

## Article

# Power Consumption Efficiency Evaluation of Multi-User Full-Duplex Visible Light Communication Systems for Smart Home Technologies

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**Abstract:** Visible light communication (VLC) has recently gained significant academic and industrial attention. VLC has great potential to supplement the functioning of the upcoming radio-frequency (RF)-based 5G networks. It is best suited for home, office, and commercial indoor environments as it provides a high bandwidth and high data rate, and the visible light spectrum is free to use. This paper proposes a multi-user full-duplex VLC system using red-green-blue (RGB), and white emitting diodes (LEDs) for smart home technologies. It utilizes red, green, and blue LEDs for downlink transmission and a simple phosphor white LED for uplink transmission. The red and green color bands are used for user data and smart devices, respectively, while the blue color band is used with the white LED for uplink transmission. The simulation was carried out to verify the performance of the proposed multi-user full-duplex VLC system. In addition to the performance evaluation, a cost-power consumption analysis was performed by comparing the power consumption and the resulting cost of the proposed VLC system to the power consumed and resulting cost of traditional Wi-Fi based systems and hybrid systems that utilized both VLC and Wi-Fi. Our findings showed that the proposed system improved the data rate and bit-error rate performance, while minimizing the power consumption and the associated costs. These results have demonstrated that a full-duplex VLC system is a feasible solution suitable for indoor environments as it provides greater cost savings and energy efficiency when compared to traditional Wi-Fi-based systems and hybrid systems that utilize both VLC and Wi-Fi.

**Keywords:** full-duplex; smart home; visible light communication; energy consumption

## 1. Introduction

With the rapid increase in the number of multimedia-capable and internet-connected devices, there is an increasing need for further development of wireless technology in order to meet these demands. The most common means of data consumption are watching high-definition (HD) videos and accessing cloud-based services. Most of the data consumption has been observed to occur in indoor environments, where users consume data using their smart devices at their residence, in shopping malls, in aircrafts, and in other vehicles. This high demand of data usage is expected to continue to grow in the foreseeable future. With highly-congested radio frequency (RF) bands, visible light communication (VLC) is considered to be a supplementary technology that can be adopted to bridge the gap between user demand and capacity.

VLC uses light emitting diodes (LEDs) to accomplish illumination and data communication. VLC has shown potential to be an integral part of the upcoming 5G network. While the market has continued to push the limits of the network data rate and capacity offered to users, the wireless

communication industry has found it difficult to meet these demands. It is estimated that for 5G networks, there will be a thousand-fold increase in data traffic [1]. In order to meet these demands, 5G networks will have to rely on more efficient technology. It is highly likely that it will incorporate smaller cells (atto-cells), utilize additional spectrum resources, employ techniques to ensure communication is more energy efficient, and have a provision for heterogeneous network (Het-Net) integration [2].

In comparison to traditional RF wireless communication, VLC has many favorable characteristics [3]; for example, it provides a spectrum of visible light for free, it can be securely used for indoor transmission as light cannot penetrate solid objects, it can be deployed wherever LEDs are installed [4], and it usually has a high signal-to-noise ratio (SNR) due to its high illumination requirements.

VLC can provide a high bandwidth density, which can help in bridging the gap between the demand and supply of high bandwidth that currently affects RF-based networks. Considering these favorable characteristics, VLC is currently best suited to assist Het-Nets in 5G networks, making it a promising supplementary technology for 5G systems that can be deployed as an affordable commercial product for smart homes in the near future. However, it has various new challenges that will spark interesting new research in the future [5,6].

### 1.1. Related Work

There is a currently a limited amount of work on multi-user full-duplex VLC systems in the current literature. The authors in [7,8] proposed color shift-keying (CSK)-based downlink multi-user schemes; however, the proposed schemes were not bidirectional. Researchers in [9], addressed the bidirectional issue by proposing time division duplexing (TDD), however, this was implemented only for a single-user environment. Recently a new user allocation scheme for bidirectional multi-user access for VLC networks was proposed by authors of [10,11]. However, this scheme limited the operation of its users to their respective color cluster, thus making it difficult for the user to be mobile. Apart from the aforementioned papers, other work that has been proposed includes the deployment of LEDs on the room ceiling to control the SNR fluctuation for multi-user scenarios [12], a code division multiple access (CDMA)-based multi-user VLC transmission scheme [13], and a multi-user VLC scheme based on channel control [14,15]. The authors in [16] proposed a new single gallium nitride (GaN)-on-silicon platform that helps in making an in-plane full-duplex VLC system operate at the same frequency on a single chip. The authors in [17] provided a complementary technology for the internet of vehicles that can use VLC as a full-duplex system to assist the vehicles in better communicating with other vehicles and traffic signs. Several other applications of VLC are in underwater communications [18], localization and tracking [19], and visible light communication local area networks (VLN) [20].

With the introduction of the Internet of Things (IoT), smart homes have become a very active area of discussion and research. In [21], the authors proposed a real-time evaluation of energy management systems for smart hybrid home microgrids. Özkan [22] developed an appliance-based control for home power management systems. Other authors [23–25] focused on energy management and power consumption in smart cities. Zhang et al. [26] and Jiang et al. [27] proposed energy efficient schemes for non-cooperative cognitive radio networks. Although there have been major advances in relevant research areas such as smart grids, smart cities, and radio networks, there has been limited research on increasing the energy efficiency and minimizing power consumption for VLC systems in smart homes. Hence, there is a need for a robust multi-user full-duplex VLC system that can be easily integrated in smart home applications.

### 1.2. Contribution

In this paper, a multi-user full-duplex VLC system is proposed which supports multi-user full-duplex communication. The main contributions of this paper are as follows:

- A multi-user full-duplex VLC system is proposed.
- The system is capable of handling both user devices and smart devices.

- The downlink section of the system separates the data based on the type of user. A red light is used to transmit user data while green light is used for smart device data. Asymmetrically clipped optical orthogonal frequency-division multiplexing (ACO-OFDM) is used as the modulation scheme to cater to multiple users and minimize interference.
- A resource allocation scheme is also implemented to efficiently assign resources during downlink transmission.
- The uplink section of the system uses blue light to transmit both user and smart device data. The modulation scheme used is on-off keying (OOK).
- Pulse amplitude modulation (PAM)-OOK is used to efficiently assign resources during uplink transmission.
- The performance of the system is analyzed and an in-depth cost-power evaluation is provided to test for feasibility.
- The proposed system is compared with other available systems such as traditional Wi-Fi and hybrid VLC-Wi-Fi implementations.

The rest of the paper is outlined as follows. Section 2 discusses the VLC system model. Section 3 describes in detail the proposed multi-user full-duplex VLC system designed for a smart home. In Section 4, the resource allocation scheme is explained. In Section 5, the cost and energy evaluation is presented. In Section 6, results of the proposed system along with the evaluation of the cost and power consumption is discussed. In Section 7, conclusions based on the results are provided.

## 2. System Model

The proposed multi-user full-duplex VLC system for smart homes is shown in Figure 1. For a particular smart home scenario, there are two types of traffic that mainly need to be taken into consideration: traffic from the user data and from smart devices. In order to account for these two types of traffic and ensure transmission occurs without any interruption, a well-defined mechanism needs to be implemented. The system can best be understood if it is broken into two sections: uplink and downlink. In this section, a simple overview of the two sections is given, followed by a more detailed description in Section 3.



**Figure 1.** Proposed multi-user full-duplex visible light communication (VLC) system.

Since red-green-blue (RGB) LEDs are used in the proposed communication system, three primary channels are available for use. Red and green lights are chosen over blue light as the latter has a shorter wavelength, which means it travels a comparatively shorter distance before being scattered. The proposed system is divided into downlink and uplink sections, the majority of data used by the users and devices flows in the downlink section. To ensure that the system is robust, red and green light are used for user data and device data respectively. Unmodulated blue light is used for downlink transmission. The intensity of the three lights is controlled so that the output light is white, making it easy for the human eye to adjust to the environment such that people can continue their daily tasks without interruption. Receivers present in the downlink section are equipped with red or green optical filters so that the user data and the device data are separated. To ensure simplicity in the system design, the ACO-OFDM scheme is used to modulate the signal on the downlink channel. A brief description of ACO-OFDM is given in Section 3.

A phosphorus LED, which is a blue LED coated with a phosphorus layer to emit white light, is used in the uplink section. Blue is chosen over red or green to avoid interference between uplink and downlink transmission. Receivers present in the uplink section are equipped with blue optical filters to receive incoming data. An OOK scheme is chosen as the uplink modulation scheme as it simplifies the system design, ensures robust performance and helps uplink devices like smartphones, which have limited power resources, to extend their battery life and efficiently utilize their computational power.

The channel and LED deployment designed for use in smart homes is given in [28]. Results obtained in [29] show that circular LED deployment provides best average received optical power distribution (ROPD) on the receiving plane. It performs better than traditional rectangular- and array-based deployment of LEDs on the ceiling. Additionally, the number of LEDs required in this configuration is lower than that required by traditional deployment techniques, thus reducing the power consumption and deployment cost. Moreover, it utilizes particle swarm optimization (PSO) to create room specific deployment to ensure that every room obtains the minimum luminosity required as per the IEEE 802.15.7 VLC Standard [30]. Consequently, it has been chosen as part of our system design, as shown in Figure 1.

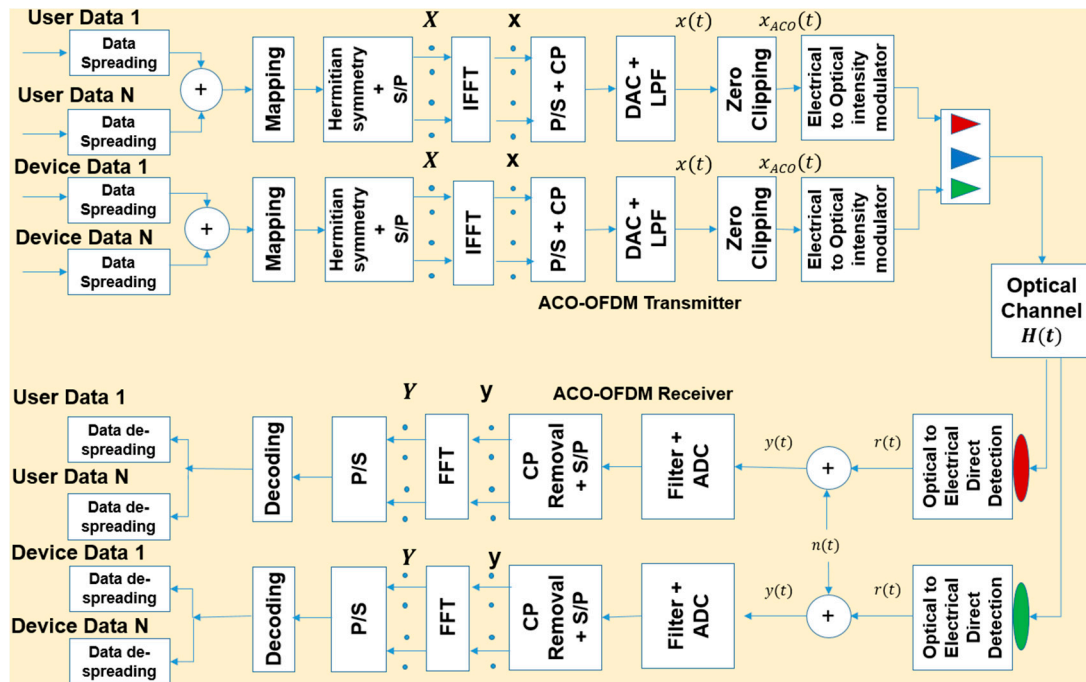
### 3. Proposed Multi-User Full-Duplex Visible Light Communication System

The proposed multi-user full-duplex VLC system is designed to allow users located in a smart home to fully utilize the advantages of VLC in both downlink and uplink channels. Owing to this, the system is divided into two main sections: the downlink section and the uplink section. For the downlink section, as was briefly explained in Section 2, RGB LEDs are used. The red and green primary colors are used to carry user and device data respectively, while the uplink section utilizes phosphorus LEDs. Both of these are described in detail in this section. First, the downlink section is explained in detail and later the uplink section is discussed.

#### 3.1. Downlink Section

The downlink section of the proposed system consists of a transmitter and receiver. The block diagram of the downlink section is shown in Figure 2. Working of the transmitter shall now be examined. Data streams (from users and/or devices) are fed into the data spreading block. The block spreads the user/device data by using a unique orthogonal Walsh code. The next step combines all the encoded data streams and sends it to the modulation block. The ACO-OFDM scheme is used as it is power efficient and to avoid DC bias [31]. The ACO-OFDM is described in detail in Section 3.1.1. The modulated signal is then passed through the DC bias to make sure the overall output of the LED is a bright white light. The signal then propagates through the optical wireless channel and is received by the user or a smart device. The architecture of the user and smart device receiver is mostly similar except a slight modification is made in the photodetector section. Since the user data is sent over the red light region, the user receiver must have a red optical filter at the photodiode (PD). Similarly, as the device data is sent over the green light region, its receiver must have a green optical filter at the PD.

After filtering the respected signals, the reverse procedure is performed to recover the original data. Every user has his/her own orthogonal Walsh code to increase security and avoid interference and data corruption during data transmission.



**Figure 2.** Block diagram of the downlink section. S/P: serial to parallel; IFFT: inverse fast Fourier transform; P/S: parallel to serial; CP: cyclic prefix; DAC: digital-to-analogue converter; LPF: low pass filter; ACO-OFDM: asymmetrically clipped optical orthogonal frequency-division multiplexing; and ADC: analogue-to-digital converter.

### 3.1.1. Asymmetrically-Clipped Optical Orthogonal Frequency-Division Multiplexing

VLC uses intensity modulation with direct detection (IM/DD) and the signal generated by the OFDM modulator is complex and bipolar. However, the main requirement of a VLC system is that it is given only real and positive values from the optical modulator as input. As a result, it is necessary to make the OFDM signal unipolar and real. The ACO-OFDM modulator inherently performs this task.

To ensure that the output of ACO-OFDM is real and unipolar, the following procedure is followed [24]. There are  $N$  sub-carriers, out of which only odd ones are used to send data. At the transmitter, the source bits are first modulated using a Gray-coded  $M$ -ary quadrature amplitude modulation (QAM) mapping block, where  $M$  is the modulation order, which produces a complex bit stream. Subsequently, in order to maintain the real OFDM symbols in the time domain, the encoded data are passed through a Hermitian symmetry block. The data are then passed on to an inverse fast Fourier transform (IFFT) block and a clipper. A cyclic prefix (CP) is later added to avoid inter-symbol interference (ISI), which then drives the LED. The addition of a CP has a negligible impact on the SNR or the spectral efficiency of the VLC system. To reduce the peak-to-average-power ratio (PAPR), clipping is performed to combat two types of distortions, namely, the out-of-band distortion and the in-band distortion. The former is reduced by filtering and the latter is reduced by the addition of the CP. In ACO-OFDM, only odd sub-carriers are used for signal transmission [32]. The signal is subsequently converted from analog to digital using an analogue-to-digital converter (ADC) and later using optical intensity modulation (IM), data is sent over the optical wireless channel.

At the receiver end, using direct detection (DD), the signal is received by a PD. This will convert the signal from optical to electrical domain. The estimated signal is then passed to the ACO-OFDM



demodulator block. After demodulation, the signal goes through the de-mapping block and the original data stream is recovered.

The received signal at the receiver in the time domain is represented as follows:

$$y(t) = h(t)x_{aco}(t) + n(t) \quad (1)$$

where channel  $h$  can be either line-of-sight (LOS) or non-line-of-sight (NLOS). The main property of  $h$  is that it is always real and positive. The received signal in the frequency domain can be expressed as:

$$Y = HX_{aco} + N \quad (2)$$

where  $X_{aco}$  is the ACO-OFDM signal,  $H$  is the optical wireless communication (OWC) channel response and  $N$  is the noise, which for simplicity, is assumed to be additive white Gaussian noise (AWGN) with mean equal to zero and variance  $\sigma^2$ . Perfect synchronization between transmitter and receiver is assumed.

The expression of LOS optical channel and NLOS optical channel is given by Equations (3) and (4) respectively. The total diffused channel response can be computed by Equation (6).

$$H_{los}(0) = \begin{cases} \frac{A_r(m_1 + 1)}{2\pi d^2} \cos^{m_1}(\phi) T_s(\psi) g(\psi) \cos(\psi), & 0 \leq \psi \leq \psi_c \\ 0, & \text{elsewhere} \end{cases} \quad (3)$$

$$H_{nlos}(t) = \frac{(m_1 + 1)}{2\pi} \sum_{j=1}^K \rho_j \cos^{m_1}(\phi_j) \frac{\cos(\psi)}{d_j^2} \text{rect}\left(\frac{2\psi}{\pi}\right) \times H_{nlos}^{(k-1)}\left(t - \frac{d_j}{c}\right) \Delta A \quad (4)$$

$$H_{nlos}(t) = \sum_i^K \sum_{k=0}^{\infty} H_{nlos}^k(t) \quad (5)$$

$$H_{total}(0) = H_{los}(0) + \sum_{refl} H_{nlos}(0) \quad (6)$$

In the above equations,  $A_r$  is the photodetector area,  $m_1$  is Lambert's mode number expressing the directivity of the source beam,  $T_s(\psi)$  is the receiver with the optical bandpass filter,  $g(\psi)$  is the concentrator gain,  $\psi$  is the radiation incident angle,  $\phi$  is the angle with respect to the transmitter,  $d$  is the distance from the transmitter,  $\Delta A$  is the area of reflecting elements,  $k$  is the total number of reflector elements in the room,  $\rho_j$  is the reflection coefficient of  $j$ , and  $H_{nlos}^{(k-1)}$  is the impulse response of order  $k - 1$  between the reflector and receiver.

### 3.2. Uplink

For the uplink section, a simple yet robust technique is required as the devices transmitting the uplink signal have limited resources. A simple OOK scheme is used to transmit the data from the user or smart devices to the receiver. Phosphorus LEDs are used for this purpose. A phosphorous LED is a blue LED coated with phosphorous in order to emit white light.

The block diagram of a simple OOK transmitter is given in Figure 3. The user or smart device data is first passed through a pre-emphasis circuit. This is done to improve the 3-dB bandwidth of the VLC link. The pre-emphasis uses negative-positive-negative (NPN) transistors to increase receiver sensitivity. Subsequently, the signal is passed through an amplifier to increase the modulation depth and is superimposed onto the LED bias current via the Bias-T block. The output of the Bias-T block is directly applied to the commercially available phosphorous LED. The signal then propagates through the optical wireless channel and is received by the receiver that has a blue optical filter. A directional lens is also used so that the light emitted can be focused onto the receivers so that maximum light falls on the PD.

At the receiver side after receiving the signal through the blue optical-filtered PD, a trans-impedance amplifier is used to amplify the electrical signal. This electrical signal is then passed through a post-equalization block so that the signal level is amplified and the original data is received. The performance of the system is analyzed in Section 6.

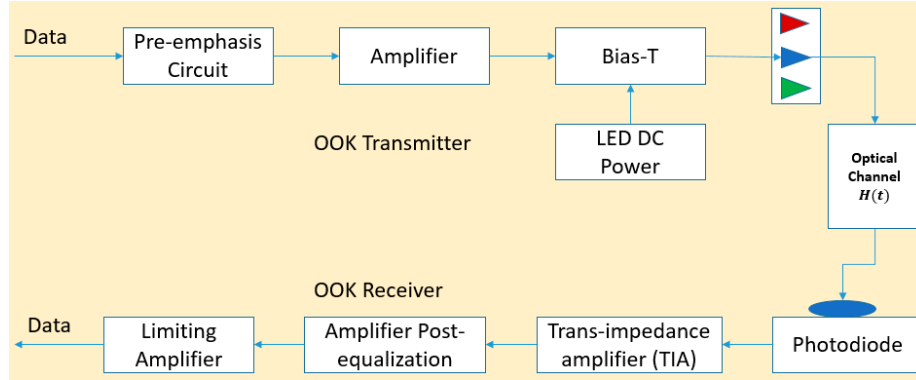


Figure 3. Block diagram of the uplink section. LED: light emitting diode; and OOK: on-off keying.

#### 4. Resource Allocation for Downlink and Uplink

The proposed system is divided into two sections, namely, downlink and uplink. In this section, the resource allocation scheme used for each is discussed. Before discussing the proposed system, let us briefly discuss the resource allocation scheme used in traditional systems, traditional Wi-Fi and hybrid VLC-Wi-Fi that we will compare the proposed system with. The resource allocation scheme used for traditional Wi-Fi is based on the latest IEEE 802.11ac Standard [33]. The hybrid VLC-Wi-Fi system uses a cooperative load balancing scheme, which was recently introduced in [34]. Their system is divided into two sections: downlink and uplink. The downlink section is based on a hybrid VLC and Wi-Fi system while the uplink section is based on the traditional Wi-Fi system. Cooperative load balancing that achieves proportional fairness is implemented by using a dual decomposition method. The detailed architecture of the two mentioned systems is discussed in Section 5. In Sections 4.1 and 4.2, the resource allocation scheme for the downlink section and the uplink section is described respectively.

##### 4.1. Downlink

In this section, ACO-OFDM, which is the resource allocation scheme used in the downlink section, is discussed. The LEDs installed on the ceiling are given a unique identification (ID) number (LEDID). Since OFDM is used, each LEDID is divided into subcarriers, which are further divided into different resource blocks (RBs). The users can send their data on the RBs allocated to them. Every RB within a specific LEDID is unique; however, the same RB can be used by different LEDIDs. This can result in co-channel interference. The signal-to-interference ratio (SNIR) of a user who has been allocated an RB of an LEDID can be expressed as follows:

$$\gamma_{u,LEDID}^{RB} = \frac{R_{PD} H_{u,LEDID} P_{u,LEDID}^{RB}}{\sum_{u=1,LEDID}^U H_{u,LEDID} P_{u,LEDID}^{RB} + noise} \quad (7)$$

where  $R_{PD}$  is the responsivity of the PD,  $H_{u,LEDID}$  is the channel gain between the user  $u$  and the LEDID,  $P_{u,LEDID}^{RB}$  is the transmission power of the LEDID for a given RB, and  $noise$  is the cumulative noise power. The cumulative noise power is given by:

$$noise = 2qR_{PD}I_{amb}B_{noise} + \frac{4kTB}{R_L} \quad (8)$$

where  $q = 1.6 \times 10^{-19}$  C,  $I_{amb}$  is the ambient light intensity,  $B_{noise}$  is the noise bandwidth,  $k$  is Boltzmann's constant,  $T$  is the absolute temperature, and  $R_L$  is the amplifier gain.

The utility function is constructed based on the user and what type of transmission is required. Since there are two types of users present in this system, the quality of service (QoS) differs based on the type of device trying to access the system. The utility function should primarily reduce the transmission power required and cater to the needs of the user or smart device. Secondly, it should try to extend the battery life of the associated mobile device(s), provide high data rates, and reduce interference in the multi-user environment. Each user or device has their own independent utility function based on their QoS requirements and the value of the aforementioned parameters. The utility function that accounts for the above parameters is given by:

$$U_{u,LEDID}^{RB} = \frac{W \cdot f_u(\gamma_{u,LEDID}^{RB})}{N_t \cdot P_{u,LEDID}^{RB}} \quad (9)$$

where  $N_t$  is the number of users served by the LED,  $W$  is the bandwidth available, and  $f_u(\cdot)$  is the efficiency function. The efficiency function represents the probability of a successful packet transmission.

The proposed algorithm is called non-cooperative resource allocation (NRA) and is defined in Table 1. It is decentralized and determines the user or device LEDID selection and resource allocation in a distributed manner. It is iterative and has a low complexity. It consists of two parts. The first part is the selection of the LEDID. This is based on the maximum gain selection (MGS) policy. The second part is the resource allocation where the RBs are allocated depending on their QoS requirements. The second part is iterative and it will keep repeating the algorithm until it converges to a unique solution. The user is assumed to have perfect knowledge of the channel matrix  $H(u, LEDID)$ , i.e., the channel between the user/device and the LED.

**Table 1.** Non-cooperative resource allocation (NRA).

Light-Emitting Diode Identification Number Selection	
Step 1:	At the start of each time slot, the user will have perfect knowledge of the channel matrix $H(u, LEDID)$ .
Step 2:	A pool of users that are contending for data transfer is created.
Step 3:	Each user/device will select an LEDID based on the highest available channel gain using the maximum gain selection (MGS) policy.
Step 4:	After successful selection of LEDID, the user is connected to one LED and it waits for data to be allocated to it. After data, has been allocated to the user, it is deleted from the pool. If the user pool is empty the LEDID selection is halted, otherwise, Step 3 is repeated for the next user/device.
Resource Allocation	
Step 1:	From LEDID Selection, the user pool information is available.
Step 2:	Based on the user pool information, if the number of users is equal to the number of available resource blocks (RBs), then every user will be allocated an RB. Else, if the number of RBs is less than the number of users, it will allocate at least one RB to each user and sort the remaining users based on their channel gain. At this point, the RB allocation will be based on the channel gain, that is, depending on which users have the best channel. Else if the number of RBs is greater than the number of users, it will allocate the RB to each user which can be accommodated (users will be sorted based on the channel gain) while the users that are left will be rejected from the LEDID.

#### 4.2. Uplink

For the uplink section, PAM-OOK, a fairly simple resource allocation scheme, is deployed. OOK allows the users to be separated on the basis of their amplitudes. A lookup table is created which has all the information about the users/devices. In the simulations conducted, there were a minimum of 15 user/devices and a maximum of 30 user/devices. Consequently, a 5-bit encoder was sufficient

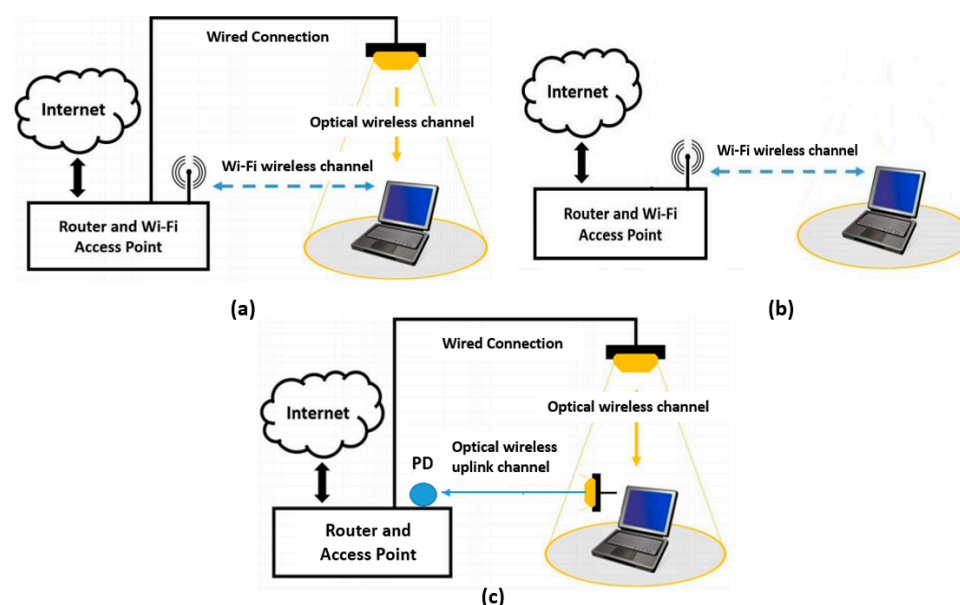


to allocate a unique amplitude to each user/device. Using PAM, each user is assigned a different amplitude level and using the lookup table the receiver is able to differentiate between different users/devices. The composite signal is transmitted to the uplink section and the receiver decodes the signal and separates the user data using the lookup table. In this way, a low-cost multi-user PAM-OOK is implemented which can cater up to 32 users and deliver acceptable performance for full-duplex multi-user VLC system.

## 5. Cost and Energy Evaluation

To deploy a multi-user full-duplex VLC system in the market, it must be both cost and power efficient. The proposed system is compared with two other systems that are commercially available and have been widely reviewed in the existing literature. The first system is the traditional Wi-Fi system that is currently one of the most widely used wireless systems in the world. The second system is the hybrid VLC-Wi-Fi system that is currently being widely studied and researched [34]. In this system, the downlink transmission can either be carried out using VLC or Wi-Fi but the uplink transmission is always based on Wi-Fi technology. This design was aimed at resolving issues that affect uplink transmission in VLC systems and ensures uninterrupted connection for the user or device. In this section, we compare the proposed system to the aforementioned systems and present analysis of the simulations results in Section 6.

The architecture of the two systems is described as follows. The simple Wi-Fi system consists of a router with a wireless access point. The router is connected to the wide area network (WAN) and using RF radiation, transmits and receives data. A simple Wi-Fi system is shown in Figure 4a. On the other hand, a hybrid VLC-Wi-Fi system utilizes both technologies to achieve a robust system performance. The downlink transmission can be based either on VLC or Wi-Fi, while the uplink transmission is based on Wi-Fi. The hybrid system is depicted in Figure 4b. Figure 4c shows the depiction of the proposed system.



**Figure 4.** (a) Traditional Wi-Fi model; (b) hybrid VLC-Wi-Fi model; and (c) proposed full-duplex multi-user VLC system. PD: photodiode.

In order to implement a VLC system, the use of signal processing unit (SPU) is essential. The nature and scope of the signal processing required depends on the size of the home and the number of users. This study presents different types of SPUs, whose architecture differ based on processing power, cost, and power consumption. Since VLC systems are yet to be commercially available, unlike Wi-Fi systems,

the initial installation cost that is included in the simulation and the results is an approximate value. As is the case when any new product is launched, the initial equipment price will be high when VLC is launched but as it becomes more common, the price will also decrease substantially. This is similar to what was observed when Wi-Fi was initially introduced in 1999.

In this study, the SPUs with different architectures are used and comparatively studied. The architecture of SPU can differ with respect to the number of cores and general-purpose input-output (GPIO) registers it offers. This can significantly affect the processing speed and power consumption of the whole system. As the number of cores increase, the performance of the unit increases but the cost and power consumed also increase and vice-versa. Thus, the SPU has to be carefully designed to ensure optimum balance. Table 2 presents several SPU architectures with different cost, power, and processing power. Since this paper is related to smart home technologies, architecture 1 will be used for simulation purposes. Both hybrid and full-duplex VLC systems use the same architecture and the results and analysis are given in Section 6.

**Table 2.** Architecture of different signal processing units (SPUs) with their approximated power consumption and cost [34].

Architecture	Specification	Signal Processing Power	Approximated Cost (USD \$)
1	1 Core	100 W	120
2	2 Core	100 W	200
3	4 Core	200 W	300
4	8 Core	400 W	400

As per Table 2, architecture 1 has one core and four GPIO registers. This is the most basic, low cost, and power-efficient processing unit. Since the number of sub-channels is not yet defined in the VLC standard, it is safe to assume that there are 32 sub-channels. Therefore, with the architecture 1 processing unit,  $4 \times 32 = 128$  users and devices can be accommodated. This is more than enough for a smart home application.

Table 3 provides the power consumption of an average American household. The table only shows devices that have the potential to use VLC in the future.

**Table 3.** Average household electronics power consumption and yearly cost. LCD: Liquid crystal display; HDTV: high-definition television; WLAN: wireless local area network; and ADSL: asymmetric digital subscriber line.

Device	Consumption in 1 h (kWh)	Cost per Year (USD \$)
LCD TV	0.346	466.65
HDTV set-top box	0.021	28.32
Apple iMac	0.108	145.66
Video player	0.028	37.76
Gaming console	0.016	21.58
Linksys WLAN	0.011	14.84
D-LINK switch	0.01	13.49
Belkin ADSL2 + Modem	0.005	6.74
Incandescent lamp (60 W Mirabella)	0.053	71.48
Energy-saving LED lamp	0.009	12.14

The performance evaluation of the three systems in terms of device cost and power consumption against data throughput is carried out. No commercial VLC products are currently available, which makes a comparison on the basis of cost and power consumption difficult. Consequently, we develop a criterion to illustrate the potential comparison between the three systems. For the hybrid VLC-Wi-Fi system and the proposed full-duplex VLC system, the cost of the SPU, which is typically used for commercial telecommunication system implementation and is based on the Texas Instrument

digital signal processing (DSP) board series C6000, is approximated [34]. The computation of the device cost and power consumption includes the cost of maintenance and electricity used in the long run. The indoor VLC environment simulation model is taken from [29]. Other simulation parameters are discussed in Section 6.

The calculation of the cost and power consumption of the first system, which uses simple LED lighting with Wi-Fi, is done using the following equations:

$$Cost = No\_LED_R \times No_{LED_N \times LED_{cost}} + WiFi_{cost} \quad (10)$$

$$Power = No_{LED} \times LED_{power} + WiFi_{power} \quad (11)$$

In the above equations,  $No\_LED_R$  is the number of LED lights replaced during the length of the simulation,  $No\_LED_N$  is the total number of LEDs used in a specific room,  $LED_{cost}$  is the cost of LEDs used,  $WiFi_{cost}$  is the cost of Wi-Fi equipment and the internet connection used,  $LED_{power}$  is the power consumption of the LEDs, and  $WiFi_{power}$  is the power consumption of both the Wi-Fi access point and the router.

The calculation of the cost and power consumption of the second system, which is a hybrid VLC-Wi-Fi system, is done using the following equations:

$$Cost = No\_LED_R \times No_{LED_N \times LED_{cost}} + SPU_{cost} + WiFi_{cost} \quad (12)$$

$$Power = No_{LED} \times LED_{power} + No_{LED} \times SPU_{power} + WiFi_{power} \quad (13)$$

In the above equations,  $SPU_{cost}$  is the cost of the SPU and  $SPU_{power}$  is the power consumed during the operation of the SPU. Here, the  $SPU_{power}$  is multiplied by the number of LEDs used because the LEDs are connected to the GPIO register of the SPU and consequently, will draw power according to the number of LEDs that are attached. The method of connecting the LEDs to the GPIO register can vary. For example, they can be connected such that each GPIO will entertain one LED, which is an expensive solution. Alternatively, an array of LED lights that serves one room can be connected to a specific GPIO, which would allow the whole home to be covered using only one SPU. As mentioned earlier, if there are 32 VLC sub-carriers, then by using a simple one-core and four GPIO register-based SPU, a total of 128 users or devices or both can be entertained.

The calculation of the third system, which is the proposed full-duplex VLC system, can be done using the following equations:

$$Cost = No\_LED_R \times No_{LED_N \times LED_{cost}} + SPU_{cost} \quad (14)$$

$$Power = No_{LED} \times LED_{power} + No_{LED} \times SPU_{power} \quad (15)$$

The main difference between the second and the third system is the removal of the Wi-Fi device. The analysis of the simulation is given in Section 6.

## 6. Result and Analysis

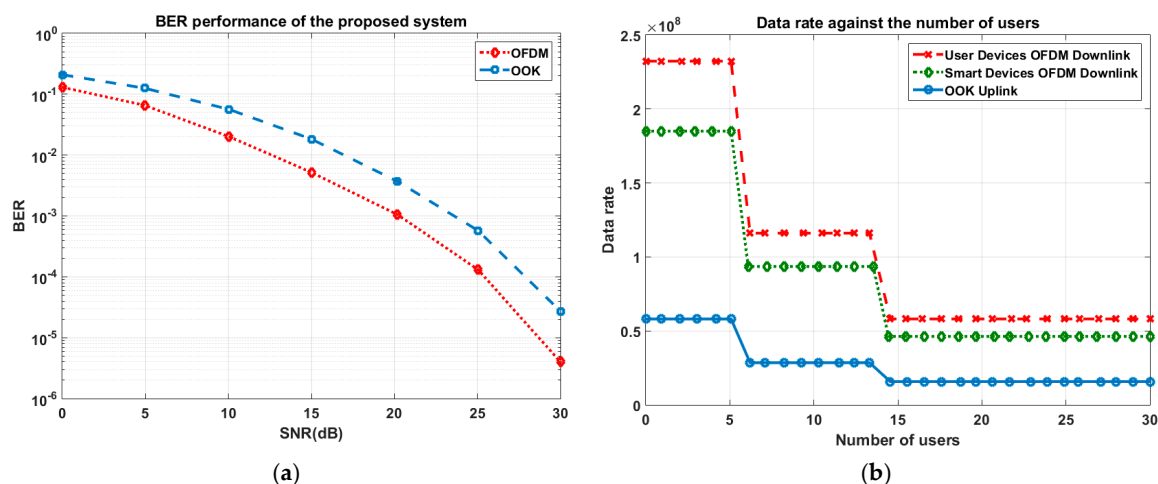
This section has two main parts: the first part will discuss the performance analysis of the multi-user full-duplex VLC system and the second part will evaluate the cost and power consumption against the data throughput of the proposed system. The section has been split into two parts as the analyses are based on different measuring criteria. The associated simulations are explained in detail in Sections 6.1 and 6.2.

### 6.1. Multi-User Full-Duplex Visible Light Communication System Performance Analysis

To simulate the performance of the proposed system, two main parameters were investigated, namely, the data rate and the bit error rate (BER). The simulation environment was identical to the one

set up in [29]. The room dimensions were  $5\text{ m} \times 5\text{ m} \times 3\text{ m}$ . The LED lights were deployed on the ceiling in a circular scheme to ensure optimized ROPD at the receiving plane. The receiving plane was set to an average height of 0.8 m. The system considered both LOS and NLOS signals to improve the system performance. In a VLC system, the dominant and most reliable signal path is an LOS path, however, as it is sometimes unavailable, the NLOS or the diffused path is considered. The power level of the NLOS path is significantly lower than that of the LOS path, however under certain conditions, it is strong enough for the receiver to successfully detect the correct signal. The resulting data were simulated for an average of five users and ten smart devices. As mentioned earlier, the downlink section is based on an ACO-OFDM scheme while the uplink section is based on a simple OOK scheme implementation.

Figure 5 shows the BER simulation results of the downlink and uplink sections of the proposed scheme along with the respective data rates. From Figure 5a, it can be seen that the BER performance of the proposed system for user and smart home devices is similar. The performance of the proposed system is compared to a simple OOK-based implementation of the same system for downlink transmission. It can be seen that the ACO-OFDM performs better than simple OOK implementation, which is due to the inherent advantages of ACO-OFDM and the added orthogonal Walsh codes used to avoid multi-user interferences. For uplink transmission, the performance of the proposed system is similar to that of a typical OOK system. This is an acceptable result as there are limited power resources present to achieve high SNR and the performance was sufficient to ensure reliable data transmission. While the use of OFDM instead of OOK for uplink will improve the data rate, the robustness, and the performance of the system, the main parameters under consideration were cost, energy consumption, and power consumption. As a result, the significant increase in cost of hardware required for OFDM made OOK a more favorable option. The results in Figure 5 show that an acceptable performance is achievable with the current implementation. With the current cost of hardware, the VLC system deployment will become very expensive, as a stronger SPU would be required and by looking at Table 2, the cost of SPU doubles as the number of cores and memory is increased. Please note that the system performance is not compared with the other two systems that were earlier mentioned as they utilize different techniques and resource allocation methods, consequently any comparison would be unfair. Further, the aforementioned systems are compared in terms of cost, energy, and power consumption to the proposed system in Section 6.2.



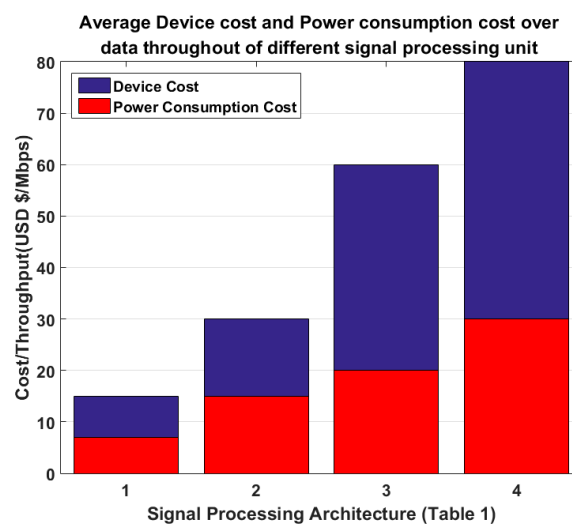
**Figure 5.** Simulation of the proposed system: (a) bit error rate (BER) performance of the proposed system and (b) data rate against the number of users. OFDM: orthogonal frequency-division multiplexing; and SNR: signal-to-noise ratio.

Figure 5b shows the downlink and uplink rates. The data rate for user devices and smart devices are shown in red and green respectively. The uplink data is shown in blue. From the figure, it can be seen that the user data rate is higher than the device data rate because smart devices do not consume a large amount of data while the user engages in data intensive activities such as streaming videos and surfing the internet. The uplink has the slowest rate but this is acceptable as in a smart home environment downlink is utilized more than uplink. It can also be seen that as the number of the users increased, the data rate decreased; this is because more users share the same amount of bandwidth. From this figure, one can conclude that the proposed system is capable of handling the user and smart device data, and provide acceptable performance that meets the requirements of an average smart home.

## 6.2. Cost and Power Consumption Against Data Throughput Analysis

The second part of this paper analyzes the cost and power consumption against the data throughput of the proposed system. The proposed system is compared with two other systems as was previously detailed in Section 4. Before discussion of the results, the simulation environment is explained. The system model used in this simulation is adopted from [29]. Circular LED deployment is used to conserve the energy. Additionally, since LEDs are used, they use 85% less energy and last 20 times as long as traditional incandescent light. This simulation was done for a four-year period with an average LED lifespan of 40,000 h, after which, the LED was replaced.

The first simulation is based on the cost and power consumption of the SPU. There are currently many high-quality SPUs available in the market, which are specifically designed for telecommunication purposes. For this simulation, a comparison of the different products of Texas instruments C6000 series DSP boards is done. The list of the DSP boards used is provided in Table 2. From Figure 6, it can be seen that as the computational power of the DSP increased the device cost also increased. The same trend can also be seen with power consumption and cost. Since the DSP industry is now moving towards efficient low power boards, the prices mentioned here are estimated based on this trend. It is expected that as power-efficient boards are introduced in the market, their device and power cost will decrease. For simulation purposes, a basic DSP board capable of handling the proposed system according to its specifications was chosen [34].



**Figure 6.** Simulated average device cost and power consumption cost over data throughput for different SPUs (Table 2).

A comparison was made individually between device cost, power cost, and total against data throughput. Figure 7 shows the device cost against the data throughput for each system as described in Section 4. It can be seen that the device cost for the proposed system is initially high but as



time passes, the system becomes cheaper due to low maintenance costs. The maintenance cost in this simulation includes replacement of light bulbs and hardware upgrades for the Wi-Fi device. Significantly, there would be no hardware upgrade needed for a VLC system as it would be able to handle the required data throughput for an average smart home for at least the next five years.

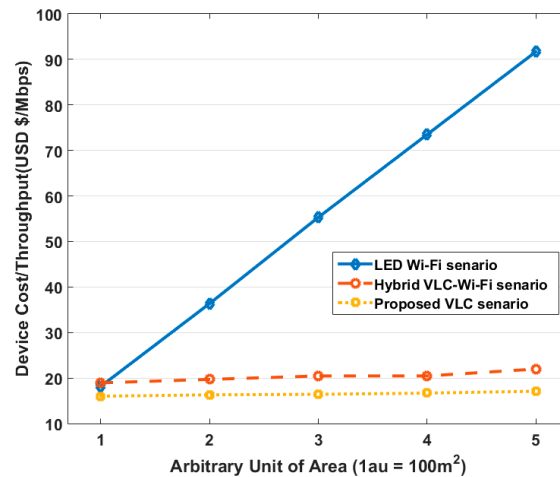


Figure 7. Device cost comparison of architecture 1 for all three systems.

Figure 8 shows the power cost against the data throughput for each system as described in Section 4. From the figure, it can be seen that systems 1 and 2 are expensive as they draw more power against data throughput. In comparison, due to the availability of a power-efficient DSP board, the power cost of the proposed system against data throughput is significantly less, which results in an overall low total cost when compared with that of the other two systems.

The total cost against data throughput is shown in Figure 9. It can be seen that the initial cost of the proposed system is higher than that of the other two systems, but as they approach the four-year mark, the proposed system turns out to be more cost- and power-effective. The purpose of this result is to illustrate a recurring pattern in the energy industry and resolve any confusion an average person may have on whether we should invest in VLC systems or not. The same trend was seen when LED lights were first introduced. The initial cost was much higher than that of the traditional incandescent lights, but with time, the savings owing to the LED lights were much higher than those for traditional incandescent lights. This has led to LEDs becoming more prominent than their traditional counterparts.

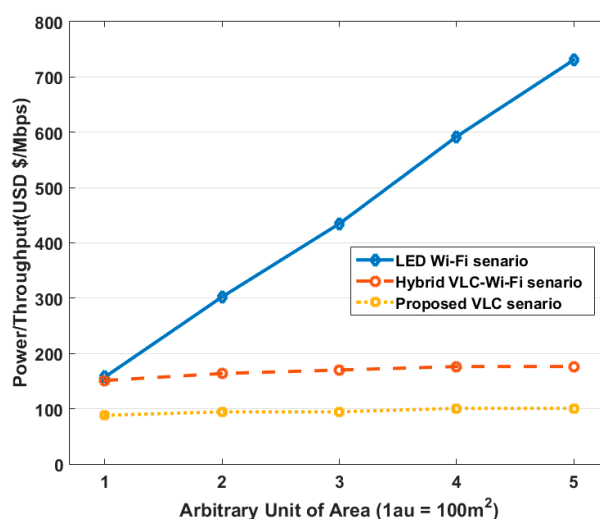


Figure 8. Power consumption cost comparison of architecture 1 for all three systems.

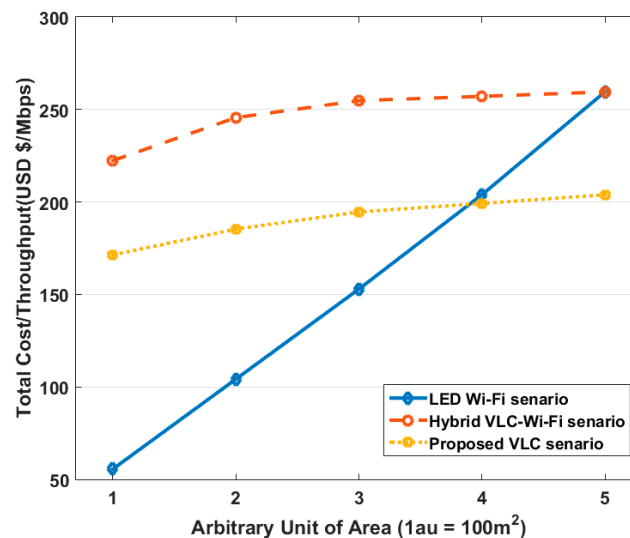


Figure 9. Total cost comparison of architecture 1 for all three systems.

## 7. Conclusions

This paper proposes a new multi-user full-duplex VLC system to be used in a smart home environment. The proposed system is capable of accommodating data for both users and smart devices on downlink while also providing uplink connectivity. The proposed system was analyzed on the basis of two parameters. The first parameter was the performance of the proposed system. The performance was based on two key variables, namely, the BER and the data rate. The second parameter was the cost and power consumption of the system. Three systems were compared when analyzing the cost and power consumption, namely, simple LED lights with Wi-Fi, a Hybrid VLC-Wi-Fi system, and the proposed VLC system. The simulation was averaged for four years. From the results, it can be seen that the proposed system performance was met the requirements of data transmission in an indoor environment such as a smart home. As far as the cost and power consumption are concerned, it was noted that the initial cost of the proposed VLC system is high but when compared to the running cost, which includes the power consumption and maintenance costs, the proposed VLC system turned out to be a more cost-effective solution. Although the VLC market has yet to be commercialized, the results obtained from this research show that it can be a cost- and power-efficient complementary system for smart home users when developing the upcoming 5G wireless network.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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