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Research on the Application of Visible Light Communication in IoT System Configuration

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Abstract

The growing need for seamless connectivity on the internet of things (IoT) paradigm has fueled the development of innovative technologies. This research deeply focuses on the integration of visible light communications (VLC) to configure the wireless sensor network (WSN) nodes in an IoT system. VLC, an emerging technology that uses visible light to transmit data, is not limited in frequency and maximizes security in wireless data transmission. Furthermore, due to the use of light-emitting diodes (LEDs) in almost every aspect of our daily lives, VLC is providing massive connectivity for various types of large-scale IoT communications, from machine to machine, vehicle to infrastructure, infrastructure-to-vehicle, chip-to-chip as well as device to device. This article presents an investigation of the multifaceted applications of VLC, especially its role in configuring wireless fidelity Wi-Fi connectivity for smart devices and their location in the system within the IoT framework. In addition to conventional data transmission capabilities, VLC has emerged as a key technology for transmitting configuration data and location data, thereby supporting an accurate positioning system. This study shows the effective interaction between VLC and IoT, shedding light on the applications of VLC in IoT systems, especially in smart building...

Keywords: internet of things (IoT), light-emitting diodes (LEDs), visible light communication (VLC), VLC-IoT communication.

1. Introduction

The increasing demand for wireless connectivity for various "Things" through the internet infrastructure has gained significant attention, particularly with the expansion of smart city initiatives, smart grids, and smart manufacturing [1-4]. The surge in the IoT and advancements in wireless communication has led to a substantial rise in the number of connected devices within IoT, resulting in a scarcity of available radio frequency (RF) spectrum [5-7]. Addressing this challenge has become a genuine concern, prompting extensive research efforts to explore alternative wireless communication solutions capable of providing massive connectivity, diverse data rates, low latency, high capacity, efficiency, and robust security.

Among various emerging wireless communication techniques, the VLC stands out as a promising solution to overcome key challenges in the wireless communication industry [8]. VLC is one of the advanced technologies in optical wireless communication technology, based on the visible light region (wavelength 375-780 nm) of the electromagnetic spectrum as a data transmission medium, in Fig. 1 . Taking advantage of existing LED lighting infrastructure, researchers are bringing the ideas of data transmission via LED signals to commercial applications, which have been growing rapidly in recent years. The VLC system will reduce the cost of setting up a wireless communication system like traditional methods as well as overcome the limitations that RF is facing.

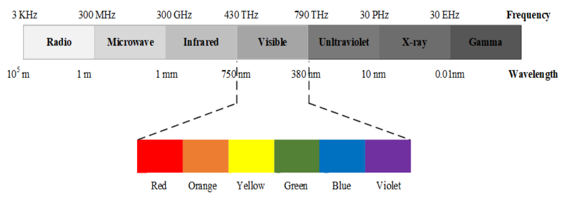

Fig. 1. The electromagnetic spectrum

Notably, VLC has demonstrated potential in mitigating challenges associated with the implementation of 5G technology, offering a viable alternative to the heavily burdened RF spectrum [6]. Its most notable advantage lies in providing a staggering 10,000 times more capacity than the RF spectrum, and it remains unregulated and unlicensed [9]. VLC's unique capability to address RF spectrum scarcity while coexisting with critical communication systems, such as those used in airplanes and hospitals, positions it as a valuable and safe-to-use bandwidth

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solution [10].

Furthermore, VLC has shown promise in transmitting medical data, including photoplethysmography, electrocardiography, and body temperature monitoring, with ongoing studies exploring its applications in various healthcare scenarios. Unlike RF signals, visible light cannot penetrate through walls and maintains controlled transmission, making it suitable for highly secure connections within the range of an access point. This characteristic renders VLC applicable to a wide range of IoT-based smart systems.

The convergence of IoT and VLC has given rise to a novel paradigm known as the Internet of LED, utilizing LED technology to integrate IoT with VLC This innovative approach has found application in diverse fields, such as indoor navigation and transmission data. The automotive industry has also embraced VLC by using LED headlights and taillights for vehicular VLC in collision prevention systems. Additionally, VLC-IoT holds promise in transmitting medical data for biomedical sensing and data transmission.

In the IoT era, connecting smart devices to Wi-Fi networks is very important. When it comes to challenges in IoT connectivity: an increasing number of IoT devices require efficient and user-friendly Wi-Fi configuration methods. Traditional manual setup is cumbersome. Therefore, simplifying the process is essential. In wireless networking, various techniques have been developed to simplify and improve the Wi-Fi configuration process. These methods meet diverse needs and preferences, providing a seamless and efficient programming experience:

- Scan quick-response (QR) code: Allowing users to scan QR codes for automatic setup; streamlining the configuration process through visual recognition;

- Push button and LED: Monitoring button and LED signals to facilitate configuration; providing a visual and tactile method for users to confirm and set up Wi-Fi connections;

- Wi-Fi protected setup (WPS): Entering a PIN code for a swift and secure connection; simplifying the configuration process for users seeking quick and easy connectivity;

- Set up bluetooth low energy (BLE): Configuring devices via a mobile app and Bluetooth; leveraging Bluetooth capabilities for efficient and wireless configuration;

- Set up wired Ethernet: Initiating the configuration process with a wired connection; offering a reliable and straightforward method to configure Wi-Fi settings;

In the realm of VLC, as it undergoes continuous development and widespread adoption, configuring Wi-Fi for devices using VLC emerges as a viable and efficient solution. This approach facilitates quick and easy connection, unifying all devices within the same system under the umbrella of VLC-enabled connectivity. Notably, devices within the system utilizing the same light for communication contribute to easy management, further enhancing the overall connectivity experience within the IoT ecosystem. The evolution of VLC technology presents a promising avenue for transforming Wi-Fi configuration methods, ensuring that the connection process is not only efficient but also seamlessly integrates with the expanding landscape of IoT devices.

This paper introduces a novel feature for device management and data transmission within IoT networks using VLC. Our proposed VLC-based IoT scheme addresses the need for effective management of VLC devices, encompassing both transmitters and receivers while facilitating seamless VLC data transmission in IoT networks. In the envisioned VLC-based IoT framework, one-way VLC transmission was emphasized, originating from the VLC transmitter and terminating at the VLC receiver. The WSN is focused on smart office buildings. The sensor nodes measuring temperature, humidity, and atmospheric pressure will be installed along with electrical devices such as smart lighting systems, air conditioners, ... These parameters support the usage of energy in the building to bring the building to become a net-zero building. Besides that, the number of sensor nodes is large, which will cause difficulties for the building configuration team during installation and operation. This research implementation therefore proposed a quick, easy installation method for this configuration step.

The transmission mode is dedicated to configuring the Wi-Fi access of the data collection device and determining the global positioning system (GPS) location of the entire system. The transmitter (*Tx*) is the LED bulb (in smart lighting system) that transmits the configuration data like the name of the Wi-Fi network, the password of the Wi-Fi network, the LED identification (LED-ID), the LED internet protocol address (LED-IP), and GPS location. The receiver (*Rx*) is a WSN for acquiring the environment parameters described above. So, *Rx* will receive configuration data transmission easily and fast (for the first time or the replacement, repair, and maintenance). This configuration process is particularly relevant in the context of a single-node system within the broader IoT framework.

All data collected by the sensor node, along with relevant information about the system, is systematically updated to the server through the message queuing telemetry transport (MQTT) protocol. This data transmission protocol ensures efficient and reliable data transfer, facilitating real-time monitoring of the system.

The rest of the work is organized as follows. Section 2 discusses related contributions. In Section 3, an overview of the VLC-IoT concept is presented. Section 4 proposes the design of a VLC-based IoT system. In Section 5, the detailed experimental results are presented. The scenario for configuration data transmission and the distance that can be utilized from 0.3m to 6m depending on the frequency of *Tx* will be presented. Finally, Section 6 presents conclusions based on the acquired results and the potential future development directions.

2. Literature Review

The evolution of VLC has been guided by the IEEE 802.15 Task Group 7, which introduced the VLC standard in 2011 [11]. This standard defines the physical (PHY) and media access control (MAC) layers for short-range optical wireless communication using visible light and categorizes devices as infrastructure, mobile, or vehicle [12-13]. While the existing standard covers peer-to-peer, star, and broadcast MAC topologies, ongoing revisions, such as IEEE 802.15.7r1, extend support to infrared and near ultraviolet wavelengths, optical camera communications (OCC), and light fidelity (Li-Fi). The internet protocol version 6 (IPv6) over low-power wireless personal area networks (6LoWPAN) ensures IP-based communication over IEEE 802.15.4 networks, evolving to support BLE and near-field communication (NFC). Additionally, protocols like constrained application protocol (CoAP), MQTT, and machine-to-machine (oneM2M) have been designed to accommodate IoT device constraints, offering communication, management, and security solutions.

In exploring related contributions, the literature has primarily focused on VLC applications for various wireless technologies, with limited emphasis on their integration into IoT systems. For instance, studies have investigated indoor VLC systems, channel modeling, and the potential of Li-Fi in wireless communication. Some contributions propose innovative VLC system designs for IoT, incorporating orthogonal frequency division modulation (OFDM) and evaluating performance through bit error rate analysis. Others discuss the challenges and applications of optical IoT (OIoT) in VLC and OCC within the framework of 5G standards. While previous work has laid the foundation for VLC applications, our paper aims to bridge the gap by proposing a comprehensive framework for VLC-based IoT networks, focusing on device management, and data transport. This research adds value by addressing the underexplored area of effectively integrating VLC services into IoT networks, positioning VLC as a wireless access medium for IoT connectivity.

3. Overview of the VLC-IoT Systems

This section provides a comprehensive overview of the integration of VLC services into the IoT network, beginning with a detailed exploration of VLC and IoT individually.

3.1. VLC Overview

In the contemporary landscape, LED lights have become pervasive in our daily lives, forming the basis for VLC. The IEEE 802.15.7 group has played a pivotal role by issuing a draft standard on optical wireless communication (OWC), specifically focusing on the advancements in LED-based VLC at the physical and data link layers. Defined in IEEE 802.15.7-2011, VLC is recognized as a communication solution addressing specific challenges in environments with limited RF communication capabilities, such as factories, mines, or underground facilities. VLC emerges as a compelling choice for supporting IoT communication due to several key factors. These include network scalability, effective interference mitigation, and the scarcity of RF frequency bands. Importantly, VLC operates without interfering with existing RF-based communications, offering the significant advantage of not requiring a license to utilize the visible light spectrum. Furthermore, VLC provides precise location-based communication, distinguishing itself from other low-power communication technologies like BLE and NFC.

3.2. IoT Overview

The IoT has evolved from a limited M2M communication system to a global network service with profound implications for daily life. In conjunction with artificial intelligence (AI) and robotics, IoT stands as a cornerstone of the fourth industrial revolution (4IR). Its impact extends to various domains, including smart cars, smart cities, smart campuses, and smart manufacturing. Wireless communication technologies, such as narrow band-IoT (NB-IoT), BLE, and ZigBee, alongside protocols like CoAP and MQTT, form the backbone of IoT networks. As IoT transitions towards comprehensive digitalization, cloud computing emerges as a crucial support mechanism. Standards and software, such as those developed by the Open Connectivity Foundation (OCF) and oneM2M, facilitate the development of IoT systems and products.

At the device level, a significant challenge lies in achieving scalability, especially concerning physical media access. While 5G is expected to provide the necessary frequency bands, relying solely on cellular network providers for IoT support faces impediments, including legislative variations across countries regarding frequency band allocation and limitations in the under 1 GHz band.

3.3. Integration of VLC into IoT Networks

The integration of VLC services into the IoT network emerges as a strategic response to the unique advantages offered by VLC, including network scalability, interference mitigation, and precise location-based communication. As IoT continues to shape the global digital landscape, the incorporation of VLC introduces a novel and efficient wireless access medium, providing a viable solution to the challenges faced in specific communication environments and contributing to the seamless evolution of IoT connectivity.

4. Proposed VLC-Based IoT Scheme

4.1. Proposed Overview System

The proposed VLC-integrated IoT system has the architecture shown in Fig. 2

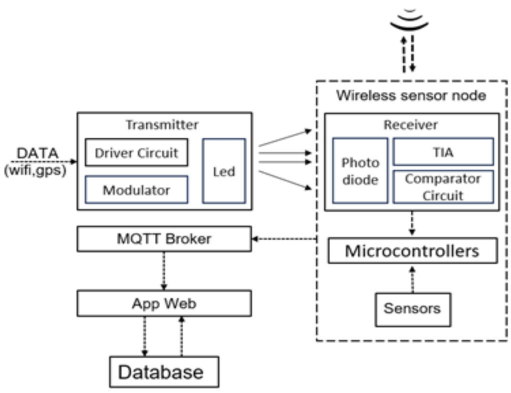

Fig. 2. System overview

- Transmitter (*Tx*) uses LEDs and LED controllers to transmit data. Transmitted data includes Wi-Fi information, and GPS coordinates of the room, data will be modulated before the LED lights up for data transmission;

- Receiver (*Rx*) employs a photodiode to capture the light signal, which is subsequently transmitted to the microcontroller for processing. Once the processing is finalized, the microcontroller utilizes the refined Wi-Fi data to configure the Wi-Fi connection. Additionally, it reads sensor parameters such as temperature, humidity, pressure, and light intensity. Subsequently, this compiled data, along with GPS coordinates obtained from the lamp, is sent to the MQTT broker. The overarching objective is to monitor the specified parameters within the room and pinpoint the location of the room where the transmitter is installed;

- Web application will play the role of working with data once it has been sent to the MQTT broker. Then it will visually display all the data so users can easily observe the information from the node.

4.2. Transmitter Section

4.2.1. Transmitter design

Fig. 3 shows the hardware architecture of the LED driver circuit and shows a reference architecture for transmitting data to LED.

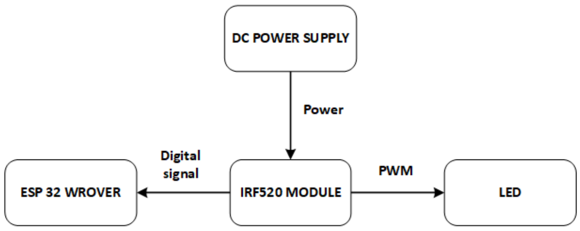

Fig. 3. Tx hardware architecture

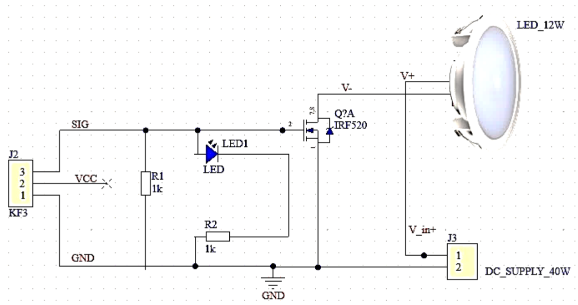

Fig. 4. Schematic diagram of *Tx*

In Fig. 4, data is sent to the LED via the I/O pin of the ESP32. The ESP32 will control the metal-oxide semiconductor field-effect transistor (MOSFET) to open/close to turn the LED on/off. In this test, the test is at frequencies from 1kHz - 500 kHz.

4.2.2. Modulation technique

In the realm of VLC modulation studies, On-Off Keying (OOK) modulation is a popular choice owing to its practical design and straightforward implementation. However, despite its simplicity, OOK modulation presents certain drawbacks, notably in the form of flickering issues, especially when representing extended data strings with numerous '0' and '1' bits. This limitation imposes constraints on the achievable data transmission speed. To overcome the flickering challenges associated with standalone OOK modulation, a hybrid approach is introduced by combining OOK with Manchester encoding. In this innovative modulation technique, each '0' and '1' bit is uniquely represented by the sequence of symbols '01' and '10,' respectively. This strategic design ensures that no more than two consecutive matching symbols occur, effectively mitigating the flickering issues characteristic of traditional OOK modulation. One significant advantage of this combined modulation method is its ability to maintain a balanced representation of '0' and '1' bits, regardless of whether the transmitted data has undergone encryption. This feature contributes to the consistency and reliability of the modulation scheme across different data scenarios.

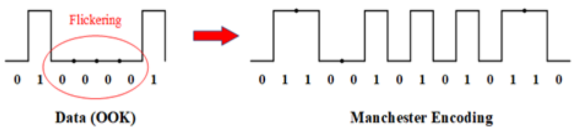

Fig. 5. Eliminate harmful flickering by utilizing Manchester encode

Fig. 5 visually illustrates the distinction between standalone OOK modulation and its amalgamation with Manchester encoding. In the former case, a prolonged sequence of '0' bits may result in noticeable flickering, especially if the modulation frequency is insufficiently high. In contrast, the combined OOK and Manchester encoding approach ensures a more evenly distributed symbol ratio, effectively addressing the flickering challenges associated with traditional OOK modulation. This hybrid modulation technique represents a significant advancement, offering a practical solution to enhance the performance of OOK modulation in VLC systems. By intelligently combining OOK with Manchester encoding, this approach provides a more robust and versatile method for data transmission, overcoming the limitations posed by flickering and enabling more efficient and reliable communication in VLC applications.

Fig. 6. Architecture data string

In OOK modulation, LEDs are switched on and off according to the bits in the data string. The content and the number of signal bits in a data packet are determined according to the specific decoding method employed. However, the fundamental principle of these data packets remains consistent: they are transmitted and repeated an appropriate number of times to prevent data loss. Fig. 6 shows a reference architecture for transmitting data to LED.

Table 1. Data string

Name		Data
Wi-Fi	SSID Password	SSID: Password
GPS	Longitude Latitude	Longitude, Latitude
Data	SSIS: Password; Longitude, Latitude	
Ex	Dophuong:123456789; 20.983333, 105.832670	

The input data string includes an 8-bit preamble, followed by information that specifies the length of the data string (8 bits). Afterward, the data to be transmitted includes Wi-Fi configuration details and the GPS location of the system. Table 1 shows the format of all data sent. GPS information helps better manage the device during indoor usage conditions. However, due to these conditions, most GPS modules may not work properly, so the device with fixed GPS information from where the LED is installed was provided.

4.3. Receiver Section

4.3.1. Hardware design

The hardware in the proposed *Rx* design is a WSN. At the *Rx*, there is a transition impedance amplifier (TIA) and a comparator that acts as a signal conditioner. Technical specifications of the white LEDs and photodiodes used in the experiment are presented in Table 2.

Table 2. Technical specifications of LED and Photodiode

Component	Specification
LED	Name: Kingled Ceiling LED Voltage rating: 26 -40 VDC Power: 12 W View angle: 120◦ Wavelength: 380-760 nm
Photodiode	Name: BWP34 Spectral response: 430-1100 nm Rise/fall time: 100 µs

Fig. 7 shows the block diagram of the *Rx* design. The microcontroller used for internet connection in this design is ESP8266-07 and incorporates a BME280 measuring sensor to represent a specific measuring device.

The analog circuit on the receiver side is used for conditioning the output signal from the photodiode because the output signal of the photodiode will be attenuated and distorted. Photodiode output is current, TIA is needed to convert current to voltage. Current to the voltage converter is done by op-amp as shown in Fig. 8. After being converted into voltage, this signal is sent to the comparator to correct the internal distortion signal. RV1 potentiometer can be adjusted manually to set the comparison threshold. The output of the comparator is then connected to *Rx*.

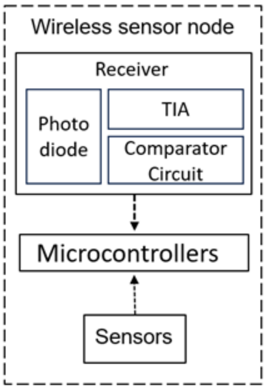

Fig. 7. Rx diagram

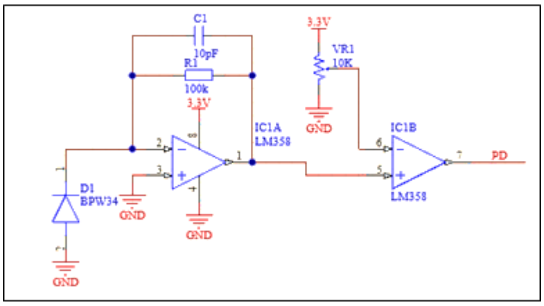

Fig. 8. TIA and comparator on the receiver

4.3.2. Software design

The algorithm diagram on the microcontroller is depicted in Fig. 9. The data packet is received once the header (start bit) is detected, and the data reception concludes upon the successful establishment of the Wi-Fi connection. Subsequently, the microcontroller will retrieve data from the sensor, compile all necessary information, and transmit it to the internet.

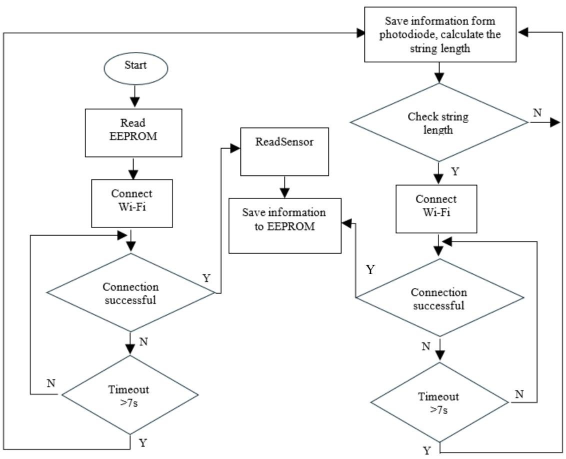

Fig. 9. Algorithm diagram

Storing received data in EEPROM enables us to re-establish a Wi-Fi connection in case the light is no longer in use.

5. Experiment and Results

5.1. Experimental Setup

The device used in the first experiment, as shown in Fig. 6, employs a 10cm diameter recessed LED for *Tx* and a photodiode for *Rx*. This setup is designed to assess the impact of distance, frequency, and environmental factors on the likelihood of data errors. The data received at *Rx* will be monitored via a PC's Serial port, as shown in Fig. 10.

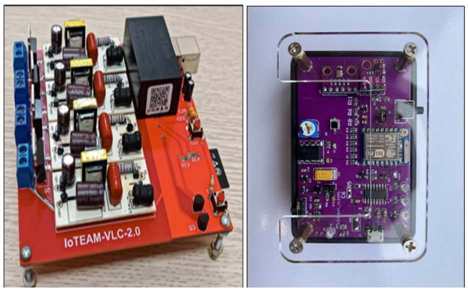

Fig. 10. *Tx* and *Rx* in the first experiment

In this setup, the experiment is Rx, which will be positioned opposite Tx, as shown in Fig. 11. In reality, the transmission and reception process continue as long as the photodiode receives light from the lamp, regardless of any reflected light.

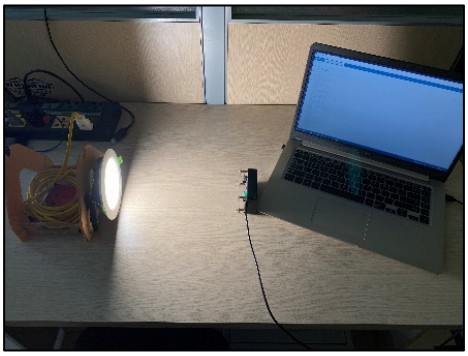

Fig. 11. Experimental scenario design

5.2. Experimental Results

5.2.1. Data from LED

Fig. 12 shows the data which is observed over serial from the terminal of IDE software. And Fig. 13 is a chart displaying the data error rate across frequency conditions ranging from 1kHz to 500kHz, as well as increasing distances and the influence of environmental factors.

In conditions where there is no interference from external light, the transmission and reception process remain stable. Consequently, the achievable distance and frequency are quite substantial. However, at higher frequencies, the generator circuit overheats due to rapid MOSFET switching, and the LED may also overheat due to rapid on-and-off cycling. This affects the LED's luminous efficiency.

```
........................-----------------------------------
>>> Read from Buffer Light
>> Check SUM: 25
>> Buffer: Dophuong:123456789;21.00702,105.84419
........................-----------------------------------
>>> Read from Buffer Light
>> Check SUM: 25
>> Buffer: Dophuong:123456789;21.00702,105.84419
........................-----------------------------------
>>> Read from Buffer Light
>> Check SUM: 25
>> Buffer: Dophuong:123456789;21.00702,105.84419
........................-----------------------------------
>>> Read from Buffer Light
>> Check SUM: 25
>> Buffer: Dophuong:123456789;21.00702,105.84419
........................-----------------------------------
```

Fig. 12. Received data observed over serial

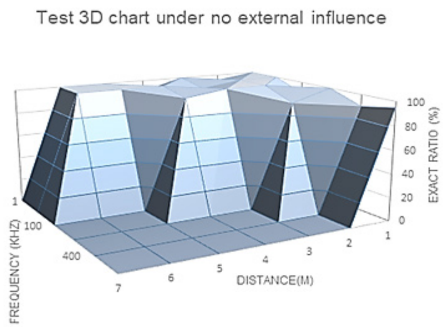

Fig. 13. Test 3D chart under no external influence

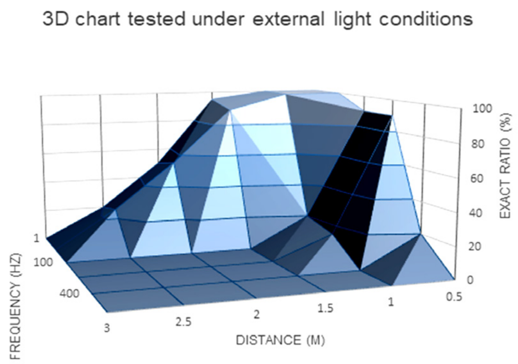

Fig. 14. 3D chart tested under external light conditions

In conditions influenced by external light noise, the light-sensitive characteristics of the photodiode BWP34 result in unstable transmission, see Fig. 14. Through the above experiment, the system at the frequency of 1kHz-100kHz and the distance from 1 - 3 m were recommended to achieve the best stability.

5.2.2. Sending data to MQTT Broker and connecting with Web app to monitor

MQTT broker is provided by the company HIVEMQ, the service is free to use at: broker.hivemq.com. Connection information and node activities will be logged in the serial when connected to the computer including Wi-Fi connection information, Wi-Fi connection status and MQTT connection, and data sent.

```
-----------------------------------
...........Connected from EEPROM
>>>>>>>>>>>>>>>>>>>>>>>>>>>>>
Attempting MQTT connection...connected
Error:  -30
{
  "temperature": "30.15",
  "humidity": "68.99",
  "pressure": "1004.90",
  "light": "0.00",
  "pin": "83",
  "gps": "20.983333, 105.832670"
}
>>>> SLEEP <<<<
```

Fig. 15. A node activity is logged in the serial

Fig. 16. Server MQTT HiveMQ

As soon as data (see Fig. 15) is published to the MQTT broker, it is immediately retrieved by the server to send to MongoDB. If the data is saved successfully, it will be written to the command on the server side. After being stored, data will be retrieved and sent to a static file for processing and display on the Web interface in Fig. 16. Each node will be placed in different locations, the locations will be displayed on the same map as Fig. 17.

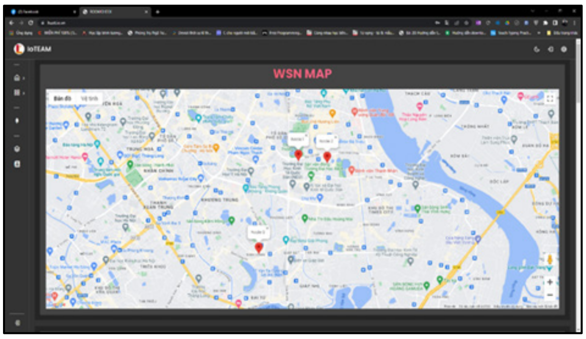

Fig. 17. Map includes devices

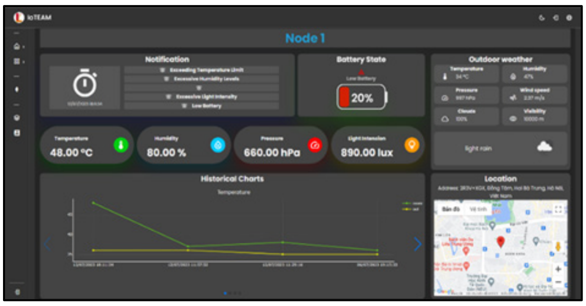

Fig. 18. The general interface of each node

In addition, the data collected from the sensor, as well as the parameters of each node, will also be displayed on the web interface as shown in Fig. 18.

6. Conclusions and Discussions

In this paper, a conducted experiment is presented to develop a fundamental device design capable of transmitting and receiving data with VLC system. In a smart office building, the sensor nodes measuring temperature, humidity, and atmospheric pressure will be installed along with electrical devices such as smart lighting systems (LEDs), and air conditioners, ... These parameters support the usage of energy in the building to bring the building to become a net-zero or green building. That's why the number of WSN nodes is very large, which will cause difficulties for the building configuration team during installation and operation. So, this paper proposes a faster and easier installation method for the configuration step. With one source of LED in the room, the configuration man can set up all the WSN nodes quickly (for the first time or the replacement, repair, and maintenance).

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