Evaluation of SiPM based Optical Receiver for Low Energy Devices

Yangchun Li, and Danial Chitnis

Abstract—Silicon Photomultipliers (SiPMs) are photon-counting detectors with great potential to improve the sensitivity of optical receivers. However, its recovery time and dark count rate could limit its dynamic range that effectively detects single photons, hence limiting the sensitivity. Recent studies of SiPMs in communication focus on the speed rather than the power consumption of the receiver. The gain and bandwidth of the designed receiver circuit to read out SiPM output are much higher than required for the target data rate. Additionally, the SiPM experiments for optical communication are performed using an offline method which uses instruments including oscilloscopes and personal computers to process chunks of the transmitted data. In this work, we have developed an embedded real-time system FPGA-based platform to evaluate a commercially available 1 mm$^2$ SiPM. Moreover, simulations for investigating the relationship between the electrical bandwidth of the receiver circuit and the target data rate to achieve a target Bit Error Rate (BER) are established. The experimental results show that the implemented real-time system achieves a Bit Error Rate (BER) of $10^{-3}$ with less than 5 pW of incident optical power with an average of 11.35 photons per bit at 100 kbps under 620 nm LED, approaching the Poisson limit. It was found that the minimum receiver electrical bandwidth required to maintain the Poisson limit is 50 times higher than the target data rate. The analysis of the minimum receiver bandwidth in photon counting and BER enables the potential future adoption of this receiver technology in high sensitivity applications in underwater and visible light communications, especially for low energy devices.

Index Terms—Silicon Photomultipliers (SiPMs), Optical Communication, Photon Counting, Bit Error Rate (BER), Bandwidth.

I. INTRODUCTION

The demand for a wider communication spectrum has prompted the development of optical wireless communication, which could utilise the unlicensed spectrum in the communication link [1]. The ideal optical receiver for communication devices should have high sensitivity, low power consumption and cost, which could be reduced by integrating the electronic circuit in Application Specific Integrated Circuits (ASICs) or Field Programmable Gate Arrays (FPGAs).

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The most popular photon detectors in optical receivers are PIN photodiode [2] and Avalanche Photodiode (APD) [3]. Typically, the Noise Equivalent Power (NEP) of a PIN photodiode is restricted to the other components in the receiver, including the trans-impedance amplifier (TIA). In contrast to the PIN photodiode, an APD provides an internal gain which is closer to the photodetection stage. However, the gain-dependent excess noise increases the NEP more than the PIN photodiode. A solution to minimise this noise is operating the APD in the photon-counting mode above its breakdown voltage, and alongside a quenching resistor as a single-photon avalanche diode (SPAD) [4], [5]. However, the SPAD requires a recovery time, typically a few tens of nanoseconds, to quench the self-sustained avalanche current triggered by a photon detection event within its avalanche region of the p-n junction. Once a photon is absorbed within this region, the impact ionisation will generate the avalanche photo-current, which leads to a voltage drop and subsequent quenching of the photo-current. The challenge created by the recovery times is the non-linear response of the output events when receiving a large number of photons in a short time. One method to reduce the recovery time is implementing an array of SPADs in parallel, known as silicon photomultipliers (SiPMs) or multiple pixel photon counters (MPPCs) [6]. This type of SPAD array has been explored in a wide range of applications, including Time-of-Flight Positron Emission Tomography (TOF-PET) [7], Visible Light Communication (VLC) [8]–[12], Light Fidelity (LiFi) [13], [14] and light detection and ranging (LIDAR) [15], [16]. In recent years, CMOS SPAD arrays for optical receivers were investigated [17], [18]. Additionally, the advantages of passive quenched MPPC were demonstrated through theoretical analysis [19]. Furthermore, research proved that using SiPM as a detector in the receiver will be more sensitive than the optoelectronic integrated circuit containing an APD at 1 Gbps with $10^{-3}$ BER [9] [20].

In order to obtain the number of detected photons, a resistor is added to the anode or cathode of the SiPM to convert the total avalanche current into a measurable voltage. Hence the SiPM’s output is represented by an analogue pulse. Since SiPMs do not have a built-in photon counter, two multi-photon readout methods were developed to count SiPM pulses: voltage thresholding and summation output [21]. The voltage thresholding method is achieved by counting pulses above the voltage threshold. In contrast, the summation method is achieved by sums of the pulses and has a higher dynamic range than the voltage thresholding method [21]. Recently, to achieve higher data rates, the summation output method has
been evaluated with a larger array of SiPMs. For example, a commercially available $3.07 \times 3.07 \text{ mm}^2$ SiPM has been used to achieve On-Off Keying (OOK) data rates up to 2 Gbps at BER of $10^{-3}$ with a sensitivity of -29 dBm by using Decision Feedback Equalisation (DFE) [9]. Another experimental result shows the data rate was improved to 5 Gbps with the Orthogonal Frequency Division Multiplexing (OFDM) method at $9 \mu W$, which is equivalent to -20.5 dBm [11]. Apart from the VLC application, the scenario of Underwater Wireless Optical Communication (UWOC) has also been investigated. Recent work in this field showed that by applying the summation readout method with DFE, the data rate could reach 1 Gbps [22], which is higher than the voltage thresholding method. More recent research demonstrates the potential of using low power consumption circuits for SiPM-based UWOC systems [23] and satellite-based optical communication [24].

The previous literature showed that the summation method with DFE has the advantage of a higher OOK data rate [9], [11], [22]. However, it no longer uses single-photon counting and instead takes advantage of the relatively long recovery time of the SiPM and equalisation on its analogue output. In addition, the data rate cannot be reduced, hence operating at a specific data rate which is expected to be twice the recovery time in OOK [17]. In this case, the receiver is optimised for a specific data rate instead of a broader range required in real-world communication scenarios. Whilst the recent research has focused on improving the data rate of the receiver, the low speed requires further investigation, especially for low-energy devices, including Internet of Things (IoT) [25]. Additionally, these experimental tests were performed using offline data processing based on Arbitrary Waveform Generators (AWG) and high bandwidth oscilloscopes, which emulate a physical communication link. In the offline method, a pre-generated data set is transmitted via the link using an AWG, and the output of the SiPM is captured using the high bandwidth and sampling rate oscilloscope, which is later transferred to the PC for processing and calculating the BER. This offline method does not consider the effect of electronic circuits within a real-world transceiver. Also, the high-bandwidth instruments used in SiPM experiments for optical communication are not realistic for evaluating real-world use cases for such devices, especially in terms of power consumption of the electronic circuitry. Furthermore, due to the number of sequential steps required to process the data, achieving BER smaller than $10^{-4}$ is challenging due to a large amount of data that needs to be captured and processed.

In this paper, we investigated the feasibility of implementing a SiPM-based real-time receiver for low-energy devices in optical communication. The effect of the electronic circuits, especially noise and digital circuits timing, was analysed in system-level integration. The paper is organised as follows. Section II introduces the SiPM operation background and characterisation result. Section III contains the experimental demonstration BER result for the realtime SiPM based optical receiver. The effect of the receiver circuit bandwidth and simulation result was described in Section IV. The result discussion and future works were provided in Section V. Finally, section VI concludes this paper.

## II. SiPM Characterisation

### A. SiPM Background

In this work, the detector is a commercially available $1 \text{ mm}^2$ C-Series SiPM from On Semiconductor [26]. The technical parameters for the SiPM are listed in Table I.

When a photon is absorbed by the junction, the photocurrent generated by the avalanche event flows through a load resistor to convert the total avalanche photo-current into a measurable voltage. After the amplification, this voltage is an analogue pulse, which represents the received photon count. The incident photon energy is characterized by the wavelength of the light source and is calculated using Planck’s equation [27]:

$$E = \frac{hc}{\lambda} \quad (1)$$

Where $E$ is the energy of a photon, $h$ is Planck’s constant, $c$ is the speed of light, and $\lambda$ is the wavelength of the light source. Due to the quantum efficiency of silicon, only a certain percentage of the incident photons are detected and converted into analogue pulses. This is usually described with Photon Detect Probability (PDP) and is defined as [28]:

$$PDP (\lambda, V) = \eta (\lambda) \times \varepsilon (V) \times F \quad (2)$$

Where $\eta (\lambda)$ is the quantum efficiency of the p-n junction at a given wavelength, $F$ is the fill factor of the SiPM, and $\varepsilon (V)$ is the avalanche initiation probability, which is a function of the applied bias $V$. Then, the detected photon count is written as:

$$\lambda_s = \frac{E_{total}}{E_{photon}} \times PDP (\lambda, V) \quad (3)$$

Where $E_{total}$ is the total energy of the SiPM receiving optical power and $E_{photon}$ is the energy for a single photon, calculated from (1). Since SiPM detects single photons, its photon statistics are based on Poisson (shot noise) statistics. When a random bit sequence is transmitted, the Probability of Error (PE) is estimated using the following equation [29]:

$$PE = 1 - 2 \times \sum_{k=0}^{n_T} \frac{\lambda_s + \lambda_b}{k!} e^{-(\lambda_s + \lambda_b)} + \frac{1}{2} \times \sum_{k=n_T}^{\infty} \frac{\lambda_b}{k!} e^{-(\lambda_b)} \quad (4)$$
Where $\lambda_s$ is the number of detected signal photons per bit time and $\lambda_b$ is the number of background photons per bit time, which is calculated from (3). The background photons are counted when 0s are transmitted. However, when 1s are transmitted, the photon count includes both signal and background photons. The background photons include dark counts of the SiPM and light leakage in the measurement setup. The $n_T$ is an integer decision threshold to determine 0s and 1s, and it is always selected to achieve the best PE. Based on (4), a PE of $10^{-3}$ can be achieved by an average of 6.2 photons if there is no background photon. When the background photons are presented, more $\lambda_s$ is required to maintain the PE of $10^{-3}$, hence, a power penalty is considered. Once the practical Bit Error Ratio (BER) of $10^{-3}$ is achieved, Forward Error Correction (FEC) could be used to further improve the BER [30].

B. Experimental Configuration

To demonstrate the real-time optical receiver with SiPM, an AMD/Xilinx PYNQ-Z1 evaluation board with Zynq-7000 SoC XC7Z020-1CLG400C FPGA was chosen as the platform to characterise SiPM output pulses. Considering the peripheral connection between SiPM output and FPGA board, the PMOD interface provided by the board was used [31]. The PMOD interface was developed by Digilent Inc. for the low frequency, low I/O peripheral connections. The expected bandwidth of the PMOD interface is tens of megahertz. Since the digital signal characteristics are not specified, the maximum speed for digital SiPM pulses detection was evaluated.

Fig. 1(a) shows the experimental setup for measuring the minimum digital pulse width, which could be detected by the PMOD connector using a loop-back test. (a) experimental setup (b) the minimum pulse width of detected pulse without error.

Fig. 1(b) shows the missed pulse counts during the pulse width changes. It could be observed that the minimum pulse width of the PMOD connector detected without error is approximately 5 ns. In this condition, the pulse amplitude was tested at approximately 3.3 V, which meets the LVCMOS 3.3 V and LVTTL 3.3 V logic standards. Therefore, the expected SiPM pulse width to demonstrate the real-time receiver should be longer than 5 ns.

The offline experimental setup shown in Fig. 2 was then built to characterise the SiPM output before the implementation of the real-time setup. The transmitter consists of a Tenma DC power supply, which powers a TI voltage buffer BUF634 to drive a 626 nm LED. The optical intensity is controlled by the bias voltage of the DC power supply. On the receiver side, since the receiving light intensity of SiPM needed to be accurately measured, a Thorlabs IS200-4 integrating sphere was used to generate equal photon flux among the LED, MicroFC-10010 SiPM, and optical power meter. When the diffused light irradiates the SiPM, the measured optical power is equal to the optical power that SiPM received. The SiPM output signal was then amplified by two Mini Circuit Amplifier blocks: ZX60-43-s+ and ZFL-1000+. The average gain and maximum bandwidth of ZX60-43-s+ is 18.6 dB and 4 GHz, and ZFL-1000+ is 17 dB and 1 GHz. After the amplification, the SiPM output pulse was captured by the LeCroy oscilloscope. The internal memory of the oscilloscope allowed a maximum 10 ms waveform capture each time. When the PC remotely captures and saves sufficient waveform data from the oscilloscope, the PC analyses the data samples. During the setup configuration, the PDP and the dark counts have been calibrated to 3.5% and 30 kcps.

C. SiPM Pulses Characterization

The traditional SiPM readout depends on the resistor between anode and cathode, referred to as the standard output. In addition to the resistor, a capacitor coupling the output of each microcell was developed to obtain a shorter pulse, referred to as the fast output. Based on the setup in Fig. 2, the pulse capture and statistic were performed to evaluate whether both outputs were compatible with PMOD connectors.

Fig. 3 shows the offline processed pulse shape of a single SiPM output pulse for fast and standard outputs, with 1000 accumulated pulses displayed in the coloured histogram. In Fig. 3(a), it was observed that the amplitude of the fast output pulse was around 50 mV when the SiPM was biased at 27.5 V.
The amplitude of the standard output pulse was approximately 40 mV, which was lower than the fast output pulse, shown in Fig. 3(b). The FWHM of the fast output pulse was shorter than the standard output pulse, 1 ns versus 8 ns, which means the bandwidth of the PMOD connector is insufficient to read out the fast output pulses. In this case, the standard output was chosen to perform the real-time connection to FPGA hardware.

To convert the analogue pulse of the standard output to a readable digital pulse, a robust thresholding method was developed based on the behaviour of the electronic op-amp comparator with hysteresis. In a comparator circuit, hysteresis is applied by using positive feedback to add a control voltage between the upper and lower threshold voltages. This hysteresis minimises the electronic noise and improves the decision accuracy. Hence, the hysteresis was applied in offline and realtime processing.

Fig. 4 illustrates the offline processed Analog-to-Digital Conversion (ADC) with a single pulse waveform captured by the oscilloscope with 1 GS/s sampling rate. From this figure, the pulse’s falling edge has a long tail with a relatively large noise compared with the pulse amplitude. Under this circumstance, the wrong decision would happen if threshold voltage $V_{th}$ was lower than the noise amplitude. To develop a robust thresholding method, a 5 mV hysteresis voltage $V_{hyst}$ was added based on the amplitude of DC noise shown in Fig. 4(b). When the pulse sample amplitude is detected higher than $V_{thu}$, the next series of samples will be converted to a digital 1s until the subsequent samples are detected lower than $V_{thl}$.

Fig. 5. The output photon count when the threshold voltage $V_{th}$ varies from 6 mV to 29 mV. The detected dark count is approximately 30 kcps when the $V_{th}$ was configured as 18 mV.

**D. Dynamic Range**

To find the suitable threshold voltage $V_{th}$, a threshold sweeping was performed with a step of 1 mV. Fig. 5 shows the counting result of the sweeping threshold voltage under different SiPM received optical power. It was found that the detected photon count increased with the increasing optical power. When $V_{th}$ increased, the photon counts were independent of $V_{th}$ due to relatively fixed counts. Hence, a $V_{th}$ of 18 mV was chosen for all optical power measurements.

The measured photon count event per second at different optical power after employing threshold voltage $V_{th}$ was shown in Fig. 6. In this figure, the linear theoretical response was calculated from (3) when the calibrated effective PDP of 3.5% was applied. It was observed that when the optical power was lower, the dark count played a primary role in the measured photon count, which was at 30 kcps. When the incident power increases, the photon count response is close to linear hence approaching the Poisson limit. As the incident power further increases, the detected photon count deviates from the theoretical incident photon count due to the effects of overlapping output pulses [32]. This non-linearity limited
the effective dynamic range of the SiPM and was expected to match the paralysable dead-time model [10].

However, under saturation conditions, the results show a relatively constant non-paralysable photon count, which is due to the coupling of the SiPM output pulse to the analogue signal chain. The inset in Fig. 6 shows the waveform difference between AC and DC coupled SiPM output captured from the oscilloscope. Regarding DC coupling, the voltage thresholding method was not sustained due to the increasing offset of the pulse waveform when the photon counts are higher, hence a paralysable photon count. In contrast, the output of AC coupling oscillates around 0 V, hence a constant count. Therefore, since the amplifiers in the signal chain are AC coupled, a non-paralysable photon is expected for the offline and realtime configurations.

III. EXPERIMENTAL BER MEASUREMENT

A. Setup

The experimental setup used to investigate the realtime received photon count of varying incident light intensity and BER result is first time built and shown in Fig. 7 [33]. The digital parts of the system were developed based on the FPGA board, including clock generation, a Pseudo-Random Bit Stream (PRBS) generator based on Linear Feedback Shift Register (LFSR), an XOR comparison block, counters to count errors and photons, and a UART interface sending the counter data to a PC. To achieve reasonable signal integrity, a differential transmission was employed to connect the LED to the FPGA board.

The transmitter (Tx) PCB included a DS90LV011A LVDS differential line driver, a DS90LV012A LVDS differential Line receiver and a voltage buffer to drive the LED. The receiver (Rx) part, considering the low amplitude of the SiPM pulse, used three amplifier blocks, including one Mini Circuits ZFL-1000+ and two Mini Circuits ZX60-43-S+, were connected in series to amplify the SiPM pulse amplitude to approximately 400 mV. After the amplification, a TLV3501 comparator with a 4.5 ns response time designed on the Rx PCB was used to convert the analogue SiPM pulse to a readable digital pulse by FPGA. Although threshold voltage $V_{th}$ was selected as 18 mV in the offline processing, the $V_{th}$ of the comparator in realtime setup requires to be selected again due to the increasing noise floor after amplification of the three amplifiers.

To maintain a low power consumption, an asynchronous SiPM pulses counter was implemented in the FPGA. This asynchronous counter was triggered by the rising edge of the random pulses from the SiPM so that it did not require a high frequency clock for sampling the input pulses. However, the decision of bit 0s and bit 1s for each time slot is still required to be made by selected digital threshold $n_T$. To achieve uninterrupted realtime counting, two inter-leaved counters were implemented. When the digital pulses during one bit time arrived at the FPGA, only one counter received and counted the pulse at any time. Then, the other counter would save the counting result to the full photon counter for accumulation of whole bit counting information to calculate the BER. When the counting information was saved, the counter would be reset and wait for pulses for the next bit. Therefore, continuous pulse counting for each bit without any dead time was achieved.

B. BER Result

Before the BER measurement, the analogue threshold voltage $V_{th}$ of the comparator was swept to find the the region where counts were independent of the $V_{th}$. From Fig. 8(a), the realtime dark counts remain 30 kcps when the threshold is swept from 0.1 V to 0.3 V. These output counts matched the typical dark counts from the SiPM’s datasheet. When the SiPM incident optical power was high, the counting results also increased and maintained the real receiving photons. Based on this observation, the analogue threshold voltage was configured as 0.2 V. This is higher than offline processing $V_{th}$ due to the addition of the third amplifier.

Based on the selected threshold, we chose 100 kbps for the BER evaluation. If the data rate is too low, then the dark count is higher per bit, and it takes a long time to accumulate sufficient errors to declare a reliable BER. If a high data rate is chosen, the LED could exhibit non-ideal effects related to bandwidth and timing. The BER performance was investigated by choosing six optical power intensities to cover a range of BER between $10^{-1}$ to $10^{-6}$ at 100 kbps. Fig. 8(b) shows the bathtub curves of the digital threshold $n_T$ for each bit versus the BER result, which is expected as $H_i$.

The best BER performance was then chosen to plot for each optical power, which is shown in Fig. 8(c). The theoretical BER is calculated by $H_i$ with the average dark count of 0.316 per bit at 100 kbps, and the photon count for bit 1s is calculated by $H_i$ from the measured incident optical power. Fig. 8(d) shows the photon counts required per bit to achieve the relative target BER. The Poisson limited photon counts are calculated using $H_i$ to fit the experimental BER test result. It is observed that the tested experimental BER range almost fits the theoretical BER, and the experimental incident photon count also fits the Poisson limit. The maximum photon count deviation is around 8.47% at -79 dbm (25.8 photons per bit compared with the Poisson limit.

IV. EFFECT OF ELECTRICAL BANDWIDTH

In the previous section, the receiver was designed based on the typical setup used to investigate the SiPM performance.
Fig. 8. The results for the experimental realtime setup (a) The output photon count when the comparator’s threshold voltage varies from 0 V to 0.42 V (b) The measured BER result when the digital threshold $n$ varies from 0 to 15 (c) Experimental BER versus incident optical power compared with the expected theoretical BER (d) Experimental BER vs incident photon count per bit. The collection time for BER below $10^{-3}$ is 1 second. BER $10^{-4}$ is 10 seconds. BER $10^{-5}$ and $10^{-6}$ are 100 seconds.

However, the receiver components often contain lowpass or bandpass hardware filters, which affect the shape of the SiPM output pulses to the FPGA. To ensure the best transmission performance of the SiPM pulses, three high bandwidth amplifier blocks were used in the realtime experiments. However, these high-performance amplifiers also increased the receiver power consumption, a disadvantage, especially in IoT applications. In this case, the effect of the receiver’s electrical bandwidth on the BER was investigated. Since changing the bandwidth of each amplifier is not practical due to experimental limitations, the rest of this investigation is offline using the oscilloscope data based on the previously developed offline processing method in section II. The captured sample waveforms were filtered through a first-order Butterworth Low Pass Filter (LPF) implemented in software with a bandwidth below 1 GHz.

Fig. 9 shows the histogram of 1000 captured pulses after filtering within the bandwidths of 1 GHz to 5 MHz. It was found that the pulse amplitude became lower when the selected bandwidth decreased. An adaptive threshold was chosen based on the sweeping threshold method described in section II to obtain the photon count event for each bandwidth. The hysteresis for each bandwidth depended on the noise amplitude on the pulse’s falling edge. Fig. 10 shows the incident optical power versus count under different electrical bandwidths. A similar deviation trend was found between the count event and the theoretical limits for all the filter bandwidths. However, the bandwidth reduces the effective dynamic range of the bandwidth-limited SiPM.

Fig. 11 presents the simulation result between data rate versus incident optical power at BER of $10^{-3}$ under different bandwidths. The BER was calculated based on the photon events per bit through (4). From Fig. 11, it can be observed that the minimum bandwidth to maintain the theory BER of $10^{-3}$
Photon count event [cps]

40  80  120  160  200
          10  1  2  3  4

10  10  10  10

simulation result, the required bandwidth is approximately

including Photomultiplier Tubes (PMT) [34]. Based on the
required. This is similar to the other photon-counting detectors,
circuit, hence, a higher power consumption receiver circuit is
pulses in each bit time, which needs a high-bandwidth readout
circuit and the target data rate to achieve a BER of $10^{-3}$ was
evaluated through simulation and offline data processing. The

is 5 MHz when the data rate is 100 kbps, and the ratio between
bandwidth and data rate to maintain the theoretical BER is
approximately 50. In addition, a higher data rate requires more
optical power. If the SiPM is saturated, the measured BER will
deviate from the theory PE, which was calculated from (4).
This suggests the minimum receiver bandwidth to achieve a
BER of $10^{-3}$ is 50 times the desired data rate.

**V. Discussions**

Considering the bandwidth limitation of the PMOD connector on the FPGA evaluation board, we focused on the SiPM standard output to present the SiPM’s dynamic range and Poisson limited BER performance, as well as the bandwidth limitation on the SiPM readout circuit. We have verified that the Poisson limit can be approached at 100 kbps under -83.03 dBm for the standard output. However, the high sensitivity of the SiPM was achieved by counting individual pulses in each bit time, which needs a high-bandwidth readout circuit, hence, a higher power consumption receiver circuit is required. This is similar to the other photon-counting detectors, including Photomultiplier Tubes (PMT) [34]. Based on the simulation result, the required bandwidth is approximately

50 times higher than the transmitted data rate, which is similar to other modulation schemes such as Pulse Position Modulation (PPM) [35]. Because of the advantages of high power efficiency and noise immunity, PPM is used in many applications, such as VLC [36] and UWOC [37].

The obtained results for the standard output of SiPM were not optimum due to the larger single-photon pulse width compared with the fast output leading to a smaller dynamic range. However, we can estimate that the fast output or the other SiPMs with shorter pulse widths performs similar to the standard output results. In the future, to achieve a higher dynamic range and data rate, a higher bandwidth interface on FPGA evaluation board is required, for example, FPGA Mezzanine Card (FMC). However, the implementation of fast output still requires higher bandwidth amplifiers which increase the power consumption, and higher bandwidth FMC connectors increase the overall complexity and cost, especially for low energy and battery-operated devices. Additionally, due to the relatively fixed gain of the amplifiers in setup, the lower selected bandwidth in simulation reduced the Gain Bandwidth Product (GBW), hence reducing the amplifier’s expected power consumption [38]. A more flexible solution to change the bandwidth is required to experimentally demonstrate the relationship in bandwidth, data rate and sensitivity while maintaining low noise figures. Moreover, since the current commercially available SiPMs have a higher PDP in the visible blue-green spectrum, for example, in UWOC, VLC and Li-Fi, it is expected that a lower optical power is required to achieve the same BER at a longer wavelength. However, it is not yet suitable for NIR communication such as IrDA, which is 850 nm. The NIR SiPM is expected in the near future due to progress in SPAD fabrication technology [39]. The theory and experiment result demonstrated in this work remains valid for any wavelength range since it is based on the detected photons.

**VI. Conclusions**

To our understanding, for the first time, we have demonstrated the feasibility of a SiPM-based receiver for optical communication using real-time hardware. During the characterizations of SiPM’s standard output, the average FWHM of pulses was approximately 8 ns. A voltage thresholding method was developed and implemented using an op-amp based comparator with hysteresis to count the detected photons avoiding the background electrical noise. The final configured threshold was decided based on sweeping this threshold voltage in simulation and real-time hardware. Results show that both offline and real-time voltage threshold methods approached the theoretical Poisson limit through the standard output of the SiPM. In addition, the demonstrated real-time system achieved a Bit Error Rate (BER) of $10^{-3}$ with less than 5 pW of incident optical power with an average of 11.35 photons per bit at 100 kbps under 620 nm LED, which shows the SiPM has potential in high sensitivity and low power applications, including low energy devices. Moreover, the relationship between the bandwidth of the SiPM readout circuit and the target data rate to achieve a BER of $10^{-3}$ was evaluated through simulation and offline data processing. The
simulation results show that receiver bandwidth needs to be at least 50 times higher than the target data rate to maintain the Poisson limit photon counting capability. Further work is required to confirm these bandwidth related predictions using modifications in the real-time hardware receiver developed in this paper.

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REFERENCES

[1] H. Haas, J. Elmigrani, and I. White, “Optical wireless communication,” p. 20200051, 2020.

[2] J.-Y. Su, K.-F. Chung, S.-C. Kao, C.-H. Cheng, C.-T. Tsai, T.-H. Liu, H.-T. Cheng, C.-H. Wu, T.-T. Shih, D.-W. Huang et al., “Ge pin Photodiode as 60-Gbit/s Optical NRZ-OOK Data Receiver,” Journal of Lightwave Technology, vol. 40, no. 13, pp. 4326–4336, 2022.

[3] M. Nada, F. Nakajima, T. Yoshimatsu, Y. Nakajishi, S. Tatsumi, Y. Yamada, K. Sano, and H. Matsuaki, “High-speed III-V based avalanche photodiodes for optical communications—the forefront and expanding applications,” Applied Physics Letters, vol. 116, no. 14, p. 140502–2020.

[4] A. Spinelli and A. L. Lacaia, “Physics and numerical simulation of single photon avalanche diodes,” IEEE Transactions on Electron Devices, vol. 44, no. 11, pp. 1931–1943, 1997.

[5] S. Cova, M. Ghioni, A. Lacaia, C. Samori, and F. Zappa, “Avalanche photodiodes and quenching circuits for single-photon detection,” Applied optics, vol. 35, no. 12, pp. 1956–1976, 1996.

[6] S. Dolinsky, G. Fu, and A. Ivan, “Timing resolution performance comparison for fast and standard outputs of SensL SiPM,” in 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference (2013 NSS/MIC). IEEE, 2013, pp. 1–6.

[7] G. Akamatsu, S. Takyu, E. Yoshida, Y. Iwao, F. Nishikido, and T. Yamaya, “Evaluation of a Hamamatsu TOF-PET Detector Module,” IEEE Transactions on Radiation and Plasma Medical Sciences, vol. 5, no. 5, pp. 645–650, 2021.

[8] L. Zhang, H. Chun, Z. Chen, Z. Li, H. Wang, R. Jiang, W. Shi, and A. Zhang, “Over 10 attenuation length gigabits per second underwater wireless optical communication using a silicon photomultiplier (SiPM) based receiver,” Optics Express, vol. 28, no. 17, pp. 24986–24980, 2020.

[9] J. Li, D. Ye, K. Fu, L. Wang, J. Piao, and Y. Wang, “Single-photon detection for MIMO underwater wireless optical communication enabled by arrayed LEDs and SiPMs,” Optics Express, vol. 29, no. 16, pp. 25922–25944, 2021.

[10] A. D. Griffiths, J. Herrndorf, R. K. Henderson, M. J. Strain, and M. D. Dawson, “High-sensitivity inter-satellite optical communications using chip-scale LED and single-photon detector hardware,” Optics Express, vol. 29, no. 7, pp. 10749–10768, 2021.

[11] B. A. Yousf, M. Musa, T. Elgorash, and J. Elmigrani, “Energy efficient distributed processing for IoT,” IEEE Access, vol. 8, pp. 161080–161108, 2020.

[12] Onsemi, “Silicon Photomultipliers (SiPM), Low-Noise, Blue-Sensitive C-Series SiPM Sensors,” C-SERIES SiPM datasheet, 2014 [Revised Feb. 2022].

[13] D. J. Griffiths and D. F. Schroeter, Introduction to quantum mechanics. Cambridge university press, 2018.

[14] A. Stewart, L. Wall, and J. Jackson, “Properties of silicon photon counting detectors and silicon photomultipliers,” Journal of Modern Optics, vol. 56, no. 2-3, pp. 240–252, 2009.

[15] R. M. Gagliardi and S. Karp, “Optical communications,” New York, 1997.

[16] A. Tychopoulos, O. Koufopavlou, and I. Tomkos, “FEC in optical communications-A tutorial overview on the evolution of architectures and the future prospects of outband and inband FEC for optical communications,” IEEE Circuits and Devices Magazine, vol. 22, no. 6, pp. 79–86, 2006.

[17] T. D. Singh and M. Kumar, “Design and development of Bluetooth based home automation system using FPGA,” International Journal of Applied Engineering Research, vol. 16, no. 10, pp. 830–838, 2021.

[18] S. Gnecci, N. A. Dutton, L. Parmesan, B. R. Rae, S. Pellegrini, S. J. McLeod, L. A. Grant, and R. K. Henderson, “Analysis of photon detection efficiency and dynamic range in SPAD-based visible light receivers,” Journal of Lightwave Technology, vol. 34, no. 11, pp. 2774–2781, 2016.

[19] Y. Li and D. Chitnis, “A real-time SiPM based receiver for FS0 communication,” in Next-Generation Optical Communication: Components, Sub-Systems, and Systems XI, vol. 12028. SPIE, 2022, pp. 67–71.

[20] J. Ning, G. Gao, J. Zhang, H. Peng, and Y. Guo, “Adaptive receiver control for reliable high-speed underwater wireless optical communication with photomultiplier tube receiver,” IEEE Photonics Journal, vol. 13, no. 4, pp. 1–7, 2021.

[21] W. O. Popoola, E. Poves, and H. Haas, “Spatial pulse position modulation for optical communications,” Journal of Lightwave Technology, vol. 30, no. 18, pp. 2948–2954, 2012.

[22] J. L. H. Rios, N. G. Gonzalez, and J. C. G. Alvarez, “Experimental Validation of Inverse M-PPM Modulation for Dimming Control and Data Transmission in Visible Light Communications,” IEEE Latin America Transactions, vol. 19, no. 2, pp. 280–287, 2021.

[23] J. Liu, Z. Gu, B. Zheng, L. Zhao, and Z. Gong, “A design of underwater wireless laser communication system based on PPM modulating method,” in OCEANS 2016-Shanghai. IEEE, 2016, pp. 1–6.
[38] L. Ye, C. Shi, H. Liao, R. Huang, and Y. Wang, “Highly Power-Efficient Active-RC Filters With Wide Bandwidth-Range Using Low-Gain Push-Pull Opamps,” IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 60, no. 1, pp. 95–107, 2013.

[39] S. Saha, Y. Lu, F. Lesage, and M. Sawan, “Wearable SiPM-based NIRS interface integrated with pulsed laser source,” IEEE transactions on biomedical circuits and systems, vol. 13, no. 6, pp. 1313–1323, 2019.