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Smart Traffic Light Controller using Visible Light Communications

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***Abstract*—We develop a low-cost visible light communication (VLC) framework that can be used for Intelligent Transportation Systems (ITS). The framework is composed of low-cost transceivers, a transmitter circuitry with embedded systems and optical electronics, and the receiver circuitry comprised of photodiodes along with other circuitry used for detecting and decoding the VLC signal coming from the traffic lights. We have conducted actual experimentation in a laboratory setting using a traffic light prototype to test the VLC framework in action. We studied the bit-error-rate (BER) versus signal-to-noise (SNR) ratio at a 30 m distance. Experimental studies show that at an SNR of 16 dB the proposed VLC system can achieve a BER of about 10^{-6}.**

***Index Terms*—Visible Light Communications, Smart Traffic Lights, Intelligent Transportation Systems.**

I. Introduction

Recently, visible light communication (VLC) has drawn a lot of attention from the research community in the areas of high data rate transmission, secure communications, and indoor localization systems as well in intelligent transportation systems (ITSs) [1], [2]. The use of VLC in ITS will lead to potential new and useful applications. Traffic lights have been used to control traffic flow, are often located at a particular place, and are rarely moved. It would be of great use to enable the traffic lights to talk to the vehicles in their proximity and convey important information about the traffic conditions. The development of ITS has been motivated by the need to reduce traffic congestion and offer better user experience in navigation and location-specific services. In this work, the aim is to develop a framework that can be used for ITSs and can potentially support infrastructure-to-vehicle (I2V) and vehicle-to-infrastructure (V2I) communication; in the present context the infrastructure refers to traffic lights using VLC [3]. Specifically, traffic lights are used not only to provide orderly traffic flow, but also to share some pertinent information with the cars. The traffic light can provide information about the traffic conditions several blocks down the road, and in case of accidents this information would be useful to enable the passenger to divert from their original driving route to help reduce congestion and save time. The infrastructure of the ITS is composed of a central station that controls the traffic flow, and when new information is provided to the traffic lights it is first routed to the central station to undergo analysis to make sure it is a legitimate information and to provide a smart traffic control.

A demonstration of the ITS traffic light controller using the VLC framework is shown in Fig. 1. As shown, the traffic lights can transmit digital pulse coded information to the vehicles for navigation or to convey important information. This information is obtained by the traffic light system from the central station via wired or wireless network.

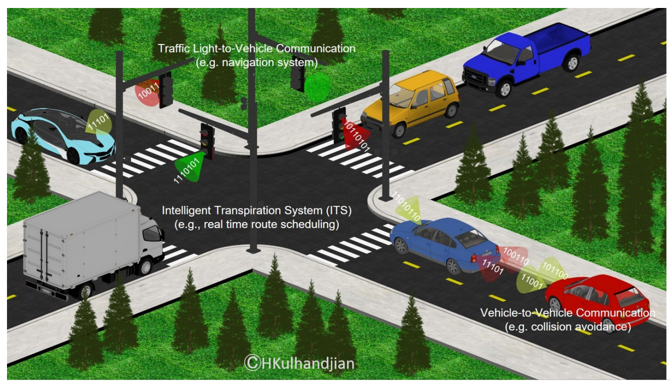

Fig. 1: Intelligent transportation system using the VLC framework.

There are only a handful of works on VLC in ITS. Kai in [4] proposes an optical camera system for ITS. Akanegawa *et al.* in [5] propose a traffic information system using existing light-emitting diode (LED) traffic lights, and focus on its visible rays and power used for traffic control, the number and location of the traffic lights. In [6], Abualhoul *et al.* propose ways on enhancing field of view limitation of VLC-based platoon using simulations. In [7], Wang *et al.* propose a VLC-based ITS for lorry fleet. Theoretical analysis and numerical calculation are performed to get the relationship between the speed of the lorry fleet and the conversion time of the traffic lights. In [8], Masini *et al.* study the performance of vehicular visible light networks in terms of message delivery rate and its full-duplex capabilities. Fakirah *et al.* in [9] propose a VLC-based assistive approach to coordinate autonomous vehicles while passing the roundabout, by providing them with the information of any changes in traffic conditions. None of those works in [4]–[9] perform an actual implementation of VLC system for smart traffic light control.

Therefore, to fill that gap, we propose to develop a low-cost VLC infrastructure to establish communications between the traffic lights and vehicles for better traffic management. To begin with, a visible light communication link is established between traffic lights and a vehicle, which is capable of receiving the information. To do that, we first develop transmitter circuitry composed of an embedded system and an optical electronics fast-switching network. The traffic lights will not only be performing their standard functionalities, i.e., providing traffic light signals to pedestrians and drivers, but they will also be sending out pertinent encoded information to the vehicles through light pulses. After presenting the transmitter circuitry, we then present the receiver circuitry composed of optical electronics circuitry in which the photodiode along with other circuit components is used for detecting and decoding the VLC signal coming from the traffic lights. The received signal is passed through an analog-to-digital converter (ADC) before being sent to the embedded system to receive and decode the transmitted signals. After developing the system, actual experimentation are carried out using a traffic light prototype. Experimental results show that at an SNR of 16 dB the proposed VLC system can achieve a bit-error-rate (BER) of about 10^{-6}.

The rest of the paper is organized as follows. In Section II, we discuss the proposed VLC system overview. In Section III, we present the LED driver circuit for the transmitter. In Section IV, we present the photodiode receiver circuit. In Section V, we discuss the experimental setup, printed circuit board (PCB) design for the receiver and transmitter circuit implementation and the proposed VLC system experimental results. Finally, in Section VI, we draw the main conclusions.

II. System Overview

In this work, a transmitter and receiver circuitry is developed that communicates pertinent information using modulated light pulses. It is meant to improve upon the existing infrastructure of LEDs by adapting their driver circuitry for high-speed VLC. This research work also serves to test the capabilities of photodiodes as viable receiver devices used in the developed VLC network. The main component of the research work is a transmitter/receiver pair design that can send and receive modulated light data. The transmitter system is designed for high-frequency operation in order to modulate the data at optimal rates. The system's microcontroller outputs a modulated bit stream to an amplifier, whose output drives the base of a transistor controlling the current flow to a high-power red LED. The binary data are encoded into the pulses of light through the quickly switching behavior of the transistor. On-Off-Keying (OOK) modulation is used for data transmission, which is simply switching on and off the LED light, i.e., the traffic light, at a very high rate. To transmit the digital information, a binary "1" information bit is represented by a square pulse and is generated by turning the LED on, while the binary "0" is generated by turning the LED off, i.e., no light transmission. The modulated light is projected into the medium where it can be detected by the receiver system's optical sensor. The information is projected to a car that is stationary at the red light; hence, Doppler will not have an effect on the system. The optical sensor is composed of a photodiode, which converts the modulated light data sent from the transmitter into a current. This current is converted into a voltage using a transimpedance amplifier (TIA). The voltage is sampled by the ADC connected to the receiver system's microcontroller, where the received signal can be processed and decoded.

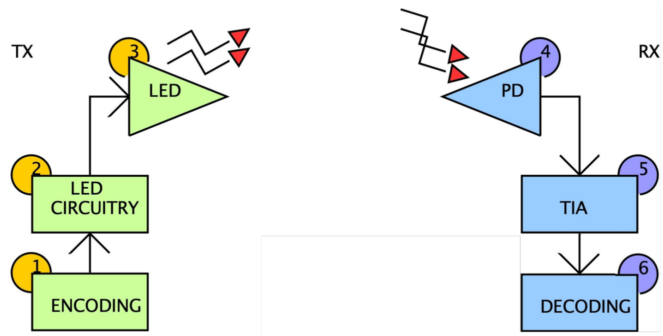

Fig. 2: Block diagram of the VLC system.

Figure 2 shows an overview of how the complete system operates. All of the main components are indicated by numbers and are described below.

1) The encoding is done through MATLAB software.
2) The LED circuitry consists of amplifiers and transistors to drive the LED with the proper amount of current.
3) The high-power LED is used to convert the modulated data into light pulses that is projected through the physical medium.
4) The photodiode collects the incident light pulses sent from the transmitter and converts the information to a current signal.
5) The current is converted into a voltage utilizing the TIA, which is optimized for fast response.
6) The signal is then sampled by the National Instrument's USB-6351 data acquisition board for ADC and decoded using MATLAB.

III. LED Driver Circuit for the Transmitter

Traffic lights are composed of high-power LEDs that require driver circuitry capable of supplying enough current to the LED. The transmitter's LED driver circuit is composed of two TIP31C transistors and a Chanzon $100\,W$ LED. The circuit design focuses on producing high current through the LED from a low current digital-to-analog converter (DAC) source, in accordance with OOK modulation. Figure 3 shows the driver circuit designed for simulation purposes using National Instruments (NI) Multisim software package.

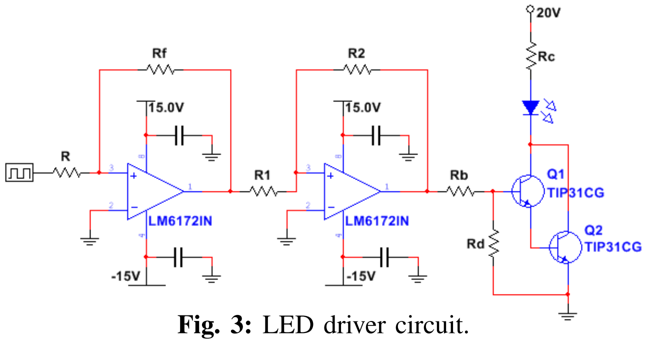

Fig. 3: LED driver circuit.

The encoded binary information is applied as a voltage signal to the input of an operational amplifier (op-amp) in an inverting amplifier configuration. Resistors R and R_f and the input voltage V_{IN} are used to amplify the voltage signal, where $V_O = -V_{IN} * R_f/R$. The output voltage from the first amplifier is returned to a positive voltage using another inverting amplifier configuration with R_1 and R_2 having the same resistance value of $1k\Omega$. The amplified voltage output from the op-amp is used to drive a transistor switch. Two BJTs are used in a Darlington pair configuration for heat dissipation and high current gain. R_b and R_d are used to set the base current, with R_d also serving as a sink for the turn-off period. R_c is used as a current-limiting resistor for the LED. Table I, shows the resistor component values used for the LED driver circuit [10].

R (kΩ)	R_f (kΩ)	R_1 (kΩ)	R_2 (kΩ)	R_b (kΩ)	R_d (kΩ)	R_c (Ω)
1	3.3	1	1	10	17	330

TABLE I: Resistor component values for LED driver circuit.

IV. Photodiode Receiver Circuit

There are two main ways to receive a visible light signal: an image sensor or a photodiode. A photodiode is used for this design to improve the response time. Our proposed receiver is composed of two BPW34 photodiodes, an OPA656 op-amp configured as a TIA using a feedback capacitor and resistor. The design process focuses on optimizing the TIA for large bandwidth and low-voltage signal processing. By modeling the OPA656 op-amp‘s transfer function and the feedback network produced by the TIA-photodiode combo, an optimal feedback capacitance can be calculated and simulated. Figure 4 shows the receiver design used for the simulation.

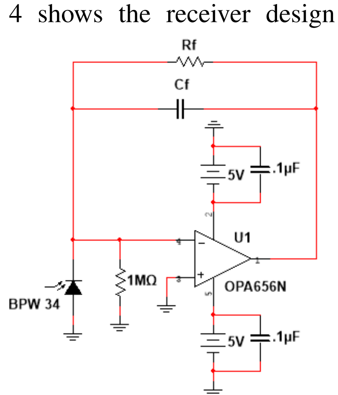

Fig. 4: Photodiode receiver circuit.

As can be seen in Fig. 4, the photodiode receives the encoded light signal sent through line-of-sight (LOS) and converts the pulses of light into a current waveform. The current is converted into a voltage using a TIA configuration. The feedback capacitor (CF) offsets the effects of the photodiode's junction capacitance. The current generated by the photodiode runs through the feedback resistor (RF) and generates a voltage at the output. The TIA maximum output voltage is set by the maximum generated photodiode current and the R_f. The relative spectral sensitivity of the BPW34 photodiode used in the system is shown in Fig. 5. Due to red light being approximately 70% of the peak spectral sensitivity for the BPW34, the maximum photodiode current is 20μA. As there were two photodiodes in the design, the maximum expected current is about $40\,\mu A$. The equation for determining the value of the feedback resistor in the transimpedance amplifier circuit for a maximum output voltage of 1V is expressed as, [11],

$$R_f = \frac{V_{out,max} - V_{out,min}}{I_{PD,max}} = \frac{1V - 0V}{40\mu A} = 25\,k\Omega. \quad (1)$$

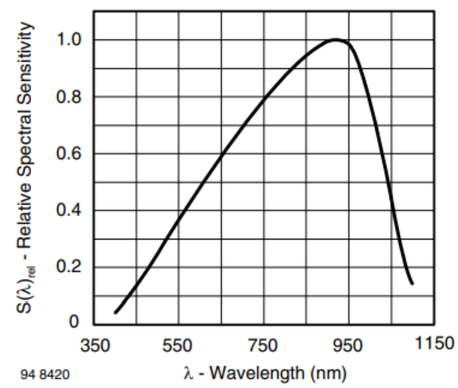

Fig. 5: Relative spectral sensitivity of BPW34 photodiode [12].

The junction capacitance of the photodiode is important in determining the frequency response of the circuit. The junction capacitance of the BPW34 operating in photovoltaic mode is about $72\ pF$. Since there were two photodiodes used in the design, this yields a total diode capacitance of $144\,pF$. The differential and common-mode capacitance of the OPA656 are $0.7\,pF$ and $2.8\,pF$, respectively [13]. Since the diode capacitance and op-amp input capacitance are in parallel the total input capacitance is determined by:

$$C_{in} = C_J + C_{diff} + C_{CM} = 147.5\,pF. \quad (2)$$

The gain-bandwidth product (GBWP) of the OPA656 is rated at $230\ MHz$. To account for variation in the process corners of the gain-bandwidth product frequency, 60% of the rated $230\,MHz$ is used for the calculations. The feedback capacitance for optimal compensation of the TIA is calculated by,

$$C_f = \frac{1 + \sqrt{1 + (8\pi \times R_f \times C_{in} \times \text{GBWP})}}{4\pi \times R_f \times \text{GBWP}} = 2.63\,pF. \quad (3)$$

The rails of the op-amp are connected to $\pm 5\ V$, with decoupling capacitors connected between each supply pin and ground. Due to the photodiode being an AC-coupled source, a DC return path is introduced at the inverting input with a $1\,M\Omega$ resistor—this prevents the voltage output of the amplifier from saturating to one of the op-amp's rails over time [14].

V. Experimentation

In this section, we present the testbed experimental results for the proposed smart traffic light VLC system.

A. Experimental Setup

The VLC experimentation is carried out on the developed testbed, shown in Fig. 6.

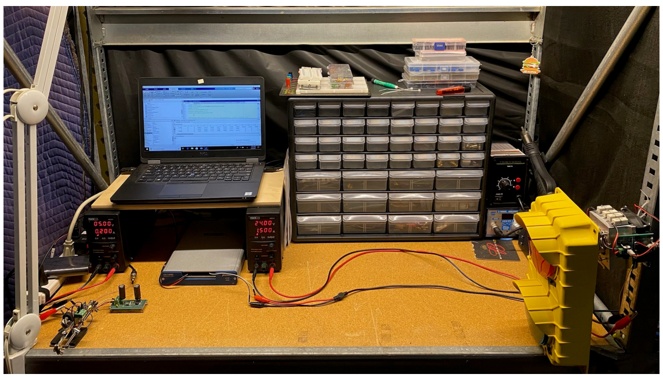

Fig. 6: Testbed experimentation.

B. PCB Design for the Receiver

The PCB design for the receiver is shown in Figs. 7 and 8. The PCB is 2 layers with a ground plane on the bottom layer; the signal and power traces are on the top layer. All traces were made at $0.3\ mm$ thickness in order to minimize inductance. Decoupling capacitors were placed close to the power supply and OPA656 rails, with surface-mount components being used to preserve high frequency operation of the op-amp [14]. Due to the inverting input pin and output pin of the OPA656 being most sensitive to parasitic capacitance [14], the feedback capacitor and resistor were placed close to both pins. An SMA socket was used in order to connect the output of the TIA stage to the ADC. The final fabricated receiver design prototype is shown in Fig. 9.

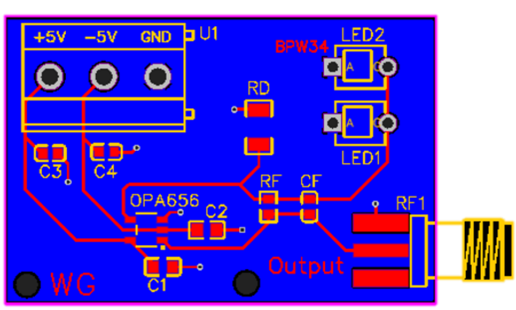

Fig. 7: Receiver trace layout.

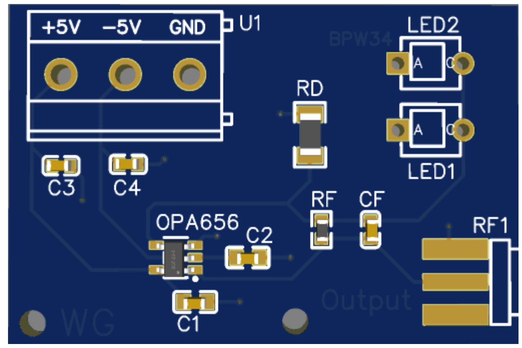

Fig. 8: Receiver component view.

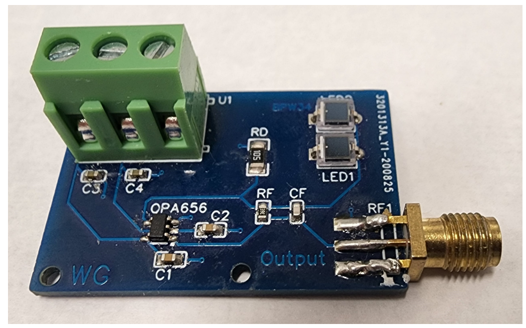

Fig. 9: Fabricated prototype of the receiver design.

C. Transmitter Circuit Implementation

The transmitter circuit is implemented on a perfboard, as shown in Fig. 10. A high power red LED of $100\ W$ is used for red traffic light implementation and information bits transmitter at fairly long distances, i.e., tens of meters. The high power LED is surrounded with a large heat sink along with a fan to avoid overheating the LED and burring out.

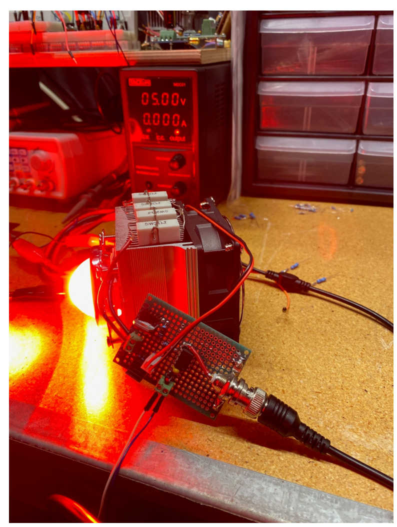

Fig. 10: The transmitter circuitry with 100 W red LED.

D. Experimental Results

Figure 11 shows the experimental block diagram for the designed VLC system. The optical channel voltage is measured and recorded with the transmitter LED "OFF" and with the LED "ON". A random stream of 1 million bits is generated in MATLAB and appended to a 100-bit preamble used for synchronization purposes at the receiver side [15]. The encoded bits are sent to the NI USB-6351 DAC board to output a voltage signal $(0 - 4\,V)$ at a rate of $50\,kHz$ that toggles the red LED "ON" and "OFF", respectively. This modulated (on-off-keying) OOK light signal propagates through the wireless optical channel where it is collected by the receiver. The large bandwidth $(3.3\,MHz)$ of the receiver increases the fidelity of the digital pulses in reception. The output voltage from the receiver is sampled by the NI USB-6351 ADC at a rate of $500\,kSamples/s$ and is passed through a matched filter using the known preamble to find the start of the transmitted data.

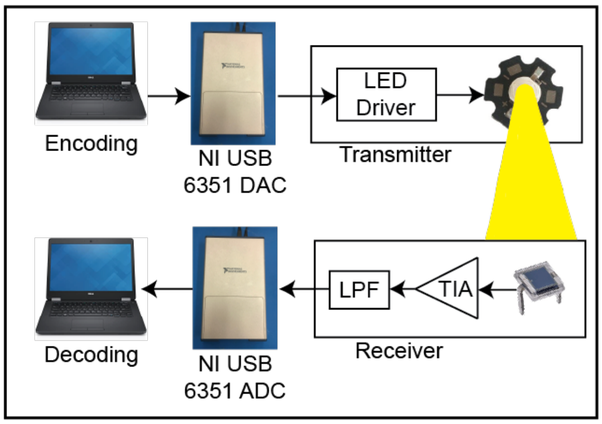

Fig. 11: VLC system block diagram.

Figure 12 shows the peak that results from auto-correlating the 100-bit preamble with the received data. From the start of the received data stream, the voltage samples are averaged and demodulated using a hard decision threshold set between the average noise level and light level.

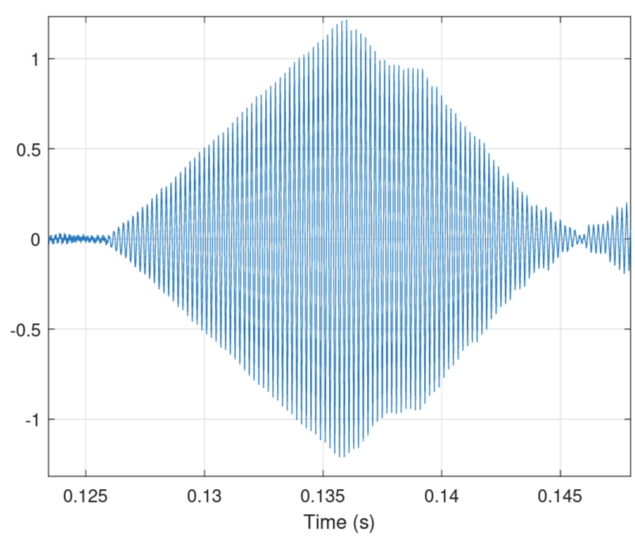

Fig. 12: Preamble detection using a matched filter.

Figure 6 shows the experimental results. The experiments are performed at a distance of 30 meters separation (the transmitter from the receiver). The transmit power is varied and the BER is calculated for different transmit powers. The BER is calculated by comparing the received data and the transmitted data. As can be seen from Fig. 13, at a signal-to-noise-ratio (SNR) of 16 dB the proposed VLC system can achieve a BER of about 10^{-6}.

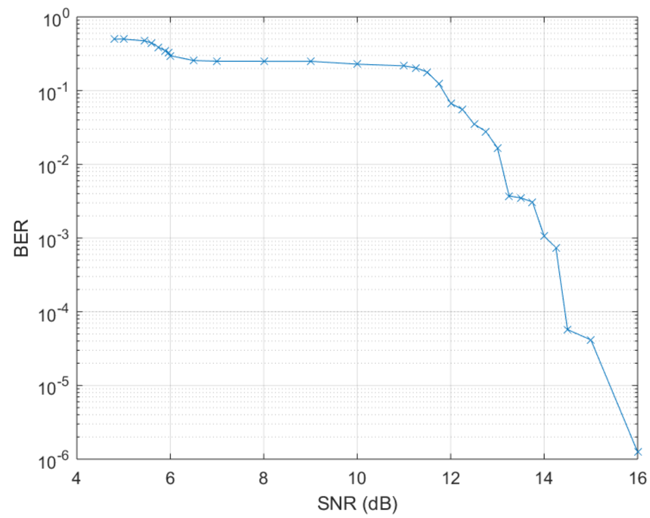

Fig. 13: BER versus SNR at 30 m distance separation.

VI. Conclusion

In this research work, a visible light communication (VLC) framework is developed that can be used for intelligent transportation systems (ITSs). Not only can the traffic light control the flow of traffic; it can also provide information about the traffic conditions several blocks down the road, and in case of accidents, this information would be useful to enable the passenger to take a detour from their original driving route to help reduce congestion and save time. In order to do that, we have developed a transmitter circuitry that is composed of an embedded system and an optical electronics fast-switching network. In addition to that, we have developed the receiver circuitry composed of optical electronics circuitry in which the photodiode along with other circuitry is used for detecting and decoding the VLC signal coming from the traffic lights. The received signal is passed through an analog-to-digital converter (ADC) before sending it to the embedded system to receive and decode the transmitted signals. After developing the system, we have conducted actual experimentation in a laboratory setting using a traffic light model/prototype and studied the VLC framework in terms of bit-error-rate (BER) verses signal-to-noise ratio (SNR). Experimental results reveal that at an SNR of 16 dB the proposed VLC system can achieve a BER of about 10^{-6}. In future, experiments can be conducted at longer distances and in different weather and light conditions.

ACKNOWLEDGEMENT

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