LiFOD: Lighting Extra Data via Fine-grained OWC Dimming

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Abstract—**Optical wireless communication (OWC) shows great potential for high-speed communication due to its broad spectrum and the exceptional intensity switching speed of LEDs. Under poor conditions, most OWC systems switch from complex and more error prone high-order modulation schemes to the more robust On-Off Keying (OOK) modulation defined in the IEEE OWC standard. This paper presents LiFOD, a high-speed indoor OOK-based OWC system with fine-grained dimming support. While ensuring fine-grained dimming, LiFOD remarkably achieves robust communication at up to 400 Kbps at a distance of 6 meters. This is the first time that the data rate has improved via OWC dimming in comparison to the previous approaches that consider trading off dimming and communication. LiFOD makes two key technical contributions. First, LiFOD utilizes Compensation Symbols (CS) as a reliable side-channel to represent bit patterns dynamically and improve throughput. Second, LiFOD synchronously redesigns optical symbols and CS relocation schemes for fine-grained dimming and robust decoding. Experiments on low-cost Beaglebone prototypes with commercial LED lamps and the photodiode (PD) demonstrate that LiFOD significantly outperforms the state-of-art system with at least 2.1x throughput on the SIGCOMM17 data-trace.**

I. Introduction

Recent trends in indoor lighting include replacing incandescent and fluorescent bulbs with high-intensity LEDs because of their high energy efficiency, low heat generation, and long lifespan [1]–[5]. LED lighting saves the average family approximately $225 in electricity bills each year [6]. Another benefit of LEDs is their capability to switch between different light intensities quickly [7]. This feature creates opportunities for LEDs to be used as OWC transmitters for both high-speed communication and efficient lighting in everyday situations [8]. However, even with LED bulbs, lighting still accounts for around 15% of an ordinary home's electricity use [6]. Thus, for indoor LED bulbs, **transmitting more data robustly** with less retransmission while **not sacrificing the user experience of lighting** is another path to improve energy efficiency.

Most recent research has focused on high-order modulation to improve throughput in OWC systems [7], [9]–[11]. However, in poor optical channel conditions, such as indoor scenarios with complex artificial light sources or with sunny or underwater outdoor scenarios, the nonlinear effect of LEDs and the short symbol distance make decoding high-order modulation more complex and fragile, which leads to more error bits and, subsequently, more retransmissions that require energy consumption [12]. Although a modulation symbol in low-order On-Off Keying (OOK) modulation represents fewer bits, it is cheaper and more practical to use low-order, robust modulation instead of trying to improve the reliability of high-order modulations. Thus most OWC systems, such as OpenVLC and LiFi [7], [13]–[16], switch from high-order to low-order modulation OOK, which is defined as primary modulation in the OWC standard IEEE 802.15.7 [17]. This allows for more robust transmission with a low bit error rate (BER), and therefore fewer retransmission.

Considering lighting, LED brightness may cause undesired flickers when transmitting data via the optical spectrum [9], [10], [17]. Meanwhile, dimming is essential to adjust light intensity for a variety of purposes, such as office or hallway lighting, sleeping, reading, or other activities, with benefits that include reduced eye strain, mood setting, and LED life extension. Therefore, within the OWC standard [17], compensation symbols (CS) are employed in OOK modulation for smooth lighting and dimming, while not affecting OWC. As shown in Figure 1 (a), the entire PHY frame in OOK-based OWC is split into multiple subframes. In each subframe, a continuous number of CS symbols proportional to the length of the subframe are inserted in front of the OOK symbols (`P, H, RF, DS` fields) to adjust (i.e., increase, keep or decrease) average brightness (`AB`) smoothly.

Challenge: A tradeoff is observed when more control is needed to achieve fine-grained dimming, there is less of an opportunity for wireless communication transmission, which results in lower throughput [17], [18]. Moreover, CS symbols are solely used for dimming [19]. This consumes transmission resources in the time domain and limits the data rate of OOK, which already has a limited number of bits.

Motivation: There are two key observations that motivate our approach. **(1) Bit patterns** [20], [21] occur in transmitted bit-streams. A bit pattern is a bit sequence (i.e., multiple continuous bits), that frequently occur in traffic during a historical period. **(2) Compensation symbols** have not been used for data transmission in OOK-based OWC networks. In related dimming research [22]–[24], approaches focus only on dimming itself without considering the potential for data transmission. However, we can use CS as a reliable **side-channel** to denote bit patterns for improved throughput considering the significant symbol distances between CS and OOK symbols.

In this paper, we propose **LiFOD** to exploit compensation symbols, which previously have been used solely for dimming, to carry data bits **firstly** for improved throughput in OOK-based OWC networks. In our work, CSs are used in both

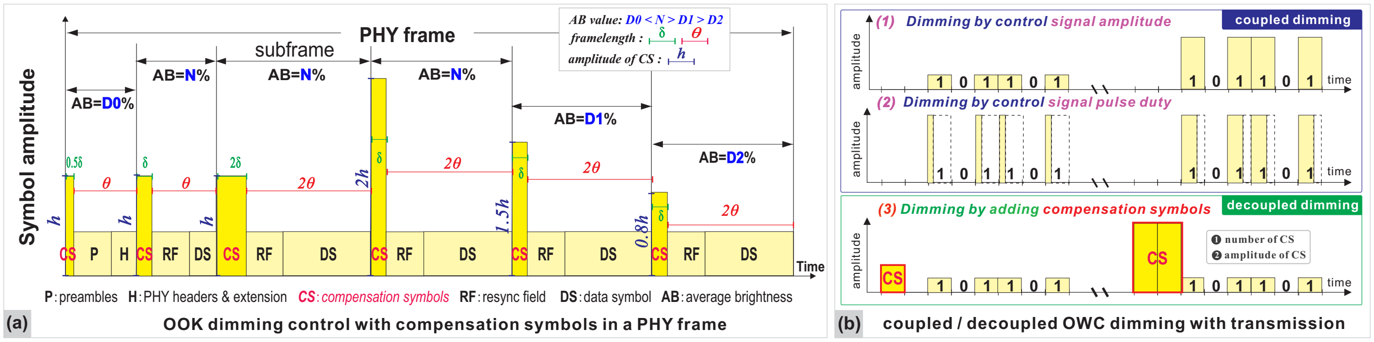


Fig. 1: (a) Adjust CS frame with varied symbol amplitude and frame length for OOK dimming, redesigned from IEEE standard [17]. (b) CS dimming is decoupled with transmission by adding variable number and amplitude of compensation symbols.

dimming controls and transmission. A bit pattern in a transmitted bitstream can be represented by one relocated CS symbol in the PHY subframe. The transmitter periodically conducts lightweight bit pattern discovery in parallel with modulation and notifies the receiver of the latest bit patterns via preambles.

Network throughput improves remarkably due to improved data rate and decoding performance. **(1)** Data rate: CS symbols become data symbols without consuming transmission resources in the time domain. Moreover, each CS symbol carries more bits than an OOK symbol. **(2)** Decoding: CS symbols have a lower detection error rate than OOK symbols. Furthermore, the receiver decodes the CS symbol to its corresponding bit pattern directly instead of decoding multiple OOK symbols for that bit pattern, which reduces decoding error possibilities. Our **contributions** are summarized as follows:

- We creatively exploit compensation symbols (CS symbols) to improve throughput. CS symbols were traditionally used only for dimming in OOK-based OWC systems. We explore bit pattern possibilities and propose a greedy mining algorithm to identify multiple bit patterns to maximize the overall throughput.
- We redesign non-flicker optical symbols (OOK and CS symbols) for smooth lighting and communication. This ensures the robust identification of symbol types in a changing environment. Initially, CSs are inserted continuously and proportionally into subframes for constant lighting. In our approach, CSs are relocated to discrete locations to denote bit patterns, which may introduce undesired flickers, however, we also design CS relocation schemes for stable lighting.
- We implement a LiFOD prototype on commercial devices and validate its lighting and communication performance in different transmission settings. Our comprehensive evaluation results demonstrate that **LiFOD** can achieve up to **400 Kbps** up to **6m** with fine-grained dimming, effectively **doubling** throughput at a longer range compared with SmartVLC on the SIGCOMM17 datatrace.

II. Background and Related Work

We provide a primer of OWC dimming functions and modulation below to better define our research problem.

A. Dimming in OWC

Light dimming is defined as controlling a light source's perceived brightness to users. We classify the primary OWC dimming methods in the IEEE OWC standard [17] into two types, **coupled** or **decoupled** dimming with transmissions.

For **coupled dimming with transmission**, as shown in Figure 1 (b), the control signals' amplitude has no impact on the time slots/carrier bandwidth of transmission while the control signals' pulse width influences the carrier's bandwidth. As observed in SmartVLC [25], a drawback of fine-grain coupled dimming control is the lower throughput that can be achieved because complex modulations that allows fine-grained dimming control wastes transmission bandwidth and adds more error bits. The researchers proposed AMPPM, which designs super symbols to generate more pulse width combinations for fine-grained dimming. However, AMPPM is still discrete step dimming with more modulation cost than the same-order OOK.

Decoupled dimming with transmission inserts compensation symbols (CS) into the data frame and sends constant brightness symbols of OOK modulation to adjust the average brightness of the light source. This treats data transmission and light dimming as two relatively individual modules with limited interaction. It has more robust communication and fine-grained dimming control while also providing the potential of using CS symbols to transmit extra data in comparison to coupled dimming methods. However, CS symbols take up time slots for data symbols compared with coupled dimming.

CS symbols have two ways to control a light source's average brightness shown in Figures 1 (a) and (b): (1) change the **number** of CS symbols in data frames and (2) adjust the **amplitude** of CS symbols. We can decrease the number of CS symbols as much as possible and adjust the amplitude of CS symbols for dimming to avoid taking up time slots for data transmission. Also, we can use CS symbols as a reliable side-channel to transmit specific data such as bit patterns. CS symbols will not waste time slots/carrier bandwidth anymore and even improve the communication performance.

B. Communication in OWC

Besides lighting, it is also crucial to provide users with high-speed communication. Based on the receiver type and modulation, we classify OWC into two types:

(1) Camera-based OWC with high-order modulation. It is hard to achieve a sufficiently high data rate as the switch speed of the transmitters is too fast for the limited frequency response of the cameras as receivers [10], [26]. Rolling shutter cameras on smartphones offer a frequency response only up to a couple of **tens of kHz**, which is well below the needed value for high speed communication of **hundreds of kHz**.

To overcome the bottleneck of camera-based OWC systems, many researchers [1], [9], [10], [27] focus on designing high-order modulation schemes to improve throughput. In [9], authors proposed ColorBars to utilize Color Shift Keying (CSK) modulation to improve the data rate via Tri-LEDs. They achieved a data rate of up to **5.2 Kbps** on smartphones. Similarly, Yanbing et al. proposed Composite Amplitude-Shift Keying (CASK) [10] to improve the throughput of the Camera-based OWC system. CASK modulates data in a high-order way without a complex CSK constellation design. CASK achieves a data rate of up to **7 Kbps** by digitally controlling the On-Off states of several groups of LED chips.

(2) Photodiode-based OWC with primary modulation. PDs are single-pixel with a small surface area, which allows PDs to have a fast response time of sensing processing. This means the receiver can achieve a fast and robust symbol detection for high-speed communication. Most OWC systems, such as LiFi [13] and OpenVLC [16], [25], [28] adopt PDs as receivers for high-speed transmission and achieve a frequency response of a couple **hundreds of kHz**.

To suit a high-speed transmission frequency, PD-based OWC adopts primary and low-order modulations such as **OOK**. This occurs because it is non-trivial to demodulate higher-order optical symbols (e.g., 8-CASK, 32-CSK) at the PD-based clock speed of hundreds of kHz, due to reduced symbol distances compared to OOK symbols. Higher-order modulations will bring more error bits and need more re-transmission for the required BER. Thus most popular OWC systems such as LiFi [13] switch from high-order modulations to low-order modulation such as OOK for robust transmission with a low BER in changing environments with poor channel conditions. The latest version of OpenVLC [28] can achieve, on average, about **150 Kbps** at 4m under optical interference.

Our scope: We focus on the indoor OWC systems equipped with low-cost **PD** sensors and single-color commercial **LED** lamps, which are resilient lighting infrastructures. Our goal is to boost throughput and fine-grained dimming simultaneously without additional cost.

III. System Overview

LiFOD consists of commercial LED lamp based transmitter and PD-based receiver. The architecture diagram and work-flows of LiFOD are shown in Figure 2.

We encode p-length bit patterns into a Compensation Symbol Code (**CSC**) as shown in the middle right in Figure 2. Each instance of a CSC code increases transmission speed because more bits are transmitted if $p>1$. When allocating bits, we first check whether the next p bits match the predefined CSCs from our bit pattern discovery. If false, one bit is allocated to

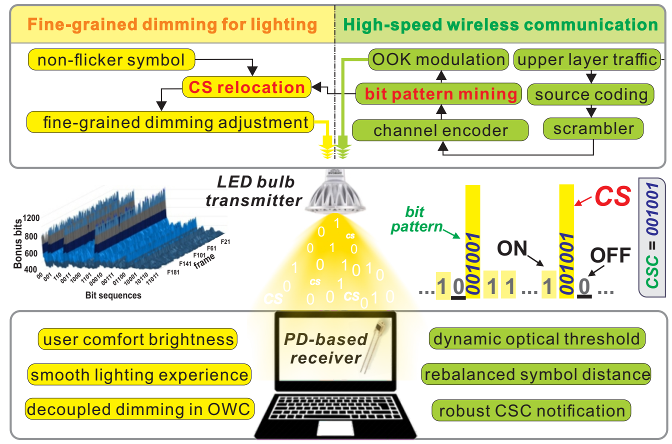


Fig. 2: System architecture and workflow of LiFOD.

an OOK symbol as usual. On the contrary, we define it as a **hit** if the bits match the predefined CSCs. Instead of mapping only one bit to an OOK symbol, p bits are transmitted through a CS symbol. Once the receiver detects a CS symbol's existence, it inserts a p-bit CSC into the data stream. The receiver now can detect only one CS symbol that denotes p bits, instead of needing to detect p OOK symbols. Because (p-1) more bits (i.e., **bonus bits**) are transmitted when there is a hit and all symbol types/(ON/OFF/**CS**) are used for transmission, it is clear that the data rate of our system will increase.

IV. Bit Pattern Discovery

A. Mining Challenges

Throughput improvement depends on the length of p and the hit rate in a given data frame. For example, as the length of a bit sequence increases, the probability of a hit decreases, and vice versa. There is a clear tradeoff between bit sequence length and hit probability. Moreover, as shown in Figure 2, not only one bit sequence is likely to be a bit pattern. When one bit sequence is selected as a bit pattern, the bitstream will be split by this bit pattern. After one bit pattern is assigned, depending on which pattern is chosen, the resulting allocation of the data bits is wholly changed. The next challenge, is to decide which pattern will be selected as the next bit pattern. All options need to be explored based on the choice of the previous bit patterns.

An example is illustrated in Figure 3. Suppose the bit sequence "01" appears most often when allocating the bitstream "...1001010101110001...". Also, it offers the maximal bonus bits when compared with other potential bit sequences. In this case it is $(2-1)\times 5 = 5$ bonus bits. We may encode bit sequence "01" as one type of CSC. However, other bit sequences may also exist, such as "10", which often appears and brings the same level of bonus bits as "01", $(2-1)\times 5 = 5$. A challenge of LiFOD is deciding which bit sequence, in this case "01" or "10", should be selected as the bit pattern. **(1)** If we choose "01" as the bit pattern, the bit stream will be split into three bit segments: "...10", "...1100..." and "...". **(2)** If choosing "10", the bit stream will be split into four bit segments: "...", "0", "11", and "001...".

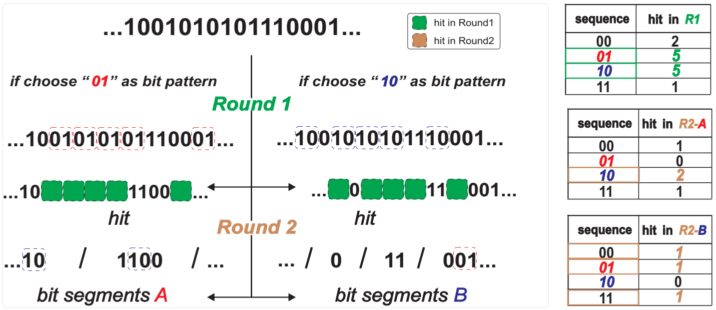


Fig. 3: Bit pattern candidates change in next round.

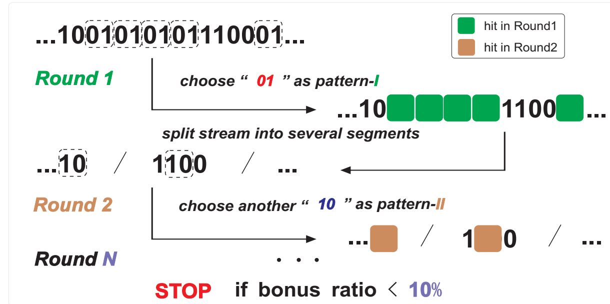


Fig. 4: The illustration of multiple rounds mining.

Additional bit sequences also frequently appear in the split bit segments produced after the first round of bit pattern selection. These sequences can be chosen as another bit pattern to further speed up the data rate. However, the bit pattern selected for a specific round impacts the bit pattern choice for the next round, and previously discovered bit pattern candidates in earlier rounds may not be candidates anymore. When choosing bit patterns, we need to consider the total bonus bit performance of all chosen bit patterns of all rounds.

B. Identify Patterns Greedily

To address the problem above, we execute bit pattern mining in multiple rounds shown in Figure 4. The bit pattern for each round will be selected as different types of CSCs. After several rounds of mining, there will be less opportunity to find bit patterns because bitstreams have already been split into short-length segments. Consequently, any obtained bonus bits will decrease as the number of rounds increases. Furthermore, if there are too many types of CSCs, the compensation symbol design for modulation will be more complicated and therefore increase the error rate of demodulation. Therefore, the choice to continue bit pattern mining is a tradeoff between increased data rate and error rate. The number of rounds we run for bit pattern mining depends on the bonus ratio for each round. The bonus ratio is defined as the ratio of bonus bits introduced by CSC for a specific round to bit numbers of the entire data frame. When the bonus ratio is less than **10%**, bit pattern mining stops at that round, and any previously mined bit patterns are chosen as CSCs.

Based on our experimental results, we've determined that with a bit sequence length larger than six bits the total number of bonus bits we gain starts to fall, and therefore we search for bit sequences whose length is up to 6 as bits long. The number of bit sequences possible is $\sum_{i=2}^{6} 2^i = 124$. We scan each of them in the frame, count hit number, and calculate bonus bits. We then choose the bit sequence with the most bonus bits as the bit pattern at that mining round. We calculate the bonus ratio of the bit pattern for each round and compare it with the 10% threshold. If the bonus bit ratio less than the threshold, mining will stop at that round.

V. Ablation Study of Bit Pattern

Real-world Daily Data-trace. We conduct CSC code abstraction based on two sets of real-world wireless traffic data from the (1) SIGCOMM 2017 trace [29], which is the recorded wireless network activities at the SIGCOMM 2017. (2) Another trace is from CAIDA 2019 [30], which collects the daily network traffic of a city in the US. These data packets are scrambled and encoded with the convolutional encoder specified in the IEEE 802.11 standards.

A. Bonus Bits Distribution and Potentials

Figure 5 shows heat maps of our bit pattern mining results in Round 1 and 2 among different frames from our two traces. There are more bit pattern candidates in Round 1 (i.e., six strongly highlighted columns). In Round 2, there are fewer bit pattern candidates (i.e., two significant highlighted columns) and the bonus bits in Round 1 are much more significant than Round 2. It implies that there are abundant known bits in the first round of mining used because of the high probability of having a hit on the CSCs. In high-order rounds, opportunities to use CSCs are few.

B. Tricks of CSC Decision in a Round

In general, the decision to choose a particular bit pattern candidate as a CSC code for each round depends on their bonus bits. However, if two bit pattern candidates have identical bonus bits, as occurs in Round 1 of the SIGCOMM17 trace shown at the top in Figure 6, we choose the longer bit

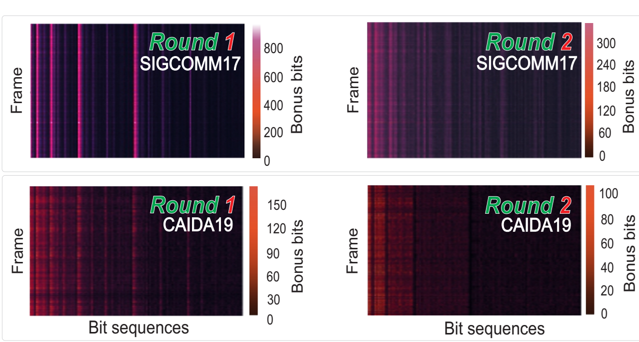


Fig. 5: Bonus bit heat maps for two rounds mining

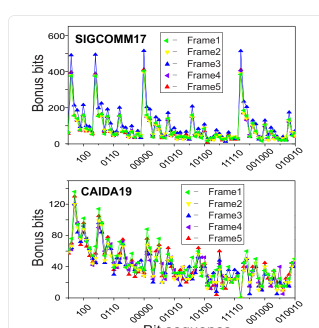


Fig. 6: CSC decision tricks

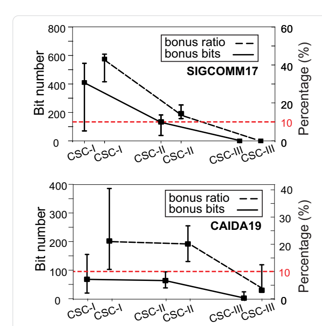


Fig. 7: Considerable bonus.

pattern candidate “000000” as the bit pattern even if other bit pattern candidates have the same bonus ratio performance for that round. The reason is that when two or more bit pattern candidates have identical bonus bits the longer one will make the bit segments shorter after splitting the longer bit pattern to achieve as fewer mining rounds as possible. Thus, there will be less hits in the next round which means there will be more CSC-I and less CSC-II.

C. *Two CSC with Considerable Exta Data*

Figure 7 shows that in Round 1 of mining, more than 40% of all bits are transmitted as bonus bits through CSC-I of the SIGCOMM17 trace. The CAIDA19 trace, also achieves a bonus ratio of more than 20% for CSC-I. As the number of mining rounds increases, a lower percent of bonus bits can be used, however, the bonus ratio is still above 10% Round 2 in the SIGCOMM17 trace. The bonus ratio in Round 2 for the CAIDA19 trace remains near 20%. In Round 3 of mining for both traces, the bonus ratio falls below the threshold of **10%**, and subsequently, the mining stops after Round 3.

Finally, we choose **two CSCs** (CSC-I and CSC-II) that will be used for transmission. The total bonus ratio of the two rounds of mining on two real-world traces is, combined, more than **40%**. Although the transmission rate benefits less directly from bonus bits when utilizing CSC-II, it still provides decoding benefits from the known bits represented by CSC-II. Overall, the more bits represented by CS symbols, the fewer opportunities for the false detection for OOK symbols.

D. *Delay and Overhead Measurement*

We analysis and measure the overhead of bit pattern mining based on real-world data traces. The bit pattern mining process for SIGCOMM 17 and CAIDA 19 consumes 0.78 s and 0.37 s in average, which is short enough as normal delay time before transmission. The computation cost of our pattern mining for these two data-traces are both 144 MiB of memory in average, which is pretty low even compared with the computation abilities of MCU devices (e.g. 512MB RAM in BBB). The results show bit pattern mining of LiFOD is lightweight, real-time, and thus suitable for usage in the real world.

VI. Fine-grained Dimming via CS

A. *Non-flicker Symbol Design*

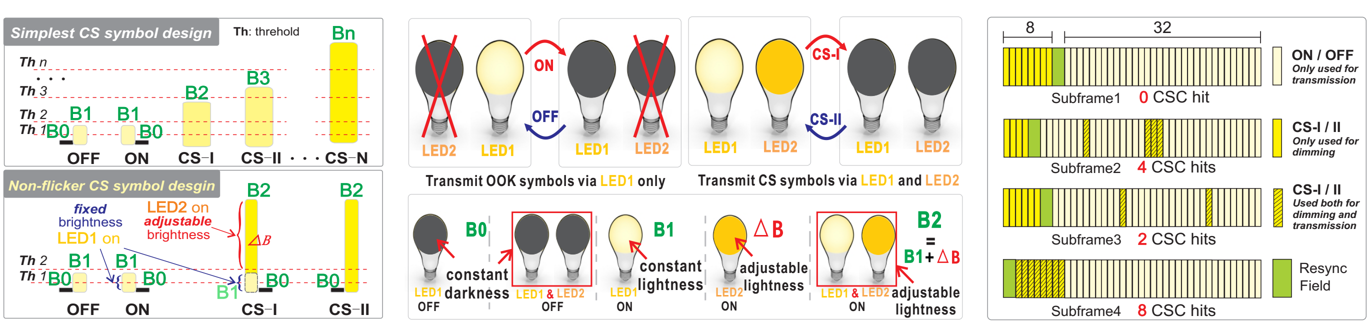
Flicker is the temporal modulation of lighting perceivable by the human eye, which can negatively affect a user’s lighting experience. The maximum flickering time period (MFTP) is the maximum time period over which the light intensity can be changed and not sensed by human eyes. Thus any brightness changes over periods longer than MFTP must be avoided (i.e., significant low frequency brightness changes cause flickers and should be mitigated) [17]. In the current standard, OFF/ON and CS symbols have different amplitudes as shown in the top of Figure 8 (a), CS-I and CS-II also have different amplitudes. The random distribution of CSCs encoded by LiFOD that appear in PHY frames at low frequencies causes significant flickering. To address this, our flicker-mitigation solution is inspired by Manchester coding [17], where each symbol is extended to include itself and its complementary symbol. This guarantees that any significant brightness changes will appear too fast to be sensed by human eyes.

There are three amplitude scales in the new symbol design: B0, B1, and B2 (brightness: B0 $<$ B1 $<$ B2) for OFF, ON, CS-I, and CS-II symbols instead of four brightness amplitudes in the original symbol design. Symbol **OFF** is designed as **B0+B1**. In the first half of a symbol’s duration, it has an amplitude of B0. In the second half of a symbol’s duration, it has an amplitude of B1. Similarly, symbol **ON** is designed as **B1+B0**. And we design **CS-I** as **B2+B0**, while **CS-II** is **B0+B2**. Our newly designed symbols only need two thresholds rather than three for demodulation, decreasing the complexity and load of symbol detection. This increases the symbol distance and decoding robustness further. Additionally, CS-I and CS-II have the same brightness in our non-flicker symbol design, which further reduces the flickering possibility compared to the standard symbol design.

Note that there exists more CS-I symbols than CS-II symbols. It is easier for the receiver to distinguish the amplitude difference between B2 and B0 than between B1 and B0. Suppose a symbol has an amplitude of B2 in the first half of symbol duration. In this case, the symbol will be decoded as one CS-I symbol directly without estimating the amplitude of the second half symbol duration. That is why we design the CS-I symbol as B2+B0 instead of B0+B2. This design decreases the detection error rate (DER) of the CS-I symbol, which carries more data than the CS-II symbol. Finally, this benefits total throughput and BER performance.

B. *Compensation Symbols Relocation*

Fine-grained dimming control. LiFOD consists of two commercial LED lamps that are controlled synchronously shown in Figure 8 (b). The transmitter sends out OOK symbols



(a) optical symbol design in LiFOD (b) two commercial LED bulbs to generate ON, OFF, CS-I and CS-II (c) CS symbol relocation scheme

Fig. 8: Optical symbol design with fine-grained dimming and CS relocation scheme illustration in LiFOD.

via LED1 and sends out compensation symbols via LED1 and LED2 together. LED1's brightness is set by the user and fixed before OWC begins. Users can continuously adjust LED2 by the dimmer knob to provide the additional brightness of (B2-B1, i.e., ΔB) to increase or decrease the average brightness (**AB**) without impacting optical symbol detection. This saves transmission bandwidth and does not affect symbol decoding. The number of CS symbols is proportional to each frame's length to guarantee the same AB between frames. This mitigates **inter-frame** flickers and keeps constant brightness, even after an updated dimming is set.

Random CSC Locations and Numbers. There are subframes in each frame. Currently, compensation symbols are continuously inserted into subframes for dimming control in the IEEE OWC standard [17]. However, these are incapable of denoting the bit patterns that may appear discretely in the bitstream of one frame for transmission. Moreover, the hit numbers of CSC-I and CSC-II are not always the same in subframes, even though different subframes should have the same brightness to reduce **intra-frame** flickers. This means each subframe should have an equal proportion of CS-I and CS-II symbols.

CS Relocation. In Figure 8 (c), there are 40 OOK and CS symbols in each subframe. We set $\frac{1}{5}$ of the symbols (i.e., 8 CS symbols) for dimming to keep a constant AB of the subframe. There are 8 CS symbols at the beginning of each subframe initially. If there is a CSC-I/II in the subframe, we put one CS-I/II symbol in that location. These picked CS-I/II symbols are used both for dimming and assisting transmission. The left redundant CS-I/CS-II symbols at the front part of the subframe are only used for dimming. The CS symbols only used for dimming are separated by the resync field (RF) in Figure 1 with symbols used for transmission (OOK and picked CS symbols). We only decode the symbols after the RF field. Compared with the original, continuous CS symbols, CS relocation provides the potential to create robust side-channels for data transmission and mitigates the flickering possibility further as an unintentional benefit while keep constant brightness.

VII. Robust Decoding of CS

A. Dynamic Optical Threshold

As shown in Figure 8 (a), the receiver checks grayscales of two parts in one received symbol to identify its symbol type by its grayscale threshold. In LiFOD's non-flicker design, there are three brightness levels B0, B1, and B2. The receiver distinguishes them based on grayscale thresholds informed by a preamble from the transmitter.

However, as shown in Figure 9, a received grayscale is not identical to the one transmitted by the transmitter under four different dimming levels (i.e., B2's incremental brightness). The received grayscale of different brightness may overlap with others, and B2 in different dimming settings can influence the perceived brightness of B0, B1 due to their continuous distribution in the PHY frame. To identify an optical symbol's type with varying brightness, the receiver should be informed of dynamic thresholds among B0, B1 and B2 via a **preambles** from the transmitter. Grayscale thresholds are measured and calculated based on short training symbols in the preamble field. The threshold values are dynamically adjusted based on the measurement informed by the preamble.

B. Rebalanced Magnitude Distance

In addition to our dynamic threshold measurement with preambles for different dimming settings in varying environments, we also need to combat any environmental influences. When an optical signal radiates away from its transmitting light source, the signal spreads out in different directions. Parts of spreading light beams reflect off objects and arrive at receiving light sensors from different paths. Consequently, different ambient light brightness will impact detection of original optical symbols. If the ambient light is weak, the brightness of B1 or B2 will dominate the receiver's sensed intensity. When ambient light gets stronger, the ambient light will dominate the received brightness and the brightness of B0, B1, and B2 will have a similar high grayscale level, as shown in the left of Figure 10. The same case happens when the transmission distance increases. When the transmission distance between transmitter and receiver becomes larger, ambient light will dominate the receiver's brightness as well, as shown in the right of Figure 10. The intensity of B0, B1, and B2 will have a similar low grayscale level.

These two factors significantly cause the perceived magnitude of brightness transmitted to be harder to distinguish from one another, and therefore, the received symbol is not identical to the transmitted optical symbol. We need to estimate the optical channel response using the **preamble** to further conduct equalization to eliminate the influence of ambient light and transmission distance.

C. Robust CSC Notification

Preambles are used in LiFOD to notify the receiver of the CSC codes used in our system. CSC-I and CSC-II are

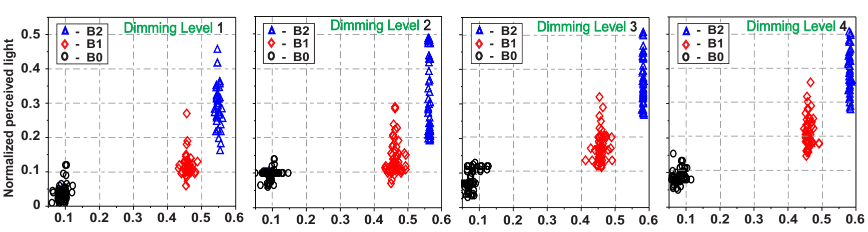


Fig. 9: Grayscale diagram of B0, B1, B2 on four incremental dimming levels.

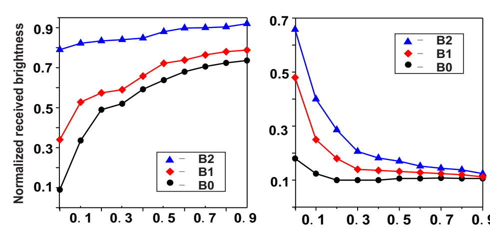


Fig. 10: Influence of two factors.

prepended to the data packet in the preamble field to inform the receiver of the bit patterns being used. The receiver stores CSC codes and understands that they are specified for CS-I and CS-II symbols separately.

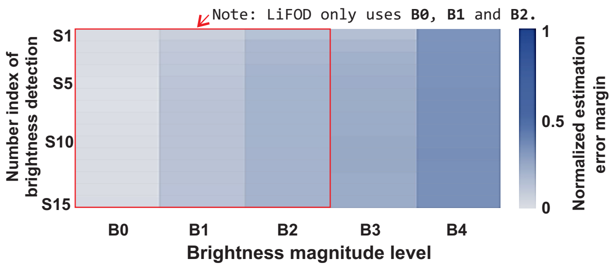


Fig. 11: The normalized magnitude estimation error margin of 15 detections in varying environment.

When the receiver estimates the transmitted brightness magnitude by dividing the estimated optical response of channel $\hat{H}(O)$, the absolute magnitude change on a symbol with a lower magnitude is lower than that on a higher magnitude symbol, as shown in Figure 11. For example, if the estimation is that a received symbol should be magnified by 20%. The absolute magnitude changes of symbols are different. Low magnitude symbols have a minor error margin, while magnitude errors of high magnitude symbols are scattered in a broader range than that of low magnitude symbols. Because LiFOD only adopts three brightness magnitudes (B0, B1, B2) in symbol design, the equalization can successfully eliminate the influence of the varying environment.

VIII. Implementation

A. Hardware

Transmitter. Our LiFOD transmitter consists of several commercial components: two regular LED lamps (LED1, LED2), and MOSFET and BeagleBone Black (BBB) boards. LED1 is used to generate constant-brightness OOK symbols, LED1 and LED2 are used to generate variable brightness CS symbols as introduced in Section VI-B. They are controlled uniformly by the BBB board. Because BBB can only provide 3.3V control signals, which can not drive high-power LEDs, we use a MOSFET transistor as a fast switch to drive the high-power LEDs (12V). To provide variable and fine-grained dimming, we wired a potentiometer as a dimmer knob between the DC power with the LED positive lead. We removed the AC-DC converter in our daily LED lamp, which affects the ON-OFF switching speed significantly.

Receiver. The LiFOD receiver prototype has three main components: analog-digital converter (ADC), operational amplifier (OPA), and the photodiode (PD). The light is sensed by the PD to convert light signal to a small current and amplified by OPA. Finally, analog values are converted to digital values in SPI data format and then is processed to estimate analog light intensities for symbol decoding. The driving circuit can be fully powered and controlled by the BBB.

System cost. The Beaglebone Black board ($80) in our prototype can be fully replaced with Beaglebone pocket($37), which is cheaper. Thus, totally including transmitter and receiver, the LiFOD system costs less than $100.

Component	Brand/Model/Type	Unit Price (USD)
LED Bulb	BAOMING-5W-MR16	**4.2**
MOSFET	BOJACK-30N06LE	**0.7**
Photodiode	OSRAM SFH206K	**1.4**
Op-amplifier	Todiys-TLC272	**2.4**
ADC	TI-ADS7883	**3.2**
potentiometer	HUAREW-PTM15	**0.1**
BBB board	Beaglebone-Black or Pocket	**80** or **37**

TABLE I: Price table and system cost of LiFOD.

B. Software

There are two main tasks on the software side: (1) send out optical symbols at high speed from the transmitter; (2) demodulate received optical symbols at high speed with reliability on the receiver. We use low-cost BBB platforms. In this work, we set the transmission frequency at *hundreds KHz* level, which is the same as the state-of-art SmartVLC or OpenVLC. Other software modules, such as our lightweight bit pattern mining and CS relocation, as shown in Figure 3 are run on BBB as firmware to provide services among PHY and upper layers.

IX. Evaluation

A. Setup

(1) Dataset. We choose two real-world datasets SigCOMM17 and CAIDA19, to simulate user's daily Internet traffic. **(2) Transmission frequency.** We set the transmission frequency to be lower than 200KHz. **(3) Sampling rate.** To better detect the optical symbol shape, we set the ADC sampling rate to 1.2MHz, six times of transmission frequency. **(4) Ambient light setting.** Based on real-world scenarios, we conduct experiments in a 4 x 8 m^2 living room in the day and night scenarios. **(5) Dimming setting.** We set the dimming

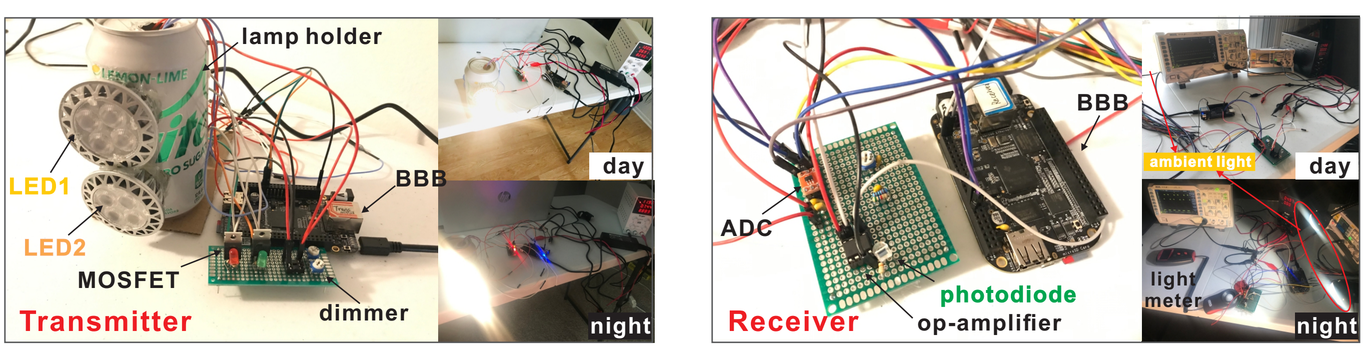
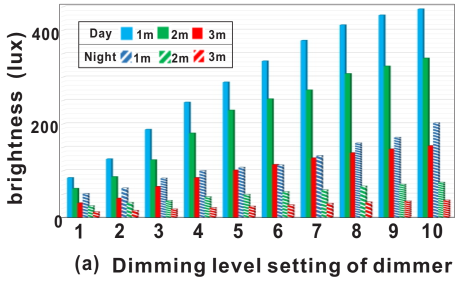
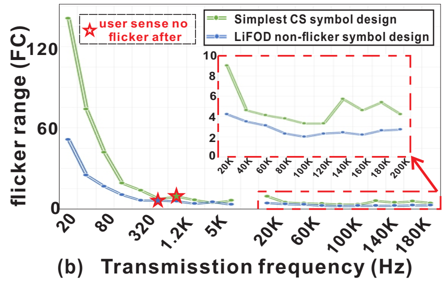


Fig. 12: LiFOD prototype: transmitter, receiver and experiment scenarios in day and night.





Total Scores at 10 Dimming Settings		User A		User B		User C		Average	
		FLK	LIT	FLK	LIT	FLK	LIT	FLK	LIT
View	direct view	9	10	10	10	10	10	9.7	10
	side view	10	8	10	10	10	9	10	9
Distance	1 m	8	9	10	9	9	9	9	9
	3 m	10	8	10	10	10	9	10	9
	5 m	10	8	10	10	10	9	10	9

Flickering (**FLK**) and lighting (**LIT**) scores for 10 dimming setting at 100 KHz transmission frequency. If one senses no flickers or has comfortable lighting at specific setting, the score is 1, otherwise 0. The score value in each cell is the sum of 10 settings.

(c) Users' perception scores

Fig. 13: Evaluation of fine-grained dimming and non-flicker performance.

level by adjusting the dimmer knob neatly and using a light meter to measure its granularity.

B. Performance

1) Lighting performance:

Fine-grained dimming: The brightness of LiFOD can be manually adjusted to any continuous setting. We evaluate ten incremental dimming levels at different distances, as shown in Figure 13 (a). The dimming range is from 0 lux to 450 lux, which meets the office lighting requirement from U.S. General Services Administration [31]. In the different dimming setting index, the brightness sensed by the user increases depending on the day or night scenarios. The experiment results prove that the dimming function works well.

Non-flicker performance: We measure the non-flicker performance with the light meter via the photometric quality, which measures the foot candle (FC) value range from its minimum to maximum values. The more extensive range of FC values, the more flickering possibility. When the transmission frequency increases, the flicker possibilities reduce for the two optical symbol designs. Figure 13 (b) shows that users sense no flickers since the transmission frequency for LiFOD's non-flicker symbols are lower than the original optical symbols. Due to the unexpected low frequency of CS symbols, LiFOD's non-flicker symbols will provide more smooth lighting without flickering than the original symbol design, even at a very high transmission frequency such as 200KHz. Results show that our flicker-mitigation solution addresses the flicker well.

We also investigate users' perception of flickering and comfortableness of lighting, as shown in Figure 13 (c). Three volunteers are invited to experience the lighting function of LiFOD. Each user scores their user experience for at 10 dimming settings in different conditions such as facing directly or indirectly, at different distances to LED lamp. The results show all users have good experience with comfortable and stable lighting perception.

2) Communication performance:

(1) Impact of transmission frequency and distance.

We first evaluate throughput performance at different transmission frequencies and distances based on two real-world data traces. As shown in Figure 14 (a), the throughputs increase significantly as transmission frequency increases at the same distance setting. Although increasing distance will cause the throughput decline, it decreases less noticeably due to our robust symbol detection. Due to the higher bonus bits introduced by CSC, LiFOD achieves up to **400 Kbps** in data rate at a range of up to **6m** in SIGCOMM17 traffic. It is about **2.7** times better for throughput and **1.5** times better for communication range compared with the latest OpenVLC (average **150 Kbps** at 4m under optical interferences).

(2) Impact of incidence angle and position.

Because light beams emit and spread in the line-of-sight (LOS) manner, the pointing and direction setting is essential in high-speed OWC systems. We evaluate the influence of different facing angles and the receiver's relative locations as shown in the experimental schematic Figure 14 (b). The transmitter is fixed while the receiver's location and its facing angle are changed incrementally at 5°and 2cm from its base location L_0 and direction. We set the transmission distance from L_0 of the receiver to the transmitter at **3.5m** and the transmission frequency to **125KHz** for our two data traces.

As shown in Figure 14 (b), when the receiver is set at L_0, LiFOD can tolerate more unaligned angles. When the receiver is moved left or right in small ranges such as 2 or 4 cm, it is the same. For long-range location movement, throughput drops dramatically unless setting proper angle. The trend is consistent for two data traces. Thus, it is important for real-world usage of LiFOD to make sure the transmitter's light directly points to the receiver. However, this is consistent with normal usage habits of using lamps for our daily lighting.

(3) Throughput comparison with the state-of-art.

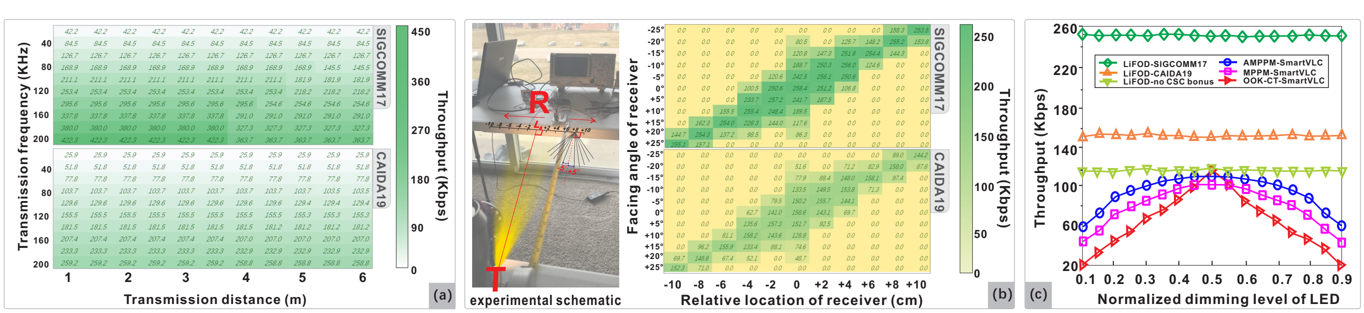


Fig. 14: Throughput performance evaluation of LiFOD. (a) Throughput vs. distance and frequency, (b) Throughput vs. incidence angle and position, and (c) Comparison with state-of-art [25].

Finally, we make comparisons among LiFOD with state-of-art methods: OOK-CT, MPPM, and AMPPM in SmartVLC [25] shown in Figure14 (c). We set the same transmission frequency to **125KHz** and distance to **3.5m**. OOK-CT is OOK with Compensation Time, it keeps the CS symbols' amplitude constant and only changes the inserted number of CS symbols for dimming. Thus, OOK-CT, MPPM, and AMPPM are coupled-dimming-based OWC. We evaluate LiFOD with SIGCOMM17 and CAIDA19 data traces. We transmit OOK symbols without CSC bonus in LiFOD as a comparison.

First of all, our LiFOD throughput performances are better than **coupled-dimming**-based OWC methods in all scenarios. The reason is that LiFOD decouples the dimming with transmission and releases most times slots for standard data symbol transmission. Based on different CSC bonus ratios in various data traces, LiFOD for SIGCOMM17 traffic performs best and achieves **250 Kbps** in all dimming settings, which is an improvement of at least **110%** compared to AMPPM. Although lower than SIGCOMM17, LiFOD for CAIDA19 traffic which collects the daily network traffic of a city in the US still achieves **155 Kbps** in all dimming settings, which corresponds to at least a **34%** improvement over AMPPM in SmartVLC (the best throughput performance is **120 Kbps**).

Generalizability. The throughput improvement ratio in LiFOD is based on the bonus ratio of traffic. Other OWC platforms, such as the LiFi system, can apply LiFOD approach to imporve their performance. Suppose the common OWC platforms are improved such as robust symbol transmission and decoding at the **MHz/GHz** level. In that case, LiFOD can also be adopted to achieve the throughput improvement at the same boost ratio at **hundreds of Mbps/Gbps** level with fine-grained dimming support.

X. Conclusion

This paper exploits opportunities of expanding dimming methods for its use in data transmission: using compensation symbols as a side-channel to carry data bits to improve the throughput in OOK-based OWC networks. First, we design a lightweight greedy algorithm to identify bit patterns to maximize the total bonus bit performance in real-world traces. Then we utilize the preamble to notify CSC codes, dynamic thresholds, and estimate channel conditions for robust demodulation in the changing optical environment. Most importantly, we design non-flicker optical symbols and compensation symbol relocation scheme to support smooth lighting and communication with improved throughput. LiFOD can achieve up to **400 Kbps** throughput in the communication range up to **6m** with fine-grained dimming. Compared with SmartVLC at the same transmission parameters, LiFOD improves more than **34%** and **110%** throughput for two real-world data traces respectively in all dimming levels.

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