Poster: Towards Backbone-Free VLC Networking via NLOS Optical Channels

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Abstract

Existing VLC backhaul solutions typically rely on rigid wired (*e.g.*, Ethernet or power-line) or alignment-sensitive LOS links for inter-attocell connectivity, which renders the overall network vulnerable to backbone link failures. In this poster, we introduce a novel network architecture that exploits the inherent non-line-of-sight (NLOS) optical channels between adjacent attocells to enable inter-attocell communication. In particular, we design a chirp signal based on chirp spread spectrum (CSS) modulation to enhance the robustness of communication under low signal-to-noise ratio (SNR) conditions, along with a two-stage window alignment approach to achieve precise synchronization while reducing real-time decoding latency. The potential and feasibility of the newly suggested approach are demonstrated through implementations on both ESP32 and FPGA platforms.

CCS Concepts

• **Hardware** → *Sensor devices and platforms*; • **Networks** → *Network performance analysis*.

Keywords

VLC, Backbone-Free, Chirp Spread Spectrum

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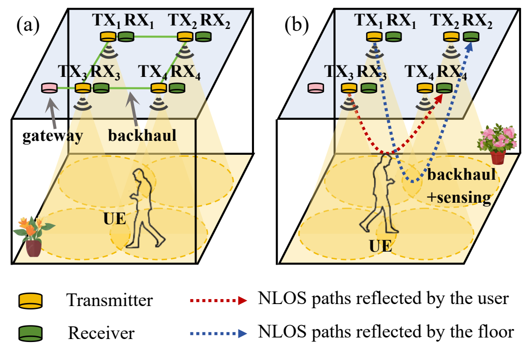


Figure 1: Schematic diagram of an indoor VLC network. (a) Wired backhaul; (b) NLOS-based wireless backhaul.

1 Introduction

Over the past decade, the widespread adoption of energy-efficient light-emitting diodes (LEDs) for general indoor illumination has driven significant advances in visible light communication (VLC) [1, 2]. VLC reuses the lighting infrastructure that is widely deployed as transmitters to generate modulated light signals without affecting illumination. Therefore, we can piggyback wireless communication on top of LED illumination almost for free. This integration of illumination and communication functions reduces redundant infrastructure while enabling the seamless convergence of indoor lighting and data services [3].

Generally, the VLC network consists of multiple small cells (*i.e.*, attocells), where each LED serves as a wireless access point (AP) that provides signal coverage and communicates with the end devices. However, most existing backhaul solutions rely on **wired links** such as Ethernet and power line communications (PLC), or **line-of-sight (LOS)-based wireless links** [4] for attocell interconnection. These solutions introduce significant challenges in terms of **deployment and maintenance costs**. Specifically, wired solutions often require extensive cabling, while LOS links demand strict alignment and are susceptible to environmental obstructions, which collectively limit their flexibility and scalability.

In this poster, we introduce a **backbone-free** VLC network architecture that broadens the use of non-line-of-sight

(NLOS) channels beyond traditional end-user downlinks to support attocell interconnection. Specifically, the transmitter and receiver are co-located on the ceiling, enabling backbone-free data transmission via inherent NLOS channels between adjacent optical attocells, as illustrated in Fig. 1. To enhance noise immunity and ensure reliable data transmission under low signal-to-noise ratio (SNR) conditions, we design a chirp signal based on chirp spread spectrum (CSS) modulation for intensity-modulated VLC, combined with a two-stage window alignment scheme for precise synchronization while reducing the real-time decoding latency.

2 Network Design

Chirp Signal Design in VL-CSS: Traditional CSS signals face non-negativity and hardware constraints in VLC. To address this, we propose a novel CSS-based modulation scheme tailored for IM/DD VLC without DACs (denoted as VL-CSS). Specifically, VL-CSS employs real-valued chirp signals limited to the $[0, B]$ frequency band, ensuring compatibility with low-cost transmitters. At the transmitter, real chirp signals are sampled and binarized into ON-OFF sequences, enabling direct drive of LEDs via a microcontroller and a MOSFET driver. At the receiver, the low-pass effect of the NLOS channel preserves the chirp shape. We apply a dechirp operation (each chirp signal is element-wise multiplication with a basic down-chirp signal) to convert chirps into single-frequency signals, followed by frequency analysis to extract encoded symbols. Finally, a low-complexity energy merging technique replaces traditional phase search, improving decoding efficiency without sacrificing accuracy.

Two-Stage Window Alignment: Real-time demodulation of VL-CSS requires precise window alignment, which is challenged by sampling offsets in low-cost devices and the high computational overhead of conventional methods. Thus, we design a two-stage synchronization method that combines coarse detection and fine alignment. In detail, the preamble is designed as an up-chirp followed by a down-chirp, where the initial low-frequency component forms a distinct wide pulse in the time domain, enabling fast detection through lightweight temporal feature analysis. Upon coarse detection, fine alignment is performed by dechirping both chirps and applying FFT to estimate the frequency offset, as shown in Fig. 2. This two-stage approach efficiently combines the simplicity of coarse-grained detection with the accuracy of fine-grained alignment, ensuring precise synchronization while reducing computational complexity. For specific implementation details, please refer to [5].

3 Evaluation

3.1 Prototype Implementation

As illustrated in Figs. 3 (b)-(e), we build two NLOS VLC attocell prototypes based on ESP32 and FPGA, respectively.

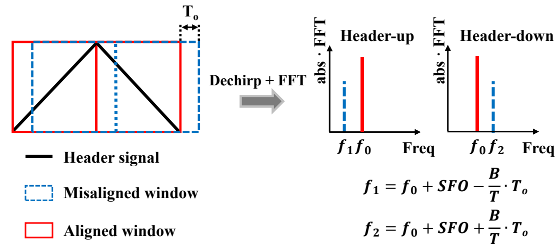


Figure 2: Illustration of window alignment.

Specifically, we consider an experimental space of $10 \times 1.65 \times 2.7$ m with two pairs of ceiling-mounted transceivers to simulate the setup of two adjacent attocells within a corridor scenario, as shown in Fig. 3 (a). White LEDs are driven by dedicated MOSFET-based drivers to emit modulated light under OOK, FSK and CSS modulation schemes. The received optical signals are converted into electrical signals by the PD, amplified by a pre-amplifier, and then sampled by an analog-to-digital converter (ADC). Finally, the recovered data packets are transmitted to a host for real-time calculation of key performance metrics, including *Bit Error Rate (BER)*, *Packet Reception Rate (PRR)*, *Goodput*, and *Latency*.

3.2 Experimental Results

We adjusted the horizontal separation between the transmitter (TX_1) and receiver (RX_2) from 2 to 10 meters to measure the *BER*, *PRR*, *Goodput*, and *Latency* of the three modulation schemes. The results obtained from the ESP32 and FPGA are shown in Fig. 4 and Fig. 5, respectively.

3.2.1 ***ESP32 platform***. It can be observed that the BERs of the three modulation schemes gradually increase as the horizontal separation between the TX_1 and RX_2 increases, as shown in Fig.4a and Fig.4b. In particular, OOK fails beyond 4 m due to its limited interference resilience, while FSK and CSS maintain stable performance due to their frequency-based modulation and spread spectrum techniques. Specifically, the performance of OOK deteriorates rapidly with

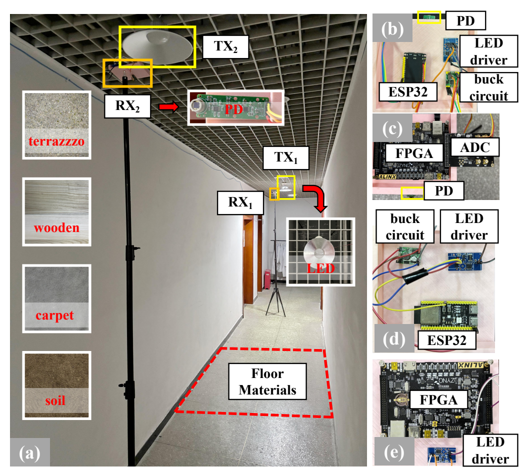
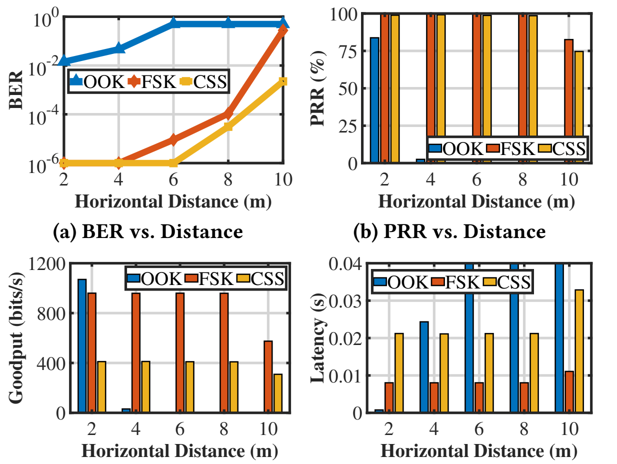
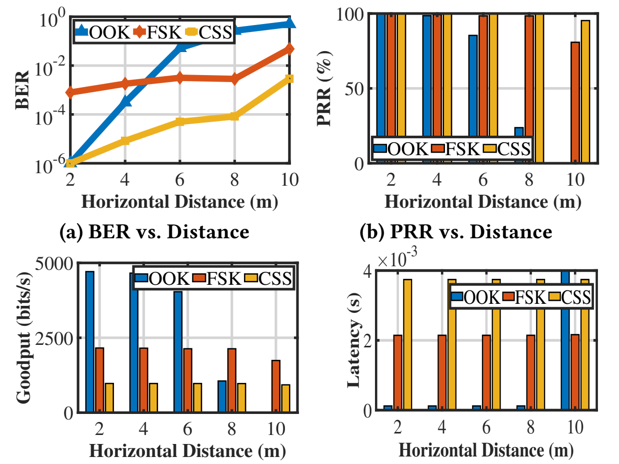


Figure 3: Illustration of the prototype implementation.



(a) BER vs. Distance (b) PRR vs. Distance (c) Goodput vs. Distance (d) Latency vs. Distance

Figure 4: The BER, PRR, goodput, and latency of three modulation schemes on the ESP32 platform.



(a) BER vs. Distance (b) PRR vs. Distance (c) Goodput vs. Distance (d) Latency vs. Distance

Figure 5: The BER, PRR, goodput, and latency of three modulation schemes on the FPGA platform.

increasing separation, with goodput dropping to just 31 bps at 4 m. In contrast, FSK and CSS maintain a stable link up to 8 m, after which the goodput decreases from 959 to 575 bps for FSK and from 409 to 309 bps for CSS. Notably, FSK consistently outperforms CSS in terms of goodput and latency due to its higher spectral efficiency and shorter symbol duration.

3.2.2 ***FPGA platform.*** On the FPGA platform, BER and PRR trends are similar to those observed on the ESP32 platform, with both deteriorating as the distance increases. Specifically, OOK's BER sharply increases from 3.1×10^{-4} to 5.2×10^{-2}, while its PRR decreasing from 100% to 24%. However, its performance improves significantly due to enhanced ADC sampling, extending its effective communication range to 4 m. In contrast, FSK and CSS maintain BER below the FEC limit up to 8 m, with FSK achieving a BER of 2.84×10^{-3} and PRR of 98.42%, while CSS shows an even lower BER of 8.3×10^{-5} and PRR of 99.71% at this distance. In particular, the higher I/O frequency supported by the FPGA enables an 8× boost in OOK goodput and a 2× gain for FSK and CSS, along with a 10× latency reduction, as shown in Fig. 5c and Fig. 5d. These results indicate that OOK is advantageous for short-range, low-latency applications, while FSK and CSS are preferable in noise-prone, low-SNR scenarios. In particular, FSK is more suitable for medium-range applications requiring higher throughput and lower latency, whereas CSS is better suited for long-range or severely degraded channels.

In summary, the preliminary link characterization demonstrates the feasibility of utilizing NLOS channels as a backhaul solution for inter-attocell communication, as both FSK and CSS maintain reliable performance under low SNR conditions, which in turn substantiates the applicability of the proposed architecture in practical scenarios.

4 Conclusion

In this poster, we explored the feasibility of leveraging inherent NLOS optical channels for attocell interconnection. We experimentally evaluated three modulation schemes—OOK, FSK, and CSS—under various horizontal distances using both ESP32 and FPGA prototypes. Our results show that FSK and CSS exhibit superior robustness in low-SNR environments. These findings provide insights for designing reliable and efficient attocell interconnects in dense optical networks.

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