4 Gbit/s Optical Wireless Communication with High-Power Transmitter

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Abstract *We present a VCSEL-based transmitter prototype using pulsed modulation for optical wireless communication, designed for a large coverage area and offering a data rate comparable to mm-wave radio systems. We demonstrate data rates up to 4 Gbit/s using on-off-keying modulation. ©2023 The Author(s)*

Introduction

Optical wireless communication (OWC) is a promising alternative to radio frequency (RF) communication in many specialty use cases. OWC operates in unused license-free optical spectrum and it is robust against electromagnetic interference. Light does not penetrate walls and causes no interference with transmissions in other rooms. For these reasons, OWC can be used for applications with increased privacy requirements and can also offer higher reliability and lower latency than RF systems in controlled environments.

Current OWC technology is, however, limited by the modulation bandwidth of high-power light emitting diodes (LEDs). With sophisticated LED drivers, up to 100 MHz 3 dB bandwidth have been reached [1]. With laser diodes, the modulation bandwidth can be extended into the gigahertz range. The idea in this paper is to exploit this enhanced bandwidth, while keeping the range and coverage area comparable to recent LED-based OWC systems, i.e., achieving a coverage of some square meters per access point inside which the signal is broadcast to mobile users. The goal is the next generation of OWC systems that reach link data rates of multiple Gbit/s while supporting user mobility seamlessly in a practical coverage area.

The main approach is based on vertical-cavity surface-emitting laser (VCSEL) arrays. VCSELs are small laser diodes with an optical power of a few milliwatts that have been increasingly used for free-space applications like LIDAR and OWC [2, 3]. VCSEL arrays contain many lasers on the same chip and can scale the power accordingly. However, it is a challenge to modulate all lasers jointly at gigahertz speed, due to the high driver current required. We have previously reported an initial performance evaluation of a high-power VCSEL array transmitter based on

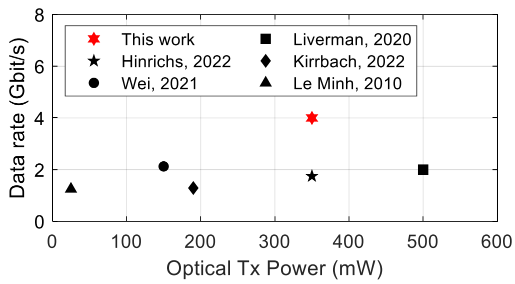

Fig. 1 Overview of high power gigahertz OWC experiments by data rate over optical transmitter power [2, 3, 4, 8, 9].

on-off-keying (OOK) modulation using a limiting-amplifier based driver design for maximizing bandwidth and output power [4]. The focus was on the achievable spatial coverage.

In the work presented here, we increase the data rate feasible with the same transmitter design by using a receiver with larger bandwidth. Moreover, we introduce more efficient line coding combined with frequency- and time-domain equalizers. Finally, the interface between driver and laser has been optimized. Driving amplitudes and optical transmitter characteristics are identical to [4], which we confirm by reference measurements. By using a faster receiver with smaller effective area, the enhanced transmitter supports a significantly higher data rate of 4 Gbit/s compared to our previous work. The development of receivers with multi-gigahertz bandwidth and large effective area, using APD arrays and imaging optics, is subject of ongoing research.

Fig. 1 places our new result within the state of the art. It compares the achieved data rates of various OWC systems reported in the literature with respect to the realized optical output power. While the highest power of 500 mW has so far been demonstrated in [3], data rate was limited to 2 Gbit/s. In the work presented here, we double that data rate and realize a similar output power of 350 mW. Note that our parallel transmitter design is easily scalable to higher power by using more VCSEL arrays.

Experimental Setup

The experiments are done in a line-of-sight setup with offline signal processing using MATLAB. A Keysight M8190A arbitrary waveform generator (AWG) is used for generation of transmitted signals, with its sample rate matching the OOK symbol rate. A LeCroy WavePro 804HD oscilloscope is used for recording of the received signals at a sample rate of 20 GS/s.

The transmitter prototype under test carries four VCSEL arrays with a nominal power of 140 mW operating at 940 nm (Brightlaser VD-0940V-140M-1C-5A1). Light is coupled out via diffusors with emission angles of 60° and 45° in x- and y-direction, respectively. The average optical power at the operating point is 350 mW. As shown in [4], the power distribution within the combined emission cone is relatively homogeneous with some concentration at the edges. The four VCSEL arrays are driven by four integrated MAX3736 drivers designed for pulsed modulation signals, behaving like limiting amplifiers. Compared to the initial hardware described in [4], the analogue interface between the drivers and lasers has been optimized by minimizing the cut-off frequency in the high-pass characteristics and reducing non-linear distortions by impedance adaptations.

To assess the impact of those design changes on the signal fidelity and spatial coverage, at first, a reference measurement with the same setup used in [4] is carried out for calibration. The receiver Thorlabs APD210 with a nominal bandwidth of 1 GHz is taken as a reference, coupled with a lens with a diameter of 25.4 mm and a focal length of 34.9 mm. 16,384 bits of random data, encoded with 8b10b line coding and modulated with OOK, are transmitted over distances of 1, 1.75, and 2.5 m. A Gold sequence for channel estimation (CE) and cyclic prefixes (CPs) are inserted, and a zero-forcing (ZF) frequency-domain equalizer (FDE) is applied at the receiver. Channel estimation is carried out in the frequency domain, excluding frequency bins where the CE sequence has zero-power. The estimated channel response is interpolated and smoothened with an LMMSE filter using assumptions evaluated in [5]. Error vector magnitude (EVM) with and without FDE and root mean square (RMS) of the received signal are evaluated at a symbol rate of 1 GBd.

A second setup, shown in the inset of Fig. 3, serves to explore the bandwidth limitation of the transmitter prototype. For this purpose, a Femto

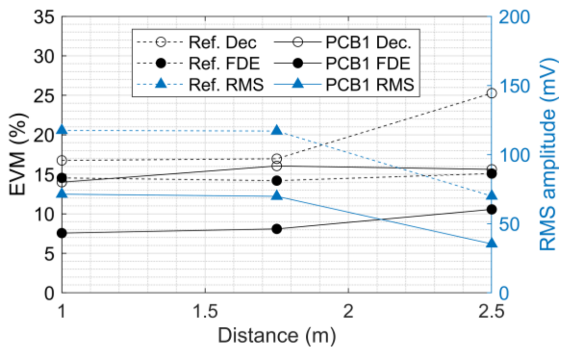

Fig. 2 Results of the reference measurement: EVM and RMS signal amplitude at the receiver output over distance

HSPRX-I-1G4-SI receiver with a nominal bandwidth of 1.4 GHz is used. Since the area of this receiver is small when used without a lens, the transmission distance is 2.5 cm. Longer distances can be achieved using a lens, like in the reference setup.

The symbol rate is varied from 1 GBd to 5 GBd in steps of 250 MBd. Measurements are conducted with varying line codes 8b10b, 64b67b, and 64b66b, see [6]. In addition to the ZF-FDE also used in the reference measurement, a 10-tap time-domain equalizer (TDE) is evaluated here. The number of bits per transmission is increased to 820,144 to make BER evaluation more accurate.

Results

Fig. 2 displays the EVM values observed in the reference measurement on the left y-axis, and the corresponding RMS amplitudes on the right one. For both metrics, the reference data taken from the evaluations of the first transmitter version as presented in [4] are indicated by *Ref.* in the legend and shown with dashed lines. The data obtained with the new hardware revision are referred to as *PCB1* in the legend and shown by solid lines. EVM values without equalization are denoted by *Dec.* (for decimation) and depicted by hollow marks and those with FDE by solid marks.

The RMS values indicate that the received signal strength decreases by roughly 40 % with the new board revision. However, the EVM values also decrease. Without equalization, EVM is reduced by 1−2 % points and barely varies over distance. With equalization, it is reduced by 30−50 % compared to the reference. This points out a significant reduction of non-linear distortions, and thus, a higher signal fidelity in the new transmitter frontend, resulting in a net benefit for the system performance across the target distance, despite the lower signal amplitude.

Fig. 3a shows the EVM values observed for the enhanced bandwidth measurement up to symbol rates of 5 GBd. Remarkably, the EVM

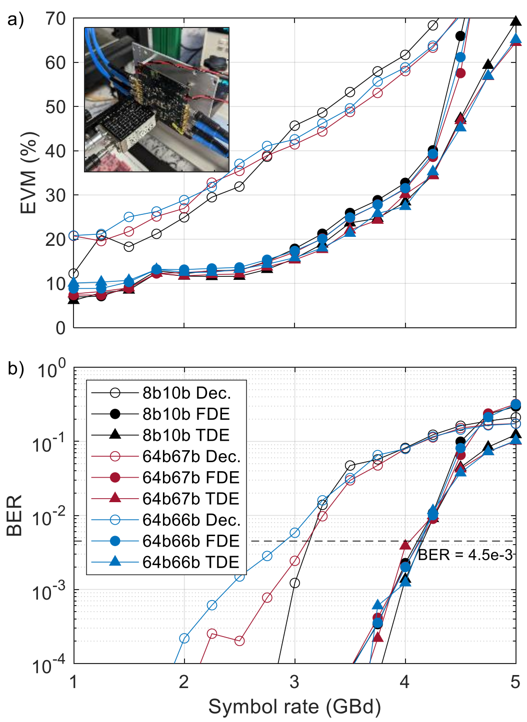

Fig. 3 Results of (a) EVM and (b) BER evaluations for the high bandwidth measurement. Inset in (a) shows experimental setup.

without equalization (*Dec.*) does not reflect significant differences between the line codes. At symbol rates below 2.75 GBd, 8b10b slightly outperforms the others, but above this mark, this effect reverses. This is most likely due to the higher rate of symbol transitions in the 8b10b line-encoded data stream, which reduces distortion due to high-pass effects at low symbol rates, but increases fading of overall signal power at high symbol rates, due to the low-pass characteristics. With equalization, the differences between line codes disappear. Slightly lower EVM values are observed for the TDE at high symbol rates, especially above 4 GBd.

The BER evaluation in Fig. 3b shows that the most notable effect of line coding is on the BER of the non-equalized signal: While 8b10b enables error free operation up to 2.5 GBd instead of only 1.25 GBd (64b66b) or 1.5 GBd (64b67b), the BER limit of 4.5×10^{-3} is exceeded with 64b67b and 8b10b at the same symbol rate (3 GBd), 64b66b crosses the threshold after 2.75 GBd. The BER limit is selected to enable a block error rate of 10^{-3} using an LDPC FEC with an overhead of 5% and an block size of 4320 bits [7].

As observed when using LED transmitters [6], the effect of equalization significantly outweighs the effectiveness of line coding. Equalized transmissions are barely distinguishable between different line codes for FDE, with the first errors appearing at 3.5 GBd and no transmission exceeding the BER threshold up to 4 GBd. With TDE, again, no errors are observed below 3.5 GBd, while there is slightly more variation between line codes. The BER threshold is also crossed after 4 GBd for all transmissions. At very high symbol rates between 4 and 5 GBd, TDE enables lower BER than FDE, but well above the FEC limit. This observation might be useful for using lower code rates and repetitions, however.

The overhead factors for the line codes are 5/4 for 8b10b, 67/64 for 64b67b, and 1 for 64b66b, since the control bits provisioned for the original scheme are not inserted here. With these factors, data rates of 2.4, 2.87, and 2.75 Gbit/s are achievable for the respective codes without equalizer. With both equalizers, all line codes achieve the same maximum symbol rate of 4 GBd. For FDE, CP insertion causes an additional overhead of 9/8. This is not the case for TDE, since no CPs are used. This results in data rates of 2.84, 3.4, and 3.56 Gbit/s for FDE, and 3.2, 3.82, and 4 Gbit/s for TDE, for the respective line codes.

Conclusion

We show that our high power OWC transmitter is capable of providing a data rate up to 4 Gbit/s at 350 mW output power. Compared to previous findings, in which the same module reached 1.75 Gbit/s in 3 m² coverage area, here we improved the optical frontend design and introduced more advanced signal processing. By using a higher bandwidth, improving the interface between driver and laser, and using a scrambler together with an equalizer instead of 8b10b line coding, the performance was improved while the overhead was reduced at the same time. While the time-domain equalizer has no overhead and, thus, achieves the highest data rate of 4 Gbit/s, the frequency-domain equalizer is more compatible with OFDM-based systems and reaches 3.56 Gbit/s. Operation without equalizer is possible, e.g., for ultra-low power systems, and enables up to 2.87 Gbit/s by using the guided scrambler in the 64b67b line code.

Acknowledgments

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