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Research Article

Design and Implementation of a Real-Time Street Light Dimming System Based on a Hybrid Control Architecture

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Smart street LED lighting systems have received much attention driven by the need to save energy and the dramatic advances in the Internet of Things. This work proposes a new smart street lighting system that adaptively changes the street lights' intensity based on traffic and weather conditions and provides a platform for monitoring road conditions and detecting lamp faults. The system transfers the data using the UDP protocol over NBIoT radio technology. It also maintains two-way communication between the luminaires and the central node. In order to ensure real-time response to traffic and avoid dimming delays, each light is locally controlled by a microcontroller based on the sensed traffic and weather data. The measurements of each luminaire are also sent to the central control node to locate lamp faults, detect emergency situations, and, if needed, broadcast on/off messages to the whole network's luminaires. The system was implemented in a suburban street in Ras Al Khaimah. Evaluations proved that the system can locate and detect faulty lamps and vary the light intensity in real time based on traffic. It also resulted in energy savings of up to 55% compared to a normal LED street light network.

1. Introduction

Street lighting networks are fundamental to planning urban areas and intercity roads. Besides their utmost importance for city aesthetics, they provide safety and security for road users and residents alike. However, they currently account for about 53% of outdoor lighting use worldwide leading to enormous energy consumption around the world [1]. In many cases and during late-night hours, roads are usually fully lighted while they tend to be empty which leads to unjustified energy losses. Accordingly, many researchers are working now on innovative solutions that can reduce energy wastage while preserving road security and safety.

Various methods have been proposed in the literature to improve the efficiency of street lighting systems and save energy. These can be broadly divided into two main streams: saving energy by using more efficient light sources [2] or employing control strategies that adapt the light intensity based on traffic. Traditionally, street lighting systems have used high-pressure sodium (HPS) or metal halide (MH) light sources. Besides their high energy consumption, those types of light sources are considered inefficient because of their short lifetime. They require regular checkups and replacements leading to increased maintenance costs. In contrast, light-emitting diode (LED) lamps are more durable and offer longer lifetime [3]. They consume less power, require less maintenance, and produce less thermal energy. In addition, they provide better visibility and enable enhanced color recognition as compared to conventional light sources [3]. Without the need of any reflectors, LED lights emit the light in half spherical space. When directed down, they do not waste fractions of light up to the sky and thus have less light pollution effects. This also makes them more efficient in directing the light to the desired areas and preventing light escaping to nearby unwanted environments. Moreover, they are more environmentally friendly in the sense that they do not contain poisonous mercury and sodium gases or toxic lead [3, 4].

Different protocols have been used in practice for lighting control. Based on the required operational lighting scenario, a designer can choose out of open protocols like TCP/IP, BACNet, DMX 512, LONWorks, X-10, 0–10 V, and Digital Addressable Lighting Interface (DALI) to name a few [5]. DALI's use in street lighting has recently gained momentum as an effective protocol for street lighting control. In addition to enabling multilevel light dimming [6], it facilitates a two-way link between the control devices and the lighting devices [7] and is capable of sending broadcast messages to address multiple lamps. DALI was initially developed for wired networks and later provided support for devices with wireless connectivity. A smart system for managing public lighting networks based on IEEE 802.15.4 wireless technology and the DALI protocol was introduced in [8]. On the downside, it was reported in [9] that DALI suffers from delays which makes it not preferable for use in controlling luminaires on busy roads where real-time diming is required. As a result, they proposed the use of TCP/IP communication to control LED lamps over a Zigbee-connected street light network.

Many researchers have worked on proposing innovative control strategies to produce more convenient and energy efficient street lighting systems. Such systems are referred to in the literature as smart street lighting systems. Smart street lighting systems are aimed at reducing energy consumption by dimming light [10] depending on the time of day or traffic conditions [11]. They are usually managed and controlled by a central node which makes it easier to detect faulty lamps [12] and meter energy consumption [13]. The availability of real-time data about the network simplifies the planned optimization tasks and makes maintenance costs minimal.

A smart street lighting system can be realized by the existence of three main components, a sensor node equipped with a light source and sensors, network connectivity, and a management and control system [11]. The sensor node collects environmental and road traffic data to be used as a basis for controlling/dimming the light. Network connectivity is required to enable communication between sensor nodes and the management and control center (center node) or among the sensor nodes themselves. While wired methods such as Ethernet cables [14] and/or power line communication (PLC) technology [15, 16] were used to provide the required connectivity, wireless methods such as Zigbee [17, 18], 2G/3G/4G [12, 19–22], and low-power wide area networks (LPWANs) [23] are more favorable because of their practicality, especially when used with solar-powered, physically disconnected luminaires.

The management and control system, on the other hand, observes energy consumption, detects failures, and controls the light intensity based on the measurements collected from the sensor nodes. Both centralized and distributed control strategies were explored in the literature. The centralized management and control systems allow the central unit to track energy consumption in the luminaires relevant circuitry [24] and to locate failures as well [25]. In distributed and decentralized systems, the luminaires are controlled locally and operate autonomously. When the sensor node detects a movement within its sensing range, it turns the light on at the maximum intensity [26]. It dims the light to the minimum intensity later when the object gets out of its sensing range. A hybrid system that uses the centralized approach for collecting and managing the street luminaire data and the distributed approach for locally controlling them was proposed in [17].

The dynamic nature of the smart street light problem and the rapid movement towards implementing these systems revealed many challenges and concerns. Being mostly built using wireless IoT technology makes smart street light systems subject to interference and cyberattacks. Cybersecurity [27], intrusion attack detection [28], and compatibility within the IoT smart city ecosystem [29] are key design issues that are being considered. AI and statistical modelling are to be used for predicting the traffic status and detecting and locating emergency incidents [30, 31]. They can also be used for building weekly dimming profiles [32] which can help in implementing continuous dimming to result in further energy savings [33]. Another direction is to design and use long-range RF motion sensors instead of PIR motion sensor for higher directivity, faster response, and immunity to various weather conditions [33]. Installed together with LPR cameras, these RF sensors can also be used to detect speeding vehicles [33].

The massive number of Internet of Things (IoT) devices and sensors involved in applications such as smart cities [34] made it imperative to develop communication protocols specially designed for IoT communications. LPWAN technologies have recently emerged as more suitable methods for connecting sensors within IoT frameworks [23]. They are characterized by their low power consumption, low data rate, and long communication range of up to 10-40 km in rural zones and 1-5 km in urban zones [35]. Such characteristics make them suitable for IoT devices that transmit tiny amounts of data over long distances. Accordingly, LPWAN technologies are widely used in industrial and research communities [35].

LPWAN can be broadly divided into cellular- and noncellular-based protocols [35, 36]. Among the cellular-based protocols, Narrow Band Internet of Things (NBIoT) is the most commonly used technology while long-range radio (LoRa) is the most famous of the noncellular ones. There are many benefits on using NBIoT over LoRa [35, 37]. It provides an end-to-end efficient, flexible, and secure management solution. The NBIoT network is based on the cellular network infrastructure and uses a licensed spectrum which has many benefits like strong antijamming capability, high data security, convenient technical services, and easy deployment on network operators, which easily makes the terminal connected to the cloud platform for the smart street light system having many vital devices connected to it.

NBIoT offers as well better scalability, quality of service, security, penetration of structures, and better data rates compared to unlicensed band-based standards. Another advantage of NBIoT is that it can coexist with LTE in the guard band with minor interference between them in uplink [38]. It is possible for many mobile operators which run on GSM 900 MHz and LTE 800 MHz, to upgrade to NBIoT.

Several studies explored the use of LoRa network for smart street luminaire connectivity. A LoRa-based smart street light management system that automates street luminaire operation based on road use was introduced in [39]. In [40], it was demonstrated that a smart street light system with LoRa connectivity can save energy, detect faulty lamps, and reduce the need for manual surveillance on each pole. The paper analyzed the performance of LoRa technology in terms of Doppler robustness, scalability, and coverage and showed that with a transmission power of 14 dBm and a spreading factor of 12, more than 60% of packets could be received at a 30 km distance. An Arduino-based open-source electronic platform for smart public lighting control was proposed in [41]. The paper showed that the LoRa-based system was able to adjust in real time the light intensity according to the data gathered from the sensors comprising the network.

Chen et al. [38] described the design and structure of an NBIoT smart street lighting system and the involved IoT platform. It showed that telecom companies can use the combination of NBIoT network, IoT platform, and cloud computing to provide IoT intelligent solutions. While the paper presented a centralized control strategy where the system management can use the basic data to detect lamp failures and perform remote metering and group management, it did not consider decentralized control options at the level of each street light to perform dimming based on road traffic. On the contrary, Zhao et al. [42] presented a smart street lighting solution that enabled local light intensity control at each lamp post together with centralized control at the cloud server. In order to report sensor readings to the cloud server, two means of communication were used. Lamp posts in a local neighborhood communicated with their respective central road units using PLC. On the other hand, the central road units reported to a cloud server using NBIoT.

In this paper, we propose a new smart street lighting system. The system provides instantaneous control of street light intensity based on road traffic and weather conditions. Like [43], it employs a hybrid control system where the centralized control approach is applied for collecting and managing the street luminaire data, and the distributed/decentralized approach is used for locally controlling each light based on its surrounding sensors. However, our proposed system uses a highly directional RF motion sensor to detect moving objects rather than cameras in the case of [43]. It only uses NBIoT for connectivity rather than Zigbee and 3G/4G technologies that [43] utilized or NBIoT and LoRa together, as in the case of [44].

Unlike [41], we use, for connectivity, NBIoT rather than LoRa for the abovementioned reasons. The proposed system differs from [38] in that it allows for decentralized control at each lamp post which is reflected in a real-time light dimming response. It assumes no physical connection between poles (through wires) as opposed to [42] and, therefore, is suitable for solar-powered street luminaires. It provides, as well, a powerful diagnostic tool for locating faulty system components including lamps. New luminaires can be added to the system without affecting the other luminaires or changing the network configuration deeming it a scalable solution.

The paper is organized as follows: Section 2 presents the problem statement and system requirements. Section 3 provides a description of the proposed solution in terms of the involved topology and control strategies. The system's experimental setup and results are discussed in Section 4. The conclusion and recommendations for future work are outlined in Section 5.

2. System Requirements and Problem Statement

Consider a road lit at night by equally spaced lamp poles. Each lamp pole is equipped with environmental sensors, a current sensor, a motion sensor, and a LED light and has NBIoT connectivity. The aim of this work is to manage the road light network in such a way to provide suitable light for drivers, save energy, detect faults, and provide continuous monitoring of the road for safety, security, and future planning reasons. The proposed solution employs two control strategies. It utilizes the centralized control approach for collecting, displaying, and managing the street luminaire data in the center node. In order to avoid dimming delays due to the long routes travelled by the signal between the sensor node and the central node, the system also employs the decentralized approach for locally controlling each luminaire based on traffic and weather conditions. The light in the sections of the road where there is no traffic is dimmed and only made bright again when traffic is detected. Figure 1 shows the layout of the luminaires in a section of the road under consideration.

Each luminaire or lamp pole is equipped with a directional RF motion sensor that has a sensing range of R. The distance between one pole and the other is $d = R/3$. Initially, at nighttime, all lamps are dimmed. Referring to Figure 2, when a vehicle is at a distance d or less from lamp pole n, it becomes within the coverage range of the motion sensors attached to luminaires n, $n+1$, and $n+2$. This leads to driving LEDs n, $n+1$, and $n+2$ to the full light intensity state. On the other hand, when the vehicle just passes luminaire n, it gets out of the coverage range of motion sensor n and becomes within the coverage range of motion sensors $n+1$, $n+2$, and $n+3$. As a result, lamp n dims, whereas lamps $n+1$, $n+2$, and $n+3$ become fully lighted. This setup guarantees that three luminaires (covering a distance R) in front of any moving car are fully lighted while the following luminaires are dimmed as can be seen in Figure 2. This will guarantee that the area close to the driver is fully visible and the driver can take immediate action should an object, pedestrian, or an animal suddenly appears in the street. Although lighted at lower intensity, the area after R will be still visible to the driver allowing extended visibility range. The overlap in sensor ranges and light coverage guarantees

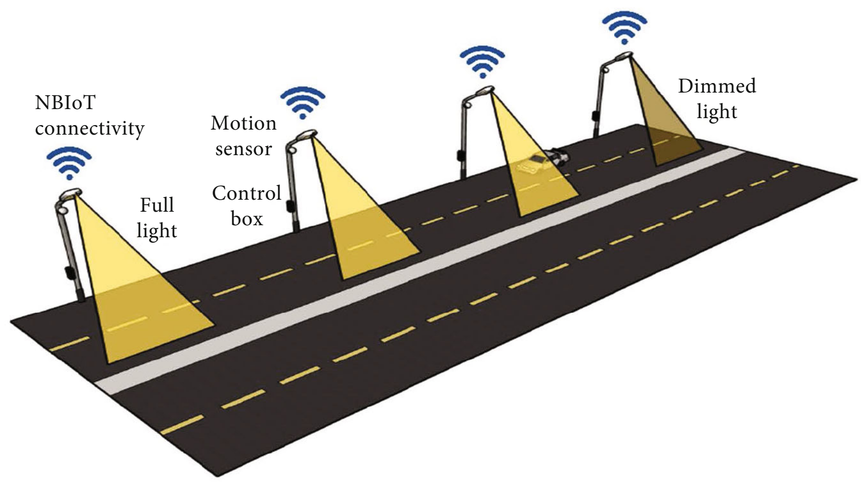

Figure 1: Layout of the luminaires in a section of a road.

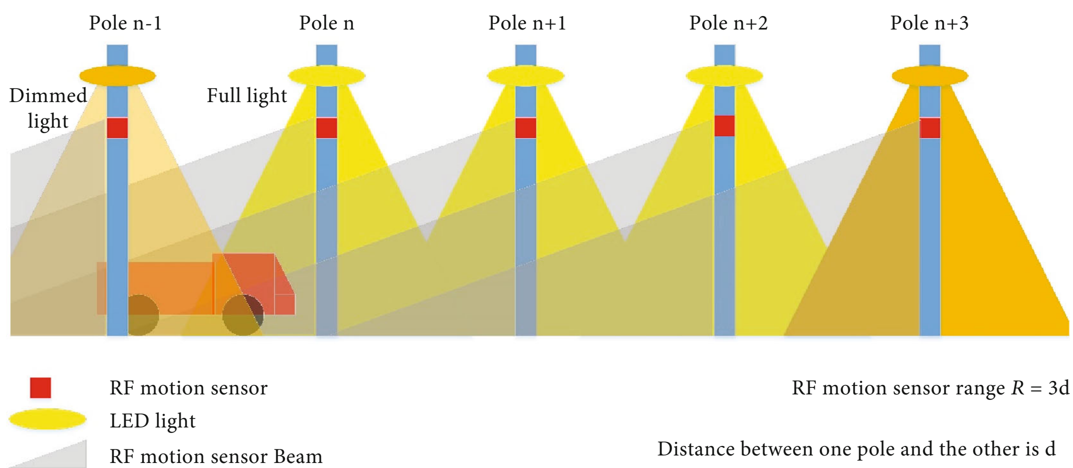

Figure 2: Proposed dimming approach.

convenient driving experience as there will be no abrupt change in the light intensity affecting the driver.

3. System Description

The proposed design offers two levels of control, a local control at the lamp post level and an overall system control at the central node. In the sections below, we explain each of these levels of control strategies in detail.

3.1. Local Control. Each pole or lamp post is equipped with a sensor node, a light dimming circuit, and an LED lamp. The sensor node used is the Arduino-based SODAQ SARA R412 IoT module. It includes a microcontroller and an NBIoT transceiver. Integrated within the module are a GPS module, an accelerometer, and magnetometers. It can take input from multiple external digital and/or analog sensors. The external sensors connected to the node include weather-related sensors such as temperature, humidity and dust level sensors, a current sensor, a light sensor (LDR), and an RF motion sensor. The current sensor measures the current drawn by the LED light and is used as an indicator of whether the LED light is working fine or faulty and needs replacement. The measurements of all these sensors are sent using the NBIoT technology to a cloud-based platform for monitoring and visualization as will be explained in the next section.

The light dimming circuit serves as the core of the local control. It controls the light intensity based on the measurements of the motion sensor and the measurement of the light sensor. It provides three different light intensity levels. When the light sensor detects daylight, the LEDs are turned off. On the other hand, when it is nighttime and motion is detected, the LED light goes to full intensity. Otherwise, it goes to the dimmed state. It is important to note here that based on the LDR output, a timer is initiated to calculate the overall time a LED lamp is on. Another timer is also used to accumulate the overall time a LED is in the full intensity state over the period of a whole night. Figure 3 shows a flowchart description of the local control process. A block diagram of the local control system (sensor node) is given in Figure 4.

The dimming circuit is shown in Figure 5. It includes three relays and a 90 W LED light consisting of three 30 W

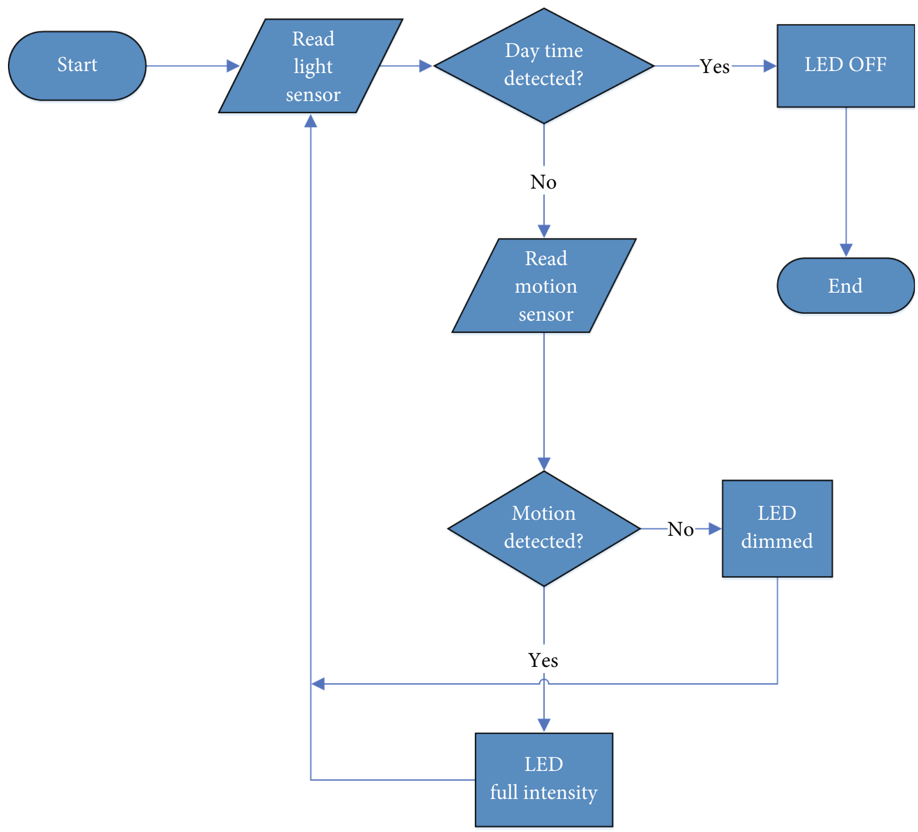

Figure 3: A flowchart of local control algorithm performed at each lamp post.

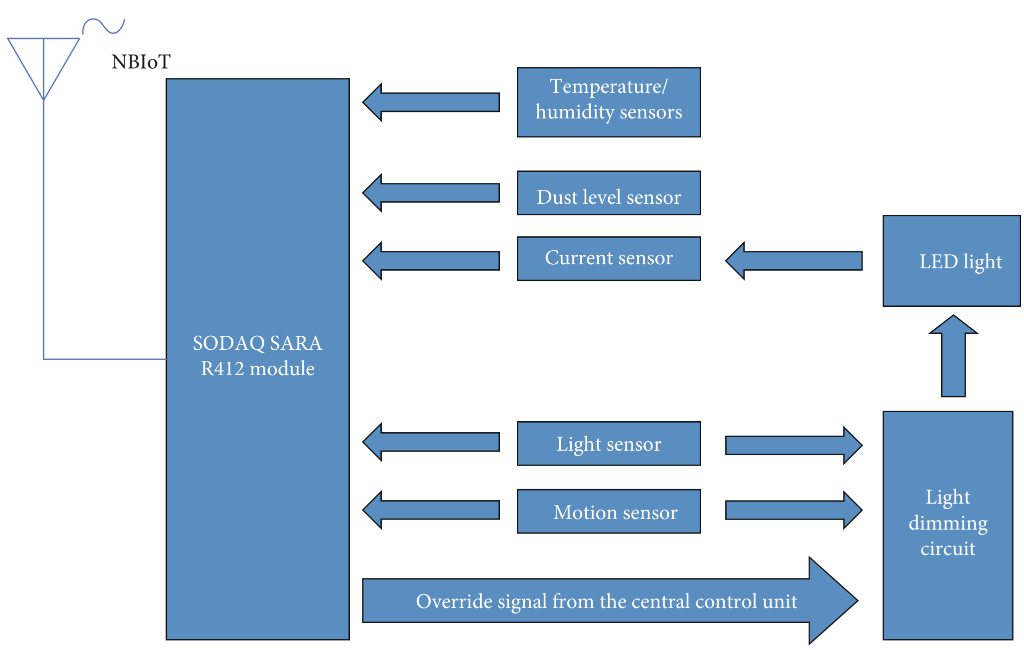

Figure 4: A block diagram for the sensor node.

LED units. The LED light is controlled by the three relays to operate in three different states, off, fully on when the three LED units are on, and dimmed when one LED unit is on while the other two are off. As can be seen in the figure, relay R1 is controlled by the RF motion sensor while relays R2 and R3 are controlled by the on and off signals coming from the local weather sensors or sent by the central control systems in case of an emergency request to fully turn all the light sources on or off. Initially, at nighttime, the light stays in the dimmed status until a moving vehicle is sensed. It is then

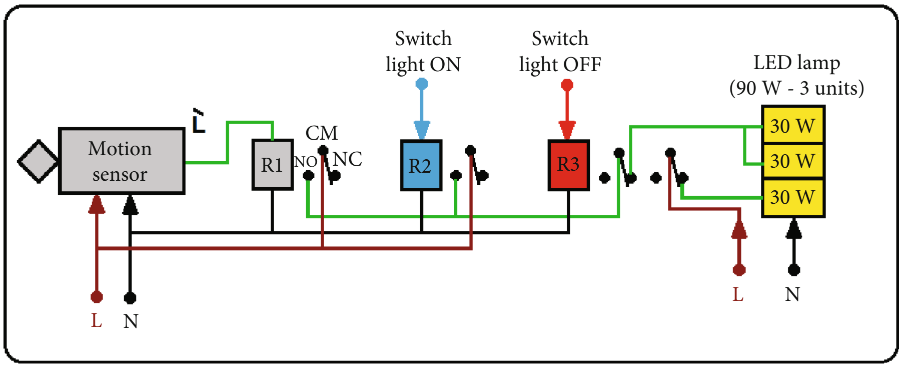

FIGURE 5: The dimming circuit.

that R1 is activated by connecting the CM (common point of the relay contacts) to the NO (normally open point of the relay contacts) leading to turning on the other two units of the LED lamp. Based on weather conditions and/or commands sent by the central control system, the additional two relays are operated where activating R2 switches the light fully on while activating R3 switches the light fully off.

3.2. Overall System Control. The overall system control involves receiving data reported by each pole including weather-related data such as temperature, humidity and dust level, LED lamp current readings, lamp ID, GPS location, and light sensor data. Once daytime is detected, it also receives from each sensor node the overall time the LED was on and the overall time the LED was in the full intensity state.

The aim of this level of control is to automatically detect and locate faulty lamps, monitor traffic and weather information, and take decisions at the level of the whole network or a certain neighborhood. Such decisions may include sending an override signal to increase or decrease the light intensity within an area, contacting the emergency services and road traffic authorities in case of detected risks on the roads, or informing the municipality of the locations of faulty lamps.

The transmitted data is stored in a cloud-based database and is made available to be pulled out by an application server for further processing. The application server can employ machine learning algorithms to predict congestion and then notify the authorities to direct the drivers to change their driving routes or to warn them of upcoming dangers. This will ensure better use of the road infrastructure, better use of energy, reducing the wait time, and reducing the resulting gas emissions. It will also enhance the safety and security of the residents and road users.

As described previously, each pole is equipped with NBIoT-enabled SODOQ SARA module that reports the pole measurements using the NBIoT technology. In our case, the pole data are reported over the cloud to AllThingsTalk platform which serves as a platform for visualizing and storing data. It can also be used to analyze the data and draw conclusions. However, in our design, we use an application server to serve as the central control unit (node). It imports the data from the cloud platform, analyzes it, and contacts authorities regarding the traffic and weather conditions. The server is also equipped with NBIoT connectivity which makes it capable of sending orders to some or all the luminaires to change the light intensity in case of high dust levels or fog or turn the light sources off when needed. Figure 6 shows the flow of data between the sensors, LEDs, and the application server.

The application server gathers data from the IoT cloud platform and processes it. In the case of a faulty IoT module (sensor node) or LED, it sends a message with the faulty lamp ID and location to the relevant authorities. In case of emergencies, the application server takes control of the light network by sending an override command to turn all the LEDs off or increase the light intensity. On the other hand, when the server detects high dust levels or fog during nighttime, it sends a command to all the IoT modules to increase the light intensity. Figure 7 explains how the central control works.

The network architecture employed in the proposed systems can be broadly divided into three layers, the perception layer, the transmission/network layer, and the platform/application layer, as shown in Figure 8. The perception layer which is also known as the physical layer includes the sensing devices that measure the street light system parameters. The transmission/network layer is responsible for data communication to the base station using NBIoT and from there to the cloud-based platform over the Internet. The platform/application layer is represented here by the cloud-based platform that collects, stores, and visualizes the data and makes it available for the application server that could further analyze the data, locate faulty lamps, and contact the authorities in case of emergencies.

In this layer, various IoT-related applications can be deployed. These include access management, device management, application enablement, and service analysis capabilities [45]. Device-to-device (D2D) communication [46] can also be implemented when there is a need for communication between lamp posts and vehicles in the context of the Internet of Vehicles (IoV) systems [47]. Different protocols like MQTT and CoAP can be used as per the requirement. Figure 8 shows the three-layer NBIoT network architecture used in our experimental setup. The cloud platform used in this work is AllThingsTalk maker website. It is an open-source platform that is used for all kinds of IoT networking applications and IoT devices.

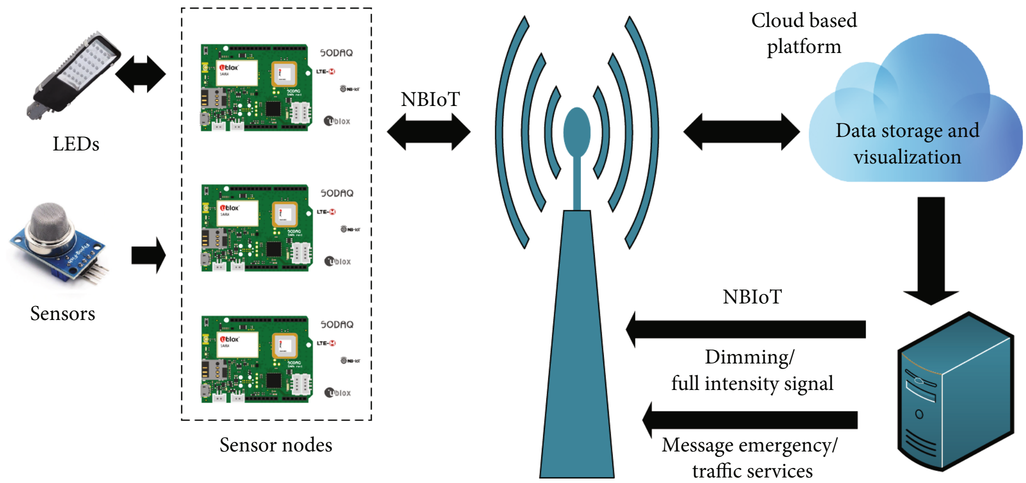

Figure 6: Flow of data between the sensor nodes and the application server.

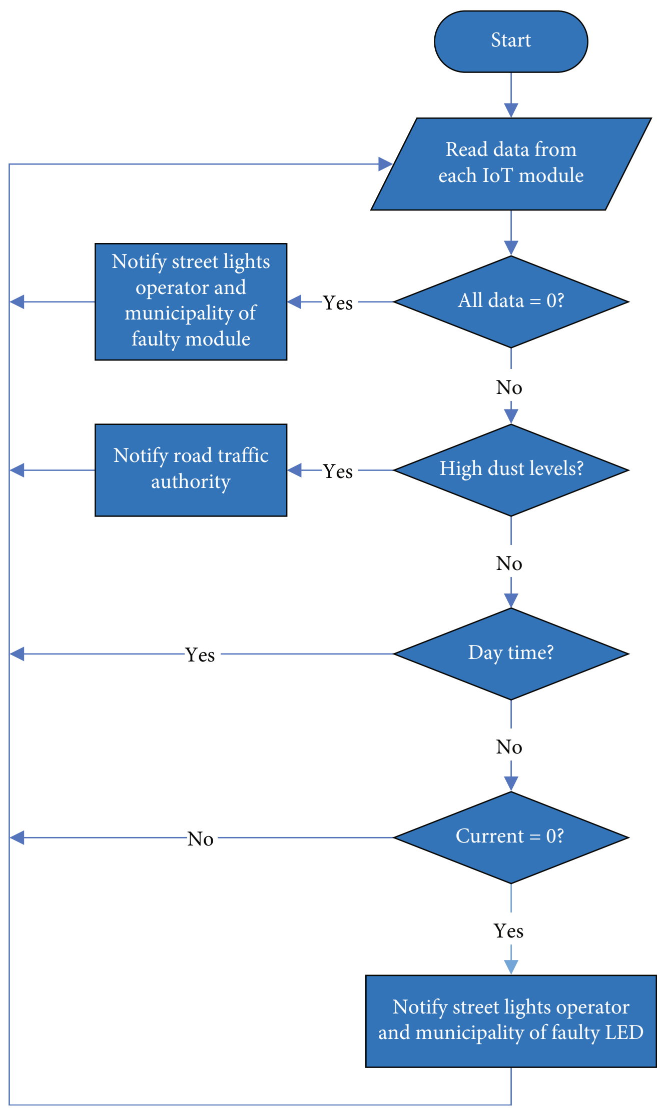

Figure 7: A flowchart of the central control algorithm.

In our project, we send the data over the Emirates Integrated Telecommunications Company (du) cellular network which only supports the use of UDP protocol over NBIoT. In order to send data over the Internet, UDP does not need to establish a connection. It is possible to manage security using UDP protocols as data travels end-to-end encrypted. The authentication and decoding of the data are the responsibility of the cloud server. UDP is also simple and is characterized by its low power consumption. It is important to note here that in conjunction with NBIoT, UDP is chosen over TCP for IoT applications which are unsusceptible to varying delays [48]. It is shown in [49] that CoAP/UDP-based transport performs consistently better both in terms of latency, coverage, and system capacity, whereas MQTT/TCP works better when the system is less loaded. In this work, we use CoAP over UDP to ensure two-way communication between the server (the central node) and the luminaires.

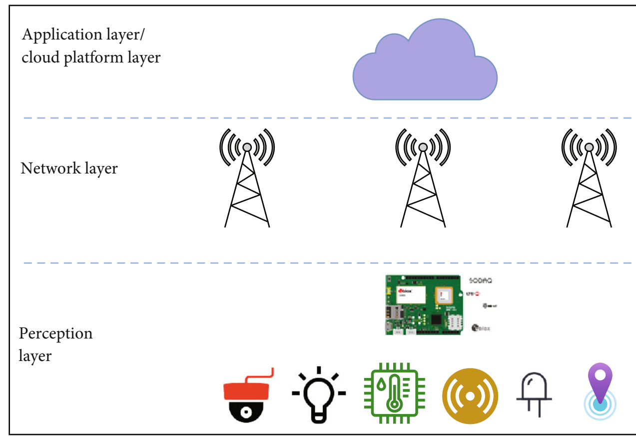

Figure 8: Network architecture of the NBIoT-based smart street system.

4. Experimental Results and Discussion

The proposed solution has been implemented in a section of a 2-way local street located in the city of Ras Al Khaimah, UAE, close to the American University of Ras Al Khaimah campus. The speed limit of the street is 50 km/h. The section under consideration includes ten luminaires spaced 15 m ($d = 15$ m) from each other. Each lamp post has a 90 W LED lamp installed at a height of 5.5 m. The LED lamp consists of three 30 W LED units. It is controlled by the dimming circuit described in Figure 5 to operate in three different states, off, fully on (full intensity) when the three LED units are on, thus consuming 90 W, and dimmed when one LED unit is on while the other two are off leading to the power consumption of 30 W. Attached to each pole is a control box that includes contactors, circuit breakers, the dimming circuit, the IoT module (sensor node), and a DC power supply to power the IoT module.

The IoT module used in this project is a SODAQ SARA R 412 AFF (Arduino form factor). It comes with a powerful 32 bit microcontroller, two grove sockets for connecting sensors, two JST connectors for battery connection and solar panel, accelerometer, GPS, and NBIoT transceiver. The module has also a built-in temperature sensor and a GPS receiver to monitor ambient temperature and provide the exact location of the pole. In order to measure humidity and dust levels, a DHT11 basic temperature-humidity sensor and a grove–dust sensor are connected directly to the IoT module. An LDR connected to the IoT module is also used to detect daytime and nighttime. In addition, an RF motion sensor that is directly connected to the dimming circuit is used for detecting moving cars and pedestrians. The RF motion sensor has a range of $R = 45$ m and is highly directional. The data is transmitted using the NBIoT network of Emirates Integrated Telecommunications Company (du). Figures 9–11 show the system's various components.

Initially, at the setup stage, AT (attention) modem control commands were used to search for the available cellular network operators, attach each IoT module to NBIoT, and establish a wireless connection for data transfer using the UDP protocol. The connection was established using the

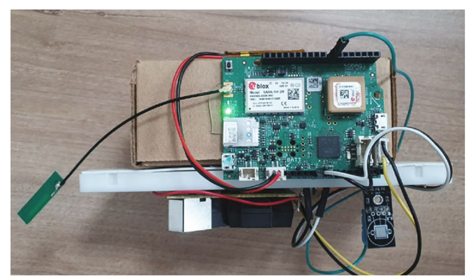

Figure 9: IoT module with connected sensors and NBIoT SIM card installed.

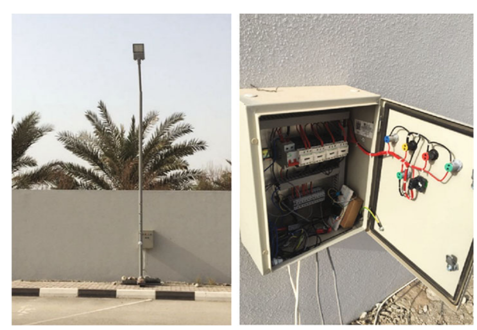

Figure 10: A luminaire with the control box.

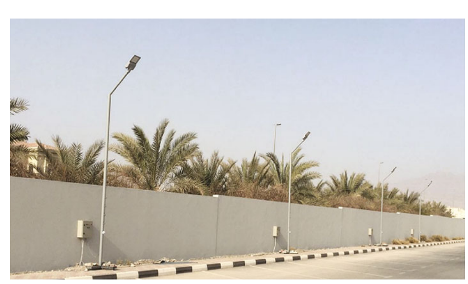

Figure 11: A section of the street where the luminaires are installed.

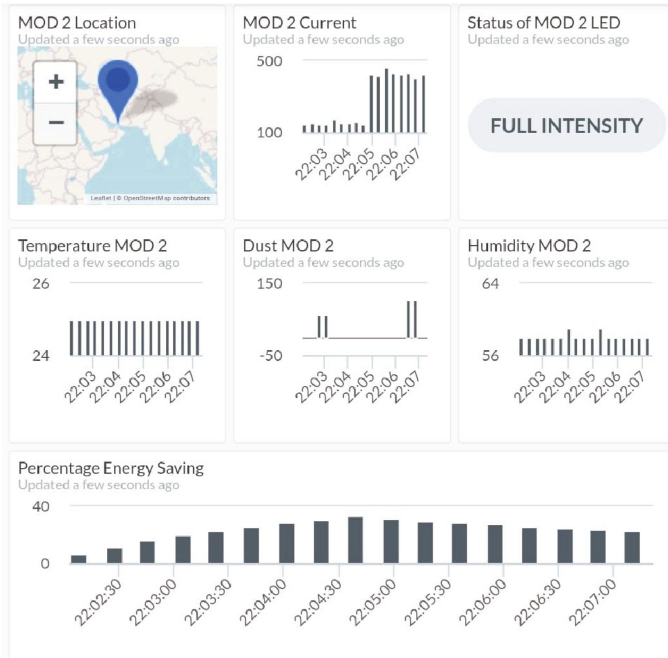

Figure 12: A screenshot from the AllThingsTalk environment for the readings of module 2 for the full intensity state.

network of Emirates Integrated Telecommunications Company (du) over NBIoT frequency band 20. After that, each module was programmed to transmit the sensors' measurements to the IoT cloud platform for storage and visualization. The IoT cloud platform used here is AllThingsTalk. Each IoT module uploads its data to its assigned session in the cloud platform. Figures 12 and 13 show screenshots from the AllThingsTalk environment for the readings of one of the IoT modules for both the full intensity and dimming cases, respectively.

Referring to Figures 12 and 13, it can be seen that when a moving car is detected by the motion sensor, the dimming circuit operates the light in a full intensity state. The current sensor shows then that a high current has been drawn and the status field shows a status of FULL INTENSITY. The status field can also show DIM when no car is passing. It shows OFF when the system is off or at daytime and FAULTY when the lamp, the current sensor, or the sensor node module is faulty. The figures show as well the temperature, dust, humidity readings, the location map, the time stamp (the horizontal access), and the instantaneous relative energy saving at a time with respect to an unregulated street light system that always operates the same LEDs at full intensity. It is clear from Figure 12 that the current sensor readings were low until the time stamp 22:05 when the system switched from the dimming state into the full intensity state. It can also be seen that the relative instantaneous energy saving continued increasing until the time stamp 22:05 when the light went into full intensity and the relative instantaneous energy saving started decreasing. The decrease continued in Figure 13 until 22:08 when the light sources switched back to the dim state and the current readings went low leading to a gradual increase in the relative instantaneous energy saving.

Recalling that the light source's full intensity consumed power is 90 W, while it is 30 W when the light is dimmed, the energy E_i consumed by LED lamp i over a whole night is given by

$$\begin{aligned} E_i &= 30T_{i\mathrm{DIM}} + 90T_{i\mathrm{FULL}} \\ &= 30(T_{i\mathrm{ON}} - T_{i\mathrm{FULL}}) + 90T_{i\mathrm{FULL}} \\ &= 30T_{i\mathrm{ON}} + 60T_{i\mathrm{FULL}}, \end{aligned} \tag{1}$$

where $T_{i\mathrm{FULL}}$ is the overall time in a night the LED was operating at FULL INTENSITY, $T_{i\mathrm{DIM}}$ is the overall time in a night the LED light was in the DIM state, and $T_{i\mathrm{ON}}$ is the overall time in a night the LED light was ON at either the DIM state or at FULL INTENSITY. Both $T_{i\mathrm{ON}}$ and $T_{i\mathrm{FULL}}$ are recorded by the system as described in the previous sections. The difference $(T_{i\mathrm{ON}} - T_{i\mathrm{FULL}})$ is the overall time the LED was in the dim state $T_{i\mathrm{DIM}}$.

The energy consumption of an unregulated LED which operates at full intensity for the whole night is $E_{i-\mathrm{unregulated}} = 90T_{i1}$ (90 W multiplied by the total time the LED was on over a night). The percentage relative energy saving (PRES_i) of a node i when employing our proposed solution is calculated then by

$$\mathrm{PRES}_i = \left(1 - \frac{E_i}{E_{i-\mathrm{unregulated}}}\right) \times 100\%. \tag{2}$$

Substituting (1) into (2) reduces PRES_i to

$$\mathrm{PRES}_i = \left(1 - \frac{Ti_{\mathrm{ON}} + 2T_{i\mathrm{FULL}}}{3T_{i\mathrm{ON}}}\right) \times 100\%. \tag{3}$$

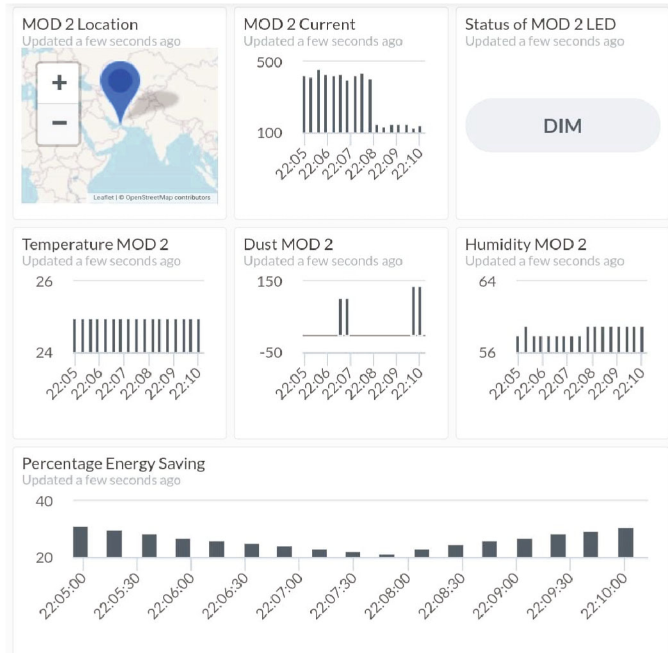

Figure 13: A screenshot from the AllThingsTalk environment for the readings of module 2 for the dimming state.

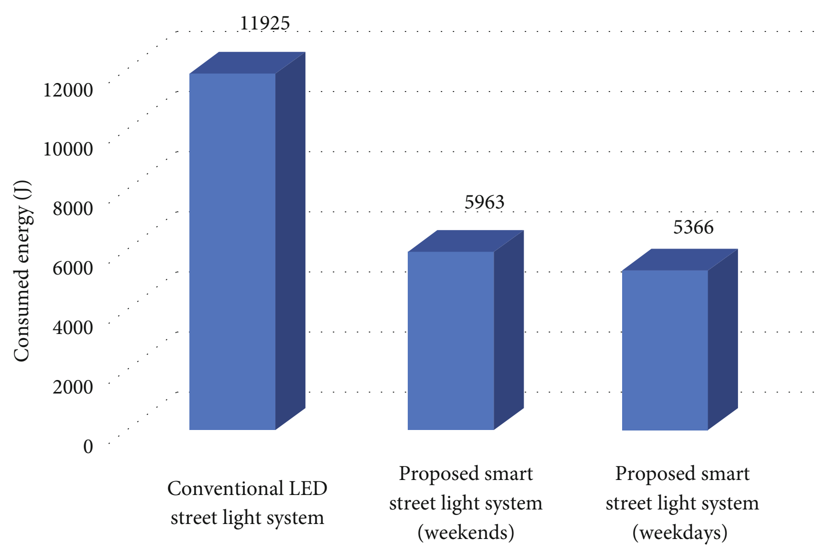

Figure 14: A comparison of the average system energy consumption between our proposed solution and the conventional LED-based street light system.

The overall system percentage relative energy saving (OPRES) is then calculated by

$$\text{OPRES} = \sum_{i=1}^{N} \frac{\text{PRES}_i}{N}, \tag{4}$$

where N is the number of lamp posts in the system.

The system was tested for a period of one month during May 2022 with a nighttime ranging from 13.0 to 13.5 hours. The energy consumption was recorded for both weekday and weekend scenarios. A comparison of the average system energy consumption between our proposed solution and the conventional unregulated system is given in Figure 14. The resulting average relative energy saving over the month is reported in Table 1. Referring to Figure 14 and Table 1, the superiority of the proposed solution is clear. Our proposed solution results in a percentage energy saving ranging between 50% and 55% depending on whether the testing was

Table 1: Relative energy saving over the month of May 2022.

Scenario	Relative energy saving
Weekday	55.5%
Weekend	50%

Table 2: A comparison of the different smart street light systems.

Metric/method	[38]	[42]	[41]	[43]	[44]	Proposed system
Communication technology	LPWAN (NBIoT)	LPWAN (NBIoT)+PLC	LPWAN (LoRa)	Zigbee+3G/4G	LPWAN (LoRa+NBIoT)	LPWAN (NBIoT)
Architecture of management and control system	Centralized	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Communication energy consumption	Low	Low	Low	High	Low	Low
Types of lamps used	Not specified	LED	Not LED	LED	Not specified	LED
Real-time dimming	No	Yes	Yes	Yes	Only on/off	Yes
Lamp fault detection and localization	Yes	Yes	Yes	Yes	Yes	Yes
Suitability for use with solar-based street light systems	High	Low	High	Medium	High	High
Relative lighting energy saving	Depends on deployment scenario	Depends on deployment scenario	Depends on deployment scenario	Depends on deployment scenario	Depends on deployment scenario	Depends on deployment scenario

done over a weekday or a weekend. As expected, the energy consumption on a weekend is higher than on a weekday since the streets tend to be busier on weekend nights.

A comparison of the proposed smart street light system with others reported in the literature is presented in Table 2. The metrics used in the comparison are the communication technology involved, the architecture of the management and control system, the communication energy consumption, the types of lamps used, the ability of real-time dimming and lamp fault detection, the suitability for use with solar-based street light systems, and the relative lighting energy saving.

Referring to the table, it can be seen that the systems that are based on a hybrid architecture ([41–44] and our system) provide real-time dimming and fault detection and localization. The systems that use LPWAN technologies and hybrid architecture ([41, 42, 44] and our system) consume less energy on communication than the system proposed in [43] which does not use LPWAN technologies. The systems that only use wireless technologies ([38, 41, 43, 44] and our system) are more suitable for use with solar-based street light systems. The relative lighting energy saving is dependent on the deployment scenario. On busy roads, the relative saving in lighting energy is expected to be less than that in suburban streets because of the shorter dimming times involved due to the increased traffic. In order to hold a fair quantitative comparison, the lighting energy consumption should be evaluated over the exact conditions that include the street traffic, the luminaire heights and spacing, the lamps, the time of the year, and the weather and environmental conditions. In general and referring to Table 2, it can be seen that as opposed to [44], our system is only based on NBIoT which is the most energy-efficient LPWAN system [42]. It is well known that NBIoT is more energy efficient than 3G/4G used in [43]. The proposed system is totally wireless and thus very suitable for use with solar-based street light systems. It employs a hybrid architecture and provides real-time dimming and fault detection. It controls the light intensity based on traffic conditions leading to considerable energy savings.

5. Conclusions

This work has proposed and implemented a new NBIoT-based system for controlling street luminaires with the primary aims of saving energy used to light streets and providing continuous monitoring of the street light network to detect emergency situations and lamp faults. It provides two levels of control for the system: the local control at the level of the lamp post and the overall system control at the level of the central control unit.

It utilizes the centralized control approach for collecting, displaying, and managing the street luminaire data in the center node. In order to avoid dimming delays due to the long routes travelled by the signal between the sensor nodes and the central node, the system also employs the decentralized approach for locally controlling each light based on traffic and weather conditions. The luminaires in the sections of the road where there is no traffic are dimmed and only made bright again when traffic is detected.

Each pole is equipped with a microcontroller that receives current, light, speed, humidity, and dust measurements, and based on their fusion, a decision of dimming or changing the light intensity is made. The decision is taken locally. The microcontroller instantly then triggers the pole's corresponding dimming circuit to change the light intensity to adapt the street lighting levels to the local traffic and weather conditions and, at the same time, to ensure the reduction of power consumption.

The system was implemented in a suburban street in Ras Al Khaimah. Evaluations proved that the system can locate and detect faulty lamps, continuously monitor the street conditions, and change the light intensity in real time based on road traffic including vehicles and pedestrians. In terms of energy savings, experimental results have shown that the system can result in energy saving of up to 55%.

In the future, we will implement the system in a highway and test it in several other traffic scenarios.

Data Availability

The measured data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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