

ILLUMINATE - VIsibLe Light CommUnication enabled SMart Indoor lightiNg And control SysTEm

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Abstract— In India, as per the Bureau of Energy Efficiency (BEE) report for the year 2020-21, building sector contributes to 34% of total electricity consumption and is predicted to rise 3 fold by 2032. Energy consuming devices in commercial buildings includes lighting, heating, ventilation and air conditioning (HVAC), and other auxiliary equipments. Lighting accounts for 20% to 40% of total energy consumption in buildings. Lighting control plays a major role in reducing the energy consumption. Most of the commercial wireless lighting control solutions available in the market use Radio Frequency (RF) for communication. Visible light communication (VLC) is an eco-friendly green optical wireless communication technology that combines illumination and communication thereby saves energy and reduces carbon footprint. This paper addresses the limitations of the existing RF based solutions and proposes an indoor lighting control solution using VLC for RF free zones.

Keywords— Green Communication, Lighting Control, Line of Sight, Occupancy Control, Visible Light Communication

I. INTRODUCTION

In India, as per the Bureau of Energy Efficiency (BEE) report for the year 2020-21, building sector contributes to 34% of total electricity consumption [1]. For developing countries like India, with rapid urbanization and growth in building infrastructure, demand for energy in buildings will increase many folds. Energy consuming devices in commercial buildings includes lighting, HVAC and other auxiliary equipments. Indoor lighting in buildings is classified into natural and artificial lighting. Artificial lighting in offices consumes more energy and accounts for 29%–35% of the overall energy demand of the building [2].

Lighting control plays a major role in reducing energy consumption. Some of the lighting control mechanisms include (i) ON/OFF control based on occupancy state, (ii) time based scheduling that turn off or dim the lights at set times of the day, (iii) daylight harvesting that adjust the brightness level in response to the ambient light levels, (iv) user preferred light settings that allows individual to control the lights through web/mobile and (v) demand response control that automatically reduces the consumption during peak hours. Lighting control can be centralised or distributed. By reducing the light ON interval or intensity, lighting controls reduces energy consumption thereby reduces the cost.

Lighting control can be wired or wireless control. Wired lighting control solutions use power line communications (PLC) and Digital Addressable Lighting Interface (DALI). Most of the commercial wireless lighting controls solutions available in the market are based on RF. Wireless communication protocols such as ZigBee [3] and LoRa [4] are used for lighting control in indoor and outdoor environment. Electromagnetic (EM) spectrum consisting of gamma rays, X-ray, ultraviolet (UV) rays that are harmful to humans, whereas IR ray is dangerous to eyes and can be used only with low power levels. Other EM spectrums like visible and IR spectra are relatively safe for human health when compared with radio and microwave frequencies [5-6].

Visible Light Communication is an Optical Wireless Communication (OWC) technology that utilizes unlicensed optical spectrum. VLC combines illumination and communication hence it is energy efficient and reduces the carbon footprint. Optical wireless transmission through visible light is safe for human health as human bodies are transparent to radio waves and not to visible light. Due to harmless EM radiation and energy efficient system, VLC is an eco-friendly green communication technology. VLC does not interfere with the RF emissions from navigation equipment, control systems, and medical devices. VLC is suitable for applications where sensitive electronic devices are used, such as in hospitals, chemical plants, and airplanes [7].

Due to the above mentioned issues with RF and with the advantage of VLC, lighting control using VLC for use in RF free zones has been developed.

Rest of the paper is organized as follows. Related work and limitations of existing indoor lighting control system are discussed in Section 2 and Section 3 respectively. Section 4 and 5 describes the proposed system and its results. Section 6 concludes and discusses on the future work.

II. RELATED WORK

Several researches have been carried out in the development of smart lighting control system by utilizing daylight harvesting [8-9] and occupancy sensing [10-12]. Luminaires are not only turned ON/OFF based on the occupancy state but their illuminance level is also controlled [10-11, 13-14] based on the measured illumination levels. Wireless communication technologies such as Wi-Fi [12],

Zigbee [10-11, 19-21] and LoRa [15-18] are used by researchers for controlling the lights in an indoor and outdoor environment. Zigbee and Wi-Fi communication have been used for smart home and office lighting control whereas LoRa has been used to control street lights in an outdoor environment. [22] briefs about a wireless lighting system simulated using proteus software to troubleshoot fault in the power supply and fault due to damage in the AC lamp has been realized with the aid of a current sensor and a Light Dependent Resistor (LDR).

Few researchers [23-26] have worked in lighting control through visible light communication. Intelligent lighting system using VLC that saves energy and provides the desired illuminance based on the information from mobile light sensors was proposed in [24]. Green energy based highway lighting system has been discussed in [25]. [23] analyses the packet error rate and system performance through simulations and experiments. Authors in [26] proposed a networked lighting control system based on VLC that adapts to daylight and occupancy changes and presented the simulation results.

Unique features of the proposed system are as follows

- Quad directional full duplex communication using VLC to communicate with adjacent luminaires on all 4 sides
- RF free indoor lighting control
- Zone based distributed control based on user preference

III. LIMITATIONS OF EXISTING LIGHTING CONTROL SOLUTIONS

Limitations of existing RF based lighting control solutions available in the market are as follows:

A. Visual Discomfort due to Passive Infrared (PIR) Snoozing Effect

Limitation: Most of the commercial lighting control solutions use PIR sensors for occupancy sensing. PIR detects the occupancy whenever there is a change in the infrared radiation. PIR sensors may sense unoccupied even if there is very little movement. This phenomenon is referred to as snoozing effect. Because of PIR snoozing effect, lights may be turned off and on frequently that leads to visual discomfort.

Solution: To avoid this, occupancy based zone control using VLC has been proposed. Lights are grouped in zones and are turned off only when all the lights in a zone sense unoccupied.

B. Energy Efficiency Gap in Communication Technologies

Limitation: Lighting control devices are energy efficient but still there exists an energy efficiency gap in the communication technologies. Information and Communication Technologies (ICT) contribute 2% to 2.5% of global emission of the Green House Gas (GHG) [5]. Energy consumption of communication devices has impact on electricity generation which in turn affects GHG and carbon footprint.

Solution: Proposed system addresses the issue by utilising visible light for communication. VLC, a green communication technology [27] is energy efficient as it utilizes illuminating

energy for communication. Usage of energy efficient VLC not only reduces energy consumption but also reduces the emission of GHG.

C. Lighting Control Solution for RF Free Zones

Limitation: Most of the commercially available indoor lighting control solution uses RF based communication and hence not suitable for use in RF free zones. As discussed in [28] use of RF-based wireless technologies is not feasible and/or not desirable in (i) areas (eg. mines, petrochemical plants, and oil rigs) where there is a risk of explosions, (ii) environments (eg. nursery schools) where RF technologies may raise some health concerns, (iii) spaces (eg. airplanes and hospitals) with equipment that requires isolation from electromagnetic interference (EMI).

Solution: VLC utilizes the optical spectrum which is unlicensed, non-hazardous part of Electro Magnetic (EM) energy for wireless communication. Hence proposed VLC based lighting control solution has minimal impact on user's health. It is also suitable for use in RF restricted areas.

IV. PROPOSED SYSTEM

A. Overall Architecture

VLC enabled luminaires are fixed on the ceilings. Visible light is used as a medium of communication between the adjacent luminaire. Architecture of the proposed system is shown in Fig 1.

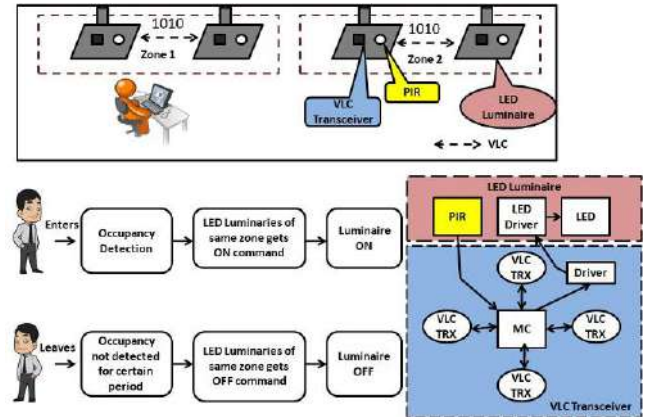


Figure 1. Architecture

In addition to illumination LEDs, each luminaire consists of a VLC Transceiver module. VLC transceiver consists of a microcontroller, occupancy module, communication module and a driver module to control the illumination LEDs.

VLC requires line of sight to establish communication between the adjacent luminaire on all the four sides. A quad directional full duplex VLC transceiver has been designed with 4 communication LEDs that acts as a transmitter and 4 photo detectors that acts as a receiver. Luminaires are grouped into zones based on user preferences. VLC Transceiver is designed with adjustable slits for enabling zone control.

Luminaires are controlled through visible light based on the occupancy state. Upon detection of occupancy by any

luminaire in a zone, all the luminaires under the zone are turned ON. Upon detection of non-occupancy state, a luminaire will be turned OFF only when all other luminaire in a zone are non-occupied.

B. VLC Transceiver

VLC Transceiver module consists of communication module, occupancy module and luminaire control module. All these modules are interfaced with GPIO pins of AVR based microcontroller (MCU). Overall block diagram of VLC controlled luminaire is shown in Fig. 2.

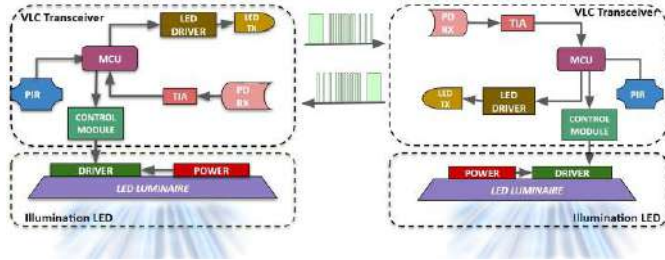


Figure 2. Overall Block Diagram

1) Occupancy Module: Occupancy is sensed using PIR sensor. PIR with 110° horizontal detection angle, 93° vertical detection angle and 10 m detection type is used.

2) Communication Module: Communication module consists of VLC transmitter and receiver as shown in Fig 3.

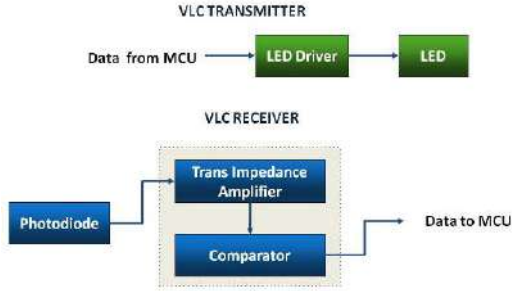


Figure 3. Internals of VLC Transceiver

VLC Transmitter: VLC transmitter consists of LED driver and a communication LED. Driver provides the necessary voltage and current for the operation of LED. Specifications of communication LED used in the proposed system are shown in Table 1. Microcontroller module generates commands based on the occupancy state. Generated command is sent to the LED through the driver. LED transmits the command to the receiver module of adjacent luminaires grouped under the zone through visible light.

TABLE 1. SPECIFICATIONS OF COMMUNICATION LED

Parameter	Value
LED Type	5 mm
Wavelength	631 nm
Forward Current (I_F)	50 mA
Forward Voltage (V_F)	3 V

Angle of Half Intensity (ϕ)	$\pm 4^\circ$
Luminous Intensity (I_v)	65 cd

To achieve more focussed beam, conical reflector as shown in Fig 4 has been designed and 3D printed with an apex angle of 10°. All the dimensions mentioned in Fig 4 are in mm.



Figure 4. Design of LED Reflector

VLC Receiver: VLC receiver consists of photodiode, trans-impedance amplifier (TIA) and a comparator. At receiver side, to decode the data, the following steps are performed:

- Photodiode converts the incident light (data) into corresponding current
- TIA converts the photo diode current to voltage
- Comparator converts the voltage into microcontroller readable voltage level

Specifications of photodiode used in the proposed system is shown in Table 2

TABLE 2. PHOTODIODE SPECIFICATIONS

Parameter	Value
Reverse Voltage (V_R)	32 V
Half angle (ϕ)	60 °
Radiant sensitive area (A)	7.02 mm ²
Rise Time (t_r)	0.02 μ s
Dark Current	2 nA
Wavelength of max. Sensitivity ($\lambda_{S_{max}}$)	920 nm

Photodiode is designed to operate in photo voltaic mode. Dual/Quad op-amp is used for TIA and comparator. Output voltage from TIA is very low for the microcontroller to detect. A non-inverting op-amp comparator with reference voltage connected to the inverting terminal and TIA output connected to the non-inverting terminal has been designed.

Optical concentrator plays a vital role in increasing the range between transmitter and receiver. Aspherical biconvex lens of 25 mm diameter and 45 mm focal length has been used.

Each luminaire consists of four pairs of transmitter and receivers to communicate with adjacent luminaires on all 4 sides. VLC Transceiver is designed with adjustable slits for enabling zone control. Closing of slits will block the communication with the adjacent lights and vice versa.

3) Luminaire Control Module: To control the illumination LEDs, control module has been developed. Based on the commands received from the microcontroller, control module turns ON/OFF the illumination LEDs. Luminaire control module can control any 2'x2' LED luminaires' up to 100 W.

C. Systems Developed

Developed VLC enabled LED luminaire and VLC transceiver enclosure are shown in Fig 5 and Fig 6.

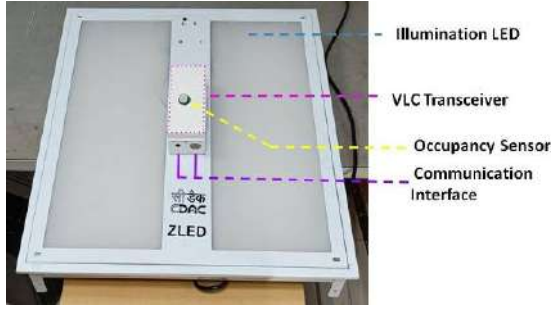


Figure 5. VLC enabled LED Luminaire

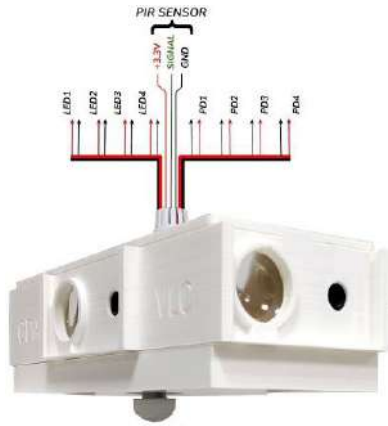


Figure 6. VLC Transceiver Enclosure

VLC transceiver shield for AVR microcontroller has been developed. Assembly set up of all 4 transmitter LEDs (T1, T2, T3 & T4) and receiver photodiodes (R1, R2, R3 & R4) are shown in Fig 7.

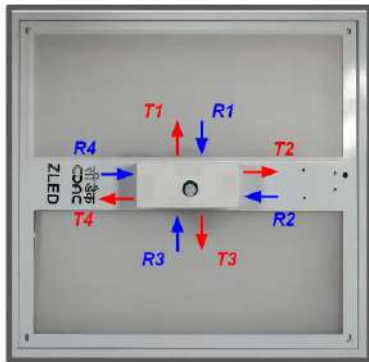


Figure 7. VLC Transceiver Assembly Setup

D. Application Firmware

Flow diagram of application firmware is depicted in Fig 8. Data to be transmitted has been modulated using Pulse Width Modulation. Duty cycle of 70% has been used to transmit occupied state 30% has been used to transmit an unoccupied state.

1) Occupied State: When occupancy is sensed under a luminaire the microcontroller in the VLC transceiver will activate the driver to turn ON the illumination LEDs and also issues a command to corresponding communication LEDs to turn ON the adjacent luminaire grouped under a zone. Then a non-occupancy timer is started to run for 30 seconds interval. VLC transceiver unit of adjacent luminaire which is positioned in line of sight receives the command and activates its driver to turn ON the illumination LED. When occupancy is re-sensed within the 30 seconds interval, non-occupancy timer is restarted. Upon detection of occupancy, each luminaire in a zone will transmit the occupancy state to each other thereby each luminaire maintains a record of occupancy state of all the luminaire under a zone.

2) Un-Occupied State: When non-occupancy timer is elapsed, then non-occupancy state is detected. Upon detection of non-occupancy state, a luminaire will be turned OFF only when all other luminaire in a zone are un-occupied.

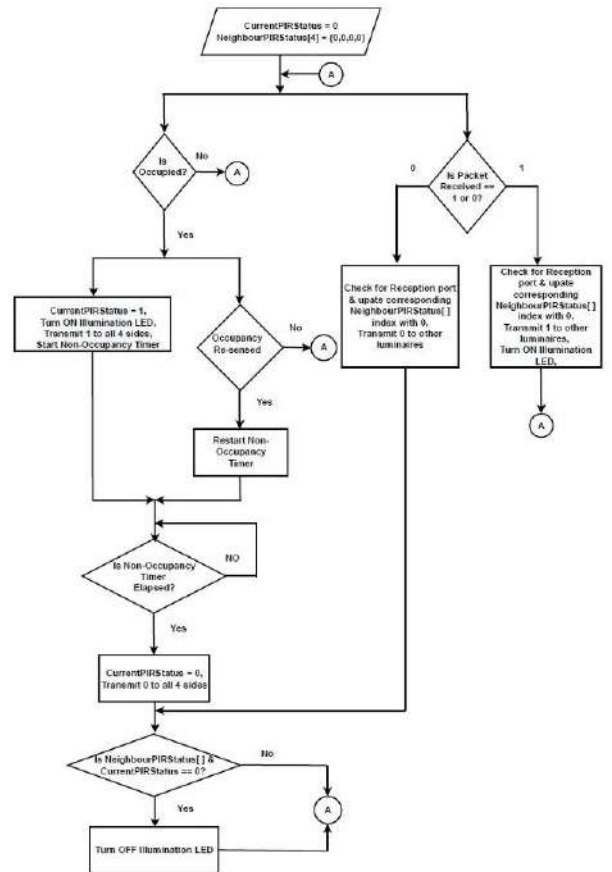


Figure 8. Flow Diagram

V. EXPERIMENTAL RESULTS

Experiments have been conducted to find the maximum communication range of full duplex VLC transceiver. The flow of the experiment is depicted in Fig 9.

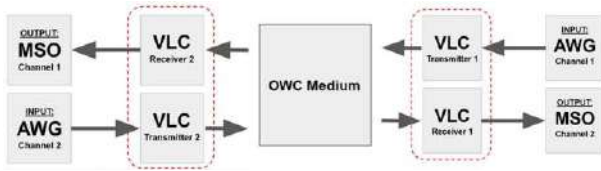


Figure 9. Experiment Flow

Arbitrary Waveform Generator (AWG)1 generates a square wave of 2 KHz and AWG 2 generates waveform of 1 KHz with amplitude of 3.45 V. Generated square wave is fed to the transmitter module which in-turn transmits the data through VLC. Receiver module receives the data and displays the output in Mixed Signal Oscilloscope (MSO). Experimental setup of transceiver 1 and 2 to find maximum communication distance is shown in Fig 10.



Figure 10. Experimental Setup

Waveform generated at AWG and captured at MSO via visible light is shown in Fig 11.



Figure 11. AWG Generated Waveform (L), MSO Captured Waveform (R)

Data decoded by the microcontroller for VLC Transceiver 2 is shown in Fig 12.

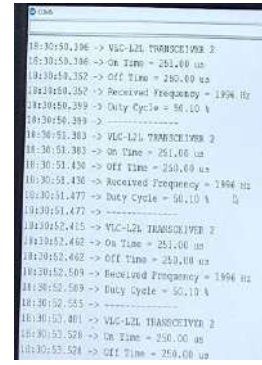


Figure 12. Decoded Data in MCU

Photocurrent measured at different distances with and without lens is shown in Fig 13.

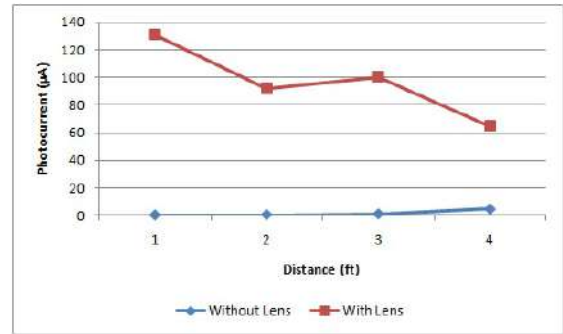


Figure 13. Distance vs. Photocurrent

With the developed quad directional full duplex VLC transceiver, up to 4 feet communication range has been achieved.

VI. CONCLUSION AND FUTURE WORK

An indoor lighting control solution using visible light communication has been developed for use in RF free zones such as hospitals, industries and airports. Proposed solution uses zone based distributed control of luminaire based on occupancy. A quad directional full duplex VLC transceiver has been designed and developed to communicate with adjacent luminaire on all 4 sides. As per the experimental analysis, up to 4 feet communication range has been achieved using the proposed system. Range can be extended further using more focussed high brightness communication LED. In future we are working towards improving the aesthetics and communication range of VLC Transceiver.

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