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VLC-based Data Transfer and Energy Harvesting Mobile System

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Abstract

This paper explores a low-cost portable visible light communication (VLC) system to support the increasing needs of lightweight mobile applications. VLC grows rapidly in the past decade for many applications (e.g., indoor data transmission, human sensing, and visual MIMO) due to its RF interference immunity and inherent high security. However, most existing VLC systems heavily rely on fixed infrastructures with less adaptability to emerging lightweight mobile applications. This work proposes Light Storage, a portable VLC system takes the advantage of commercial smartphone flashlights as the transmitter and a solar panel equipped with both data reception and energy harvesting modules as the receiver. Light Storage can achieve concurrent data transmission and energy harvesting from the visible light signals. It develops multi-level light intensity data modulation to increase data throughput and integrates the noise reduction functionality to allow portability under various lighting conditions. The system supports synchronization together with adaptive error correction to overcome both the linear and non-linear signal offsets caused by the low time-control ability from the commercial smartphones. Finally, the energy harvesting capability in Light Storage provides sufficient energy support for efficient short range communication. Light Storage is validated in both indoor and outdoor environments and can achieve over 98% data decoding accuracy, demonstrating the potential as an important alternative to support low-cost and portable short range communication.

Keywords: *Visible Light Communication; Energy Harvesting; Solar Panel.*

1. Introduction

The prevalence of wireless technologies has made Internet access widely available for various activities in our daily lives including electronic transactions, mobile information sharing, online entertainment, etc. Short range communication, which enables peer-to-peer communication without resorting to any wireless infrastructure, experiences fast growing pace in recent years due to the enhanced mobility and high security assurance. Among all the emerging short range communication technologies, Visible Light Communication (VLC), RFID, and Near Field Communication (NFC) techniques are increasingly establishing themselves as the most promising technologies for wireless communication over short distances. Many applications for cashless payments, automatic ticketing, in-vehicle signing, and identity and access tokens will therefore be made possible leveraging these communication technologies in near future if not already in place.

Especially, due to the RF interference immunity and inherent high security, VLC is advantageous to facilitate many applications. There are active research exploring possible ways to carry information over screen/light emitting arrays-to-camera channel, such as HiLight [10], Uber-in-Light [6], and Visual MIMO [2], etc. Furthermore, VLC systems are applied to accomplish sensing tasks, such as user skeleton posture reconstruction [11] and portable device localization [8]. However, all these studies require the support of lighting or displaying infrastructure, which may prevent them from meeting the rapid growth on the need of mobile applications. Thus, recent investigations initialize the efforts to develop low cost and portable VLC systems leveraging the widely available mobile devices [19, 1]. The external power supply is a must to enable either the transmitter or receiver in these systems, which may reduce the flexibility on supporting various mobile applications. Therefore, it is desirable to design a portable VLC system that has the capability of effective data communication and energy harvesting at the same time.

Toward this end, we propose a portable Light Storage system, which aims to achieve concurrent data transmission and energy harvesting leveraging visible light signals from COTS mobile devices (e.g., smartphones and tablets). Such a system provides the flexibility on serving various emerging mobile

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applications. For example, in the corporate domain, tracking the attendance and access record in conference/training centers when a fixed infrastructure is not available is a critical but difficult task to ensure the corporations are in compliance with mandated laws. The proposed Light Storage system can track the attendance and access of each individual by reading the unique light signature emitted from the flashlight of their mobile devices. In another example, Dash button [12] provides great convenience for in-home shopping with a simple one-click solution, which can order daily supplies automatically, but most of existing dash buttons are not programmable or inconvenient for information update. The Light Storage system can employ the programmable flashlight of mobile devices to update the information stored in dash button in a flexible way. Another interesting usage of the portable VLC system is tickets checking, e.g., in daily commuter trains, instead of the assistance of specialized optical readers or smartphones to scan the bar code on tickets by the train staff, a portable VLC sink would allow the passengers to forward their ticket information via the smartphone flashlight for verification.

Utilizing existing visible light signals on mobile devices such as the smartphone flashlight provides a convenient and low-cost way for portable and small-data communication needed in many emerging mobile applications. However, there are many challenges to build such a system under practical lighting conditions in dynamic environments. The key challenges are as follows: 1) In order to improve the throughput of the proposed system, multi-level light intensity modulation leveraging the flashlight of mobile devices is highly desired, but the current flashlight on COTS mobile devices only support on and off switching; 2) Dynamic lighting conditions in various environments have unpredictable impact on the communication performance, so it is critical to develop adaptive noise reduction scheme to mitigate such impact during data transmission for a portable system; 3) Due to the inaccurate time and light intensity control of COTS devices, it is challenging to maintain the synchronization and signal representation consistency between the transmitter and receiver; and 4) Concurrent data receiving and energy harvesting requires sophisticated hardware design to provide stable power supply while maintaining reliable data reception.

The proposed Light Storage system is designed to overcome the above challenges. It consists of the flashlight of COTS mobile devices as the transmitter and a solar panel equipped with both data reception and energy harvesting modules as the receiver. Before data transmission, the environmental noise assessment is performed leveraging the built-in light sensors in COTS mobile devices to assist reliable data modulation and synchronization. Based on the noise assessment results, an adaptive error correction scheme is proposed to provide a balance between the data rate and error correction capability of the proposed system. In order to improve the system throughput, the encoded data will be mapped to different light intensity levels based on the proposed multi-level light intensity modulation/demodulation mechanism. Due to the inaccurate time control on both transmitter and receiver, we also develop a new synchronization scheme integrated with a pre-defined pilot signal to ensure the success of data transmission. Finally, to achieve the portability of the system and get rid of the dependency on the external power supply for the proposed system, the energy harvesting module at the receiver is developed to provide reliable energy supply for the data reception.

The key contributions of our proposed Light Storage system are summarized as follows:

- We build a portable low-cost light storage system exploiting the existing flashlight of COTS mobile devices, and it is capable of energy harvesting leveraging solar panel as the receiver allowing transmitting the data and energy at the same time.
- We propose a flexible data modulation mechanism utilizing multiple levels of light intensity to increase the data throughput and develop an adaptive error correction scheme resilient to dynamic lighting conditions in various environments.
- We design a time-synchronization method, overcoming the limitation of low time control ability in mobile devices and combating the shortcoming of the noisy detected signals at the portable receiver side.
- We implement a prototype using COTS mobile devices, which demonstrates the system feasibility and provides guidance for the future mobile short range communication technology.

2. Related Work

The wide deployment of wireless technologies such as WiFi [22] [17] and Bluetooth [9] [13] has brought great convenience and efficiency to access the Internet in many aspects of our daily life. Due to the increasing need on short range communication to facilitate people's daily activities (e.g., electronic transactions [3], mobile information sharing [15], mobile payment [16], in-vehicle signing [18] and online entertainment [21]), Near Field Communication (NFC) and Visible Light Communication (VLC) techniques emerge in recent years. Specifically, NFC utilized magnetic field induction to enable communication between devices that are within a few centimeters of each other, whereas VLC relies on visible light signals generated by any lighting sources (e.g., fluorescent lamps, LED bulbs, and TV/PC screens, etc.) as a means of wireless data transmission. Both of these short range communication techniques greatly enhance the security of wireless connection and effectively protect the privacy of users.

Active research also explores many possible ways to carry information over VLC. For example, HiLight [10] and Uber-in-Light [6] encodes data into subtle pixel intensity changes on top of arbitrary screen contents. Similarly, Visual MIMO [2] adopts light emitting arrays for data transmission through the optical wireless channel and decodes through a camera receiver. Furthermore, VLC systems are applied to accomplish sensing tasks, such as fine-grained user skeleton postures [11] and smartphone localization [8]. These studies usually heavily rely on the lighting or displaying infrastructure support, thereby preventing them from meeting the rapid growth on the need of mobile applications.

In order to satisfy the ever-growing requirements on mobile computing applications, recent investigations seek to develop low cost and portable VLC systems to provide more convenience and efficiency on short range communication. For example, portable VLC transmitter or receiver are developed by utilizing the audio jack on smartphones as the power supply [19, 1]. Wang et al. [20] exploit the LED lamps controlled by Android development board as the VLC transmitter, and the photonic diode detector as the receiver. All the above studies need external power supply to enable the VLC transmitter or receiver, which may reduce the flexibility on supporting various mobile applications.

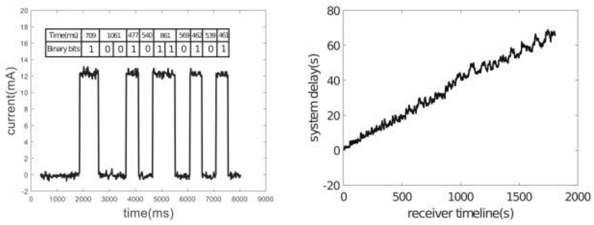
Recent efforts seek to integrate the energy harvesting capabilities on mobile VLC system. Carrascal et al. [4] propose to wake up the receiver in sleeping mode leveraging the energy harvested from the predefined signal emitted from the VLC transmitter. But the approach does not explore the ability of normal data communication. The mobile VLC system proposed by Park et al. [7] demonstrates the possibility of using the flashlight of smartphones to emit on and off visible light signals. Towards this direction, our portable Light Storage system explores multi-level light intensity from smartphone's flashlight to achieve reliable and scalable data transmission.

3. Feasibility Study & Applications

3.1 Feasibility Study

In our preliminary experimental set up, the smartphone flashlight acts as the transmitter to emit light signals, while the receiver, consisting of an Arduino board, a solar panel, and an energy management unit, captures the corresponding signals. During the experiments, the flashlight flashes every 500ms to simulate a short binary data sequence of '10010110101' with on indicating as 1 and off as 0. The receiver works at a sampling rate of 100Hz.

Sensitivity Study. Unlike the photodiode, solar panels are fabricated with low sensitivity on light energy detection, and thereby does not output electricity unless enough light power is received. The flashlight on mobile devices has limited energy output, which makes it challenging to trigger the solar panel and enable the differentiation on high and low levels of light intensity. Figure 1(a) shows the detected electrical currents after the flashlight is turned on and off based on the binary sequence '10010110101'. It is clear that the solar panel has the ability to differentiate the high and low levels of light intensity with an appropriate threshold. This suggests that the harvested power from the flashlight is sufficient to invoke energy harvesting function to facilitate short range communication.



(a) flashlight generated current example (b) PLL system time difference study

Fig. 1. Feasibility study.

Flashlight Control. The flashlight on mobile devices is not designed for visible light communication, so a critical issue to explore is whether the mobile device (e.g., smartphone) can accurately control the flash light intensity. We conducted experiments of repeatedly switching flashlight on and off for 30 minutes. As shown in Figure 1(b), there are two types of time offset contributing to the overall offset, i.e., the linear offset caused by inherent hardware difference between the transmitter and receiver, and the non-linear offset resulted from unpredictable noise and interference in the environments. The linear offset can be mitigated with appropriate linear time shift applied to the received signals, but the non-linear offset cannot be easily corrected. In Section 5, we further study how the time offsets affect the signal transmission over the VLC channel and how to mitigate them through developing accurate time control schemes.

3.2 Applications

Attendance and Access Card Recording. Light Storage can be used to track the attendance and access records for smooth management in corporations and organizations. The infrastructure deployment efforts will be minimized by assigning each individual with an unique light signature (i.e., a specific pattern of light intensity changes) for his mobile device.

Environmental Sensors Adapter. Light Storage can also be used for software upgrading in the sensor nodes used for monitoring the situation in wild areas, such as sunlight, air quality, humility and etc. We rely on the solar panel to power up the system, and utilize mobile device flashlight to transmit the upgrading signals to the corresponding receiver. Our proposed system eliminates the restrictions on external power supply, and significantly (a) flashlight generated current example improve the sensor life-time and efficiency on wild area surveillance.

Adjustable Dash Button. Dash button [12] nowadays provides great convenience for in-home shopping with a simple one-click solution, which can order daily supplies (i.e., kitchen needs, laundry, cleaning stuff etc.) automatically. By connecting the dash button with our light storage receiver, the default information stored in dash button can be easily updated by reading the data emitted from the flashlight of mobile devices.

Automatic Ticket Checking. More and more people tend to purchase the electronic tickets for daily commuter trains via their smartphone rather than going to ticking window or ATM. The portable VLC sink (i.e., the receiver of Light Storage) allows the passengers to forward ticket information via the smartphone flashlight for verification, and thereby largely release the efforts of the train staff for ticket checking.

4. System Design

In this section, we first describe the key challenges in the system design and then provide an overview of the proposed Light Storage system.

4.1 Challenges

The goal of the proposed Light Storage is to enable a portable low-cost VLC system leveraging the low-grade flashlight on off-the-shelf mobile devices. Such a portable system needs to support effective data transmission and carry the ability of energy harvesting at the same time. To achieve this goal, the system design needs to overcome the following challenges:

Support Data Modulation Leveraging Multi-level Light Intensity. To increase the data throughput, the traditional VLC systems resort to utilize the multiple levels of light intensity. However, the flashlight on off-the-shelf mobile devices only supports switching on and off, making it difficult to adjust the light intensity in a flexible way. To maintain the reasonable data throughput in the proposed Light Storage, we need to enable the adjustment of light intensity in mobile devices and utilize the availability of multiple levels in the light intensity to perform data modulation.

Ambient Noise Reduction. Visible light communication suffers from the ambient noise coming from external light sources. Different environments create various impact on the communication performance, especially for the proposed portable Light Storage system that is most likely exposed to dynamic environmental scenarios. Thus, it is challenging to build a portable VLC system comparing to traditional VLC systems with a fixed infrastructure. Building the noise adaptation ability will be crucial for a successful portable VLC system.

Low-grade Transmitter and Receiver. In most existing commercial VLC systems, the transmitter could accurately control the LED light intensity and transmission rate leveraging high standard hardware [5] , and the receiver could capture the fast light changes with advanced photodiodes. However, it is challenging to achieve effective data transmission when developing portable VLC systems with commercial mobile device flashlights and low-cost solar panels due to their limited capability on both time control and light intensity control. With the requirement of system portability, the low-grade power management chip adopted by the proposed system may also degrade the quality of received signals, and make it even more difficult to perform effective data transmission.

Concurrent Data Reception and Energy Harvesting. The proposed Light Storage system needs to achieve concurrent data reception and energy harvesting, but utilizing the light intensity

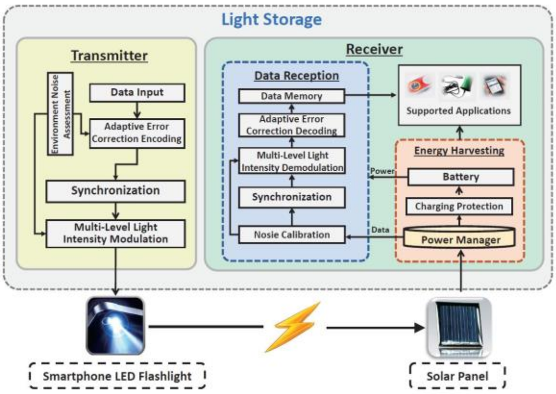


Fig. 2. System architecture overview.

changes of flashlight to increase the data throughput could cause unstable current conversion of energy harvesting at the receiver. There is a trade-off between maintaining stable power supply and obtaining reliable data reception.

4.2. System Overview

Our proposed Light Storage system, consisting of a transmitter and a receiver, aims to allow the users to transfer and store both of information and power through VLC channel concurrently. We employ the flashlight on COTS smartphone as the transmitter without the assistance of additional devices, while the solar panel as the receiver to capture the data embedded in the flashlight signals. Energy management unit is used to perform the control the energy flow on both data reception module and energy harvesting module. Lithium battery receives and stores electricity harvested from flashlight signals and support data reception module. The architecture of our proposed system is shown in Figure 2. Before the data transmission, the smartphone first performs environmental light noise assessment leveraging the built-in light sensor. Given the estimated ambient noise, the hamming code [14] with appropriate mode, which has the flexibility on the tradeoff between data rate and error correction capability, is adopted to encode the transmitting data as binary sequence. Next, in order to mitigate the inaccurate time control of the hardware on both transmitter and receiver, we define a pilot signal integrated into the transmitting signal and develop a new synchronization scheme to ensure the success of data transmission. The encoded binary sequence is then modulated into different levels of light intensity based on the pre-defined mapping rule to increase the throughput of the proposed system. For the data encoding and modulation process, the parameters derived from noise assessment module will be used for ambient noise reduction during data transmission. At last, the flashlight of the smartphone emits the modulated light signals to visible light channel.

Once the visible light signals are captured by the receiver, the solar panel will convert the light signals into electricity and forward it to the power manager, which continuously monitors the incoming voltage and current. Next, the electrical signals are managed from 2 perspectives - readings and energy. The data extracted from the electrical signals is passed to the data reception module for information storage, while the electricity charges the energy harvesting module to provide the energy supply for the data reception module.

The data reception module filters out the ambient light interference from the extract signals, and then perform multilevel light intensity demodulation to derive the encoded binary data sequence. Next, by extracting the pilot signal, the receiver will synchronize with the transmitter with the proposed synchronization scheme. Finally, the hamming code helps to correct the error bits during data transmission recover a part of wrong bits. The recovered data will be stored in local memory and complete the data reception. The power module is equipped with circuit protection, while serving energy for data reception.

5. Methodology

In this section, we first present our environment noise assessment and adaptive hamming error correction scheme, and then propose the approaches for synchronization and energy harvesting.

5.1 Environment Noise Assessment

We aim to design a carry-on VLC system which needs to be able to allow the user to use it anywhere. Unfixed transmitter and receiver position and various environments lead to the potential noise changes. To solve this issue, firstly we do the environment noise assessment by using the light sensor on the smartphone.

The experiment shows the results of ambient noise in the sunlight sensed by the light sensor and solar panel simultaneously. The light sensor senses the same trend the noise signal which can reveal and be correlated with the real-time noise on the solar panel. Thus, we derive environment noise into 2 major components - dc component and noise variance. In the system, smartphone detects the ambient light intensity Lt_0 by the light sensor on the top of the smartphone when the transmitter starts up at t_0 and keeps updating current ambient light intensity $\boldsymbol{L_t}$ every second. The ambient noise offset indicator $\boldsymbol{\gamma_t}$ is calculated as follows: $\boldsymbol{\gamma_t} = \boldsymbol{L_{t0}} - \boldsymbol{L_t}$. $\boldsymbol{\gamma_t}$ helps the multiple light intensity modulation referring to Section 5.2. At the meanwhile, system also evaluates and calculates the ambient noise variance indicator σ as follows: $\boldsymbol{\sigma} = \sqrt{\frac{\sum_{t=t0}^{ts}(L_t-\mu)^2}{n}}$, where $\boldsymbol{\mu}$ is the average detected luminance and n is the number of the samples within $\boldsymbol{t_s} - \boldsymbol{t_0}$. The system starts with $\boldsymbol{t}_{\boldsymbol{delay}}$ in microsecond level and starts detection window from $\boldsymbol{t_0}$ until $\boldsymbol{t_1}$.

Here we empirically set the $\boldsymbol{t_s} - \boldsymbol{t_0}$ as 1s. σ helps the adaptive error correction referring to Section 5.3.

5.2 Multi-Level Light Intensity Modulation

Modulation. Firstly, we introduce our modulation design. To improve the throughput of the system, we utilize multiple levels light intensity of the flashlight to modulate the data so that each light intensity can represent three bits binary during data transmission. We also input ambient noise indicator into the transmitter to adjust the modulation in real time to make the communication reliable. Once the input bit stream arrives at the transmitter, the data is modulated onto the multiple levels light intensity, which are represented as periodic luminance changes of the flashlight. The reason multi-level light intensity is adopted to our modulation mechanism is because it allows the transmission signal include additional light intensity information which helps to increase the throughput of the system. Thus, we create a mapping rule as shown in Table 1 which allows each three-bit segment associated with an individual light intensity level. This approach becomes available to the developer is due to the higher access authority from rooted Android system. To facilitate the reliability of modulation mechanism for noise resistance, the system inputs the real-time ambient noise indicator γt to compensate during the data transmission and uses gray coding with adaptive error correction scheme to eliminate the noise influence. The final modulated light intensity L_{TX} is calculated as $L_{TX} = L_{TX_{level_n}} + \gamma_t$ where $L_{TX_{level_n}}$ is the transmitting light intensity of nth level. The real-time modulation mechanism promises the receiver detects the correct current level with ambient light changes for demodulation. Finally, the smartphone can modulate three binary bits in each level intensity L_{TX} with every $\frac{1}{f_L}$ time slot.

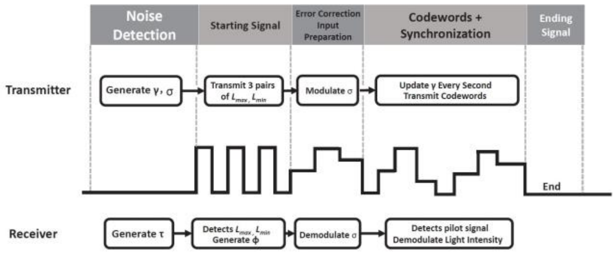


Fig. 3. Transmission process illustration.

Table 1. Multi-level light intensity modulation and demodulation map.

Level	L_{TX}	Data bits	$I_{RX_{Nor}}$range
0	0 +γ_t	Pilot signal	[0,0.15]
1	30 +γ_t	0 0 0	(0.15,0.3]
2	60 +γ_t	0 0 1	(0.3,0.44]
3	90 +γ_t	0 1 0	(0.44,0.55]
4	120 +γ_t	0 1 1	(0.55,0.65]
5	150 +γ_t	1 0 0	(0.65,0.75]
6	180 +γ_t	1 0 1	(0.75,0.85]
7	210 +γ_t	1 1 0	(0.85,0.97]
8	240 +γ_t	1 1 1	(0.97,1]

Demodulation. When stepping into demodulation process, the receiver demodulates the normalized signal based on the demodulation map which secures the reliability of the system under different environment. Firstly, the receiver senses the ambient light which induces the DC offset τ on receiving signal. Then, it listens to the starting signal which includes the maximum and minimum transmission light intensity. The maximum generated current Imax and minimum generated current Imin are recorded as preparation for normalization. Once the starting signal is received, the receiver starts to normalize the next incoming signal into the range [0,1]. Normalization helps to improve the robustness of system against various transmission distance, angle and environment during data communication. The changes of these factor causes different scale and DC offset of receiving signal which affects the results of demodulation. Thus, the receiver normalizes generated current I_{RX} to $I_{RX_{Nor}}$ as follows: $I_{RX_{Nor}} = \frac{I_{RX} - \tau}{I_{max} - I_{min}}$. After obtaining $I_{RX_{Nor}}$ in each time slot, the system follows normalized multi-level current demodulation map to demodulate the data bits as shown in Table 1. Each range is carefully chosen and tested corresponding to multi-level light intensity modulation map to perform the best matching between each level light intensity of the transmitter and generated current of the receiver.

We can see that the key point of improving the accuracy of demodulation is to calculate and obtain the correct I_{RX} in each time slot. The smartphone transmits each 3-bit segment at frequency f_L, thus, the time slot duration should be $\frac{1}{f_L}$. However, due to the reason that receiver does discrete sampling, it cannot promise there is a sample at each $\frac{1}{f_L}$ time point so that we need to find the closest sample point to each margin with minimum time different. Therefore, the n_{th} transmission slot t_n is calculated as following equation: $t_n = \arg\min_{\forall t_x \in T_{RX}} \left(\left(t_0 + \frac{n}{f_L} - t_x \right)^2, t_x \right)$, where x is the the sample index, n is the transmission slot index, t_0 is the starting time point, t_x is x_{th} sample time point and T is total transmission time duration. This equation represents the system starts to search for the sample point at t_x at t_0 which has minimum time difference with the nth $\frac{1}{f_L}$ to be the margin of time slot n and n+1. The system then divided the total transmission time duration T into multiple time slots to demodulate the 3-bit segment in each time slot.

During the transmission, there are two kinds of outliers: 1) A sudden generated current drop. 2) Out-sync samples approach 50% in one time slot. We use cluster-based outliers elimination to deal with these cases in order to maintain the demodulation accuracy.

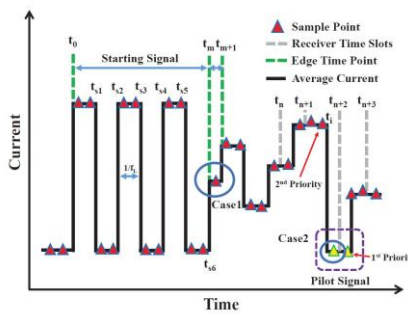


Fig. 4. Illustration of a data transmission example during synchronization.

5.3 Synchronization

The proposed synchronization scheme aims to solve two types of time offset existing between transmitter and receiver - linear and non-linear.

Light intensity based synchronization. We do not utilize phase and frequency information to serve synchronization due to the fact as the results shown in Section 3 which illustrates the limited flashlight control ability in time domain. In proposed the system, we implement level 0 light intensity as the pilot signal with ambient noise offset indicator $\boldsymbol{\gamma_t}$. There are two reasons for choosing level 0 as the synchronization point. Firstly, there is larger light intensity difference between level 0 and adjacent level intensity comparing to others which makes the receiver easier to differentiate the pilot signal. Secondly, level 0 is the lowest light intensity in the multi-level light intensity modulation map so that any occasional decreased light intensity changes in the environment can still be categorized into level 0 during synchronization process.

Linear time offset elimination. Linear time offset exists in any two independent devices once they communicate based on their local time, and it shows as the monotonic increasing time offset during the transmission which causes severe issue as long as accumulated. Based on the observations in Section 3, we choose the following way to mitigate it. Firstly, the system needs to find the linear offset coefficient Φ which represents the ratio of two local time systems. As shown in Figure 4, the transmitter sends starting signal consisting of three pairs of level 8 and level 0 with minimum level changes time interval $\frac{1}{f_L}$. The receiver detects each edge time points within starting signal as t_{s1} to t_{s6}. The time duration of each level represents the transmitter's timeline which is supposed to be $\frac{1}{f_L}$, and each edge time point represents receiver's timeline. Thus, the linear offset coefficient Φ can be calculated as follows:

$$\Phi = \overline{(t_{s1} - t_0) + (t_{s2} - t_{s1}) + \cdots + (t_{s6} - t_{s5})} * f_L$$

The linear time offset between transmitter and receiver is deducted by multiplying Φ on each receiver sample point as $\Phi \times t_x$. It helps especially when the users use various devices that may cause the different linear offset.

Non-linear time offset elimination. Next, scheme targets to solve the non-linear time offset. Non-linear time offset in our proposed system is mainly caused by low-grade time control performance of the smartphone's flashlight and it shows as unpredictable fluctuation of the transmission slot time duration. In Figure 4, We illustrate 2 special cases of outliers which shows during data transmission and may severely cause synchronization failure. In the first case, one transmission slot is tremendously shorter than other slots. In second case, the pilot signal is not detected due to the number of level 0 pilot signal samples is smaller than the number of other high-level samples in both transmission slots from t_n to t_{n+1} and t_{n+2} to t_{n+3}. We need to design our algorithm to handle these two cases to avoid synchronization failure.

Firstly, the system detects the time point tm of all rising and falling edges where m is the index of the edge. The time duration between each two adjacent edges Δt_m is calculated as $\Delta t_m = t_{m+1} - t_m$. The smartphone sends each individual level signal with transmission slot time duration $\frac{1}{f_L}$. In another words, any transmission slot received by the receiver should not be shorter than $\frac{1}{f_L}$. Thus, the system compares each Δt_m with $\frac{1}{f_L}$ and adjust the receiving time slots. If Δt_m is equal or larger than $\frac{1}{f_L}$, the system keeps Δt_m. The reason is that there may have more than one slot continuously transmitting the same level signal, so in this case Δt_m is larger than $\frac{1}{f_L}$ but it is still correct. If Δtm is smaller than $\frac{1}{f_L}$, then the system starts to search and move the edge to closest sample point to correct transmission time slot edge t'_{m+1} which is calculated as follows:

$$t'_{m+1} = \begin{cases} \arg\min\limits_{\forall t_x \in T_{RX}} \left(\left(t_0 + \frac{n}{f_L} - t_x \right)^2, t_x \right), & if\ \Delta t_e < \frac{1}{f_L} \\ t_{m+1}, & if\ \Delta t_e \geq \frac{1}{f_L} \end{cases}$$

Linear time offset elimination After updating tm+1, all transmission slots shorter than minimum are corrected to the right time points. Another scenario that induces non-linear delay is illustrated in Figure 4 as case 2. In this case, the receiver separate time slots as t_n, t_{n+1}, t_{n+2} and t_{n+3}. During t_{n+1} to t_{n+2} slot, the number of the high level samples is larger than low level samples because the smartphone transmits slot longer than $\frac{1}{f_L}$ on high level. From t_{n+2} to t_{n+3}, the high level samples are still more than low level samples. The system is not able to recognize the pilot signal based on the demodulation rule as mentioned in 5.2. Thus, we make the different priority to all samples to solve this problem. The samples in high priority dominate the result when calculating the current level in one transmission slot.

After linear and non-linear offset mitigation, we also apply adaptive hamming code to do the error correction. The environment ambient noise σ is introduced to the scheme to help choosing the better error correction scheme in hamming code in order to maintain a good tradeoff between the accuracy and throughput.

6. Performance Evaluation

We implemented our transmitter on rooted Samsung Galaxy S3 with RootTools 3.4 library so that the multiple levels of light intensity can be accessed. As shown in Figure 5, the receiver includes one 53mm × 30mm mini solar panel, INA 219 sensor, charging protection chip, one lithium battery and the arduino board with data memory shield. Our default experimental environment consists of transmitter and receiver set parallel to each other at 2cm. By virtue of this arrangement the light coming from the flashlight is perpendicular to solar panel. In our experiment we tested 500 random data samples ranging from 100 to 9k bits while adjusting one of the aforementioned variables and controlling the rest as default to achieve consistent results.

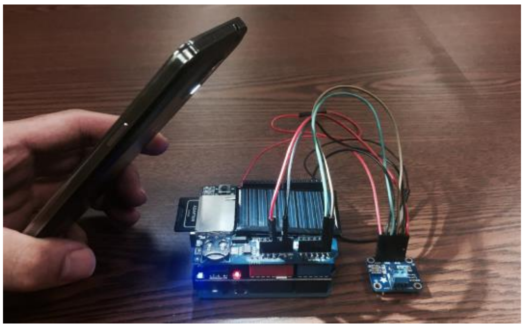
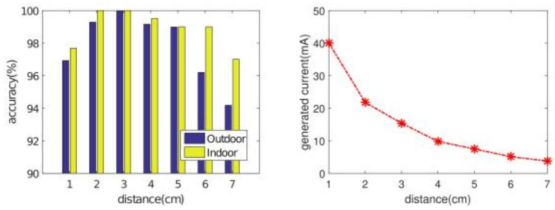


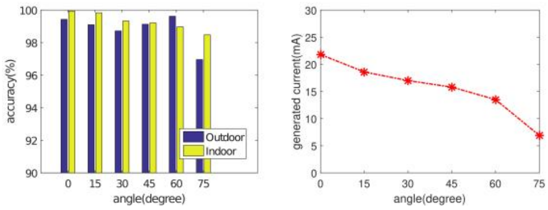
Fig. 5. Experiment setup.

Our default experimental environment consists of transmitter and receiver set parallel to each other at 2cm. By virtue of this arrangement the light coming from the flashlight is perpendicular to solar panel. Initially we set the flashlight transmission rate fL at 10Hz and pilot signal insertion length k as 12 and set the first priority samples percentage pprior as 20%. In our experiment we tested 500 random data samples ranging from 100 to 9k bits while adjusting one of the aforementioned variables and controlling the rest as default to achieve consistent results.



(a) Transmission accuracy. (b) Energy harvesting.

Fig. 6. The impact of distance.



(a) Transmission accuracy. (b) Energy harvesting.

Fig. 7. The impact of angle.

6.1 The Impact of Distance

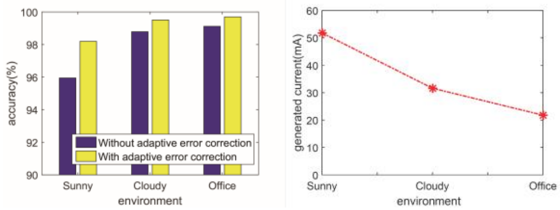
We first evaluate the impact of the distance between transmitter and receiver in both indoor and outdoor environments. As shown in Figure 6(a), as the distance increases from 1cm, the transmission accuracy first increases and then decreases. The highest accuracy (i.e., at almost 100%) is achieved at 2cm and 3cm for indoor environment, while at 3cm for outdoors.

The energy induced by different light intensity follows a fixed ratio as indicated in Section 5.2, but this ratio will be slightly changed when the transmitter and receiver are close to each other (i.e., 1cm). So the accuracy is slightly affected comparing to those at further distance (i.e., 2cm and 3cm). As the distance further increases, the signal-to-noise ratio(SNR) will accordingly decreases and dominate the system performance, resulting the degradation of the transmission accuracy.

Moreover, Figure 6(b) shows the results of energy harvesting by the solar panel in indoor environment. The generated current achieves the 40.1mA and starts to decrease until 3.8mA at 7cm. At distances greater than 7cm the flashlight cannot induce enough power for any meaningful energy harvesting.

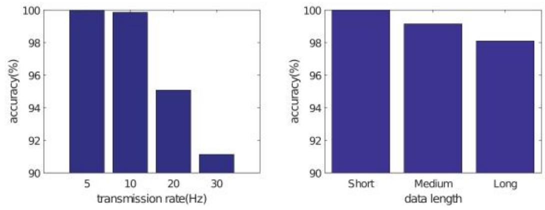
6.2 The Impact of Angle

Since the user may not have the transmitter right face to the receiver, it is critical to study the impact of different angles between transmitter and receiver. We change the relative angle while maintaining a constant distance (i.e., 2cm) between transmitter and receiver, and evaluate the system in both outdoor and indoor environments. As shown in Figure 7(a), the highest accuracy is achieved with 0 degree for indoor environment. As the angle increases, the accuracy is reduced. However, for outdoors, the accuracy varies randomly as the degree increases, this is because the environmental noise plays as the dominant factor affecting the system performance. Furthermore, Figure 7(b) also shows that the impact of the angle on energy harvesting is less than the impact of the distance. The receiver still harvests 6.9mA when the angle gets 75 degree. To conclude, the system can achieve overall 99.31% accuracy indoor and 98.45% outdoor at different angles.



(a) Transmission accuracy. (b) Energy harvesting.

Fig. 8. The impact of environment.



(a) Transmission rate. (b) Data length.

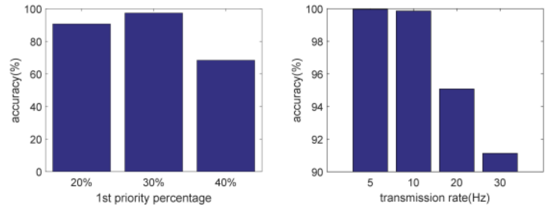
Fig. 9. The impact of transmission rate and data length.

6.3 The Impact of Environment

We next evaluate the proposed system under three different environments (i.e., outdoors on a sunny day, outdoors on a cloudy day, and indoors) with and without adaptive error correction as shown in Figure 8. The system can harvest the highest current but with the lowest accuracy at outdoors on a sunny day due to the strong ambient noise. Adaptive error correction can reduce the error and achieve 98.20% accuracy compared to 95.95% accuracy without adaptive error correction. In contrast, the ambient noise on a cloudy day is relatively stable, so the proposed system achieves over 98% accuracy with and without adaptive error correction. Lastly, the system reaches the highest accuracy in an indoor environment but only harvests the least current (i.e., 20mA). Above all, the tradeoff between transmission accuracy and energy harvesting should be taken into consideration for practical use.

6.4 The Impact of Transmission Rate and Data Length

Figure 9(a) presents the results under the impact of transmission rates f_L in an indoor environment. Specifically, the accuracy is over 99% at 5Hz and 10Hz, and then decreases to 95.1% and 91.2% for 20Hz and 30Hz due to the inherent timing errors of flashlight. We also present the ability of our system to accurately capture data of different length in Figure 9(b). Specifically, we define short, medium and long data length as 100, 2k and 8k bits respectively. The system achieves over 99% for short and medium length data, and over 98% for long data bits. The results demonstrate that the synchronization scheme is robust to different data lengths with high accuracy.



(a) Pilot signal insertion length. (b) 1st priority samples percentage.

Fig. 10. The impact of pilot signal length and 1st priority samples percentage.

6.5 The Impact of Pilot Signal Length and priority percentage

Finally, we present the impact of pilot signal length k on accuracy in Figure 10(a). Larger k increases the time interval between each two adjacent pilot signals, leading to more errors during transmission, but it also reduces the transmission overhead. When the transmitter has a pilot signal with k = 12 and k = 15, the accuracy maintains over 98%. In comparison, the accuracy drops to 91% when k = 18. The above results suggests that k = 12 or 15 could ensure high accuracy in practical use. Figure 10(b) presents the impact of the 1st priority samples percentage $p_{priority}$ referring to Section V-C. If over ppriority percentage samples are 1st priority level 0 samples, the current transmission slot will be demodulated as a pilot signal. Larger ppriority helps to avoid missing detection of a pilot signal, but it causes more errors on the neighbors. Thus, the results show that the system only achieves 65% accuracy with $p_{priority}$ = 40% and 89% with $p_{priority}$ = 20%. The optimized performance is achieved when $p_{priority}$ = 30%.

Table 2. The energy harvesting comparison of Light.

Product	Max current	Typical voltage
Light Storage	50mA	5V
M24LR-E-R ST25DV-I2C	6mA	3V
NT3H1101 NT3H1201 NXP	5mA	2V
NF4 EM Micro-electronics	5mA	3.6V
SIC4340 SIC4341 Silicon Craft	10mA	3.3V
SL13 AMS AG	4mA	3.4V

6.6 The Energy Harvesting Comparison with Existing Work

Table 2 shows the comparison of Light Storage with most popular energy harvesting NFC ICs. It suggests that Light Storage can achieve much more powerful tasks with over 500% maximum current and 138% typical voltage comparing to most NFC ICs. Besides, functional wise, Light Storage also works on the smartphone without NFC function so that the wider implementation environment provides users an easier solution to do self-energy harvesting data communication.

7. Conclusion

In this work, we build the first portable low-cost Light Storage system exploiting the existing flashlight of COTS mobile devices as the transmitter and leveraging solar panel with data reception and energy harvesting modules as the receiver which allows to transmit the data and energy at the same time. We propose a flexible data modulation mechanism utilizing multiple levels of light intensity and adaptive error correction scheme resilient to dynamic lighting conditions in various environments. We design a time-synchronization method, overcoming the limitation of low time-control ability in mobile devices and combating the shortcoming of the noisy detected signals at the portable receiver. In the evaluation, the results show that Light Storage system can achieve overall 98% accuracy in various environments condition.

Light Storage is the first step towards mobile VLC system combining the data transmission and energy harvesting. It opens up new possibilities to many promising applications and benefits the development of mobile industry and other research and commercial fields. In the meanwhile, some open issues are raised and to be solved in the future work.

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