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Design of Smart LED Streetlight System for Smart City with Web-Based Management System

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***Abstract*—Smart LED streetlight system is one of the enabling technologies for a smart city, giving low-cost, low power outdoor lighting also with benefits for vehicle users as well as pedestrians. Integration of sensors and ZigBee based wireless sensor modules can furnish an optimal platform for an innovative LED streetlight application. Psychological studies suggest that different level of color temperature can significantly affect human circadian rhythm. For this reason, correlated color temperature (CCT) based illumination gives a significant lighting performance both in terms of energy efficiency and in overcoming traffic accidents in low visibility areas. Previous works usually assume only specific platform and did not consider CCT based illumination towards smart LED streetlight system. In this paper, we consider the importance of CCT based illumination and propose a novel integration of public weather data awareness, ZigBee based wireless communication, and dynamic web-based management system for the state-of-art of smart LED streetlight system applicable to smart city. In particular, we design a central web server that can receive weather information and real-time sensor data from each LED streetlights and provides a dynamic and flexible web interface for authorized users. Furthermore, real-time implementation of the proposed system shows perfect transmission-reception parameters such as throughput and signal strength among the different LED streetlights, which fulfills the wireless communication range and signal quality between each LED streetlights.**

***Index Terms*—Light emitting diodes, wireless sensor networks, web server, wireless communication, ZigBee, smart city, smart streetlight system.**

I. INTRODUCTION

THE trend of global urbanization brings about advancement in the digital technologies and design of smart cities. Streetlight technology is one of the trend in the development of smart city. The application of streetlight is crucial and often found in the big or small cities all over the world. Streetlight can provide light at nighttime to the streets and public places, which can mitigate the probability of accident happening and enhance the safety of drivers and pedestrians. The odds of driving accidents and pedestrians accidents are lower when the streetlights are present [1], [2]. The main purpose of streetlight system is to be able to illuminate the target area such as roadways. Moreover, it also gives psychological effect, which can increase street user's alertness and provide a sense of personal security.

Recently, the use of light-emitting diode (LED) lamp for streetlight has grown significantly. LED based streetlight technology has considerable advantages in terms of both energy efficiency and optical luminescence as compared to conventional streetlight technologies such as the high-pressure sodium (HPS) and low-pressure sodium (LPS) lamps. In addition to being eco-friendly due to its low electrical energy consumption, it also affords plenty of benefits, namely, uniformity of illumination levels via arrays of many LED chips, visibility of the streetlight through correlated color temperature (CCT), and visual performance improvement by virtue of high color rendering index [3]. Even though LED streetlight has higher initial cost, it has a longer lifespan which makes the maintenance cost cheaper over the time compared to HPS streetlight [4]. LED streetlight also produces less heat, which makes the physical design simpler, whereas HPS streetlight needs a proper cooling mechanism to keep its temperature in normal range [5]. Thence, due to incredible promise of LED technology and also as part of smart city applications, many countries nowadays have started replacing the HPS/LPS lamp system by LED for both indoor and outdoor lighting systems.

In order for smart cities to harness the full potential use of LED streetlight system, there still is an open research area we need to dig out. First of all, making the streetlight LED lamps smart and use of a web-based management system can further bring an enormous energy savings. Secondly, incorporating energy-efficient electronic sensors and integration of wireless networked modules can furnish an optimal platform for an innovative LED streetlight application. Finally, the use of weather data aware CCT based smart LEDs in streetlights will be an incredible success towards building a user-friendly platform for smart cities, which is our subject in this article.

In this paper, we investigate the use of an integrated web-based management system for the wirelessly networked sensor-equipped LED streetlight system. Speaking of the wireless network infrastructure, we use a low power, low-cost and low data rate ZigBee based wireless sensor network (WSN). We chose ZigBee over other WSN protocols because it is more suitable to public streetlight system in terms of data rate, distance of communication coverage, as well as price. It offers a self-healing, self-forming, tree, star, or mesh topology network structure that facilitates significant secure communication among the different streetlight elements. Our proposed streetlight system also employs sensors to detect

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and measure several environmental and electrical parameters such as relative humidity, temperature, particle concentration, voltage, and current acting as an input for the web based server.

Weather variables such as fog, frost, and air pollutants have severe consequence on traffic accidents [6]. Decreased driver visibility-related weather risks have critical impacts on traffic accidents [7]. In particular, nowadays, urban areas have experienced traffic accidents that happen due to low visibility effect caused by fog or pollution. We are therefore motivated to develop weather data aware smart LED streetlight system in order to detect a driver's blind spot when climate hazards such as too foggy, rainy, snowy, etc. will cause traffic accidents due to low visibility. For example, in February 2015 traffic accident has happened on a foggy day on Yeongjong Bridge, South Korea, which caused a chain collision accident where approximately 106 vehicles were involved [8]. Thence, by collecting the climate data from the web and/or public weather data, not only can we change the color temperature of LED streetlight dynamically, but also can we improve the visibility of car drivers thereby improving the prevention of the aforementioned traffic accidents. For this reason, our proposed system can mitigate a traffic accident during climate alarm issues such as fog, haze, etc., which then gives dynamic feedback based on a tunable CCT LED arrays. For the software development part, we developed streetlight web server using Java application server based on Tomcat 8. Moreover, in this work, we used the following application programming interfaces (APIs): SKPlanet, AirKorea, and OpenStreet Map. Therefore, the integration of public weather data aware system, ZigBee based WSN and web-based management system for the street lighting opens a new door in terms of dynamic and innovative solutions, advanced control functionality, flexibility through remote access, and improvement of blind spot traffic accidents.

Therefore, in this paper, we propose an integrated smart LED streetlight technology, which will be a substantial and appealing input for smart city. In particular, our main contribution includes:

1) a novel architecture comprising of central web server with a tunable CCT based smart LED streetlights
2) a compact algorithm for the request processing among smart LED streetlights
3) a practical implementation system applicable to public street lighting; giving solution to traffic accidents due to bad weather data such as fog
4) performance evaluation of the proposed system, from the sensors, the network, and the web interface side

The remainder of the article is structured as follows. In Section II, we discuss about related works and include our contribution of this paper showing the difference with existing works. In Section III, we comprehensively investigate the proposed system design including communication among streetlights and between streetlights and server, design of streetlight platform, and web server. Section IV covers experiment results and discussion on network and web interface performance tests. Finally, we conclude our paper in Section V.

II. Related Works

In this section, we explain the existing works related to smart LED streetlight system and associated control systems. In particular, we examine correlated works on the application of WSN for smart LED streetlight system and remote control and management system as applied to smart city-centric LED streetlight systems. We also presented the drawbacks of existing works and made a concise comparison with our proposed scheme.

Smart city delivers a smart health, smart energy, smart traffic, smart building, and smart streetlight system. These different applications need a communication medium such as cellular data networks, wireless local area networks (WLANs), or low power and low cost WSNs such as ZigBee, LoRa, and Sigfox [9] to safeguard a complete fusion of all kinds of sensor data and to avail the information for further monitoring. Especially, WSNs are more promising than any other communication network entities for LED streetlight application. In our paper, we use ZigBee for the wireless communication part, as also used in [10], [11], [12], [13], and [14].

Most existing works studied control of LED streetlight system without consideration of any weather data such as fog or pollution to account for traffic accidents. To the best of our knowledge, none of existing works implemented weather aware smart LED streetlight system. Works in [10], [11], [12], and [13] study smart LED streetlight system, which also contribute for efficient, simple, proper, and dynamic remote monitoring. The work in [10] proposes a smart streetlight system consisting of brightness sensors, motion sensors and short-distance communication networks that turn on when it is necessary and turn off when it is not. Similarly, authors in [11] proposed smart LED system to dim the light in room environment. The author in [12] proposed remote control based intelligent LED streetlight. The proposed system uses commercially available XBee modules to transmit the gathered sensor information to a central station. Although works in [10], [11], and [12] contribute to the smart LED system, their contribution towards outdoor streetlight system is constrained. Other work in [13] proposed IEEE 802.15.4 based public streetlight control system over digital addressable lighting (DALI) interface. This paper mainly focuses on the use of DALI protocol in controlling LED streetlights. It is known that DALI protocol is one of the commonest methods used in LED lighting control applications. However, DALIs high latency for the dimming and controlling action is not preferable for LED streetlight lamps, which require fast response time. Its low dimming resolution, less number of devices per controller, and the requirement of hardware-software commissioning also makes it less preferable. Instead, in our system we use TCP/IP communication to control every LED lamps. In other words, electrical and environmental sensors are employed to gather information about each LED lamp and the surrounding environment, which will act as an input to the system thereby responding the dimming or other similar functionalities transmitted over the TCP/IP protocol. Unlike the mentioned related works, our proposed work investigates implementation of weather data-aware smart LED outdoor lighting, which

TABLE I
COMPARISON OF PROPOSED SYSTEM WITH PREVIOUS WORKS

Comparison Attribute	Proposed System	Previous Works
Traffic accident mitigation feature	Considered by implementing two LED arrays with different CCT (3000 K and 5000 K)	Not considered
Utilization of weather APIs	Considered	Not considered
LED streetlight control system	TCP/IP protocol	Considered in [13] (DALI protocol)
Utilization of sensors	Four sensor modules are equipped at each LED streetlight for real-time status report to web based server	Considered only few sensors.
Validation of the wireless communication among different LED streetlights	Considered through the validation on the end-to-end wireless communication such as received signal strength and throughput tests among the LED streetlights.	Considered in [12] and [14]

mainly focuses on traffic accident reduction due to bad weather conditions such as fog, or pollution. Authors in [14] propose an integrated intelligent LED streetlight system with adaptable and efficient lighting system, which considers presence of pedestrians, or vehicles based on environmental sensors for temperature, humidity, and ambient lighting.

Due to the effects of light on human physiology, it is important to use light with appropriate CCT in different situations. Study in [15] and [16] inform that the exposure of high CCT light on human body will suppress the fall of body core temperature and secretion of melatonin, but the exposure of low CCT light will likely reduce physiological activity. Other study in [17] examined on the lighting performance of LED streetlight systems and found out that LED streetlight with low CCT light has better fog penetration quality compared with LED streetlight with high CCT light. Therefore, it is recommended to use high CCT light in clear weather as it can increase the concentration and reduce drowsiness of drivers and pedestrians on the street and to use low CCT light where fog or haze is present on the street.

Unlike the existing research findings, our proposed architecture employs multiple sensors for collecting different parameters including humidity, temperature, particle concentration, voltage, and current that act as an input for the web based server. Then, the central database will send a CCT tuning command to adjust the color temperature and hence the illumination of each streetlight system. The detail explanation of our proposed scheme is presented in Section III. Table I shows a comparison between our proposed system and previous works.

III. PROPOSED SYSTEM DESIGN

We propose an architecture of smart streetlight system as shown in Fig. 1. Several streetlight groups are installed on different areas. Each streetlight group consists of one streetlight group coordinator (SGC) and several streetlight group members (SGMs). These streetlights are connected in tree topology, with SGC as the network coordinator. The SGC also acts as a gateway between the streetlights and streetlight web server (SWS). All data from streetlights will be stored in SWS. The SWS provides the web-based user interface for the authorized user. The authorized user can also launch requests to a specific streetlight by using the user interface.

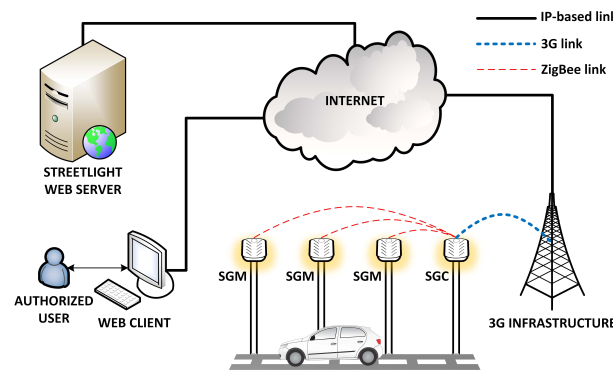

Fig. 1. Proposed architecture of smart streetlight system.

A. *Communication Among Streetlights*

The streetlights are communicating with each other over ZigBee network. ZigBee is a wireless communication protocol developed by ZigBee Alliance. ZigBee protocol defines the Network Layer (NWK) and Application Layer, while the Physical Layer (PHY) and Medium Access Control Layer (MAC) are defined by IEEE 802.15.4, a technical standard for low-rate wireless personal area networks (LR-WPAN) [18]. In ZigBee network, there are three types of devices: ZigBee coordinator, ZigBee router, and ZigBee end device. ZigBee coordinator is a node that provides and manages a ZigBee network for other nodes. ZigBee router is a node that can extend the coverage of the ZigBee network and pass the data between nodes. ZigBee end device is a node with reduced function, enough to be able to communicate with ZigBee router or ZigBee coordinator.

ZigBee protocol supports the operation in different frequency bands: 868 MHz, 915 MHz, and 2.4 GHz [19]. Theoretically, the communication data rate in ZigBee network can achieve up to 250 kbps. This specification allows for application with low-cost, low power usage, and energy-efficient requirement, such as monitoring of domestic property [20], natural disaster [21], or livestock health [22]. By adopting carrier-sense multiple access with collision avoidance

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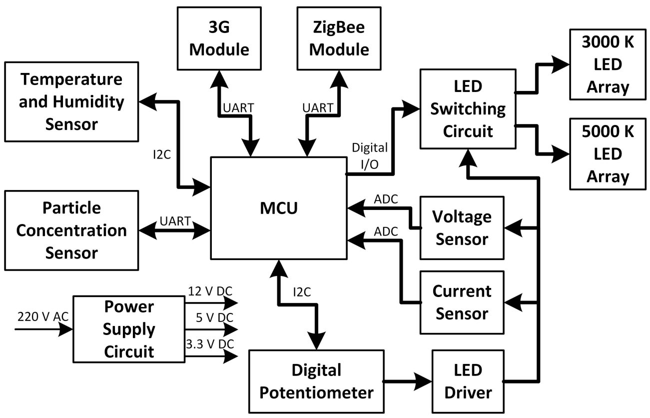

Fig. 2. Block diagram of proposed streetlight platform.

(CSMA/CA) method, the collision among ZigBee devices can be reduced. With the use of direct-sequence spread spectrum (DSSS) for modulation method, the interference diversity in ZigBee network can be improved. As a means to interconnectivity, ZigBee devices can form into star, tree, or mesh topology to fit their purpose.

ZigBee module in each SGC is configured as ZigBee coordinator, while the ZigBee module in each SGM is configured as ZigBee router. This configuration is used while considering the installation of streetlights on the street that usually forms a line. If the wireless network coverage of SGC cannot reach both ends of the street, the SGM can extend the network and ensure the connectivity of other streetlights to SGC. This configuration also provides flexibility in network expansion.

In our proposed system, communication between streetlights is always done in unicast fashion. Each SGM communicates only with SGC, so it only needs to know SGC's address in the network. When SGC wants to send data to a particular SGM, SGC needs to set the address of the targeted SGM as the destination address. This method requires SGC to store all SGM addresses. Broadcast transmission is not used because data from one streetlight is only for another targeted streetlight, and thus deemed unnecessary.

B. Communication Between Streetlights and Server

Every streetlights can communicate with SWS with SGC as its gateway. The SGC in every streetlight group is equipped with 3G module with operating frequency band of 2100 MHz for Universal Mobile Telecommunication System (UMTS) networks. The 3G module also supports High-Speed Downlink Packet Access (HSDPA) protocol, with downlink and uplink data rates of 3.6 Mbps and 384 kbps respectively.

The data packet from SGC to SWS and vice versa is transmitted using Transmission Control Protocol/Internet Protocol (TCP/IP). The use of TCP/IP allows SWS to be accessed from any device with any operating system. At the beginning, each SGC from every streetlight group needs to establish connection to SWS, and SWS will keep the connection open with timeout mechanism. This method will make the connection always available if there is no failure from either SGC or SWS.

C. Design of Streetlight Platform

Fig. 2 shows the block diagram of our proposed streetlight platform. It is driven by an 8-bit ATMega2560 microcontroller unit (MCU). It is set with the operating frequency of 16 MHz. This MCU can be programmed through its in-system programming (ISP) feature. With 256 KB of Flash memory, it can store quite large program. The MCU design is based on reduced instruction set computing (RISC) architecture, that allows the MCU to improve power usage while maintain its processing speed [23]. It also is able to work properly in industrial temperature range ($-40\,^{\circ}$C to $85\,^{\circ}$C).

This streetlight platform is powered by a 220 V ac from power grid. A power supply circuit is designed to convert the input AC to 12 V dc. An RT7272A switching regulator IC is used to convert 12 V to 5 V, and an LM1117 linear regulator IC is used to convert 5 V to 3 V.

A 3000 K and a 5000 K LED array are combined in the proposed streetlight platform with separate power line, so that each of them can be controlled independently. An LED switching circuit is designed to control both LED arrays, with input coming from MCU through its digital I/O pins, to control the CCT of light from the streetlight. The MCU also controls the dim level of LED arrays by sending control command through Inter-Integrated Circuit (I2C) bus to an AD5258 digital potentiometer IC, to drive the current that coming out from LED driver circuit, which will be feed to LED arrays. The amount of current received by LED arrays will determine the dim level of LED arrays.

This streetlight platform is equipped with a ZigBee module for communication among streetlights and a 3G module only for SGC to communicate with SWS. We use Digi XBee S2 as the ZigBee module and M2Mnet WM-215 as the 3G module. Both communication modules are connected to MCU by universal asynchronous receiver/transmitter (UART) interface.

Our proposed streetlight platform is equipped with sensors to detect and measure several physical and electrical parameters: temperature, relative humidity, particle concentration, voltage, and current. The temperature and relative humidity are sensed by a Sensirion SHT71 sensor module [24]. The MCU sends commands and receives data from SHT71 through I2C interface. The particle (PM_{10}) concentration is sensed and measured by Cubic PM1001 dust sensor module [25]. It communicates with MCU through UART interface. The voltage sensor and current sensor circuitry are designed from combination of resistors, capacitors, and operational amplifiers. They are used to measure the voltage and current of LED arrays. The output of each sensor is fed to an A/D converter (ADC) pin of the MCU. The description of each sensor is summarized in Table II.

The flowcharts of request processing in SGC are shown in Fig. 3. In a streetlight network, any streetlight can be controlled by SWS. SWS will send a request to the streetlight network, to control a streetlight. The request will be first received by SGC and processed if the request is for it, otherwise the request will be send to targeted SGM. Periodically, SGC will get data from its sensors and send the data to SWS. Whenever the timer goes off, SGC will send the data packet

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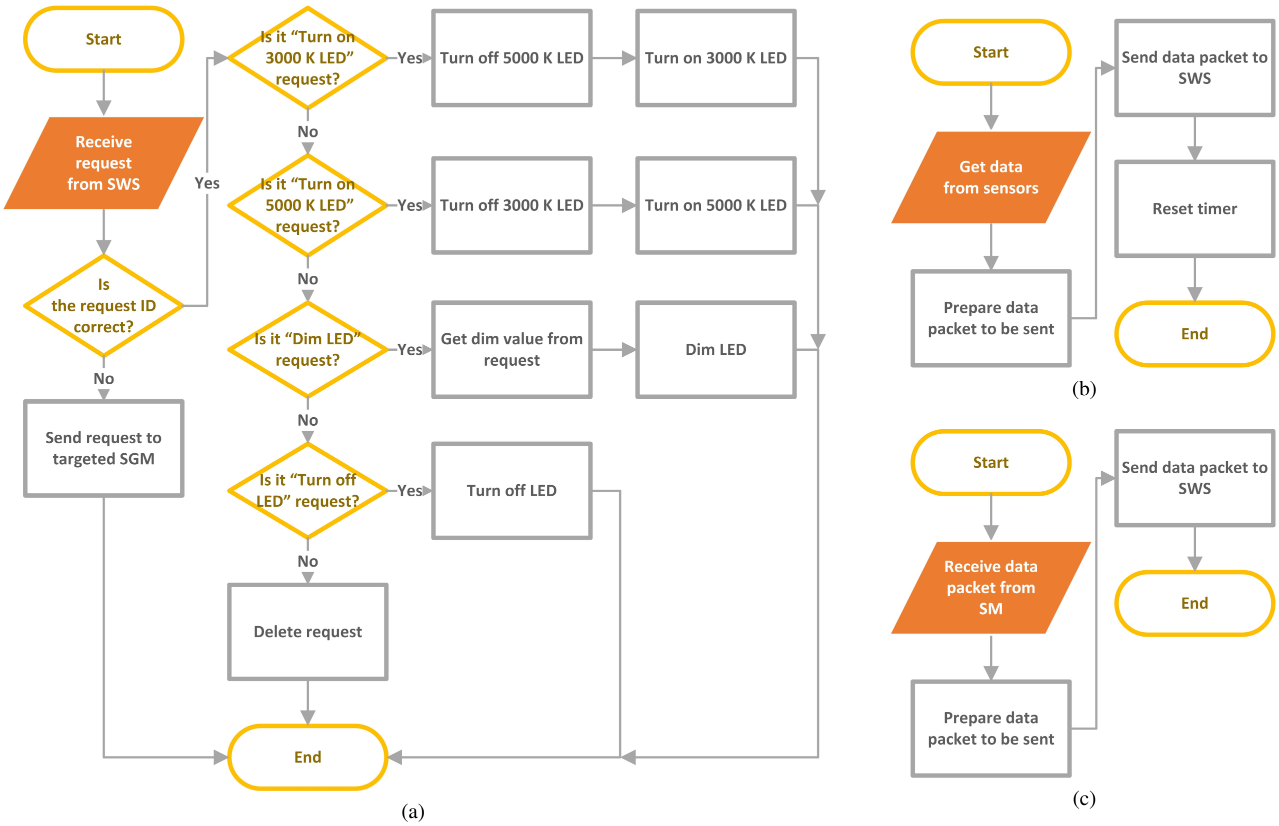

Fig. 3. Flowchart of SGC when (a) it receives request from SWS, (b) the timer for sending periodic data goes off, and (c) it receives data packet from SGM.

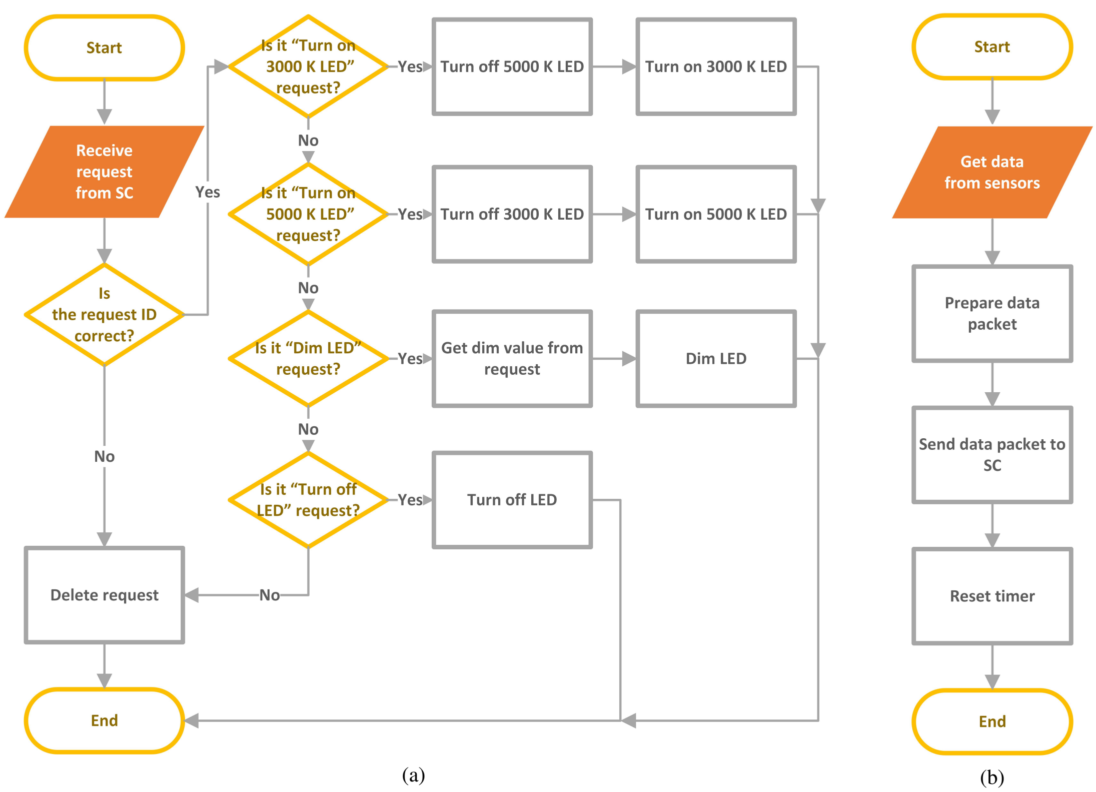

Fig. 4. Flowchart of SGM when (a) it receives request from SGC and (b) the timer for sending periodic data goes off.

TABLE II
SUMMARY OF SENSORS USED IN PROPOSED SYSTEM

Sensor	Measured Parameter	Measurement Range	Communication Protocol	Resolution	Unit
SHT71	Temperature	-40 to 123.8	I2C	0.01	°C
	Relative Humidity	0 to 100		0.05	%
PM1001	Particle Concentration	0 to 8000	UART	1	$\mu g/mm^3$
Voltage sensor	Voltage	0 to 280	ADC	0.01	V
Current sensor	Current	0 to 2	ADC	0.01	A

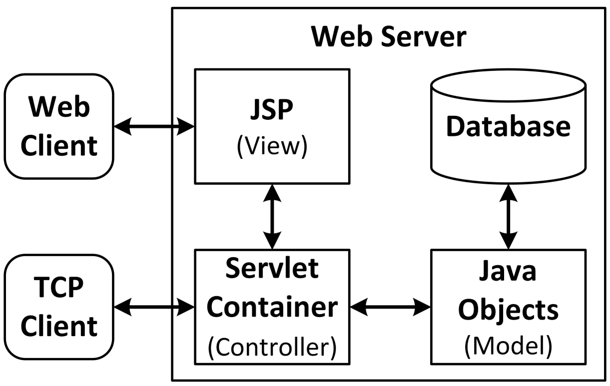

Fig. 5. Model-View-Controller architecture.

TABLE III
LED STREETLIGHT FAILURE TYPES AND THEIR CONDITIONS.

Failure Type	Condition		Warning Icon
	Voltage	Current	
LED Module Open	>150 V	<10 mA	
Power Supply Broken	0 V - 10 V	10 mA - 100 mA	

containing the data from its sensors to SWS, then reset the timer. When SGC receives data from SGM, SGC will directly forward that data to SWS.

The flowcharts of request processing in SGM are shown in Fig. 4, which is basically similar with SGC. When SGM receives a request that has been forwarded by SGC, SGM will process the request according to its content. SGM will also send periodic data to SGC so that SGC can forward the periodic data to SWS.

D. Design of Streetlight Web Server and Web Interface

The SWS is designed using Java application server based on Tomcat 8. All data are recorded in the database, which is created and managed using MySQL 5.7. The SWS main functions are:

- to receive sensors data from all streetlights
- to store all data in databases;
- to provide web interface for authorized user;
- to forward the control request from authorized user to the streetlight group;
- to request weather information from several APIs.

The SWS is designed by following Model-View-Controller (MVC) architecture, as shown in Fig. 5. MVC architecture is a server design pattern that divides all software parts inside the server into three type of components according to their main function: the Model component, the View component, and the Controller component [26]. The Model component includes several Java objects that directly update the database or providing dynamic content to client by retrieving data from database. The View component consists of JavaServer Pages (JSP) to provide static content when requested by web client. The Controller component is a servlet container, where all servlets are contained. The servlets will translate the request from client to a specific operation, which can invoke the Java object to update the database or display the page that is requested by client.

In Fig. 5, there are two kinds of clients shown: web client and TCP client. The web client requests and receives response through the View component, because the requests and responses are accessed from the web interface from the View component. TCP client does not communicate through web interface, but directly to the Controller component. These two kinds of clients represent the clients in our system: the web browser that is being used by an authorized user is web client and the SGCs are the TCP clients.

The web interface can be accessed from a web browser. The authorized user needs to input his/her username and password that already registered in SWS before getting into the main page. The main page design is shown in Fig. 6. The left side contains the list of streetlights with their status and sensor values. The right side contains a map with location of each streetlight. An add button with green cross icon is put to add a new streetlight to database. One request button with cogwheel icon is put for each streetlight for request purpose. When this button is clicked, a page with request option is displayed as shown in Fig. 7. We can delete the streetlight from the database by clicking the delete button with red diagonal cross icon.

An LED streetlight failure detection mechanism is designed at SWS so warning icon can be displayed in web interface for the failing LED streetlight. There are two kinds of failure: ”LED Module Open” and ”Power Supply Broken”. LED Module Open means that the LED module in an LED streetlight is not connected to the system or becomes open circuit. Power Supply Broken means the power supply module does not function well in a LED streetlight. The voltage and current values of each LED streetlight that are sent periodically to SWS become input for this detection mechanism. The details of the failures and their conditions are presented in Table III.

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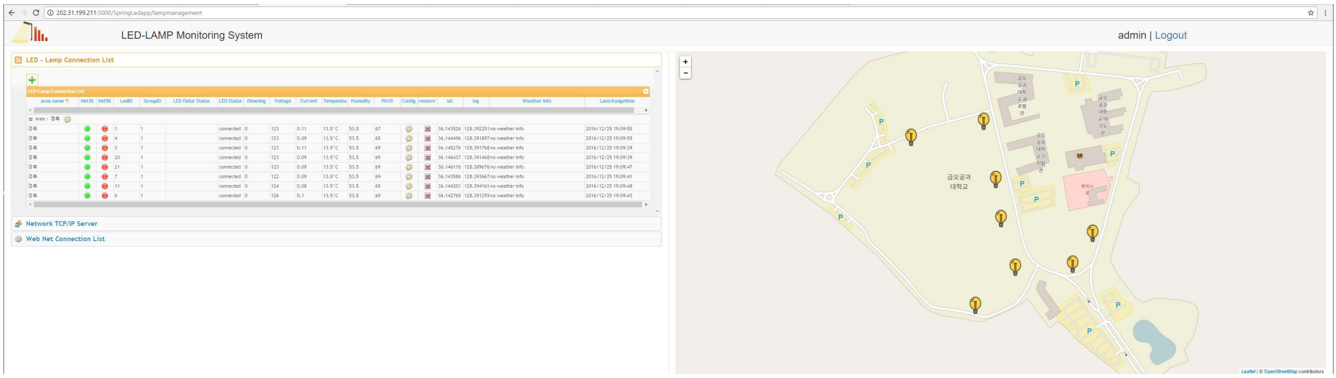

Fig. 6. Front page of web interface with the list of all streetlights on the left side, and the map with the streetlights' location on the right side.

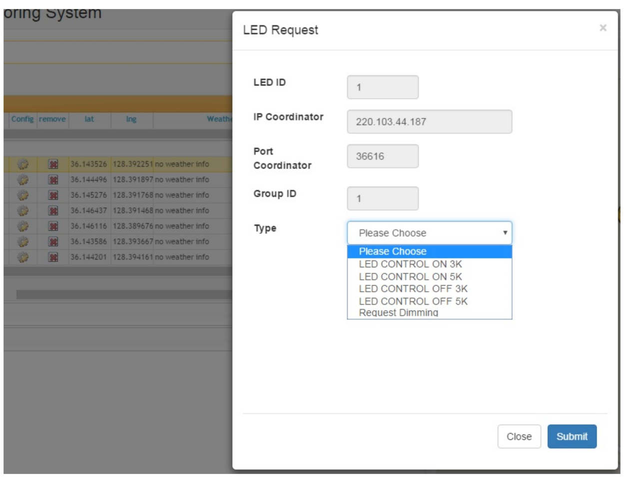

Fig. 7. Web page for control request. It shows up when the request button is clicked.

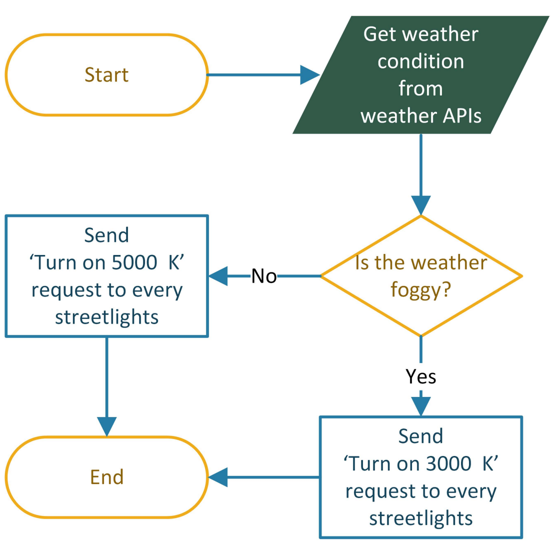

Fig. 8. Flowchart of automatic CCT switching in SWS.

TABLE IV
XBEE S2 RF CHARACTERISTICS

Parameter	Value
Transmission power (P_{Tx})	2 mW (3.01 dBm)
Receiver sensitivity	-96 dBm
Operating frequency	2.4 GHz
Indoor/urban coverage	40 m
Outdoor LOS coverage	120 m

The switching of the CCT of streetlights is controlled automatically from the SWS side. The SWS uses weather condition retrieved from weather APIs as input to switch the CCT to 5000 K or 3000 K. Basically, when the weather API informs that fog is present in the area of LED streetlights, SWS will automatically request all LED streetlights to switch the CCT to 3000 K, to improve the visibility in foggy condition. When the weather is clear, the SWS will request all LED streetlights to switch the CCT to 5000 K. This algorithm is executed hourly during time of operation of LED streetlights. This automatic switching is illustrated in Fig. 8.

The SWS is also equipped with a failure recovery mechanism called Distributed Replicated Volume (DVR). DVR is a method where data in server are distributed over replicated bricks in the volume. DVR is very useful to scale the storage, maintain high-reliability of server and improves read performance of server in most environment [27]. Also noted in [28] that DVR can help in back up process when link or network failure happens.

IV. PERFORMANCE EVALUATION AND DISCUSSION

A. *ZigBee Network Performance Test*

The motivation behind performing this design layout is that we want to ensure the wireless network performance of each SGM subject to the maximum coverage of ZigBee modules in the streetlight environment. In this subsection, we illustrate the steps followed in our experiment and try to analyze the path loss prediction of the wireless channel considering outdoor scenario. As it has been mentioned in Section III, we used Digi XBee S2 ZigBee module for the wireless communication, in which the main RF characteristics of the XBee S2 modules are described in Table IV. We used XCTU 6.3.5 for the ZigBee

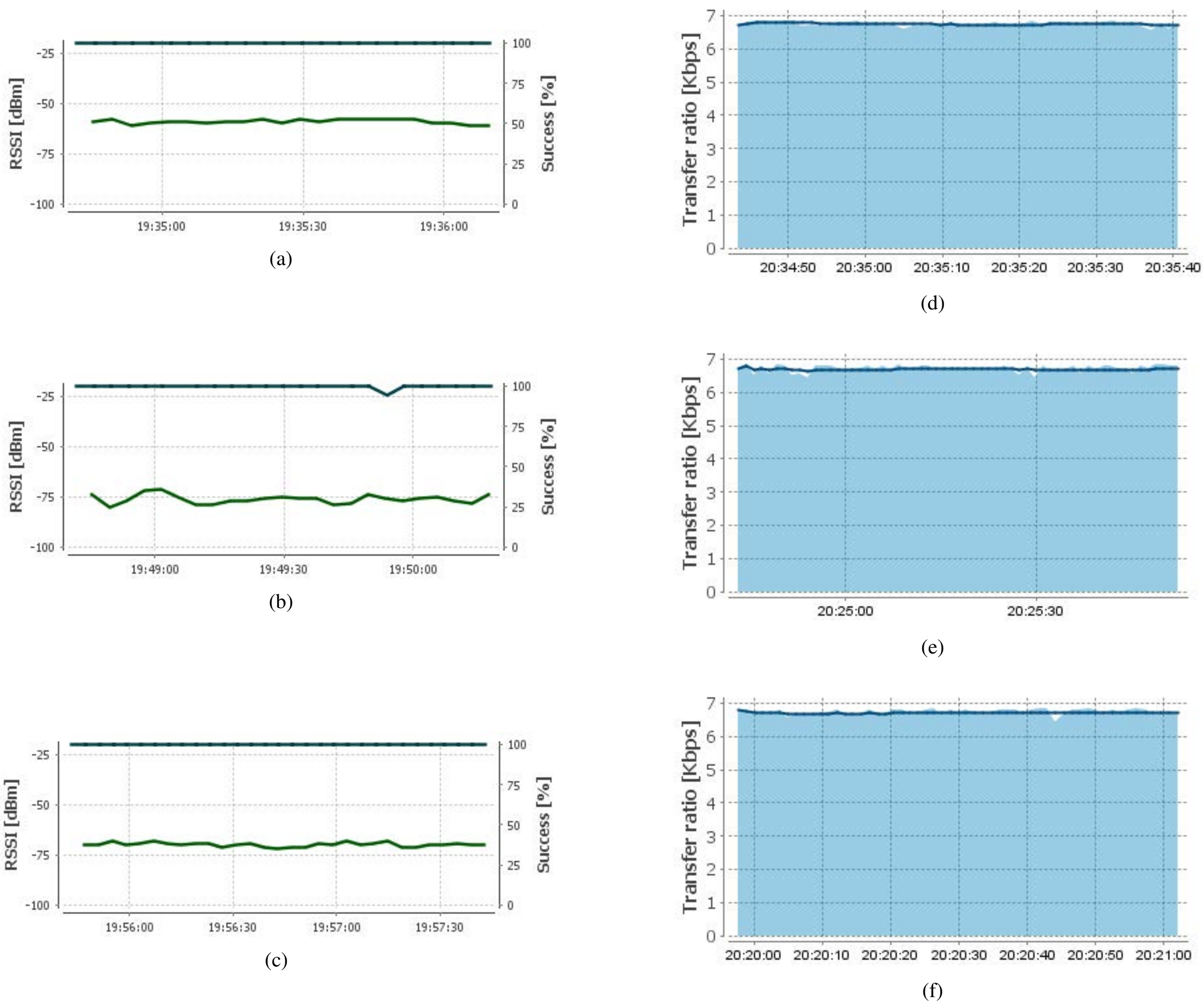

Fig. 9. RSS and throughput measurement result at different distances over time. (a)-(c) RSS measurements at 15 m, 35 m, and 45 m respectively. (d)-(f) throughput measurements at 15 m, 35 m, and 45 m respectively.

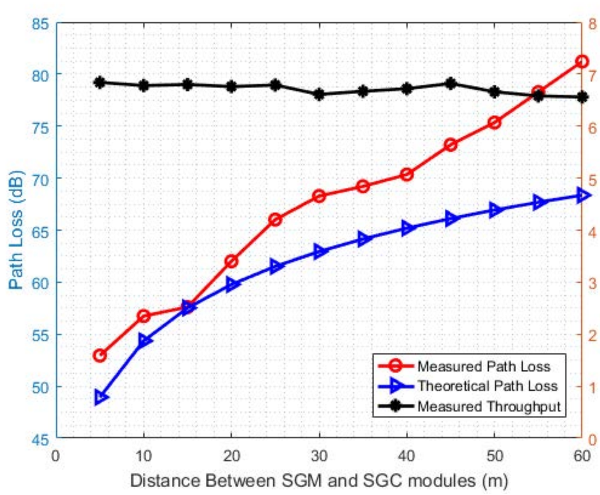

Fig. 10. Measured and expected path loss of transmission between SGM and SGC modules.

TABLE V
MEASURED RSS AND THROUGHPUT

Transmission distance (m)	Average RSS (dBm)	Standard deviation (dBm)	Average Throughput (kbps)
5	-49.93	0.968389254	6.84
10	-53.73	0.679869268	6.78
15	-54.60	0.711805217	6.80
20	-59.00	0.894427191	6.76
25	-63.00	0.632455532	6.79
30	-65.27	0.679869268	6.61
35	-66.20	1.326649916	6.67
40	-67.33	0.471404521	6.72
45	-70.20	0.909212113	6.82
50	-72.33	1.0749677	6.66
55	-75.27	1.730767331	6.58
60	-78.20	1.375984496	6.56

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network performance test. In our experiment, we considered two ZigBee modules where one acts as an SGM and the other acts as an SGC.

For the link budget analysis of the wireless communication, we considered range and throughput tests in the outdoor scenario. Accordingly, we evaluated the received signal strength (RSS) with respect to distance between the SGM and SGC. ZigBee wireless transmission is not only affected by the wireless environment but can also be influenced by the co-existing technologies such as Wi-Fi as both wireless technologies utilize same ISM band of 2.4 GHz. In this paper, we did not consider the potential interference effect of Wi-Fi transmission on the ZigBee channels, nor did we consider expected data loss and re-transmission as it is beyond the scope of this article.

In most cities of South Korea, the public streetlights are separated by 30 m distance between each other, so we follow the same procedure for the orientation of the LED lamps. To make sure the ZigBee device covers well and throughput requirement of the transmission-reception fulfills we demonstrated up to 60 m separation between the SGM and SGC. We made extensive range tests between the SGM and SGC in Kumoh National Institute of Technology, South Korea. We fixed the SGC's location, varied the distance of the SGM from 5 m to 60 m with 5 m distance interval, and took 15 different measurements for each location. The average measured RSS values of range test as well as the throughput are described in Table V. We also computed standard deviation to account the variance of the measurement values at each measurement location. The RSS value P_{Rx} is related to the transmit power P_{Tx} and the path loss PL [29] as in (1).

$$P_{Rx} = P_{Tx} - PL \tag{1}$$

In our case, for each measured RSS values with $P_{Tx} \cong$ 3.01 dBm (Table V), we computed the corresponding path loss. For the theoretical path loss, we used a log-distance path loss model [29], [30] and given in (2).

$$PL_{theoritical} = PL_0 + 10\gamma \log_{10}\left(\frac{r}{r_0}\right) + \sigma \tag{2}$$

where PL_0 is the path loss at a reference distance r_0, γ is the path loss exponent, r is the distance between transmitter and receiver, and σ denotes the variance of measurement.

Our experimental results show that the transmitted data is received well beyond the receiver's sensitivity and this is confirmed by the results demonstrated in Fig. 9. For example, from Fig. 9(a), 9(b), and 9(c), we can see that the transmission-reception is 100 % successful with an average throughput also depicted in Fig. 9(d), 9(e), and 9(f). The wireless channel is characterized by the measured and theoretical path loss results depicted in Fig. 10. Which is still subject to the overall requirement. The path loss as well as throughput results show that the ZigBee based wireless communication fulfills beyond the overall requirements for the public streetlight system.

B. End-to-End Packet Transmission Test

We performed test to analyze the packet transmission from the web client to several streetlights and vice versa. Seven LED streetlights were used in this test. They were set to send periodical data every five minutes for this test. The screenshot from web interface in web client is shown in Fig. 11. All periodic data from every LED streetlights are received at web client promptly. The updates of each LED streetlight are displayed well as expected.

We also performed control requests from web client side to LED streetlights. We first tried to toggle the CCT of all LED streetlights between 5000 K and 3000 K. The illuminations of both CCT are shown in Fig. 12(a) and 12(b). Secondly, we tried to adjust the dim level of all LED streetlights from the highest level to the middle level of light intensity, with CCT of 5000 K. Both level is compared in Fig. 12(c) and 12(d). The LED streetlights were able to process the request and produce the appropriate output in a timely manner.

C. LED Streetlight Failure Detection Test

We tested the LED streetlight failure detection mechanism at SWS. In one of the seven LED streetlights, we tried to disconnect the LED module from the system, making the voltage measurement higher than the threshold and no current flows. These measurements, along with other data, were then sent to SWS as periodic data.

Fig. 13 shows the screenshot of the web interface when the adjustment is set. The LED Failure Status column shows LED Module Open for one LED streetlight. In the map, the failing LED streetlight icon also change to the warning icon as shown in Table III. When we reconnected the LED module in the failing LED streetlight, the SWS received the new periodic data, updated the database, and changed the icon back to normal like the rest of LED streetlights.

D. Voltage Sensor and Current Sensor Performance Test

In this subsection, we discuss about the voltage sensor and current sensor that are used in our proposed system. The test is performed by comparing 10 samples of measurement of each sensors with 10 samples of measurement by multimeter. The samples are averaged and the error rate of sensor measurement is calculated with measurement of multimeter as reference.

The result of the test is presented in Table VI. The measurements performed by sensors show values that have relatively small difference compared with multimeter measurement. The error rates of voltage measurement and current sensor also are not too large and still acceptable for our purposes. To reduce the error of measurement in real-time operation, the average of multiple measurements can be used instead of just from one-time measurement.

TABLE VI
VOLTAGE AND CURRENT MEASUREMENT RESULTS

Measured Parameter	Multimeter Measurement	Sensor Measurement	Error Rate
Voltage	122.5 V	123.7 V	1.2 %
Current	0.105 A	0.115 A	1.0 %

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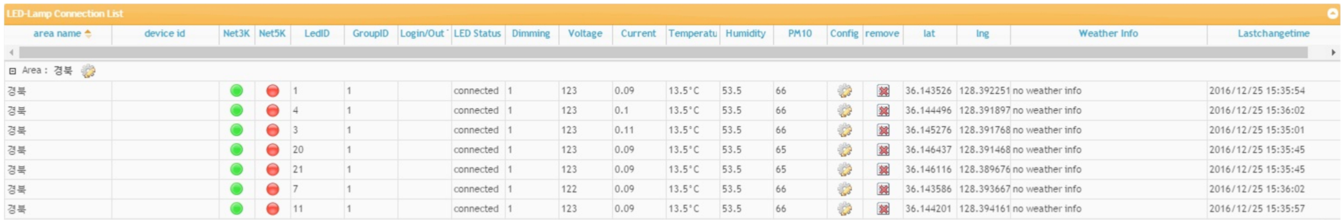


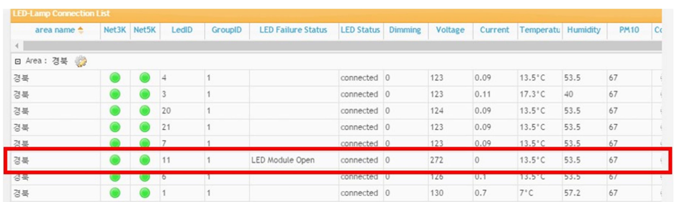
LED-Lamp Connection List

area name	device id	Net3K	Net5K	LedID	GroupID	Login/Out	LED Status	Dimming	Voltage	Current	Temperatu	Humidity	PM10	Config	remove	lat	lng	Weather Info	Lastchangetime
Area : 경북																			
경북				1	1		connected	1	123	0.09	13.5°C	53.5	66			36.143526	128.392251	no weather info	2016/12/25 15:35:54
경북				4	1		connected	1	123	0.1	13.5°C	53.5	66			36.144496	128.391897	no weather info	2016/12/25 15:36:02
경북				3	1		connected	1	123	0.11	13.5°C	53.5	66			36.145276	128.391768	no weather info	2016/12/25 15:35:01
경북				20	1		connected	1	123	0.09	13.5°C	53.5	65			36.146437	128.391468	no weather info	2016/12/25 15:35:45
경북				21	1		connected	1	123	0.09	13.5°C	53.5	65			36.146116	128.389676	no weather info	2016/12/25 15:35:45
경북				7	1		connected	1	122	0.09	13.5°C	53.5	66			36.143586	128.393667	no weather info	2016/12/25 15:36:02
경북				11	1		connected	1	123	0.09	13.5°C	53.5	66			36.144201	128.394161	no weather info	2016/12/25 15:35:57

Fig. 11. Screenshot of web interface displayed at web client, showing all connected LED streetlights with their sensors' reading value, status, and last update time.

(a) (b) (c) (d)

Fig. 12. Photos of LED streetlight with different CCT ((a) 5000 K, (b) 3000 K) and different dim level ((c) highest level, (d) mid level).



LED-Lamp Connection List

area name	Net3K	Net5K	LedID	GroupID	LED Failure Status	LED Status	Dimming	Voltage	Current	Temperatu	Humidity	PM10	Co
Area : 경북													
경북			4	1		connected	0	123	0.09	13.5°C	53.5	67	
경북			3	1		connected	0	123	0.11	17.3°C	40	67	
경북			20	1		connected	0	124	0.09	13.5°C	53.5	67	
경북			21	1		connected	0	123	0.09	13.5°C	53.5	67	
경북			7	1		connected	0	123	0.09	13.5°C	53.5	67	
경북			11	1	LED Module Open	connected	0	272	0	13.5°C	53.5	67	
경북			6	1		connected	0	126	0.1	13.5°C	53.5	67	
경북			1	1		connected	0	130	0.7	7°C	57.2	67	

(a)

(b)

Fig. 13. Screenshot of web interface when one LED streetlight was failing. The web interface shows (a) one LED streetlight with LED Module Open at LED Failure Status column and (b) the failing LED streetlight icon changed to warning icon.

V. Conclusion

This paper has discussed an in-depth implementation of smart LED streetlight system for smart city with web-based management system. In particular, the proposed architecture comprises LED streetlights in groups, which connected to web based management system to provide interface to authorized user. We defined an algorithm for the request and reply transmission between the SGC to SGMs and vice versa along with tuning between the 3000 K and 5000 K color temperatures and dimming functionality when necessary. In addition, the streetlight network is developed in such a way that each streetlight can be controlled by a central web server called streetlight web server where the control signaling goes through the coordinator first then to each routers according to their ID and the other way. Unlike the existing works on LED streetlight system, our proposed system, through the tunable CCT LED arrays, can mitigate the chance of traffic accident happening due to low visibility during climate alarm issues such as heavy fog, haze, etc.

We examined the wireless communication quality among ZigBee devices in each streetlight through experimental setup and theoretical analysis. We evaluated the wireless channel through path loss prediction considering in-building scenario. In our experimentation, the average measured received signal strength and throughput shows a 100 % successful packet transmission-reception between each streetlights. Therefore, our proposed system provides optimal platform for an innovative LED streetlight system for a smart city application.

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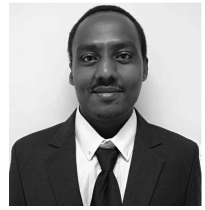

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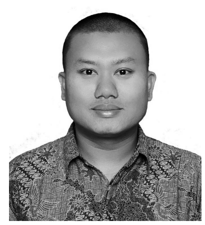

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