Intelligent energy efficient street lighting system with predictive energy consumption

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***Abstract*—This paper considers an autonomous intelligent street lighting system with energy efficient predictive algorithm. The work is related to control of the system which uses algorithms that could provide with energy each lamppost during the night time. To this end, lamp posts are equipped with batteries, motion and light sensors and uniaxial solar trackers with azimuth orientation to the Sun. To simplify system monitoring, several lampposts are grouped together and controlled by a single control unit. The control unit is equipped with XBee 3 wireless module. Based on weather forecast for the coming days, the system adapts to weather condition changes and makes calculations of consumption and operating time. These calculations allow us to distribute the system energy consumption evenly during these days.**

Keywords—internet of things, wireless sensor network, solar energy, sensors, intelligent system, autonomous system

I. Introduction

Today, in many cities and metropolitan areas, the street lighting system is an integral part that provides the entire city with illumination and prevents crime in all district areas at nighttime and helps the movement of traffic and provides comfortable night activity for citizens [1-2]. Every year, the idea of smart cities is being developed to reduce energy consumption and outdoor lighting system cost, because the simple street lighting posts have very high energy consumption and according to some research it takes 2,3 % of world electricity utilization [3]. In addition to it, the conventional street lighting posts cause millions of tons of CO2 that emit to the atmosphere [4]. To solve this large-scale problem, many ideas have been proposed regards to minimizing, facilitating and improving energy efficiency of street lighting system [5-10]. For example, one of that consider not to use all street lighting posts on "always on" mode, but propose switching lighting posts on only when there is an object, moving along the road and increasing the level of illumination of nearby stand lighting posts, but giving lower output for distant lampposts. Lighting posts are connected via wireless sensors, making "TALISMAN" – a Traffic-Aware Lighting Scheme Management Network [11]. It saves up to 50-90 % energy (depending on traffic on the road) compared to conventional lighting system.

Another way to save energy is to use the LED lamps, which gives more efficiency than old gas lamps. Researches showed that application of LED instead of gas lamps save up to 50% annual energy on different dimming scenarios [12].

Nowadays, it is common to use solar panels for transforming Sun energy to electricity in order to provide power to street lighting posts. There was a work [13] on energy management in street lighting system where the idea was to provide each lighting post with power from stand-alone solar panel that collects Sun energy. Traffic, weather conditions and energy tariffs for controlling desirable configuration is monitored by central controller. Lightings work on motion sensor to detect and illuminate. Using all previous methods Raffaele Carli proposes an optimization tool for energy efficiency in street lighting system [14]. Their method is an energy manager's decision support tool for planning and optimizing existing lighting system. The main disadvantage of most previous field research papers is that all methods are used to retrofit existing street lighting system, which powered from central electricity station grid or static solar panel that provides lightings with power. In this work, solar trackers have been used for each lamppost for autonomy of the system. The design and mechanism of the solar tracker also the calculation of the energy consumption and its efficiency are presented in [15-17] works. This paper is going to propose autonomous and energy efficient street lighting system that can be achieved via uniaxial solar tracker and wireless sensor network based on weather forecast to adapt and minimize energy consumption of lampposts during night time.

II. Structure of the Proposed Street Lighting System

A. General architecture of proposed intelligent street lighting system

The proposed system consists of group of lampposts, which include 3 lampposts interconnected by common electronic device. In particular, as shown in Fig. 1, three lampposts have common battery and control unit. This idea helps to reduce the cost of electronic devices and system can be integrated rapidly in daily usage.

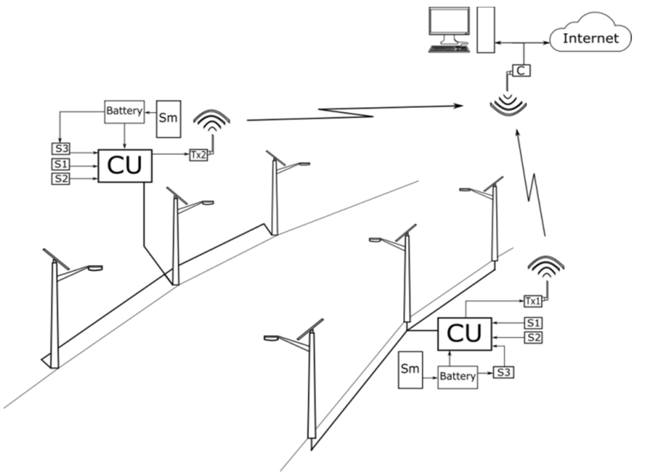

Fig. 1. General architecture of intelligent energy efficient street lighting system.

Each of the three lampposts is equipped with a solar module and sensors for illumination, movement, current and

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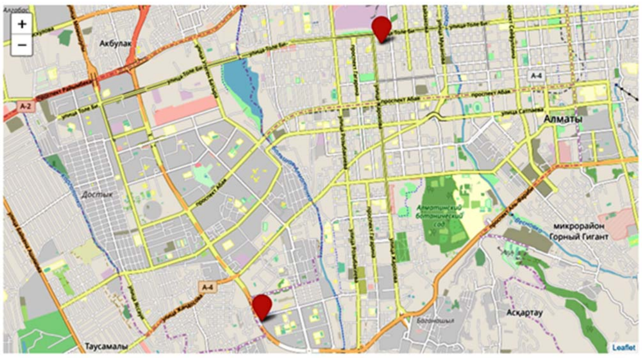
voltage. Solar energy is transformed into electrical energy and charges the common battery. The control unit and the battery of grouped lampposts are located on the central lamppost. Two neighboring lampposts charge the common battery via the power cable between them. And the data from the sensors, which are located on the neighboring lampposts, are transmitted to the control unit through simple wires. The control unit receives this data and then transmits all the necessary information to the network coordinator via the XBee 3 transceiver module. XBee 3, unlike its previous models, has many advantages, such as self-healing (when a single network element breaks down), remote module configuration and the ability to write program code in MicroPython. The network coordinator receives data from all the grouped lampposts and sends them to the database via the Internet. Data is processed and prepared for web monitoring of the network, where the data can be tracked from all nodes of networks. For this purpose, we developed a web site http://streetlight.all-in.kz/ to track and monitor the entire system. Fig. 2 shows a web site interface with mapped lampposts and their state.

Mapping



Device Id:	light sensor:	motion sensor:	bright:	battery:	check time:
2	920	1	50	95	2019-05-01 00:14:12
2	850	0	82	41	2019-05-01 00:06:12

Fig. 2. Website interface of street lighting system monitoring.

The most important feature of the system is its dynamic adaptation to weather conditions. The network coordinator determines the weather for the next 3 days via the weather forecast API and chooses the various modes of operation for the system. These modes allow the system to work in the correct algorithm where the system will save energy. For example, if tomorrow's weather is cloudy the grouped lampposts work in energy saving mode all night.

B. Topology of wireless network

The topology of the proposed system consists of several levels, such as end devices, routers, coordinator (for large cities, the presence of several coordinators is possible) and a control center. Fig. 3 demonstrates wireless sensors network topology of the street lighting system. Data from mounted on lampposts sensors are transmitted via XBee from end devices to the router. The next step is encapsulating packets and finding the best route for the data to send. Then data is transferred to the network coordinator that receives and stores it in its database. Using this data, the Control Center of the system manages and monitors the system state via a web site. If one of the control blocks fails, the system will receive an error message from one of the end devices. This is how the emergency system works. Then an engineer or service team visit the broken-down lamppost and fix a trouble.

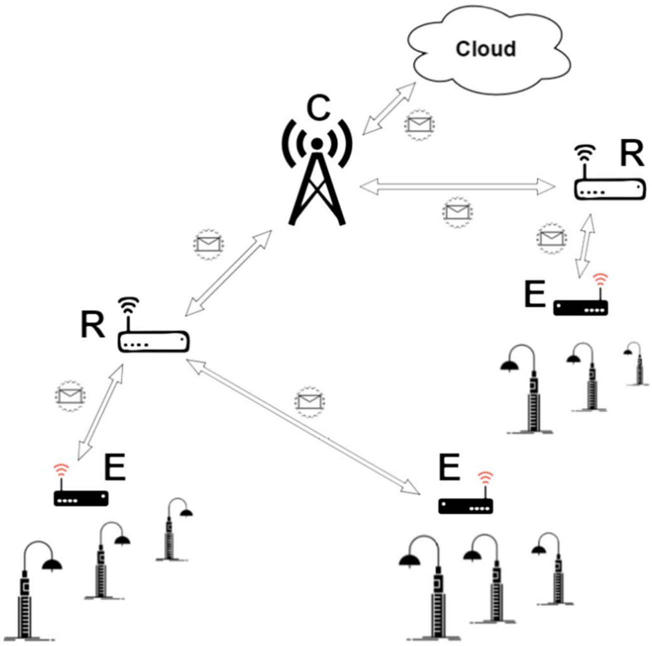


Fig. 3. Wireless sensors network topology of the street lighting system.

Since the system is adaptive to weather conditions, the weather information about the upcoming days is transmitted by broadcast messages. In accordance with weather conditions, each control unit applies the appropriate energy saving operation algorithm for lampposts.

C. Control unit

The most important part of the proposed system is the control unit. The control unit consists of a controller, transceiver module and sensors. The controller is ATmega328PU, transceiver devices - XBee 3.0. Sensors are: illumination sensor on a photoresistor, infrared motion sensor, INA219 current and voltage sensor. The light sensor is designed to determine the time of the day, the motion and presence sensor indicates the presence of pedestrians in sight zone, the current and voltage sensor plays the role of a battery charge indicator. The control unit diagram is shown in Fig. 4.

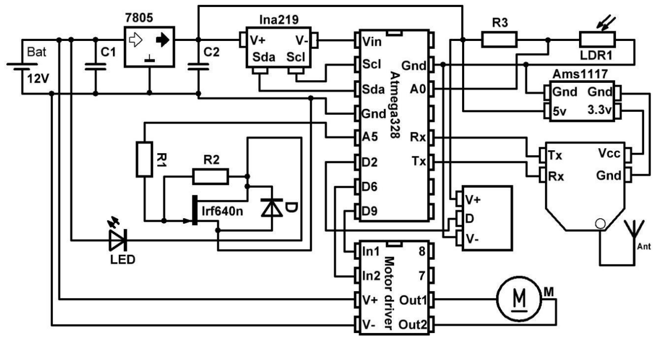


Fig. 4. The electric circuit of the control unit of the end devices.

The control unit is powered by a battery with a nominal voltage of 12 V. The LM7805 chip is used for matching the voltages. The XBee module is powered by the AMS1117 chip, which is a 5V-3.3V down-DC-DC converter, since the XBee modules operate normally at 3.3 V. A motor driver is connected to the uniaxial solar tracker. The speed and direction of the motor rotation is set by the controller. The brightness of the lamp is controlled by the field-effect transistor IRF640N.

The electric circuit of coordinator is shown in Fig. 5. The coordinator is an XBee 3.0 transceiver connected via the built-in serial port to the computer. Received data from nodes is sent to the cloud for graphical visualization.

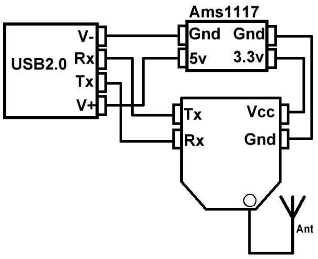


Fig. 5. The electrical circuit of the coordinator.

III. CONTROL UNIT ALGORITHM

Since our proposed system is adaptive to weather conditions, the algorithm of the system has different modes of operation. Fig. 6 shows a general algorithm of control unit.

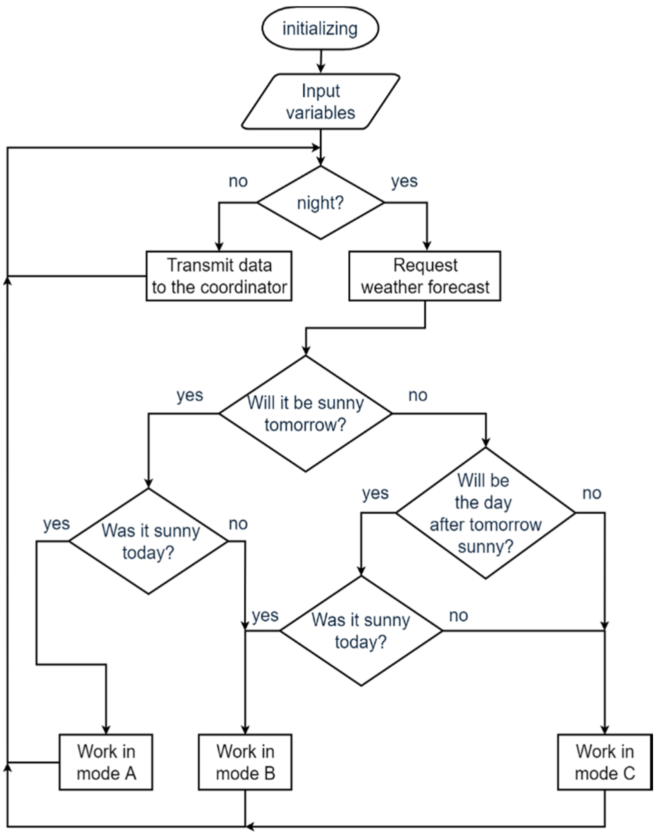


Fig. 6. General algorithm of control unit.

During the daytime, there is only process of data transmission to the network coordinator. Since the battery is charged by solar modules at daytime, information about charging status will be sent to the control center. When night falls, a request for next day weather forecast is sent to the network coordinator. If next day weather is mostly sunny, then in accordance with current day weather, the system changes the mode of operation for upcoming night. If today's weather was mostly sunny, then the system chooses the operation mode A. If today's climate was mostly cloudy, the system selects the operation mode B.

Let's return to the condition where there is a request for the weather forecast for tomorrow. If tomorrow's weather is mostly cloudy, the system asks the weather forecast information for the day after tomorrow. The system adapts to the weather conditions in order to provide the lampposts with energy as long as possible. If the weather on the day after tomorrow is cloudy, the controller selects the most energy-efficient mode C. If the day after tomorrow is sunny, then the system looks on today's weather, and if it was sunny today, the controller switches on mode B, if not, it switches to mode C.

In mode A, shown in Fig.7, the controller turns on lamps of lampposts at 50% intensity. If there is a movement of pedestrians or vehicles, the intensity of the lamp is increased up to 100%. So the system works in this mode till morning.

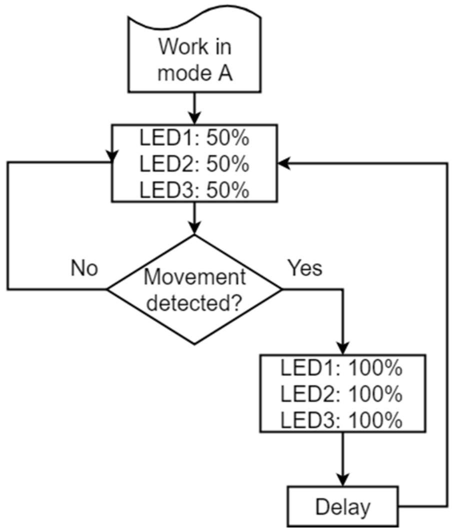


Fig. 7. Algorithm of control unit in mode A.

In mode B, shown in Fig. 8, the system switches to a more energy-saving mode compared to mode A. Here the controller turns on the intensity of the central lamppost lamp by 50%, and the neighbors by 25%. When motion is detected, the lamp of the central lamppost lights at 100%, while neighboring lamp posts remain at 25%.

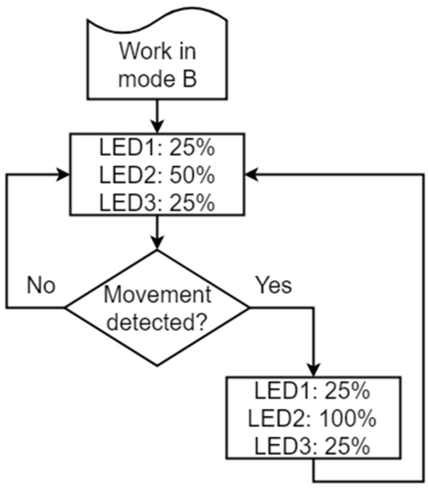


Fig. 8. Algorithm of control unit in mode B.

In mode C, shown in Fig. 9, the controller turns off the lamp of the central lamppost, and turns on the lamps of neighboring lampposts with an intensity of 25%. If the object movement is detected, the intensity of the neighboring lamps changes to 50%. This mode is more energy efficient compared to the others. Neighboring lamps always remain on in order to provide the necessary conditions at nighttime.

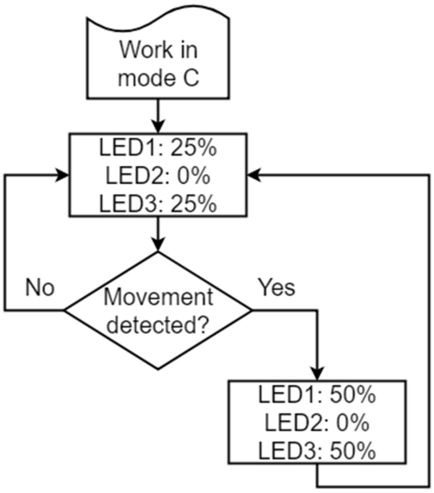


Fig. 9. Algorithm of control unit in mode C.

IV. Experimental Results and Simulations

A. *Energy generation*

Consumption of the proposed autonomous street lighting system is provided by solar panels. In order to study the energy generation by a uniaxial solar tracker under different weather conditions, experiments were carried out on a clear and cloudy days. Observations were made at Al-Farabi Kazakh National University in Almaty in April 2019. The uniaxial solar tracker was set at an angle of 43° to the horizon by the latitude of the location. The power of the solar battery is 40 W. The observation was carried out using a wireless data transmission system. The obtained results, shown in Fig.10, are average power values on clear and cloudy days respectively.

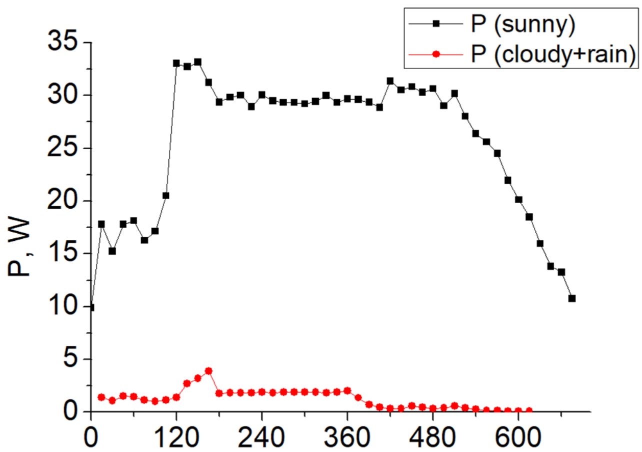


Fig. 10. The power of a uniaxial solar tracker on a clear and cloudy day.

As shown in above graphic, there is huge difference in the generated power between clear and cloudy day. As a result, it is necessary to consider dynamics of charge and discharge on cloudy, sunny days and according to this, regulate the consumption of the device. The average amount of energy received during the clear day was 291.6 Wh, and on a cloudy day — 12.7 Wh, which is 4.35% of the energy on a clear day. For full usage of the energy received on a clear day, a battery with a nominal voltage of 12 V and a capacity of 24 Ah is sufficient.

B. *Energy consumption*

The control unit and connected to it grouped lampposts constitute the unit cell of the system. To simulate the consumption of the entire system, it is necessary to determine the consumption of a single cell. In our case, we used a 7-watt LED lamp as a lighting lamp. Each lamppost in accordance with the algorithm can operate in four modes, three at nighttime and one at daytime. The power consumption of devices in various modes was obtained using the INA219 voltage current sensor and the LabView graphical development environment. Table 1 shows the power consumption of a single cell, which consists of three lampposts and a control unit.

TABLE I. Energy consumption of one cell in different modes

Mode	**Power in standby mode, W**	**Power at motion detection, W**
Mode A	12,775	21,7175
Mode B	6,39	9,37
Mode C	1,065	8,5
Day mode	0,625	

In the proposed model, we consider three possible scenarios, as shown in Table 2. In this model, the countdown always starts from clear day. The least favorable scenario is № 3 from table 2. As a result, the proposed algorithm can only be used for areas in which a maximum of two days in a row can be cloudy with precipitation.

TABLE II. Weather possible scenarios

№	**1st day**	**2nd day**	**3rd day**	**4th day**
1	Clear	Clear	Clear	Clear
2	Clear	Cloudy with precipitation	Clear	Cloudy with precipitation
3	Clear	Cloudy with precipitation	Cloudy with precipitation	Clear

Using the data from the table, we constructed a graph of energy consumption during the day and night for four days, considering the operation algorithms and weather forecasts.

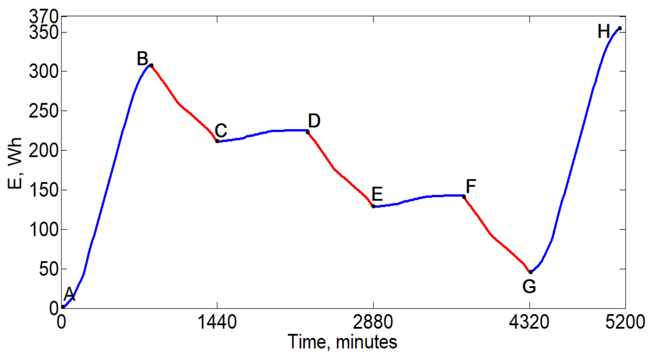


Fig. 11. The power of a uniaxial solar tracker on a clear and cloudy day.

Fig. 11 shows a graph of energy consumption by a single cell over a period of four days in the third scenario: clear-cloudy-cloudy-clear. The x-axis is the time in minutes. Day corresponds to 1440 minutes. On the y-axis it is represented the energy consumed or generated by the system at different times of day. On the interval AB of the graph, the battery is charged on a clear day. Since a clear day is followed by two days with cloudy weather or precipitation, therefore, the device switches to mode C. The gaps of BC, DE and FG correspond to mode C at night. The gaps of CD and EF correspond to the charge of batteries during a cloudy day with precipitation. The GH gap shows the battery charge on a sunny day.

Thus, the proposed model of a street lighting system is able to remain in working condition even if the day was cloudy or with precipitation. Our further task is considering various combinations of the lamppost operation in a group and collect data in other seasons of the year.

V. Conclusion

As a result of this work, an autonomous intelligent predictive algorithm has been developed. A system for remote monitoring of the device's state has been developed based on XBee 3.0 wireless modules. Algorithms for the distribution of energy between lampposts using weather forecast over the next four days have been developed. To increase the efficiency of solar cells uniaxial solar trackers were used. The developed concept of an intelligent street lighting system is one of the elements of Smart cities and can be used as an alternative to existing street lighting systems for regions with suitable weather conditions. In the future, it is planned to research various operating modes of lampposts, as well as the behavior of the system in other seasons of the year. The collected data can be used to apply neural networks to calculate the energy consumption of the system under various weather conditions.

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