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Multiplying the number of effective channels in time-domain single-photon counting applications

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ABSTRACT

This study investigates the possibility of exploiting the time-tagging modality and high throughput of modern time-correlated single-photon counting electronics to convey the signal from multiple detectors to the same time-to-digital converter (TDC) channel, effectively reducing the costs and complexity of time-resolved spectroscopy systems. This approach provides the capability of employing a large number of detectors, laying the groundwork for developing sophisticated multichannel systems capable of managing up to more than 100. detectors, significantly enhancing photon-counting capabilities, and paving the way for future advancements in the field.

Keywords: Time-correlated single-photon counting, Multichannel systems, Reconstruction algorithm, Time-Tagged Time-Resolved, Photon arrival times.

1. INTRODUCTION

Time-correlated single-photon counting (TCSPC) is a precise technique for recording single photons, primarily used for determining fluorescence lifetimes and in other areas of applied physics.[1–3] This technique detects individual photons and records their arrival times relative to a synchronized excitation pulse. The excitation pulse corresponds to the reference of timing. Advances in TCSPC technology, particularly through Time-Tagged Time-Resolved (TTTR) data collection, have enhanced its capability by capturing each photon event individually, allowing for comprehensive analysis of photon dynamics.[4]

In particular, it is nowadays possible to capture high synchronization rates, which enables precise reconstruction of the photon's arrival time on an absolute time scale, improving the depth and precision of data processing.[5] However, traditional TCSPC approaches face challenges related to prolonged acquisition times and a trade-off in performance when scaling systems to include a large number of detectors (>100). These limitations underscore the need for novel methods to overcome the inherent trade-offs between scalability, accuracy, and system complexity.

The state-of-the-art Time-to-Digital Converters (TDC) boards typically offer up to 16 channels, while solutions supporting 64 channels or more are available but remain significantly more expensive. Our research investigates a multichannel approach to increase the number of available effective channels in time-resolved applications, such as Raman spectroscopy with detector arrays and diffuse optical tomography, by using a time-tagging correlation technique.[6–8] Specifically, this study explores the potential of modern TTTR electronics to utilize a pair of TDC channels for multiple detectors. This innovative strategy not only has the potential to reduce the cost and complexity of time-resolved spectroscopy systems but also paves the way for highly scalable configurations capable of supporting up to more than 100 detectors.

2. MATERIALS AND METHODS

The schematic of the setup is shown in Figure 1. A pulsed diode laser (PDL 800-D) operating at a wavelength of 683 nm is used as the excitation source. The laser light is attenuated to control its intensity and then directed through an optical fiber to two silicon photomultipliers (SiPMs), called Detector 1 (D1) and Detector 2 (D2).[9] These detectors are set up to capture photon signals. Most of the data in this study were collected in Instrument Response Function (IRF) mode, where no sample was used. This allows the system to measure only the response of the detectors to the laser light, ensuring accurate calibration before adding a sample for further tests.

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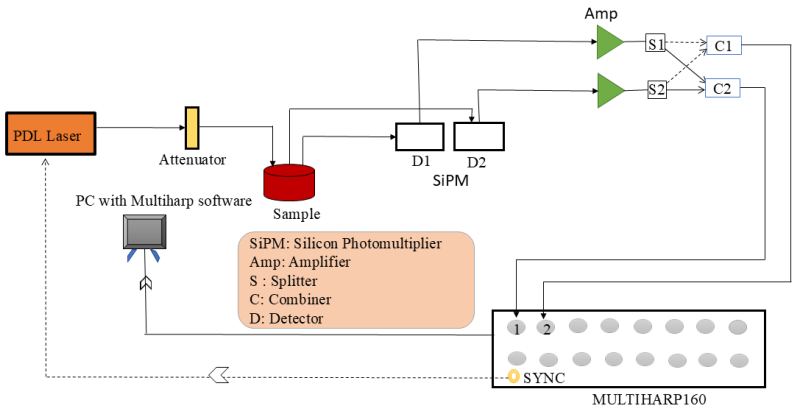

Figure 1. Scheme of the experimental set-up.

The electrical output signal from each SiPM module is split into two using radiofrequency splitters S1 and S2, as reported in Figure 2. The two outputs from the splitters constitute the 'Signal Arm' (continuous line) and the 'Reference Arm' (dashed line) of each SiPM. The signal arms from both detectors are combined via a radiofrequency signal combiner (C1) and transmitted directly to a single channel (Sig) of a TCSPC board (MultiHarp 160, PicoQuant).[10] This channel is used to record photon arrival times with high temporal precision. The reference arms from the detectors are instead combined through C2, after adding a delay (electrical cable) to the reference arm of D2. The electrical output thus obtained is fed to a second TDC channel of the TCSPC board (Ref). Delay lines of 20 cm and 40 cm, which correspond to 1.0 ns and 2.0 ns, respectively, are used. These delays create a measurable time shift in the photon arrival times, allowing us to reconstruct to which detector the recorded photon event corresponds through a correlation algorithm between Sig and Ref.

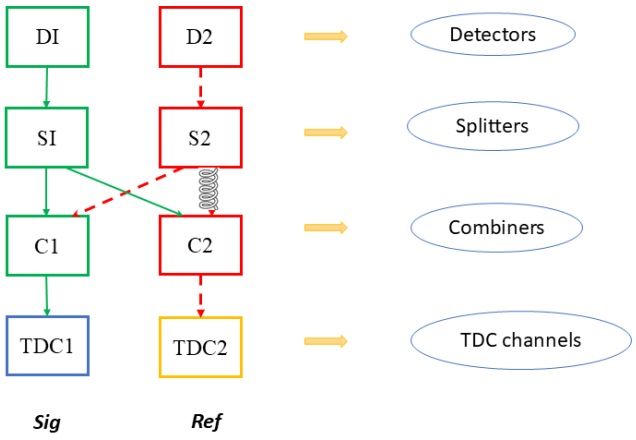

Figure 2. Detail of the electrical scheme for the correct assignment of the firing detector.

The absolute photon arrival times are recorded by the TCSPC board via their proprietary software and saved as .ptu files. The data thus collected are analyzed using a custom Python-based reconstruction algorithm. After

testing the system in IRF mode, we wanted to test it with a diffusive sample to ensure the capability of the system to discriminate between the two detectors even when a diffusive medium broadens the Direct Time-of-Flight (DTOF) curves. To this aim we used tissue-mimicking phantoms with absorption and reduced scattering coefficients $\mu_a = 0.01\,\mathrm{cm}^{-1}, \mu_s' = 10\,\mathrm{cm}^{-1}$ to emulate the optical properties of biological tissues.[11] Detector 2 was placed at a source-detector distance of 1 cm from the injection, while Detector 1 was placed at 2 cm from the source.

3. RESULTS

The primary objective of this study was to accurately identify which detector received the illumination during the experiments. To validate the technique, experiments were conducted using controlled delays and a reconstruction algorithm to identify the illuminated detector. Delays of 1 and 2 ns were introduced into the reference signals, which created distinct time shifts that enabled the reconstruction process to clearly distinguish between Det1 and Det2. Figure 3 illustrates the reconstructed signals for both detectors, Det1 and Det2, with delays of 1 ns (first row) and 2 ns (second row) introduced in the reference. The TDC1 and TDC2 signals represent the DTOF recorded directly from the TDC channels Sig and Ref. Det1 and Det2 are the reconstructed DTOF curves for each detector. We first illuminated only Detector 1 (Figure 3 a,d), then only Detector 2 (Figure 3 b,e), and then both detectors at the same time (Figure 3 c,f): it is evident that the reconstruction algorithm accurately identified the illuminated detector, as the peaks clearly indicate which detector received the light.

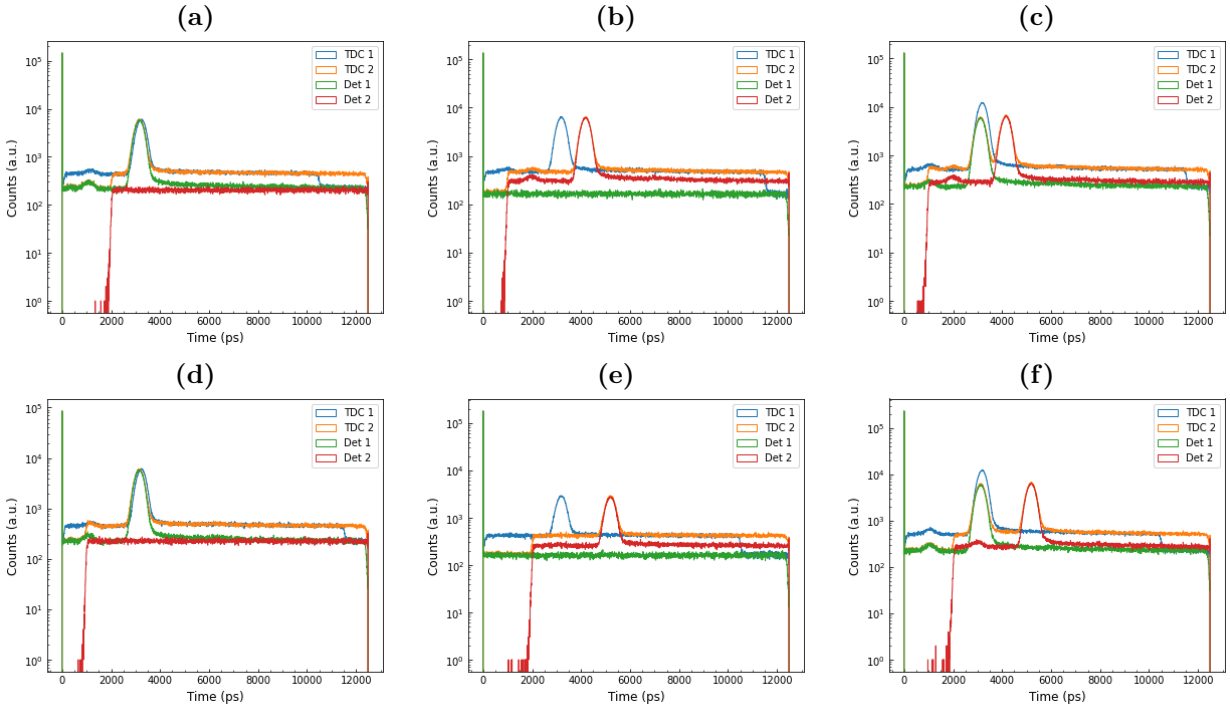

Figure 3. Raw TDC signals and reconstructed curves for various illumination configurations of detectors that are illuminated at: (a) Detector 1 with a 1 ns delay, (b) Detector 2 with a 1 ns delay, (c) Detectors 1 and 2 with a 1 ns delay, (d) Detector 1 with a 2 ns delay, (e) Detector 2 with a 2 ns delay, and (f) Detectors 1 and 2 with a 2 ns delay.

In real measurements, the time-of-flight (DTOF) curves are broadened as a result of the medium's optical properties. These effects result in reduced peak sharpness and delayed photon arrival times. In these conditions, peaks pertaining to the different detectors in the Ref TDC channel might overlap, thus possibly creating issues in the correct assignment of photons. To test this scenario, we used tissue-mimicking samples. The results are reported in Figure 4, which illustrates the time of flight (DTOF) distributions for TDC1, TDC2, Det1, and Det2, recorded while the light illuminated the phantom sample under study. Despite the evident broadening of

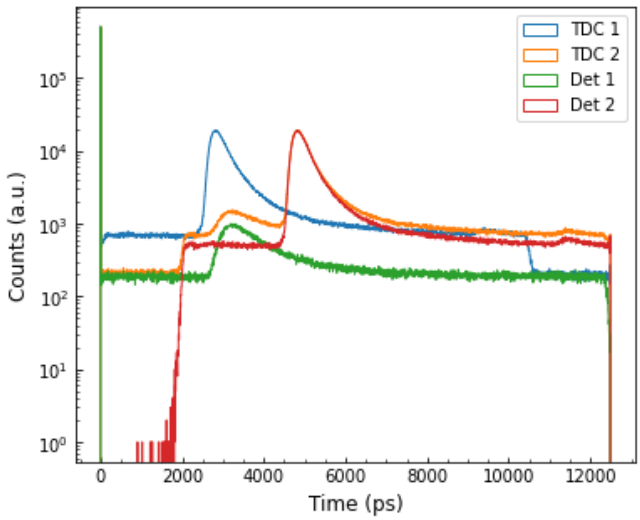

Figure 4. Photon detection of the phantom at source-detector distances of 1 cm and 2 cm with a 1 ns and 2 ns delay introduced.

the DTOFs, the reconstruction algorithm effectively identifies the illuminated detector. The distinct differences between Det1 and Det2 highlight how the system captures the influence of both the source-detector distance and the optical properties of the phantom. These results confirm the effectiveness of the reconstruction algorithm in identifying the illuminated detector by analyzing relative time shifts in the DTOFs, even in a complex diffusive medium. This step would solidify the applicability of the method to biomedical imaging in clinical and experimental settings.

4. CONCLUSION

This study demonstrates the ability of our approach to identify illuminated detectors and reconstruct photon arrival times for multiple detectors with high precision using a single TDC channel. The results validate the system's reliability and potential for scaling to advanced multichannel setups, paving the way for applications in quantum optics, fluorescence lifetime measurements, and biomedical imaging. Our future work will explore the system's performance under diverse experimental conditions to extend its capabilities for managing up to more than 100 detectors, advancing precision measurement and detection in scientific research.

5. ACKNOWLEDGMENTS

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