Low-Cost Visible Light Communication System based on Off-the-Shelf LED for up to 4.3 Gb/s/λ Transmission

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Abstract: Multi-Gb/s/λ visible light communication is demonstrated using a commodity LED rated for 150 Mb/s and OFDM/Nyquist-FDM with 256-QAM sub-carrier modulation. 1Gb/s/λ throughput and real-time video streaming is achieved over 10dB optical budget and PIN receiver.
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1. Introduction

Wireless communication, in particular based on radio frequency (RF) technology, has been an enabler for modern telecom connectivity serving a mass market. However, the performance of RF systems is facing limitations with respect to modulation bandwidth, robustness to interference, energy efficiency or security. These drawbacks are propelling optical wireless links [1]. Visible light communication can build on mature laser technology and more cost-efficient light emitting diodes (LED). Recent research work demonstrated 5 Gb/s transmission using a tailored light emitting diode (LED) prototype [2]. Higher rates towards 10 Gb/s can be realized through WDM-based LED schemes [3] while laser-based communication promises capacities beyond 10 Gb/s [4]. Although these earlier works indicate the potential of optics, the associated cost and immaturity poses a roadblock for practical deployment.

In this work, which aims to proof the maturity of current LED technology for low-cost visible light communication, we experimentally demonstrate multi-Gb/s transmission with a commercial off-the-shelf LED rated for 150 Mb/s. A throughput of 4.3 Gb/s is facilitated through broadband OFDM with sub-carrier formats up to 256-QAM. We further investigate Nyquist-FDM transmission at 100 Mb/s per sub-channel with an analogue receiver and show real-time high-definition video streaming over the LED-based link with a simple, PIN-based receiver.

2. Low-Cost LED-based Transmitter for multi-Gb/s Transmission

The employed optical transmitter is based on a commercial resonant-cavity LED (model RC-LED-650) packaged in a transistor-outline (TO) can. The LED features threshold-less operation and shows an optical output power of 0 dBm at a bias current of 36 mA. The emission spectrum is centered at 657 nm and has a FWHM bandwidth of 6.9 nm. An important characteristic is the electro-optic modulation bandwidth, which is presented in Fig. 1a. The original (■) response of the LED features a -3 dB modulation bandwidth of 75 MHz at a bias current of 18 mA. By applying passive frequency response equalization with a RLC filter circuit, as it has been previously applied for analogue frequency response compensation in combination with low-cost transmitters in optical access [5], a 2.4-fold improvement in modulation bandwidth is obtained (●). The resulting -3dB modulation bandwidth for the packaged commercial off-the-shelf device is 190 MHz. The moderate roll-off of -2.8 dB/100 MHz is beneficial in view of multi-carrier modulation with adaptive bit loading. Measurements of 3rd-order inter-modulation (IM3) distortion indicate a high SFDR of 45 dB at an input power of -5 dBm for the LED-PIN combination (Fig. 2b). The input IP3 point for the optical link is 17.8 dBm, which renders the LED as a suitable analog electro-optic modulator.

3. Experimental Evaluation of Transmission Performance

Figure 2 shows the experimental setup. The LED was biased at 18 mA and driven by either an arbitrary waveform

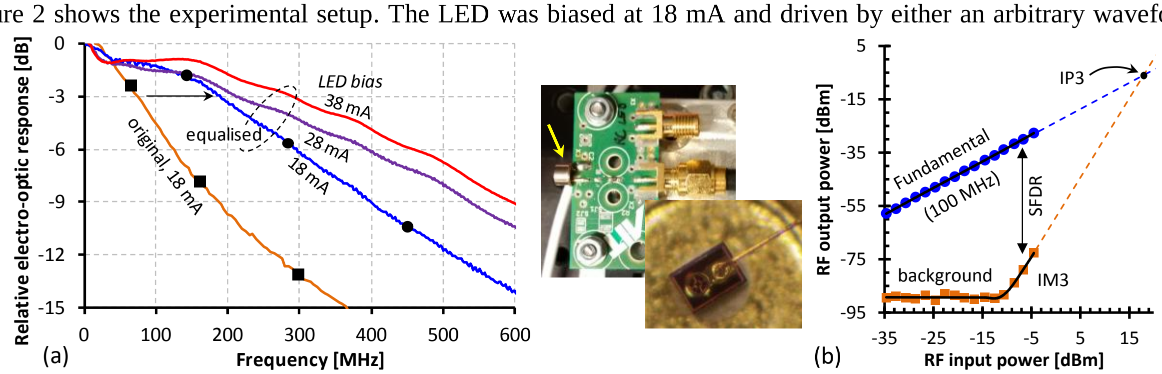

Fig. 1. (a) Modulation bandwidth of the LED before and after analogue equalization. (b) IM3 measurement for the LED link with PIN receiver.

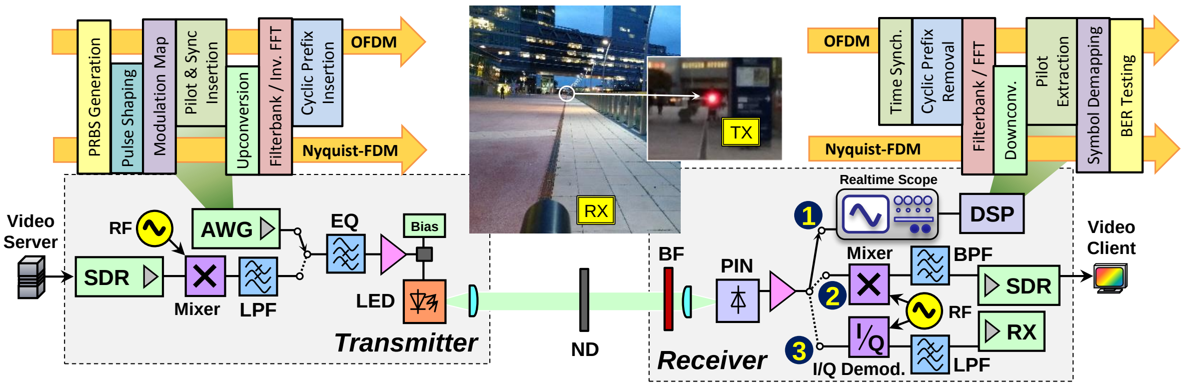

Fig. 2. Experimental setup to evaluate the performance of the low-cost LED-based transmitter. The insets show the employed DSP stacks.

generator (AWG) or a software-defined radio (SDR) whose signal was down-converted to an intermediate frequency (IF). The analogue RF equalizer (EQ) circuit was included at the transmitter. The optical output of the LED was collimated and coupled to a 1-GHz PIN-based receiver that feeds the signal to (1) a realtime-scope for off-line DSP, (2) to the SDR receiver with preceding IF up-converter, or (3) to an I/Q demodulator with local oscillator for DSP-less reception of the I/Q baseband data. In order to conduct measurements on the bit and block error ratio (BER/BLER), neutral density (ND) filters have been inserted in between LED and PIN receiver to emulate link loss. A long-pass filter (BF) with a filter edge at 655 nm suppressing background light has been additionally inserted in front of the receiver for free-space measurements.

Three multi-carrier formats have been selected for performance evaluation. The first is a broadband OFDM that guarantees optimal use of precious modulation bandwidth. In total 256 sub-carriers have been spanned over a bandwidth of up to 1 GHz. The QAM format for the 248 data sub-carriers has been adapted to the channel response and loaded with up to 8 bits/symbol. The second format is frequency division multiplexed (FDM) Nyquist-shaped QAM at 25 Mbaud in view of distinct, 32.5-MHz spaced sub-channels as it will be further used for simple, DSP-less reception. Carrier-selective bit loading with up to 7 bits/symbol has been performed for the 24 sub-channels. The DSP stacks employed for Nyquist-FDM and OFDM modulation are included in Fig. 2. It shall be noted that the transmission spectrum can be sliced and flexibly allocated to either of these formats for co-existence purposes, as it is shown in Fig. 3a. The third format used in the experiment is a narrowband OFDM with 64 sub-carriers over a modulation bandwidth of 20 MHz as used in radio systems. The OFDM carrier frequency of 4.6 GHz signal has been converted to an IF of 480 MHz for use with the LED-based link. Real-time transmission has been implemented on the NI USRP-2953R SDR and used combination with HDTV streaming at a resolution of 1280×720p.

Figure 3b shows the back-to-back results in terms of spectral efficiency (♦) and BER (▲) per sub-carrier for broadband OFDM transmission exploiting the entire LED bandwidth. In this back-to-back case no ND filter has been inserted, leading to a received optical power of -2.9 dBm. 256-QAM performance below the FEC threshold of 3.8×10^{-3} was achieved for the lower sub-carriers. The average spectral efficiency over all sub-carriers was 4.9 bits/symbol. The aggregated data rate obtained after cyclic prefix removal is 4.62 Gb/s. Taking into account the typical 7% overhead for hard-decision FEC the post-FEC data rate is 4.3 Gb/s. The dependence of the link data rate on the optical budget is presented in Fig. 4a. The OFDM data rate decreases with 0.31 Gb/s/dB (■) and reaches 1

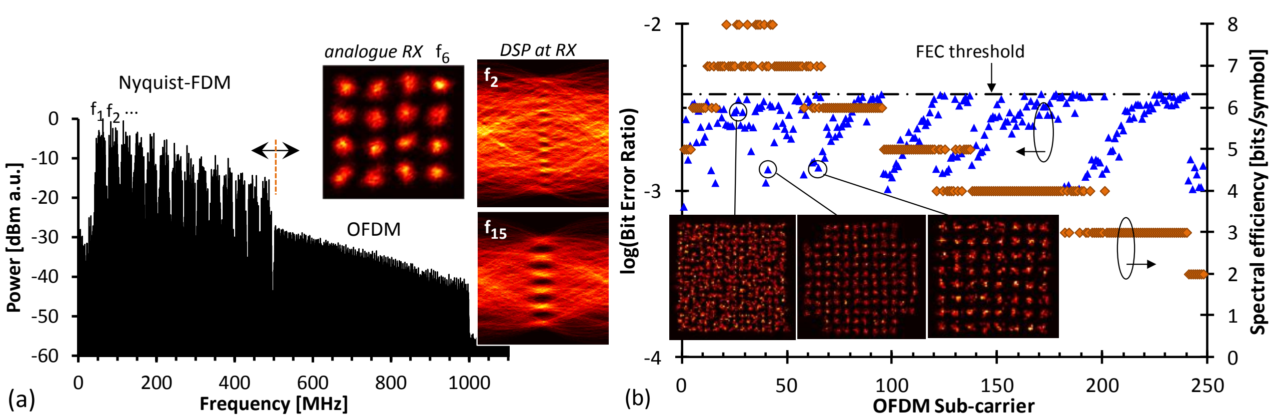

Fig. 3. (a) Received spectrum as mix of Nyquist-FDM and OFDM. (b) BER performance and spectral efficiency for OFDM modulation.

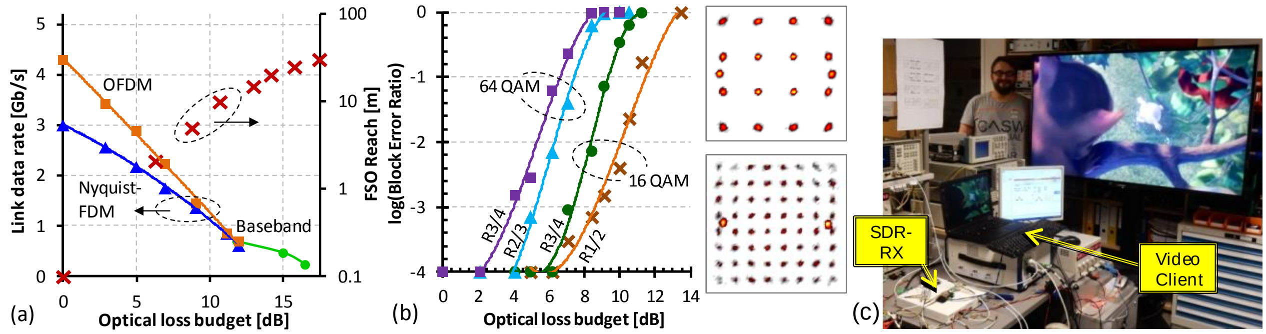

Fig. 4. (a) Nyquist-FDM and OFDM rates and (b) BLER over optical loss budget. (c) Real-time HDTV video streaming over LED link.

Gb/s at an optical budget of 11 dB in combination with a simple, PIN-based receiver. This corresponds to a reach of 10 m (×), as validated through free-space measurements performed in an urban environment (see inset in Fig. 2). For larger distances a LED with higher output well beyond 1 mW or APD receivers would be preferred.

In case of devoting the entire LED bandwidth to Nyquist-FDM the average spectral efficiency is 5.4 bits/symbols. 128-QAM is supported for the lower sub-carriers. The eye diagrams for a Nyquist-shaped QAM tributary are inserted in Fig. 3a for the case of 128-QAM at sub-channel 2 and 32-QAM at sub-channel 15. The eye opening is clearly visible for this fragile modulation format. A post-FEC data rate of 3 Gb/s is achieved over all 24 sub-channels. This proofs that the LED as low-cost transmitter suits rather wide sub-channel bandwidths, i.e., 25 MHz, in combination with Nyquist-shaped QAM – without being affected by distortions such as a ripple in the electro-optic response. When increasing the loss budget the Nyquist-FDM data rate decreases with 0.2 Gb/s/dB (Fig. 4a, ▲) and results in a compatible budget of 10.8 dB for 1 Gb/s.

DSP-aided receiver implementations can be avoided by introducing passband receivers that utilize analogue down-conversion of a specific sub-channel (option 3 in Fig. 2). Such a reception scheme has been evaluated with a fully-loaded Nyquist-FDM signal comprising of 24 sub-channels, each of them modulated at 16-QAM yielding 100 Mb/s per sub-channel. The obtained constellation for the 6th sub-channel at 480 MHz is presented in Fig. 3a. A BER of 3.6×10^{-3} right below at the FEC level has been obtained after multi-level symbol slicing. While lower sub-channels have been performing better, 16-QAM can be maintained up to the 10th sub-channel in case a stronger error correction suitable for a pre-FEC BER of 2×10^{-2} is adopted. The use of an analogue receiver guarantees simplicity and low cost and can co-exist with DSP-based broadband reception in a potential multi-user scenario.

Finally, single-channel narrowband OFDM transmission at the IF of 480 MHz has been evaluated in terms of BLER measurements with a payload size of 9024 bits/packet. Different sub-carrier modulation formats and convolutional code rates R have been investigated (Fig. 4b). 54 Mb/s 64-QAM OFDM with R=3/4 is supported up to a loss budget of 5 dB, for which a BLER of 10^{-2} is reached. Higher loss budgets of up to 10 dB can be supported through 16-QAM subcarrier modulation. Real-time streaming of HDTV video content (Fig. 4c) has been performed without the notice of visual artifacts, which is also evidenced by the clear constellation diagrams shown in Fig. 4b.

4. Conclusion

A commercial off-the-shelf TO-can LED rated for 150 Mb/s has been experimentally demonstrated at the multi-Gb/s regime. Nyquist-FDM and OFDM modulation schemes enable data rates of up to 4.3 Gb/s/λ by exploiting high-order sub-carrier formats such as 256-QAM. Gb/s connectivity can be maintained for a loss budget up to 10 dB with a simple, PIN-based receiver. Moreover, artifact-free HDTV streaming has been validated in real-time. This proves the maturity of commercially available LED technology for applications in short-reach visible light communication.

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