803 Mbit/s Visible Light WDM Link based on DMT Modulation of a Single RGB LED Luminary

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Abstract: We report the first visible light link based on WDM and DMT modulation of a single RGB-type white LED, operating at an aggregate rate of 803 Mbit/s within the FEC $2\cdot10^{-3}$ limit.

OCIS codes: (060.2605) Free-space optical communication, (230.3670) Light-emitting diodes

1. Introduction

High-power white light-emitting diodes (LEDs) are an emerging technology for energy-efficient artificial lighting. Besides appealing lighting properties, like the ease of colour rendering, the potential synergy of illumination and data transmission functions by use of one optical source has stimulated worldwide research and development activities [1] as well as global standardization efforts [2].

Whereas the phosphorescent white LEDs (a blue chip plus phosphor layer) are the simpler variant, white LEDs consisting of red, green and blue chips (i.e. RGB LEDs) offer the possibility for wavelength division multiplexing (WDM) in VLC links, and hence service or user separation as well as potential increase in overall data rate.

Concerning the phosphorescent white LEDs in VLC wireless links, we recently demonstrated a record 230 Mbit/s rate with a low-cost PIN photodiode in the receiver [3]. Later, utilizing a phosphorescent LED module featuring 30% larger bandwidth than that in [3] and an avalanche photodiode (APD), that result was topped and 500 Mbit/s was demonstrated [4]. Quadrature-amplitude-modulation (QAM) on discrete multitones (DMT) was used to modulate a single white LED luminary in both cases.

A single channel system using an RGB LED array at 100 Mbit/s has been reported in [5], whereas a demonstration of WDM has recently been reported in [6], however at low-speed (<200 kbps). WDM in VLC has also been investigated theoretically in [7], regarding multiple mono-chromatic LEDs. There, the signal powers in different WDM channels were adapted to the wavelength dependency of the photodiode responsivity.

In this paper, we report for the first time a demonstration of a high-speed WDM VLC link operating at an aggregate rate of 803 Mbit/s, based on DMT modulation (with off-line digital signal processing) of a single RGB white LED luminary. The resultant bit error ratios (BERs) in all three WDM channels were below $2\cdot10^{-3}$, i.e., within the FEC limit. The illuminance level at the receiver site was in the range recommended for working environment.

2. Experimental Setup

The experimental setup for BER measurements of the WDM system is presented in Fig. 1. The optical source in this experiment was a commercially available white LED luminary (Seoul Semiconductor F50360, generating a luminous flux of 105 lm at typical driving currents, with a radiation angle of 120°), consisting of three chips radiating in the wavelength regions of 700 nm (red), 530 nm (green) and 470 nm (blue). In order to drive all 3 LED chips (corresponding to 3 WDM channels) at the same time, two different DMT signals (of same powers) were generated by software and fed into the arbitrary waveform generator. The DMT signal from the AWG output 1 was then used to modulate the WDM channel (LED chip) under test (Fig. 1 shows the case of the red LED test). In lack of the third independent output, the DMT signal from the AWG output 2 modulated the other two chips (blue and green in Fig. 1). Before the modulation of optical sources, the AWG output signals were amplified (AMP1 in Fig. 1) and via a Bias-T combined with the dc signal (300 mA) corresponding to the LED working point.

DMT signals consisted of N=32 subcarriers within a baseband bandwidth of B=50 MHz (1.5625 MHz carrier spacing). Bit and power loading was applied on N-1 subcarriers (without dc), in order to adapt to the channel quality at individual frequencies. Subcarrier modulation orders used in the experiments are given in detail below.

After transmission over the visible-light channel, at the site of the ac-coupled analog receiver, a suitable optical dichroic filter was mounted in front of the photodiode, depending on the channel under test (Edmund Optics V52-528, V52-534 and a custom designed filter by Berliner Glas for the red, green and blue channel, respectively). A commercially available large-area silicon APD (3 mm diameter, 80 MHz bandwidth) combined with a glass lens (0.5 NA and 8 mm focal length) was used for detection, followed by two low-impedance amplifiers (AMP2 in Fig. 1) needed to bring the signal level up to the operation range of the storage oscilloscope.

After filtering by a high-order low-pass filter (cut-off 50 MHz), time traces of the received signal were recorded by a storage oscilloscope (4 GSps sampling rate) and further processed offline. The received DMT signal was demodulated and de-mapped according to the applied bit-loading mask. A training sequence was used for channel estimation. Perfect synchronization between transmitter and receiver was assumed (the start of the transmission frame was manually determined). BER was calculated for each modulated subcarrier.

The measurements have been performed under the condition of a 1000 lx brightness level (illuminance) at the receiver, which is a value within the range recommended by the lighting standard for the working environment [8]. This was realized by setting an appropriate wireless link length and checking the brightness level by a light-meter placed at the receiver site in the otherwise dark laboratory. Deployment of a single luminary with wide radiation angle and no additional optics in the experiment resulted in link length of about 12 cm (for 1000 lx), but typical indoor distances of a few meter could be easily achieved by using several LED modules in parallel.

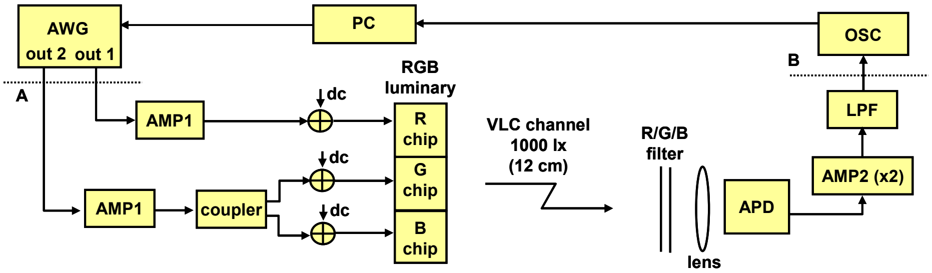

Fig. 1. Experimental setup for measurements of 3 WDM channels (red, green and blue). AWG: arbitrary waveform generator, PC: personal computer, OSC: storage oscilloscope, AMP: amplifier, LPF: low-pass filter.

3. Results and Discussion

Prior to transmission performance assessment, the frequency characteristic of the electro-optical (EOE) channel was measured (between points A and B in Fig. 1) for all three WDM channels. Channel gains are shown relative to the (measured) maximum in Fig. 2a. Different gains of the three WDM channels at low frequencies can be attributed mainly to the filters' transmission properties and wavelength dependency of the Si-APD responsivity. Moreover, a "bump" around 10 MHz due to the interaction between otherwise flat LED chips and the amplifier, is especially observable for the green and blue channel. Nevertheless, it can be concluded that the link bandwidth is limited by LED chips and that the three channels have similar frequency characteristics with 3-dB points around 15-20 MHz.

In the transmission performance measurements, we applied bit- and power-loading in order to efficiently exploit the capacity of each WDM channel. An optimal and fast-converging loading algorithm initially proposed by Krongold et al. [9] for DSL systems was chosen. Based on the knowledge of the EOE channel, this algorithm determines the QAM orders and powers of individual subcarriers, leading to a maximized aggregate transmission rate. Hereby, it complies with the constraints on the overall DMT signal power and on the maximum BER as specified for a given system.

The channel information, i.e. the noise-enhancement coefficients $\sigma^2/|H_n|^2$ on subcarriers $n=1..N-1$, σ^2 being the additive white Gaussian noise (AWGN) power within the subcarrier bandwidth and $|H_n|^2$ the corresponding channel gain coefficient, were first obtained by an initial BER measurement. For this initial measurement we chose to modulate all subcarriers with equal powers and an arbitrary bit allocation mask. From the measured initial BERs, the channel information was derived by the corresponding analytical BER-vs-SNR expressions, valid for an AWGN channel [10], and fed into the loading algorithm for throughput maximization.

The loading algorithm resulted in the optimal bit- and power distribution for the measured channel and chosen BER. We considered a total BER limit in our system $\mathrm{BER}_{TOT} \leq 2\cdot10^{-3}$, which can be suppressed below 10^{-16} by use of forward-error correction (FEC) algorithms [11]. Such procedure has been done for all WDM channels.

The BER measurement results with the optimal distributions are shown in Fig. 2 b-d. With the bit-loading masks as shown in Fig. 2c, the gross transmission rates $R_{TOT} = (B/N)\sum_{n=1}^{N-1} R_n$ achieved were ~293.7 Mbit/s, ~223,4 Mbit/s and ~286 Mbit/s for the red, green and blue channel, respectively, leading to an aggregate rate of about 803 Mbit/s. The gross rate does not include subtraction for redundancy of cyclic prefix and overhead needed for error correction coding or training, which can be estimated in total at 11% [3].

The measured resultant BERs are shown in Fig. 2b. Even though the loading algorithm predicted the BER values on each subcarrier below $2\cdot10^{-3}$, it can be observed that some of the subcarriers resulted in a higher amount of errors. The possible causes are the non-linearity of system components and disturbances from the adjacent WDM channels, which were not considered by the loading algorithm. It can also be seen that the BER values of the subcarriers with non-square QAM constellations (R_n={3, 5, 7}) were significantly below $2\cdot10^{-3}$. This is because the theoretical BER-vs.-SNR expressions on which the loading algorithm is based were actually the upper bounds for those constellations. Considering all the effects discussed above, the overall $\mathrm{BER_{TOT}}$ values, denoting the total number of falsely detected bits over the total number of sent bits, resulted within the set $2\cdot10^{-3}$ limit in all WDM channels.

Figure 2d shows the distribution of the DMT symbol power among the subcarriers. From Fig. 2c and d can be seen how the algorithm result is adapted to the overall low-pass character of the transmission channel. Namely, with the increase in frequency, the number of allotted bits decreases. Moreover, within a group of subcarriers of the same modulation order, the allocated powers increase with the frequency (as needed for the same SNR). The exception are the lower frequencies (up to the ~10th subcarrier) of the green and to a smaller degree blue chip, where the channel is not low-pass (see Fig. 2a).

It should be noted that the performed measurements had a hero character with a purpose to reveal potential of modulating the commercial low-cost optical source (devised for illumination) in combination with WDM. For practical implementation, issues such as DAC and ADC resolution vs. QAM order or APD-vs.-PIN should be considered.

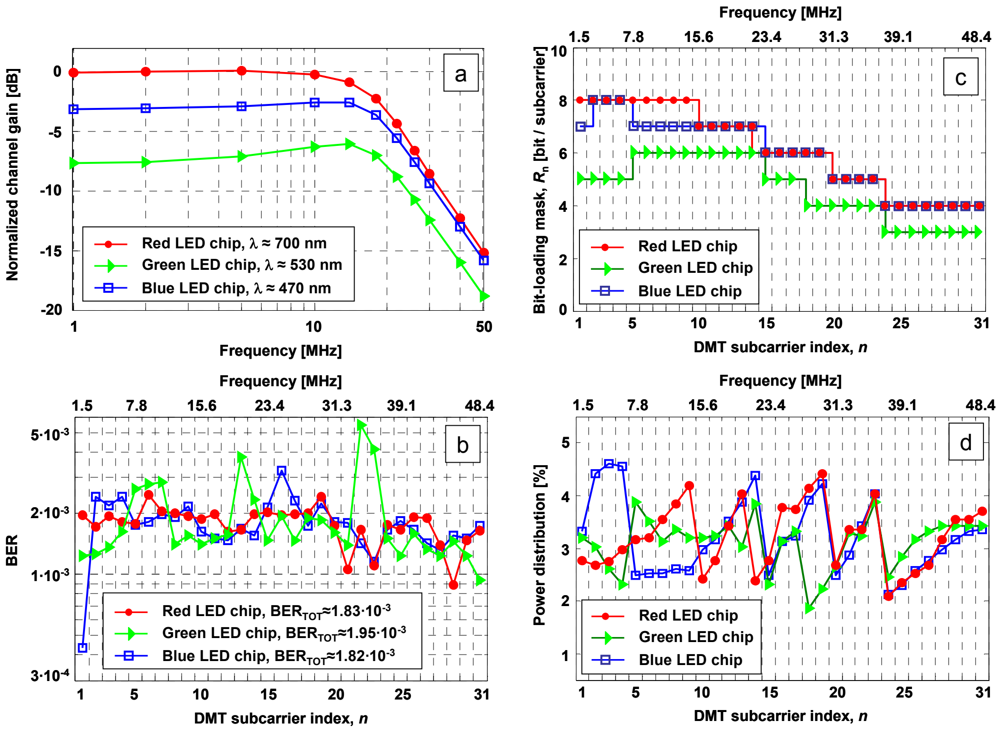

Fig. 2. Measurement results for 3 WDM channels (red, green and blue). a) Electro-optical channel frequency characteristic, $|H_n|^2$. b) BER values on individual subcarriers, c) Optimal bit-loading masks, d) Optimal power distributions (percentage of the total DMT symbol power).

4. Conclusions

In this paper, an aggregate rate of 803 Mbit/s over a wireless visible light link based on WDM and DMT modulation (with off-line digital signal processing) of a single RGB white-light LED was reported for the first time. The illuminance level at the receiver site was in the range recommended for working environment. The measured bit error ratios in all three WDM channels were below $2\cdot10^{-3}$, i.e., within the FEC limit.

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