Flexible WDM VLC System with LEDs as Multi-Gb/s Receivers and Beacon Emitters for Integrated Localization

Bernhard Schrenk
AIT Austrian Institute of Technology, Center for Digital Safety&Security / Security & Communication Technologies, 1210 Vienna, Austria.
Author e-mail address: bernhard.schrenk@ait.ac.at

Abstract: Multi-color in-door VLC is demonstrated at 5.3-Gb/s λ-bonded pencil-beam transmission after receiver localization through multi-purpose LEDs. Flexible spectrum allocation with <65-ms switching time and the robustness to optical reflections at the VLC fronthaul are proven.

1. Introduction

Optical wireless communication provides an attractive alternative to RF-based wireless access by virtue of the spectral abundance in the optical domain, the robustness to electro-magnetic interference and the inherent privacy of beam-centric schemes, paired with multi-Gb/s transmission capacities accomplished for pencil beams. Recent works have accomplished well-beyond 10-Gb/s transmission [1, 2]. On top of this, considerable effort has led to demonstrations of optical beamforming and -steering, effectively enabling pencil-beam transmission schemes [3-5].

As a sub-set of optical wireless technologies, visible light communication (VLC) can capitalize on the adoption of luminaries in a wide range of home appliances. Given the abundance of LEDs in consumer electronics, their use as opto-electronic converter becomes highly appealing, not only as transmitters [6, 7] but also as receivers [8].

This work expands previous findings on LED receivers by demonstrating the multi-purpose use of commercial SMD LEDs as (*i*) beacon emitter to serve the localization of the LED receiver, followed by a rate-adaptive beam narrowing to (*ii*) accomplish 5.3-Gb/s pencil-beam transmission in a multi-color WDM VLC system that additionally offers flexible bandwidth allocation among two VLC receivers with <65-ms beam switching at the wavelength level through a tunable MEMS mirror at the VLC hotspot. On top of this, the robustness of isolator-free sources to optical reflections at the VLC fronthaul is experimentally confirmed through a small penalty of 0.83 dB.

2. Multi-Color VLC System with Multi-Purpose Luminaires

As demonstrated earlier [8], a LED can serve as bandpass-filtering photodetector, provided that its bandgap energy is smaller than the corresponding photon energy – thus requiring an emission wavelength larger than that of the signal. This work employs LED receivers as multi-purpose elements, serving also their localization through wide-beam beacon emission. By scanning the scene through the VLC hotspot and remoting the received LED emission to a centralized detector operating with high sensitivity, active network terminals can be identified. As will be shown, a LED can thereby provide a strong-enough beacon to cover indoor distances for this localization purpose, followed by a gradual narrowing of an initially wide data beam to eventually accomplish multi-Gb/s transmission rates over the same LED, now operated as a receiver. Taking advantage of the common use of multi-color LED luminaries in consumer electronics, a WDM-based VLC link can not only build on the filtering-detector property of a LED to select channels; It further permits a flexible bandwidth allocation among network terminals through switching a pencil beam among LED receivers, as will be demonstrated through this work for the first time.

3. Experimental Setup of WDM VLC System and Characterization of Multi-Color Laser-LED Pairs

Figure 1a presents the experimental setup. Three laser diodes (LD) operating at λ_C = 494, λ_G = 520 and λ_R = 638 nm

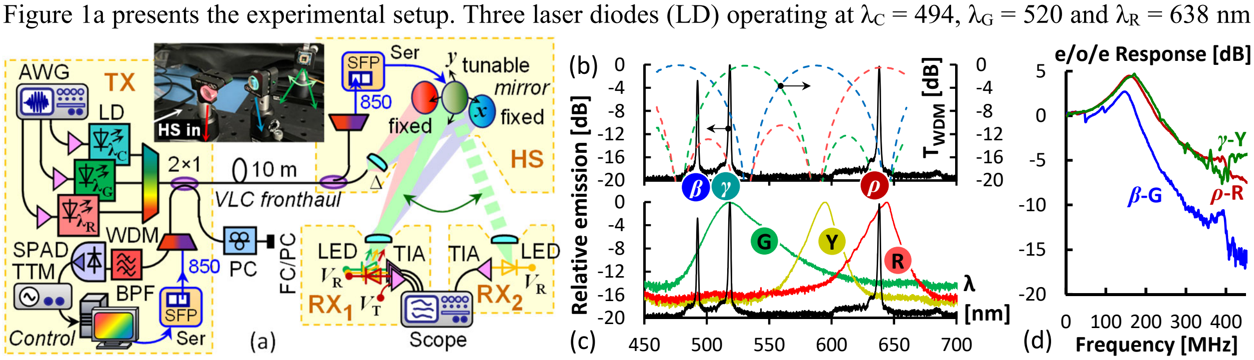

Fig. 1. (a) Experimental setup. (b) Optical emission of LDs and WDM channels. (c) Spectral allocation and (d) e/o/e link response of LD-LED pairs.

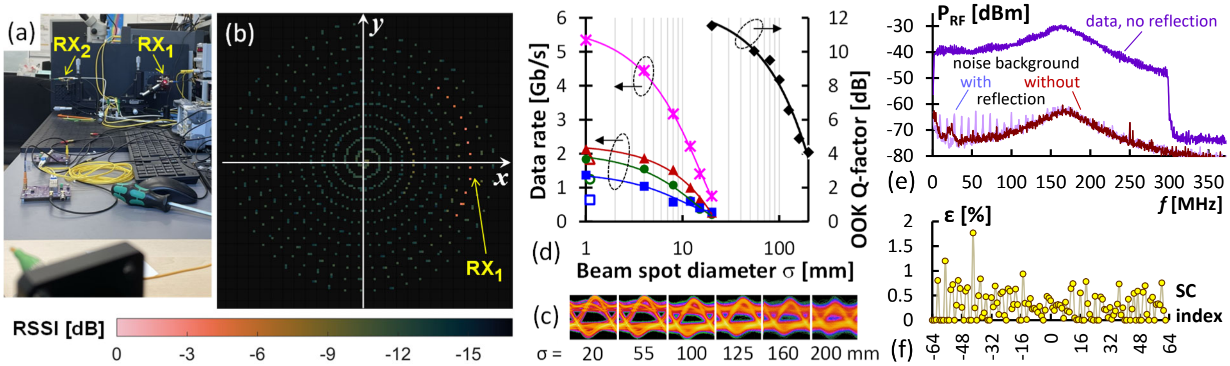

Fig. 2. (a) View on LED receivers from the hotspot and (b) spiral-search of receivers emitting a beacon. (c) Wide-beam OOK eye diagrams. (d) Supported OFDM rates and OOK Q-factor for narrowed beam. (e) Received RF spectrum in presence of reflections and (f) EVM penalty.

were directly modulated at the centralized TX and multiplexed with a power of 2 mW/λ to a short VLC fronthaul feeder of SM630 fiber that connects to an optical hotspot (HS). The wavelength-dependent coupling to the free space through lateral chromatic aberration (Δ) allows the use of three mirrors to deflect cyan, green and red light to particular receivers at a distance of 1.5m from the HS. In the evaluated scenario, the two mirrors for the red and cyan channels are in a fixed position, targeting receiver RX_1, while the green channel will be switched between RX_1 and RX_2. The latter is accomplished through a tunable MEMS mirror that is remotely controlled through an 850-nm serial communication link with customized DC-coupled SFP optics multiplexed to the single-mode VLC fronthaul.

The receivers are comprised by a triple-LED with a 9-mm lens. The LEDs are reversely biased at V_R = 4V to serve as filtered detectors whose photocurrents are enhanced by transimpedance amplifiers (TIA). To facilitate initial alignment, the red LED of RX_1 serves as multi-purpose element that provides a beacon by forward-biasing (V_T) the LED. The portion of the beacon that is received within the mirror's field-of-view is fed back towards the head-end, where its magnitude is acquired within a 10-nm wide spectral window of a 635-nm bandpass filter (BPF) through a highly sensitive silicon single-photon avalanche photodetector (SPAD) with a detection efficiency of 34% and a dark count rate of 110/s. In this way, the position of the receiver can be coarsely determined by scanning the scene with the remotely-controlled tunable mirror at the HS, as will be proven shortly.

To further investigate the penalty that arises from the detrimental interplay of optical reflections with cost-effective yet isolator-free LD transmitters, a Fresnel reflection of a FC/PC connector has been included close to the transmitter. The optical feedback has been maximized through polarization control, leading to a worst-case scenario.

The transmitted WDM spectrum is presented in Fig. 1b, together with the transmission T_{WDM} of the multiplexer. The cyan (β), green (γ), red (ρ) LDs are spectrally matched with the green (G), yellow (Y) and red (R) LED receivers so that the bandgap energy is small enough to detect the corresponding transmit laser (Fig. 1c). The end-to-end RF response of the three laser-LED transceiver pairs yields 3-dB bandwidths of 205, 288 and 283 MHz for the β-G, γ-Y and ρ-R pairs, respectively, and are mainly determined by the capacitance of the LED detectors (Fig. 1d).

4. Localization, Beam Narrowing and Multi-Gb/s Pencil-Beam Transmission with Flexible Rate Allocation

Figures 2a/b demonstrate the initial alignment through a red LED beacon emitted solely by RX_1. Results are shown for performing a spiral-shaped search with the tunable MEMS mirror for the presented lab setup (Fig. 2a), which is seen from the viewpoint of the MEMS mirror. A clear signature is noticed in the SPAD counts towards the direction of RX_1 (Fig. 2b), in which the received counts exceed 53 kcts/s. This corresponds to a 12-dB higher signal compared to the background counts that result from the ambient light at an illuminance of 640 lx. This proves that a course pointing towards the LED receiver can be accomplished despite its limited luminous intensity of ~50 mcd.

After determining the position of RX_1, a low-rate on-off keyed (OOK) signal can be already transmitted by the TX through the red channel. Figure 2c presents the eye diagrams for beam spot diameters ranging from 200 mm to 20 mm, together with the corresponding Q-factors (◆) in Fig. 2d. A Q-factor of 6 is obtained for a beam spot diameter as large as 145 mm. The Q-factor can be further used to narrow down the initially wide beam to a pencil beam. This eventually enables OFDM transmission, which becomes feasible for the smallest OOK beam spot diameter of 20 mm. A similar procedure can then be applied to shape the beam for an optimal transmission condition, taking the supported modulation efficiency as an indicator for the reception quality. At the same time, all WDM channels can be lit up to boost the data rate of the VLC channel to the multi-Gb/s regime.

The OFDM signals had a bandwidth of up to 300 MHz for the narrowest pencil beam and its 128 sub-carriers were adaptively loaded with 4- to 256-QAM. The data rate as function of the beam spot diameter is shown in Fig. 2d for the red (▲), green (●) and cyan (■) channels, together with the aggregated WDM rate (✳). A net WDM rate of

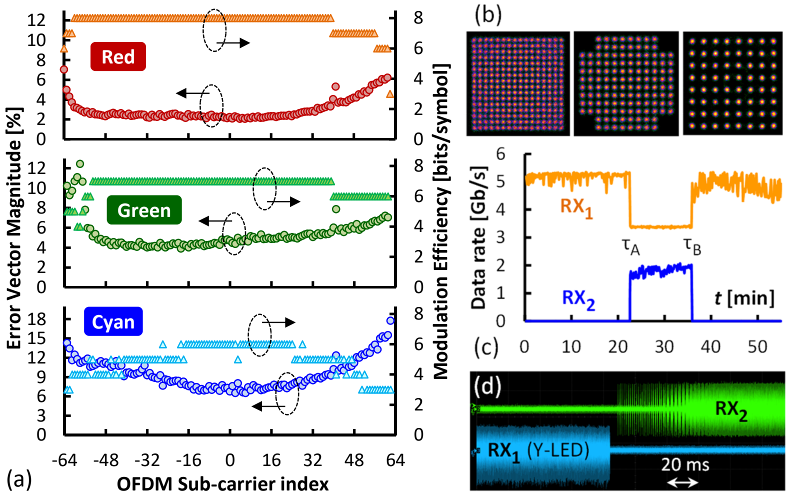

Fig. 3. (a) EVM and spectral efficiency for pencil beam reception and (b) constellations for the red WDM channel. (c) Aggregated WDM rates and (d) received signal when switching of the green channel between the two receivers.

2.5 Gb/s was achieved for a large beam diameter of 11 mm, while the smallest beam diameter of 1 mm yielded a λ-bonded post-FEC rate of 5.3 Gb/s.

Figure 3a presents the modulation efficiency (▲) and error vector magnitude (EVM, ●) for all OFDM sub-carrier at this narrowest pencil beam setting for all three WDM channels. An average modulation efficiency of 7.71, 6.64 and 4.95 bits/symbol were accomplished for the red, green and cyan channel. The clean constellations, shown in Fig. 3b for the red channel, evidence the good linearity of the low-cost LED+TIA receiver. When omitting the lens for the LED detectors, the data rates of 2.13, 1.84 and 1.37 Gb/s for the red, green and cyan WDM channels drop to 1.83, 1.25 and 0.64 Gb/s, as annotated in Fig. 2d (△,○,□). Although this omission of the optical lens would save packaging cost for the receiver, it inhibits high data rates and beam alignment under a high signal-to-noise ratio.

The impact of optical reflections at the VLC fronthaul link is reported in Fig. 2e. It shows the received 300-MHz OFDM spectrum of the red channel without Fresnel reflection. A reflection was then introduced through the unterminated FC/PC connector, leading to an optical feedback of about -21 dB to the TX laser. The instability in laser emission caused by this feedback can be noticed in the background of the LED+TIA receiver without OFDM data. The optical cavity modes are clearly discernible from the background under reflection-free operation. An EVM penalty ε (Fig. 2f) results when transmitting OFDM data. It is patterned by the feedback cavity, though the penalty per sub-carrier varies with time. Nevertheless, given the <2% penalty in EVM, the data rate of the red channel is slightly affected as it drops by 0.83 dB from 2.13 to 1.82 Gb/s. This proves the VLC fronthaul as rather tolerant to optical reflections and permits simple and more cost-effective laser packaging without visible-light isolator.

Finally, we have switched the green WDM channel between RX_1 and RX_2 to temporarily provide a data shower towards RX_2 without interrupting data transmission to RX_1. Figure 3c presents the received OFDM data rate for RX_1 and RX_2 over ~1 hour when the green channel is switched to RX_2 at τ_A and back to RX_1 at τ_B. For such a TDMA scenario, capacity within the VLC spectrum is flexibly distributed as per the constituent per-channel rates. The instability in the (aggregated) data rate when the MEMS-actuated green channel is received by either VLC end-node is attributed to the insufficient opto-mechanical damping in a busy lab environment. Figure 3d reports the transition region at τ_A from RX_1 to RX_2. A small dead-time of 4.5 ms can be noticed when the MEMS mirror flips to target RX_2, followed by a longer settling time of 58 ms between first light and mirror stabilization at its new position.

5. Conclusion

A VLC system based on multi-color laser-LED pairs featuring integrated localization with >10 dB SNR has been demonstrated through mirror-based tracking of the faint emission from the multi-purpose LED receiver by the VLC hotspot. A λ-bonded data rate of 5.3 Gb/s was accomplished for color-selective reception using pencil beams. Owing to the spectral flexibility of a WDM-based VLC system, flexible allocation of channels between two LED receivers has been demonstrated to be feasible with switching times as low as 62.5 ms. Moreover, the robustness of the VLC system to optical reflections at its fronthaul has been verified through a <1-dB penalty in data rate, permitting the use of cost-effective optical sources without visible-light isolator. Uplink VLC operation is left for future work.

6. References

[1] C. Lee et al., "26 Gbit/s LiFi System With Laser-Based White Light Transmitter", JLT **40**, 1432 (2022).
[2] R. Bian et al., "15.73 Gb/s Visible Light Communication With Off-the-Shelf LEDs", JLT **37**, 2418 (2019).
[3] T. Koonen et al., "High-Capacity Optical Wireless Communication Using Two-Dimensional IR Beam Steering", JLT **36**, 4486 (2018).
[4] M.C. Shin et al., "Chip-scale blue light phased array", Opt. Lett. **45**, 1934 (2020).
[5] Y. Li et al., "High-Data-Rate and Wide-Steering-Range Optical Wireless Communication via Nonuniform-Space Optical Phased Array", JLT **41**, 4933 (2023).
[6] D. Maclure et al., "Hundred-meter Gb/s deep ultraviolet wireless communications using AlGaN micro-LEDs", OpEx **30**, 46811 (2022).
[7] Z. Wei at al., "Micro-LEDs Illuminate Visible Light Communication", IEEE Comm. Mag. **61**, 108 (2023).
[8] D. Milovancev et al., "Gb/s Visible Light Communication With Low-Cost Receiver Based on Single-Color LED", JLT **38**, 3305 (2020).