A 3-Gb/s Single-LED OFDM-Based Wireless VLC Link Using a Gallium Nitride μLED

Dobroslav Tsonev, Hyunchae Chun, Sujan Rajbhandari, Jonathan J. D. McKendry, *Member, IEEE*, Stefan Videv, Erdan Gu, Mohsin Haji, Scott Watson, Anthony E. Kelly, Grahame Faulkner, Martin D. Dawson, *Fellow, IEEE*, Harald Haas, *Member, IEEE*, and Dominic O'Brien, *Member, IEEE*

***Abstract*— This letter presents a visible light communication (VLC) system based on a single 50-μm gallium nitride light emitting diode (LED). A device of this size exhibits a 3-dB modulation bandwidth of at least 60 MHz—significantly higher than commercially available white lighting LEDs. Orthogonal frequency division multiplexing is employed as a modulation scheme. This enables the limited modulation bandwidth of the device to be fully used. Pre- and postequalization techniques, as well as adaptive data loading, are successfully applied to achieve a demonstration of wireless communication at speeds exceeding 3 Gb/s. To date, this is the fastest wireless VLC system using a single LED.**

***Index Terms*— Visible light communication, OFDM, optical modulation, optical wireless communication.**

I. Introduction

WIRELESS data traffic is growing exponentially. Recent forecasts indicate that it will be challenging to satisfy the data-rate demands of mobile users because the available radio frequency (RF) communication spectrum is very limited [1]. A potential solution to the looming spectrum crisis lies in the migration of wireless communication into the visible light spectrum. Using visible light offers a number of advantages over RF: 1) 100s of THz license-free bandwidth; 2) simple front-end devices; 3) no interference with sensitive electronic equipment; 4) possibility for integration into the existing lighting infrastructure.

Incoherent solid-state lighting elements such as LEDs are the most likely candidates for VLC transmitters. Several challenges are hindering the development of commercial VLC systems [2]. Among them is the slow modulation response of commercial white LEDs based on blue LEDs with a yellow phosphor coating. The slow response time of the phosphor restricts the modulation bandwidth of the device to several MHz [2]. The application of a blue filter at the receiver removes the slow component from the modulated signal and enables modulation frequencies of up to 20 MHz [2]. Despite the bandwidth limitation of the LEDs, techniques such as equalization, high-order modulation/multiplexing, and parallel data transmission have enabled communication of up to 1 Gb/s using a single phosphor-coated LED and up to 3 Gb/s using red-green-blue LEDs [2]–[4].

Significant research effort is being directed towards the development of faster LEDs. Among them are resonant-cavity light emitting diodes (RCLEDs) [5]. Using an RCLED has enabled communication links of up to 3 Gb/s over a plastic optical fiber (POF) [6]. Devices with comparable modulation bandwidth can be manufactured by reducing the innate junction capacitance of diodes and by controlling the differential carrier lifetimes through injected current density. In [7], a light emitting diode with a diameter of 50 μm (μLED) is introduced. The significantly-reduced size of the device leads to notable improvements in its frequency response. VLC links with a speed of up to 512 Mb/s [7] and up to 1 Gb/s [8] have been successfully established for such μLEDs using on-off keying (OOK) modulation. For a similar device, a 1.07 Gb/s communication link over a POF has been reported in [9].

In this letter, the communication capabilities of Gallium Nitride μLEDs [7] in conjunction with Orthogonal frequency division multiplexing (OFDM) are investigated. A characterization of the μLED bandwidth and an actual experimental realization of an OFDM-based system are presented. OFDM is selected because it allows cost-effective equalization with single-tap equalizers in the frequency domain. Moreover, OFDM allows adaptive data and energy allocation to different frequency bands based on the communication system properties. In addition, the scheme provides an easy way to avoid low-frequency interference caused by ambient light and by the baseline wander in electrical components. In the current work, a comparison is made between the performance of two techniques for overcoming the effects of frequency-dependent signal attenuation: 1) fixed-rate subcarrier loading with pre-equalization; and 2) adaptive bit and energy loading. As a result, to the best of the authors' knowledge, the fastest single-link wireless VLC system is presented in this letter.

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D. Tsonev, S. Videv, and H. Haas are with the Institute for Digital Communications, Joint Research Institute for Signal and Image Processing, The University of Edinburgh, Edinburgh EH9 3JL, U.K. (e-mail: d.tsonev@ed.ac.uk; s.videv@ed.ac.uk; h.haas@ed.ac.uk).

H. Chun, S. Rajbhandari, G. Faulkner, and D. O'Brien are with the Department of Engineering Science, University of Oxford, Oxford OX13PJ, U.K. (e-mail: hyunchae.chun@eng.ox.ac.uk; sujan.rajbhandari@eng.ox.ac.uk; grahame.faulkner@eng.ox.ac.uk; dominic.obrien@eng.ox.ac.uk).

J. J. D. McKendry, E. Gu, and M. D. Dawson are with the Institute of Photonics, University of Strathclyde, Glasgow G4 0NW, U.K. (e-mail: jonathan.mckendry@strath.ac.uk; erdan.gu@strath.ac.uk; m.dawson@strath.ac.uk).

M. Haji, S. Watson, and A. E. Kelly are with the School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K. (e-mail: m.haji.1@research.gla.ac.uk; s.watson.2@research.gla.ac.uk; anthony.kelly@glasgow.ac.uk).

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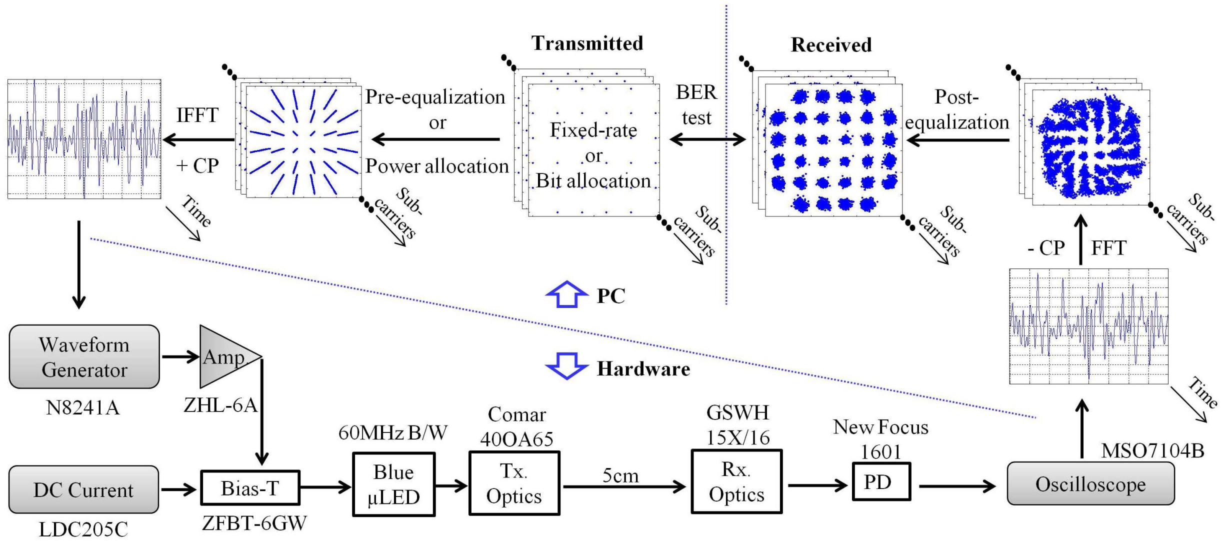


Fig. 1. Experimental set-up.

The rest of this letter is organized as follows. Section II provides a description of the experimental setup. Section III presents the experimental results and offers a discussion. Finally, Section IV provides concluding remarks.

II. System Description

A. Experimental Set-Up Parameters

Fig. 1 presents a diagram of the experimental OFDM-based VLC system set-up. First, an incoming bit stream is encoded into M-ary quadrature amplitude modulation (M-QAM) symbols. Then, the resulting M-QAM symbols are assigned to different frequency subcarriers and rescaled accordingly if pre-equalization is employed. Afterwards, an inverse fast Fourier transform (IFFT) operation is applied on a block of symbols, which produces a discrete time-domain signal. This signal is conditioned for transmission by clipping any values outside the allowed operational range set by the electrical properties of the μLED. All digital processing steps are performed in MATLAB®. Afterwards, the conditioned digital signal is supplied to an arbitrary waveform generator (AWG), Agilent N8241A, which maps it to an analog signal. The analog signal is amplified with a high-power amplifier, Mini-Circuits ZHL-6A, which drives the μLED. The μLED emits blue light with a wavelength distribution centered around 450 nm and has a maximum optical power of around 4.5 mW [7]. A direct current (DC) bias from a laser driver is added to the drive signal using a bias-T, Mini-Circuits ZFBT-6GW. Light from the μLED is imaged onto a high-speed photodetector, New Focus 1601FS-AC, using a high numerical aperture (NA) microscope objective, model 40OA65 from Comar Optics. The output signal of the photodetector is captured by a digital oscilloscope, Agilent MSO7104B. Afterwards, it is processed in MATLAB with a sequence of steps that include: synchronization, fast Fourier transform (FFT), equalization, and M-QAM demodulation.

The distance between the transmitter and the receiver is set at 5 cm. This is limited by the optical power of the μLED and the small area of the photodiode (PD). It can be increased further with the addition of improved μLEDs, improved optics, an avalanche PD detector, or additional transmitter elements whose combined radiation power provides a sufficient signal-to-noise ratio (SNR) at the receiver.

B. OFDM Parameters and Operating Condition

VLC with incoherent illumination devices can only be realized as an intensity modulation and direct detection (IM/DD) system. Hence, modulation signals have to be both real and unipolar. However, conventional OFDM signals are both complex and bipolar in nature.

It is possible to obtain a real OFDM signal by imposing Hermitian symmetry in the IFFT operation during the signal generation step [2], [3]. As a prerequisite, the DC subcarrier and the π-shifted subcarrier are set to zero. In addition, half of the subcarriers are set as complex conjugates of the other half. In OFDM, a total of N_{fft} subcarriers are equally distributed in the frequency range $[-1/2T_{\text{s}}; 1/2T_{\text{s}}]$ where T_{s} is the sampling period in the time domain. Data loading can be omitted on some subcarriers in order to avoid interference stemming from ambient light sources and from the DC-wander effect. Subcarriers can also be left unused if SNR levels are not sufficient in a certain frequency band. The spectral efficiency of the scheme is:

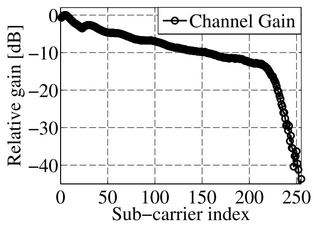
$$\eta = \frac{\sum_{k=0}^{\frac{N_{\text{fft}}}{2}-1} \text{sgn}\,(M_k) \log_2 M_k}{N_{\text{fft}} + N_{\text{cp}}} \text{ bits/s/Hz} \tag{1}$$

where N_{fft} is the FFT size, M_k is the constellation size on the kth subcarrier, N_{cp} is the size of the cyclic prefix in the time domain, and $\text{sgn}(x)$ is the sign function. The single-sided bandwidth of the system is calculated as:

$$B = \frac{1}{2T_{\text{s}}} \text{ Hz} \tag{2}$$

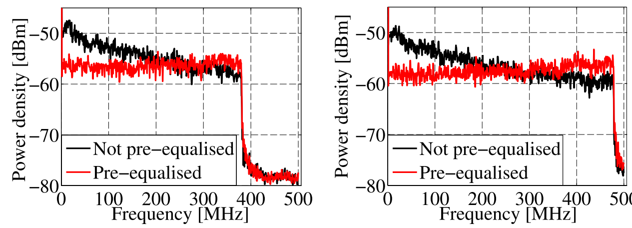
Then, the data rate of the system is:

$$D = 2B\eta \text{ bits/s} \tag{3}$$



(a) (b)

Fig. 2. Estimated: (a) channel gain; and (b) SNR.



(a) (b)

Fig. 3. Power spectrum density of 64-QAM DCO-OFDM with the last (a) 100 and (b) 60 subcarriers unused.

In this letter, the FFT size is N_{fft}=512. The optimal cyclic prefix length is set to N_{cp}=5 after exhaustive experiments.

A bipolar OFDM signal can be employed in an IM/DD system if a suitable DC-bias is applied [2], [3]. This allows the bipolar OFDM signal to vary around a fixed positive operating point. The resulting scheme is known as DC-biased optical OFDM (DCO-OFDM). The time-domain OFDM signal is characterized by a very high peak-to-average power ratio (PAPR), which grows with the number of IFFT points. The dynamic range of the μLED is limited in terms of a minimum and a maximum signal level. Hence, clipping of the signal on both sides of the time-domain distribution is practically unavoidable. In the current work, exhaustive experiments have determined that clipping levels at -3.2σ and 3.2σ, where σ is the standard deviation of the time-domain signal:

$$\sigma^2 = \frac{2\sum_{k=0}^{\frac{N_{\text{fft}}}{2}-1} E_{\text{b}k} \log_2 M_k}{N_{\text{fft}}}, \tag{4}$$

lead to an optimal utilization of the limited μLED dynamic range. In (4), $E_{\text{b}k}$ is defined as the energy per bit on the kth subcarrier. The optimal biasing point is determined to be at a voltage of V_{bias}=5.2 V which corresponds to a bias current of I_{bias}=40 mA. The peak-to-peak voltage swing of the modulating signal is set at $V_{\text{pp}} = 2.5$ V in order to utilize the full dynamic range of the μLED. The sampling frequency of the AWG is fixed at F_{s}=1.25 Gs/s, which results in a maximum achievable single-sided bandwidth of B=625MHz.

C. Channel Gain and SNR Per Sub-Carrier

Channel estimation is performed with a pilot sequence that consists of random binary phase-shift keying (BPSK) symbols with constant energy. The relative channel gain and the absolute SNR values, obtained through error vector magnitude estimation, are shown in Fig. 2 for the different frequency subcarriers. The channel attenuation follows closely the frequency profile of the μLED whose 3-dB attenuation occurs at a frequency of 60 MHz. The remaining elements in the system are guaranteed to have a flat bandwidth up to a frequency of at least 500 MHz. This assumption is supported by Fig. 2(a) where the gain factor experiences a sudden drop after subcarrier 220 which corresponds to a frequency of about 540 MHz. The estimated SNR profile of the communication channel follows closely the estimated frequency profile, see Fig. 2(b). This suggests that the additive white Gaussian noise (AWGN) distribution in the system is uniform within the communication bandwidth. The SNR values at the low-frequency subcarriers are slightly lower than expected. This is attributed to low-frequency noise from ambient light and from the baseline wander effect. Nevertheless, the SNR on these subcarriers is sufficient for successful communication.

III. Results and Discussion

In the current study, two approaches are employed for maximizing the utilization of the μLED communication capabilities. In the first approach, a fixed M-QAM constellation size is employed on all modulated subcarriers. Energy pre-equalization is used in an attempt to equalize the achievable SNR values on each subcarrier at the receiver. In the second approach, both the constellation size and the energy on each subcarrier are determined based on the achievable SNR at that particular frequency. Based on widely-accepted results from information theory, it is expected that the adaptive bit and energy loading will exhibit better results as it provides more freedom in the signal optimization procedure [10].

A. Fixed-Rate With Pre-Equalization

Pre-equalization consists of applying the inverse function of the system frequency response on all subcarriers before transmission. This effectively scales the energy in each frequency band with the inverse of the system gain. Hence, after propagating to the receiver, all subcarriers should exhibit the same average energy level. The power spectral density (PSD) of the received signal for the case without pre-equalization and for the case with pre-equalization is illustrated in Fig. 3. This shows pre-equalization leads to uniform SNR distribution on all subcarriers. In the current experimental setup, the highest data rate with this approach can be achieved for a constellation size of M=64. Fig. 3(a) illustrates the signal PSD when the last 100 subcarriers are not used, *i.e.*, the signal bandwidth is about 380 MHz. Fig. 3(b) illustrates the case when the last 60 subcarriers are omitted, *i.e.*, the signal bandwidth reaches 480 MHz. The case in Fig. 3(a) achieves higher SNR values and so a lower bit error rate (BER) because the signal energy is distributed over a smaller frequency range. The system throughput, however, is also lower than in the case presented in Fig. 3(b) where the data rate reaches a value of D=2.8 Gb/s for a BER$<$0.002. Based on the recommendations of the International Telecommunication Union (ITU), it is expected that the addition of a forward error correction (FEC) code with an overhead of about 7%, such

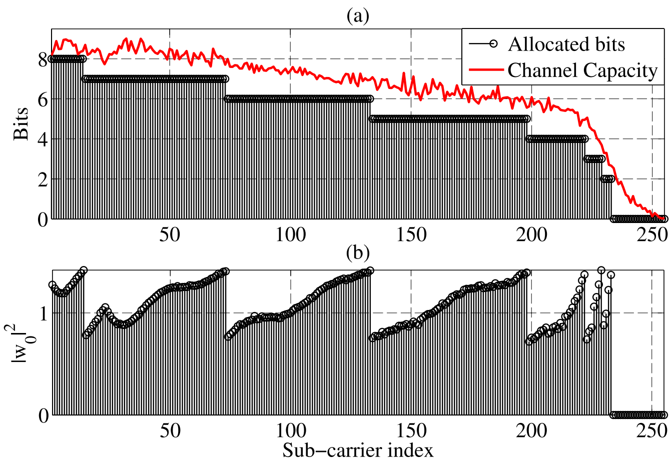


Fig. 4. Allocated: (a) bits; and (b) energy.

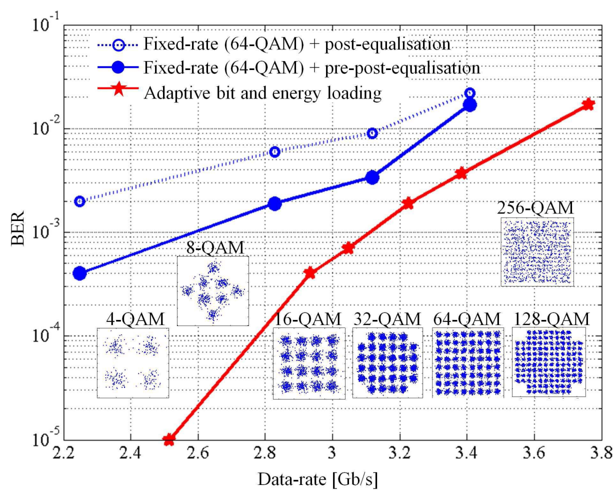


Fig. 5. BER results and received constellations for D=3.22 Gb/s with adaptive bit and energy loading.

as the RS(1023,1007)/BCH(2047/1952), can guarantee reliable communication for BER < 0.002 [11]. Due to the overhead, the throughput decreases to D=2.63 Gb/s.

B. Adaptive Bit and Energy Loading

The algorithm in the current approach is based on the work of Levin [12]. The optimal bit allocation for the current set-up can be observed in Fig. 4(a). The theoretical system capacity for the achieved SNR values on the different subcarriers is also shown [13]. The small gap between the system throughput and the capacity can only be closed through channel coding techniques. Fig. 4(b) shows the assigned energy on each subcarrier. The algorithm aims to ensure a constant SNR on all received subcarriers with the same constellation size. This optimized modulation signal achieves D=3.22 Gb/s with a BER < 0.002. With the 7% overhead for FEC, the data rate becomes D=3 Gb/s. In general, reducing the data rate allows the BER to be improved even without FEC. The results are summarized in Fig. 5. The received M-QAM constellations are also shown.

IV. Conclusion

The feasibility of a 3-Gb/s wireless link with a single Gallium Nitride μLED is demonstrated in the current work. OFDM is employed as a modulation scheme because it allows optimal usage of a frequency-dependent communication system. Two separate approaches are tested for optimization of the communication system utilization: 1) pre-equalization; and 2) adaptive bit and energy loading. The latter is shown to be better with a maximum achieved data rate of D=3 Gb/s. To the best of the authors' knowledge, this is the fastest single-link wireless VLC system demonstration up-to-date.

The system throughput in the presented scenario is limited not only by the μLED properties, but also by the characteristics of the additional electrical components. The sampling rate of the AWG and the frequency response of the amplifier limit the modulation bandwidth. Work to further improve the data rate is under way. The current demonstration is performed for a narrow-field-of-view link over a 5-cm distance. The coverage can be improved with the introduction of dedicated optics as well as with ganging of multiple μLEDs in order to increase the transmitted optical power.

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