5.6 Gbit/s Downlink and 1.5 Gbit/s Uplink Optical Wireless Transmission at Indoor Distances (≥ 1.5 m)

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Abstract *We experimentally realized a bi-directional high-speed optical system working at common environment distances and illumination levels. The downlink record aggregate bitrate of 5.6 Gbit/s is achieved exploiting WDM approach, commercial LEDs and DMT modulation.*

Introduction

Light Emitting Diodes (LEDs), which will be future lighting technology, will also allow distribution of broadband optical wireless signals. Two types of white LEDs are common for lighting applications: the phosphor-based type consisting of a blue chip plus a yellow phosphor layer and the multi-color type consisting of three or four individual chips[1]. While the first ones are preferable for very low cost-efficient installations mainly thanks to their simple design, the latter are preferable for very high-speed data transmission applications because they allow wavelength division multiplexing (WDM)[2].

In the past, we demonstrated visible light communication (VLC) wireless links using both types of white LEDs. For phosphorescent white LEDs and for multi-color LEDs the aggregate rates of 1 Gbit/s[3] and 3.4 Gbit/s[4] were achieved, respectively. In both cases the Quadrature-amplitude-modulation (QAM) on discrete multi-tone (DMT) was used. Although in these experiments the considered illuminance levels were always below the standard limit for indoor environment, the measurements were performed at short distances (ranging from 10 to 30 cm). Slightly longer distance was achieved in[5] where 2.25 Gbit/s over 65 cm free space transmission was reported.

In this paper, we demonstrate a significant increase on bit rate for a WDM VLC link based on an integrated 4 channel-LED board. For the first time the aggregate value of 5 Gbit/s using visible light is obtained using commercial available LEDs. Moreover this is attained at common indoor distance (from 1.5 to 4 m). Furthermore we also include an infrared (IR) channel that can be used for high-speed uplink.

Experimental details

The experimental setup of the optical wireless system is presented in Fig. 1. The downlink transmitter (Tx_D) exploited a custom board hosting 12 low cost chips, 3 for each color (red, green, blue, and amber), closely mounted and separately connected in series by color. This source generates a total luminous flux of around 700 lm at nominal driving currents of 350 mA, with 120° Lambertian emission, reduced down to 22° by proper low cost plastic lens.

The DMT signals were generated by a PC and an arbitrary waveform generator (AWG). They consisted of N = 512 subcarriers within a baseband bandwidth of B = 220 MHz (429 kHz subcarrier spacing). Bit and power loading was applied on N-1 subcarriers, in order to adapt the individual carrier loading to the channel signal to noise ratio (SNR).

The gross data rate includes the cyclic prefix (3%) and the training sequence (2%). FEC overhead of 7%[6] should also be considered, leading to a total aggregate value of 12%.

The DMT signal generated by positive output of port 1 of the AWG was used to modulate the channel under test. In lack of four independent outputs, the negative output of the port 1 and the two outputs of the port 2 (positive and negative) were used to modulate the other three LEDs. In port 2 a similar DMT signal with

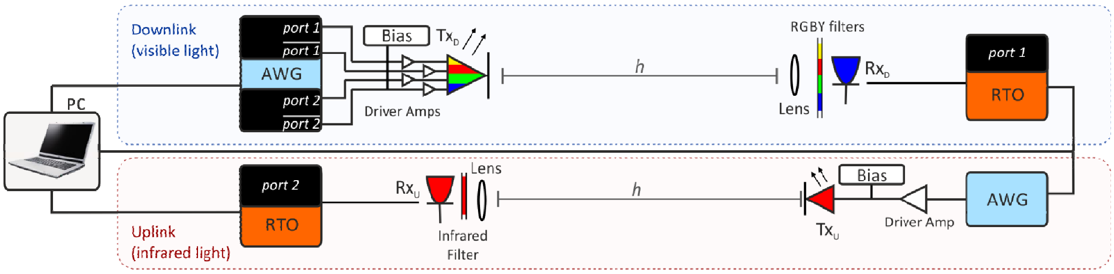

Fig. 1: Block diagram of the experimental setup of the VLC system. AWG: Arbitrary waveform generator; RTO: Real Time Oscilloscope.

different bit stream was loaded.

The four AWG outputs were amplified by means of four identical power amplifiers (Minicircuits, 25 dB gain, 29 dBm minimum output power at 1-dB compression, 130 MHz 3 dB bandwidth), superimposed on the dc bias currents and used to drive the LEDs. At the receiver side (Rx_D), a lens (Thorlabs, 50 mm diameter) was used to collect the light onto an ac-coupled analogue avalanche photodiode module (Hamamatsu APD, 0.42 A/W responsivity at 620 nm and gain = 1) having 3.14 mm^2 active area and an integrated transimpedance amplifier (280 MHz 3-dB bandwidth). In order to test each color separately a proper optical dichroic filter was mounted in front of the photo-detector at the Rx_D (the spectral emissions of the LEDs and the respective bandpass filters are shown in Fig. 2). Finally, the received signal was recorded by a real-time oscilloscope (LeCroy, 2 GSa/s sampling rate) for offline post-processing.

The uplink was similarly realized, but here we used as transmitter source (Tx_U) an IR-LED emitting at 850 nm (0.6 W optical power at 160 mA bias current) with 130° Lambertian emission. No optical lens was used for the uplink source. The IR-LED was specified compliant with the eye-safety standards[7] also at his maximum bias current (1 A). The uplink signal was received by the same APD used for downlink. We used a high-pass filter (805 nm edge wavelength) and the optical lens in front of Rx_U. The Rx_U output was than acquired and stored by the RTO for offline demodulation.

System characterization

The bipolar DMT signal is very sensitive to nonlinear distortions because of its large dynamic range. Moreover, the LEDs have nonlinearity due to the exponential behavior of current-voltage characteristics and of the nonlinear characteristics of the output power as a function of the input current. The overall distortion levels can be controlled by changing the input power and the bias current of the LEDs. In Fig. 3 we present the achievable bitrate as a function of the electrical power of the DMT signal for different values of applied bias current. The chosen value of current and signal power for each LED is highlighted with a circle. The LEDs (especially the green) showed a wide range of optimal working bias, then we chose the bias currents that reduce color tendencies of the overall white.

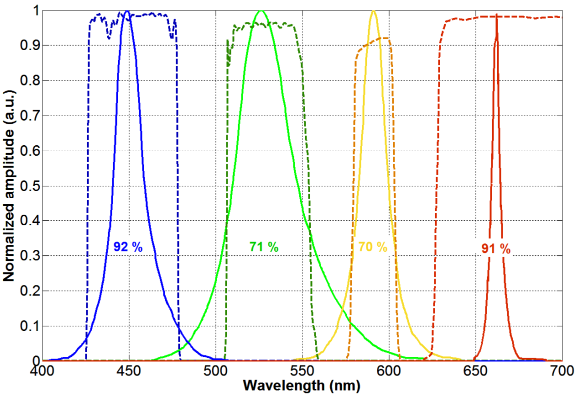

Fig. 2: Normalized optical spectra of the LEDs used for the downlink experiment with the corresponding optical filters. The percentages values represent the transmittance of the filters.

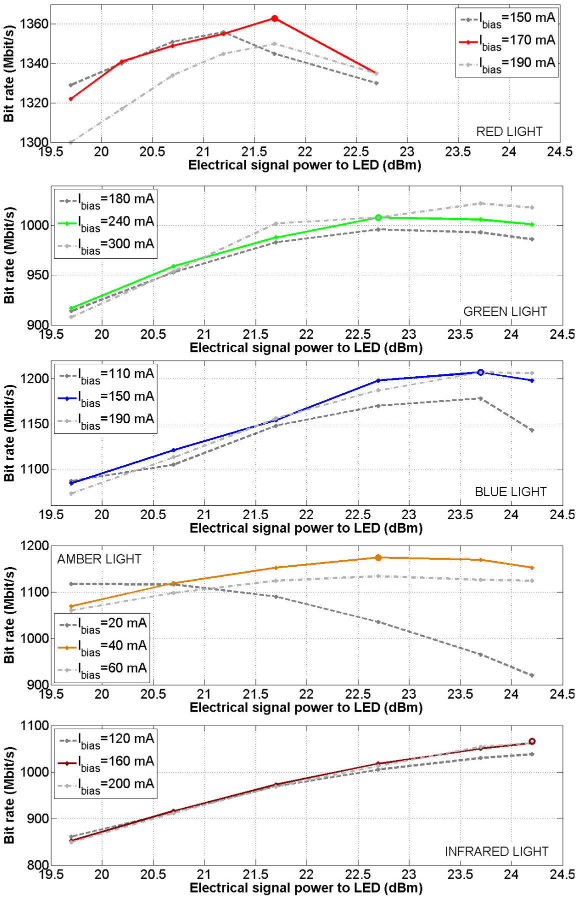

Fig. 3: Achievable bitrate as a function of the electrical signal power to the LEDs for different bias currents.

This analysis gave us the optimum working conditions for red (170 mA, 21.7 dBm), green (240 mA, 22.7 dBm), blue (150 mA, 23.7 dBm), amber (40 mA, 22.7 dBm), and infrared (160 mA, 24.7 dBm).

In order to characterize the WDM system, we also performed cross-talk measurements. We assessed the decrease of bitrate when the others channels were switched on. The measured cross-talk was found to be not null only for the amber channel, where the bitrate decreases by 3%. For the other channels the cross-talk had no noticeable effect. These cross-talk values are a direct conclusion of the overlap areas of the optical spectra between adjacent channels (see Fig. 2). Among those, the only significant area is that one where the 2% of the green light pass in the amber filter.

Transmission experiment

Once the system was characterized and optimized, a bidirectional transmission could be demonstrated. We experimentally evaluated the system performance in terms of bit rate at different distances, ranging from 1.5 m to 4 m, with illumination levels in the range (approximately) from 720 lx to 120 lx respectively. In Fig. 4 we report the maximum transmission speed of such downlink channel WDM as function of the distance. The corresponding illuminance levels are also reported in the secondary X axis. The different performance of the four channels follow the receiver responsivity, which is higher for the red and lower for the blue light. Moreover the green and the amber channels suffer from the higher losses of the corresponding band-pass filters.

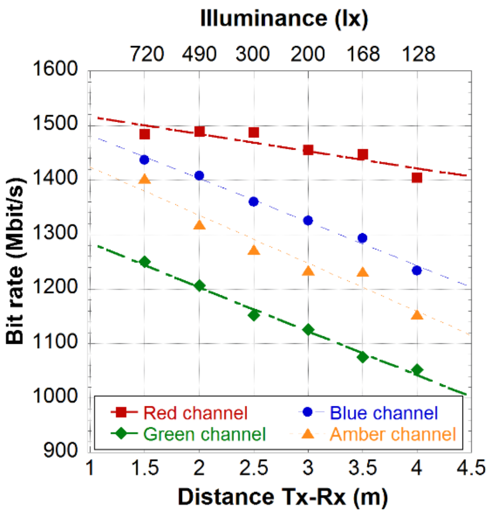

Fig. 4: Achievable downlink bitrates as a function of the Tx-Rx distance for the single channels.

We summarize these results in Fig. 5 where we report the total downlink bitrate (black squares) together with the uplink bitrate as a function of the distance. A total downlink data rate ≥ 5 Gbit/s is achieved for distance ≤ 3.5 m (168 lx), with a maximum of 5.6 Gbit/s at 1.5 m (720 lx). On the other side, the uplink data rate ranges from 1.1 to 1.5 Gbit/s passing from 4 m to 1.5 m (see Fig. 5, red diamonds). Although the uplink transmitter source was not equipped with a lens in order to reduce the beam divergence, the performance is similar to the downlink of one WDM channel, due to the better responsivity of the receiver at this wavelength.

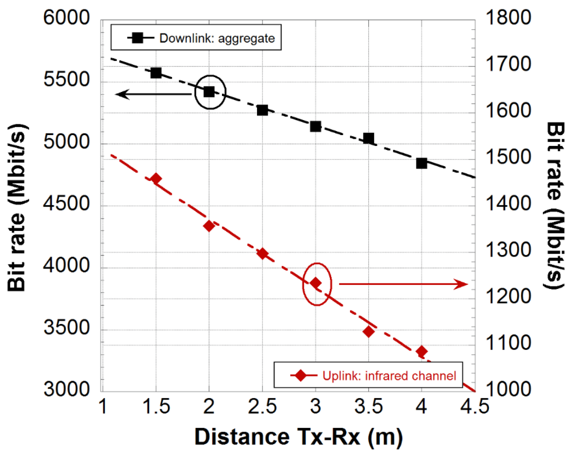

Fig. 5: Achievable bitrates for downlink (left axis) and uplink (right axis) as a function of the Tx-Rx distance.

Conclusions

In this paper, we proposed and experimentally demonstrated a bi-directional high-speed VLC system based on WDM and DMT modulation (with offline processing) of a custom RGBY LED source.

For the first time, record capacities of 5.6 Gbit/s (downlink) and 1.5 Gbit/s (uplink) were achieved. The resultant bit error ratios (BERs) in all the channels were below the forward error correction (FEC) limit[6] of $3.8 \cdot 10^{-3}$. Mostly we outline that this result was obtained at common indoor distances, maintaining illuminance levels within the standards of working environment.

Acknowledgements

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