230 Mbit/s via a Wireless Visible-Light Link based on OOK Modulation of Phosphorescent White LEDs

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Abstract: We report a first indoor wireless visible-light link operating up to 230 Mbit/s by use of on-off-keying and with bit-error-ratios below $2{\cdot}10^{-3}$. The results were achieved for illuminance levels recommended by lighting standards.

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1. Introduction

Novel high-power white light-emitting diodes (LEDs) are a major candidate for the future lighting market. The potential synergy of illumination and data transmission functions by use of one optical source has stimulated numerous research and development activities [1]. Visible light communications (VLC) technology has many attractive assets, such as worldwide available and unlicensed bandwidth, non-interference with radio bands, and the potential of spatial reuse of the modulation bandwidth in adjacent communication cells. On top of these, and due to an ubiquitous lighting and signaling infrastructure, VLC may offer an additional service at comparably low extra cost. An overview of the technical constraints and challenges for VLC links can be found elsewhere [1].

Typically, commercially available white LEDs are based on a blue LED covered by a phosphor layer. Slow response of the phosphorescent component limits the modulation bandwidth of these devices to the lower MHz range. In our previous work, we have shown that the bandwidth can be enhanced by at least an order of magnitude if the phosphorescent portion of the optical spectrum is suppressed before detection, revealing the potential for high data throughputs (hundreds of Mbit/s) in indoor environments [2].

First experimental demonstrations showed 40 Mbit/s with on-off-keying (OOK), but also higher data rates (100 Mbit/s) when using spectrally efficient modulation such as discrete multitone (DMT) [3]. Most recent demonstrations using OOK modulation considered combining the “blue-filtering” with analogue equalization at the receiver to achieve 100 Mbit/s [4] and 125 Mbit/s [5]. In parallel, with the use of DMT signals and offline signal processing, 200 Mbit/s were demonstrated [6].

In this paper we report a first demonstration of a visible-light link with OOK operating at 230 Mbit/s with use of an avalanche photodiode (APD) and 125 Mbit/s with use of a PIN diode, both without equalization. The resultant bit-error-ratios (BERs) were below $2{\cdot}10^{-3}$, which is within the limits of standard forward-error-correction (FEC) mechanisms.

2. Experminental Setup

The experimental setup is shown in Fig. 1. The output signal from the pattern generator was amplified (in order to increase the LED modulation depth) and then superimposed onto the LED bias current by aid of a bias T. The output was directly supplied to the LED module. The light source was a commercially available phosphorescent white LED module (Ostar E2), devised for lighting applications. This module consists of four chips, providing a luminous flux of ~250 lm (at 700 mA dc) and a 130° full opening angle at 50% maximum intensity.

All the experiments have been performed under the condition of a desired brightness level (illuminance) in front of the receiver. Illuminance values were chosen in agreement with the lighting standard for the working environment [7], and realized by setting an appropriate length of the wireless link. Brightness levels were checked by a light-meter placed directly in front of the receiver in the dark laboratory (light coming only from the LED lamp). Deployment of a single lamp in the experiments resulted in relatively short link lengths (see Table 1). Nevertheless, as previously shown in [5], the illuminance at Rx is the most relevant design parameter (given that the primary function of these LEDs is lighting), not only for illumination but also for transmission performance. In a practical indoor scenario with Tx-Rx distances of several meters, the specified brightness levels needed for illumination are achieved by using several LED modules.

The ac-coupled analogue receiver consisted of several key components. An optical short-pass filter with a cut-off wavelength of 500 nm (“blue filter”) was mounted in front of the photodiode to suppress the phosphorescent component of the white light. In measurements, two commercially available large-area silicon detectors were considered. One was an APD (C30872 by RCA Electro Optics, 3 mm diameter) combined with a glass lens (0.5 NA and 8 mm focal length), and the other a PIN diode with an integrated polymer lens providing a wide field of view (~70°) and an effective area of about 100 mm² (S6968 by Hamamatsu). After detection by the APD, two low-impedance amplifiers (see Table 1) were used to bring the signal level up to the operation range of the error detector. On board with the PIN detector, there was a low-noise transimpedance stage and a post amplifier. The gain of the connected amplifier was 6 kΩ and the 3-dB-bandwidth about 67 MHz at an equivalent input voltage noise power (NEP) of 0.23 nW/$\sqrt{\text{Hz}}$. Thus, for this configuration, only one additional amplifier (see Table 1) was used to reach the range of the error-detector. After detection and amplification, the signal was filtered by a high-order low-pass filter, having a cut-off frequency of 150 MHz (APD) and 100 MHz (PIN). Finally, BER was measured and the corresponding eye-diagrams were recorded on an oscilloscope.

For both detector types, we have performed BER measurements as a function of data rate and illumination level at Rx. NRZ data carrying pseudo-random bit sequences (PRBS 2^{23}-1) was provided by a signal generator. The output of the amplifier, set to 4 Vpp amplitude, was fed to the LED (via bias-T). To achieve the best results, in the case of the APD-based Rx, an LED dc of 500 mA was used, which corresponded to a modulation index of about 4%, whereas for the PIN-based Rx, the LED dc level was set to 300 mA, resulting in a modulation index of about 6%. These values are relatively low due to the impedance mismatch between pattern generator/amplifier output and LED. All differences between setups for the two Rx configurations are given in Table 1.

Furthermore, we measured the magnitude of the channel frequency-response characteristic, for both Rx configurations. The same experimental setup was used, except that a function generator replaced the pattern generator and that the filters were omitted in these measurements (Fig.1). The input amplitude of a sine wave provided by the function generator was varied and the output amplitude was observed at the oscilloscope.

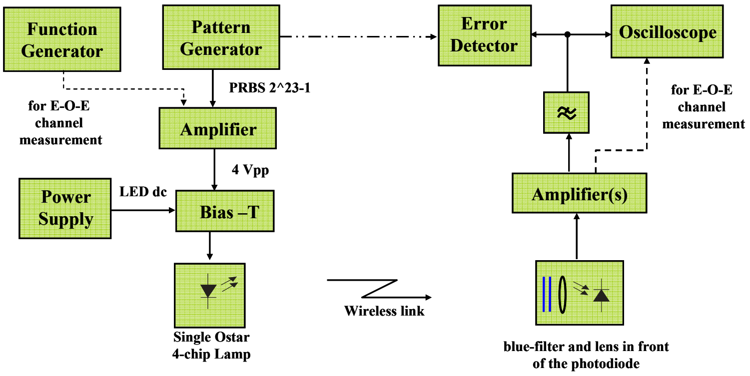

Fig. 1. Experimental setup for bit-error-ratio measurements, and for the E-O-E channel measurement.

Table 1. Setup differences for two Rx configurations considered.

Rx-Configuration	APD-based	PIN-based
LED bias (dc)	500 mA	300 mA
Modulation index	~ 4 %	~ 6 %
Link length for 400 lx	~ 44 cm	~ 39 cm
Link length for 1000 lx	~ 27 cm	~ 22 cm
Filter cut-off frequency	150 MHz	100 MHz
Amplifiers after detection	pA4-00125-76 (Pico-Amps) SHF74A (SHF Design)	SAG TIA SHF74A (SHF Design)

3. Results and discussion

In Fig. 2, we present the measured magnitude of the E-O-E channel frequency response, for the two considered Rx configurations. Since both receivers have significantly large bandwidths (PIN-based Rx ~67 MHz, APD-based Rx ~200 MHz), it can be concluded from the figure that the system bandwidth is limited by the LED. In both cases, the 3dB frequency is ~35-40 MHz.

Figure 3a presents the results of BER measurements when the data rate is varied. The two receiver configurations are differentiated by open and filled markers, and the two chosen illuminance levels by color and shape of the markers (blue circles for illuminance of ~400 lx and red squares for ~1000 lx in front of the Rx). With the PIN-based Rx, 125 Mbit/s are achievable (at 1000 lx) within the FEC limit ($2\cdot10^{-3}$), whereas, 200 Mbit/s at 400 lx and even 230 Mbit/s at 1000 lx were demonstrated with the other Rx-configuration primarily due to the enhanced sensitivity of the APD receiver. Two illustrative eye-diagrams are presented at the side of the BER graph. Figure 3b depicts the BER performance when the illuminance at the receiver is varied. Three data rates are considered with the APD configuration (100, 150, 200 Mbit/s) and one (100 Mbit/s) with the PIN Rx. The shape of the plots reveals an error floor for high illuminance levels, which arises earlier for higher data rates. Such error floor was already observed in independent measurements [5], and is a result of some pattern effects due to the limited system bandwidth (it does not occur for short patterns, e.g., 2^7-1). Interestingly, one can observe that with the APD configuration, 150 Mbit/s can be achieved even at 200 lx illumination, which is just about enough to recognize the book title on a shelf. Moreover, 100 Mbits/s are possible under an even lower level of 100 lx.

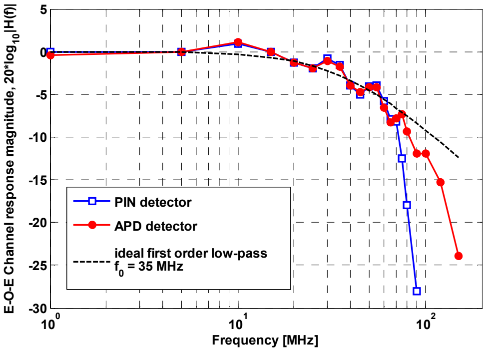

Fig. 2. Measured magnitude of the E-O-E channel frequency response.

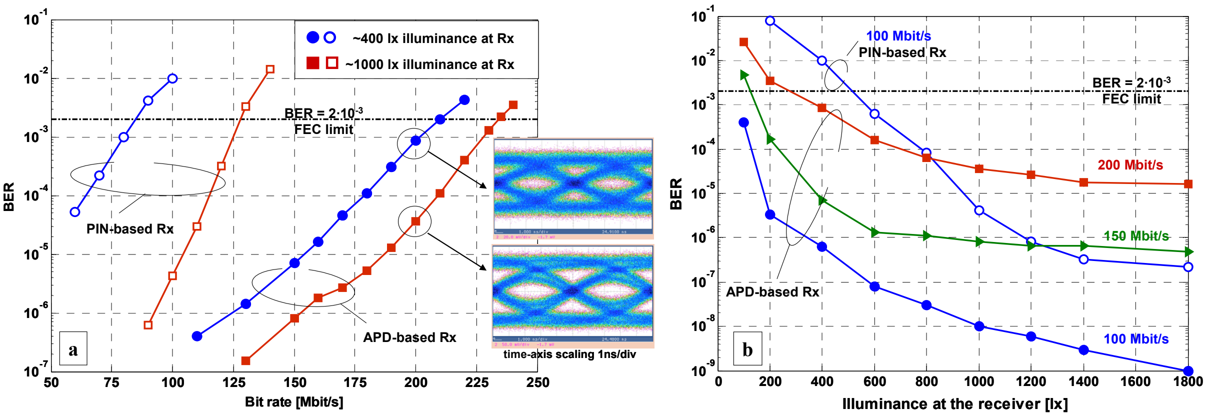

Fig. 3. a) Measurement of the bit-error ratio for two Rx structures depending on the bit rate. b) Measurement of the bit-error ratio for two Rx structures depending on the illuminance level at the Rx.

4. Summary and conclusion

We demonstrated for the first time an indoor visible-light link based on commercially available phosphorescent white LEDs operating up to 230 Mbit/s. OOK was used and the distance between transmitter and receiver units was varied according to a desired illuminance level (specified by the lighting standard for home and office environment) in front of the receiver. The resultant BERs are sufficiently low to be compensated by a standard forward-error-correction mechanism. Even higher data rates can be achieved by use of pre-distortion or equalization.

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