Influence of on-off keying duty cycle on BER in wireless optical communication up to 75 Mbit/s using an SPAD and a RC LED

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Abstract—**In this paper we analyze the influence of the on-off keying duty cycle on the achievable bit error ratio (BER) in a optical wireless communication (OWC) system which employs a single photon avalanche diode (SPAD) based receiver and a red LED transmitter as a source. In a line of sight (LOS) channel configuration at a transmitting distance of 3 m the bit error rate (BER) improvement is demonstrated by varying the duty cycle of return to zero (RZ) line coding at 50 Mbit/s. Compared to NRZ line coding at the same transmitting distance and data rate the BER improvement is almost up to an order of magnitude lower when RZ coding is used. The reached BER values are below the limit for forward error correction (FEC) thus promising the increase of the maximum achievable transmission distance. Additionally, the BER improvement allowed the transmission below FEC limit over 3 m at an increased data rate of 75 Mbit/s.**

Keywords—optical wireless communication, integrated SPAD receiver, LED transmitter

I. INTRODUCTION

Power efficiency and pervasive networking have been strong driving forces in developing technologies. This is underlined by the need for communication capabilities of mobile devices as well as immobile devices in households and industry. In order to fulfill these ever increasing demands lightweight energy-efficient communication systems are needed that can complement existing wireless fidelity (Wi-Fi) technology. In recent years a light fidelity (Li-Fi) technology surfaced as a promising area of wireless optical communications offering inherent security, immunity to electromagnetic interference (EMI) and high bandwidth [1]. Li-Fi involves transmission of visible light via LED sources which depending on the application could be potentially used at the same time as an indoor light source. The limited modulation bandwidth of LED light sources is a major problem especially in low cost applications. Despite this they are a first choice in many visible light communication (VLC) systems due to their high optical powers and power efficiency [2].

A great attention is paid to the optical receiver side in VLC. Since the receiver must offer high sensitivity and operate in the presence of ambient light, the design is very challenging. An integrated solution is a preferred choice, since it can offer system-on-a-chip (SoC) capabilities and smaller area. A novel approach for optical receivers that could be used in some VLC applications has been pursued in research recently [3-5]. A single photon avalanche diode (SPAD) receiver has an avalanche photodetector biased above its breakdown voltage, where a detection of one out of a few photons can trigger a self-sustaining avalanche response. The self-sustaining avalanche is stopped by a quenching circuit which biases the APD below the breakdown voltage for a short period of time and restores it afterwards. The conventional linear APD receiver is limited by the noise of electrical circuitry and the excess noise of the APD, while the SPAD receivers do not operate in linear region and have a very large gain which results in a signal level that can overcome the above mentioned noise sources. The SPAD receivers do not need standard high gain analog circuits for postamplification, instead SPAD receivers are usually digital circuits. For these reasons the SPAD receivers are promising to decrease the number of necessary photons for optical detection and to reduce power consumption. However, the SPAD based receivers have their own set of limiting factors such as dark count rate and afterpulsing [6] which require an SPAD receiver to remain in an idle state i.e. below breakdown voltage, for a predetermined amount of time. The resulting dead time of an SPAD (quenching and recovery time) limits the counting rate in this kind of receivers. In order to combat these effects an array of SPADs has been proposed [7]. In such an array, if one of the SPAD pixels finds itself in the idle mode, at the same time the other pixels could still be operative. The optimum size of an array is influenced by the optical crosstalk [8]. The optical crosstalk is a major drawback affecting SPAD arrays and it arises from the hot-carrier-induced photon emission in silicon i.e. the SPAD itself emits secondary photons. These photons can trigger false detection in neighboring SPADs.

In this paper we are using an SPAD based receiver and a red RC LED source in a line of sight (LOS) optical wireless communication similar like in our previous study [9] where we varied the transmission distance at a data rate of 50 Mbit/s NRZ, except now we fixed the transmission distance at 3 m and varied the duty cycle of RZ line coding at two different data rates in order to observe the BER dependence. The paper is

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organized as follows. The used 4-SPAD array receiver and LED transmitter are described in Section II and Section III, respectively. In Section IV the measured results of the BER improvement will be shown by using different RZ duty cycles at 50 Mbit/s and 75 Mbit/s. Concluding remarks are given in Section V.

II. SPAD RECEIVER

The integrated 4-SPAD array receiver was developed in a 0.35 µm PIN-photodiode CMOS process and has a photodiode diameter of 200 µm (divided in four parts) and a fill factor of 53 %. The characterization of the receiver was done in [10] using a fiber coupled 635 nm laser source with an extinction ratio above 100. The receiver reached sensitivities of –51.2 dBm in NRZ coding at 50 Mbit/s and –53.7 dBm in RZ coding at 50 Mbit/s. In the following OWC measurements the 4-SPAD array receiver is unlensed and placed in a shielded box with small opening for an interference filter to reject ambient light.

III. LED SOURCE

For the LED source we used a 650 nm resonant cavity light emitting diode (RC) LED which was housed in a Firecomm's package that provides integrated optics to focus the light beam. The LED is capable to operate up to data rates of 250 Mbit/s. A laser driver from Mindspeed (MC2042-3) was used to drive the LED with 30 mA which gives a total average optical power of 1.1 mW. In front of the LED an aspherical lens was added to further collimate the beam, see Fig. 1.

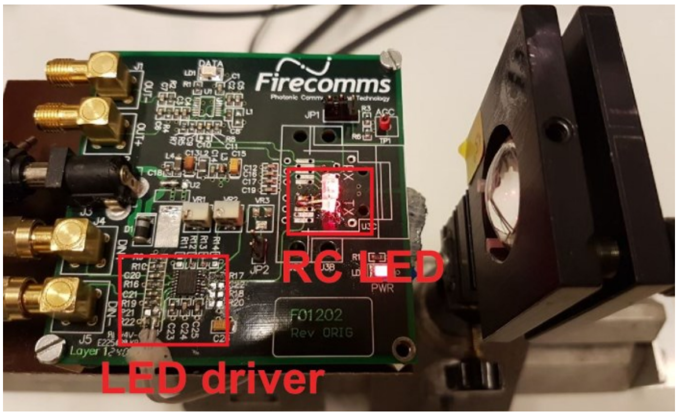

Fig. 1. Firecomms's development board with RC LED source and collimating optics

The LED extinction ratio was measured using a DC coupled wideband linear PIN photodetector. The LED light output was coupled via a plastic optical fiber (POF) to the PIN receiver. First the output of the PIN detector was recorded on an oscilloscope without the LED input signal. This resulting output signal level was then averaged and taken as an offset (necessary due to ambient light). After this, the output from the PIN detector was recorded with the input signal from the LED, the resulting pulse shape when the offset is subtracted is shown in Fig. 2. The high voltage level was taken at its peak, and the low voltage level is averaged over the slice marked in red, the extinction ratio is calculated as the ratio of these two voltages and its value is 195.

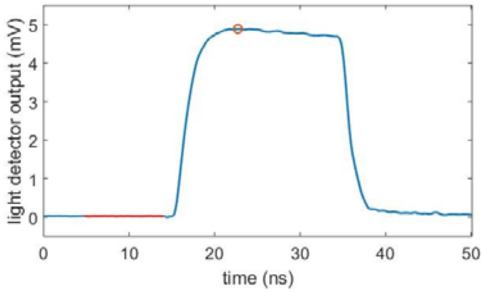

Fig. 2. LED pulse shape at 50 Mbit/s NRZ, I_{LED} = 30 mA

IV. MEASUREMENTS

In our previous study [9] the 650 nm LED source was pointed to an optical mirror to double the transmission distance (because of the small size of the laboratory) and the beam was aligned with the filter opening inside the shielded box in which the 4-array SPAD receiver was placed. The maximum achieved transmitting distance was 5 m when a 50 Mbit/s NRZ coding was used. This performance was maintained even at high ambient light levels up to 2000 lux. During these measurements the APD substrate voltage (Vsub) was varied at each distance in order to achieve the optimum working point. At the same time during the digital signal postprocessing in MATLAB the outputs of the four SPADs were summed and the threshold was varied to determine the optimum number of channels to obtain the lowest BER value. By taking the optimum substrate voltage and number of channels at each distance give us the highest range of working distances spanning from 1 m to 5 m [9]. However we would need to adjust the operating substrate voltage at each distance. If we would fix the substrate voltage Vsub for the optimum at the maximum transmitting distance of 5 m, which is –26 V, the dynamic range would span from 1.5 m to 5 m, see Fig. 3. The step size of 1 m was chosen due to time consuming alignment of receiver and transmitter when using an optical mirror to reflect the beam.

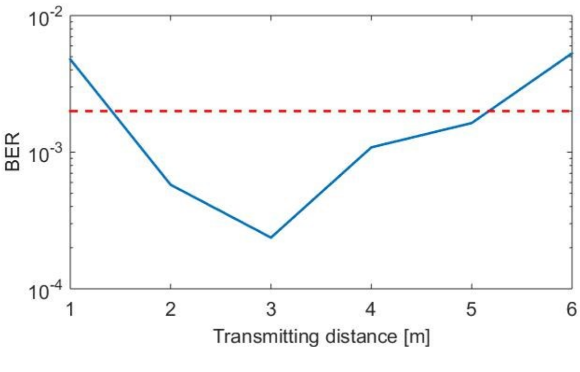

Fig. 3. BER vs. transmitting distance for a fixed Vsub = –26 V at data rate 50 Mbit/s in NRZ

We can see from Fig. 3 that the lowest BER ($2.4 \cdot 10^{-4}$) is achieved at 3 m and it is well below the limit of $2 \cdot 10^{-3}$ (red line)

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which is needed for forward error correction (FEC). Since the 3 m distance leaves the largest margin for BER we decided to test at this distance the influence of the different duty ratios at two different data rates (50 Mbit/s and 75 Mbit/s). For this measurement setup we did not use the Thorlabs mirror as it was done in [9]. Instead, the SPAD receiver and LED transmitter were placed opposite of each other, and the transmitter beam was perpendicular to the filter opening in front of the SPAD receiver. The measurement setup is depicted in Fig. 4.

A. BER vs duty cycle at 50 Mbit/s

At the data rate of 50 Mbit/s a pseudorandom sequence PRBS of length 2^7–1 was generated using a Sympuls pattern generator BPG 40G which was programmed using LabVIEW to produce different duty cycles spanning from 12.5% to 100%. Fig. 5 shows the BER dependence on different duty cycles at Vsub = –26 V which is the optimum for maximum transmitting distance at 50 Mbit/s NRZ.

As we can see from Fig. 5, the lowest BER of $8.8 \cdot 10^{-5}$ is obtained for 50 % duty cycle when 3 out of 4 SPADs needed to be triggered for a logical '1' decision. If we take a closer look at the BER curve when 3 SPAD outputs are needed, we see that as the duty ratio increases toward 100 % i.e. NRZ, the BER rises.

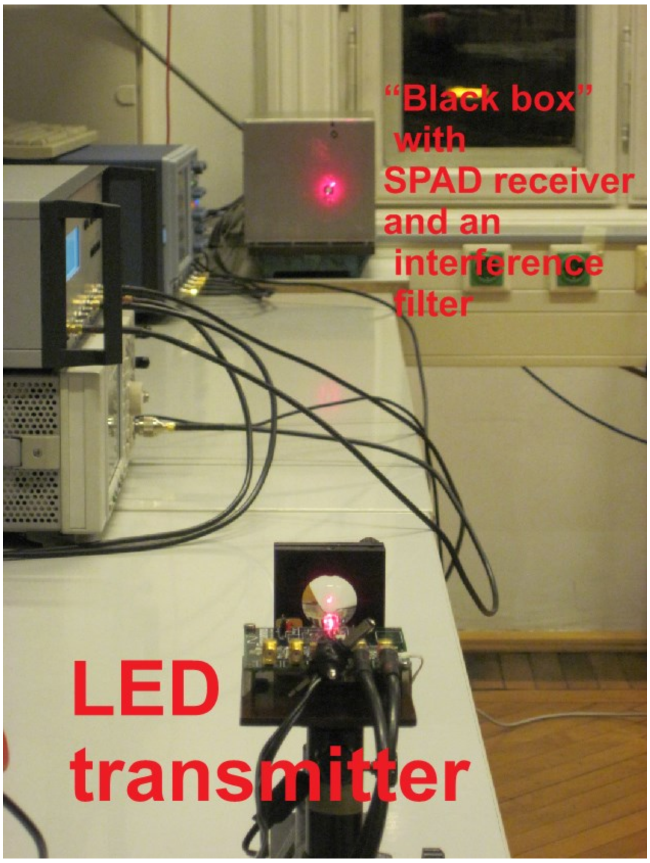

Fig. 4. Measurement setup

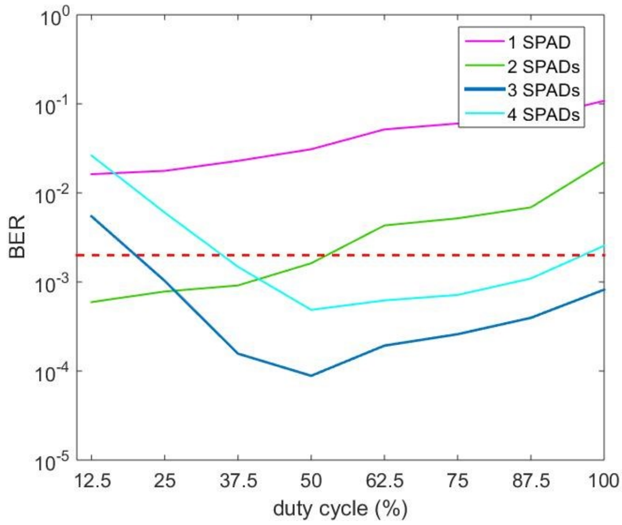

Fig. 5. BER vs. duty cycle at a distance of 3 m with 50 Mbit/s

This gives a BER improvement of almost an order of magnitude by using the RZ (minimum BER = $8.8 \cdot 10^{-5}$) instead of the NRZ coding (minimum BER = $8.2 \cdot 10^{-4}$). In this system setup the NRZ BER ($8. \cdot 10^{-4)}$ for 3-SPAD threshold is higher than the BER ($2.4 \cdot 10^{-4}$, minimum BER in Fig. 3) archived when optical mirror was used in the setup [9]. The small difference could be due to small changes in alignment between receiver and transmitter.

Possible explanation for BER increase with the increase of duty cycle is threefold. Firstly, during the bit period of 20 ns if a logical '1' is detected, the SPAD will become inactive during the dead time of 9 ns meaning that the transmitted optical power during this period will be wasted. As the duty cycle becomes smaller the time window in which logical '1' is transmitted becomes narrower and therefore there is no loss of photons for duty ratios below 50%. The second possibility for BER deterioration is the jitter of the SPAD i.e. the time it takes for an SPAD to react after the photon is absorbed since the photon must travel a certain time from the location of its absorption up to the multiplication zone. Due to this jitter in the NRZ signaling it can happen that the photon is detected at the end of the bit duration for logical '1' but a delayed response of the SPAD can overlap with the next bit period and cause an error if a logical zero is to be detected next. In the case of the RZ coding each bit is ending with a low logical level. The duration of this low level depends on the duty cycle and can give enough time for the SPAD to react during the given bit period. The third possibility is the limited speed of the LED source. Fig. 6 shows the transient response of a linear PIN detector coupled with a POF cable to the LED source driven at 50 Mbit/s at three different duty cycles. We can see that the falling edge of the LED has a long settling time which can make problems when a '1' bit is followed by a '0' bit. In this case the zero may not reach its low power value immediately. The 'tail' of the logical one may raise the zero level and cause a false '1' detection. As the duty cycle shortens there is more time after a logical one to settle to the zero level.

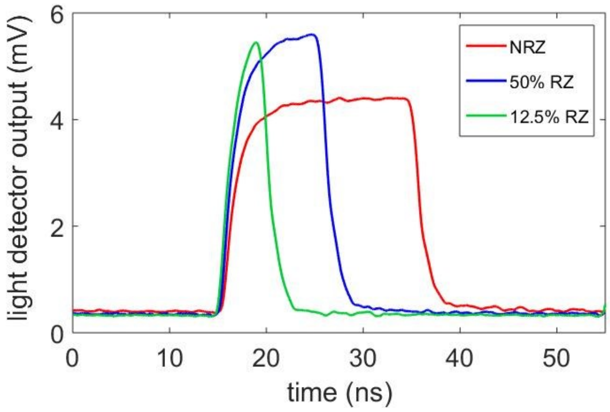

Fig. 6. LED transient response at 50 Mbit/s and different duty cycles

Another interesting behavior for the case when a threshold of 3 (or 4 detections) is used for detection is that at some point as the duty ratio decreased the BER started to increase again, see Fig. 5. Possible reason for this could be that at lower duty cycles the peak optical power is higher at logical '1' since it is located in a shorter time window, which for a given extinction ratio also results in higher logical '0' that can trigger false events. Interestingly, when one or two SPAD outputs are used the BER continues to improve as the duty cycle is decreased. However in the case when one or two SPADs are needed to "fire up" for a logical '1', their optimum working voltages were below –26 V and the BER vs. duty cycle curve shape is then similar to the case when a threshold of 3 or 4 detections in 3 or 4 of the total four SPADs are used.

B. *BER vs. duty cycle at 75 Mbit/s*

Since the BER improvement at 50 Mbit/s by using RZ line coding was quite large at 3 m of transmitting distance, we increased the data rate up 75 Mbit/s and again varied the duty cycle at a fixed substrate voltage of – 26 V. The best BER performance is achieved when a threshold of 3 SPADs is used, and the minimum achievable BER is $2.3 \cdot 10^{-4}$, see Fig. 7.

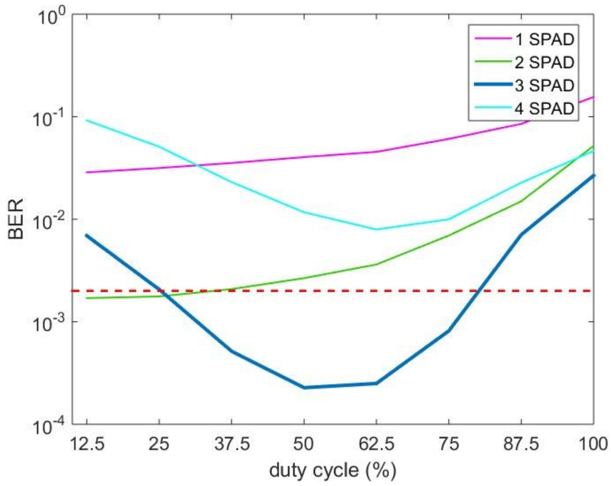

Fig. 7. BER vs. duty cycle at a distance of 3 m with 75 Mbit/s

The overall behavior of the SPAD receiver is similar like in the case of 50 Mbit/s data rate. The lowest BER curves for the two data rates are shown in Fig. 8. The 75 Mbit/s BER curve is shifted upwards which is to be expected since the data rate is increased 1.5 times and the dead time of our receiver is fixed to 9 ns. A possible explanation for the steeper slope of the BER curve for higher duty cycles at 75 Mbit/s is the smaller ratio of bit period (13.33 ns) and dead time compared to the case of 50 Mbit/s.

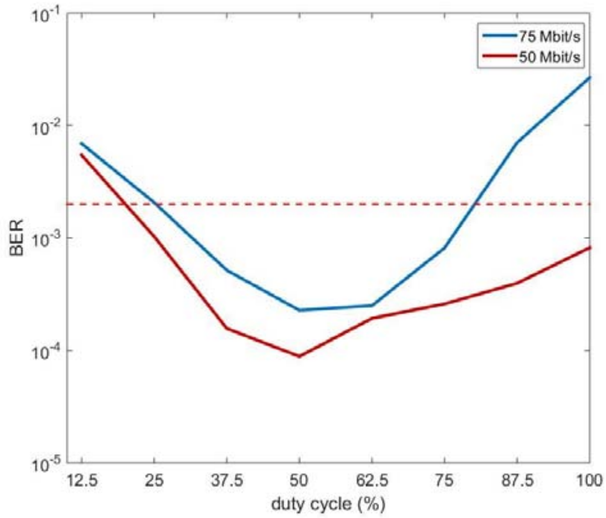

Fig. 8. BER vs. duty cycle at 50 Mbit/s and 75 Mbit/s at transmitting distance of 3 m and theshold of 3 SPADs

V. CONCLUSION

In this paper a VLC system was presented that uses a highly sensitive 4-SPAD array receiver and a red LED light source in a LOS communication at 3 m. At this distance we demonstrated the improvement of the BER by using the RZ coding and varying its duty cycle. At the data rate of 50 Mbit/s the BER improved from $8.2 \cdot 10^{-4}$ for NRZ to $8.8 \cdot 10^{-5}$ when a 50 % duty cycle in RZ was used. The measurements were performed in normal lighting conditions and the substrate voltage that biases the SPAD was fixed to the optimum for the maximum achieved distance of 5 m [9]. Since the minimum BER for FEC is $2 \cdot 10^{-3}$ the archived results promise to increase the maximum transmitting distance above 5 m, which was reached at 50 Mbit/s in [9]. At the data rate of 75 Mbit/s optical transmission using NRZ was not possible at 3 m (BER = 0.027), but by using RZ with 50 % duty cycle we reached a BER of $2.3 \cdot 10^{-4}$ which still leaves some margin that could allow for an increase of the transmission distance.

A similar data rate in VLC using an SPAD receiver was achieved in [11] where a large array of 128×32 SPADs was needed for 60 Mbit/s (divided in 3 channels with a transmitter each) at a transmitting distance of 2 m. Here we need only one transmitter for a data rate of 75 Mbit/s over 3 m and a relatively small matrix of four SPADs.

For a future work a mathematical model of the used receiver and the system that could give a complete insight into the influence of various effects on the obtainable BER should

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be developed. At the moment of writing this paper such model was not available and would go beyond the scope of this initial research. However, there is ongoing work within our group toward modeling the behavior of the used SPAD receiver.

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