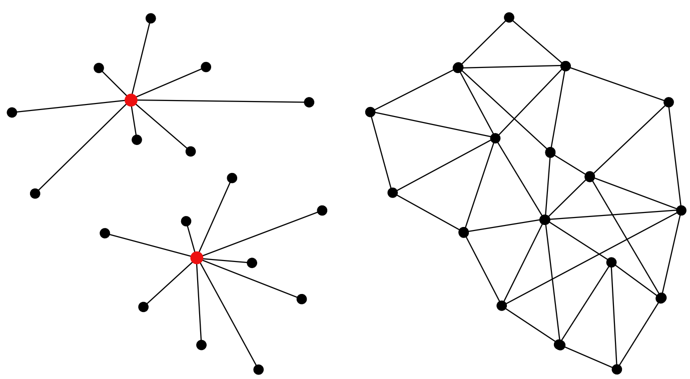

Figure 3: Left: a decentralized network. Right: a distributed network. Each one has its own advantages and disadvantages, but a distributed one is generally stronger to attacks and flexible to faults. In this case, a distributed network has been chosen for communication between lights, while a decentralized one is implemented to handle errors and technical assistance for every neighbourood.

[3]Radio Frequency

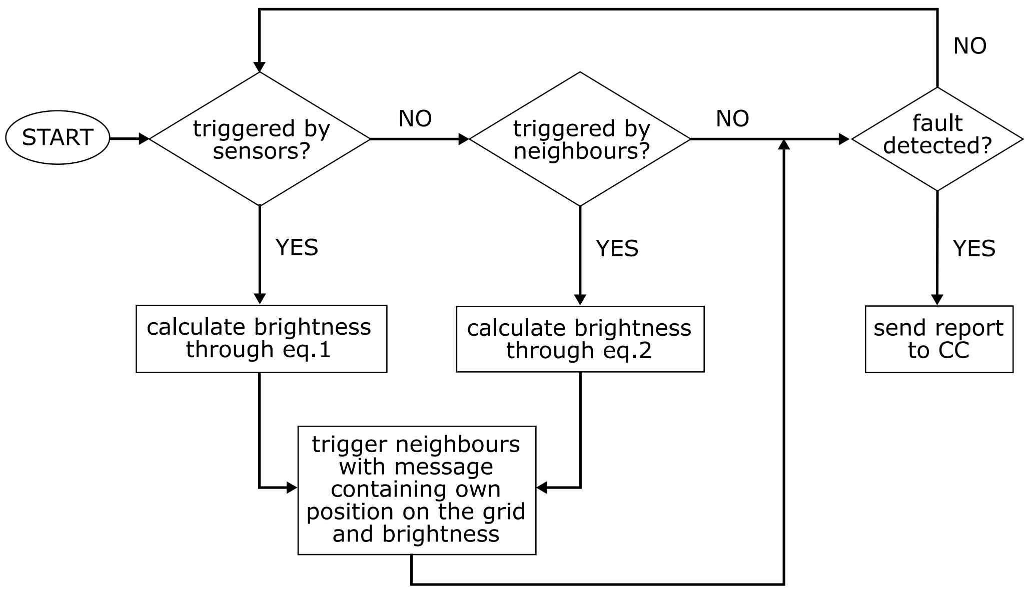

Figure 4: Flowchart of the algorithm suggested for brightness management. Equations (1) and (2) are exposed below.

$$l(l_0) = 1 - l_0 \tag{1}$$

$$l(\boldsymbol{r}, \boldsymbol{r_1} \cdots \boldsymbol{r_n}, l_0) = \min\left(1, Q \sum_{j=1}^{n} \frac{l_j}{|\boldsymbol{r} - \boldsymbol{r_j}|^K}\right) - l_0 \tag{2}$$

Equations (1) and (2) express the brightness l of a single light with values from 0 to 1, with 0 meaning the light is turned off and 1 meaning it is shining with maximum power.

Referring to figure 4, the first equation is used when PIR sensor is triggered by movement near the pole. Consequently (1) is a function solely dependent on the natural light l_0, so that artificial light can be adapted to actual needs.

The second equation is used when the zigbee receiver/transmitter intercepts a signal from one of the lights in its range. So, (2) is far more complex and requires appropriate Q and K parameters. Since the radius of the light circle around a vehicle/pedestrian and the quickness of its fading depend on these, their values should be determined by the distance between poles, road width and other factors - weather conditions, for example, which could be monitored through additional sensors on the pole.

Equation (2) evaluates brightness in dependency of distance and brightness of other turned on lights. This explains the presence of a summation on the n lights that may be sending a signal, all at the same time, to our pole. In this summation, $\boldsymbol{r_j}$ is the position on the grid of each transmitting node and l_j is its brightness.

It should be noted that, as shown in figure 5, since a transmitting node might not have been triggered by its PIR sensor but by another light, a chain builds up and must opportunely be interrupted when equation (2) returns $l \sim 0$.

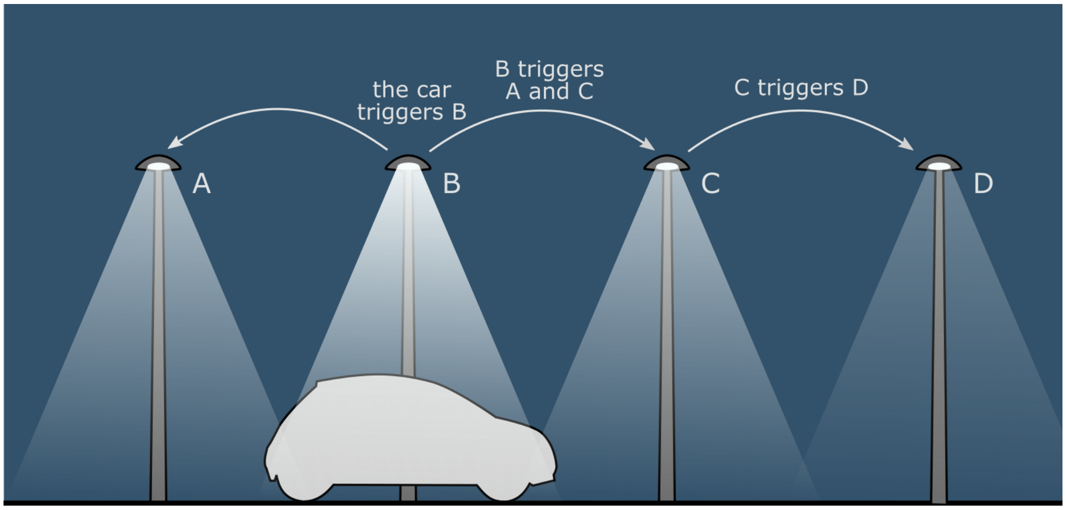

Figure 5: Example of how lights would interact with one another and with anything that could pass by them.

4. Feasibility and impact analysis

4.1. Energetic sustainability

Smart light poles could efficiently sustain themselves in terms of energy consumption. Indeed, assuming that an average LED street light requires a supply between 40 and 100 W (depending on the brightness, namely the lumens produced), the latter would be continually sustained for $12-14$ hours implementing a lead-acid battery - which should be preferable for its high power-to-weight ratio - charged with solar panels with a nominal power ranging between $70-80$ Watt-peak for at least 5 hours during the day.

Besides, communication nodes would sustain themselves thanks to RF energy harvesting antennas [10], which should be accurately designed to have the higher gain possible in the most crowded frequencies in urban areas; these are the one associated with DTV, GSM and 3G as shown in [11], where data from a survey in London are exposed.

Referring to [12] it can be observed that zigbee protocol proved to be the better choice for communication, both in terms of low power requirement and responsiveness. Furthermore using the following equation:

$$P = \frac{S\lambda^2 G}{4\pi} \tag{3}$$

where λ is the mid-band wavelength in which we are harvesting, S the average power density and G the antenna gain (both referred to λ), it is possible to predict the average power that could be harvested. Under the ipothesis of $G \sim 14$ dB[13], table 4.1 has been filled combining (3) with data from [11] and [12].

Band	Frequencies (MHz)	Average harvested power (μW)
DTV	470-610	$3,11$
GSM900 BTx	925-960	$41,07$
GSM1800 BTx	1805-1880	$23,95$
3G BTx	2110-2160	$2,62$

Table 1: Average harvested power with a 14 dB antenna in London, according to [11]. It should be noted that data about DTV might be highly underestimated, since measures has been done during digital TV switchover.

If we assume good efficiency in converting and storing energy, it should then be possible to satisfy the peak power demand of a zigbee node transmission. But, since power harvesting heavily depends on the location, it is possible that some node would not be able to harvest everything they need, and would therefore be forced to rely on the solar-charged battery. On the other hand, nodes in proximity of transmitting stations would harvest way more energy than needed.

Indeed, despite being still an active research field, RF energy harvesting is surely a promising supply for smart, low power networks, especially considering that with a steady diffusion of IoT[4] in everyday life the RF power density in cities is expected to rapidly grow.

4.2. Economic sustainability

Even if the initial cost of smart street lighting would be higher than usual, relying on batteries charged with solar energy and RF energy harvesting allows each light pole to be independet from the utility grid; thus, it is possible to ignore costs normally associated with the building and connection of new branches.

The main cost associated with the infrastructure would be battery replacement every $5 - 10$ years, for which the battery compartment should be located on ground-level to fasten substitution; but overall, the self-sufficiency of nodes would reduce the risk of accidents and required maintenance [14][15]. Also, autonomous lights would prove their worth in case of natural disasters and power supply discontinuity, or in case of deployment in remote areas.

5. Conclusion

Considering all the studies carried out on the subject, it is clear that growing cities and developing technologies urges the deployment of smart street lighting systems. Out of all the proposed solutions, the more cost-effective implements wireless communication and makes use of renewable and unused energy, such as solar and RF from transmitters, smartphones and wifi stations.

The idea suggested in this paper proves to be environment-friendly and far less costly than traditional lighting, while being more resilient, flexible and time-saving than alternatives; so, even if such a complex and smart system requires initial investments in devices and planning, it should be noted that these would be greatly rewarded over time.

[4]Internet of Things

Word count: 1815

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