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A Wireless Communication Model for a Streetlight System

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***Abstract*—Streetlights have been previously designed with laborious and bulky wired connections. The demand for a simpler, more efficient, and yet cheaper alternative is on the increase in recent times. This paper presents a simulated wireless communication model of a more efficient and economical streetlight system integrated with visible light communication (VLC) for smart illumination and communication performance. The system uses LEDS for communication through illumination by modulating light in the visible spectrum (375-780) nm, in which by varying the light intensity, data is encoded in the light. This VLC setup combined with sensors and control units contributes to the system's smart illumination function. Considering a model main road in Afe Babalola University Ado-Ekiti (ABUAD); showing street light positions, vehicle lane and pavement, a model design of white LED lights and the received optical power are obtained, which were numerically analyzed and simulated using the MATLAB software, comparing vehicle lane length, width, and the distance between streetlights on the road. The results showed that better illumination and communication performances (in terms of received power) were observed when more streetlights are used for a smaller vehicle lane width at constant vehicle lane length.**

***Keywords*—Communication, Model, Simulation, Streetlight, Wireless Network.**

INTRODUCTION

Wired networks are starting to lose their importance in today's competitive world as the demand for quick and easy access to the internet, telecommunications, and other advanced technology that can help make our day-to-day activities easier grows, particularly the need for a more versatile system that saves cost. This has led to the preference of wireless communication networks over the conventional wired networks [1]. A situation that explains the reason for this preference can be represented using wired networks on streetlights which have been found to have the problems of have high installation and maintenance costs, high power usage, and trouble controlling and maintaining the streetlights. These problems can be solved by implementing the wireless communication on street light systems through visible light communication [2].

Wireless communication system is one of the most rapidly evolving and dynamic technical fields in the field of communication [3]–[6].

Wireless communication is a means of sending data from one location to another without the use of wires, cables, or any other physical medium. In conventional communication systems, information is transmitted from a transmitter to a receiver over a short distance but in wireless communication, transmitter and receiver can be located anywhere between a few meters (like a television remote control) and a few thousand kilometers (like in satellite Communication) [7], [8]. This is possible because the system uses electromagnetic waves such as radio frequency, infrared rays, etc. to transfer information from one point to another through free space, which makes the system easily accessible from anywhere, at any time. Mobile phones, remote controls, Bluetooth, and Wi-Fi, etc. are some examples of the most widely used wireless communication systems in our daily lives [9].

A. Intelligent Street Lighting

Intelligent street lightning is a type of public illumination that responds to the movement of people, cyclists, and automobiles. When no activity is detected, it dims, but when movement is detected, it brightens to a specified illumination level (depending on the time of the day). It provides a cost-effective approach to controlling metropolitan street lighting. Taking the ever-increasing energy prices into consideration, energy-saving technologies are required for metropolitan lighting. For instance, work has already commenced in Sheffield to replace all its 68000 streetlights with white LED lights [10]. These white LED lights can be remotely brightened and dimmed street by street or lamp by lamp. It also gives a significant reduction in glare making the city brighter and safer. These LEDs are expected to reduce energy consumption by 40 percent and would last for 25 years giving them a significant edge over the present bulbs that have to be replaced every 4 years. Also, if a 50 percent reduction in the power consumed by the around 4.4 million streetlights in ten major US cities can be achieved; around 1.5 billion kWh of electricity would be used annually compared to the around 3 billion kWh being used. Since streetlights account for about a third of a city's electricity bill, it's among a city's most expensive assets. In Intelligent lightning systems, the light intensity of the lamp is optimized using the most recent technologies. Also, the lamps can be accessed and even controlled remotely.

Intelligent lighting has numerous benefits some of which includes reduction in energy cost, reduction in green house emission, reduction in maintenance costs, increased community satisfaction since the lamps are automated, there would be less complaints from the community about spoilt lamps as issues can be dealt with at the appropriate time [11], [12].

B. LED Street Lighting

LED street lighting refers to streetlights with an integrated light-emitting diode (LEDs) for illumination. This technology which is now in use brings significant improvement to streetlight quality as it reduces glare, allows for better color rendering, and offers energy saving of around 52 percent and 26 percent when compared to Mercury vapor1 HID and Sodium HID respectively. LEDs are also beneficial as they have a lifetime of around 60000 hours (10 to 15 years). This long-life span makes up for the initial set-up cost as the cost can be compensated for between four and six years [3], [13]. Also, the inherent dimming property of the LED chip reduces the cost of adding an additional dimming circuit to the installation. Therefore, LED Street lighting technology is presently regarded as the best solution to the shortcomings of traditional metropolitan street lighting. In addition to the LED light, a remote management system is required so that each LED lamp post can be accessed and controlled separately. Technologies such as GPRS, Power Line Communication (PLC) or GSM can be employed to achieve this process of remote management. Renewable sources of energy (i.e. solar energy) can also be introduced to each lamp post so as to further reduce maintenance costs and environmental pollutions [14]–[16].

C. Visible Light Communication (VLC)

Although wireless communication using radio frequency is one of the leading means of communication, interference, and high latency problems plague radio frequency (RF) communication. Another disadvantage of RF communication is that it requires a separate setup for RF wave transmission and reception. These problems can be avoided by using Visible Light Communication (VLC) as it has high bandwidth and sensitivity to interference from electromagnetic sources [17]. Visible light communication is a subset of optical wireless networking technologies that uses visible light for communication by modulating light in the visible spectrum shown in Figure 1.

This form of communication occupies between 400 and 800THz (780–375 nm) of the electromagnetic spectrum, because of the wide bandwidth available in VLC as shown in figure 1, thus the low bandwidth problem in RF communication is solved [18].

In Illumination systems, the visible light communication (VLC) technology has brought about new opportunities that allows for energy savings and reduction in maintenance costs[19]. Recently, Light emitting diodes (LED) devices used for VLC technology are rapidly replacing traditional illumination devices due to the numerous advantages they offer and their usefulness as information broadcasters [20], [21]. Unlike incandescent and fluorescent light bulbs which send information as a result of their thermal inertia, visible light waves are used to modulate information in LEDs which is achievable since at moderate frequencies, LEDs - as solid state devices – can switch between the off and on states [19]. This is one major advantage of VLC as it can be used for both illumination and communication purposes. With the above benefits in mind, VLC is one of the most promising candidates due to its non-licensed networks, high bandwidth, and low power consumption [17]. Although streetlights may not be on or at full illumination intensity during the day because there is no need for an artificial light source since the sun illuminates the atmosphere at this time, it can still perform the communication function when the streetlights are dimmed low enough such that the streetlight appears to be off. Hence their usefulness is maximized at night where they can be used for both illumination and communication [22]. An example is a scenario where street lights are required at night to illuminate streets for all road users, but they are also required to function as VLC transmitting and receiving antennas [23]. In a nutshell, this system provides an intelligent solution to street lighting system where the system not only provides illumination but also effective communication. Due to its unidirectional communication principles, visible light communication requires additional wireless communication technology.

The ZigBee and Wi-Fi wireless communication networks would be a good candidate for LED street lighting system considering the range they cover [24]. Most street lighting systems have more than 10m separation which makes the Bluetooth technology inadequate. Though the ZigBee technology is preferable while considering cost the entire system would stop being operational if three consecutive lampposts communication device becomes faulty.

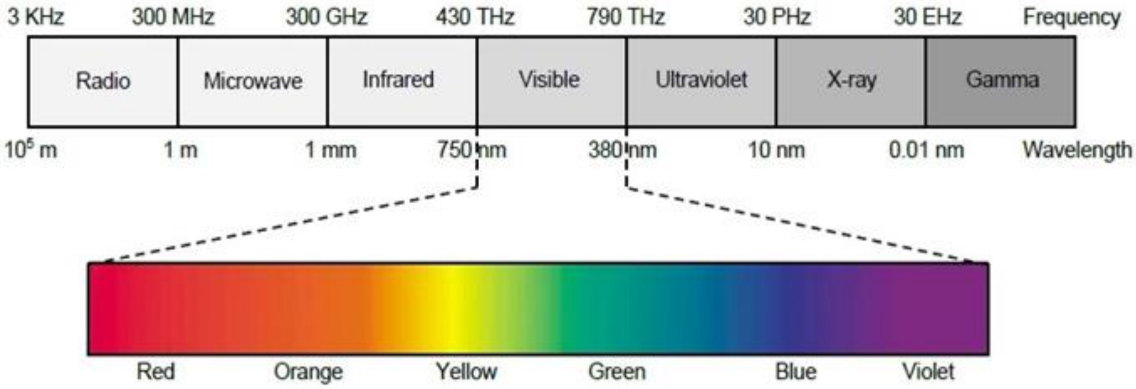

Figure 1: Visible light spectrum[17].

This makes the Wi-Fi technology the most reliable for LED street lighting as it is more flexible and more accessible to vehicles and pedestrians [16], [25]–[27].

Due to the huge cost of energy especially electricity, efficiency can be one ogisf the main ways to save energy in the world. Since lighting consumes around 20% of the world's total electrical energy with street lighting contributing a great amount to this percentage, applying efficient lighting can save lots of energy. Hence, an efficient technology such as wireless communication to control streetlights is introduced which features effective and autonomous operation of lighting for pedestrians, cyclists, and drivers to carry out late night activities safely, to reduce energy waste and environmental conservation. The study aimed at modelling and simulating wireless communication on street light system which targets the energy saving and autonomous operation of the streetlights. The objectives of the study were to model a wireless system used to control streetlights, simulate the designed model, analyse, and evaluate the simulated model.

RELATED WORKS

An indoor visible light communication system to improve uniformity in terms of high received power, signal-to-noise ratio (SNR), and bit rate, with RMS delay spread reduction has been proposed by [28]. It features a novel model that utilizes a 13-optical attocells configuration on the ceiling. This model was evaluated at different semi-angle at half power. The average received power and SNR were improved to 2.85 dBm and 75.5 dB, while achieved received power and SNR levels at the center of the room were 4.92 dBm and 79.5 dB, respectively. A minimum average RMS delay spread of 0.4749 nanoseconds was obtained, while the highest average bit rate calculated is 211 Mb/s..

Umar et al., proposed a cloud-based energy sufficient smart street lighting system in Pakistan which was able to revolutionize the traditional street light system particularly the areas with low traffic and pedestrian frequency.

The proposed system uses an Arduino and its various shields based on a movement-based actuation system like Light Detection and Ranging (LiDAR). This design is executed and implemented on a one-way road. Thus, by using the concept of LiDAR and Arduino sensor this system was made with which is highly efficient and reduces power consumption and helpful in overcoming the CO_2 emission. The power consumption is reduced by 99.01325 % in the best-case scenario [27], [29].

In 2021, Ngu et al., gathered public insights through a quantitative research approach in Malaysia and applied the information gathered in proposing a prototype model that demonstrates how a smart street lighting system can achieve optimal performance by embedding the street lighting system with IoT technology [30].

Utama et al., proposed and designed a smart street lighting with data monitoring to optimize the use of the streetlamps. The system checks the sunlight brightness condition to determine when the system will start workingsince it is not needed on daytime. The sidewalk and vehicle sensors start working on nighttime, checking the pedestrian and traffic condition. If any vehicles on the street or any activities on the sidewalk are detected, then the closest streetlamp will be at its maximum brightness level. The farther from the detecting sensors they are, the lamps will be dimmed or turned off completely. Information on the public street condition can be monitored using a smartphone application. The application also displays temperature and humidity of the surrounding area, which is useful for the public street management. The result proves that the smart street lighting system works exactly as designed and required[29], [31].

Saleheen et al[32]., develop a smart street light system which glows when the vehicle or pedestrian enters the certain point of the road and make the light be in OFF/Dim position when it is not required. An illustration consisting of a transmitter and a receiver are made to accomplish the goal. The proposed system can turn ON the lights while nightfall and OFF the lights detecting the appearance of daylights.

The system is incorporated with a speed measuring section to reduce rash driving while the road has relatively low traffic density. Compared to the conventional street light system, this streetlight can reduce redundant energy consumption as well as reckless driving tendency.

In 2021, Fuada et al.[33] designed an IoT-based smart street lighting system using ESP8266 configured as a Mesh network. The ESP8266 was programmed to control the light level by producing a PWM signal, then it sends a dimmer value and reads the sensor's data. The system can be accessed wirelessly via a web server. The overall system was successful as a smart street lighting system in a wireless Mesh environment.

In 2019, Song et al.[34] developed a 24GHz millimeter wave smart radar for intelligent street lighting system. The developed radar operates at a frequency of 24GHz with 200MHz bandwidth and CW (continuous wave) mode. The two radars are used to cover the street in both directions and detect obstacles moving at the speed of more than 1 km/h including moving pedestrians. The radar detection controls the street lighting. Therefore, the energy-saving performance has been improved because the proposed smart lighting system works only when obstacles around the streetlight exist.

METHODOLOGY

A typical main road with streetlights located along the pavement is depicted in Figure 2. For analysis purposes, there was an assumption of using a straight lane, which results can be used to predict the condition for a non-straight road network. Also, it was assumed that the LEDs are pointed vertically downwards, and the receiver is pointed vertically upwards.

To model the street light communication system, mathematical expressions representing the design of white LED lights and the received optical power were first obtained, and thereafter numerically analysed and modelled using the MATLAB software.

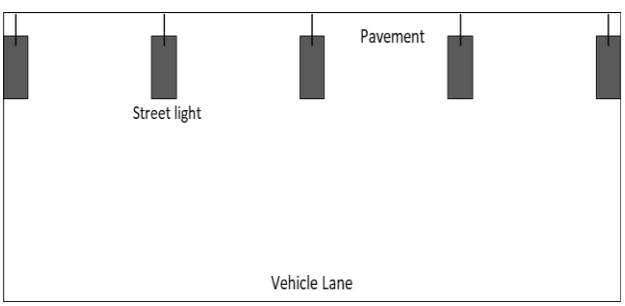

Figure 2: A model main road showing street light positions, vehicle lane and pavement.

A. White LED Light Design

A transmitted optical power and a luminous intensity are the two basic properties of LED lights. The energy flux per solid angle is described by the luminous intensity and it also shows how bright an LED is. The total energy emitted from the LED is also described by the transmitted optical power using [20]. The luminous intensity was defined with equations (1) and (2).

$$I = \frac{d\Phi}{d\Omega} \qquad (1)$$

where Ω = Spatial angle and Φ = Luminous flux.

$$\Phi = K_m \int_{380}^{780} V(\lambda)\Phi_e(\lambda)d\lambda \qquad (2)$$

where Φ_e = Energy Flux, $V(\lambda)$ = Standard luminosity function (i.e. 0.999997 at 555.016nm). Now, in all directions the transmitted optical power, P_t is the integral of the energy flux and it is represented by equation (3).

$$P_t = \int_{A_{min}}^{A_{max}} \int_0^{2\pi} \Phi_e d\theta d\lambda \qquad (3)$$

where the sensitivity curve of the photodiode is used to determine A_{max} and A_{min}.

The illuminated surface brightness is described by the illuminance. From the angle point of view, the luminous intensity ϕ is defined in equation (4), while the horizontal illuminance, E_{hor} at the point(x, y), is defined in equations (5) and (6).

$$I(\phi) = I(0)cos^m(\phi) \qquad (4)$$

$$E_{hor} = \frac{I(0)cos^m(\phi)}{D_d^2 cos(\psi)} \qquad (5)$$

$$m = \frac{-ln2}{\ln(cos\Phi_{1/2})} \qquad (6)$$

where $I(0)$ = LED Center luminous intensity, m = Order of Lambertian emission (i.e. the directivity of the radiation pattern), $\Phi_{1/2}$ = Transmitter semi-angle at half power, ϕ = Irradiance angle, ψ = Incidence angle, D_d = Distance separating an LED from a detector surface.

B. Received Power of Directed Light

Considering an optical link using LEDs, the average received optical power,

$$P_r = H(0)P_t \qquad (7)$$

where $H(0) =$ Channel DC Gain. In conventional (surface-emitting) LEDs, the radiation model can be approximated as Lambertian (i.e. meaning that LEDs have a large beam divergence causing the radiation pattern resemble a sphere) thus obeying Lambert's cosine law (i.e. stating that the light "intensity is proportional to the cosine of the angle from which it is observed" [28]). In a typical indoor setting, the average received optical power is given by contributions from the received power from the directed light and the received power from the reflected light. For a directed light, the Channel DC gain;

$$H(0) = \begin{cases} \frac{(m+1)A}{2\pi D_d^2} cos^m(\phi)T_s(\psi)g(\psi)cos(\psi), & 0 \le \psi \le \psi_c \\ 0, & \theta > \psi_c \end{cases} \qquad (8)$$

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2\psi_c}, & 0 \le \psi \le \psi_c \\ 0, & \psi > \psi_c \end{cases} \qquad (9)$$

where $A =$ Photodetector (PD) physical detection area, $\phi =$ Angle of irradiance, $\psi =$ Angle of incidence, $D_d =$ Distance separating the transmitter from the receiver, $T_s(\psi) =$ Optical filter's signal transmittance (i.e. the optical filter gain), $g(\psi) =$ Gain of concentrator (i.e. the lens gain), $n =$ Refractive index and $\psi_c =$ Receiver's concentrator field of view (FOV).

Results And Discussion

The simulated results for the distribution of illuminance and received power obtained from the analysis of the mathematical expressions using a constant vehicle lane length of 30m, vehicle lane widths at 6m and 10m, and distance between the streetlights at 7.5m and 15m respectively are presented and discussed. The parameters used in the analysis is as shown in Table I. These parameters were used for the analysis based on their capability to give acceptable system performance.

TABLE I
Parameters Used for the White LED Streetlight Analysis

Parameters	Values
Transmitted optical power per LED chip	1W
Semi-angle at half power	70^0
Centre luminous intensity	0.73
Transmitter height	6m
Receiver height	1.5m
Number of LEDs per LED light	504(14×36)
LED interval	0.02m
Size of LED light	0.26×0.7m
Detector area of a PD	$1.0cm^2$
FOV at a receiver	70^0
Gain of an optical filter	1.0
Refractive index of lens at a PD	1.5
O/E conversion efficiency	0.53A/W

A. Distribution of Illuminance

The distribution of illuminance for the white LED Street light is shown in Figure 3 where the vehicle lane width is 6m, thevehicle lane length is 30m and the distance between the streetlights is 7.5m. As shown in Figure 3, the minimum illuminance is around 9 lx and the maximum illuminance is around 20 lx. The distribution of illuminance for the white LED Street light is shown in Figure 4 where the vehicle lane width is 10m, thevehicle lane length is 30m and the distance between the streetlights is 7.5m. As shown in Figure 4, the minimum illuminance is around 3 lx and the maximum illuminance is around 20 lx. The distribution of illuminance for the white LED Street light is shown in Figure 5, where the vehicle lane width is 6m, thevehicle lane length is 30m and the distance between the streetlights is 15m. As shown in Figure 5, the minimum illuminance is around 5 lx and the maximum illuminance is around 19 lx. The distribution of illuminance for the white LED Street light is shown in Figure 6 where the vehicle lane width is 10m, thevehicle lane length is 30m and the distance between the streetlights is 15m. As shown in Figure 6, the minimum illuminance is around 2 lx and the maximum illuminance is around 19 lx.

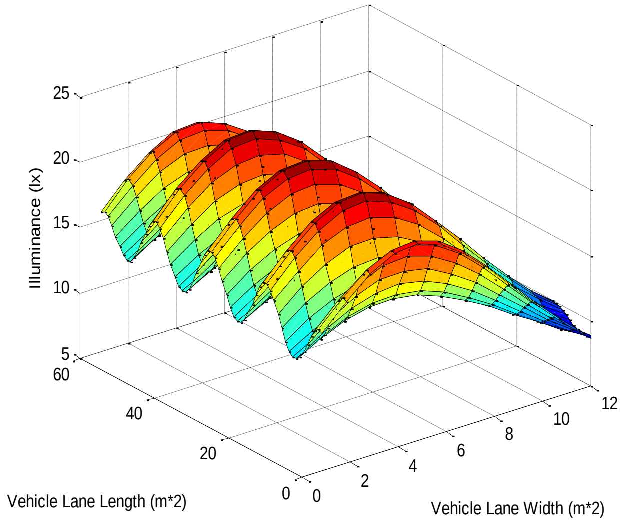

Figure 3. Distribution of Illuminance in lx (Vehicle Lane length = 30m, Vehicle Lane width = 6m, Distance between streetlights = 7.5m)

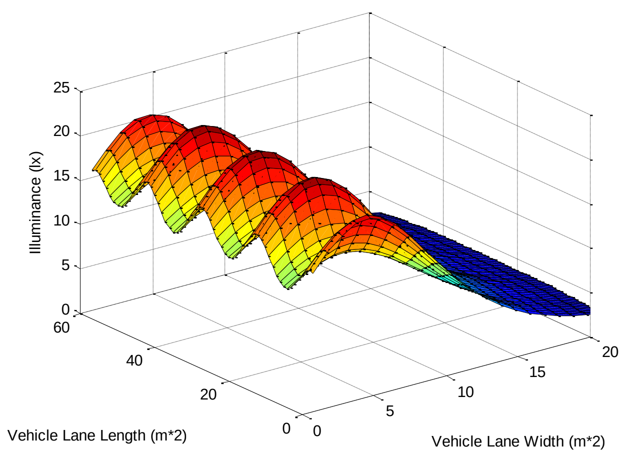

Figure 4: Distribution of Illuminance in lx (Vehicle Lane length = 30m, Vehicle lane width = 10m, Distance between street lights = 7.5m).

B. Received Power

The distribution of received power for the white LED Street light is shown in Figure 7 where the vehicle lane width is 6m, thevehicle lane length is 30m and the distance between the streetlights is 7.5m. As shown in Figure 7, the minimum received power is around -1.5dBm and the maximum received power is around 2.5dBm.

The distribution of received power for the white LED Street light is shown in Figure 8 where the vehicle lane width is 10m, thevehicle lane length is 30m and the distance between the streetlights is 7.5m. As shown in Figure 8, the minimum received power is around -7dBm and the maximum received power is around 3dBm.

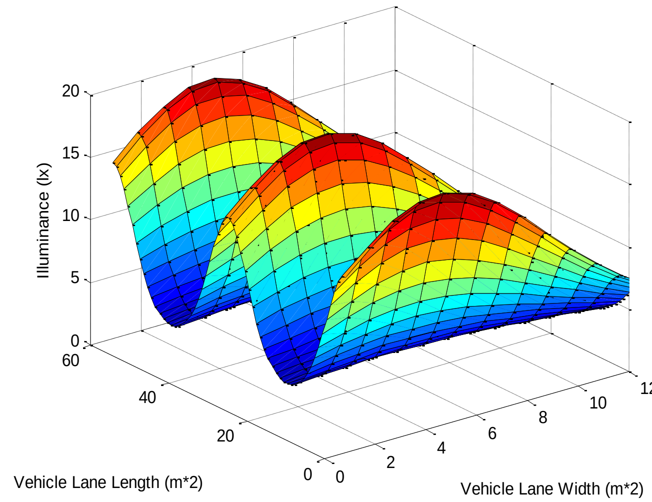

Figure 5:Distribution of Illuminance in lx (Vehicle Lane length = 30m, Vehicle Lane width = 6m, Distance between streetlights = 15m).

The distribution of received power for the white LED Street light is shown in Figure 9 where the vehicle lane width is 6m, thevehicle lane length is 30m and the distance between the streetlights is 15m. As shown in Figure 9, the minimum received power is around -6dBm and the maximum received power is around 2.5dBm. The distribution of received power for the white LED Street light is shown in Figure 10 where the vehicle lane width is 10m, thevehicle lane length is 30m and the distance between the streetlights is 15m. As shown in Figure 10, the minimum received power is around -11dBm and the maximum received power is around 2dBm.

The results considering a fixed vehicle lane length of 30m are summarized in Table II. The distribution of illuminance and the distribution of received power showed better results when there are more streetlights, and the vehicle lane widths are smaller. Additionally, the distribution of illuminance and the distribution received power showed worse results when there are fewer streetlights, and the vehicle lane widths are wider.

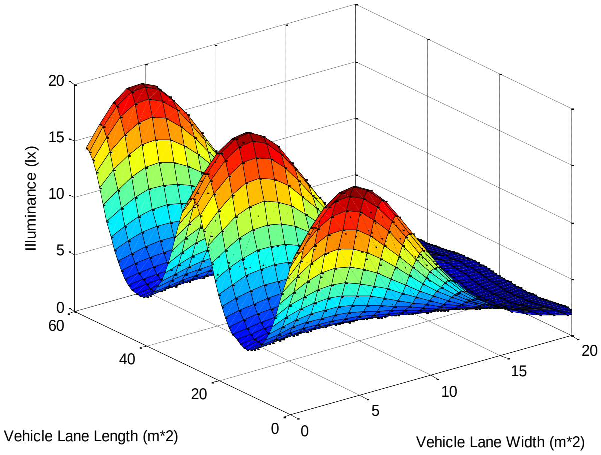

Figure 6: Distribution of Illuminance in lx (Vehicle Lane length = 30m, Vehicle Lane width = 10m, Distance between street lights = 15m).

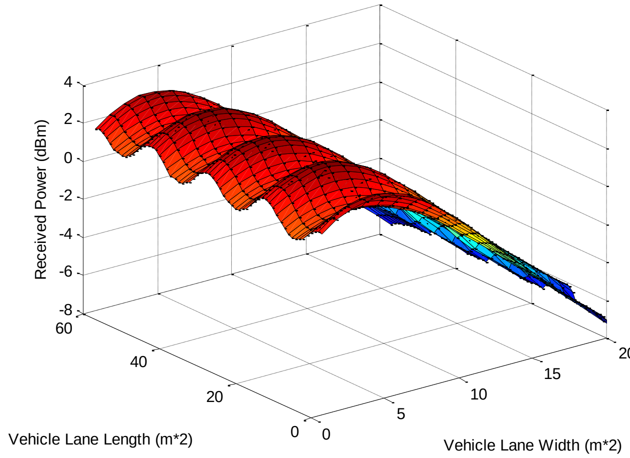

Figure 8. Distribution of received power. (Vehicle lane length = 30m, Vehicle Lane width = 10m, Distance between streetlights = 7.5m).

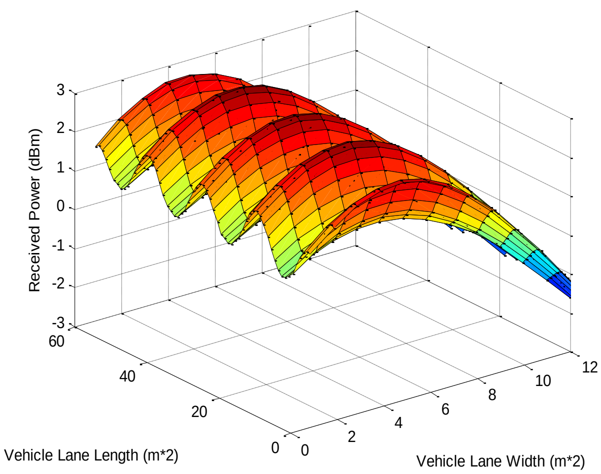

Figure 7. Distribution of Illuminance in lx (Vehicle lane length = 30m, Vehicle lane width = 6m, Distance between street lights = 7.5m).

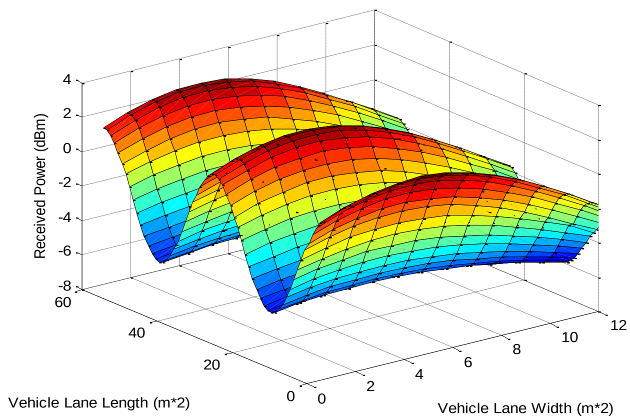

Figure 9: Distribution of received power. (Vehicle lane length = 30m, Vehicle lane width = 6m, Distance between street lights = 15m).

TABLE II
SUMMARY OF RESULTS

Vehicle Lane Width. (m)	Distance Between Street Lights. (m)	Min. Distribution of Illuminance(lx)	Max. Distribution of Illuminance (lx)	Min. Received Power (dBm)	Max. Received Power. (dBm)
6	7.5	9	20	1.5	2.5
10	7.5	3	20	-7	3
6	15	5	19	-6	2.5
10	15	2	19	-11	2

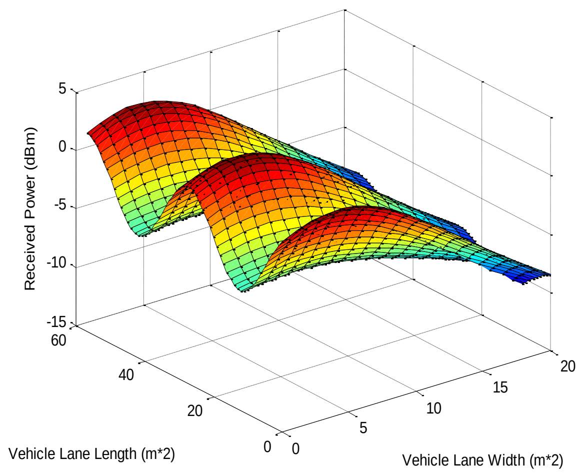

Figure 10: Distribution of received power. (Vehicle lane length = 30m, Vehicle Lane width = 10m, Distance between streetlights = 15m).

CONCLUSION

A model for a wireless communication on the streetlight system has been established by this study to combine visible light communication with WI-FI. The study focuses on the distribution of illuminance and received power obtained for a fixed vehicle lane length, while varying vehicle lane width and distance between streetlights.The distribution of illumination and the distribution of received power shows that the LED lighting is appropriate for street lighting and communication purposes. Hence, this system is achievable and could bring improvements in major research areas such as energy efficient lighting, human health, and others. Thus, by combining VLC with WIFI, an extremely efficient, low-power street lighting, simple to maintain system which has a high data transmission rate is achievable.It is recommended that further research and implementation of this system should be carried out for easy control of streetlights. Also, researchers should concentrate on designing a hybrid system for seamless integration of VLC to reduce the size and cost of systems and for further simplification and optimization. Further studies should implement hybrid integration with other wired and wireless technologies, and the utilization of space-division multiple access to operate several optical wireless lines in parallel as an internationally coordinated approach on standardization which is becoming increasingly crucial to develop the ecosystem required for the future spread of this technology.

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