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Adaptive lighting systems and the method of implementing dynamically adjustable on-demand strategies – conclusions from research

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Abstract

Street lighting is an important aspect of the operation of not just every city or municipality but also the operation of the roads and highways in every country. The search for energy-saving solutions has become a ubiquitous number-one topic and leads to the need for lighting management systems to make lighting more efficient and economical from a financial and environmental point of view. There are many important needs of cities and municipalities strictly connected with the type of roads and areas in cities and their surroundings. Highways, country roads, main city roads, parks, cycling paths and residential areas all have different requirements with regard to efficient lighting management. Lighting and power schedules, adaptive lighting schemes based on the density of road usage, dynamically adjustable on-demand lighting which lights up the way ahead of moving objects (vehicles or pedestrians). All of the above are important and can help in the achievement of the main goal, which is efficient energy usage properly managed for the given situation and which will ensure safety and comfortable lighting for all kinds of roads. This paper is focused on dynamically adjustable on-demand lighting, it proposes a solution capable of achieving optimal lighting management for cities and surrounding areas.

Keywords: street lighting, adaptive lighting system, dynamically adjustable on-demand lighting, adaptive lighting scheme, smart lighting, smart city

1. Introduction

The idea of adaptive lighting is that the lighting follows a moving object, with the area directly in front of the object being illuminated more intensely than the area behind the object, and areas where occupancy has not been detected are illuminated minimally. According to different reports, street lighting is one of the biggest electrical energy consumers, responsible for almost 40% of the total energy consumption in cities. Therefore, it is important to take action in order to reduce the energy consumption in these kinds of installations. All around the world, especially in cities, monitored lighting installations of public spaces are implemented and controlled manually or remotely. In the long term perspective the integration of various control and city infrastructure maintenance systems, including street lights, is expected to enable the implementation of complete, integrated networks of data and information exchange, as well as integrated monitoring and control systems – so-called Smart Cities systems (Ożadowicz, Grela, 2015: 1–8). Moreover, networked streetlights offer a foundation for smart-city applications by introducing various cutting-edge Internet-of-Things devices, such as urban planning and traffic management systems, mobility pattern identification solutions, and emergency assistance systems (Mohsen et al., 2020: 24–33).

As an important element of Smart Cities, the method of managing street lighting significantly reduces the total cost of energy consumption. The use of adaptive lighting allows the luminous flux to be reduced in selected areas to the level required by the system supervisors. Technically, it is possible to reduce the luminous flux down to 10% of the nominal value and quickly illuminate the area where movement has been detected for its duration. Traffic safety requires that motion sensors act not only on the luminaire in which they are installed, but also on a certain number of required luminaires, usually five to thirty luminaires. The number of them depends on environmental factors and the top speed of movement in the controlled area.

For the efficient management of adaptive lighting, reliable and fast communication is necessary; this enables highly efficient local management.

2. Methodology

A number of analyses of existing solutions were performed for the purposes of this article, including patented solutions. The aim of the research was to find an infrastructural lighting system with the focus on dynamically adjustable on-demand (abbreviated to adaptive) lighting designed for lighting roads, streets, park alleys, bicycle paths or extensive parking areas. The subject of research is particularly focused around adaptive lighting management, requiring the quick response of local devices to data from sensors located in the system's operation area. Adaptive lighting solutions have already been analysed by, among others (Siddiqui, Ahmad, Yang or Lau, Merret, Weddell, 2015: 192–207).

Mohsen and others describe an autonomous intelligent street lighting control system as a system that dynamically adjusts the brightness of street lighting to an optimal level (Mohsen and others., 2020: 29-33). Owing to the use of autonomous network sensors, the proposed system detects the presence of vehicles and pedestrians and appropriately controls the lighting of the lanterns based on the desired lighting intensity of street users (pedestrians or drivers).

The research process of the lighting system also included the analysis of inventions in the field of adaptive lighting control systems. The European patent specification EP3018977B1 (Network of lights, 2019) discloses a lighting network consisting of multiple lamps, each equipped with a control module and a server involved in a network comprising one or more groups of lamps, each lamp being equipped with a control module for adjusting the lighting parameters, and each group having a control module operating as its group controller. The group controller communicates with the server via the long-range

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communication module. The other control modules communicate with each other and with the group controller via the short-range communication module. At the same time the control modules communicate with the server through the group controller, wherein each control module is able to function as a group controller. The control module for controlling the lighting parameters of the lamp consists of a long-range communication module, a short-range communication module, a geolocation module, a controller, at least one sensor and a control output for managing the light controller from the server, which is accessible via a long-range communication module in which the control module is designed to transmit environmental, light and/or control module information to the server.

The European patent specification EP 3017661B1 (*A method for operating a communication device in a communication network, a communication device, a luminaire equipped with such communication device*, 2017) discloses a system consisting of controllers equipped with a short-range communication module in accordance with IEEE802.15.4 and a long-range communication module featuring GPRS, UMTS or LTE technologies and dedicated central software which the controller can use to operate in the edge router mode, communicating with the central system via a long-range module and to adjacent controllers via a short-range module. After installing devices that report their position based on GPS location and long-range communication. The central system, after discovering the location of all connected devices, may issue a command to turn off the long-range communication module to selected controllers. These controllers then communicate with the system through edge gateways where both communication systems are active.

British patent GB2582810A (*Deployment of mesh network*, 2020) discloses a method of installing a mesh system dedicated, for example, to the management of urban lighting infrastructure. The mesh nodes of this description also include communication modules for establishing mesh communication according to the IEEE802.15.4 protocol and an Ultra-low Narrow Band UNB communication module which allows communication with base stations up to several kilometres away. When establishing a network, the controllers use the UNB network, report their GPS position to the central management system and check what mesh subnets are possible to build. On this basis, the mesh access point function is allocated which is used to transfer information about the network to the central system through the system gateway, communicating with devices via UNB communication and with the system via another link, by default in long-range GPRS, UMTS, LTE or wired technology.

British document GB2578746A (*Monitoring system*, 2020) describes a monitoring system composed of a central unit and edge devices to which external sensors can be connected (e.g. a camera, a motion sensor and an RFID sensor); such devices have a functional connection with the central unit via a wired or a radio link using communication dedicated to this solution or other technology existing within the Smart City. The edge node receives data from the sensors and stores them in the memory. Additionally, it may send certain pieces of data to the central system according to the predefined algorithm or upon the request of the central system.

3. Communication technologies

Remote monitoring and control systems are important to prevent events such as missing pieces of data. In order to perform remote monitoring and control, a local network has to be established (either wired or wireless), which connects a set of light fixtures to a gateway. Each gateway can connect to the Internet through cellular technologies, such as 2.5G/3G/4G. Communication between street lighting and gateways can also be provided by ZigBee, IEEE 802.15.4, DALI (Digital Addressable Lighting Interface), LoRa and PLC (Power-line Communication). Over time, the dissemination of the IoT (Internet of Things)

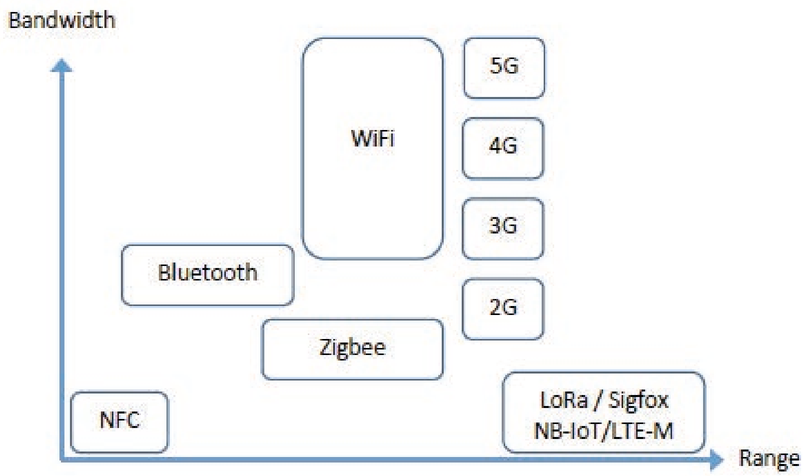

Fig. 1. Protocols used in IoT
source: (Montagny, 2021: 10)

concept has also led to the development of systems that are linked directly to the cloud via microprocessors and are managed over the cloud. This way, the central management system can monitor the street lighting and control the system directly if necessary (Bingöl, Kuzlu, Pipattanasompornm, 2019: 67).

In the IoT world, we can find many protocols such as Bluetooth, Zigbee, Wi-Fi, 2G, 3G, 4G, 5G, NFC, and more. We usually classify them according to their bandwidth and range, as can be seen in the figure below. From the system designer point of view, it is always beneficial to be able to reach greater range and bandwidth. When quickly glancing at the figure, it may seem that protocols in the top right area are much better than all the others (better range and better bandwidth), while the protocols on the bottom left should be the worst-performing ones. What we are missing here is that this graphic does not represent the power consumption induced by the protocol. Indeed, NFC is a really low-power protocol: it even runs without any energy storage (Montagny, 2021: 10).

Most of the known solutions do not enable the technically and economically effective organisation and management of adaptive lighting. Solutions supported by communication via long-range networks, such as subscriber networks in 2G/3G/4G/5G technologies, are technically expensive as well as being very expensive to operate due to the need for a subscription fee for a sim card in each device associated with each luminaire belonging to the system. The use of 2G/3G/4G/5G technology, in particular 4G-LTE and 5G, enables the transmission of a large amount of data, although the problem may be ensuring low total latency, i.e. the time required from sending a signal from the sensor to receiving the message in executive devices. Furthermore, the 2G/3G/4G technology is completely dependent on the central management system, hereinafter referred to as CMS, and any failure in the operator network or server failure will disable the system. The solution using 2G/3G/4G technology is also sensitive to the consumer traffic load, so in the case of increased telephone traffic, for example during mass events, concerts, cultural events, holidays, the system may be blocked for many hours.

Solutions supported by LTE cat. M.1, and especially NBIoT, do not guarantee a sufficiently low latency, although the NBIoT technology is clearly more resistant to the load of consumer traffic. The use of these technologies forces the centralisation of decisions at the CMS level, so they make the functioning of lighting dependent on both communication and the operation of the CMS.

The use of radio communication in the 2.4 GHz frequency band may be an alternative. In a star topology network using the 2.4 GHz frequency for communication, direct communication between devices is not possible. In this case, the signal from the sensor must be sent to the network hub and from there to the executive devices. The advantage of such a solution is independence from the CMS system, which is not involved in the decision-making process, thus eliminating communication in the telecom area. The system can make decisions locally and therefore has low latency and, furthermore, full bandwidth utilisation. Radio communication in the 2.4 GHz frequency band has the disadvantage that the range of a single device can in theory reach 1,000 m, but in practice, it is 400–600 m in optimal conditions, which significantly limits the number of supported devices and the territorial area for the system. In order to eliminate the influence of the buildings, the hub/gate must be placed in such a way as to ensure optical visibility between the concentrator and each installed device, which results in additional investment costs.

A greater range can be achieved by using communication in the sub-GHz band. For the LoRa standard, the range of individual devices reaches 5–7 km, but the bandwidth usage, both for end devices and hubs, is normatively limited to 1%. Restraining the bandwidth usage limits the maximum number of messages that each device can send per day to about 140 messages. Due to these limitations, communication in the sub-GHz band is not applicable in the adaptive lighting design, as it does not provide the required traffic density (in terms of communication frequency) and thus the required traffic safety.

Full use of the band and greater range can be achieved using radio communication in the 2.4 GHz band with support of a mesh topology. The mesh network is built on the basis of three essential types of devices: steering devices (controllers) taking the role of a "child", steering devices taking the role of a "parent" (mesh routers), and a network gateway configuring the network and ensuring its connection with the "world" via long-range communication – subscriber network or wired connection to Ethernet. The role of the "child" or "parent" router is taken over by the network nodes automatically, whereas each of them constitutes a controller associated with the luminaire, motion sensor or luminaire equipped with a sensor. In a mesh topology network, the messages sent by the sensor can be transmitted through subsequent mesh routers, thanks to which, the actual communication range is significantly extended. The limitation of this solution is the number of devices that can be organised in the local mesh network. The use of a mesh network for communication in the lighting system allows for direct communication between the elements managing the lighting fixtures. In such a configuration, the controllers and traffic detectors can directly communicate with each other. Combining that with the relatively large network capacity resulting from the applied band, communication with the neighbouring nodes in the shortest possible time can be ensured, thus meeting the requirements for the adaptive lighting management systems.

A mesh topology network is therefore suitable for a tracking lighting-management system for a limited number of smart lighting elements located in a limited area, but it is not suitable for managing adaptive lighting over a large area, for example, throughout the entire city. Although smart lighting elements organised in a local network in mesh topology may work properly, on the border of adjacent areas, where smart lighting elements are organised into their own local networks, communication "holes" will arise.

At present, sufficient reactivity of the infrastructure lighting system can only be ensured by the use of local networks for communication in mesh topology, in the 2.4GHz band or higher, in accordance with the IEEE802.15.4 standard. The standard allows devices to communicate with each other as well as with the communication elements of the infrastructure lighting system with the lighting CMS (Central Management System) via IoT gateways. The reliability of the network operation is achieved by the use of at least two active IoT gateways in each local network in the mesh topology, while maintaining the continuity of communication at the border of the coverage areas of adjacent mesh networks has been achieved through the use of the IoT gateway, which supervises many local mesh networks and enables the transfer of information between gateway supervised local mesh networks. The IoT gate, which is also fully active in each of the supervised local mesh networks, ensures full security because all transmitted data is encrypted and the network nodes sending and receiving information are authenticated.

4. Research

By implementing the research process in accordance with the scientific research project entitled "Intelligent sensor systems for lighting management in solutions from smart lighting to smart city. Research and prototyping" (Agreement No. RPLB.01.01.00-08-0009/17), under Priority Axis 1. Economy and innovation, Measure 1.1 Research and innovation of the Regional Operational Program – Lubuskie 2020, co-financed by the European Fund Regional Development, an innovative lighting system was created and tested. This infrastructure lighting system is characterised by the fact that it includes IoT controllers (2.xx) integrated with lighting fixtures or installed on the lighting fixture using dedicated, standardised sockets, motion detectors, system operation devices and IoT network gateways. The IoT gateway contains at least two radio communication modules operating in the IEEE802.15.4 standard. The IoT controller includes a radio communication module in the IEEE802.15.4 standard, equipped with a processor and a luminaire control interface in the 1–10V standard, digital in DALI standard, or universal operating in one of the indicated modes. Each IoT gateway radio communication module operating in the IEEE802.15.4 standard is a node of its own, independent, local short-range radio network in the mesh Sx topology, and the other nodes of this local radio network in the mesh topology Sx, are communicated with it via radio communication modules in the IEEE802.15.4 standard of IoT controllers. Information sent in the local mesh radio network can be redirected, via the IoT gateway, to another local mesh radio network, created by another radio communication module in the IEEE802.15.4 standard of the same IoT network gateway, and to the Central Management System (CMS) installed in a computing cloud or on a dedicated server via the Internet or a long-range communication module. The Central Management Server (CMS) is a high-performance Linux-based network appliance that extends the reach of E-Detective across your huge enterprise or even ISP scale networks, providing real-time centralised reporting, searching and querying, as well as alert and notification functions. The CMS aggregates and manages a cluster of distributed E-Detective systems (which can be in the same location or in multiple locations) in real-time and facilitates a single and hierarchical enterprise view across the network. "CMS – the central management server is specially designed to aggregate data hierarchically from multiple or distributed E-Detective systems for ultimate scalability and deployment flexibility across various organisation-specific or ISP scale network topologies and infrastructures. The CMS design also allows hierarchical analysis, or investigation operation and visibility which includes querying, searching, alerting, notifying and reporting that extends to multiple E-Detective systems. This provides a single point of access to multiple E-Detective systems" (CMS, n.d.).

The system must meet the following requirements (system assumptions):

- A motion detector is designed to inform the controllable element of the lighting fixture or the IoT controller that motion has been detected in the monitored area.
- The IoT controller is designed to count off clock time and solar time for any given location.
- The IoT controller is designed to store multiple individual schedules (at least ten) for the operation of the lighting fixtures, wherein each schedule is defined in clock, solar or mixed time.
- The IoT controller is associated with an illuminance sensor.
- The controller is integrated with the illuminance sensor.
- The IoT controller is equipped with a power-supply-parameter measurement system, which is the measurement system that provides the CMS with information containing the actual power supply parameters of the luminaire, such as current consumed, supply voltage, active power, reactive power, apparent power, cumulative active energy, cumulative reactive energy, power factor, frequency and detected emergency states

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based on the actual power supply parameters of the system components.

- The measurement error of the power-parameter measurement system is no greater than 1 percent of the measurement range.
- The controller is equipped with a relay for turning the light fitting on and off.
- The controller is equipped with a GPS module.
- The controller is equipped with a long-range communication module with 2G, 3G, 4G and 5G technologies.
- The IoT gateway comprises a long-range communication module in the 2G-GPRS or 3G-UMTS or 4G-LTE standard.
- The IoT gateway comprises 2 to 6 radio communication modules conforming to the IEEE802.15.4 standard.
- The IoT gateway is mounted on a light pole or in a lighting cabinet.
- The operating device for the infrastructure lighting system is a laptop, tablet or mobile phone equipped with a web browser or a mobile application.

5. General characteristics of the lighting system

The benefits of lighting management need no proof. Smart street lighting systems integrate smart technology and control capabilities to reduce energy costs for every city. The system provides remote lighting control that can better adjust the amount of time for which the lamp is turned on to minimise energy costs without reducing safety levels. This system has played an important role in improving urban safety as well as maximising energy savings. Smart lighting can also significantly reduce maintenance costs and simplify asset management. A smart street-lighting system is capable of combining with the electrical system and other applications in a smart city. Installing a smart street-lighting system is done for the following basic benefits: reducing energy costs due to better control of light usage; providing contextual lighting to enhance public safety at major events or in important areas; allowing access to data from street light sensors can reduce maintenance and asset management costs; creating a foundation for other smart city applications, providing communication networks and a power grid (Ngo Thanh Tung and others, 2019: 328). As can be seen from the above quoted authors, the most important issue is the intelligent management of the lighting system.

The operation method of the infrastructure lighting system, which is the result of the realised research and is presented in this article, assumes three cascading levels of management. The first level is the autonomous edge management implemented at the controller level; the second level is implemented in the local mesh network, which may also include a mesh gateway; the third level is carried out by the Central Management System (CMS), with each subsequent level extending the system functionality – the number of available functions is greater on each successive level of management.

The above-described organisation of decision-making in the infrastructure lighting system makes the operation of lighting independent from the operation of individual elements of the management system. For example, during a failure of the Central Management System (CMS) or long-range communication, the second and first levels remain active. A failure of the second level is unlikely; however, it may happen that the luminaire with the controller is outside of the radio communication range of the local network and then the controller remaining outside of the system takes over control of the luminaire.

A particularly important feature of the infrastructure lighting system is that from the beginning, it has been designed to operate autonomously, which means that in static mode, when no response to external signals is required, the system is only used for status reporting and the updating of the luminaire's operating curves if the user determines such a need.

The controller includes a clock that is synchronised in the mesh network in between all devices and via the gateway against the server time. Based on the calendar time and latitude, the controller calculates the solar time. Knowledge of the clock time and date allows it to choose the right work schedule for each day of the year and enables the implementation of the schedule defined in the clock time, while the knowledge of sunrise and sunset times allows it to implement a relative schedule, and the knowledge of both times allows one to choose any schedule, including a schedule where some points are defined in clock time and some in solar time. The possibility of defining the schedule in clock, solar or mixed time means that the resulting number of static schedules does not have to be very large. Due to the fact that the controller stores in its memory many different schedules adapted to the expected mode of operation for different days, weeks, months, as well as exceptions to the mode of operation on certain days, it is possible to work completely autonomously for several months or even years.

Figure 2 shows a diagram of an infrastructure lighting system.

The infrastructure lighting system includes controllable lighting fixtures 1, 2.xx IoT controllers, where xx refers to the individual marking of the controller, and 5.X IoT network gateways, where X is the individual marking of the gate, mounted in lighting cabinets 4. Each 2.xx IoT controller is integrated with the

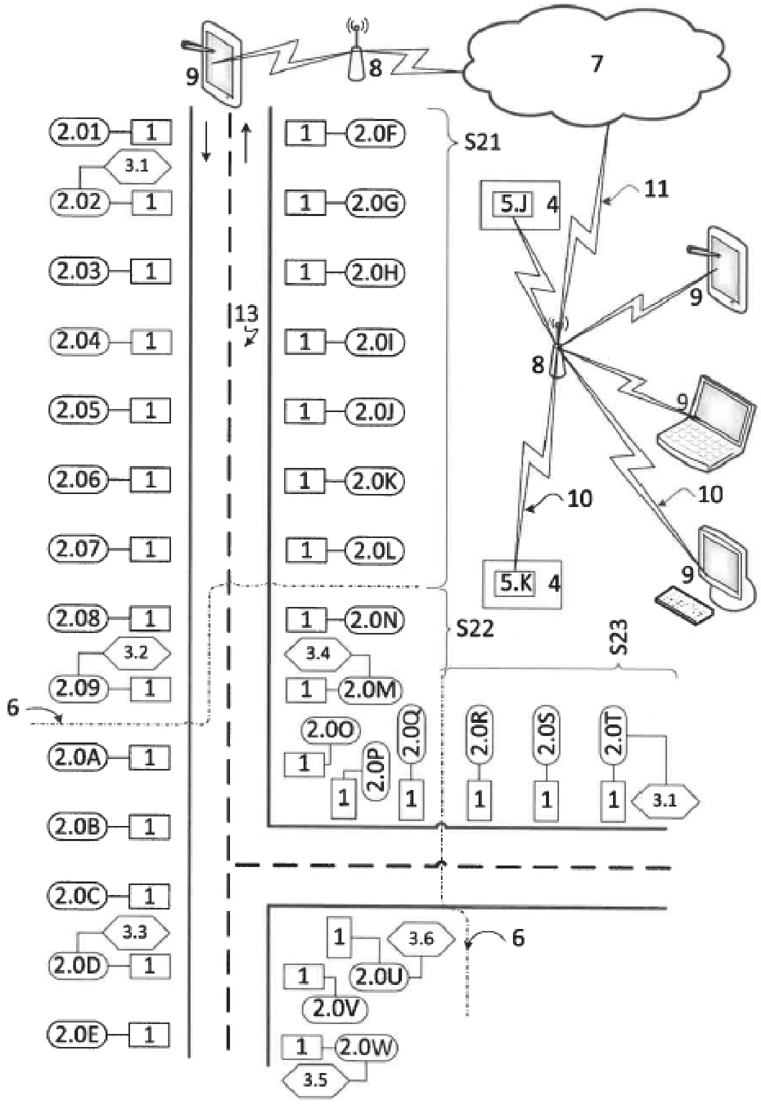

Fig. 2. Diagram of an infrastructure lighting system. Source: own study

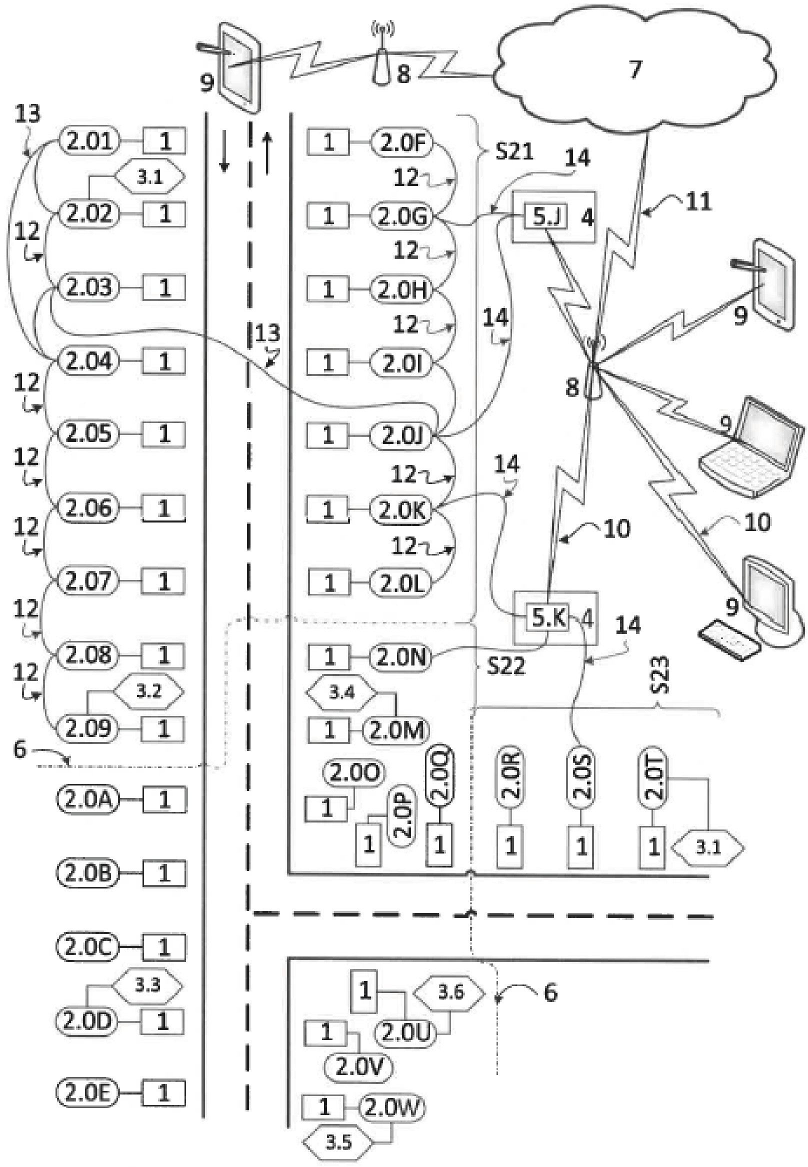

Fig. 3. Diagram of connections formed between the controllers of an infrastructure lighting system. Source: own study

lighting fixture 1 and electrically connected to it. The 2.xx IoT controller includes an IEEE802.15.4 communication module with a processor, power supply, and a DALI lighting fixture control interface. The 5.X IoT gateway contains at least two radio communication modules compliant with the IEEE802.15.4 standard. The housing of the 5.2 gateway is fitted with three radio communication modules. The selected luminaires 1 are physically connected to the 3.x motion detectors, which are electrically connected to the 2.xx controllers. Local networks are established between the 2.xx controllers and the 5.X IoT Gateway using the short-range radio communication in Sx mesh topology, where x is the number of the network.

Figure 3 presents a diagram of connections formed between the controllers of an infrastructure lighting system.

Figure 3 shows exemple close-proximity connections 12, remote connections 13, and connections 14 to network gateways 5.J and 5.K. Figures 1 and 2 indicate the areas of the three local mesh networks S21, S22 and S23, marked with curly brackets and separated by lines 6, with the IoT gateway 5.K being in three independent networks S21, S22 and S23, and the gateway network IoT 5.J only participates in the S21 network. The gateways 5.X establish a radio link 10 with the mobile station 8 via a long-range communication module. The mobile station 8 maintains a permanent connection 11 to a computing cloud 7 in which the CMS is installed. The end devices for operating the infrastructure lighting system are desktop computers, portable computers or mobile devices such as a smartphone or tablet 9 together with the software running on them.

6. Characteristics of the adaptive lighting control system

Żagan defines adaptive lighting as a transfer of a recognised street-lighting method and the space in front of the car through its own headlamps to the lighting conditions with the use of stationary lanterns. The area that covers the light spot realised on the road by car headlights keeps moving with the movement of the vehicle, running in front of it (Żagań, 2012: 154–155). The practical implementation of this idea for street lighting relies on the area in front of the car being lit by several lanterns preceding the car's position (Fig. 4), creating the same perception conditions as stationary lighting (the driver observes next 60–160 m of the road section ???). Until recently, this idea could not be used due to the fact that it was used for street lighting and in the last half century, light sources did not enable free ignition and extinguishing at any time moment in time and also because the time taken to reach full luminous flux far exceeded the need for immediate, full lighting.

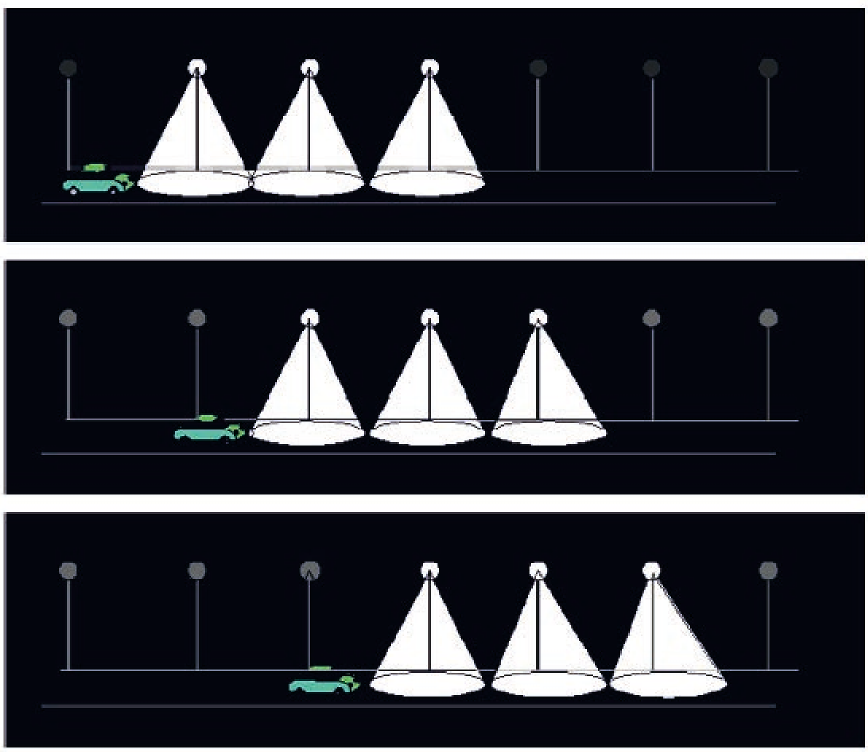

Fig. 4. Follow-up street lighting implements a moving light spot in front of the triggering vehicle by lighting a few lanterns, and the illuminated stretch of road moves with the movement of the vehicle. Source: (Żagań, 2012: 155)

The method of dynamic lighting operation, in particular adaptive lighting, is based on very fast communication within the mesh network related to the controller and in networks associated with network gateways, and on the knowledge of the availability of controllers, particularly controllers to which motion detectors are connected. The knowledge of the availability of the controllers is built on the basis of information referred to as a "life signal" sent by each controller within a defined time interval, preferably not longer than three minutes. Aforementioned "life signal" is sent by each controller and interpreted in the network associated with the controller by the network gateway, which sends this information to other networks if this is indicated by the assigned affiliations to the detector, and is then immediately sent to the CMS, which also interprets the data.

The adaptive lighting control method is based on the fact that for each IoT controller associated with a lighting fixture or for a group of IoT controllers belonging to a specific motion detector, a response to the signal coming from one or more motion detectors is defined in CMS. Each loT controller for which the response to the motion detector signal has been defined determines the presence and activity of the motion detector on the basis of the information referred to as a "life signal" sent by each loT controller in a defined time interval, preferably not longer than three minutes. Aforementioned "life signal" sent by the IoT controller is interpreted in the network associated with the IoT controller and by the IoT gateway, which sends this information to other local mesh networks managed by this IoT gateway, as well as to the CMS. If this is the result of affiliations assigned to this detector, and on the basis of a signal from the motion detector, the IoT controller triggers the action of switching the lighting from the idle state to the operating state. Both of the previous aforementioned states are defined at the CMS level, independently for each group of luminaires, as are the time intervals in which the adaptive lighting mode should be active. Assumptions of the adaptive lighting control system are as follows:

- The controller assigned to act on data from the motion detector interprets the "life signal" from the controller physically associated with the motion detector and, in the absence of such a signal, switches the associated lighting fixture to an active state. This gives a guarantee of normative illumination of the area under each luminaire in the event that the sensor data is potentially inaccessible due to failure of the detector, controller or mesh.
- The controller associated with the motion detector collects statistical information about the detector trigger density around the clock, while all controllers in which the adaptive mode is activated collect statistical data from the response density, which is sent to the CMS along with regular reports from the controller.
- The CMS defines the rules of adaptive lighting in terms of parameters such as: operation hours of the adaptive mode; affiliation of groups of controllers to detectors; idle and active values in the adaptive mode; uphold time; detector deactivation time; projected speed of the object's movement.
- The CMS informs the user by means of icons and alerts that he has not received the "life signal" information from the controller within no more than seven minutes from the last information about the IoT controller status.

Figure 5 shows a simplified infrastructure lighting system on an enlarged scale and in conjunction with Figure 6, which illustrates the operation of adaptive lighting in an infrastructure lighting system.

Figure 5 shows a simplified diagram of the system on a larger scale, in which, for the sake of good drawing legibility, the shapes corresponding to the luminaires 1 connected to the corresponding controllers 2.xx and the motion sensors 3.x physically connected to the selected light fixture 1, and electrically connected to the corresponding controller 2.xx have been omitted. In the simplified diagram, controllers 2.xx of lighting fixtures 1 with motion sensors 3.x connected are marked with the symbol "*" next to the controller 2.xx designation, for example *2.11. Controllers 2.xx installed in lighting fixtures 1 create local short-range Sx radio networks, in mesh topology, building a system of connections with IoT gates 5.X. The connection system in the Sx local networks is not shown in figure 4 so as to not obscure the drawing. The IoT gateways 5.X establish a connection 10 with a mobile telephony base station 8. Such stations are then used to establish a connection with the CMS in cloud 7. Figures 4 and 5 only show example connections 10 between the gateway 5.X and the cellular telephony base station 8 in order to not lose legibility of the drawing.

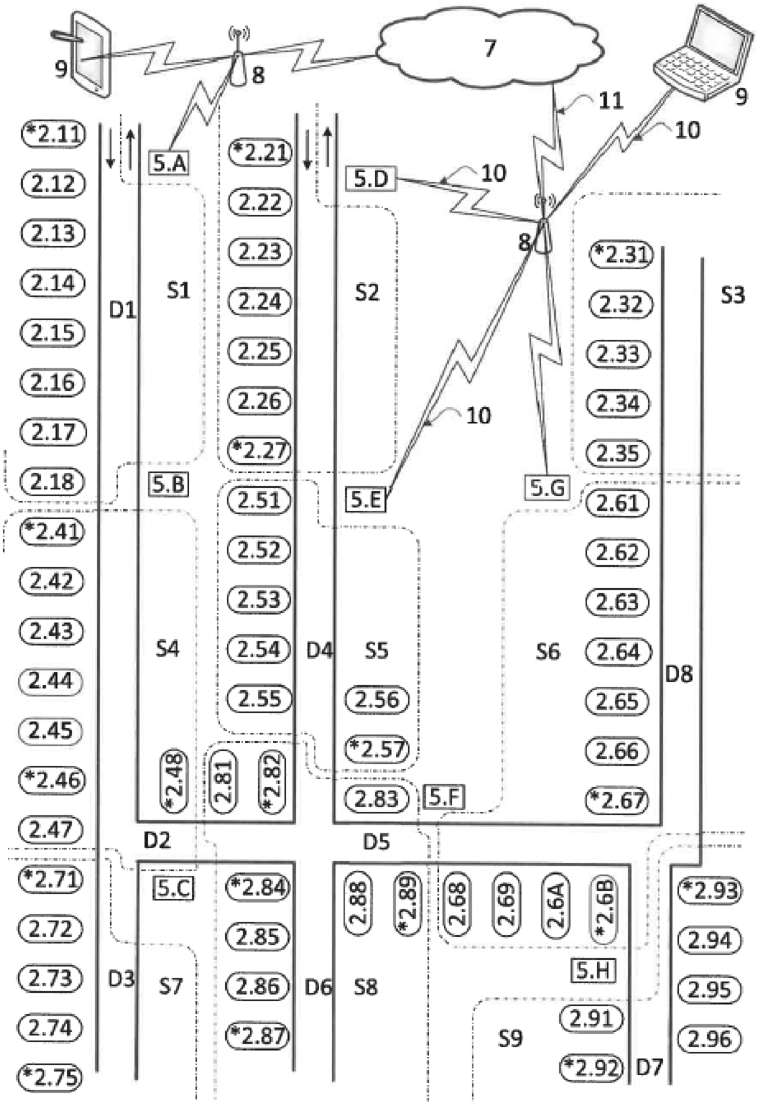

Fig. 5. Simplified infrastructure lighting system on an enlarged scale.
Source: own study

Gate 5.A together with gate 5.B form a local network S1 with controllers from 2.12 to 2.18 and controller *2.11 which is connected to the motion sensor. Controller *2.11, and controllers from 2.12 to 2.18 are integrated with the corresponding lighting fixtures 1, installed on the D1 road.

Gate 5.B using the second short-range radio communication module, compliant with the IEEE802.15.4 standard, together with the gateway 5.C, creates network S4 with controllers 2.42, 2.43, 2.44, 2.45 and controllers *2.41 and *2.46 connected to the motion sensor, located on the road D1, as well as with the controller *2.48 with a connected motion sensor, located on the road D2. Gate 5.C, using the second short-range radio communication module, creates a network S7 containing controllers 2.72, 2.73, 2.74, and controllers *2.71 and *2.75 with a connected motion sensor located on the road D3. In addition, the gate 5.C, using the third short-range radio communication module, creates a common local network S8 with the gateway 5.F, which also includes the controllers 2.81 and *2.82, equipped with a motion sensor, mounted on the road D2, as well as the controllers 2.83, 2.88 and *2.89 equipped with a motion sensor, installed on the road D5, and controllers 2.85, 2.86 and controllers *2.84, *2.87 equipped with a motion sensor, installed on the road D6. The gateway 5.F creates two more local networks using a second and third short-range radio communication module and with gateway 5.E, it forms the network S5, while

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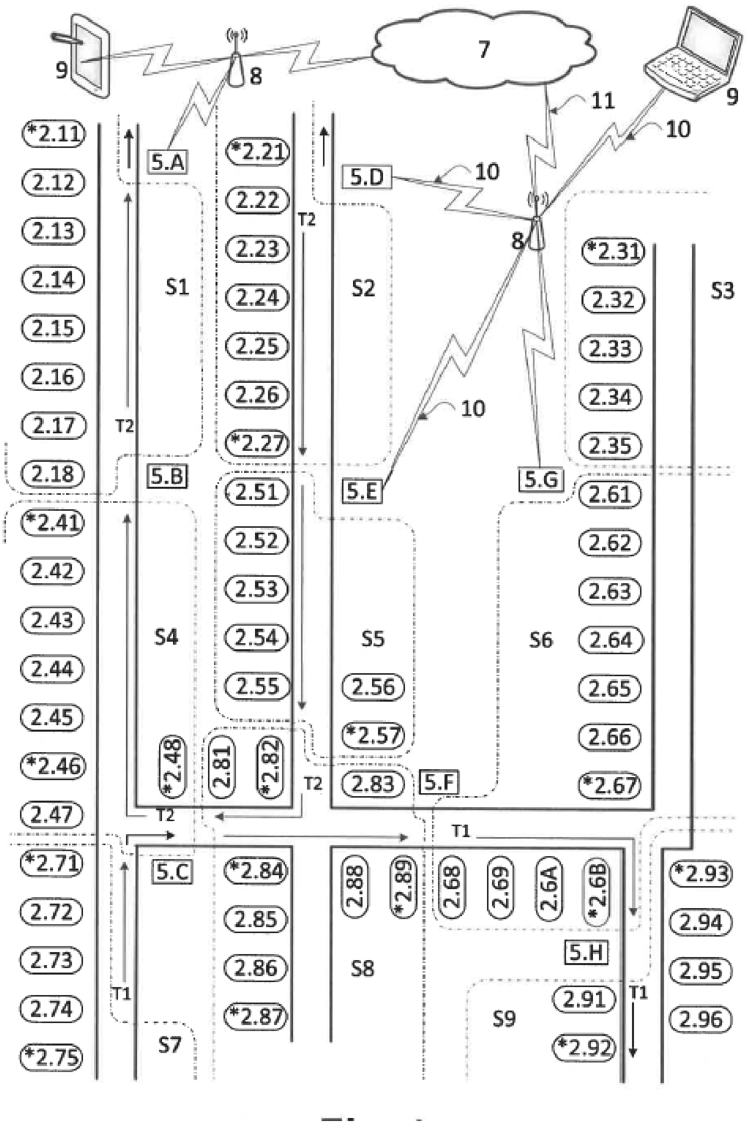

Fig. 6. Operation of adaptive lighting in an infrastructure lighting system. Source: own study

with gateway 5.H and gateway 5.G, it forms the network S6. Similarly, gate 5.E and gate 5.D form the network S2, while gate 5.G forms a standalone network S3. Each of the motion sensors distributes information on motion detection in the local radio network, which is transmitted in the network and interpreted by the controllers assigned to the group of a given sensor.

The network association of the motion sensor with the corresponding luminaires is shown in Table 1 below.

Table 1. Network association of the motion sensor with the corresponding luminaires, source: own study

Number of the controller with the connected motion sensor	Number of the controller integrated with the lighting fixture
*2.11	From *2.11 to 2.18, and *2.41 i 2.42.
*2.41	2.18 and from 2.41 to 2.47
*2.46	*2.41 to 2.47 and *2.71, 2.48.
*2.71	*2.71 to *2.75, and 2.47, *2.46, *2.48

Number of the controller with the connected motion sensor	Number of the controller integrated with the lighting fixture
*2.75	*2.71 to 2.75
*2.48	*2.48, 2.81, *2.82, 2.83, *2.84, 2.88, *2.71, 2.72, 2.47,*2.46, 2.45;
*2.82	*2.48, 2.81, *2,82, *2.84, 2.85, 2.88, *2.89, 2.83 and *2.57
*2.84	*2.84 to *2.89, 2,83, *2.57, 2.81 and *2.82
*2.87	*2.84 to *2.87
*2.89	2.81 to 2.85, *2.57, 2.88, *2.89, 2.68 to *2.6B
*2.6B	2.88, *2.89, 2.66 to 2.6B, *2.93, 2.94;
*2.92	2.91 to 2.96
*2.93	*2.91 to 2.96, and 2.6A, 2.6B, 2,66, *2.67
*2.67	*2.31 to 2.35, 2.61 to *2.67; 2.6A, *2.6B, *2.93, 2.94
*2.31	*2.31 to 2.35, and 2.61 to *2.67, *2.6B, *2.93
*2.57	2.51 to *2.57, 2.26, *2.27, 2.81 to 2.85, 2.88, *2.89
*2.27	*2.21 to *2.27, 2.51 to *2.57, 2.83
*2.21	*2.21 to *2.27, 2.51, 2.52

The presented configurations of connections of sensors *2.xx with controllers 2.xx show that they exceed the boundaries of the area of operation of local mesh networks. The information is transmitted between controllers 2.xx in adjacent Sx networks associated with the gateway 5.X. The gateway 5.X contains two or three short-range radio communication modules. The presented configuration makes it possible to build a network for any area, regardless of the required number of devices, and ensures maximum dynamics of operation due to the transmission of information at the local level, without the need to communicate with the CMS.

The method of operation of adaptive lighting in the infrastructure lighting system according to the system shown in figure 5 is that the vehicle following the route T1 triggers a motion sensor connected to the controller *2.75 which controls the connected luminaire and sends information to the mesh network about the detection event. Controllers belonging to the controller's *2.75 mesh network switch on the "active" state in the connected lighting fittings and forward information concerning motion detection after receiving a motion detection signal.

The vehicle travelling further along the T1 route triggers the activation of a sensor connected to the controller *2.71, which again sets the slave luminaire into an active state for a given time and broadcasts information in the mesh network S7. This information is received by the other controllers 2.xx in the network S7 from 2.72 to *2.75 and by the gate 5.C, which checks if the traffic information should be forwarded to other networks belonging to gate 5.C, and after confirmation, gate 5.C, by means of the remaining short-range radio modules, broadcasts information about the detection of traffic in the network S4, in which the controllers *2.46 to *2.48 interpret this information and switch their luminaires from the rest state to the active state, while the *2.41 to 2.45 controllers ignore this information.

The vehicle then triggers the motion sensor assigned to the controller *2.48, triggering the procedure described above, where gateway 5.C broadcasts the information on the three subordinate networks S7, S4 and S8 where the controllers associated with the motion sensor connected to the luminaire *2.48

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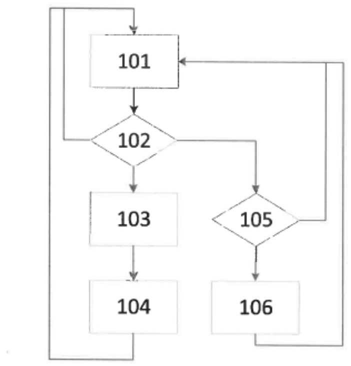

Fig. 7. Block diagram of an infrastructure lighting system controller supporting adaptive lighting. Source: own study

will switch the state of the luminaires, while controllers to which the reaction has not been assigned will ignore the command.

The way the infrastructure lighting system works is closely related to the way the IoT controller works, which is illustrated in the block diagram of Fig. 7, and includes the following steps (Table 2).

Table 2. Diagram description, source: own study

Number of the step	Description
101	The loT controller 2.xx monitors the interruption indicator, which is primarily responsible for the attached motion sensor 3.x, if the sensor is connected to the controller, and the local radio communicates with mesh network Sx. It counts down the time and verifies saved schedules with priorities by performing the function of edge control of the luminaire. In addition, the loT controller 2.xx sends a "life signal" at a defined time interval, monitors the status of the luminaire 1, and checks that the motion sensors 3.x associated with the controller 2.xx send regular "life signals" via the local mesh radio network Sx. In case the signal is available from all associated sensors 3.x, the IoT controller 2.xx waits for information from sensors 3.x about motion detection. If at least one of the sensors 3.x related to the controller 2.xx does not report its presence in the required time, the loT controller 2.xx will take the action defined for this situation by the system operator via the CMS, for example, by switching the luminaire 1 from the standby state to the active state.
102	If an interruption is detected, the loT controller 2.xx recognises the source of the notification, among which the most important factors from the point of view of adaptive lighting are: interruption from the connected motion sensor 3.x, and interruption from the radio network through which information about motion detected by the sensor 3.x is provided to the controller linked to the controller via the local radio communication mesh network Sx.
103	In cases when the interruption comes from the motion sensor 3.x connected to the loT controller 2.xx, the controller switches the luminaire 1 from the rest state to the active state.
104	The loT controller 2.xx sends the motion detection information to the local radio communication mesh network Sx, giving the unique number of sensor 3.x and the detection time stamp, and returns to the operation described in step 101.
105	For motion detection, when the interrupt in step 102 originates from the local mesh Sx, the loT controller 2.xx checks to see if it is assigned a response to a unique sensor 3.x signal; if not, it returns to the action described in step 101, if yes, it checks the required type of response: 1. Transmission of a motion detection signal to subsequent nodes of the local radio communication mesh network Sx – loT controllers 2.xx; 2. The change of the operating mode of the luminaire 1 understood as switching from the idle state to the active state and the transmission of traffic detection information to subsequent nodes of the local radio communication mesh network Sx. 3. Changing the operating mode of the luminaire 1, understood as switching from the standby state to the active state, without further propagation of information about motion detection, and then the loT controller 2. xx goes to step 106.
106	The loT controller 2.xx carries out activities in accordance with the type of required response to the signal of the unique sensor 3.x. The loT controller 2.xx counts the number of received commands and the number of performed switches from the standby state to the active state for a defined time interval, which can be from 10 minutes to 1h. The collected data will be sent to the CMS in step 1 along with the standard reports of the controllers. After execution of step 106, the loT controller 2.xx returns to monitoring the operation of the luminaire 1 and the local radio communication mesh network Sx, described in step 101.

The controller operation described above is limited to the area of one local mesh network. To overcome the limitation of a single network, an IoT gateway 5.X that is designed to connect local IoT networks is needed. The connection of adjacent local mesh networks takes place through the IoT gateway 5.X, through dedicated short-range radio communication modules. The IoT gateway 5.X supports many, or at least two, local mesh networks Sx and is permanently present in each of the subordinate Sx networks through a radio communication module dedicated to a given Sx network. The way in which the IoT gateway 5.X works is as presented in Table 3.

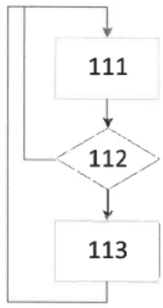

Fig. 8. Block diagram of an IoT gateway operation supporting adaptive lighting

Table 3. Diagram description, source: own study

Number of the step	Descriptions
111	The IoT gateway 5.X supervises the subordinate local Sx radio communication networks through dedicated short-range radio communication modules, records relevant information from the network Sx, distributes the current calendar time appropriate to the installation site and communicates with the CMS system to provide up-to-date information for the system observer and also transmits commands defined by the system operator to subordinate Sx networks and verifies information from subordinate SX networks. In addition, it sends reports generated by the controllers and transmits "life signals" to the CMS generated by the controllers, thanks to which, the system "understands" the current state of the Sx network and devices belonging to the Sx network.
112	In the case of obtaining information about motion detection in one of the subordinate local radio communication mesh networks Sx, the loT gateway 5.X verifies whether in other Sx networks subordinate to it there are loT controllers 2.xx with an assigned reaction to the motion sensor 3.x reporting activity. If, as a result of the verification, it turns out that in other subordinate Sx networks there are no loT controllers 2.xx with the assigned reaction, the IoT gateway 5X ignores this information and returns to the basic operation described in step 1.
113	If, on the other hand, it turns out that there are IoT controllers 2.xx with an assigned response to the motion sensor 3.x reporting activity, the IoT gateway 5.X transmits this information via short-range radio modules specific to the Sx networks, where the information should be disseminated.

The CMS enables flexible configuration of the previously described behaviours. The method for configuring the operation of an infrastructure lighting system, illustrated in the block diagram in figure 8, includes the steps presented in Table 4.

Table 4. Diagram description, source: own study

Number of the step	Descriptions
120	Preparation for lighting operation configuration – after installing the devices and connecting them to the appropriate local radio communication mesh network Sx, the system presents all devices on a map background, which is the starting point for the configuration of lighting operation, including the configuration of devices to work in the adaptive mode.
121	Preparation for loT controllers 2.xx configuration – first, the loT controllers 2.xx associated with controllable luminaires 1 are configured into groups affected by motion detectors 3.x. Several motion detectors 3.x can be connected to each such group. If the motion sensors 3.x have different impact zones, an appropriate group must be created for each impact zone.
122	Defining the configuration parameters for the loT controllers 2.xx – in the next step, the following parameters are defined for a given group: vehicle speed the average distance between the lighting fixtures idle and active state of luminaires the number of lost life signals which the controller will interpret as the lack of a sensor in the system time parameters relating to dates and times and adaptive lighting mode activation and deactivation The operating mode which the controller should activate in the case of interpreting the lack of a sensor in the system The number of lost life signals after which the controller will report the motion sensor unavailability error to the CMS system duration of maintaining the lighting after receiving a signal about the activity of the motion sensor time interval in which the controller will count up the amount of traffic-activity information received from the network

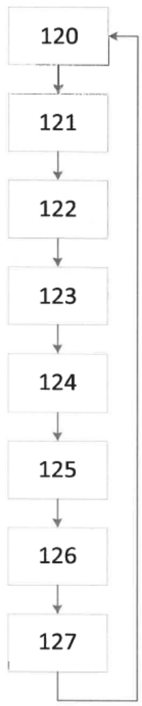

Fig. 9. Block diagram of an operational configuration of the adaptive lighting system. Source: own study

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Number of the step	Descriptions
123	Saving of IoT controllers 2.xx configuration – saving the group configuration will allow the defined behaviour to be sent to the IoT controllers 2.xx belonging to the group.
124	Preparation for motion sensors 3x operation configuration – configuration of the operation of motion sensors 3.x can be done in two ways: by configuring each sensor 3.x separately or by assigning the configuration to a group of sensors 3.x. While configuring each sensor 3.x individually gives the greatest flexibility, for larger installations, it will result in a multitude of configurations and will make configuration management difficult. For this reason, it is recommended to create groups and configure each sensor 3.x by assigning the configuration to the sensor 3.x group, even if some groups contain only one sensor 3.x. In the future, the group can easily be expanded while keeping the original configuration.
125	Configuring the motion sensors 3.x operation – the configuration of the 3.x sensor group is performed when all sensors 3.x are to operate in the same way. If different configurations are required, then a separate sensor 3.x group must be created for each configuration. The configuration of the motion sensors 3.x operation consists of saving the following parameters in the configuration menu: • The ”inactive” time – the time when the data from the sensor is ignored; this is the time when the sensor 3.x works and detects motion, and the IoT controller 2.xx counts these calls, but does not affect the connected luminaire 1, and does not propagate the data of these calls in the Sx network. This allows us to build traffic density statistics that can be used by the system or operator to modify the adaptive time settings in the system or in its areas. • The “dead” time is a short period of time immediately after the detection of motion in which the motion data from the sensor is ignored, it may be, for example, the same object that triggered the repeated activation of the sensor leaving its detection area. • The time interval in which the controller physically connected to the sensor 3.x will count the number of motion detections from the sensor 3.x both in the active and inactive time of the adaptive lighting mode in order to send this information to the CMS system as part of regular reports.
126	Saving sensor 3.x configuration data – after completing the configuration, the configuration data should be saved under a unique name, which allows us to use the saved configuration data to configure other sensor 3.x groups.
127	Sending device configuration data – after completing the configuration, the CMS system will automatically send the configuration data to all configured devices. After completing the configuration, the system will go to the basic operation mode consisting in downloading, collecting and informing the user about the current way the system operates, device availability and alarm notifications. It also allows us to observe the history of events, including those related to the operation of the system in an adaptive mode, the analysis of collected statistical data and the ability to identify which data can be used by the system or the operator to modify the system’s adaptive settings.

The research process analysed the performance of the adaptive lighting system without the CMS. Figur e 10 shows an infrastructure lighting system operating without the participation of a CMS. During commissioning and configuration, the whole process is exactly the same as described above; however, after configuring the system, connections 10 and 11 of IoT gateways 5.X to the CMS cloud computing 7 are terminated. This can be done by physically removing SIM cards installed in IoT gateways 5.X, manual deactivation of the cards at the operator’s or by integrating the CMS with the operator, removing or deactivating Wi-Fi access points, disconnecting the Internet connection or blocking data download on the CMS side. In this case, the infrastructure lighting system will work without the possibility of viewing the data generated by the system and the possibility of reconfiguring the system’s operation. For the proper operation of the system, for each local radio communication mesh network Sx, at least three IoT controllers 2.xx equipped with a GPS module for real-time synchronisation should be used.

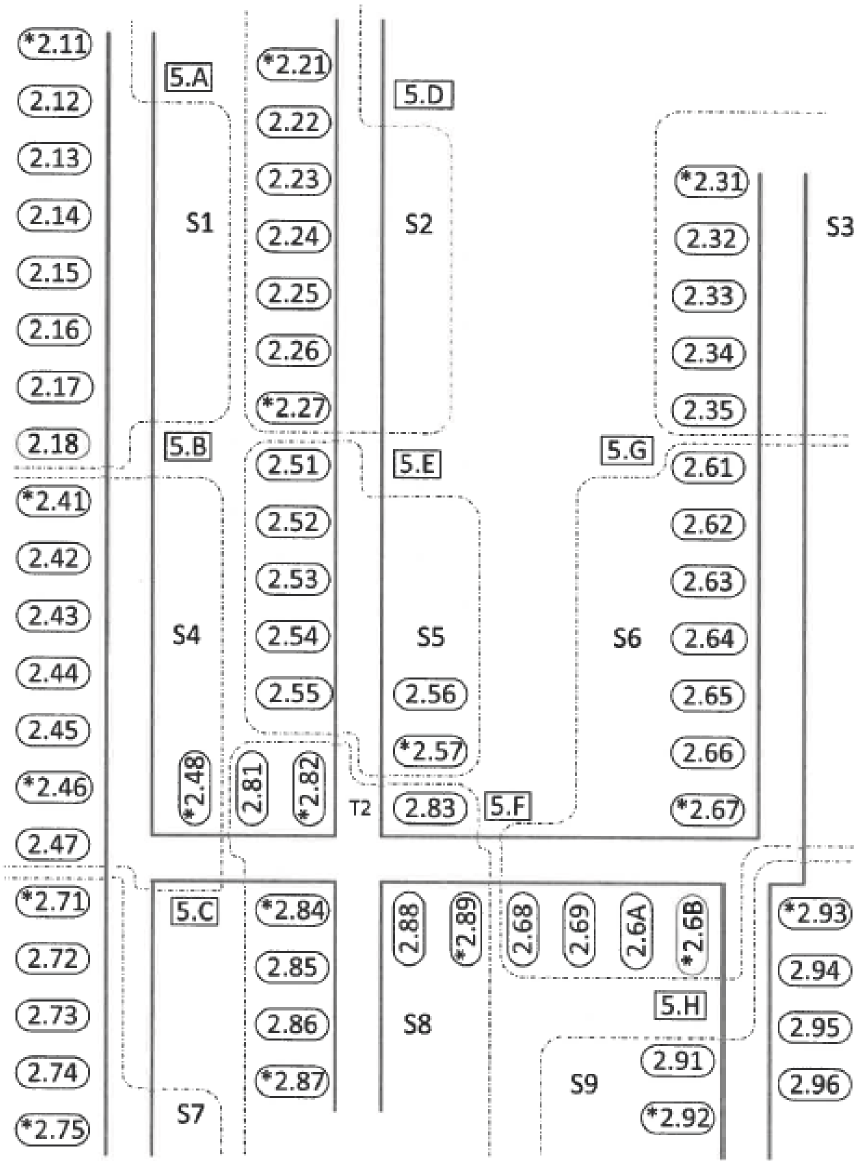

Fig. 10. Infrastructure lighting system operating without the participation of a CMS, source: own study

7. Summary

The infrastructure lighting system developed and tested under the "Intelligent sensor systems for lighting management in solutions from smart lighting to smart city. Research and prototyping" project was submitted to the European Patent Office. The article was prepared on the basis of the description of the system from the application, the results of research work and claims submitted to the EPO. The infrastructure lighting system includes IoT controllers integrated with the luminaires or installed on the luminaire, motion detectors and IoT network gateways. Each IoT gateway contains at least two radio communication modules operating in the IEEE802.15.4 standard, while the IoT controller includes a radio communication module in the IEEE802.15.4 standard and is equipped with a processor and a lighting fixture control interface. Moreover, each IoT gateway radio communication module is a node of its own short-range radio network Sx in the mesh topology, and the other nodes of this local radio network in mesh topology S are radio communication modules of IoT controllers. Pieces of information sent in the local radio mesh network can be redirected to another local radio mesh network Sx reachable from the aforementioned gateway, as

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well as to the CMS, via the IoT network gateway using the Internet or a long-range communication module. The CMS can be installed on a computing cloud or on a dedicated server. The system created in the course of research works can be an innovative solution that will significantly reduce the total cost of energy consumption. The adaptive lighting control system can become an important element of the smart city.

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