Design of a hybrid free space optical and visible light communication system for indoor wireless data broadcasting

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Abstract: The continuous development of online social services and the ever-increasing number of devices demanding high-speed and ubiquitous broadband wireless access have resulted in severe bandwidth congestion, such that the radio frequency (RF) spectrum will no longer be able to support the exponential growth in demand. Along with being faster, cheaper, greener, cleaner, and safer than current technology, visible light communication (VLC) can overcome the bottleneck issues with last-mile connectivity by offering 10,000 times broader bandwidth. In this paper, we propose a system with portable, low-cost hybrid RF/VLC and free-space optics (FSO) transceivers with a simple graphical user interface and the capability of indoor wireless communication and multimedia broadcasting, thus presenting an economical and cable-free solution to various multimedia applications, such as file transmission and real-time audio and video streaming. The proposed system deploys VLC as a hotspot for data broadcasting within an enclosed room, FSO as the backbone for data transmission between multiple rooms, and Wi-Fi for lights-off mode. Preliminary results show a transmission rate of 1kbps at a maximum distance of 4 cm.

Keywords: Visible light communication, free-space optical communication, hybrid, optical transceiver, wireless data broadcasting

1. Introduction

From the discovery of electromagnetic (EM) waves to the invention of the radio and development of wireless fidelity (Wi-Fi), wireless communication has gone through several shifts and evolutions. Nonetheless, most of the wireless communications nowadays operate using radio frequency (RF) waves, primarily due to its wide area coverage and minimal interference [1]. However, there is a continuous development of online social services and an ever-increasing number of devices requiring high-speed and ubiquitous broadband wireless access, both for personal use and as part of technological concepts such as internet of things (IoT) and smart homes [2]. Consequently, the RF spectrum suffers from severe bandwidth congestion and will not be able to keep supporting the exponential growth in demand [3]. The need for an inexpensive, high-speed solution to address the resulting bottleneck issues with last-mile connectivity has motivated research interest in the utilization of the visible light spectrum, which occupies a much wider bandwidth, for the development of wireless optical communication systems.

Visible-light communications (VLC), also known as light fidelity (Li-Fi), is a very high-speed duplex wireless communication technology that incorporates three major components, which include the light emitting diodes (LEDs) for transmission, a photo detector (PD) for reception, and a microcontroller for signal processing. In principle, the VLC technology utilizes visible light signals with wavelengths between 400 nm and 700 nm emanated from LEDs as the data transmission medium by switching these solid-state devices on and off at a very high frequency, such that the human eye perceives it as a steady glow. This technology is an apt candidate to complement and enhance the prevailing Wi-Fi technology, as it is a faster, cheaper, greener, cleaner, and safer optical version of Wi-Fi. In addition,
it offers approximately 10,000 times broader bandwidth as it uses visible light (i.e., 400-800 THz), and it is safe to operate in EM sensitive areas.

Despite the clear advantages offered by VLC systems, there are innate obstacles and limitations that need to be tackled for the technology to be implemented in real life applications. Whether VLC is to be implemented in indoor or outdoor applications, ambient light interference is inevitable. Sunlight and other artificial light sources, such as incandescent light bulbs and compact fluorescent lamps, can cause interference and effectively act as unmodulated light sources at the receiver end, thereby increasing shot noise and possibly saturating the receiver [1]. Thus, it is imperative to remove or filter out this in-band noise for the signal quality to be improved at the receiving end. In addition, illumination suffers a sharp decrease in intensity with increasing distance, which limits the transmission distance to close range communications only. Furthermore, VLC, naturally, requires a clear line of sight (LOS) for signal transmission. As a result, shadowing caused by cuts in light of sight by passing people or objects can deteriorate the signal [4]. Lastly, a proper “lights off” mode is needed, as one of the main goals of VLC is to combine illumination with communication, begging the question: what about when illumination is not desired? Since VLC depends on illumination for signal transmission, switching to Wi-Fi when the lights are off, is a likely solution.

In the past decade, there has been a plethora of research on the utilization of visible light for wireless data broadcasting. A portion of which has been focused on hybrid systems for improved performance and wider coverage. In [5], Basnayaka et al. demonstrated that the introduction of RF access points (APs) to the VLC system significantly improves the system performance, as evident from the increase of average user throughput and reduction of outage probability. In [6], Shao et al. compared a practical hybrid RF/VLC system to a standalone Wi-Fi system, showing reduced congestion in the hybrid system. Another important aspect of VLC system is power efficiency and optimization. In [7], Kafafy et al. showed that the addition of VLC transmission to complement RF transmission improves power efficiency by using simulations to compare a hybrid RF/VLC indoor system to an RF-only system. In [8], Obeed et al. proposed a scheme focused on the optimization of power allocation and load balancing in a hybrid RF/VLC system, resulting in faster convergence and better performance. In [9], Zhang et al. proposed and implemented an experimental hybrid VLC/Wi-Fi system by integrating multiple links to achieve an indoor high-speed wide-coverage network, with results showing better coverage and greater network capacity than both single VLC and Wi-Fi networks. Meanwhile in [10], Huang et al. presented a hybrid optical wireless network based on free-space optical (FSO) and VLC heterogeneous connection. The system uses FSO-based inter-communication and VLC-based intra-communication among different RF-sensitive cabins, with results validating the feasibility of an all-optical wireless network. However, despite recent efforts, practical deployments of hybrid systems remain insufficient. Furthermore, to the best of our knowledge, there is no implementation of a hybrid VLC/FSO system with supplementary Wi-Fi.

In this paper, we propose a system with low-cost, portable hybrid RF/VLC and RF/FSO transceivers with simple graphical user interface (GUI) and the capability of indoor wireless communication and multimedia broadcasting, thus presenting an economical and cable-free solution to various multimedia applications, such as file transmission and real-time audio and video streaming. The proposed optical transceiver designs for both VLC and FSO are based upon the integration of the transmitter and receiver hardware and interactive software modules. The VLC transmitter utilizes the fast switching of super bright LEDs, meanwhile the FSO transmitter uses a laser. Both the VLC and FSO systems use PDs for signal reception and Raspberry Pi 3s (Model B+) for signal processing. Multimedia sources encrypted in various formats are first encoded into a series of binary bit streams using an algorithm within the software module, then sent through free space using LEDs and laser for VLC and FSO, respectively.

The remainder of this paper is organized as follows: Section II describes the physical construction and principles of operation of our proposed hybrid VLC/FSO system. Next, Section III provides a detailed explanation on the implementation of hardware modules, which include the VLC and FSO transmitters, and the hybrid VLC/FSO receiver. In Section IV, the link integration algorithm and data
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processing mechanism are presented. Finally, concluding remarks are highlighted in Section V.

2. The proposed hybrid VLC/FSO system

Figure 1 illustrates the theoretical conceptualization of our proposed hybrid VLC hotspot network with an all-optical-based wireless backbone system for indoor deployment. The backbone links adopt the FSO communication technology, and are constructed by utilizing various optical components, which include highly coherent laser sources, beam splitters and refractors, optical lenses and filters, and PDs. The backbone solution will form the last-mile access interconnection, for enabling high-speed wireless data broadcasting from the main fiber input (server/internet) to the VLC transceiver modules located at the various lighting points in multiple enclosed rooms within a building. On the other hand, downlink transmission of bandwidth-intensive internet and multimedia data (in ranges of Mbps) will be dominated by the VLC communication link, whereas the complementary Wi-Fi link will be operated during intermittent VLC downtime (lights-off mode) and/or dedicated uplink requests.

Next, Figure 2 depicts the block diagram of the proposed hybrid VLC/FSO system for implementing the indoor wireless optical hotspot network, clearly outlining the physical construction and important functions of the FSO and hybrid VLC systems. In principle, the FSO technology is used as the backbone for data transmission between multiple rooms, the VLC technology is deployed as indoor hotspots for data broadcasting in different enclosed room, and the Wi-Fi will be enabled during lights-off mode. The main purpose of using two wireless optical mediums is to ensure that the data can be transmitted not only in one confined room but also to the other rooms within a building topology. This is due to the fact that light cannot pass through opaque objects such as walls, and hence laser is used as the light source as its refractivity property allows its light beams to be refracted.

The VLC and FSO systems, each consists of two main modules which are hardware involving the construction of the circuit and software module involving the GUI and data processing algorithm. In the Wi-Fi system, there is no need of hardware circuit module (except Raspberry Pi 3 B+) but only the GUI and the data processing algorithm. In both software module, the GUI enables user to upload selected video files (e.g., mp4, wmv, avi) to the small single-board computer, Raspberry Pi 3 B+. After selection of a media file for file transfer, the maximum file size of the media file will be estimated to enable equal partitioning of the media file into small data chunks. Conversion of the media data to the binary will be performed to allow stream of binary bits of data to be transmitted. In VLC and FSO systems, the binary bits are used to control the switching ‘ON’ and ‘OFF’ of the light source.
The method of transmission of video file or data in Wi-Fi system is through the transmission control protocol (TCP) whilst the method in VLC and FSO systems are through the controlling of the optical pulses using LED and laser diode, respectively. The GUI developed enables user to select the method of transmission between Wi-Fi (TCP), VLC (LED), and FSO communication (Laser). All transmitters and receivers are connected to a PiTFT touchscreen, where the GUI is displayed for the convenience of the end users to utilize the system.

In the hardware module, Raspberry Pi 3 B+ act as the main medium which host the GUI program and performs data processing algorithm. LED and Laser diode are used as the transmission light source for this proposed VLC/FSO communication system. These data communication is achieved by enabling the LED and laser light source to switch between “on” and “off” states based on the corresponding stream of binary bits received from the Raspberry Pi through the defined GPIO pin in the software. This system depends on the both LED and laser driver circuit to modulate the baseband information using the on-off keying non-return-to-zero (OOK-NRZ) technique. For laser, as the laser light is propagating through the atmosphere, there is an aspheric lens placed along the laser propagating course to produce a collimated laser beam. A beam splitter aid in splitting the laser beam into two components as the hybrid VLC hotspots are located separately. As the laser beam approaches the last VLC hotspot, a beam refractor is used to redirect the beam (at 90°) towards the receiver. The laser beam propagates towards the VLC hotspots are received by the silicon PD. The reason laser is proposed in this communication system is mainly because the intensity of laser light is more collimated, refractivity property and able to travel across a far distance. Hence, it is useful for long haul communication application. A PD is used to convert the respective optical information to electrical information based on the photodiode’s responsively.

After receiving the optical information by the PD at the receiving end, the output electrical signal will be decoded by the data decoding algorithm in the Raspberry Pi at the receiving end. The algorithm will convert the respective signals into series of binary data chunks and concatenate them. Upon receiving the data chunks, the data will be saved in the desired location in the Raspberry Pi in which the user can select the destination file in the GUI. While saving the files, the chunk of video files will be played accordingly.

3. Hardware implementation

VLC transmitter
Figure 3(a) shows the VLC transmitter block diagram. As previously mentioned, the data (e.g. video file) is first encoded into a binary bit stream by the Raspberry Pi 3 B+. The bit stream is then used to control the LED driver circuit, shown in Figure 3(b), for the transmission of optical pulses via free
space. As shown the LED driver circuit consists of two n-channel MOSFETs used for the switching of a 4x3 white LED array, where each transistor controls the current for two lines of three LEDs. This is achieved by connecting the drain of the transistor to the LEDs, the source to the ground, and the gate to a Raspberry Pi GPIO pin. A “0” in the bit stream is represented as a low at the GPIO pin, causing the transistor to act as an open circuit, which turns off the LEDs. On the other hand, a “1” in the bit stream is represented as a high at the GPIO pin, causing the transistor to act as a closed circuit, which allows the LEDs to draw current from the voltage source and, thus, turn on. The supply voltage is from a 12V adapter connected to an electricity plug. Each LED line is connected to a 4.7 Ω to limit the current to approximately 150mA to maximize brightness while avoiding the overheating and burning of LEDs. The LEDs used are surface-mount phosphor-based white LEDs, with an output light of mainly 450nm. The VLC transmitter prototype can be seen in Figure 4.

\[ \text{Figure 3. (a) Block diagram of the VLC transmitter; and (b) the LED array driver circuit.} \]

\[ \text{Figure 4. The VLC transmitter prototype with integrated touch screen for end user.} \]

**FSO transmitter**

Figure 5(a) illustrates the block diagram of the FSO transmitter module, which adopts the FSO technology to enable the wireless backbone transmission of data via the optical laser source. This
block diagram involves the video data as the input, Raspberry Pi B+, laser driving circuit, laser diode, beam splitter and beam refractor. The schematic diagram of the laser transmitter module operated on a 12 V DC power supply is depicted in Figure 5(b).

![Figure 5. (a) Block diagram of the FSO transmitter; and (b) the laser transmitter module.](image)

During the transmission of optical signal, a portion of it will go through the beam splitter while the remaining will be refracted (at 90°) to VLC Hotspot 2. Upon reaching the final VLC Hotspot 3, the remaining optical signal will be refracted (at 90°) using an optical prism. This allows the data to be transmitted not only in a confined room but also across multiple rooms. A visible red-light laser diode is used due to its property which lies in the visible light spectrum between 400nm and 750nm (perceivable by human eyes).

The desired video data to be transmitted (baseband information) is transferred to the raspberry pi either by downloading from the internet or through the USB 2.0 connection. This baseband information is converted into binary format for better representation and is being modulated using OOK-NRZ technique before feeding to the respective driver circuit. The OOK-NRZ modulation technique is performed using the raspberry pi to turn on the laser diode when the binary is set to ‘HIGH’ and off when the binary is set to ‘LOW’. It modulates the optical device (laser) directly in accordance with the binary signal. High speed switching of data between ‘HIGH’ and ‘LOW’ is required during the wireless backbone transmission to achieve fast transmission of data via FSO channel. Raspberry pi is chosen as the microcontroller due to its functionality resembling a computer for its high performance, Wi-Fi connectivity, USB 2.0 compliant, General Input-Output Connector (GPIO), UART functionality, etc. The transmission data rate can be set to any value suited for its application and in this case 100kbps of data is being used as the transmission rate.

The output of the raspberry pi is then connected to the laser driver circuit that uses the 2N2222 NPN bipolar junction transistor (BJT) as the switching device to drive the laser between saturation (ON) and cut-off (OFF). During the process of switching, different intensity of the optical energy of the pulses are released into the transmission channel. The changes in the intensity of laser light is imperceptible due to the high switching rate of the laser driver circuit between “ON” and “OFF” states. The light beam is focused with the use of aspheric lens to produce coherent beam that will not be dispersed easily or in other words more collimated. A beam splitter or beam refractor is placed
after the aspheric lens to redirect the light beam to the respective VLC Hotspot. This acts as the backbone for wireless data transmission across multiple rooms.

The hybrid VLC/FSO receiver

The FSO receiver act as the first receiving domain for the transmission of light across multiple rooms whilst the Hybrid VLC receiver act as the second receiving domain in multiple enclosed rooms. Both systems share the same receiver module in which the optical signal energy will be detected and collected by the PD. Figure 6 depicts the block diagram of the optical receiver module for FSO and VLC which involves the use of PD, optical filter, raspberry pi and integrated touch screen. To filter out unwanted noise caused by ambient light, the light is passed through an optical filter before reaching the PD. The PD is used to convert the optical signal into electrical signal (photocurrent) based on the received light intensity or energy. In this work, the PDA10A is used due to the following:

1. it’s application range that is able to detect light signals over range 200nm to 1100nm wavelength;
2. built-in trans-impedance amplifier in the detector that converts the photocurrent to voltage;
3. peak wavelength at 730 nm which falls in the visible light spectrum typically red light that has wavelength between 620 nm and 750 nm;
4. good detector responsivity that has peak response of 0.44A/W at 730nm; and
5. active detection area of 0.8 mm². After the signal is collected by the PD in the VLC hotspot room, the data is sent to the raspberry pi for base band signal recovery. The recovered video data will then be played on a capacitive touch screen. This process of recovering and displaying the received video data are performed concurrently to achieve multithreading.

4. Data processing mechanism

Figure 7 shows the flowchart for handling the integration between the FSO and VLC links, in order to enable inter-room and in-room data transmission within the hybrid hotspot network, respectively. An end user will be prompted to select a file to be transmitted and to identify the desired hotspot node serving the targeted receiving terminal, by using the touch screen connected to the transmitter module. The code, first, checks if the file exists; and if it doesn’t, an error message is displayed and the user will be prompted to select the file again. Upon validating the file status, the algorithm decides whether to enable the FSO or VLC link based on the specified hotspot node. If the sending is to be done within the same room, the VLC link will be enabled to transmit the file directly to the receiving terminal. On the other hand, if the data transmission is to be done across different rooms, the FSO link will be enabled for transmitting the file to the VLC AP in the desired room. Afterwards, VLC is used to forward the file to the end user.
Figure 7. Flowchart for handling the integration between the FSO and VLC links to enable inter-room and in-room data transmission within the hybrid hotspot network.

Figure 8 presents the flowchart for describing the data processing algorithm for data transmission using optical communication, which is used by both VLC and FSO transmitters. The data processing mechanism is divided into two main sections, which include the processing phase (in Figure 9(a)) and the sending phase (in Figure 9(b)). The rationale for dividing the algorithm into two phases is to maximize switching speed by avoiding delays due to conversion between every two consecutive bytes. Referring to the data processing phase in Figure 8(a), the video file is first opened for reading and the file size is checked. The file size is then divided by 10kB and rounded up if the value is not an integer. The resulting value is placed in the chunk_num variable, which is used to set the size of the chunk_array. For instance, a 433kB file has a chunk_array_size of 44. Next, the first 10kB of data is copied from the file to a data variable. Afterwards, the code loops through each byte, where b is the looping counter, converts it from Unicode to binary, and places it in string variable chunk, which is then put in chunk_array at the first index. The second 10kB are read, all bytes are converted to binary and put in chunk, which is then put in chunk_array at the second index. The process is repeated until there is no more data to be read from the file. The algorithm then proceeds to the sending phase as depicted in Figure 9(b), in which it loops through every bit in each data chunk, where i is the bit looping counter and c is the chunk looping counter, and triggers the GPIO pin accordingly. A GPIO “high” turns on the connected LEDs or laser, while a GPIO “low” turns them off. The switching is then detected by the PD and the file is recovered by the receiver. Figure 8 shows the waveform corresponding to the detection of an ASCII character “A”, which is transmitted via the LED array.
Figure 8. Waveform corresponding to the detection of an ASCII “A”.

Figure 9(a)

1. Start
2. Select a file to transmit
3. Check file_size
   - Is file_size empty?
     - No: Partition data
       - chunk_num = file_size \div 10 \, kB
       - chunk_array_size = \text{int}(chunk_num)
       - Read 10 kB from file and store in conv_data
         - Set b = 1 and data_chunk = “ ”
8. To sending phase
   - Is conv_data empty?
     - No: Read byte b from conv_data
       - Convert byte from unicode to binary and store in data_chunk
         - b = b + 1
     - Yes: Place data_chunk in chunk_array
Figure 9. Flowchart depicting the data processing mechanism, which consists of (a) the processing phase; and (b) the sending phase.

5. Conclusions

In this paper, we have proposed and initiated the implementation of portable, low-cost hybrid RF/VLC and FSO transceivers, which are based upon the integration of the transmitter and receiver hardware and an interactive software, in order to enable indoor wireless communication and data broadcasting within an enclosed room and across multiple rooms. The VLC transceiver consists of a Raspberry Pi 3 Model B+ as the system hub, an LED array as the transmitter, and the Thorlabs PDA10A as the optical receiver. Likewise, the FSO transceiver consists of a Raspberry Pi 3 Model B+ as the system hub, a laser diode as the transmitter, and the PDA10A as the receiver. The interactive software module consists of a GUI and data processing algorithms for the control of file transmission and the real-time interaction with multimedia applications. Touchscreens, with the GUI, are attached to the transmitters and receivers for the end user.

References

[1] Karunatilaka D, Zafar F, Kalavally V and Parthiban R 2015 LED based indoor visible light communications: state of the art IEEE Commun. Surveys Tuts. 17 pp 1649-78

[2] Khan LU 2017 Visible light communication: applications, architecture, standardization and research challenges Digit. Commun. Networks 3 pp 78-88

[3] Haas H, Chen C and O’Brien D 2017 A guide to wireless networking by light Prog.
Quantum Electron55pp 88-111

[4] Jha P K, Mishra N and Kumar D S 2017 Challenges and potentials for visible light communications: state of the artProc. AIP Conf.

[5] Basnayaka D A and Haas H 2015 Hybrid RF and VLC systems: Improving user data rate performance of VLC systems Proc. IEEE Veh. Technol. Conf. pp. 1-5

[6] Shao S et al. 2015 An indoor hybrid WiFi-VLC internet access system Proc. 11th IEEE Int. Conf. Mob. Ad Hoc Sens. Syst. (MASS 2014) pp. 569-74

[7] Kafafy M, Fahmy Y, Abdallah Mand Khairy M 2018 A novel bandwidth and power allocation scheme for power efficient hybrid RF/VLC indoor systems Phys. Commun. 31 pp 187-95

[8] Obeed M, Salhab M, Zummo A and Alouini M 2018 Joint optimization of power allocation and load balancing for hybrid VLC/RF networks IEEE/OSA J. Opt. Commun. Netw. 10

[9] Zhang W, Chen L, Chen X, Yu Z, Li Z and Wang W 2017 Design and realization of indoor VLC-Wi-Fi hybrid network J. Commun. Inf. Networks 2 pp 75-87

[10] Huang Z et al. 2017 Hybrid optical wireless network for future SAGO-integrated communication based on FSO/VLC heterogeneous interconnection IEEE Photon. J. 9 pp 1-10