Alexandru LAVRIC, Valentin POPA, Ilie FINIS, Daniel SIMION
Stefan cel Mare University of Suceava

The design and implementation of an energy efficient street lighting monitoring and control system

***Abstract.**.The reduction of electrical energy consumption has been a highly debated issue on a European level and represents an important topic. This paper presents the design and implementation of a street lighting monitoring and control system using a WSN (Wireless Sensor Network) communication protocol, which has the ability to incorporate a high number of nodes. The main advantages of this system consist in the reduction of the costs related to energy consumption and maintenance by integrating a vehicle detection algorithm.*

***Streszczenie.** W artykule zaprezentowano system monitoringu oświetlenia ulicznego wykorzystujący sieć czujników bezprzewodowych o możliwości podłączenia wielu węzłów. System pozwala na redukcję kosztów utrzymania i zużycia energii poprzez wykorzystanie algorytmu detekcji nadjeżdżających pojazdów. (**Oszczędzający energię system zarządzania i monitoringu oświetlenia ulicznego – projektowanie i wdrożenie**)*

Keywords: street lighting – WSN – energy saving – monitoring and control system.
Słowa kluczowe: Oświetlenie uliczne, WSN, oszczędzanie energii, system zarządzania i monitoringu.

Introduction

The reduction of electrical energy consumption has been a highly debated issue on a European level, since street lighting accounts for 20% of the worldwide electricity usage [1]. Street lighting meets the needs of local communities, ensuring: increased comfort and quality of life, increased security and safer pedestrian and road traffic. The classical street lighting control systems employ photocells. Dust or dirt build-up, improper installation or calibration may cause them to malfunction and thus compromise the entire control system. Moreover, it is difficult to measure the energy consumption of each lamp [2]. Street lighting administrators rely on the citizens' willingness to report malfunctions, since there is often no automatic lamp control and monitoring system. Another growing concern is also related to the ability of dimming the luminosity level depending on the changes in the external environment.

The concept of Intelligent Street Lighting has been advanced in recent years, prompting the employment of cost-effective schemes in street lighting systems that would primarily reduce the electrical power and maintenance costs and thus ensure the maximum safety of road traffic [3]. Such a state-of-the-art scheme entails the use of Solid State Lighting (SSL) that has certain advantages as opposed to the traditional lighting systems, such as fluorescent, incandescent or HID (High Intensity Discharge) lamps. Moreover, the high efficiency of SSL provides a series of other additional benefits in terms of energy consumption, total carbon footprint and cost-to-lifespan ratio [4].

In light of the above considerations, this paper will focus on analyzing and comparing the state-of-the-art systems presented in the scientific literature and the communication protocols that can be implemented in a street lighting monitoring and control system. The paper first introduces the proposed architecture and will continue with the detailed development of the software and hardware structure of the system. The conclusions will be presented in the final part of the paper.

The state-of-the art systems

Fig. 1 details the general structure of a street lighting control system. The studies published in the scientific literature follow this centralized structure that includes a command center, concentrator nodes and a number of actuator nodes that are fitted on each lamp. When the remote terminal unit of the command center sends a command to the actuators, the message first reaches the concentrator which forwards it to the nodes that control each lamp. The central control unit is often located in the offices of local authorities. The unit communicates with the concentrators which, in turn, communicate with each command terminal and thus ensure the monitoring of a high number of lamps. At the same time, it collects information about the status of each node and forwards it to the command center. The feedback on lamp status and any possible malfunctions is collected by the concentrator and is then forwarded to the command center [1].

One possible method to implement an automatic street lighting control system would be to integrate an IEEE 802.15.4 standard compliant transceiver in the lamp control relay, each device being thus turned into a node within a wireless network that covers the entire city. The system entails the use of numerous devices installed across a large geographical area. The communication facilities added to these devices require the development of intricate network topologies. Since the LOS (Line-of-Sight) can be limited by obstacles, the network can be implemented in a mesh topology [5].

Gustavo et al. [6] advocated the improvement of street lighting control systems. Thus, they opted for the integration of a transceiver in the photoelectric relay used for the on/off control of HPS (High Pressure Sodium) lamps. The IEEE 802.15.4 standard defines the MAC and PHY layers of the OSI (Open Systems Interconnections) model and is used for low rate wireless personal area networks (LR-WPAN), while the network and application layers are not defined [7].

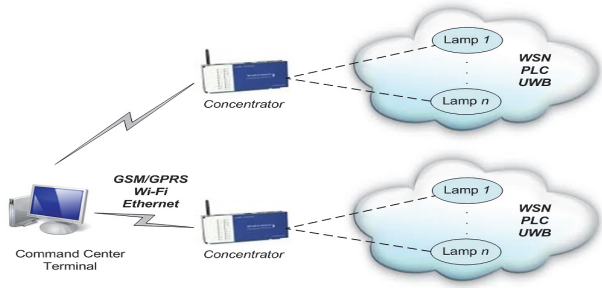

Fig. 1. Communication technologies used in street lighting control

In light of the above, the application should be developed based on an already defined standard, such as DALI (Digital Addressable Lighting Interface), ZigBee or 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks).

DALI is a lighting control standard that has been adopted by the IEC (International Electrotechnical Commission) for the control of the ballast circuits used for lighting equipment monitoring. One disadvantage of this protocol is the restricted number of nodes it can control (64 nodes) and is therefore inadequate for a street lighting control system that can comprise thousands of nodes. On the other hand, ZigBee networks can integrate a high number of nodes. This particular standard has been created for wireless networks, as a lucrative low-cost, low-power and low data rates alternative. Thus, the ZigBee communication protocol is widely deployed in street lighting control systems [8] - [10].

Another option when implementing the NWK network layer is the use of the 6LoWPAN protocol that adapts the IPv6 protocol (Internet Protocol Version 6) to the IEEE 802.15.4 standard. The 6LoWPAN protocol has the same low-cost, low-power and low-speed (maximum 250 kbps) requirements, with Internet integration features. Since the payload length supported by IPv6 is excessive, 6LoWPAN allows an adaptation layer that connects the NWK network layer to the MAC layer through compression, fragmentation and reassembly. The ZigBee routing protocol has certain shortcomings in terms of package delay and may thus cause a dramatic slowdown in network performance. 6LoWPAN does not specify any routing scheme, allowing the user to implement it. The advantage when using the 6LoWPAN protocol is that the means chosen to send the information to the command center can be either a cable or a wireless network and, thus, the implementation costs can be considerably reduced. An RTOS (Real Time Operating System) system can be integrated in order to ensure the high efficiency of the system and allow multitasking [11]. The system architecture presented in [12], [13] is based on the GPRS network that enables the transfer of information across longer distances as the one between the command center and the ZigBee network that provide the areal control.

After a careful analysis of the standards that define the wireless sensor networks, such as IEEE 802.15.4 and IEEE 1451.5 (Wireless Smart Traducers Interface), the system developed by Chunguo Jing et al. [14] recommends the integration of the transceiver CC1000 that uses a Proprietary RF communication protocol. Another possibility would be to implement a decentralized control system by employing the WSAN (Wireless Sensor Actuator Networks), as suggested by D. Curiac et al. [15]. WSAN entails the presence of two types of sensors: sensors designed to gather information about the surroundings and actuators sensors that are able to interact with the environment.
Another street lighting control system may take into account the presence and the direction of the vehicles on the road [16], [17]. This concern started from the idea that road traffic is significantly reduced during the night and it is thus unnecessary to keep the streetlight luminaries on. The system would require the road to be fitted with a set of circular loops that would detect the presence of vehicles. The main disadvantage of such a detection system is the high implementation cost. A different way to establish short-distance communication for a street lighting control system is to use the existing power lines of the lamps. Thus, communication is ensured by using PLC (Power Line Carrier Communication) [18]. The system consists in SEC (Single-Lamp Energy Controller), the central controller (Smart Server), the GPRS modules and the command center. The Smart Server sends, collects and processes the data provided by the SEC. The command center communicates with the Smart Server via GPRS.

The communication protocols used by street lighting control systems can be divided into two categories: local communication, using short range transmission (light pole-to-light pole) and long range communication such as the systems that link the command center to the sensor network. Information can be transferred by using short-range communication protocols and wireless networks such as ZigBee, JenNet, 6LoWPAN, IEEE 802.15.4, UWB (Ultra-Wide Band and Ultraband), or through the existing power lines, using PLC (Power Line Communications). A comparison between the WSN and the PLC communication protocols can be found in a related work [19]. Long-range communication can be established through standards such as Wi-Fi (802.11), Ethernet (cable), GPRS (General Packet Radio Services) or WiMax technologies.

Proposed system architecture

Fig. 2 presents the proposed system architecture. After analyzing the short-range communication protocols, the WSN is selected, while Ethernet is chosen for long-range communication, as a cost-effective solution. One way to reduce costs is to implement a decentralized network topology of the hierarchical type (client-server). The client in this network topology is the e-Box 4300 module, and the server is installed in the offices of the local authorities. This new concept represents a widely distributed Internet architecture for an energy efficient street lighting monitoring and control system. The e-Box 4300 module has the following specifications: fan-less, compact Flash slot, RS-232, on-board 10/100Mbps LAN, Wireless LAN and has a low power consumption. It acts as a gateway between the local wireless sensor network and the Internet network, being a cost-effective solution.

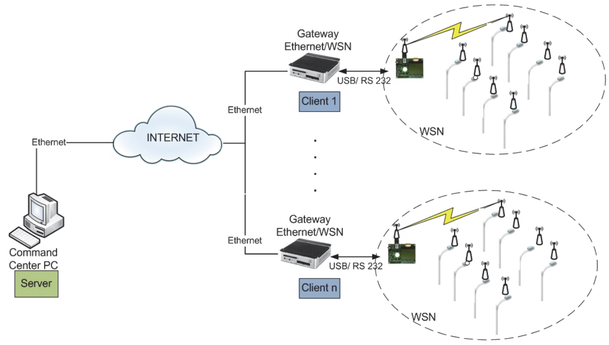

Fig. 2. Proposed system architecture

The implementation of a decentralized network topology is recommended for the WSN local area network. The area master in a local area network topology is an FFD (Full Function Device), while the slave nodes are of the RFD (Full Function Device) type, thus significantly reducing the costs. Hence, the FFD nodes should be able to control the slave nodes and also enable the retransmission of the messages to the next area master. If communication with the command center through the e-Box fails or when there is a communication error in the WSN network, the integrity of the system is not compromised, since the local area master secures the functioning of the system until communication is restored. The network coordinator is connected to the e-Box module through a USB to RS232 communication interface.

If one or several of the master nodes fail, the integrity of the network is not compromised. The system is able to execute the on/off command and the dimming in the standalone mode. The coordinator collects the information received from the WSN network and sends it to the gateway that supports a client-type application. The application sends the information about lamp status to the server. The local area master accounts for the adjustment of the light level, thus confirming the implementation of a decentralized control system. It identifies the optimal moment to broadcast the on/off command, by processing the information received from the sensors. Wireless modules are fitted with sensors that can read the luminosity level in the surrounding environment and the local area master has an additional sensor that detects the presence of vehicles. The information sent by the sensors is used when making the dimming decision.

The street lighting control system is based on a long-thin structure, encompassing a wide geographical area and with a few hundred nodes spread across several kilometers. Thus, the selected network topology is the tree type and it meets the performance criteria required for the development of a control system [2]. An assessment of network topology efficiency can be found in a related work [20]. Therefore, only the local area master has routing capabilities. Hence, when a command is sent from the center, the gateway secures the transfer to the coordinator and the message is then transmitted throughout the WSN network until the destination node is found. When a lamp malfunctions, the system must make up for the lost luminous intensity by increasing the intensity of the nearby lamps [2]. The architecture can then make the dimming decision and control the on/off command of the lamps, thus ensuring the maximum safety of traffic and be energy efficient at the same time. The system is allowed to control the lamps depending on the traffic volume within a certain time interval when the traffic flow is reduced. Thus, when a vehicle is detected, the lamps on that lane are on, while if no other presence is detected, the lamps go off or reduce their luminosity, optimizing lighting and lowering the costs. Certainly, this function can only be implemented with systems that use LED lamps with very fast on/off response times [21], [22] and higher efficiency than HID (High Intensity Discharge) ballast lamps [23].

Hardware development

The hardware is implemented by means of the JN 5148 transceiver that meets the low-cost criteria and operates in the 2.4 GHz band. The communication protocol used for the WSN network is the JenNet developed on the IEEE 802.15.4 standard and meeting the high efficiency criteria, such as: large number of nodes, reduced complexity when developing the applications and no additional license costs. The JenNet communication protocol incorporates up to 500 nodes for a single coordinator and, implicitly, one gateway. Hence, the novelty of this system primarily consists in the possibility to integrate a large number of nodes.

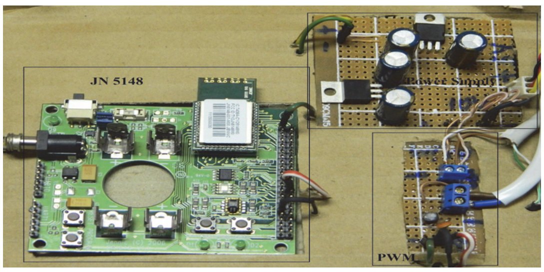

Fig. 3. Hardware design of a master node

The system incorporates a 60W Electromax lamp with 20 HB LED light bulbs, which provide the same light intensity as a 150W HPS (High Pressure Sodium) lamp. The system uses the digital PWM (Pulse Width Modulation) dimming method. Fig. 3 shows the hardware structure of a local area master node. The system consists in the JN 5148 transceiver, the power-supply and the PWM circuit. The driver that is incorporated in an LED street lighting lamp can be controlled for dimming through a PWM signal of 10V.

Since the PWM provided by JN 5148 is of 2.8 V, a PWM circuit transforms it into 10V. The power supply feeds both the transceiver and the PWM circuit. Fig. 4 shows the dimming process, from 100% to 75 % and 50%, respectively.

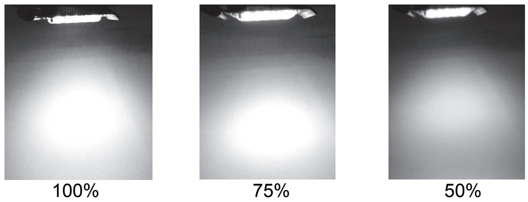

Fig. 2. Light intensity dimming of Electromax lamp

Software development

The software development stages consist in developing the local area communication software by means of a wireless sensor network, followed by the software needed for the remote transmission of the data.

The coordinator is linked to the e-Box through a USB/RS232 communication interface. This is an essential network node, performing the following tasks: it selects the radio channel the will support the communication, initializes the network and allows the nodes to join the network. The coordinator enables the transfer of data from the WSN network to the e-Box where the client application in installed through the USB/RS 232 interface. The data consists in details about the status of each node. Moreover, the coordinator transfers the commands initiated by the user from the server to the WSN network.

Fig. 5 presents the general logic diagram of a node within the proposed street lighting control system. Thus, should the network experience any kind of malfunction, the integrity of the system is not compromised. The on/off lamp switch command is performed depending on the luminosity level of the environment. If the network is operating within normal parameters, each node will monitor the received messages/commands (Message Control). After a pre-defined period of time, the node reads the sensor values, checks the lamp status in order to detect any possible malfunctions and then forwards this information to the coordinator.

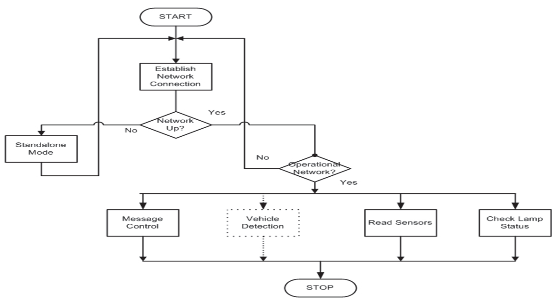

Fig. 3. The general logic diagram of a node

A slave node doesn't have an incorporated sensor that detects the presence of vehicles and, therefore, this task (Vehicle Detection) can only be performed by the local area master board.

Fig. 6 shows the logical tasks executed by each node in a standalone mode (the WSN network is not working). The node measures the luminosity level of the environment and, if it is below a certain value (set by user), commands the lamps to be switched on and afterwards checks the network performance level again.

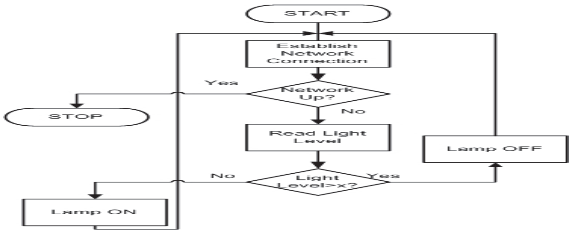

Fig. 4. Standalone mode

Fig. 7 shows the algorithm executed by an area master board in order to detect the presence of vehicles. The first check-up it performs consists in reading the luminosity level of the environment (night?). Subsequently, if a vehicle is detected, it sends a command to turn the lamps on at a predefined luminosity level and sends a message about the presence of a vehicle to the neighbor nodes. After these check-ups, a predefined time period elapses (k seconds) after which the algorithm is restarted.

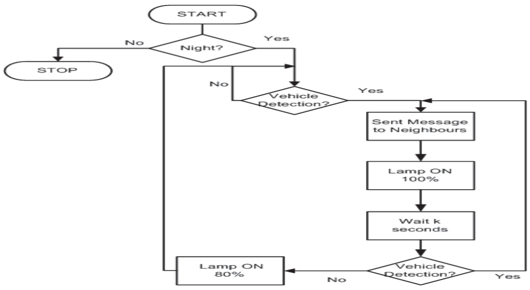

Fig. 5. Vehicle detection

When a vehicle is detected, the node sends a command to turn on the lamp at a luminosity level that can be adjusted by the user and sends a message to the neighbor nodes to execute the same task. If no other presence is detected after a predefined time period, it reduces the lamp intensity (e.g., to 80%). If the lamp at the node is switched on, and the latter receives a new command message from its neighbors, a specified period of time elapses, after which the node switches off or reduces the lamp intensity of the lamp.

All the nodes of the sensor network monitor the information received from each sensor and forward it to the local area master that further sends it to the coordinator. A very important factor that should not be overlooked is the lane detection used by the vehicle, in order the system should thus be cost-effective and save more energy by keeping the lights on the opposite lane switched off.

Hence, we suggest that each node should have one of the following IDs: 1 or 0, depending on the side of the road it is installed on (1-left, 0-right), for a predefined direction. This ID is taken into account when the devices are installed. Thus, when a vehicle is detected, the local area master accompanies a command sent to the slave nodes to turn on the lamps with its ID. The neighbor nodes that receive the message check whether their ID coincides with the ID of the source node and, if so, they execute the command. If the IDs do not coincide, the command will be ignored.

This system can limit energy consumption. Assuming that a lamp is on for an average 9 hours a day, and the light intensity is substantially reduced between midnight and 4:30 a.m. (due to low traffic) by 70% for half the time during this time interval, the daily energy savings will amount to 17.5%. This percentage does not take into account the possibility to dim the light depending on the vehicle and lane detection, thus allowing for additional savings. The energy savings can easily amount to over 20% of the total energy consumption. Maintenance costs can be reduced by approximately 5% - the equivalent of visual inspection costs (labor costs and mobility costs). If the suggested system is selected for implementation, the on-site inspection is not necessary and any possible malfunctions are detected in the reports generated at the command center [2].

Fig. 8 below shows the user interface of the server application. The user interface is an integrated platform that enables the remote control and monitoring of the lamps. It operates within the main PC unit located at the control center. The intuitive interface allows the end-user to take over the automatic control and directly operate the commands.

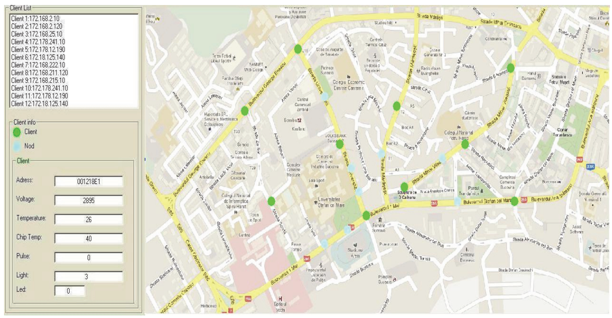

Fig. 6. Graphical User Interface

The application allows the user to manage the geographical positioning of the gateways and of the integrated nodes of each lamp encompassed by the street lighting control system. The user can easily identify the possible system malfunctions [2]. The application performs the monitoring and collecting of the information received from the gateway nodes. The latter collects the lamp status data through the WSN network. The system can trigger the on/off command according to a schedule that takes into account the sunrise/sunset tracking, as well as any other essential factors.

The street lighting control system can display regular records on energy usage as well as details about the completed or scheduled maintenance service. The application also generates statistical reports about the congested traffic areas and rush-hour intervals, since this information is essential for designing an area-specific street lighting control system or for finding the best ways to reduce rush-hour traffic intensity.

Conclusions

The main advantages of this system consist in a significant reduction of the costs related to energy consumption and maintenance services, through the adjustment of the light intensity (dimming) after processing the information received from the sensors: light intensity monitoring and vehicle detection. Moreover, the proposed system significantly lowers the implementation costs by integrating a WSN communication protocol in the system. In conclusion, the advantages brought about by the implementation of this system are: the automated periodic reports on the events that may occur (lamp malfunctioning/ communication errors within the network), the implementation of the on/off switch command depending on the time of day or changes in the environment, or by developing a flexible operating schedule.

The novelty of this system consists in its decentralized implementation, thus allowing it to operate when errors occur along the communication lines. The introduction of a vehicle detection algorithm further reduces the power consumption costs. Additionally, the system supports the monitoring of a large number of nodes (500 nodes for a single Gateway). The automated periodic reports enable the monitoring of the high traffic areas and represents tools to alleviate traffic congestion.

Acknowledgements

This paper was supported by the project "Improvement of the doctoral studies quality in engineering science for development of the knowledge based society - QDOC” contract no. POSDRU/107/ 1.5/S/ 78534, project co-funded by the European Social Fund through the Sectorial Operational Program Human Resources 2007-2013, and by PRO-DOCT - Contract no. POSDRU/88/1.5/S/52946.

REFERENCES

[1] Young M., Atici C., Ozcelebi T., Lukkien J. J., Exploring User-Centered Intelligent Road Lighting Design: A Road Map and Future Research Directions, *IEEE Transactions on Consumer Electronics*, Vol. 57, No. 2, May 2011, 788 – 793

[2] Lavric A., Popa V., Finis I., Males C., Gaitan A.-M., An original lighting monitoring and control system using Wireless Sensor Networks, *Proceedings of the Fifth European Conference on the Use of Modern Information and Communication Technologies* (2012), 167 – 173

[3] Alexandru Lavric, Valentin Popa, Codrin Males, Ilie Finis, New Technologies in Street Lighting, *International Word Energy System Conference*, (2012) 811-816

[4] E. Schubert J. Kim, Solid-State Light Sources Getting Smart, *Science*, vol. 308, no. 5726 (2005), 1274-1278

[5] Zhenfeng Hu, Xin Geng , Jin Xiao, Xiaoguang Hu, Research and realization of on-line monitoring system for high voltage circuit breaker based on ZigBee technology, *Control and Automation Conference* (2010), 190–195

[6] Gustavo W. Denardin, Carlos H. Barriquello, Rafael A. Pinto, Marcelo F. Silva, An intelligent system for street lighting monitoring and control, *Power Electronics Conference* (2009), 274 – 278

[7] IEEE Std. 802.15.4. *IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)*, 2003

[8] Yi-Hua Liu, Shun-Chung Wang, Po-Yen Chen, Development of a ZigBee-based electronics ballast system, *International Conference on Industrial Informatics* (2008), 1556 – 1561

[9] Hoon Kim, Xian-Chao Ma, Hai Xu, Hee-Jun Kim, A dimmable electronic ballast for wired or wireless remote control of electrodless fluorescent lamp group lighting system, *International Conference on Electrical Machines and Systems* (2008), 2108 – 2112

[10] Maoheng Sun, Qian Liu, Min Jiang, An implementation of remote control system based on ZigBee technology and Soc solution, *International Conference on Audio, Language and Image Processing* (2008), 629 – 632

[11] J.D. Lee, K.Y. Nam, S.H. Jeong, S.B. Choi, H.S. Ryoo, D.K. Kim, Development of a ZigBee based street light system, *Power Systems Conference and Exposition*, (2006), pp. 2236 – 2240

[12] LiLong, ChuXiumin, WuYong, WuQing, The development of road lighting intelligent control based on wireless network control, *International Conference on Electronic Computer Technology* (2009), 353 – 357

[13] Wu Yong, Chu Xiumin, Wu Qing, Li Long, The road lighting control technology research base on ubiquitous network, *International Conference on Wireless Communications*, Networking and Mobile Computing, 2009, 1-4

[14] Chunguo Jing, Dongmei Shu, Deying Gu, Design of streetlight monitoring and control system based on wireless sensor networks, *Conference on Industrial Electronics and Applications* (2007), 57 – 62

[15] D. Curiac, C. Volosencu, Hierarchical lighting control in urban environments based on wireless sensor-actuators networks, *Advances in Dynamical Systems and Control* (2008), 163 – 166.

[16] Chunyu Liu, Quangen Wang, Design and development of city street-lighting energy-saving system, *Pacific-Asia Conference on Circuits, Communications and System* (2010), 178 – 182.

[17] Hengyu Wu, Minli Tang, Guo Huang, Design of multi-functional street light control system based on AT89S52 single-chip microcomputer, *International Conference on Industrial Mechatronics and Automation* (2010), 134 –137.

[18] Yun-gui Zhang, Li-na Zhao, Li-na Wang, Sheng-Yong Zhang, A Web-based Management System for Urban Road Lighting, *International Conference on Web Information Systems and Mining* (2010), 279 – 282

[19] Lavric Alexandru, Valentin Popa, Comparative analysis of communication protocols and routing algorithms used in street lighting control systems, *Revista Sisteme Distribuite* (2011), 32-35

[20] Alexandru Lavric, Valentin Popa, Codrin Males, Ilie Finis, A Performance Study of ZigBee Wireless Sensors Network Topologies for Street Lighting Control Systems, *International Workshop on Mobile Ad-Hoc Wireless Networks iWMANET*, (2012), 130 – 133

[21] Wang Yijie, Wang Wei, Xu Dianguo, A Single-stage LED Driver for The Street Lighting System, *Przegląd Elektrotechniczny*, (2012), nr 1b, 250-254

[22] Lech Grodzki, Some aspects of PWM and constant-current LED driving, Przegląd Elektrotechniczny, (2012), nr 3a, 74-77

[23] Yijie Wang, Wei Wang, Dianguo Xu, Electronic ballast of metal halide lamp for projector with digital control, Przegląd Elektrotechniczny, (2011), nr 6, 279-283

***Authors**: Alexandru Lavric (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava, Universitatii str. 13, 720229 Suceava, Romania, E-mail: lavric@eed.usv.ro;*

Prof. Dr Valentin Popa, Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava, Universitatii str. 13, 720229 Suceava, Romania;

Finis Ilie (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava;

Daniel Simion (PhD. Student), Department of Computers, Electronics and Automation, Stefan cel Mare University of Suceava.