A Solution for Enabling Intelligent Street Lighting in Smart Cities

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Abstract

In this paper we propose a novel concept for the street lighting automation, with the primary goal to decrease the level of light pollution and the electric energy waste. The concept enables the street lights, equipped for wireless communication, to be automatically switched on or off according to a presence of humans or moving vehicles. As opposed to existing solutions for street lighting automation, the proposed concept does not require any conventional presence or motion detection sensor. Presence and motion detection is based on the known fact that the human bodies interfere with radio signals, resulting in the significant variations of the signal strength. By analyzing the variations of the signal strength, using the proposed algorithm in a distributed way, the luminaries are able to deduce the presence of a human subject or a vehicle independently, and to set a functional state of the light accordingly. The solution is mainly applicable to some novel concepts of wireless light bulbs that have just appeared on the market, introducing cost-effective software add-on that can incorporate a significant level of sensing intelligence for more advanced applications in the smart cities.

1 Introduction

Life cycles of living beings follow the natural intervals of the sun, the moon and the darkness. An abundance of artificial light, particularly coming from the streets, can negatively affect their harmony with the nature, causing different consequences that can even be fatal [1]. Therefore, in the cities of the future a requirement for decreasing the level of light pollution during the nighttime have to be addressed. Besides improving the health and environmental factors, the elimination of inefficient and unnecessary street lighting decreases the electric energy waste and improves the global energy awareness.

Proper shielding of street lights can maximize the desired effects of lighting by controlling the light output whilst minimizing the glare, light trespass and sky glow effects. Unfortunately, the problem of inefficient energy consumption still remains, because the most of the street lights are active continuously during the nighttime. From our perspective, street lights should be enabled to give 100% of luminosity only when a human or a moving vehicle is present in the vicinity of a luminary. If no humans or moving vehicles are present in the vicinity of the luminary, the luminosity should be decreased to a lower percentage. By decreasing the level of luminosity when it is not necessary for citizens, the street lights become more efficient in electric energy saving and light pollution reduction.

The integration with a specific sensor device is important to enable the automated adaptation of the luminosity level according to a presence of human subject. Such a sensor should be able to detect a moving vehicle, and motionless or moving humans (further known as objects of detection). Unfortunately, most of the conventional sensors are either very expensive to install and exploit (such as HD camera, 3D camera or radar systems) or even unable to properly detect motionless humans. An additional drawback of some sensor technologies, such as the passive infrared (*PIR*), is the dependence on ambient temperature and humidity, which makes this technology being not suitable for outdoor applications.

With all these requirements addressed, we propose Device-free Human Presence and Motion Detection Street Lighting (*DHPMSL*) concept. The concept proposes the use of luminaries enabled for wireless communication, that process the existing communication radio signals for presence and motion detection.While propagating through the environment, radio waves can be absorbed, reflected, diffracted or scattered by the objects that reside on the radio wave propagation path, resulting in the increased variation of the received signal strength indicator (*RSSI*). Without affecting the ordinary communication between wireless luminaries, the presence of an object can be easily deduced from the RSSI variation using the proposed DHPMSL concept. The proposed presence and motion detection method is based on the information entropy calculated over a set of principal components extracted from a sequence of RSSI samples incrementally, without estimating the covariance matrix [10]. Such an approach improves the accuracy of the radio based method for presence and motion detection, and the response in real time, by providing the efficient control of street lights with the decreased power consumption.

The paper is structured as follows. In Section 2 we give an overview of the existing solutions for street lighting automation and explain the conceptual advantages of our solution. In Section 3, we explain the proposed concept in details. Results of the experiment taken to verify the feasibility of the proposed concept are shown in Section 4. We finalize and conclude the paper in Section 5.

2 Related work

Street lights make an important contribution to everyday life in a city. Very important tasks are to improve public safety, energy awareness and the protection from light pollution, while complying with lighting standards and norms. In order to meet the requirements, a concept of adaptive lighting has been already proposed by some companies such as: Philips, Echelon, Libelium, TST, etc. Their adaptive lighting systems transform streetlights into intelligent, energy efficient, remotely managed networks. Adaptive controls provide the automatic lights dimming if a street is empty and brightness increase when vehicle, cyclists or pedestrians appear. In most solutions, the adaptive control is managed with conventional sensors for presence and motion detection.

Philips's Starsense, AmpLight and CityTouch [2] enable individual lights to be monitored and managed wirelessly, with the possibility to monitor power consumption and the diagnostic parameters. In order to reduce the obtrusive lights, the systems provide only a necessary amount of light to a specific area. The optimization of the electricity usage is performed by decreasing the lighting level at, for instance, off-peak traffic hours. The systems provide various interfaces that can connect different kind of sensors, but adding a new sensor requires the installation efforts and maintaining demands. Echelon's Smart Street Lighting [3] allows a street lights network to schedule lights on or off, or to set dimming levels of individual, or groups of lights. The electronic ballasts communicate over existing power line, whereas internet server provides interface to various sensors, used to improve the system intelligence. Libelium [4] proposes the Smart Lighting solution for smart cities based on wireless sensor network in cloud. The solution also provides third-party sensors interface for the interaction with the environment. TST [5] provides a wireless lighting management architecture, working at 868MHz, and enabling standard features such as on or off switch and light dim. It also supports interfaces to external sensors for presence, luminosity or temperature, important for establishment of an adaptive lighting concept.

A notable effort from academia researches in this area comes with CitySense [6] an urban scale sensor network testbed and Road Nail [7] an intelligent road marking system. CitySense supports sensors networking at urban scales. The current prototype consists of about 100 embedded PCs outfitted with dual 802.11 radios and various sensors mounted on streetlights and buildings across a city. The primary goal of CitySense is to serve as an experimental apparatus for the development and the evaluation of various wireless sensor networks and systems, including adaptive lighting concept. Road Nail presents a solar powered road marking system comprised of a wireless network of signaling devices intended to enhance driver safety. The devices are autonomous nodes powered by batteries that are charged by solar panels. The nodes can detect approaching vehicles, exchange wireless messages with neighboring nodes and turn on a road edge safety light. Vehicle detection subsystem consists of a motion sensor based on passive infrared technology and a light sensor. Additional solution proposed improves the detection performance in combination with the existing sensors or removes a need for application of conventional sensors. The proposed solution monitors the difference between the average and received signal strength of radios between neighboring nodes. If the difference exceeds a specific threshold, nodes deduce that a passing vehicle is detected. The main drawback of such an approach is that the algorithm monitors the signal strength at one link only. The signal strength varies around the average value, but depending of the sampling frequency, some samples can contain signal strength values that are below the threshold, causing false detections even if a vehicle is present. Additional drawback is low accuracy for human detection when the line-of-sight between nodes is not intersected. Therefore, this solution is acceptable only to coexists with another conventional sensor technology. As opposed to Road Nail, in DHPMSL all adjacent links are simultaneously processed, therefore in a case when a few links are corrupted by the external noise, caused with the sampling frequency rate, the power of the majority of links will minimize, or even entirely suppress the noise.

The integration with the proposed DHPMSL concept, can improve any of the aforementioned systems with the sensing capability without additional installation efforts or modifications of the current hardware design, because the concept comes as an add-on to the current software. The important thing is that manufacturers already incorporate controls-ready features to wireless LED street lights. The only requirement for DHPMSL solutions is the wireless connection support (2.4 GHz particularly), that is already the common feature of majority of systems.

3 Radio based object detection concept

DHPMSL concept requires a number of radio frequency (*RF*) enabled lighting nodes. Whereas the wireless nodes usually utilize radio signals to communicate with each other, the concept we propose exploits the existing radio signals for the detection of humans and moving vehicles, as depicted in **Fig. 1**.

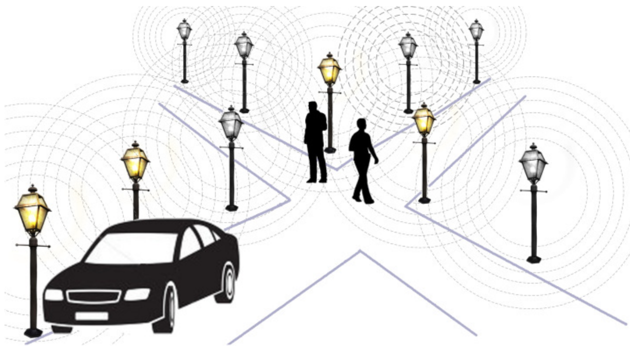

Fig. 1 Device-free Human Presence and Motion Detection Street Lighting (DHPMSL) concept

The RF nodes communicate at microwave frequencies creating a senseable radio network, where the absorption by molecular resonance of an object of detection is a major factor affecting the radio propagation. In some of the previous papers [8]-[10] we have proposed various low-cost methods for accurate indoor human presence and motion detection, using RF signals only. The proposed solutions exploit the known fact that the object of detection interferes with radio signals within the established radio network. Introduced irregularities in the radio propagation pattern, expressed in a form of received signal strength indicator's variations, indicate a possible presence of an object. The irregularities are analyzed and quantified using the identical algorithm as presented in [10], but distributed locally so each streetlight node can execute it and make an automatic selection of a functional state accordingly (as depicted in **Fig. 2**), e.g. lights switched on/off depending of the detected presence. There is no need for a centralized controller as for the case of smart home system, because the algorithm is optimized to execute in real time even at low processing power systems. The proposed adaptive light solution needs only to switch the lights on, almost immediately when somebody appears or passing, and to switch them off or dim to a specific value if no person is present.

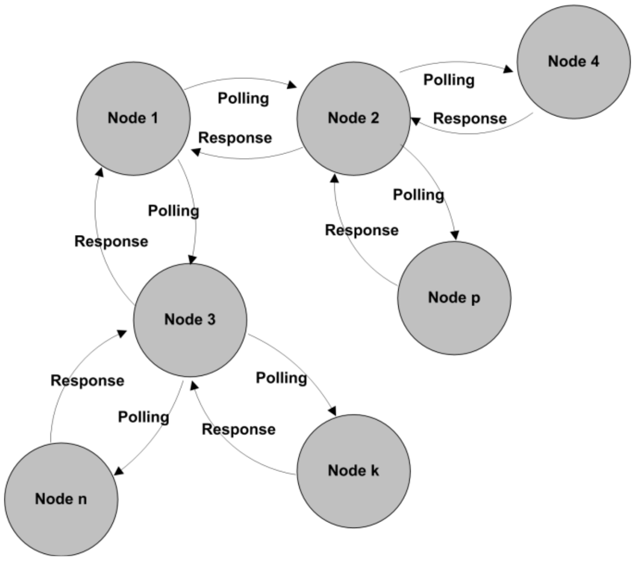

Fig. 2 DHPMSL detection algorithm – distributed motion and presence detection

It is important to mention that the external design and the hardware of the wireless lighting infrastructure does not require any modification. The only addition to the original infrastructure is the software extension that introduces the sensing capability. The RSSI variation processing, which carries the information about humans or vehicle presence, is based on the information entropy calculated over a set of principal components that are extracted from RSSI samples obtained from a number of RF enabled streetlight nodes. The diagram of the algorithm is shown in **Fig. 3**.
Candid Covariance-free Incremental Principal Component Analysis (*CCIPCA*) [11] is used for the rapid extraction of principal components without calculating the roots of characteristic polynomial from a covariance matrix which is computationally demanding operation. The proposed method requires only a single detection threshold.
Compared to PIR technology which is not fully applicable to such scenarios, the proposed algorithm is particularly beneficial in scenarios that involve motionless humans presence. The information entropy is primarily used for the suppression of sudden peaks that can appear in the processed RSSI data introducing false detection alarms.
The distributed manner of the concept implies that each wireless node can poll other nodes in range, process RSSI data and make a simple control decision according to the determined presence, and issue commands to a luminary. The processing algorithm can be described as follows: Each wireless node periodically polls other nodes in range (software defined cycles). The polling synchronization follows the addresses of the nodes, where higher priority nodes use higher address values. After a node is polled it broadcasts a message containing a vector of current RSSI values collected from links towards neighboring nodes. The same message is received at the input of the poller node, simultaneously with the neighboring nodes for their RSSI vector update. One polling cycle is completed after each node polls its neighboring nodes, generates the current RSSI vector corresponding to the established radio links, and calculates entropy over a set of principal components.

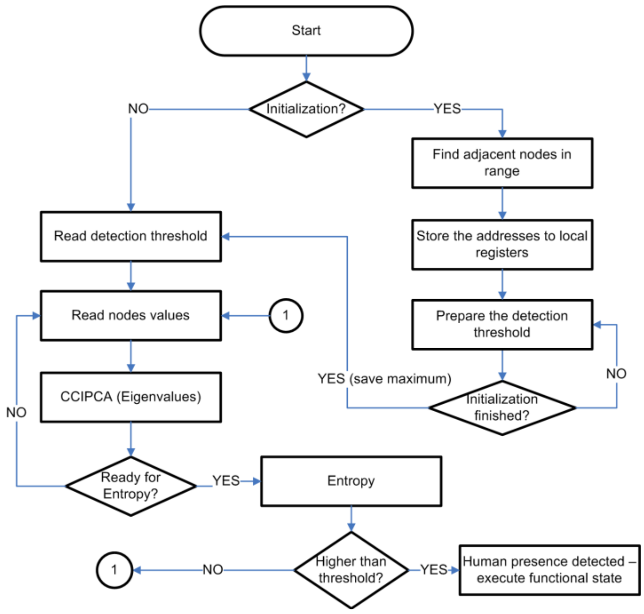

Fig. 3 DHPMSL concept – the algorithm

Before running the system, the phase of the initialization is necessary to determine the detection threshold. The detection threshold is usually calculated as a half of the lowest entropy sample obtained during the initial phase, when no humans or vehicles are present. After running the system, all the samples that are below the detection threshold report human presence, whereas all the samples which are above the detection threshold report the empty area or street.
In order to decrease the complexity of the installation, the proposed concept can also be applied to some of the novel wireless lighting technologies that would replace the standard home and outdoor luminaries. The most widely known examples are given in a form of RF enabled light bulbs [12] and [13]. Due to the incorporated electronics, these bulbs enable the establishment of small radio networks without the need for any intermediary device.

4 Experimental results

The feasibility of the proposed concept was verified in the experiment with four wireless nodes and four PIR sensors mounted alongside the nodes, as depicted in **Fig. 4**. In this experiment we tried to verify if the proposed DHPMSL method correctly detects human motion and presence. The human subject was asked first to walk during a two minutes period, and later to stand motionlessly in the particular positions P1 and P2 (Fig. 4) between the nodes (and PIR sensors), again for two minutes in each position. At the end, the subject left the monitoring area and the resulting samples were collected for an additional minute. Passive infrared technology was selected for the comparison with DHPMSL approach, because PIR sensors are the most widely used and cost-effective sensors for this kind of smart applications.

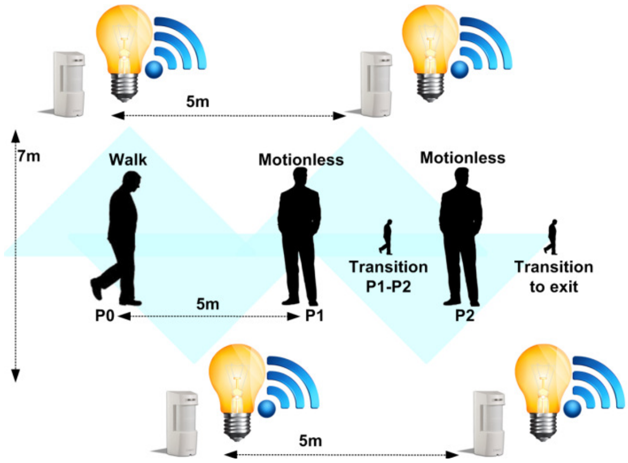

Fig. 4 Street lighting experiment

PIR sensors correctly detected the presence of the moving subject, but they failed to detect the motionless subject. It is the known drawback of passive infrared technology. Two minutes were measured for each standing, resulting in approx. 70% of correct detections rate for predefined positions detected by using passive infrared technology. DHPMSL based approach correctly determined between human presence and empty area, for both cases when the subject was motionless and moving, as shown in **Fig. 5**.

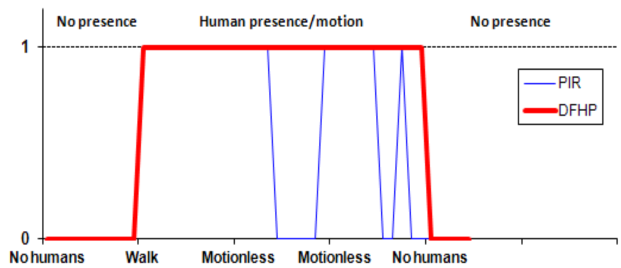

Fig. 5 The Results of the experiment for the proposed DHPMSL concept compared with PIR sensors: value 1 – presence detected; 0 – no presence detected (empty area)

In figures 6 and 7 we present the calculated values of principal components and applied entropy, respectively. These values are used to determine the presence of humans or empty monitoring area between wireless lighting nodes. First 300 principal components shown in **Fig. 6** determine the area in which no humans are present. Between the samples around 300 and 600, the human subject entered the monitoring area and started walking continuously. The samples from 600 and 1200 represent motionless human subject in the positions P1 and P2, respectively (approx. 300 samples per a position). In the **Fig. 7**, the calculated entropy for the set of principal components shown in Fig. 6 is given. First 16 principal components are used to calculate the starting entropy sample. Each subsequent entropy sample is calculated over a sliding window, counting 16 principal components. Foremost 15 principal components are calculated in the previous cycles, and the additional component is calculated in the current polling cycle. The number of components in the sliding window is not strictly defined. After a number of experiments the number of 16 is determined as optimal for this experimental setup.

From the Fig. 7, the time frames in which the human subject entered and left the monitoring area can be easily concluded. The detection threshold is marked with green line and it represents 70% of the lowest entropy sample calculated during the initial phase. The detection threshold fine tuning parameter is configurable manually (the aforementioned value of 70%), and it can be used to additionally filter out the effects of the environment (parked vehicles, aluminum street poles, etc.).

The another challenge for the future improvements is the automatic selection of fine tuning parameter during the initialization phase, which should be also based on the analysis of the radio signal strength variation.

5 Conclusion

The adaptive street lighting system proposed is mainly based on wireless communications technologies. The system detects human presence and moving vehicles, resulting in a wave-like propagation of street illumination. The concept of aggregating and analyzing the RSSI variation data from radio links established between adjacent streetlights, eliminates the need for presence and motion detection sensors.

The presented detection method exploits the fact that human body interferes with the neighboring radio signals by introducing irregularities in the radio propagation signature. The presence of a human or a moving vehicle within the wireless network range, results in significant signal strength variations, whilst the degree of variations is correlated with the level of human motion.

To verify the system performances we set up the testbed consisting of PIR sensors mounted alongside with the proposed human presence and motion detection method applied to wireless luminaries. The initial results indicate that the radio signal based detection accuracy was quite satisfactory. The proposed concept is cost-effective, easy-to-maintain and easy-to-install solution for future cities.

Acknowledgement

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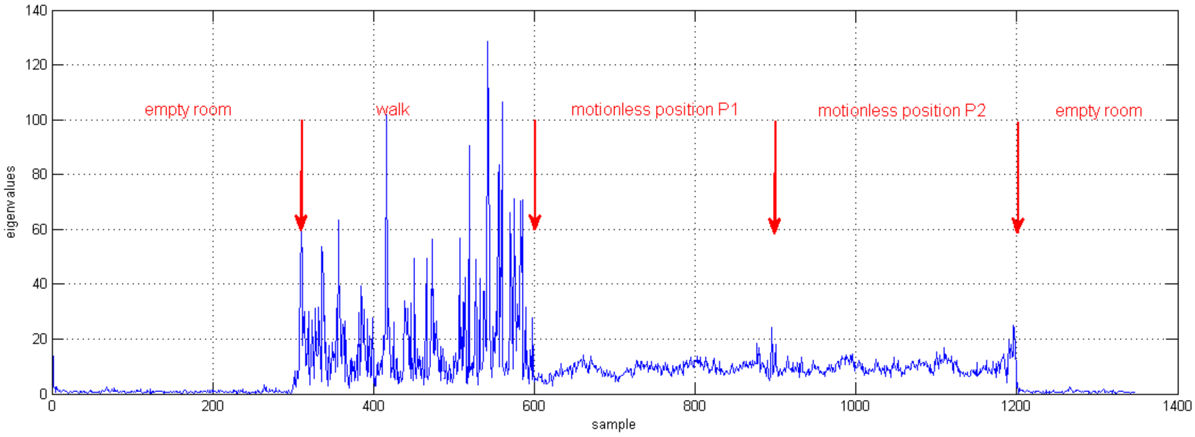

Fig. 6 Principal components values collected during the experiment

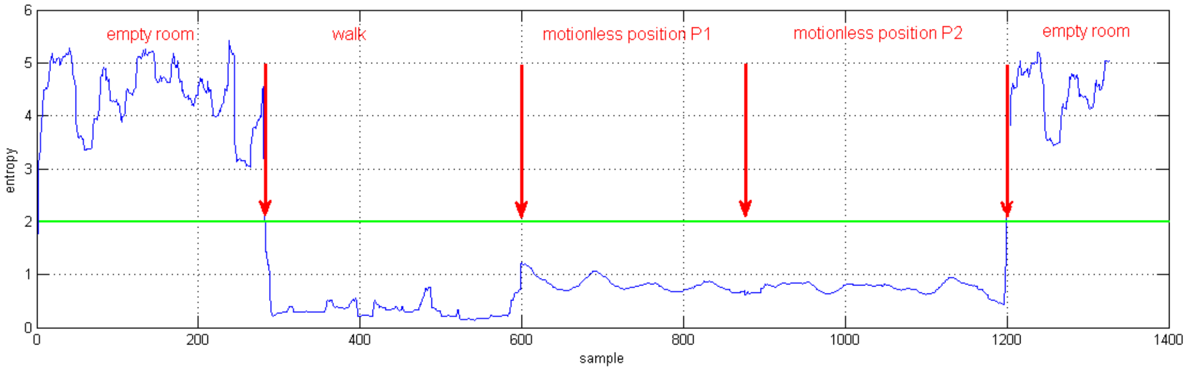

Fig. 7 Information entropy values calculated over the set of principal components

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