Energy-Efficient Intelligent Street Lighting System Using Traffic-Adaptive Control

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***Abstract*— Lighting, both indoor and outdoor, consumes a substantial amount of energy, making improved efficiency a significant challenge. A promising approach to address outdoor lighting is the smart control of public lighting. Smart lighting using electronically controlled light-emitting diode (LED) lights for adaptable illumination and monitoring is being used to achieve an energy efficient system. However, the traffic engineering integrated with smart control for energy optimization has not been widely used. In this paper, a novel concept of traffic-flow-based smart (LED) street lighting for energy optimization is proposed. The developed smart grid architecture-based system uses low power ZigBee mesh network to provide maximum energy efficiency in response to adaptive traffic on the road. Moreover, the scalable wireless network of smart LED lights offers improved reliability, reduced cost, and more user satisfaction. In order to validate the performance, the proposed system was implemented and tested in a real environment inside a university campus. Experimental results show that in comparison with the replaced conventional metal halide lighting, our system is capable of 68%–82% energy savings depending on the variations in daylight hours between summer and winter. A significant reduction in greenhouse gases, improved overall system reliability, and reduced maintenance due to smart control suggests promising results for future wide-area deployment.**

***Index Terms*— Efficient network control, smart lighting system, smart grid, sensors, traffic flow, wireless mesh network.**

I. Introduction

PROJECTIONS state that by 2050 approximately two thirds, i.e., three billion people are expected to live in cities, accounting for 70% of energy consumption and greenhouse gas emissions [1]. As a result, energy efficiency and green communications are at the heart of the global transition to a resource-efficient economy and realization of smart and sustainable strategies. Lighting is a key part of this goal, accounting for 19% of global energy usage, which results in approximately 6% of environmental pollution associated with hazardous greenhouse gases (GHG) [2]. Therefore, energy efficiency for both indoor and outdoor lighting has emerged as an essential factor in strategies for a resource-efficient economy and realization of smart and sustainable growth [3].

In the area of outdoor lighting, public lights represent approximately 40% of total energy consumption and have great energy savings potential with efficient lighting using electronics control [4]. The higher amount of energy consumption associated with street lights is mainly contributed by the inefficient system, in which luminaries require high amount of energy. Moreover, from lifecycle perspective, the major cost related to conventional lighting system stems from its operation i.e., energy and maintenance and not from original investment cost. According to an estimate, Europe alone can save three billion euros in migrating from conventional system to new street lighting [3].

Strong financial and technological drivers and rational use of electricity in street light application has resulted in the use of solid state light-emitting diode (LED). LED has dramatically changed the lighting industry via new avenues, both in light efficiency and associated control electronics. It offers the benefits of increased system life, reduced power consumption, and less environmental pollution as compared to conventional lighting. With the smart control, it has emerged as a new generation of intelligent luminaries utilizing the integration of smart sensors and control with the variety of connectivity interfaces [5]. In street lighting, the smart networked lighting using LED has added the features of adjustable dimming, occupancy control, and optimal luminaire operations, which not only reduces energy consumption but also offers longer life and less maintenance to cut the system cost.

Wireless sensor network (WSN) with its ubiquitous nature and easy to monitor and control capability is the back bone of large variety of cyber physical systems (CPS) applications in every domain [6]. In terms of outdoor smart lighting, WSN integrated with networked LED luminaires has potential to conserve considerable amount of energy with the capability of centralized sensing and computing, power management, and dynamic demand response [7]. The low power, less complex and more reliable WSN offered by ZigBee has emerged as a preferable choice for energy efficient indoor and outdoor lighting [6], [8]–[10]. Specifically addressing the energy efficient smart street lighting, the combination of LED and ZigBee protocol offers adaptable dimming in accordance with ambient conditions, occupancy control and automatic fault detection. These features have allowed many systems to demonstrate considerable amounts of energy savings with greater monitor and control capability, and reduced maintenance [11]–[13]. Energy efficient wireless systems using LED luminaries with illumination and integrated

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monitoring and control is not new. However, in this article, the concept of smart street lighting with adaptive traffic control is introduced as the next level of 'intelligence'. The major contribution of this paper is to adjust the luminance intensity of smart LED lights according to the changing diurnal traffic volume present on the road. This experimentally implemented adaptive control can be used to conserve the optimal amount of energy in accordance with varying seasonal day light timing, as well as to reduce the emissions to a minimum level. Moreover, the smart grid platform with demand response (DR) and advanced metering information (AMI) provides the possibility for the smart street lights to be an integrated part of future green cities.

The rest of the paper is structured as follows: Section II outlines the relate work. Section III discusses the proposed smart lighting system, communication architecture and developed graphical user interface (GUI). Section IV presents the theoretical modeling and mathematical analysis of the traffic flow model. Section V presents the hardware design and system buildup. Section VI describes the system implementation and a discussion of achievements and results. Finally, conclusions and areas for future work are presented in Section VII to conclude the paper.

II. Related Work

In retrospect, several works have proposed smart street LED lighting and electronic control using both wired and wireless technology. In terms of wired control, Power line communications (PLC) is presented as a feasible solution for energy efficient lighting with improved user satisfaction and fault monitoring and detection [14]. However, in most of the literature, the wireless sensor network is the preferred choice. The obvious reason to prefer wireless network is due to the major disadvantage of bundles of cable, difficult system retrofits, heavy cost and maintenance related with wired system [6]. On the other hand, the wireless system offers obvious advantages such as low cost, easy installation, extendibility of the network, and self-healing. Therefore, many systems both in indoor and outdoor lighting have implemented WSN for energy efficient smart lighting. The works in [15] and [16] have proposed energy-efficient, wireless, indoor solutions using illumination-control smart lights. In [15], the system models the illumination requirements according to user activities and makes decisions regarding light intensity to conserve energy. The test bed in [16] proposed a smart LED lighting solution with ambient intelligence. The digital addressable lighting interface (DALI) controller with LED arrays and WSN not only offers a longer operational lifetime, but also reduces the overall energy consumption of an indoor office. The study in [17] developed a prototype to demonstrate a power savings mechanism for street lighting using the existing wireless network. This system uses the SMS services of GSM mobile communication and microcontroller-based design to control the on/off switching of street lights in order to conserve energy. However, the work does not include a mechanism for smart control capable of varying light intensity or timing-based automatic light.

The rapid advancement in low power WSN, specifically the ZigBee technology combined with the fast paced growth of solid state LED lights has made wireless smart lighting products as one of the fastest growing technology markets, which witnessed thousands time more sales in previous two years [18]. Therefore, the low power and reliable wireless network of ZigBee with LED lights has been a preferred choice for both indoor and outdoor energy efficient smart lighting [6], [11], [13], [19]–[21]. The real world deployment of ZigBee communication and smart LED lighting systems in [6] suggests a viable, energy efficient, and sustainable solution. This system combines the PIR presence sensor, PWM brightness control, LED light panel, and the low-cost ZigBee communication module to reduce the energy consumption of an indoor office up to 70% based on varying daylight conditions and illumination control. The work in [19] suggests ZigBee light link (ZLL) as a viable wireless control solution for smart home lighting control. In smart street lighting, a low power ZigBee based network is developed in [21]. The network proposed an energy efficient solution with automatic fault detection and integrated renewable solar energy as an alternative source for improved power efficiency. The study based on ZigBee and LED lights for traffic safety with vehicle detection is presented in [22]. It suggests a framework for solar powered and wirelessly connected groups of LED lights, which are switched on and off based on the presence of traffic on the highway. However, the work does not present any implementation or proposed system analysis.

With respect to the recent development in internet of things (IoT) and introduction of IP based wireless sensors like ZigBee 3.0, smart lighting has emerged as a catalyst to this new technology and projected to be an integrated part of future smart cities [23]. For example, in Padova smart city (PSC) project [24], an implementation to realize IoT in collaboration with public and private parties is presented. The project targets the connected public street lighting to monitor different environmental parameters and manages power through a gateway to internet raking into account of the critical issues in designing an urban IoT based smart lighting. A commercial internet-based, energy efficient lighting solution based on JenNet-IP stack provided by NXP GreenChip is an important example [25]. However, the challenges such as interoperability among the heterogeneous networks, ease of use with different drivers, and security are the issues to be addressed to make the system adaptable for future applications.

This work designs and develops a smart grid platform system using an open standard ZigBee standard. It is intended not only to offer a low cost interoperable network, but also to optimize the energy efficiency due to adaptive traffic control. Moreover, the system is laid out on a platform that can easily be integrated in to future low power wireless network with internet connectivity and devices from different markets.

III. Proposed System

As energy consumption continues to increase, utilities seek cost effective strategies for improved network operation and consumer consumption [26]. To design networks that satisfy the requirements of AMI and DR, various

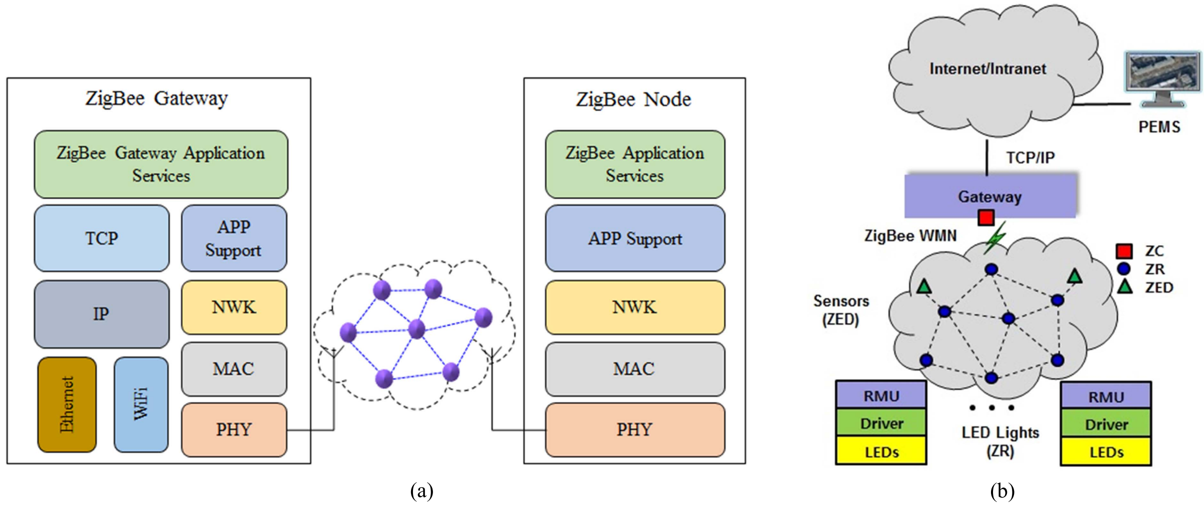


Fig. 1. (a) System network model. (b) Proposed system for smart street lighting.

communication standards are applied to comply with the smart grid framework. The customer's premise is covered by the Home Area Network (HAN), Building/Business Area Network (BAN), or Industrial Area Network (IAN). The Neighborhood Area Network (NAN) [27] is part of the AMI and connects the customer's premise network to utility companies. NAN can use either wireless (for example, RF mesh/802.15.4g, WiMAX, or 3G) or wireline networks (BPL/PLC, fiber, cable). Internet Service Providers (ISPs), such as cables, Digital Subscriber Lines (DSLs), Worldwide Interoperability for Microwave Access (WiMAX) and others will connect to the premise XAN through broadband access routers.

The network for the proposed system is implemented on the ZigBee standard based on two basic layers as defined in IEEE 802.15.4 i.e., physical (PHY) and medium access control (MAC). It uses the ZigBee home automation profile to build a wireless mesh network of LED lights. The TCP/IP protocol is used to provide the network expandability for the remote control monitoring and demand response capability by developing a graphical user interface (GUI) for a premise energy management system (PEMS).

The proposed system and its network model are shown in Fig. 1. In the system, the attributes of smart loads are remotely observed and controlled through a ZigBee gateway. A gateway node serves as a bridge between a ZigBee network and another network, performing protocol conversion between two heterogeneous networks. The designed ZigBee gateway offers interoperability between heterogeneous networks, providing message translation between ZigBee mesh networks and TCP/IP networks. The reliability of the network is maintained by configuring the ZigBee node, attached to a Smart LED, as the ZigBee router. Configuring each node as a router makes the system reliable by meshing nodes together, providing robustness to the developed system. Smart loads form a Personal Area Network (PAN) and are connected with premise intranet through the Energy Service Portal (ESP). If the deployment area is large, additional PAN with corresponding ESP may be created. All ESPs communicate with either the Premise Energy Management System (PEMS) through the premise intranet or a service provider through ISPs.

A. Communication Architecture

The major components of the communication structure of the system are smart LED lights, a ZigBee coordinator or gateway, and a monitoring and control platform.

Intelligent street lights have different sensors to monitor and control luminaries. It include temperature, luminosity and power metering sensors to control the dimming level and to check the status. These luminaries are networked together in a ZigBee mesh network that is interfaced with a streetlight coordinator making a PAN. In this PAN, devices (routers) are added through the coordinator after checking for reliable communication and security for network growth. This mesh network offers reliable communication among the devices, as nodes in the network have access to many other nodes (devices) in the network that are active within a radio range. The result is that each data packet communicated across the WMN can have multiple possible paths to its destination. This flexibility makes the mesh network robust in the sense of accommodating interference in the radio spectrum or blockages to a particular radio path. WMNs also enable networks to grow in size and cover greater physical distances.

The ZigBee streetlight coordinator collects information from all routers and interfaces with the power management system. It acts as a gateway entity between the ZigBee network and the TCP/IP network providing interoperability between both the network for the remote monitoring and control of the local network. This ZigBee gateway translates messages in two ways:

i. Acquires data from sensors and translates the ZigBee packet into an internet packet format before sending over the internet (Outgoing message).

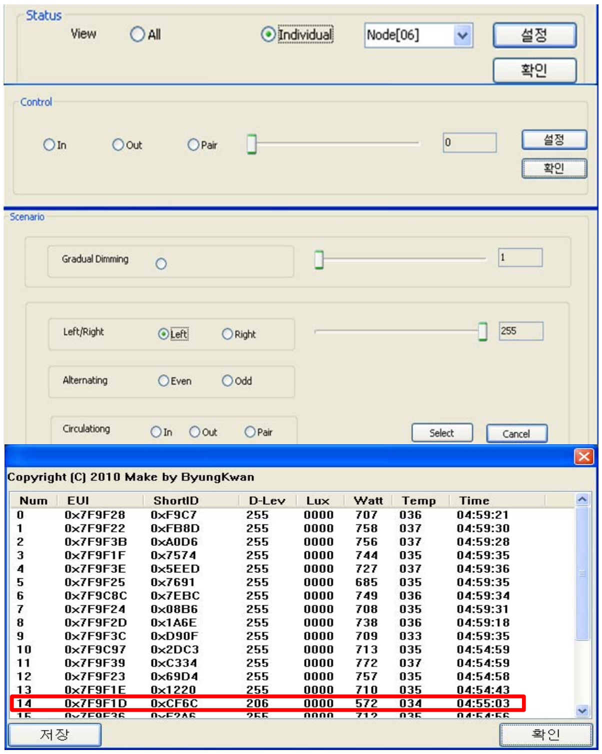


Fig. 2. Developed graphical user interface for power and energy management.

ii. The status of any LED lamp or control command sent via a remote user is translated into a ZigBee packet format through a gateway (Incoming message).

The developed premise energy and management (PEMS) software interface allows the remote operator to access, observe, and manage the current status of the system. PEMS runs on a server PC directly connected to the gateway (client) via internet, providing two way communications between the operator and the client gateway. In the current scenario, scheduled dimming level is maintained through PEMS and conveyed to the coordinator that manages streetlamps network to perform assigned task on a regular basis using the pre-defined instructions already stored. PEMS also provides an option to bypass the pre-defined schedule and control the individual or group of smart LED lights as per demand; however, group control is preferred due to the smooth change in luminosity without distracting the drivers. The remote user has the ability to control the street lights either individually or on a group basis. In addition to dimming control, it also monitors the status of ambient temperature, light, and power consumption in LED street lights.

In order to control the luminaries adaptively i.e. the decision to adjust their luminosity level based on time varying traffic, the software can be interfaced with traffic sensors installed on the road or with a vehicular communications network through the street light coordinator. Fig. 2 illustrates the status and control options; the upper part of the figure represents the graphical user interface (GUI) to the remote user, and the lower part shows the capture status of a specific node.

B. Sensor and Actuators

The system is designed to control smart LED lights efficiently in order to save energy. In the system, different sensors and actuators are associated with luminaries to monitor and control the luminary for its performance and its surroundings for adaptive control through the wireless network. Actuators primarily rely on information collected through sensors.

1) Light Sensor: Light sensors associated with smart LED luminaries monitor the vicinity of the lamp and periodically update the remote operator regarding the varying luminance level. On the basis of data making the remote user aware of the brightness status in a given location, the user controls the input power to adjust the illumination level, conserving energy as per demand or on a scheduled basis.

2) Temperature Sensor: A temperature sensor is soldered on the printed circuit board (PCB) of a controller to provide the inside temperature reading of the lamp. The temperature sensor alerts the remote user when the temperature exceeds safe limits. Acquired information is sent to the coordinator wirelessly which conveys the temperature status to server in real time.

3) Power Metering Sensor: In order to determine whether lights are functioning as desired, the power consumption of lights is periodically monitored in addition to light and temperature information. Measuring the power of smart luminaries also provides a diagnostic feature, indicating malfunctioning based on power failure.

IV. Theoretical Modeling and Analysis

In this system, an attempt is made to propose an intelligent, energy efficient lighting system based on traffic flow. The system would be capable of making decisions based on traffic distribution. This section presents a probabilistic mathematical model followed by statistical analysis and extracted results.

A. Mobility Model

In order to optimize the energy efficiency of the proposed system, a realistic mobility model reflecting the true pattern of the vehicular traffic distribution is needed. In literature, particularly for VANETs, various mobility models based on macroscopic and microscopic approaches have been proposed. In the macroscopic approach, mobility parameters such as vehicle mean velocity, density, and traffic are considered in cumulative fashion when modeling the system. The microscopic model considers each vehicle as a separate entity and utilizes a complex computation to provide more precise results [28]. The multiple dimensions and hence the complexity of defining a mobility model for VANETs of these models are out of the scope of this work. However, the model for this smart lighting solution has been adopted and developed on the same lines incorporating the necessary parameters and functional blocks to address the real problem.

For traffic patterns, the macroscopic parameters of average speed, traffic, and microscopic measures of vehicle time headway and inter spacing between vehicles are analyzed. The average of space-mean speed for the area in which the smart lights are installed is determined using $\bar{v} = l/\bar{t}$, where

TABLE I
TRAFFIC FLOW ANALYSIS OF A COMPLETE DAY

Time (pm)	*Vehicle Frequency*					*Total Vehicles*	*Sample Mean* (μ)	*Sample Variance* (σ^2)
	0	1	2	3	$\geq$ 4			
6-7	27	38	30	16	9	184	1.55	1.61
7-8	37	43	25	11	4	143	1.19	1.20
8-9	50	41	21	7	1	108	0.9	0.89
9-10	60	46	11	3	0	77	0.64	0.57
10-11	67	45	7	1	0	62	0.51	0.42
11-12	84	28	7	1	0	45	0.37	0.40

l defines the length of the road used to measure travel time, and $\bar{t}$ is the average time of vehicles determined to be traveling at 35 km/hr. The actual traffic distribution is characterized by the microscopic measures of headway (time between the arrivals of successive vehicles), and spacing between vehicles.

One simplistic approach to model the flow assumes a uniform arrival pattern; however, experimental observations suggest uninterrupted and heterogeneous traffic flow with a random number of vehicles at each time, resulting in a discrete time stochastic process. Therefore, the process can be modeled via a probability space (Ω, $\mathcal{F}$, P) in which a random number of vehicles (X) can be mapped as shown below,

$$(X : \Omega \to \mathbb{R}) \{\omega \in \Omega : (\omega) \leq n\} \in \mathcal{F} \quad \forall\, n \ \in \mathbb{R},$$

where the discrete random variable, X, is defined as $X : \Omega \to \{n_1, n_2, n_3, \ldots\}$, a set of finite and countable real values with the probability mass function (pmf)

$$P_x(n) = P(X = n), \quad n \in \mathbb{R}.$$

In order to address non-uniformity or the random nature of the process, a suitable model must be selected. The Poisson model accounts for random vehicle arrivals in any given period of time [29]. In this study, the Poisson process with a random variable, $\lambda \geq 0$, is selected to model the traffic arrival in which "X" number of vehicles arrives or passes through the 300 m area of roadway at a speed of 35 km/hr, represented by $X \sim P_x(\lambda)$ *with* $X : \Omega \to \{0, 1, 2, \ldots.\}$, given by the pmf of the Poisson process with λ, as

$$P_x(n) = \begin{cases} \dfrac{(\lambda t)^n e^{-\lambda t}}{n!} & 0, 1, 2, 3, \ldots \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

In the above expression, $P_x(n)$ is the probability of n vehicles arriving in a set time, and λ is the average arrival rate in vehicles per unit time. Therefore, the mean or expected value of X will be $E(X) = \mu_x = \sum x_i p_i$, while the variance being measured will be $V(X) = {\sigma_x}^2 = \sum (x_i - \mu_x)^2 p_i$.

B. Traffic Analysis

Data used to observe and estimate the arrival patterns and vehicle headway during the operational hours of the smart LED lights were collected using university CCTV cameras, and are summarized in Table I. The table shows the observed traffic i.e. number of cars during every hour divided into 120 time slots of 30 sec each.

In the table, a clear trend of traffic flow can be observed during the six hours of operation, both during the first three busy hours of 6 PM to 9 PM and the remaining three from 9 PM to 12 PM. Light traffic was observed between midnight and dawn, and occupied the roadway on an average of 25% of the time. To estimate the energy and savings for a complete day, the pattern was analyzed for variable traffic rates in the first six hours, whereas the lights were only operated for a quarter of the total time during the remaining seven hours. One can easily infer from the time headway data that the time gap between consecutive vehicles increases as the operational time of the lights advances.

The sample mean and variance of the randomly changing traffic is calculated using above mentioned equation to reflect the high degree of correlation for different times indicating the suitability of the Poisson distribution for the random traffic flow.

C. Statistical Analysis: Chi-Square Test

A mathematical model needs to be validated in order to ensure accurate mapping of a real mobility pattern. For this purpose, one approach compares the results of a theoretical model with measurement-based mobility patterns [19]. By adopting this approach, the inference that the theoretical distribution is the true population is made based on the parameters of mean (μ) and variance (σ^2). However, this inference is based on inspection. Therefore, in order to use the model and draw conclusions with confidence in further analysis, a more rigorous basis is needed [30].

The Pearson's chi-squared goodness-of-fit test is used to test the hypothesis that a given distribution is the true unknown distribution that has generated the sample. The value of the chi-squared test statistics can be calculated from Equation (2) as given below

$$\chi^2 = \sum_{i}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{2}$$

In the above equation, k represents the classes of data, O_i the observed values, and E_i the expected or calculated values. The decision to accept or reject the hypothesis is made on the basis of these test statistics.

Null Hypothesis (H_0): The traffic flow or number of arrivals in the given time follows a Poisson distribution, where the true distribution is the same as the postulated distribution.

Alternative Hypothesis (H_a): The true distribution is different from the postulated distribution, and does not follow the Poisson distribution.

The degree of freedom for the chi-squared goodness of fit, χ^2, is the independent choice to allocate the values to the expected frequencies and can be calculated from $k - r$, where r represents the number of constraints with the minimum value (always at least 1), and k is the number of classes. However, in a Poisson distribution with a known value of λ, one of the distribution's parameters reduces the degrees of freedom to $(k - r - 1)$, or $k - 2$.

TABLE II
GOODNESS-OF FIT TEST FOR TRAFFIC FLOW DATA

Time (pm)	Avg. Arrivals Per Interval (λ)	Number of Classes k	Degrees of Freedom $k-2$	Calculated χ^2	Critical $\chi^2_{(\alpha,k-2)}$
6-7	1.530	5	3	2.916	7.814
7-8	1.191	5	3	0.193	7.814
8-9	0.900	5	3	0.818	7.814
9-10	0.641	4	2	3.449	5.991
10-11	0.516	3	1	3.201	3.841
11-12	0.375	3	1	0.731	3.841

TABLE III
VEHICLES HEADWAY ANALYSIS

Time (pm)	Total traffic	P(h>30) sec
6-7	184	0.2158
7-8	143	0.3037
8-9	108	0.4070
9-10	77	0.5264
10-11	62	0.5965
11-12	45	0.6872

The analysis of goodness-of-fit for the data is shown in Table II. Referring to the table, the degrees of freedom and hence the chi-squared values are calculated using the observed values for each hour. However, the critical values of test, χ^2, [critical] for a 95% confidence interval or for a significance value of $\alpha = 0.05$ were taken from the standard chi-square chart.

The decision will be made on the basis of the following hypothesis test:

$$\left\{ \begin{array}{ll} \chi^2 < \chi^2_{(\alpha,k-r-1)}; & H_0 \; Accepted \\ \chi^2 > \chi^2_{(\alpha,k-r-1)}; & H_0 \; Rejected \end{array} \right\}$$

On the basis of the analysis presented in Table II, the data show a good fit between the observed and postulated Poisson distribution and we fail to reject the null hypothesis. It means that there is no evidence to indicate that true theoretical distribution differs from the postulated one.

D. Inter-Arrival Time/Vehicle Headways

The inter-arrival time among separate vehicles, also called the headway time, is an important microscopic parameter in this system. It defines the period of traffic-free time during which smart LED lights are controlled to conserve energy. The time can be modeled using the exponential distribution [31] and calculated using the Poisson distribution, which describes the times between events i.e. inter-arrival times, and the probability of n vehicles arriving in time t is given as

$$P_x\,(X = n) = \frac{(\lambda t)^n\, e^{-\lambda t}}{n!} \tag{3}$$

In the above equation, if no traffic is generated during time t $(n = 0)$, then $P\,(X = 0) = e^{-\lambda t}$, where λ is denoted as the inverse of the mean time headway and is involved in estimating the theoretical distribution. The cumulative probability function of the headway will be $P\,(h \leq t) = 1 - e^{-\lambda t}$, and the probability of a headway greater than t will be $P\,(h \leq t) = e^{\lambda - t}$. The results of headway analysis based on experimental time period are summarized in Table III. It can be seen from the table that the headway time ($h > 30$ sec) between vehicles increases almost linearly as the time advances, indicating an absence of traffic on the road.

V. HARDWARE DESIGN

The system is divided into two basic nodes, a source node and sink node. The source node is comprised of three boards: the LED driver, control, and sensor boards. The sink nodes contain the gateway module. The processor integrated in the central ZigBee radio communication module (RCM) module EM357 controls all the standard interfaces.

A. LED Driver Board

The LED driver board contains an HV9910B open-loop current mode control LED driver integrated circuit (IC), which enables both linear and PWM dimming of the LED current via voltage-based linear dimming or duty cycle control [32]. The designed LED board generates constant current for up to six LED modules. Each module consists of 7 × 4 white LED arrays that are connected to the driver board and wirelessly controlled using a remote interface through EM357 ZigBee modules. The remote operator uses information collected through sensors to efficiently control dimming of street lights. The dimming levels are duty cycled (0-100%) controlled PWM signals.

B. Control Board

The control board also contains the ZigBee RCM EM357 and ADE7753 multifunction IC, which integrates the temperature sensor and also performs power metering operations [33]. The multifunction ADE7753 was selected for its high accuracy, with a dynamic range of 1000 to 1 at 25 °C, and its on-chip temperature sensor and digital integrator, providing direct interface to current sensors. The control board is the main entity of the system, responsible for processing all information signals sent to and from LED luminaries. The control board connects sensors, LED drivers, and the ZigBee RCM, and manages signal flow among devices. It is also responsible for generating PWM signals for dimming control of the luminaries. The temperature sensor for monitoring internal temperature is mounted on the PCB, whereas the light sensor board can be connected to the I^2C port of control board. The control board is designed to incorporate diagnostic features in order to reduce debug time. In the case that the remote user is unable to observe the desired response in return to control commands, a serial port is available via the Controller to observe the signal flow. Observed data are compared with the data obtained wirelessly to fix known bugs.

C. Light Sensor

The light sensor contains BH1710FVC, a digital, 16-bit serial ambient light sensor IC to monitor light levels [34].

It was selected due to its capability to detect a wide range with high resolution (1 lx - 65535 lx). This illumination sensor is connected to the control board through the I^2C interface and lies outside the case to monitor the ambient light conditions. The integrated analog-to-digital converters (ADCs) are used to transform the sensed data to the I^2C digital output and send the results to the ZigBee RCM at regular intervals. It can be interworked with a control board or operated as a separate node by combining with an RCM, resulting in the option to deploy the light sensor node in a feasible location.

VI. Implementation and Results

The proposed smart LED lighting system is installed at the university sub street near the entrance to validate the design and to realize the offered benefits. During the deployment phase, 22 units of 140 W metal halide lamps were replaced by 70 W LED luminaires as depicted in Fig. 3. Replacement of the metal halide systems itself resulted in significant energy savings i.e. 50% in migrating from conventional system based on light lamps ratings; however, the real crux of this work is the traffic-flow-based smart lighting with maximum energy savings and reduced emissions.

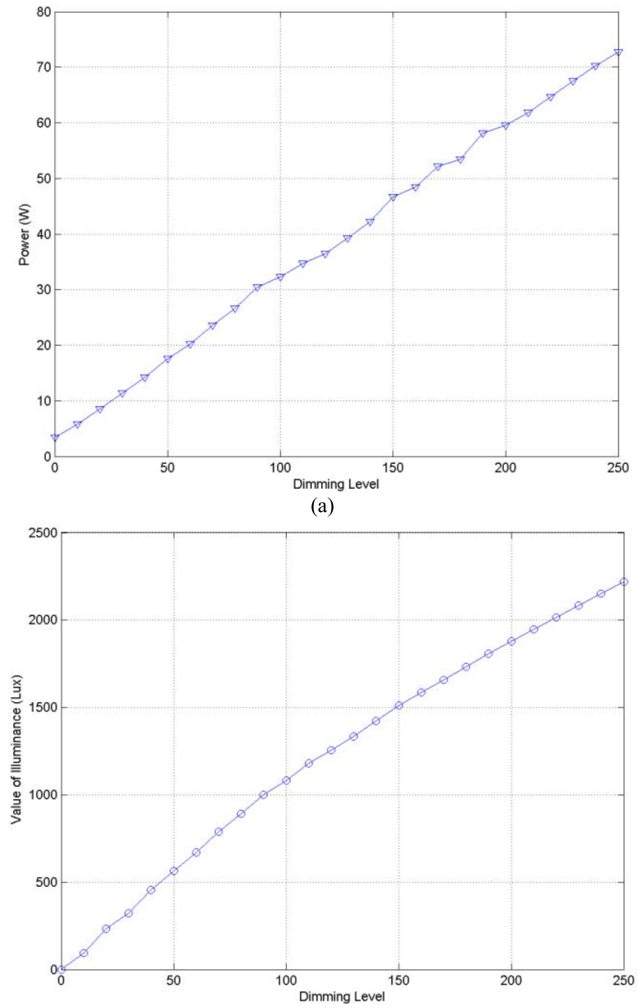
A. Network Reliability and Scalability

A real environment is composed of various obstacles, both man-made and natural, that lead to losses of signal strength and system vulnerability. For a ZigBee RCM with transmit power of 3 dBm/10 dBm and a 5 dBi gain antenna, a reliable operating range of 275 m/1 Km can be obtained in open space. Significant results were obtained in field hopping experiments, with acknowledged two-way messaging tests showing an average transmission delay of 400 ms with a packet error rate of less than 0.1% and a hopping depth of 20. These results suggest that a space radius of 2.0 km (100 m/hop□20 hops) can be covered with a single PAN if a ZigBee node is installed every 100 m to guarantee at least two nodes within its operating range. Therefore, the network is perfectly reliable for the current system, in which the installation of smart lights covers a distance of 300 m. However, a ZigBee WMN with an increased transmit power of up to 10 dBm and higher gain antenna could be a perfect fit for future systems, covering the longest path in the university campus featured in this study (1 Km) for smart lighting applications. Moreover, the network can easily be extended more efficiently in a distributed fashion for an urban scenario by adding clusters with separate PANs and gateways interfaced to a common data base. The distributed scalability of the network also addresses the issue of increased computation and communication overhead due to the addition of more routers, especially when the mobility is not an issue.

B. Power and Luminance Test

Time-dependent traffic flow and ambient-status-based dimming are primary features contributing to the energy efficiency of the smart lighting network, and are controlled by varying the current through the PWM based on power and luminance values. The correlation regarding regulation of dimming values with power and brightness control of the

Fig. 3. Metal halide lighting before implementation and smart lighting after implementation using LED smart luminaries assembled with developed hardware.



(b)

Fig. 4. (a) Power consumption at various PWM dimming levels. (b) Smart lights illumination (Lux) variation with various dimming levels.

luminaries is a critical parameter in smart lighting efficiency. Therefore, measurements were taken from both power and light sensors ICs using a Yokogawa (WT210) power meter and Tenmars (TM-203) lux/fc light meter. The data from both instruments were noted simultaneously to nullify unforeseen errors likely to occur with time differences. In light of the importance of illuminance sensors, readings were taken from five sensor boards instead of one. Experimental results are shown graphically in Fig. 4. Fig. 4 (a) illustrates a comparison of measured power between the power metering IC and power meter instrument directly attached to the smart LED luminary, while Fig. 4 (b) presents the brightness response of

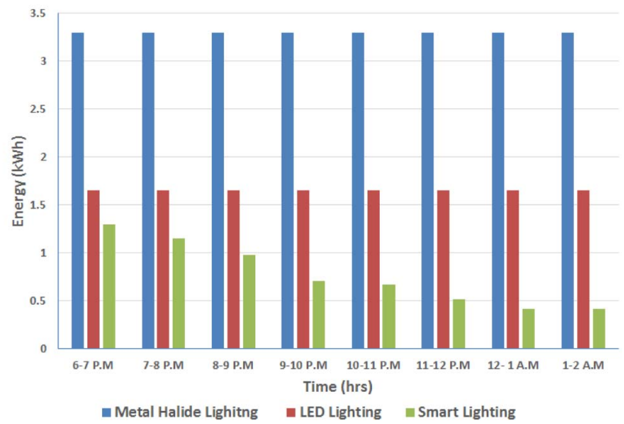


Fig. 5. Energy comparison analysis of metal halide system with LED lighting and smart adaptive control.

TABLE IV
ENERGY CONSUMPTION AND POWER SAVINGS OF A SINGLE DAY BASED ON SEASONAL DAY LIGHT TIMINGS

Month	*Avg.Power (Old System) (kWh)*	*Avg.Power LED (kWh)*	*Avg.Power Smart Control (kWh)*	*Power Saving (%)*
Jan	39.99	19.99	12.54	68.64%
Feb	40.35	20.17	11.37	71.81%
March	36.98	18.41	9.80	73.49%
April	33.21	16.60	8.04	75.77%
May	29.94	14.97	6.52	78.23%
June	28.16	14.08	5.68	79.80%

the smart luminaries to different values of pulse-modulated dimming. From the graphs, it is evident that both the power and brightness show similar responses to various values of PWM dimming control.

C. Energy Efficiency and Power Savings

In order to make a quantitative analysis of the energy savings and reduction in greenhouse gases, the smart LED lighting is compared with the conventional system being replaced. The smart lighting implements energy saving phenomena by switching LED lights to minimum power consumptions mode utilizing PWM dimming based on traffic flow. The minimum dimming value is set in accordance with the maintained average horizontal illuminance (lux) value for road type and pedestrian conditions as per recommendations of illuminating engineering society of North America (IESNA) to ensure pedestrian safety and security requirements [35]. The measurements show that the illumination of 7.6 lux (0.706364 fc) corresponds to minimum PWM dimming level of 20 and power of 8.5 W, equally satisfying the illumination requirements for streets and installed security cameras.

Based on the vehicle headway analysis presented in Table. III, it can be inferred that there is sufficient room available to smartly adjust the brightness level for energy conservation i.e., from 21% to 70% from sunset to midnight. While from midnight to dawn, the road is occupied for 25% of the time on average, allowing luminaries to operate with minimum illumination for 75% of the time.

Fig. 5 depicts the energy consumption analysis of old system with LED lighting and traffic-adaptive smart control for a single day. It can be clearly seen that smart adjustments of brightness based on traffic analysis for high and low traffic times, the smart lighting conserves a significant amount of electrical energy as compared to its conventional counterpart.

In order to account for the longest operating hours in winter to the shortest operation time in summer, the amount of average energy savings considering the same date with smart LED lighting from January to June is summarized in Table. IV. Referring to the table, it is evident that replacing old light bulbs with LED lights conserve the 50% energy for same lighting condition without any smart control and dimming. However, integrating smart wireless control and traffic-flow-based dimming saves a significant amount of energy, from 68% in winter to 80% in summer based on varying operating hours. The conserved energy also reduces hazardous gas emissions to a great extent, making the system more environmentally friendly, a critically important feature for future networks.

VII. CONCLUSION AND FUTURE WORK

The huge amount of energy and cost associated with lighting applications has driven the need to address both budget issues and environmental concerns. In this work, a smart, efficient LED lighting system is proposed and implemented, exploiting the unique opportunities of both LED and sensor and control technologies. Unlike previous works, a probabilistic approach followed by a statistical analysis of varying-time-based traffic has been considered to implement an optimal system. The system combines the additional benefits of LED technology, such as the use of a wireless control system for traffic-based dimming to conserve energy, at a savings of 80% over previously-installed metal halide bulbs. Increased reliability, enhanced system life, and reduced GHG emission are additional advantages of this system.

Since ZigBee is considered a potential candidate for AMI/DR platforms based on wireless senor networking technology with strong mesh capability [36], the proposed design utilises a remote operator, and can be extended in multiple ways. For example, to increase the transmit power with a high-gain antenna, widening the scope of the project to cover the entire campus, or to use a hybrid approach via ZigBee and PLC, where the propagation of RF signals among nodes to communicate wirelessly is unmanageable due to both natural and man-made obstacles. Utilizing essential components and basic infrastructure, the proposed system also facilitates the possibility of integration into future smart vehicle networks.

In future work, we intend to implement the proposed system on a larger scale, equipping vehicle detection sensors on the roadway to provide feedback to the smart controller for adaptive dimming; the ability to make decisions. We have already analyzed the reliability of the ZigBee mesh network for a long road (9 Km), where it is essential to continuously illuminate an unattended space, bridging the gap between the energy user and utility in order to minimize energy consumption for the benefit of users and the environment.

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