10.2 Gb/s visible light communication with off-the-shelf LEDs

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Abstract *A 10 Gb/s data rate is demonstrated experimentally for optical communication using three inexpensive off-the-shelf LEDs for the first time. An OFDM-based wavelength division multiplexing structure is used for efficiently utilizing the available bandwidth of the LEDs.*

Introduction

The radio frequency (RF) spectrum is saturated and cannot keep up with the ever increasing demand for high data rates originating from emerging new smart technologies. The visible light spectrum is readily available for communication purposes, and high speed data transmission has already been demonstrated using wireless optical communication. Light Fidelity (LiFi) is known as a high speed wireless access network that combines illumination and visible light communication (VLC) techniques using light emitting diodes (LEDs)[1]. The simple intensity modulation and direct detection (IM/DD) approach is mainly used to modulate data on available incoherent light sources. Moreover, spectrally efficient multicarrier modulation techniques, such as optical orthogonal frequency division multiplexing (OFDM) are also optimized for VLC. In spite of the large spectrum available for data transmission in VLC, the limited bandwidth of the light sources makes it difficult to exploit all the available spectrum efficiently. Therefore, different methods, such as multiple-input-multiple-output (MIMO)[2] and wavelength division multiplexing (WDM)[3], are used to increase the spectral efficiency. It is reported that using custom-made micro-sized Gallium Nitride (GaN) LEDs (μLEDs) a data transmission rate of about 8 Gb/s is achieved using a single pixel[4], while over 10 Gb/s is achieved by using three-color WDM[5]. These custom-fabricated μLEDs have much higher bandwidth but significantly lower output optical power compared to commercially available LEDs which are designed for illumination rather than data communication. Previously, 8 Gb/s[6] and 10.7 Gb/s[7] were demonstrated using four-color and five-color LED-based WDM with post or pre equalization respectively. Both works presented the overall data rate as the summation of all individual color links. However, the implementation method for separating the combined beam and simultaneous detection at the receiver side was not introduced. This is an essential part of a practical system where all individual links carry the data simultaneously.

In this paper, for the first time we demonstrate a 10.2 Gb/s WDM-VLC link without pre or post equalization using three high brightness off-the-shelf LEDs at a price of less than 50 US cents ($0.50). Three single color LEDs, blue, green and red, are utilized for WDM. And OFDM with adaptive sub-carrier bit loading is used to enhance the spectral efficiency. The results presented in this paper prove that high speed communication is possible using available inexpensive off-the-shelf components. Different optical components (e.g., lenses and mirrors) are incorporated for the WDM design presented, which can be integrated into compact transmitter and receiver units for real applications such as Internet-of-things (IoT).

Experimental Set-up

For IM/DD optical communication, some variants of OFDM are used because the input signal needs to be real and positive[1]. We use DC-biased optical OFDM (DCO-OFDM). A real-valued OFDM signal is first generated using a Hermitian symmetric OFDM frame which effectively makes half of the data redundant. Then, the real-valued signal is made positive by adding a DC bias. The DC-bias and the peak-to-peak amplitudes are determined to minimize the effect of signal clipping and nonlinearity of the LED. Before data transmission, the effective signal-to-noise ratio (SNR) of the whole system is estimated using a mean estimator with random pilots. Assuming a M-QAM modulation format, the modulation order M_k is adaptively chosen based on the estimated SNR at kth subcarrier in order to achieve an overall target bit error rate (BER). The data rate is calculated as

$$R = \frac{\sum_{k=1}^{\frac{N_{\mathrm{FFT}}}{2}} \log_2 M_k}{(N_{\mathrm{FFT}} + N_{\mathrm{CP}})/2B}, \quad (1)$$

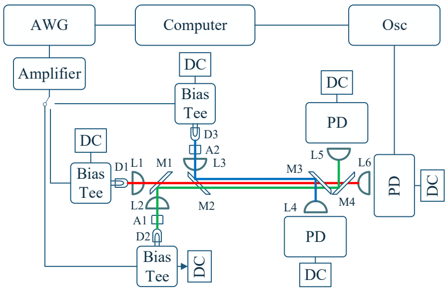

Fig. 1: The experimental set-up for WDM-VLC system

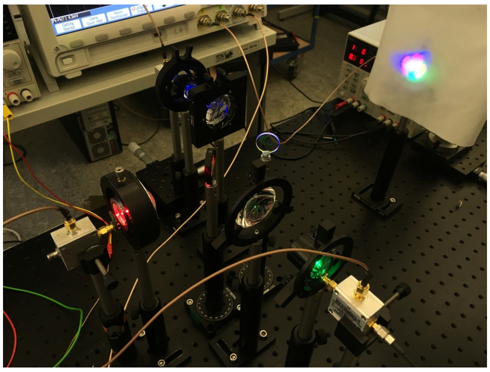

Fig. 2: The picture of transmitter side in the experimental set-up.

where B, N_{FFT} and N_{CP} are the modulation bandwidth, fast Fourier transform (FFT) size and cyclic prefix size. In this paper, the target bit error rate (BER) is chosen as the hard decision forward error correction (HDFEC) BER threshold 3.8×10^{-3}, and the number of active subcarriers is $N = N_{\mathrm{FFT}}/2 = 1024$. The details of adaptive OFDM bit loading can be found in references[3–5].

Figs. 1 and 2 show the experimental set-up for this paper. The digital data is generated using MATLAB code and is sent to an arbitrary waveform generator (AWG: M8195A) with sampling rate up to 16 GSa/s for four channels. The generated analogue signal is then amplified (ZHL-1A-S+) and sent to the LED through a bias-tee (ZFBT-4R2GW), which is used to mix the DC bias and the OFDM signal for each LED. The LEDs are chosen in three colors: red (D1: VLMS1500-GS08), green (D2: VLMTG1300-GS08) and blue (D3: VLMB1500-GS08). The optical signal generated by each LED is collimated using aspheric condenser lenses (L1-6: ACL4532). An additional condenser lens assembly (A1-2: 01TA25) is used for the blue and green colors to correct the spot of light incident to the dichroic mirrors. One dichroic mirror (M1: DLMP567) is used to reflect the green signal while it passes the red signal. The transmission band for this mirror is 584-800 nm. Another dichroic mirror (M2: DLMP490), with transmission band 505-800 nm, is used to reflect

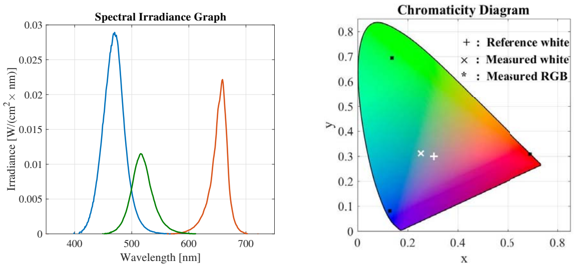

Fig. 3: The spectral irradiance measurements and chromaticity diagram for individual red, green and blue LEDs and mixed white illumination.

the blue signal while it passes the other two colors. The dichroic mirrors are chosen based on the spectral irradiance measurement results for individual red, green and blue LEDs as shown in Fig. 3. The link length for all colors is 50 cm. Fig. 3 also shows the measured chromaticity diagram values for both all individual LEDs and the combined beam with a reference value of white LED (VLMW1500-GS08) taken from its datasheet. The combination of three beams results in a white spot at the receiver side.

At the receiver side, the same configuration of mirrors (M3: DLMP490, M4: DLMP567) are used to separate different colors. Another lens is used to focus the light into the detection area of the high bandwidth photo detector (PD: New Focus 1601). The -3 dB bandwidth of this PD is 1 GHz. The received signal is captured by a high-speed oscilloscope (Osc: MSO7104B), which sends the data to a computer for processing with the MATLAB software. Note that the size of set-up presented here can be minimized, probably to the size of available lamps used for illumination only.

Results

LEDs are nonlinear light sources and cause nonlinear distortion especially in high speed data transmission. An important factor is the operation point (bias voltage and current) of each LED, which along with the signal peak-to-peak amplitude determine the amount of distortion. The optimum bias point is found by several single-color experiments. The optimum bias current I_b and voltage V_b are presented in Table. 1 for each LED. Since the characteristics of the output light varies with different bias points, the peak wavelength λ_{peak} and output power at peak wavelength P_{out} along with the chosen peak-to-peak voltage V_{pp} are also presented in Table. 1.

The estimated channel gain and measured SNR are shown in Fig. 4. While SNRs at different wavelengths are almost equal for different colors, the channel gains are different. The channel

Tab. 1: The chosen bias points and experiment results.

	I_b [mA]	V_b [V]	λ_{peak} [nm]	P_{out} [mW]	V_{pp} [V]	N_{S}	BER	R [Gb/s]
Red	125	2.6	660	4.89	0.85	852	0.0020	3.48
Green	105	4.4	516	2.14	0.80	869	0.0021	3.65
Blue	130	4.5	477	5.23	0.85	886	0.0018	3.81

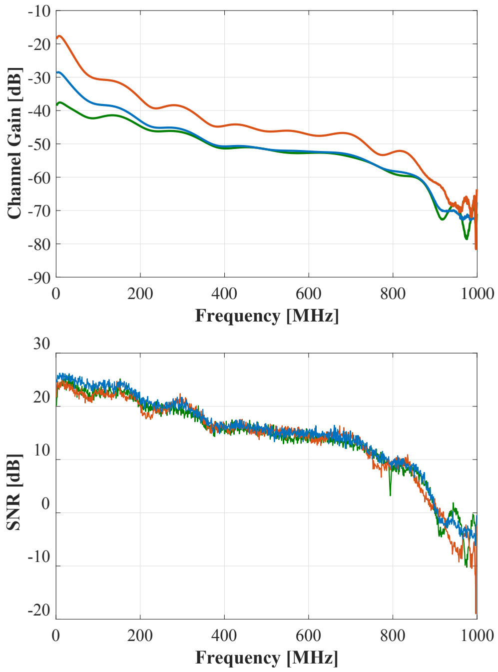

Fig. 4: The measured channel gain and SNR at different subcarriers for red, green and blue LEDs.

gain for red is higher because the used receiver has a maximum responsivity at peak wavelength of 0.45 A/W for red while 0.28 A/W and 0.24 A/W for green and blue. In addition, there is a loss for all the colors at the mirrors for some parts of the spectrum being reflected (for red and green) or passed (for green and blue) through the mirrors and not reaching the receiver. The -3 dB bandwidth of LEDs are about 33 MHz for red and blue LEDs and 65 MHz for green LED. However, frequencies higher than the -3 dB bandwidth can be used for data transmission as the SNR drops gradually and stays usable for conveying information. In this work up to 1 GHz of bandwidth is used for data modulation of all LEDs. The modulation orders allocated to each subcarrier is shown in Fig. 5. The number of used subcarriers N_{S}, BER and data-rate R are shown in Table 1. The aggregate achievable data rate is 10.94 Gb/s which reduces to 10.17 Gb/s after 7% HDFEC overhead reduction.

Conclusion

We have presented experimental results of a 10.2 Gb/s VLC WDM system, using off-the-shelf RGB LEDs which are available at a cost of less than 50 US cents. The three individual color links carry

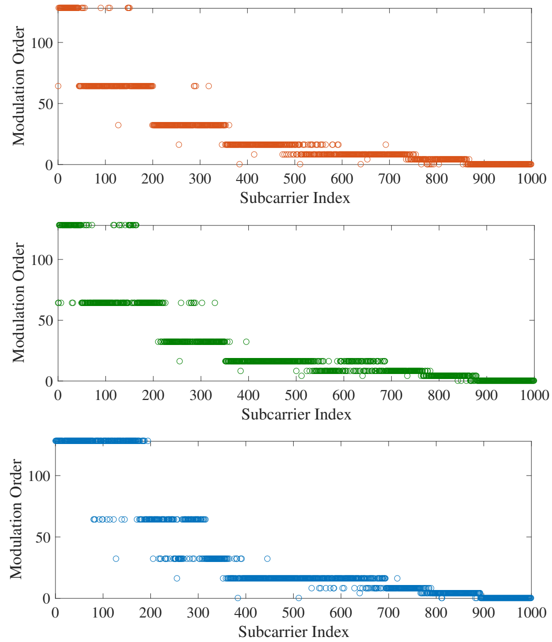

Fig. 5: The modulation order chosen for each subcarrier for colors red, green and blue LEDs.

the data simultaneously while the beams being combined at the transmitter side and then separated at the receiver side. The system offers high wireless data transmission rate with high bright white illumination which makes it a potential candidate for practical LiFi applications.

References

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