Wireless High-Speed Data Transmission with Phosphorescent White-Light LEDs

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Abstract *Wireless transmission exceeding 100 Mbit/s is demonstrated using a phosphorescent white-light LED in a lighting-like scenario. The data rate was achieved by detecting the blue part of the optical spectrum and applying discrete multi-tone modulation.*

Introduction

White-light LEDs are expected to become a major player in the future lighting market. So far, the opportunity of modulating their light emission for communication purposes remains untapped. Available modulation bandwidths lie in the MHz range [1-2] and white-light LEDs might thus serve for illumination and data transmission simultaneously, as illustrated in Fig. 1. Advantages would be the inherent low investment and maintenance cost due to the dual-use scenario; virtually zero interference with radio-frequency wireless communication; and the potential to spatially recycle the modulation bandwidth in pico- and femto-cells (due to the pronounced directivity of light and the highly efficient shielding by opaque surfaces). This technology has mostly been subjected to theoretical studies [1, 3] and a thorough experimental proof and assessment are still pending.

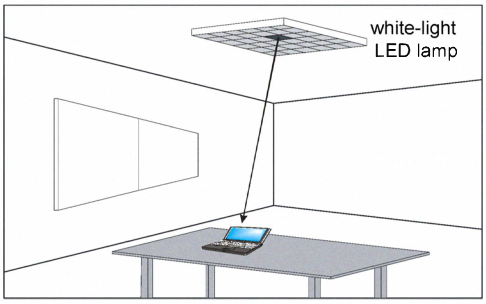

Fig. 1. Data transmission and illumination scenario from a white-light LED lamp to a laptop.

Here, we present such investigations for phosphorescent white-light LEDs. We chose this type in contrast to the triple-chip RGB type due the market dominance of the former. As observed by Grubor et al. in [1], their disadvantageously small modulation bandwidth can be increased from 3 to 20 MHz when detecting only the blue part of the emitted spectrum. We evaluated the potentials of blue filtering with simple experiments, considering first high-speed OOK transmission at 40 Mbit/s and then further improving the transmission rate beyond 100 Mbit/s by the use of discrete multi-tone modulation (DMT) [4].

Experimental Setup

Our setup is shown in Fig. 2. A white-light LED with a luminous intensity of 18 cd and a 15° full opening angle at 50% maximum intensity was used. The distance between LED and detector was chosen to be 1 cm, so that the illuminance in front of the blue colour filter (passband 300-500 nm) was ~ 700 lx (corresponding to an irradiance of 3 W/m^2), which lies well within the range of 200-800 lux for office areas, as stipulated by standard [5]. In a lighting scenario, this distance would naturally be much larger (some meters) due to the higher total luminous intensity rendered through a multitude of chips (as in Fig. 1).

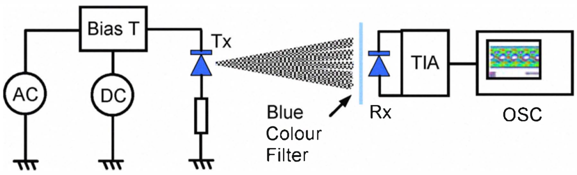

Fig. 2. The combined output from an AC and a DC voltage source is supplied to an LED. The light is detected by a PIN diode, either through or without a blue colour filter. The amplified (TIA) diode output is recorded by a real-time storage oscilloscope (OSC).

The DC component of the driving current was combined with the AC component from either a pattern generator (in the case of OOK) or an arbitrary wave-form generator (ARB; in the case of DMT) by aid of a bias tee. In order to provide sufficient modulation power the output of the ARB was additionally amplified and low-pass filtered before being combined with the DC component. As detector served a PIN diode with an integrated trans-impedance amplifier (TIA), and the output from this detector was additionally amplified and low-pass filtered (30 MHz) before being recorded with a real-time storage oscilloscope (100 MS/s).

Results and Discussion

For the first demonstration, 2^9-1 (PRBS9) pseudo-random bit sequences from a pattern generator were modulated onto the AC current with OOK at 40 Mbit/s, and the transmitted light was detected without and with the blue optical filter. Such fairly short PRBS sequences are appropriate for line-coded transmission, like, e.g., Ethernet. The modulation depth of the optical signal was 25% and was limited by the maximum output power of the generator. Without the filter (Fig. 3a), the signals were completely distorted due to the low modulation bandwidth of the emitted light (~ 3 MHz). In contrast, blue-filtering resulted in clearly visible eye openings (Fig. 3b). The prevalent high SNR (>> 20 dB) ensures a clear visibility of the partially closed eye. This opening could of course be further improved by increasing the modulation depth.

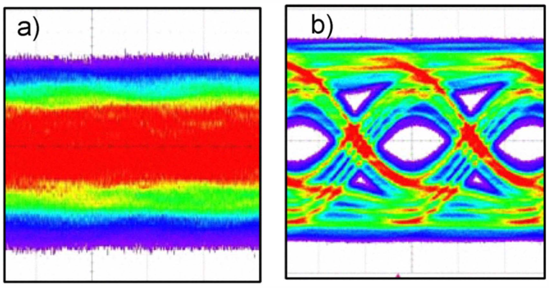

Fig. 3. Persistence plot of eye diagrams for the received PRBS9 sequences at 40 Mbit/s (abscissa: 10 ns/div); (a) without and (b) with blue filter.

For the second experiment, software generated random sequences were used for 32-QAM modulation on a 32-sub-carrier DMT signal. The time traces were then loaded into and output by the ARB. We chose DMT over simpler multi-level modulation schemes, like pulse-amplitude modulation, since it offers a higher efficiency than PAM, [1], and since the carrier spectrum can be adapted to minimise potential interference from, e.g., fluorescent light bulbs. Of the 32 sub-carriers, the first (DC) and last one (poor SNR) were not modulated. The carrier spacing was 0.781 MHz, the used transmission bandwidth 24.2 MHz, and the gross data rate 117.2 Mbit/s. The rather strong attenuation of carriers at higher frequencies was compensated by pre-emphasising their modulation, as can be seen in Fig. 4a. Figure 4b depicts the superimposed constellation diagram of all received sub-carriers. The individual constellation points are clearly discernible, which is reflected in the overall low bit-error ratio (BER) per carrier, as displayed in Fig. 4c. For this 200 000 DMT symbols were transmitted and received, equalling 30 Mbit in total. Because the serial input data is transmitted in parallel on 30 sub-carriers, the total BER of the DMT transmission system should be averaged from all 30 sub-carriers and is calculated to be $8 \cdot 10^{-5}$. Using a standard Reed-Solomon (255, 239) forward error correcting code will result in a total system BER below 10^{-14}.

From the above gross data rate one needs to subtract the following overheads: 7% for FEC, 6.3% for the cyclic prefix and 2% for pilot symbols, which leaves us with a net data rate of 101 Mbit/s.

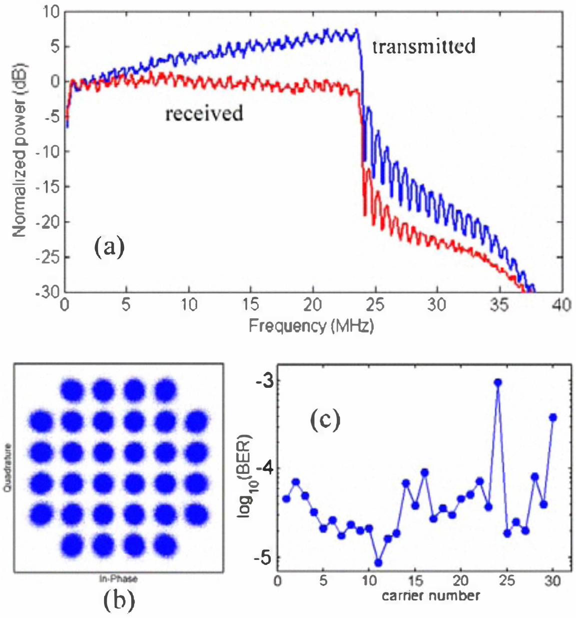

Fig. 4: Experimental results for 32-QAM DMT modulation. (a) Electrical spectrum of the signal supplied to the LED and of the received signal. (b) Constellation diagram of all sub-carriers superimposed on each other. (c) Bit-error ratio (BER) for the individual sub-carriers (circles).

Conclusions and Outlook

We demonstrated high-speed wireless data transmission by modulating and directly detecting the output from a phosphorescent white-light LED in a lighting-like scenario. Due to an increase in modulation bandwidth when detecting only the blue part of the emitted spectrum and a prevailing high optical SNR (>> 20 dB), OOK at 40 Mbit/s was successfully demonstrated. Further increase of the data rate beyond 100 Mbit/s was shown by aid of multi-level modulation on DMT sub-carriers. The development of modulated LED lighting systems is currently under way and we anticipate achieving a gross data rate of 125 Mbit/s (Fast Ethernet) for a realistic lighting scenario in the near future.

References

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5 http://www.on-light.de/din5035.htm