# Enabling Real-Life Deployment of Piggyback-VLC via Light Emission Composition

Yanbing Yang, Jun Luo, Chen Chen, and Liangyin Chen

***Abstract*—Whereas the increasing popularity of both commercial LED lighting and mobile devices certainly creates opportunity for real-life deployment of VLC systems, reaching the high throughput promised by lab experiments still faces major obstacles. In particular, lacking the sophisticated hardware and software support under experimental conditions, real-life systems are challenged in many aspects, especially low SNR, low operation frequency, uncontrollable LED non-linearity, and illumination requirements. Nonetheless, deployments tapping commercial infrastructure are critical to gain market penetration for VLC-enabled wireless applications, so boosting the performance of these real-life systems becomes imperative. In this article, we consider the multiple LED chips and/or light sources nature of indoor commercial lighting infrastructure, and propose a spatial modulation that composes the cooperative light emissions (transmissions) from multiple LEDs. In addition to gaining a higher spectral efficiency, this scheme utilizes the multiple-LED nature of commercial lighting to overcome LED non-linearity with a novel yet simplified hardware construction. We present two typical designs adopting this special modulation under different infrastructural constraints, and provide an introduction on its potential contribution to the standardization of VLC. Finally, we discuss potential extensions to further improve performance.**

***Index Terms*—Optical Camera Communication, Collaborative Transmissions, Grayscale Modulation**

## I. INTRODUCTION

Envisioned as an alternative to radio frequency (RF) due to the increasingly crowded spectrum, visible light communication (VLC) has been attracting more and more attentions in the past decades. The latest standard of short-range optical wireless communications [1] further confirms the relevance of VLC to assist local and metropolitan area networks, but it is still ignoring the multiple-LED nature of commercial lighting infrastructure envisioned as transmitters in the standard. We hence bring forward our vision on a specific type of indoor application, and present our readily deployable solutions considering the multiple-LED nature for it, aiming to serve as a potential addendum to the existing standard [1]. As shown in Figure 1, enabled by the growing adoption of light-emitting diodes (LED) in commercial lighting, our VLC system piggybacks on the lighting infrastructure and streams data flow to users' mobile devices. Such a system has the potential to offer information services, e.g., indoor localization and data transmission, yet with lower energy consumption (due to the "free" media) and less concern on electromagnetic interference. We term such a system Piggyback-VLC (or P-VLC for short) given its piggyback nature, and we focus on smartphone as the typical user device for VLC reception.

Despite the promising future of P-VLC, it comes along with quite a few challenges and limitations, notable due to the low-end devices involved, i.e., commercial LED luminaires and mobile devices. Absent of sophisticated hardware and software support, P-VLC faces the following major challenges:

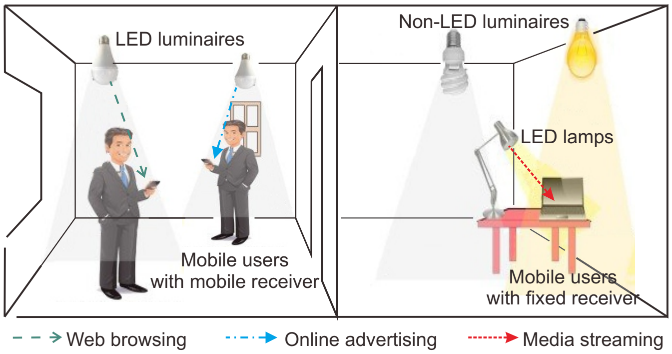

Fig. 1. The application scenarios of P-VLC systems.

- *Low Signal-to-Noise Ratio (SNR)*
- *Coexistence of non-LED lighting infrastructure*
- *Diversity in LED luminaires*
- *Flicker free*
- *Low operation frequency*
- *LED non-linearity*

Although most of these issues would not exist for experimental prototypes using high-performance LEDs and/or other accessories (as elaborated later), it is the deployability of P-VLC that makes it suitable to penetrate the market and to potentially compete with Wi-Fi. Therefore, tackling these challenges is imperative and thus the target of this article. In the past few years, many proposals have been made in order to tackle some of the aforementioned challenges [2], [3], [4], [5], [6]. Notably, Danakis *et al.* [2] increase the operation frequency from Hz to kHz level, leveraging the rolling shutter effect of complementary-metal-oxide-semiconductor (CMOS) cameras. RollingLight [3] proposes to use direct light (as opposed to reflected light in [2]) for transmission, substantially elevating the SNR. CeilingCast/CeilingTalk [7], [4] continue the same direction but drastically increases the throughput to kilobits-per-second (kpbs) level. By far, only binary modulation scheme (in particular on-off keying, or OOK) is used, hence later proposals mostly focus on improving the spectral efficiency through higher-order modulations [5], [6]. Nevertheless, all these proposals have only targeted some specific working scenarios and tackled part of the challenges faced by P-VLC. So there is a need for a holistic study on the feasibility and potential of real-life P-VLC deployments.

To this end, this article first gives a brief review on the

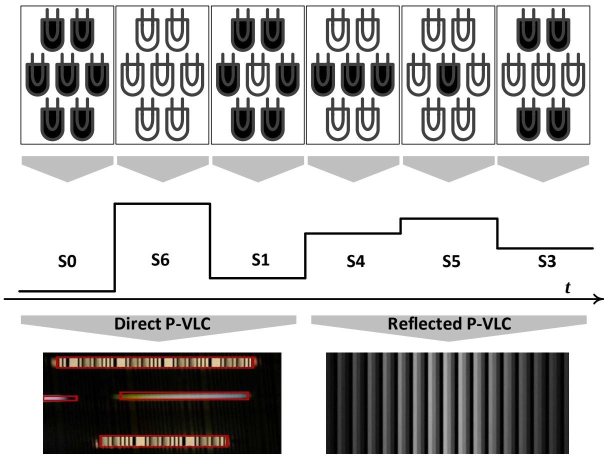

Fig. 2. Basic idea of C-ASK.

literature concerning P-VLC, aiming to reveal the weakness of existing proposals. All these lead us to the main topic of a high-order modulation scheme, termed Composite Amplitude-Shift Keying (C-ASK), formed by composing the cooperative light emission from multiple LEDs, as illustrated in Figure 2. We briefly introduce two types of implementations that accommodate various lighting constraints, and expound the potential of our P-VLC solution with C-ASK modulation scheme contributing to IEEE standard. Finally, we discuss potential enhancements to further push the limit for C-ASK in P-VLC, before drawing our conclusions.

## II. BACKGROUND AND CHALLENGES OF P-VLC

Given the piggyback nature of P-VLC, we need to better understand the particularities of the tapped commercial infrastructure, so as to design VLC adaptively. We hereby look into LED luminaires for the transmitter side and smartphone interfaces for the receiver side, and check the potential challenges.

**Commercial LED Luminaires:** Due to their massive production scale, one common feature of commercial LED luminaires is that they mostly adopt cheap and low-end LED chips, each formed by a blue LED coated with $Y_3Al_5O_{12}$:Ce (or YAG:Ce) phosphor. The consequence of this feature is two-fold. On one hand, the operation frequency of these luminaires is quite limited: whereas experimental prototypes have reported to operate at GHz level, these commercial devices can hardly get close to MHz level [8], [9]. On the other hand, using variable wavelength to form high-order modulations [10], [11] becomes infeasible, as these low-end LEDs cannot emit specific wavelengths of light. Moreover, the construction of LED luminaires has a great variety in terms of size and shape, although it is common that each luminaire consists of tens to hundreds of LED chips. The lighting can also be delivered in either direct or reflected mode; luminaires of the latter (e.g., cove light) are virtually invisible to users. Finally, the lighting infrastructure is often subject to strict regulations. Typically, the emitted light has to be flicker-free, and certain dimming control has to be abided by. Therefore, proper modulation and coding schemes are expected to improve the spectrum efficiency (hence higher data rate) and satisfy the requirements of lighting.

**Smartphone Receiver:** Since the light sensors of mobile devices are optimized for dynamic range rather than response speed, but it is feasible to interface a high-end light sensor, the camera becomes the most obvious choice for P-VLC receiver. These CMOS cameras have a common feature: rolling shutter, i.e., the whole frame is not exposed once but rather in a sequentially column-by-column manner. Using these individually exposed columns (instead of the whole frame) to sample the incoming light increases the sample rate (hence the operation frequency) by thousands of times. For example, light emission modulated by OOK produces bright-dark bands in a frame, as briefly illustrated in Figure 2. We refer readers to Figure 1 of [4] for further elaboration. Typically, rolling shutter has two critical parameters: rolling-shutter frequency $F_r$ and scanning (column) width $W_r$ [4]. Normally, $F_r$ is capped at 20 kHz and $W_r$ is only a couple of pixels. Apparently, modulation symbols should be generated at a rate lower than $F_r$, and a rate lower than 10 kHz is often needed to guarantee a robust sampling. However, lowering symbol rate increases symbol width. Since the number of symbols contained in a frame is bounded by the minimum between the screen width and the width of the transmitter's image (a.k.a., Region of Interest, or RoI [4]), widening individual symbols can only reduce throughput.

In summary, the real bottleneck of P-VLC now lies in the stringent frequency spectrum, so the only solution appears to be higher-order modulations that offer higher spectral efficiency. However, without Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK) and Color Shift Keying (CSK) [6], we are left with only Amplitude-Shift Keying (ASK) as an alternative, where we have to cope with LED non-linearity [12]. Existing proposals use a narrowed dynamic range to retain linearity [13], but the reduced SNR makes it infeasible for P-VLC. Other proposals resort to complicated rectifications [14], [15], yet requiring calibrations to suit individual LEDs given the varying manifestations of non-linearity.

## III. HIGH-ORDER MODULATION VIA LIGHT COMPOSITION

Our idea to address LED non-linearity while forming a higher-order ASK stems from the linearity of composing (i.e., adding up) multiple light emissions. In other words, the illuminance caused by two LEDs is twice of that by one LED. Essentially, C-ASK modulation gains a higher order than the binary (black-white) OOK by using grayscale symbols each representing multiple bits, as illustrated in Figure 2. This idea leverages the "multitude" nature of commercial LED lighting, i.e., a space is often lit by multiple luminaires and each luminaire consists of multiple LED chips. While this might not be a brand-new idea, we are among the first to put them onto real-life system deployment for P-VLC. Our designs involve three aspects: i) specific driving circuits to suit different types of luminaire constructions, ii) efficient demodulation schemes to recognize grayscale symbols, and iii) handling general issues such as calibrations and combating flicker. The common packet structure has been defined in [4], which starts with a preamble of consecutive brightest symbols. The transmitters differ substantially from the conventional design, avoiding non-linearity by not relying on analog signals to drive the LEDs, but rather directly controlling individual LEDs through the modulated digital signals. In the following, we introduce two C-ASK prototypes adapted to different lighting constructions.

### *A. Direct P-VLC*

A rectangle troffer often consists of tens to hundreds of LED chips, so we separate these chips into $N-1$ groups and let the modulated signal to drive them individually, as detailed in [6]. Controlling the on-off procedures of these groups yields $N$ grayscale symbols, ranging from S-0 where all groups are off to S-(N-1) where all groups are on. A grayscale symbol exactly carries multiple data bits hence forming a high-order modulation with high spectrum efficiency. To meet the lighting requirement of flicker-free, we we propose $N$'s-complement (NC) coding to mitigate flicker at both symbol and transmitter levels. The NC coding basically splits a symbol into a pair of original and complement symbols to maintain a symbol level energy balance. At individual transmitters, this scheme reduces to normal Manchester coding so as to maintain stable lighting. Experiments have verified its effectiveness of improving data rate, i.e., fourfold of that achieved by OOK [6].

### *B. Reflected P-VLC*

Not all luminaires deliver light in direct mode, so C-ASK has to work for reflected lighting. Moreover, direct LED-Camera VLC has its throughput confined by the dimension of individual luminaires [4], so it is possible to improve throughput under reflected lighting with a proper design. The major obstacle here is the low SNR caused by introducing a reflector (e.g., a wall) as the additional communication media [2], which has forced earlier proposals to switch to direct light VLC [3], [4]. Fortunately, the design in [5] is applicable to this case if we simultaneously drive multiple LED luminaires instead of LED groups in a single luminaire. Because the signal is a cooperative composition of those from multiple luminaires, achieving an adequate SNR and meanwhile avoiding interference become feasible, and the light composition can form different light levels, i.e., modulated symbols, by turning on different light sources. A testbed was built in [5] and experiment results demonstrated it can deliver an average throughput beyond 2 kb/s at a distance of 3 m.

## IV. IMPLICATIONS FOR STANDARDIZATION

A latest standard [1] about short-range wireless optical communication using visible light is published in April 2019. It introduces pervasive LED lighting infrastructure as transmitters and image sensors (camera) as receivers, which are also the basics of our P-VLC. The new standard adds new PHY operating modes in PHY IV and V to involve a P-VLC like system that employs illumination LEDs and cameras in VLC. In particular, to accommodate the camera receiver with rolling shutter, the frequency modulation based techniques such as rolling shutter frequency shift keying (RS-FSK) and camera m-ary frequency-shift keying (CM-FSK) are supplemented in the standard due to their robustness to environment changes and heterogeneous devices. Nevertheless, the frequency modulation has relatively a low spectral efficiency that seriously confines the achievable data rate: only 11.32 bytes per second reported in [3]. Moreover, all modulation schemes in the standard have ignored the multiple LED chips (or light sources) nature of VLC transmitter built upon LED illuminating infrastructure, which can be used to improve the spectral efficiency and thus the data rate.

To this end, we believe that the proposed light composition modulation in this article has a potential to contribute to the standard for improving the spectral efficiency in VLC. As detailed in Section III, the light composition modulation scheme creatively exploits the multiple-LED-chip feature of LED lighting sources to form a high-order modulation of C-ASK and hence achieves higher data rate for camera-based VLC, and its effectiveness has been verified in two typical types of lighting settings. Although ASK-based modulation may not be very robust to environment changes comparing with frequency modulation, given the dual function of indoor illuminating and data transmission of VLC, we could expect the indoor communication channel to be rather stable for C-ASK modulation. Therefore, our P-VLC solution considering the multiple-LED-chip feature of commercial lighting sources should further improve the standardization of VLC and/or optical camera communication.

## V. POTENTIAL EXTENSIONS

*Camera receiver:* Given a certain rolling shutter frequency, the bottleneck of a camera receiver lies in its frame rate. We believe that elevating this rate is possible without a costly upgrade of the hardware: leveraging on the very short exposure time and the need for only the luma component to be captured [4], a new firmware that enables a much higher frame rate specifically for VLC purpose is possible.

*Transmitter:* In order to achieve a balanced complexity between transmitter and receiver, the transmitter needs to be upgraded accordingly. Increasing the transmission frequency beyond 100 kHz can be readily achieved by replacing transistors with MOSFETs. To make a breakthrough, we need to better exploit the direct bit-to-light conversion ability of our transmitter, and potentially replace ASK by OFDM using the OFDM's IDFT output to directly drive the LED groups. As each OFDM subcarrier has a much narrower bandwidth, OFDM is much more robust against inter-symbol interference due to the limited modulation bandwidth of commercial LEDs. This is probably the most efficient way to push VLC throughput to Mbps level in practice.

## VI. CONCLUSIONS

As the stepping stone towards entering wireless market, P-VLC deserves a better attention if we ever wish to put VLC into practice. This article brings forward this application vision and scrutinizes the particularities of the commercial infrastructure that P-VLC taps. Based on the challenges imposed by these particularities, we further conduct a critical survey on the VLC literature, which has motivated us to focus on the realization of high-order modulation for P-VLC. Whereas this ambition further faces the common "curse" of LED non-linearity, we present two P-VLC prototypes adapting to various luminaire constructions. These prototypes rely on light emission composition controlled directly by digital modulation signals, enabling them to avoid non-linearity curse caused by simply scaling the input analog signals and boost achieved data rates with high-order modulation. By considering the multiple chips (light sources) nature of LED lighting infrastructure indoor, we believe the P-VLC solution has its potential contribution to the standardization of VLC and push VLC into practical applications.

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