Leveraging LED Technology in Consumer Electronics Towards Gb/s Indoor Visible Light Communication

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Abstract: SMD-LEDs intended for illumination can support modulation efficiencies of 5.98 bits/symbol and data rates of 350 Mb/s as indoor VLC receivers in combination with laser-sourced pencil beams. Gb/s operation is feasible through R/G/B channel bonding.

OCIS codes: (230.3670) Light-emitting diodes; (250.0040) Detectors; (060.2605) Free-space optical communication;

1. Introduction

Visible and near-infrared light communication is touted as an attractive alternative to radio frequency (RF) based schemes given its immunity to electro-magnetic interference, its inherent privacy due to the confined communication range and high compatible data rates in combination with unlicensed spectrum and optical beam-forming [1]. Heterogeneous networks building on WiFi while leveraging LiFi resources are under consideration for the next-generation of indoor communication. Although a variety of optical hotspot principles and technologies has been proposed for such scenarios [2,3], the optical receiver builds on components that are not common in mobile (electronic) end-user equipment – such as photodiodes – and therefore hinders commercial up-take of optical wireless solutions. On the other hand, non-telecom photonic solutions are widely applied for the purpose of lighting or sensing. The abundance of cost-effective light emitting diodes (LED) triggers the question whether or not these low-cost emitters can be applied for the purpose of data communication in consumer applications. High-speed LED modulation at data rates exceeding those of wireless short-reach solutions is well researched and has reached rates of 7.9 Gb/s [4]. Moreover, we have recently proven a close-proximity visible light communication (VLC) link operating at 1 Gb/s through exclusive use of a R/G/B LEDs, demonstrating the replacement of photodetectors with commercial off-the-shelf LEDs serving as a filtering optical receiver [5].

In this work we experimentally demonstrate the viability of such a LED-based VLC receiver for indoor scenarios. We show that the use of a pencil beam promises a data rate of 300 Mb/s per LED over a reach of 2 meters in combination with an optical hotspot that enables optical beam steering with variable spot diameter.

2. Visible Light Communication with LED-Based Receivers and Optical Beam Adjustment

Heterogeneous networks enable a high connection density through inclusion of light-based communication. The adoption of optical hotspots in luminaires introduces focused pencil beams that deliver high per-user throughput in downstream direction, while the less critical uplink direction can be implemented through traditional wireless schemes. This work poses the challenge if, in addition to these gold-class LiFi connectivity, existing and cost-effective lighting assets such as LEDs can be leveraged for the purpose of lower-rate silver-class optical wireless connectivity that might even address IoT schemes. Provided that the bandgap energy between conduction and valence band of the LED is smaller than the photon energy of the impinging light, meaning that the LED wavelength λ_R is larger than that of the incident data signal λ_T, the photons of the impinging light are absorbed. This spectral dependency further enables wavelength multiplexing [5] and improves robustness to backlighting.

Figure 1 presents the HetNet concept with LED-based receivers under the umbrella of an indoor scenario. A centralized optical power supply feeds the cost-shared optical hotspots that provide three basic functions: coarse pointing, fine beam steering and beam spot size adjustment to perform both, auxiliary management and control (AMCC) for pointing and tracking and data transmission through use of a pencil beam. The implementation of these functions will rely on *(i)* an offset feed from the focal point of the collimation lens integrated with the optical hotspot through multi-port fiber launch and port switching within the bundle in order to steer the angle α of the beam [6]; *(ii)* the thermo-optic wavelength tuning in combination with a diffraction grating [7] for fine beam squinting; and *(iii)*

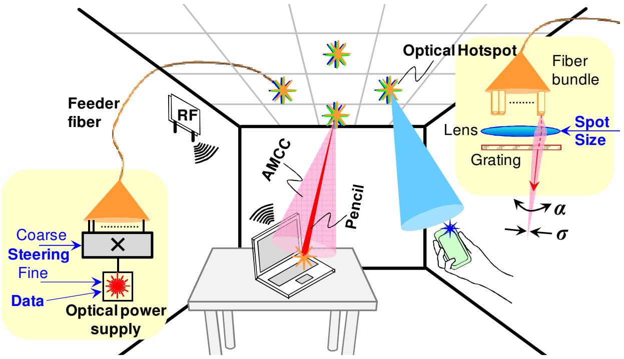

Fig. 1. Indoor visible light communication with LED-based receivers.

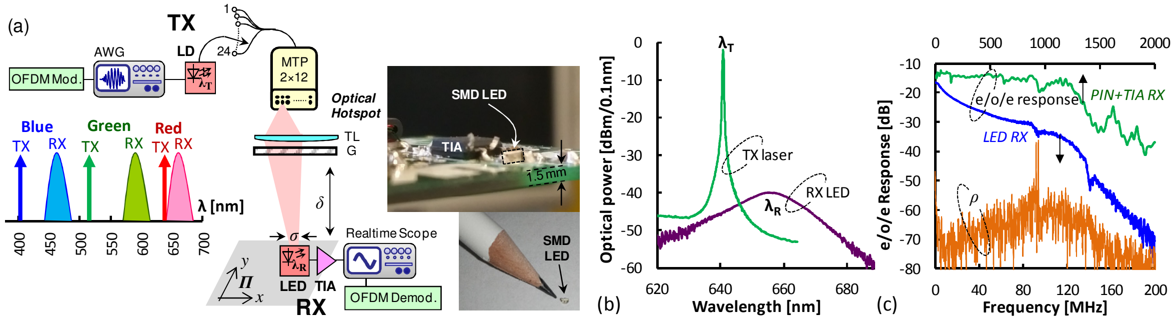

Fig. 2. (a) Experimental setup. (b) Optical spectra of red laser emitter and LED detector. (c) O/e/o response of red-λ link and RF coupling.

a focus-tunable optical lens that shape-shifts from convex to flat, which allows to de-collimate the VLC beam when switching from pencil to AMCC modes and vice versa, hence altering the spot size *σ*.

Figure 2a presents the experimental setup. The laser diode (LD) that feeds the optical hotspot is directly modulated through an arbitrary waveform generator (AWG). The multi-port feed to the optical hotspot is facilitated through a MTP cable with a 2×12 ribbon fiber that is centered to the 18-mm tunable lens (TL). The grating (G) used for beam deflection had 1200 lines/mm. The receiver that is located at a distance *δ* builds on a commercial surface-mounted device (SMD) outline LED (see inset in Fig. 2a) and a transimpedance amplifier (TIA). The acquired VLC signal is fed to a real-time oscilloscope for off-line signal demodulation and EVM estimation. For comparison a PIN/TIA based visible-light receiver was also employed.

3. Characterisation of Opto-Electronic Link and Beam Steering

Figure 2b presents the optical spectra of the red transmitter laser λ_T and the receiving LED λ_R. According to the detection scheme the emission spectrum of the AlGaAs LED under forward bias is centered at 655 nm and therefore 14.6 nm higher than that of the laser. Two further wavelength channels have been investigated, including a blue LD (405 nm) with InGaN SMD-LED (470 nm) and a green LD (515 nm) with AlInGaP SMD-LED (590 nm).

The end-to-end e/o/e transfer function of the VLC link involving red laser and LED receiver is shown in Fig. 2c. Measurements are presented for a reverse LED bias of 5V in order to minimize the junction capacitance. Although the 3-dB bandwidth is only 8 MHz, the smooth roll-off of -4 dB/octave advocates multi-carrier modulation schemes with adaptive bit loading. Figure 2c further shows the RF coupling *ρ* between transmitter and receiver, which is to be taken into consideration for short-reach links as it introduces multi-path crosstalk and compromises the privacy feature inherent to VLC. Up to a frequency of 65 MHz, which has been chosen as upper border frequency for signal modulation in later transmission experiments, the coupling remains below -31 dB relative to the e/o/e response. When substituting the LED with a PIN/TIA receiver, the 3-dB link bandwidth can be extended to 928 MHz, thus not only enabling higher data rates through multi-carrier formats, but also energy-efficient broadband modulation.

Figures 3a and 3b show the effect of optical beam steering through fiber feed selection and additional wavelength tuning, respectively. The presented profiles have been acquired at a projection plane *Π* at a distance of δ = 2 m from the optical hotspot using an optical photodetector on x/y translation stages to cover the AMCC beam and a CCD camera to resolve the pencil beam. Wide FWHM beam spot diameters of 3.2 cm for AMCC transmission show a displacement of ΔX = 13.4 cm at the projection plane for fiber ports 13/24 and 1/12 of the given 2×12 feeder fiber. Stronger deflection can be obtained through a higher port count for the feeder fiber. The displacement resulting from the use of neighboring feeder ports leads to a squint of 5.6 mm, as shown for ports 24/23 (δx) and 1/13 (δy). With this, neighboring AMCC beams overlap to ensure seamless tracking of the receiver through an appropriate RF feedback signal in case of an implemented pointing and tracking mechanism. Figure 3a also compares an AMCC beam (6) with a pencil beam (6*) formed through focal adjustment of the tunable lens. The latter has a FWHM beam spot diameter of 1.2 mm, which is resolved in Fig. 3b in order to investigate squint-free beam steering operation through additional thermo-optic detuning. The pencil beam is steered with 4.9 mm/°C is obtained as the wavelength of the emitter laser is detuned (*ξ*). This wavelength-to-space mapping enables the precise pointing of the beam to the LED detector at a mobile equipment.

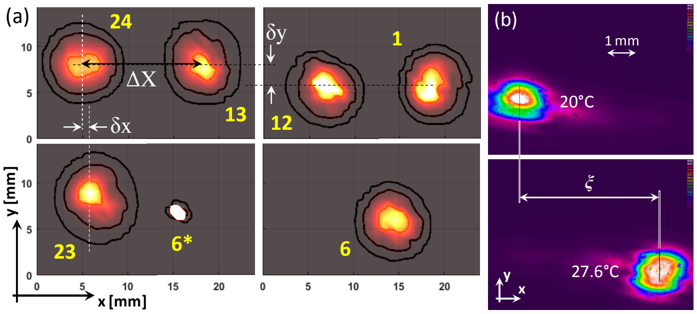

Fig. 3. Beam-steering through (a) feeder selection and (b) thermo-optic tuning.

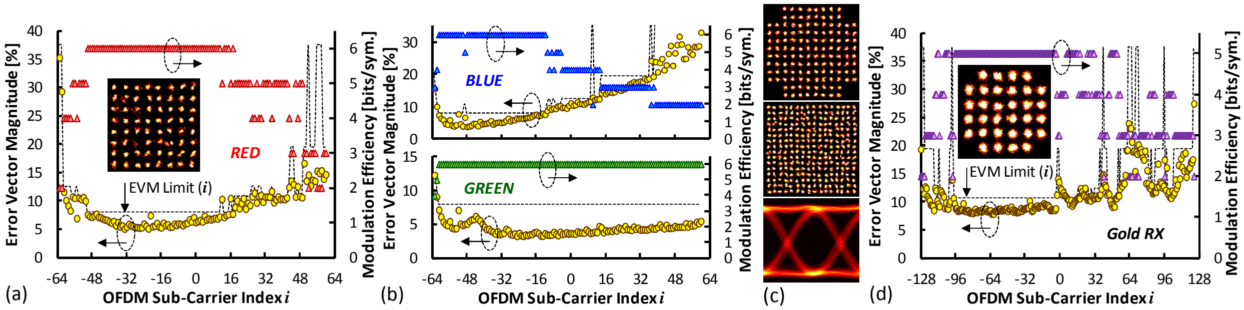

Fig. 4. EVM and bit loading for silver-class (a) red channel with LED receiver in pencil mode, and (b) blue and green channels. (c) 128- and 256QAM-OFDM constellations and gold-class 1.25 Gb/s OOK eye. (d) Reception performance of red channel with gold-class PIN+TIA receiver.

4. Data Transmission Performance

The data transmission performance was evaluated with a LED/TIA receiver placed at a distance of 2 m from the optical hotspot. The laser emitter was directly modulated by an OFDM signal with a swing of 20 mA_{pp}. The bandwidth and the bit-loading of the 128 sub-carriers were chosen according to the beam characteristics. A low bandwidth of 1 MHz and QPSK-OFDM were chosen for the AMCC-assisted pointing, while for the pencil beam the OFDM bandwidth was widened to 65 MHz with a per-carrier modulation efficiency of up to 6 bits/symbol.

The EVM results for the red pencil beam are presented in Fig. 4a as function of the sub-carrier index *i*. 64-QAM OFDM is supported for the majority of sub-carriers with a corresponding EVM below the 8% limit. The average modulation efficiency was 5.14 bits/symbol, leading to a post-FEC data rate of 301 Mb/s. For the blue channel a modulation efficiency of 4.25 bits/symbol and a post-FEC data rate of 249 Mb/s were achieved (Fig. 4b). With 5.98 bits/symbol and 350 Mb/s the green channel performed best. The EVM for 128QAM- and 256QAM-OFDM were 3.01% and 2.92%, respectively (Fig. 4c). These results had been obtained with a laser-sourced power of 5.8 mW for the pencil beam. They confirm that VLC functionality can be accommodated by lighting equipment that is widely found in consumer electronics – and thus without the need for specific receiver opto-electronics. Moreover, an R/G/B LED receiver can support a data rate in the order of 1 Gb/s.

For the AMCC channel with wide tracking beam QPSK-OFDM operation below the EVM limit is supported for all sub-carriers, leading to a signaling data rate of 1.8 Mb/s for the purpose of beam pointing and receiver tracking.

Measurements with pencil beam and a visible-light PIN/TIA receiver as intended for gold units have been conducted for comparison (Fig. 4d). The wider OFDM bandwidth of 1.25 GHz over 256 sub-carriers leads to a post-FEC data rate of 4.7 Gb/s for an average bit loading of 4.11 bits/symbol. This corresponds to a 15-fold improvement in reference to the LED-based silver units, however, requires dedicated receiver hardware. Nevertheless, the flat e/o/e response of the VLC link enables broadband modulation. A 1.25 Gb/s OOK eye diagram obtained through the gold link is presented in Fig. 4c and evidences error-free transmission without use of DSP.

5. Conclusions

Low-cost SMD-LEDs have been evaluated for indoor VLC links that build on laser-sourced pencil beams and optical hotspots with beam steering functionality. Modulation efficiencies of up to 5.98 bits/symbol and corresponding data rates of up to 350 Mb/s have been obtained at a free-space link reach of 2 m. Together with the inherent spectral filtering capability of LED a data rate in the order of 1 Gb/s can be reached through red/green/blue channel bonding. Compared to a dedicated PIN+TIA LiFi receiver operating at 4.7 Gb/s the LED receiver can be a cost-effective alternative for silver-class connectivity.

6. References

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