Time to Digital Converter Transfer Function Improvement using Poisson Process Events

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***Abstract*— This paper introduces a fast and efficient method to characterize a Time to Digital Converter (TDC) transfer function using Poisson process events. We propose a correction method appropriate for ASIC as well as discrete or FPGA TDCs, to be implemented on a post process unit located after the Time to Digital Converter. We then apply the presented method to a case study that demonstrates the efficiency of the correction by measuring the fluorescence lifetime of a test fluorophore by time-correlated single photon counting (TCSPC) with and without correction. The results show a much nicer signal and better fitting with a 3-fold improvement of the fluorescence lifetime accuracy.**

Keywords - Time to Digital Converter; TDC; Poisson Process; SPAD; Characterization; Correction; Fluorescence Lifetime

I. INTRODUCTION

With the apparition of low cost Single Photon Avalanche Diodes (SPAD) fabricated in standard CMOS technologies, more and more applications based on Time of Flight (TOF) measurements are emerging such as active 3D video cameras [1]. These systems need to measure a precise time duration separating two physical events such as a laser pulse generated by a laser diode and a photon detection event by the SPAD. By TOF measurement, it is possible to deduce the distances traveled by the photon. To measure this fast event duration, Time to Digital Converters (TDCs) are commonly used to convert the physical time information into digital information ready for a processing unit. Several techniques can be employed to design a TDC such as Tapped Delay Line, Delay Locked Loop, Gate Ringed Oscillator, etc. Those functions can be implemented on ASIC or FPGA targets [2].

The TDC transfer function includes some major and/or minor flaws, resulting from conception and/or fabrication defects and uncertainties. Certain elements of the TDC chain are slower or faster than others, resulting in a systematic error that will appear on the transfer function (nonlinearity error, missing bins, etc.). The aim of this paper is to present a characterization method and a simple corrective patch to improve all type of TDCs [3]. It is organized as follows: Section II gives a brief description of the TDC measurement principle, Section III describes the characterization method based on the measurement of Poisson Process Events. A simple correction method is introduced in Section IV and tested in Section V. We demonstrate its efficiency in a case study where the fluorescence lifetime of a fluorophore is determined by time correlated single photon counting (TCSPC) [4] carried out with a FPGA-based TDC.

II. OPERATION PRINCIPLE OF A TDC

A TDC is an electronic system used to measure time intervals between two physical events. The first event generates an electrical signal, which initiates the time measurement. The second event generates a second signal that ends the time measurement.

The time measurement is generally divided in two different processes as shown on Figure 1, corresponding to fine and coarse time scales. First, the first signal starts the coarse measurement that is synchronous with the system clock. The fine measurement is also triggered by the first signal but it is an asynchronous measurement of the time. The fine counter is used to measure with a sub-clock period precision the duration between the signal trigger and the first edge of the clock signal. In order to have the same precision between the stop signal and the last clock edge, a second fine counter is used, see (1). The fine measurement unit is the most critical element of the whole TDC because the time resolution is mainly related to its precision. According to this timing diagram, the total measured time is expressed as follows:

$$T_m = T_{Fine1} + T_{Coarse} - T_{Fine2} = N \cdot T_{clk} + T_{Fine1} - T_{Fine2} \quad (1)$$

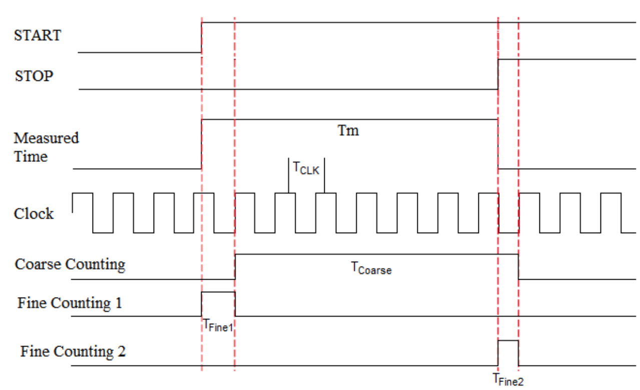

Figure 1. Operation principle of a Time-to-Digital Converter

III. TDC CHARACTERIZATION WITH POISSON PROCESS EVENTS

In order to create a correction method applicable to any type of TDC, the proposed method relies on data post processing. The first step of the proposed method is the characterization of the TDC. The approach consists in measuring a perfectly uniform distribution of temporal events in order to evaluate the accuracy of all TDC bins. Bin accuracy refers to the temporal size of each bin. Indeed, if a bin of the TDC is temporally larger than it should be, it gathers more events from the uniform distribution and thus the total count of this bin is higher. Inversely, a smaller bin shows a total count proportionally lower than expected. A perfect generator of random uncorrelated events is a SPAD that detects photons generated by a “continuous wave” (CW) light source such as a battery-powered Light-Emitting Diode (LED). Indeed, the single photon detection is well known to be an ideal Poisson Process which is completely uniform and uncorrelated.

An ideal TDC should detect the exact same number of photons per time bin, resulting in a flat histogram. If a defect appears on the TDC chain, the error is temporally static. This means that if the measurement is done several times the same error will occur every time and a Fixed Pattern Noise (FPN) will appear on the measured histogram. In addition, due to Poisson statistics, on each measurement, a random noise is added to each bin such that a bin with a value N is affected by a random value equal to $\sqrt{N}$ rms leading to a signal to noise ratio of the bin value also equal to $\sqrt{N}$. Thus one must ensure that the detected FPN is not due to the random noise of the measurement by checking that its value is well above $\sqrt{N}$.

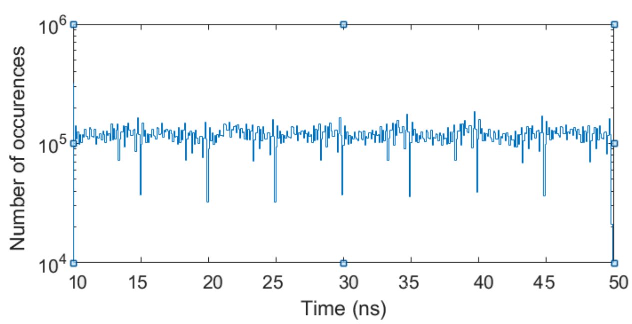

Figure 2. TDC FPN measured over a range of 40 ns by the detection of a large number of non-correlated Poisson events

For example, the histogram displayed in Figure 2 results from a 10 seconds acquisition under a counting rate of 1800 kHz with the FPGA based TDC described in [5] with a temporal resolution of 89 ps over a range of 40 ns. In the specific case of this TDC, the fine counter is a Tapped Delay Line made of 56 elementary delay cells of 89 ps for a total length of 5 ns. This fine TDC counter is thus periodically reinitialized every 5 ns when the coarse counter is incremented. Hence the overall FPN of the TDC is the periodic repetition of the FPN characterizing the 5-ns-long tapped delay line used for the fine TDC counter. Figure 3 displays a zoom on this 5-ns long FPN motif.

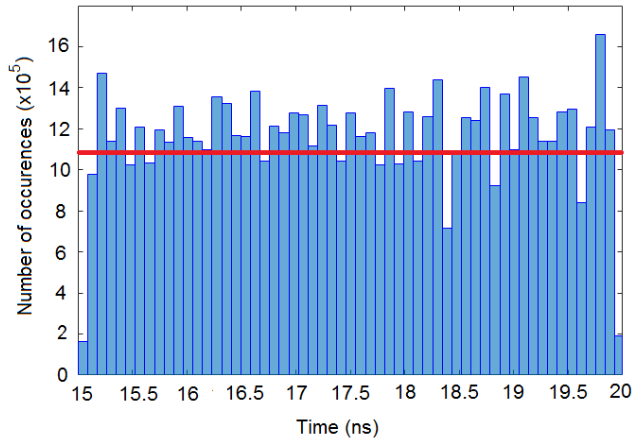

Figure 3. FPN corresponding to the fine TDC counter, periodically repeated every 5ns (coarse counter). Red line indicates the mean bin value.

The overall photon accumulation time is large enough that the uncertainty $\sqrt{N}$ due to Poisson statistic on the average number N of photons per bin becomes much less than the detected variation of N from bin to bin, i.e., the FPN amplitude (see Figure 3). The observed FPN is coming out from the delay mismatch of the tapped delay line used for the fine TDC counter.

Another method for Poisson process events generation using a SPAD is to exploit the photodetector dark count rate originating from thermal activation at ambient temperature. Figure 4 displays the FPN histogram characterizing the fine counter upon accumulating dark counts for over 10 minutes when the SPAD is maintained in pitch dark. The dark count rate is 250 Hz in this case. We note that the FPN is very similar to that of Figure 3, as expected, since it is a property of the TDC, independent of the process (light or dark counts) generating the Poisson distributed events. However, the FPN characterization with a CW light source is much faster (higher counting rate) and therefore preferred. Other light sources like day light and neon light (100 Hz frequency) have been tested yielding the same FPN histogram.

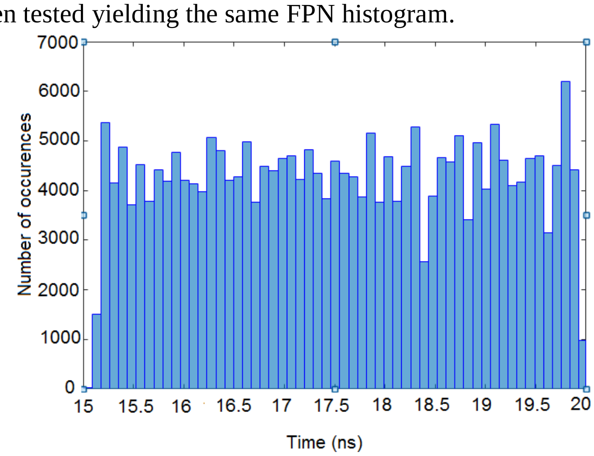

Figure 4. TDC FPN histogram measured from the dark counts generated by the SPAD

The above FPN measurement can be used to retrieve the TDC transfer function without the need of a complex delay generator. As mentioned before, if a bin of the TDC is temporally larger than the mean bin size, its number of counts is correspondingly increased. Consequently, the absolute time TDC transfer function can be extracted from the bin values with:

$$TDC(n) = \frac{T}{M} \frac{1}{\sum_{i=1}^{M} bin_i} \sum_{i}^{n} bin_i \cdot \tag{1}$$

Where T is the total time range, M is the total number of TDC bins in the time range T. The extracted transfer function of the TDC over the 5-ns time range of the fine counter is presented in Figure 5. The linear fit allows the characterization of the Integral Non Linearity of the TDC. The results obtained with this method are consistent with the measurements reported in [5].

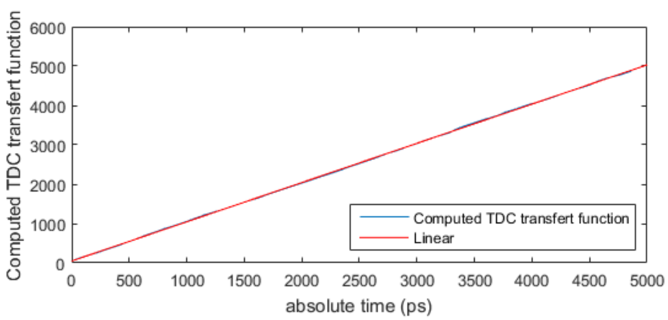

Figure 5,a. Transfer function of the 5-ns long tapped Delay Line of the fine counter of the TDC, characterized with cw light illumination of a SPAD

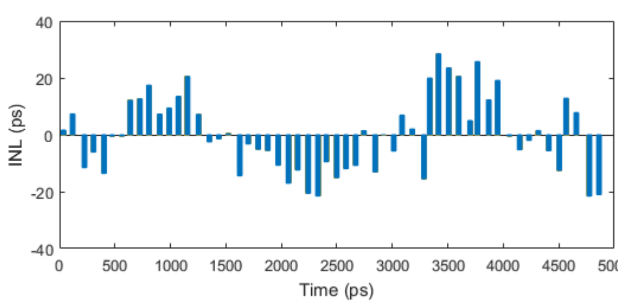

Figure 5,b. INL of the 5-ns long tapped Delay Line of the fine counter of the TDC, characterized with cw light illumination of a SPAD

IV. CORRECTION METHOD

The FPN evidenced in Figure 2 being a systematic bias, it will also affect histograms recorded in TCSPC experiments. Moreover, it can be used to define a scaling factor for each bin so as to correct, by post-processing, the TDC transfer function. This factor is simply the deviation of the count number of each bin_i of the reference FPN histogram relative to the average value (red line in Figure 3), such that the corrected bin count $binc_i$ is given by:

$$binc_i = \frac{\frac{1}{M}\sum_{i=1}^{M} bin_i}{bin_i} \tag{2}$$

Where M is the total number of TDC bins in the reference FPN histogram. The correction applied to the FPN histogram leads to a completely flat histogram, by construction.

V. CASE STUDY

In the following, the characterized TDC is used in a TCSPC experiment to measure the fluorescence lifetime of fluorescein dissolved in water buffered at pH = 7.4.

A picosecond, 405-nm laser pulse [6] excites the fluorescence. The fluorescence signal is detected by a SPAD and the arrival time of individual photons relative to the previous laser pulse is measured and stored by the TDC on the FPGA board. Figure 6 shows the raw measurement without applying the TDC correction.

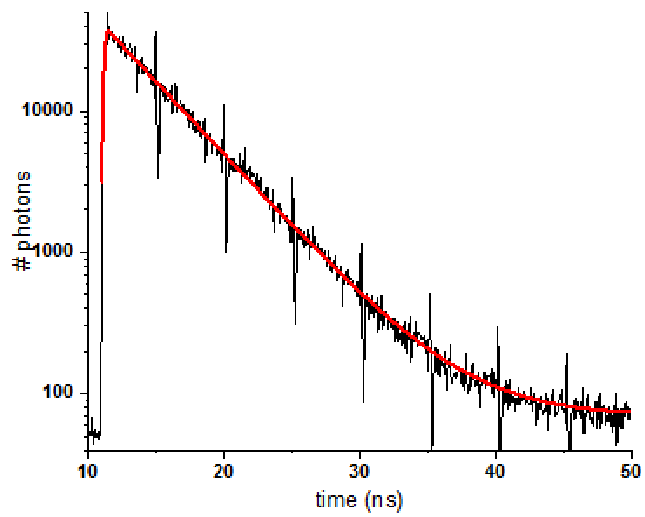

Figure 6. Fluorescence decay without correction

The imperfect transfer function of the TDC creates a static pattern (FPN) at the origin of the periodic glitches in the raw histogram. The 5-ns periodicity of the FPN is clearly seen in this data. The fit to a mono-exponential decay yield a lifetime of 4.21 ns ±0.08 ns.

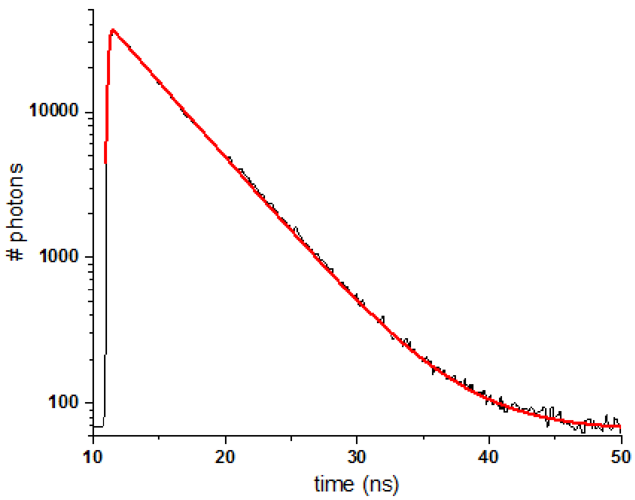

Figure 7. Fluorescence decay with correction

The same data are post-processed by applying to each bin count the correction factor introduced above, and the corrected data are plotted in Figure 7. The FPN is very efficiently attenuated, and the extracted fluorescence lifetime is now 4.19 ns with an error of ±0.02 ns, in very good agreement with the expected value for fluorescein at pH=7.4 [4].

VI. CONCLUSION

A fast and efficient correction method to improve the transfer function of a Time to Digital Converter is presented. The approach is based on the measurement of a large number of Poisson process events generated by a simple SPAD lightened by a CW light source. In addition, this characterization process permits the measurement of the TDC transfer function without the need for any expensive delay generator to calibrate the device. The proposed correction is a post process operation, and thus can be implemented for any type of TDC. Its efficiency is demonstrated in a proof of principle TCSPC experiment. The function transfer correction method is simple, fast, efficient, and does not require hardware design changes of the TDC.

REFERENCES

[1] E. Charbon, M. Fishburn, R. Walker, R. Henderson and C. Niclass, “SPAD-based sensors TOF Range-Imaging Cameras”, Springer-Verlag, F Remondino and D Stoppa ed. Berlin Heidelberg, 2013, pp 11–38, doi: 10.1007/978-3-642-27523-4_2.

[2] J. Y. Won, S. I. Kwon, H. S. Yoon, G. B. Ko, J. W. Son and J. S. Lee, “Dual-Phase Tapped-Delay-Line Time-to-Digital Converter With On-the-Fly Calibration Implemented in 40 nm FPGA,” in *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 1, pp. 231-242, 2016. doi: 10.1109/TBCAS.2015.2389227

[3] M. Fishburn, L. H. Menninga, C. Favi and E. Charbon, “A 19.6 ps, FPGA-Based TDC With Multiple Channels for Open Source Applications,” in *IEEE Transactions on Nuclear Science*, vol. 60, no. 3, pp. 2203-2208, June 2013.doi: 10.1109/TNS.2013.2241789

[4] Jérémie Léonard, Norbert Dumas, Jean-Pascal Caussé, Sacha Maillot,Naya Giannakopoulou, Sophie Barrea and Wilfried Uhring, “High-throughput time-correlated single photon counting”, in *Lab Chip*, 2014, 14, 4338, August 2014, DOI: 10.1039/c4lc00780h

[5] Foudil Dadouche, Timothé Turko, Wilfried Uhring, Imane Malass, Jérémy Bartringer, Jean-Pierre Le Normand, “Design Methodology of TDC on Low Cost FPGA Targets,” in *Sensors & Transducers Journal*, vol 193, no. 10, pp 123-134, October 2015

[6] W. Uhring, V. Zint, J. Bartringer, “A low-cost high-repetition-rate picosecond laser diode pulse generator,” Photonics Europe Proc. of SPIE, Vol. 5452, 2004. 545038, doi:10.1117/12.545038.