Improved multiplexed infrared single photon detectors

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ABSTRACT

We discuss a scheme for a photon-counting detection system that overcomes the difficulties of photon-counting at high rates at telecom wavelengths. Our method uses an array of *N* detectors and a 1-by-*N* optical switch with a control circuit to direct input light to live detectors. We conclude that in addition to detection deadtime reduction, the multiplexed switch also reduces so-called trigger deadtime, common to infrared photon counting detectors. By implementing the new algorithm we obtain an overall deadtime reduction of a factor of 5 when using just $N=2$ multiplexed detectors. In addition to deadtime reduction, our scheme reduces afterpulsing and background counts (such as dark counts). We present experimental results showing the advantage of our system as compared to passive multi-detector detection systems and our previous active multiplexing system that only reduced detection deadtime.

Keywords: photon counting, detector, down-conversion, correlated photons, statistical methods, multiplexing, infrared

1. INTRODUCTION

Single-photon technology is an emerging field that is growing as interest in quantum communication and computation intensifies [1,2]. A major limiting factor in developing Quantum Key Distribution at telecom wavelengths is efficient and error-free single-photon detection [3,4]. Because of growing demands for higher-rate secret key distribution, the single-photon detector (SPD) developer community is focused on improving relevant properties of detectors. Among these are detection efficiency (DE) [2, 5, 6], detector timing jitter [7], and detector deadtime [8]. Because the deadtime of InGaAs detectors typically used for telecom wavelengths is usually long (~ μs), deadtime is the major factor impeding higher photon-counting rates at telecom wavelengths. Unfortunately, one cannot focus on optimizing one property alone, because SPD properties are related to one another. For example, it is often the case that reducing deadtime increases afterpulsing (the subsequent retriggering of a detector caused by the non-ideal nature of the detector rather than by a new input photon). Therefore, our goal is to present a detector arrangement that reduces deadtime while other important characteristics are kept constant (or improved). While in this study we use two stand-alone SPDs, the method discussed here is increasing in feasibility as progress to integrate detectors in microchip arrays continues [9-11]. We have previously reported on active multiplexing as one possible way to reduce the effect of detector deadtime. [12-15] Here we refine our multiplexing protocol, based on a better understanding of a nature of deadtime for single- and multi-detector arrangements.

2. THEORY OF OPERATION

Deadtime, defined as the time a photon-counting detector and any necessary electronics needs to recover after it registers a photon, is present in most SPDs, but has different physical origins for different detectors. For single-photon avalanche photodiodes (SPADs) every avalanche must be quenched to allow the complete release of trapped carriers from the detection zone before the detector is ready for another photon, resulting in a deadtime of tens of microseconds for InGaAs infrared detectors. Further, because of the high level of dark counts, InGaAs SPADs are usually operated in a triggered mode. When a single photon is expected, a trigger pulse turns the detector on for 1 to 100 ns. Typically any subsequent trigger pulses are rejected for ~100-300 ns after a first trigger pulse is received by InGaAs electronics. This feature effectively increases the overall deadtime of such SPADs, even when the photon detection (an avalanche) has not

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taken place. This effect is significant for infrared detectors such as InGaAs SAPDs, which already suffer from low detection efficiency (DE) as it can become comparable to the conventional detection deadtime. In this paper we deal with the both deadtimes by optimizing our multiplexing algorithm.

The passively multiplexed detector arrangement consists of a pool of *N* detectors that are always on, and are connected via beamsplitters (i.e. "detector tree"). The actively multiplexed detector arrangement is based on an array of *N* photon-counting detectors connected via a 1-by-*N* optical switch (Fig. 1). A switch control circuit keeps track of the history of events, such as trigger pulses and detections, and then routes subsequent incoming pulses to a detector that is armed and ready to detect the subsequent photons during the deadtime of the former detector. As we showed in our previous work [12, 13], this system allows an arrangement of *N* detectors to be operated at a significantly higher detection rate than *N* times the detection rate of an individual detector, while maintaining the overall deadtime fraction.

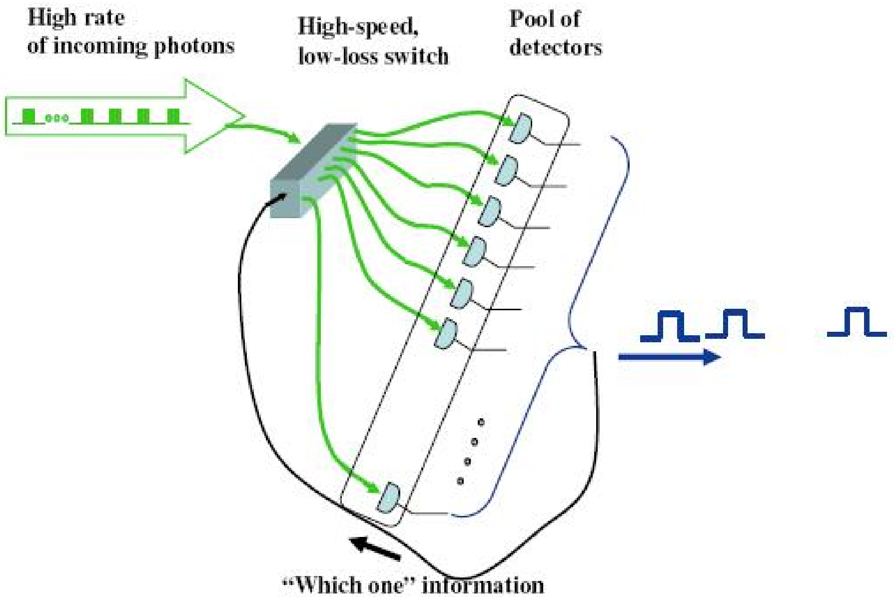

Fig. 1. Intelligent deadtime management scheme.

To compare different detector arrangements we introduce a device-independent quantity that is based on general properties of single-photon detection. We define deadtime fraction (DTF) as the ratio of time spent by the detector arrangement in its "dead" state to the total time of the experiment. This can be interpreted as a ratio of missed detection events due to deadtime, to the total number of detection events that would occur with a detector of the same characteristics, but with no deadtime with a time-independent Poissonian (cw) light source. Higher DTF increases the chance that an incoming photon will arrive during the deadtime, and thus increases the nonlinearity of detection. While the acceptable DTF for a photon-counting system is application specific, for comparison purposes we chose a single DTF level for these different detector arrangements. For our analysis, we assume DTF = 10 % to be a reasonable limit for most detection applications. The advantage of this definition is that it does not depend on a particular realization of a photon-counting arrangement and therefore allows us to compare somewhat dissimilar device systems. Our analytical calculations have been previously presented, so here we only briefly describe key definitions and results [12-15] before moving on.

The theoretical treatment of a multiplexing arrangement is best understood when starting with the ideal case, when electronic switching delay is negligible as compared to the SPAD's deadtime. It can be shown, that in such an ideal case, the actively switched detector arrangement with only 3 detectors can match the performance of a hypothetical detector with 10 times shorter deadtime (at DTF = 10 %)! In practice however, we have to consider the following times:

T_{d}, or detection deadtime is the photon detection-related deadtime (i.e. time needed to fully quench the avalanche);

T_{s}, or switching deadtime is the switching time needed for the multiplexing electronics to process a detection event.

T_{t} , or trigger deadtime is the shortest time between two trigger events that can be processed by the detector electronics.

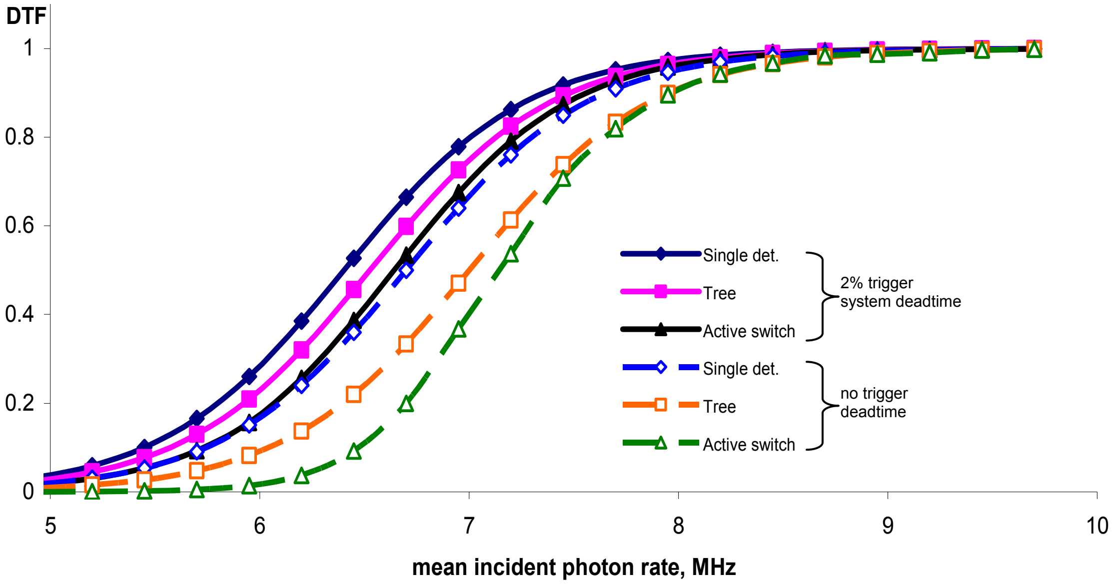

Fig. 2. Effect of nonzero trigger system deadtime on DTF for various detector arrangements of 1 and 2 detectors. Diamonds: single detector; squares: beamsplitter tree arrangement; triangles: actively switched arrangement; open markers: no trigger system deadtime; filled markers: trigger system deadtime $T_{\mathrm{t}} = 0.02\, T_{\mathrm{d}}$.

Switching and trigger deadtimes limit the performance of the multiplexed detection assembly. For the detection assemblies we studied, $T_{\mathrm{d}} = 10\mu s$, $T_{\mathrm{t}} = 0.02\, T_{\mathrm{d}}$, $T_{\mathrm{s}} \approx 0.005\, T_{\mathrm{d}}$. The effect of T_{t} is more pronounced for lower detection efficiencies, that is the combination of DE of a SPAD and transmittance of collection optics, as there will be more times when the detector is triggered but no detection is recorded. For our setup, the overall detection efficiency $\mathrm{DE} \approx 0.02$. Fig. 2 compares the performance of a single detector, a passive beamsplitter/detector tree and an actively switched group of detectors with and without trigger deadtime, for the conditions matching our experiment. The multiplexing algorithm considered here switches the detectors only when a photon is detected by the active detector (i.e. ignores the trigger deadtime issues). We see that in all cases the highest incident photon rate with DTF=10% is achieved with the active switching configuration. However, trigger deadtime significantly lowers the performance of the arrangement, thus providing the incentive to optimize both detection deadtime and trigger deadtime through multiplexing.

Let us consider other important features of detector arrangements: dark counts and afterpulsing probability. It can be shown that both dark count rates and afterpulse probabilities, [12-15] for a multiplexed system are superior to these of a passive tree.

To summarize, the theoretical study shows that the active multiplexing scheme is superior to other, passive switched detector arrangements aimed at improving deadtimes. In particular, the direct comparison of detection rates seen with different arrangements at the same level of DTF, shows that the multiplexing arrangement compares favorably to a passive “beamsplitter/detector tree”. We show that the most advantageous scheme to reduce DTF and increase photon count rates, along with the added bonus of improving the signal to background ratio and reducing afterpulsing, is the active switching arrangement that uses an external logic circuit that tracks the history of both photon detections (to eliminate detection deadtime) and trigger pulses (to eliminate trigger deadtime).

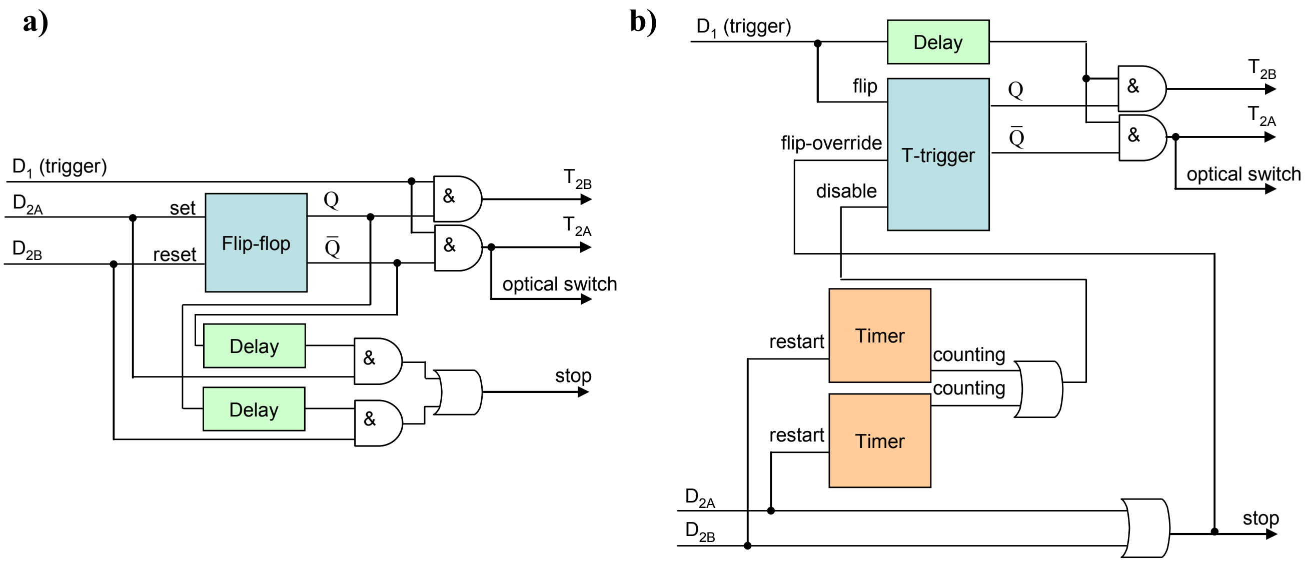

Fig. 3. Multiplexing electronics schematics for: a) detection deadtime reduction only; and b) detection deadtime and trigger deadtime reduction.

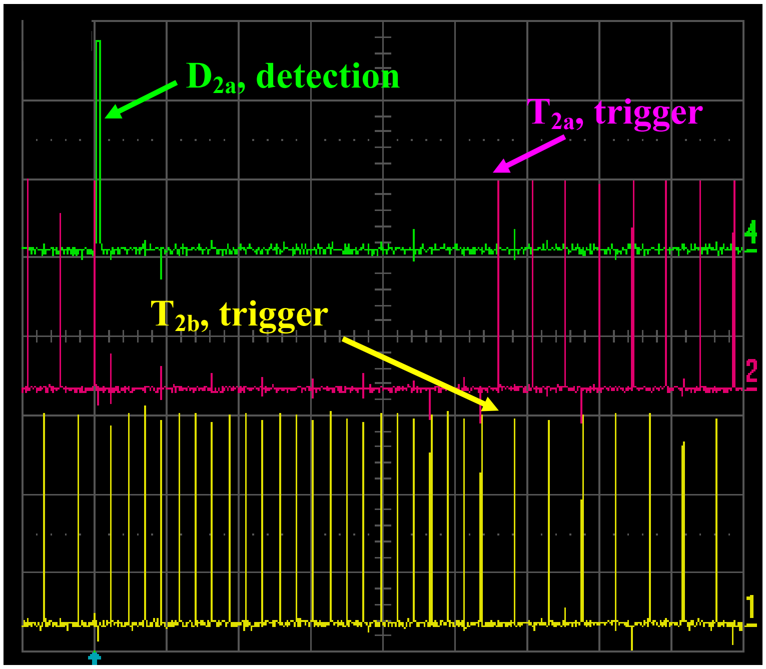

Fig. 4. Operation of the advanced version of multiplexing electronics. During normal operation, the main trigger (D_1, not shown) is split evenly between the two multiplexed detectors (T_{2a} and T_{2b}). If one of the detectors fires (D_{2a}), all the trigger pulses are sent on to a detector that is alive (T_{2b}).

3. MULTIPLEXING ELECTRONICS DESIGN

Let us consider the simplest multiplexing design, aimed at optimizing the deadtime via detection deadtime reduction. The design is based on the obvious fact that while a detector has a significant deadtime when it does fire, it has no deadtime when it does not fire. At first, all detectors are ready to detect a photon. The optical switch is set to direct the first incoming optical pulse to the first detector of the array. Control electronics monitor the output of that detector to determine when it fires. If the detector does fire, the control circuit switches the next optical pulse to the next detector. If the detector does not fire, then the switch state remains unchanged. The process repeats with the input always directed to the available armed detector that fired the longest time ago. At high count rates, many of the detectors may fire in a short period of time, but as long as the first detector recovers to its live state before the last detector triggers, the whole arrangement will still be live and ready to register an incoming photon. For the set of 2 detectors, only one bit of memory is needed: in our implementation we use a simple flip flop cell (RS-trigger), Fig. 3a.

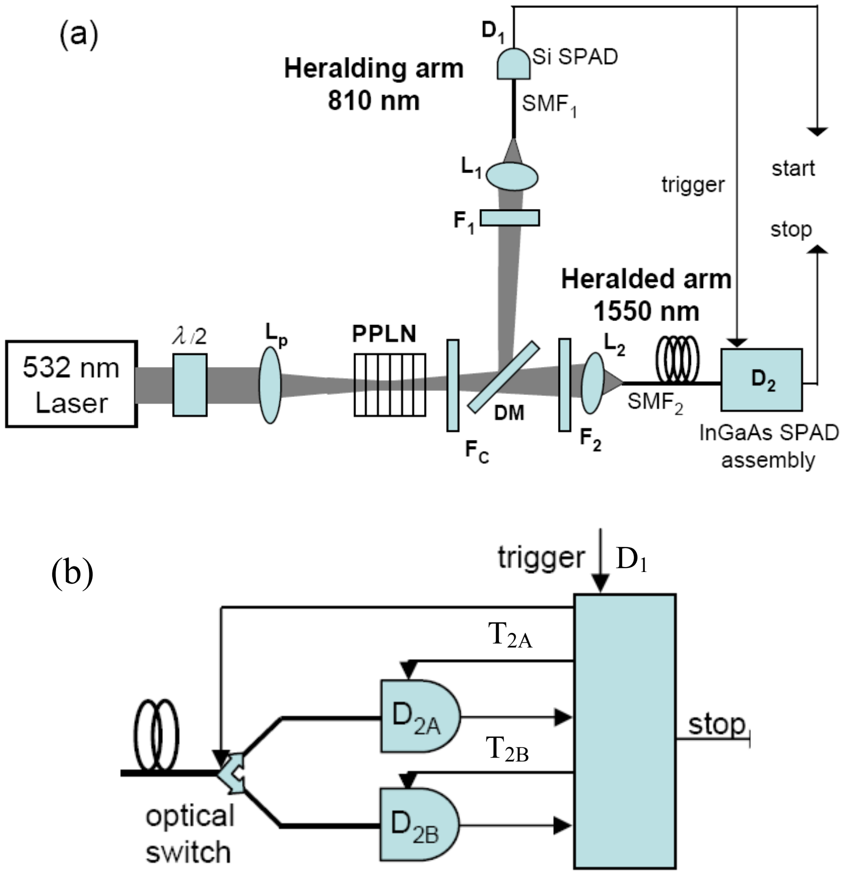

Fig. 5. a) Experimental setup, and b) actively multiplexed detector assembly.

The second design is somewhat more involved. We distribute incoming trigger pulses using a simple T-trigger (Fig. 3 b) that flips its state with each pulse at its “flip” input. This way, if no detectors fired (i.e. both of them are ready), each of them receives half of the trigger pulses. This gives additional time for detector trigger electronics to recover. At the same time, if the photon detection took place by either of the two detectors, we disable the flipping of the T-trigger, and send trigger pulses to the detector that is known to be ready. Thus, we independently keep track of detectors deadtime by measuring the time elapsed from the moment when a detector fired (separately for each detector). The timers stop then the deadtime is over, which enables the flipping of the T-trigger. If both the detectors fire during a time that is shorter than the detection deadtime, the arrangement is saturated and no detectors can accept a trigger. However, the detector that fired first will be ready sooner than the detector that fired second (and that was activated by the multiplexing electronics). We therefore need to switch the active detectors by toggling the T-trigger (via its flip-override input). The oscilloscope traces in Fig. 4 demonstrate the operation of the circuit. Note that for illustrative purposes the main trigger signal is simulated with a function generator with a constant repetition rate. In actuality, this signal is random.

Both the logic circuits, presented in Fig. 3, are implemented on a Field Programmable Gate Array (FPGA).

4. EXPERIMENT

The latest experiment was aimed at the comparative analysis of the two multiplexing designs and gauging the performance of the actively multiplexed arrangements against a single detector. (A comparative analysis of the passive schemes was published elsewhere [12-15].) The experimental setup, presented in Fig. 5a, is built around a parametric down-conversion crystal that produces photon pairs at two different frequencies. The photon at 810 nm is detected by a silicon SPAD (with a deadtime of 50 ns, that is negligible compared to the deadtime of the infrared detectors under test). The detection of an 810 nm photon heralds a photon in the signal arm (at 1550 nm), where we tested the different detector arrangements. We compared several detector configurations: (i) a single detector, (ii) a legacy multiplexed arrangement, that eliminates detection deadtime, and (iii) a multiplexed arrangement, that eliminates both detection and trigger deadtime. Fig. 5b shows the external connections for both (II) and (iii) configurations. The only difference between cases (ii) and (iii) is the firmware uploaded to the FPGA board.

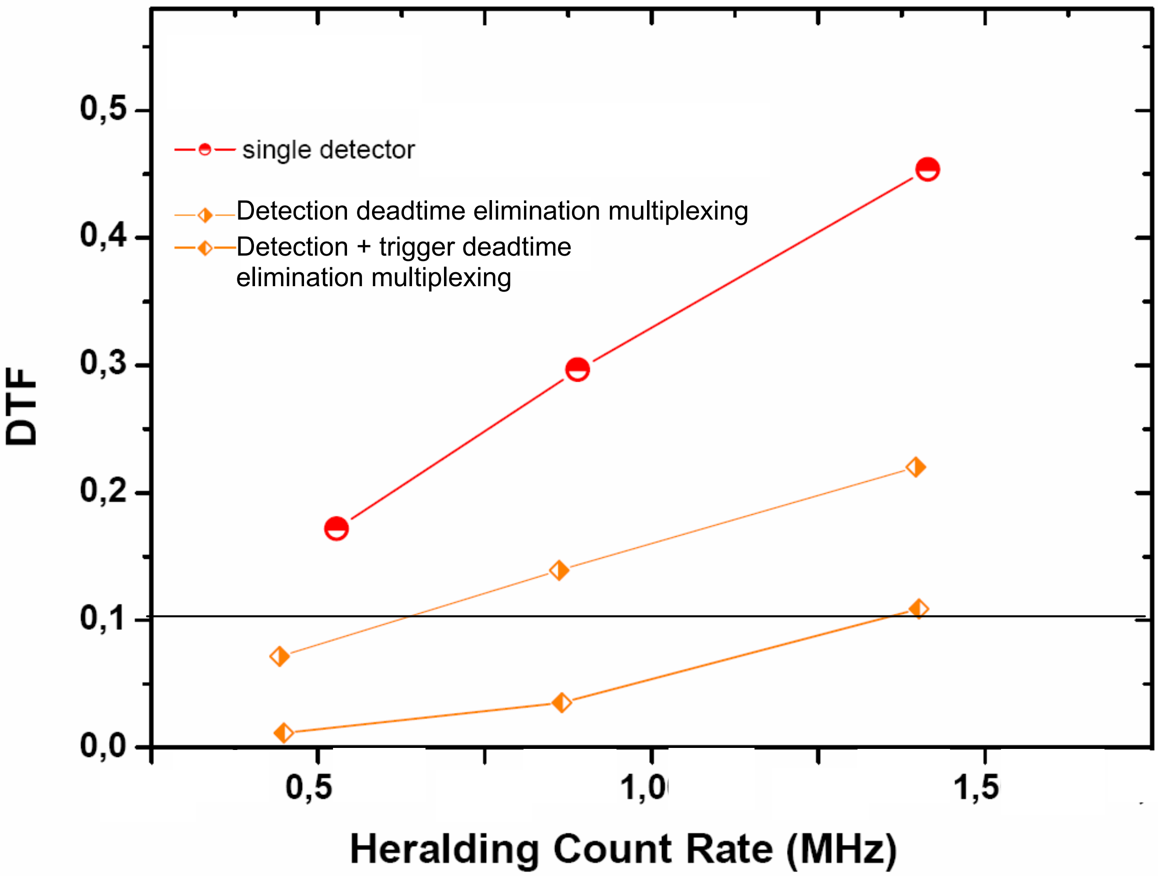

Fig. 6. Measured DTF versus the heralding (D_1) count rate for a single detector, and the two multiplexed schemes: detection deadtime elimination and detection+trigger deadtime elimination.

Fig. 6 shows the performance of the three configurations studied. Clearly, the count rate for configuration (iii) is the highest for all values of DTF. Particularly, for our chosen threshold of DTF=10% we observe a nearly 5 times higher heralding count rate for the most advanced actively multiplexed scheme (iii) as compared to a single detector. The same configuration's performance (iii) as compared to a legacy active multiplexed schematic shows a improvement factor of 2.1.

We note that this improvement factor (i.e. 5) was achieved with just two detectors.

5. CONCLUSIONS

We have presented the current status of our efforts to implement an actively switched arrangement of multiplexed detectors. We introduced a novel algorithm for multiplexing two SPADs that improves the effect of deadtime by a factor of 5 as compared to a single SPAD. We also note that together with deadtime, the afterpulse rates and dark count rates can be reduced via multiplexing.

6. ACKNOWLEDGMENTS

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