Towards Embedded Visible Light Communication Robust to Dynamic Ambient Light

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***Abstract*—The presence of ambient light is a key challenge for reliable and robust low cost embedded visible light communication system. The photodetector used by these systems can perform poorly when subjected to bright ambient light or fluctuating ambient light. To solve this problem, we present an ambient light cancellation mechanism for low cost embedded LED to photodiode communication systems that utilizes a digital potentiometer to adaptively nullify the ambient light to provide an always ZERO output no matter what the ambient light intensity is. The proposed technique allows the receiver to correctly receive the light transmitted by the transmitter without any interference from the ambient light. We provide a detailed description of the modulation and demodulation schemes as well as ambient light cancellation mechanism, and their evaluations. The results show our proposed system can provide a reliable and robust visible light communication with extremely low symbol error rate (almost 0) and an acceptable data rate up to 3kbps given an operating distance of 50 centimeters.**

***Index Terms*—VLC, Ambient Light Cancellation.**

I. Introduction

Visible Light Communication (VLC) has been proposed not only as an alternative wireless channel for communication for IoT but also as one of the ways to address spectrum crunch. Many research projects have tried to advance different flavors of VLC systems in the last few years. Most discussed VLC systems are perhaps the ones that use light bulbs at homes (e.g., LiFi [1]), however there is a body of work on low-cost low-power embedded VLC systems based on LEDs [2]. These systems commonly use a photodiode to receive the transmitted light signals. The photodiode gets saturated or performs poorly in bright light or in fluctuating ambient light conditions. Results from existing studies [3] show that with strong ambient light, the system will fail to deliver packets. In an indoor scenario, the VLC system needs to be robust against not only bright light but also to the level of changes in illumination throughout the day and night.

Addressing the poor performance of embedded VLCs in bright and changing ambient light conditions is necessary for embedded VLC systems to mature into systems that can provide robust and reliable communication. Most importantly, for VLC technology's potential to address the spectrum crunch, it is essential that these systems achieve a level of robustness far beyond what the state-of-the-art achieves.

Getting a low-cost embedded VLC system to work robustly in bright light and changing ambient light levels is extremely challenging. In presence of bright ambient light, for example in a stadium or near a window during the day time, the photodiode used as the receiver will easily get saturated causing the reception to fail: the receiver will not be able to distinguish the ambient and transmitted light because it is already saturated. Similarly, different level of sensitivity on the photodiode may be required depending on the level of ambient light in the environment. Existing prototypes of embedded VLC do not work well in these challenging environments.

Previous work on low-cost VLC systems use photodetectors that perform poorly when subjected to bright or fluctuating ambient light. In typical LED to photodiode communication systems, the existing approach is to switch to different type of receiver or transmitter when communication degrades. These workarounds however do not directly address the main problem by actively canceling the ambient light based on its intensity. In this paper, we aim to fill that gap in the state-of-the-art of embedded VLC systems.

Our approach consists of two main parts. First, we design a DC-restoration circuit that can eliminate the effect of ambient light adaptively depending on the level of ambient light. Second, we use the frequency shift keying modulation with a small number of frequencies rather than the on and off keying modulation to provide better SNR with the proposed circuit. Compared to the state-of-the-art embedded VLC system, our system demonstrates the reliability by offering extremely low symbol error rate (nearly 0) and acceptable data rate of up to 3kbps with a distance of 50 centimeters in controlled indoor environment.

We make the following contributions in this work:

- We present the circuit and accompanying physical layer design, which together form the ambient light cancellation primitive to enable communication with high reliability and robustness in bright and changing ambient light conditions.
- We prototype the system and perform extensive evaluations to understand the effectiveness of the system in challenging scenarios.

II. Related work

We briefly review work related to visible light communication.

Low Cost Visible Light Communication Prototypes:. Klaver and Zuniga in [4] introduced a low cost VLC prototype named Shine. The prototype uses LED transmitter and photodiode

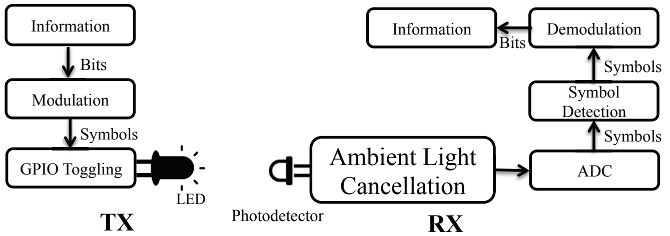

Fig. 1: System Overview: The ambient light cancellation block will filter the ambient light, leading to a ZERO output corresponding to the reception of ambient light, thereby enhancing the reception of VLC packets.

receiver. They observed that the SNR varies with the ambient light level and the distance between the transmitter and receiver. While in this paper, we argue that the SNR can be maximized by nullifying the background noise. Schmid et al. in [5] presented a LED-to-LED communication system which demonstrated a data rate of 800bps with an operating distance of 2 meters. The Linux Light Bulb idea was proposed by Schmid et al. in [6]; they embedded a wireless System-on-a-Chip (SoC) running OpenWRT into a normal light bulb to connect to the Internet. The performance of this bulb, especially the reliability of communication, is not yet reported. More recently, OpenVLC1.0 was proposed as a low-cost embedded VLC platform [7]. It has a full IP stack and can use LED or photodiode as the receiver. One key problem with this prototype is its limited reliability and robustness. Heydariaan et al. in [3] has investigated its performance under various experimental settings. It turned out that the platform cannot assure reliable communication with bright ambient light. Zhang et al. in [8] has proposed a new circuit to cancel the minimum offset voltage from the input optical signals. They demonstrate the proposed prototype can be immune towards sunlight and indoor fluorescent lights. However, they did not evaluate the prototype in a dynamic environment. We differ in both the design and evaluation in dynamic and challenging envirionment.

Ambient Light Effects:. Li et al. [9] presented a system that can reconstruct human movement using off-the-shelf LEDs and photodiodes. They claimed higher level of ambient light intensity will cause the saturation problem when the photodiode is operating outside the linearity area. Meanwhile, Yang et al. [10] also claimed this effect from the ambient light. Li et al. later proposed a method to fade the effect from ambient noise by recognizing the rising edge of the encoded light pulse from the fluctuated ambient light in [11]. However, this does not cancel the entire interference from the ambient light leading to further effort on the edge detection accuracy.

III. System Overview

In this section, we describe the system design and implementation as shown in Fig. 1.

TABLE I: OOK with Manchester Encoding used in OpenVLC1.0 and BFSK Encoding used in our design. Different from OpenVLC1.0, we represent bit ZERO with 4 symbols which are '1100'(HIGH, HIGH, LOW, LOW), we represent bit ONE with 2 symbols which are '10'(HIGH, LOW).

Bit	OOK (OpenVLC1.0)	BFSK (Our Encoding)
0	01	1100
1	10	10

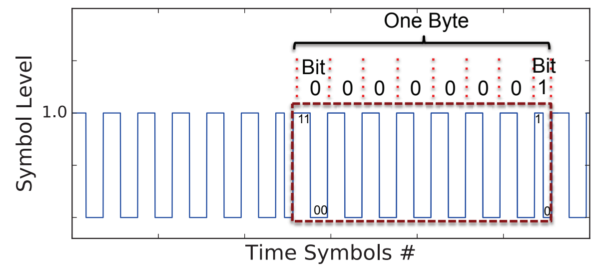

Fig. 2: Encoding method to represent bit ONE and bit ZERO.

A. Modulation

Our goal is to design a modulation scheme, that is robust to light interference, and with a simple logic that is possible to implement mostly in software in a low-cost embedded platform (in contrast to OFDM in high-resource systems such as LiFi [1]). Current low cost LED-to-LED or LED-to-Photodiode VLC systems use variations of On-Off Keying (OOK) modulation scheme due to its simplicity [7]. However, OOK is susceptible to ambient light interference [3]. Although there are other modulation schemes in the broader VLC space (e.g., LED-to-Camera [12], Binary Frequency Shift Keying or BFSK [13]), they do not directly address the ambient light interference in embedded VLC.

We use BFSK as the modulation scheme rather than OOK in our design since it is less susceptible to ambient noise. Table I shows the modulation schemes used in OpenVLC1.0 platform and our current design. The transmitter represents bit '1' with a frequency, for example, $2k$Hz to blink the LED. It represents bit '0' with a frequency, for example $1k$Hz to blink the LED. Assuming we are continuously sending one byte. We represent the modulated signal in Fig. 2 with the encoding scheme. We use more symbols to represent one bit compared to OpenVLC1.0. Our approach improves robustness, but reduces the communication rate.

B. The Receiver

The main challenge in the receiver design is dynamics of ambient light in the indoor environment (due to use of different lights at different times, movement of people, etc.) and possible saturation of the photodiode.

1) Dynamics of the Ambient Light : We perform a simple experiment to study the dynamics of ambient light in a typical indoor environment. We deploy the photodiode used in OpenVLC node in four different scenarios and plot the

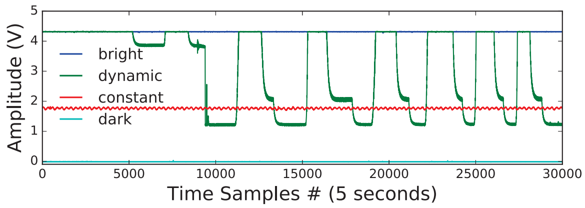

Fig. 3: Ambient light in different lighting settings.

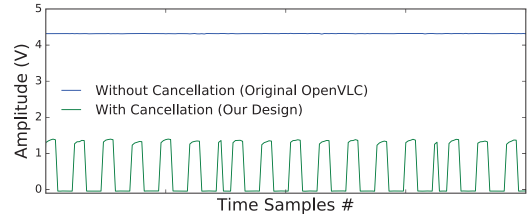

Fig. 5: Comparison of received light signal both with and without ambient light cancellation

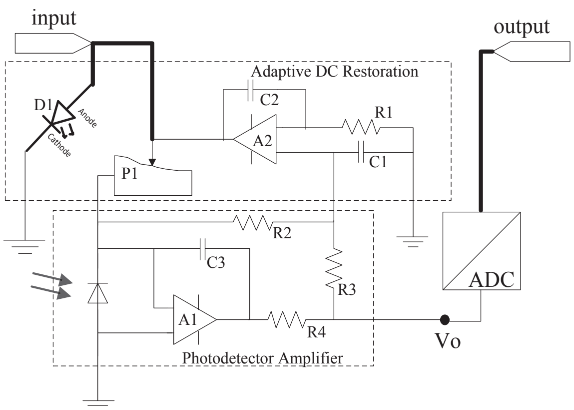

Fig. 4: Ambient Light Cancellation Circuit Diagram consisting of one block for photodetector amplifier, one block for DC restoration, and one for adaptive cancellation, which uses feedback from the output voltage V_o using a potentiometer (P1) and a LED indicator (D1). The input and output interface to the embedded VLC board.

voltage output from the photodiode in Fig. 3. In a dark environment, the output is close to 0, except for some jitters due to light from LEDs in electronics. With stable lighting in indoor environment, the voltage is nearly constant except for jitters (constant). Occupants' movement can cause fluctuation in light levels on the receiver (dynamic). Finally, when the light is too bright, the photodiode can get saturated (bright) meaning the output voltage will no longer increase. A receiver must be able to cope with all these variations it may encounter in an indoor deployment.

2) Ambient Light Cancellation: While DC restoration circuit [14] has been used to remove the effect of constant ambient light, those designs do not directly address the dynamics in ambient light in typical indoor deployments. A static DC restoration circuit would not work in the range of scenarios explored in Fig. 3, which can all occur in a single deployment. The compensated current generated from the circuit needs to be adaptively adjusted in the presence of these ambient light changes with a feedback and control mechanism. The mechanism (Fig. 4) has three main parts:

Photodetector Amplifier. This amplifier amplifies the current from the photodiode upon light reception and outputs V_o.

DC restoration. The DC restoration will generate the compensating current to the summing point between the photodetector amplifier and the DC restoration. We add the adaptive components (Fig 4) to the basic DC restoration circuit [14].

Algorithm 1 Adaptive Cancellation Algorithm

```
Input: WS (WindowSize) in
numZero = 0; numOne = 0
count = 0; min = 0; max = 255
mid = read from potentiometer
minSps = 20% * WS; maxSps = 75% * WS
while TRUE do
    value = read one symbol from ADC
    count++
    if value == 0 then
        numZero++
    else if value != 0 then
        numOne++
    end if
    if count == WS then
        count = 0
        gap = numZero-numOne
        if (gap>minSps) and (numZero>maxSps) then
            min = mid ; mid = (max+min) / 2
            write (mid) to potentiometer
        else if (-gap>minSps) and (numOne>maxSps) then
            max = mid ; mid = (max+min) / 2
            write (mid) to potentiometer
        else if (|gap <= minSps|) then
            mid = 0; max = 255
            mid = read from potentiometer
        end if
        numZero = 0; numOne = 0
    end if
end while
```

Adaptive cancellation. We use the digital potentiometer P1 to control the amount of current to provide to compensate for the current generated by the ambient light. If V_o is in saturation range, the resistance of P1 is decreased. After each adjustment, the onboard LED is turned ON and OFF using the symbol rate to calibrate the resulting ADC range. If the V_o range for ON and OFF is below a certain threshold necessary for robust disambiguation between an ON and an OFF, the resistance is decremented, otherwise the resistance is incremented until a suitable resistance value is found. Algorithm 1 uses binary search to find the resistance value for P1 that allows output voltage to stay below saturation and maintain sufficient voltage range between an ON and OFF.

Fig. 5 shows the output from the receiver with and without the cancellation mechanism. An oscilloscope is used to plot the received signal from the modified VLC node. We use a lamp that was equipped with the GE 100-Watt A21 3-way reveal light bulb as the ambient light interferer. The transmitter, which is placed 50cm from the receiver, transmits a sequence of ones and zeros with a symbol rate of 1kHz. With the bulb turned on, the light signal was fully recovered with the cancellation process, while the photodetector on the unmodified OpenVLC1.0 platform gets saturated and outputs a flat voltage.

3) Symbol detection: We separate this task into two steps: **Synchronization:**. The receiver and transmitter clocks need to be synchronized for correct decoding of symbols. In low cost platforms such as BeagleBone, that uses CPU clocks to maintain timers, the clock drifts, hence requiring transmitter-receiver resynchronization after a modest number of symbols are transmitted. We borrow this technique that uses Xenomai [15], a real time software framework from OpenVLC1.0 to keep the receiver and transmitter synchronized. Through experimentation, we found that the synchronization is consistently accurate for several thousand symbols, hence we use a symbol buffer of 1000 bytes.

Packet Framing. The ADC output from the cancellation circuit will be LOW when no packets are tranmitted. Hence we use a sequence of 50 LOW symbols to occupy the space between the packets. Reception of either ONE or ZERO starts with a HIGH symbol, which indicates the beginning of a packet after a sequence of LOWs.

IV. Evaluation

Now we describe various aspects of the system performance.

A. System Implementation

We prototyped the transmitter using OpenVLC1.0 platform [15] with a Linux kernel module implementation for our proposed BFSK modulation scheme. We prototyped the receiver using OpenVLC1.0 platform to include the adaptive ambient light cancellation circuit between the photodetector and the ADC without modifying the platform. Instead of doing symbol detection in kernel level, we dumped the symbols received from the kernel space to user space for symbol detection and symbol error rate calculation. This arrangement allows the kernel to continuously receive the signals without incurring in-line signal processing delays. Fig. 6 shows the testbed setup. We use a 5V, 2A power adaptor to power each node. Each node costs around $45 excluding the BeagleBone Board. The current draw for the receiver with cancellation is about 315 mA while the BeagleBone is running.

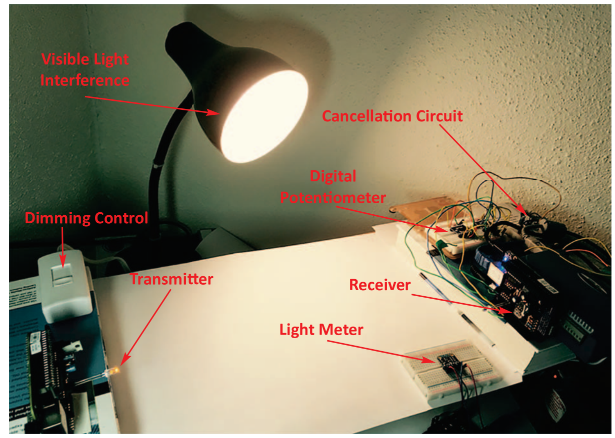

Fig. 6: The testbed setup for experiments to evaluate the adaptive cancellation mechanism.

TABLE II: The system took the adaptation time to converge to the shown potentiometer value to fully cancel the different levels of ambient light.

Ambient Light Intensity (lux)	(120)	(160)	(200)	(400)
Potentiometer Value (Ω)	2M	250.9K	188.2K	158.7K
Adaptation Time (ms)	0	34	85	102

B. Adaptation Latency

Now we evaluate how fast the system can adapt to the changing ambient light level. As we need a potentiometer to provide feedback for the cancellation circuit in Fig.4, we select AD5242 from Analog Device with the range of 1MΩ in the prototyping. AD5242 can generate 256 different resistance values in the 0-1MΩ. Binary search (Algorithm 1) allows us to determine the right resistance in a maximum of 7 steps. Assume the sampling rate is S, window size for the resistance adaptation is W, binary search steps is N. Then the time T required for one adaptation is $T = N * W/S$. With sampling at 6 kHz, 100 symbol window and maximum of 7 steps, the system will take a maximum of 117ms to adapt to a new ambient light level. We consider this latency as acceptable because we do not expect ambient light dynamics to be of higher frequency. Data communication resumes after the optimal resistance is found.

Experiment: We use the sliding dimmer on a GE 100-Watt A21 light bulb to generate different ambient light intensity. We place a photodiode 50cm from the light bulb. We then connect two AD5242 (digital potentiometer) between the photodiode and the cancellation circuit. We then utilize a TSL2561 light meter to measure the ambient light to help perform the experiments at different lux values.

Results: Fig. 7 show that the resistance from the digital potentiometer will decrease once the ambient light goes up and vice versa. It also demonstrate that resistance change is very fast (up to 117ms) towards the change of the ambient light. Note that each resistance value showing on the plot has been the optimal resistance that provides the noise-free

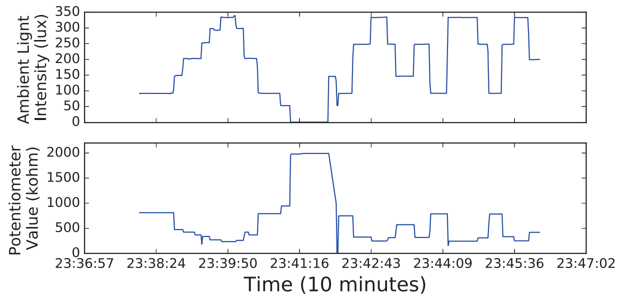

Fig. 7: The top figure shows the fluctuation of the ambient light during the experiment. The bottom figure shows the value of the digital potentiometer due to the adaptation algorithm.

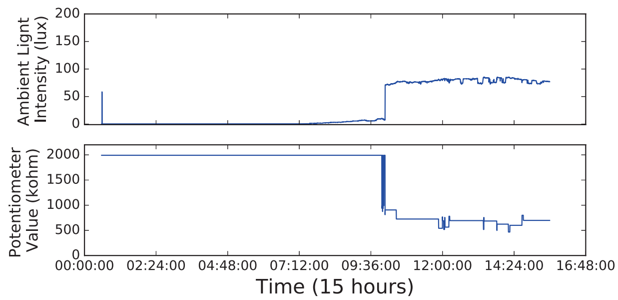

Fig. 8: Ambient light intensity and the resistance value selected by the cancellation circuit over 15 hrs in an indoor office environment. The ambient light was dynamic as people performed different activities in the office space.

TABLE III: Experiment settings to study the impact of various ambient light intensity on symbol error rate.

Ambient Light Intensity	Symbol Rate	Distance	Buffer Length	No. of Symbols
120,160,200,400lux	1kHz	50cm	1000B	30000

environment for highly accurate symbol detection. Table II shows four levels of ambient light and the corresponding four suitable resistance determined by the algorithm. As we can see on Table II, adaptation time increases with an increase of ambient light intensity. Smaller resistance value is used to cancel higher ambient light intensity, leading to more steps from the initial resistance value (2M) to the optimal value, and this requires longer adaptation time. In another experiment, we let the system run for 15 hrs in an office space, allowing the system to experience different levels of ambient light and hence different resistance values selected by the cancellation circuit in response (Fig. 8).

C. Impact of Various Levels of Ambient Light on Symbol Error Rate

Experiment: We configure the TX and RX to operate with the symbol rate 1kHz. We place the receiver and the transmitter 50cm apart. We perform the experiments at three different light levels (table III). In each experiment, the transmitter will send 1000 bytes. We also configure the unmodified OpenVLC1.0 platform to be another pair of TX and RX in this experiment setting for comparison purposes. We list the configuration on Table III.

TABLE IV: Symbol error rate under different ambient light intensity. The bulb turned on causing the heavy ambient light with 160 lux; Dimming control to make the bulb brighter generating an intensity with 200 lux; Dimming control to push the bulb to be brightest leading to an intensity with over 400 lux.

Ambient Light Intensity	SER with Cancellation	OpenVLC1.0 No Cancellation
(160lux)	0.00%	Fail
(200lux)	0.00%	Fail
(400lux)	34.67%	Fail

Result: Table IV shows the symbol error rate (SER) achieved at different light levels. This result demonstrates highly adaptive robustness and reliability can be achieved even in the strong presence of the ambient light. The proposed system fails at 400lux while the OpenVLC platform fails at the light levels on Table. IV. Thus, the proposed system is a significant improvement over the state-of-the-art.

D. Impact of Symbol Rate on Symbol Error Rate

TABLE V: Experiment settings to observe the impact of various symbol rate on symbol error rate.

Ambient Light Intensity	Symbol Rate (kHz)	Distance	Buffer Length	No. of Symbols
200lux	1,2,4,6,8,10	50cm	1000B	30000

We use experiment settings listed on Table V to study the impact of symbol rate on system performance. All experiments were conducted in a very bright ambient light background by turning on the light bulb with brighter levels. We observed that the OpenVLC1.0 platform without cancellation does not work in this lighting condition.

Result: Fig. 9 plots the relation between the symbol error rate and symbol rate. Here the symbol rate is equal to $1/symbol$ duration. It shows that the symbol error rate increases significantly once the symbol rate increased from 6kHz to 8kHz to 10kHz. This is due to higher symbol rate can lead to lower SNR, causing higher symbol error rate.

E. Impact of Distance on Symbol Error Rate

Next we study the performance of the system over distance using the settings listed on Table VI.

Result: Fig. 10 plots the symbol error rate with different distance settings when the light bulb was turned on. We are concerned about the operating distance for the system. It shows once the distance goes up to 60 centimeters. The symbol error

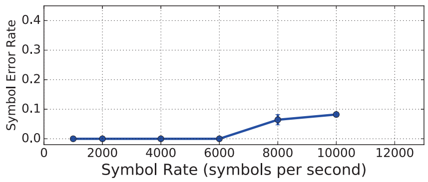

Fig. 9: Symbol error rate vs. symbol rate.

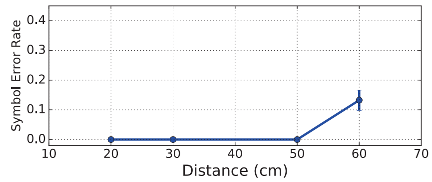

Fig. 10: Symbol error rate vs. distance between TX and RX.

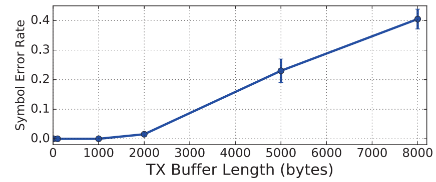

Fig. 11: Symbol error rate vs. TX buffer length.

TABLE VI: Experiment settings to study the impact of distance on symbol error rate.

Ambient Light Intensity	Symbol Rate	Distance (cm)	Buffer Length	No. of Symbols
160lux	6kHz	20,30,50,60	1000B	30000

TABLE VII: Experiment settings to study the impact of buffer length on symbol error rate.

Ambient Light Intensity	Symbol Rate	Distance	Buffer Size (x10^3B)	No. of Symbols (x10^4)
160lux	6kHz	50cm	1,2,5,8	6,12,18,24

rate can be up to 17%. We consider this error rate to be unacceptable given the reliability requirement. We then limit all our experiment to be with a distance of 50 centimeters. It also provides us the insights on how to make the system robust even under longer distances by adding another amplifier after V_o shown in Fig. 4.

F. Impact of TX Buffer Size on Symbol Error Rate

The system synchronizes the transmitter and the receiver after transmitting a buffer worth of symbols. The optical clock can have the clock drift if the TX buffer is too large. We use the settings on Table VII to study this issue.

Result: Fig. 11 plots the symbol error rate with different TX buffer size. It is interesting to notice that with a 1000B TX buffer, no symbol error found. While with a TX buffer of 8000B, the symbol error rate goes up to 41%. This suggests smaller TX buffer size should be preferred if we want to build a reliable low cost visible communication system.

V. Conclusions

We designed and implemented an ambient light cancellation mechanism for low cost embedded LED to photodiode communication system that utilize a potentiometer to adaptively remove the ambient light to provide an always ZERO environment to recognize the target light signal. The proposed technique allows the receiver to recover the transmitting signals without any interference from the ambient light. We provide a detailed description of the modulation and demodulation schemes as well as the ambient light cancellation mechanism, and their evaluations in both controlled and uncontrolled environment. The results show our system can provide a reliable and robust visible light communication with extremely low symbol error rate (almost 0) and an acceptable data rate up to 3kbps given a typical operating distance for 50 centimeters.

VI. Acknowledgment

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