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Switchable detector array scheme to reduce the effect of single-photon detector's deadtime in a multi-bit/photon quantum link

Cong Liu [a,b,*], Yongxiong Ren [a], Jiapeng Zhao [c], Mohammad Mirhosseini [c], Seyed Mohammad Hashemi Rafsanjani [c], Guodong Xie [a], Kai Pang [a], Haoqian Song [a], Zhe Zhao [a], Zhe Wang [a], Long Li [a], Joshua C. Bienfang [d], Alan Migdall [d,e], Todd A. Brun [a,b], Moshe Tur [f], Robert W. Boyd [c], Alan E. Willner [a]

[a] Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA
[b] Department of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089, USA
[c] The Institute of Optics, University of Rochester, Rochester, NY 14627, USA
[d] National Institute of Standards and Technology and University of Maryland, 100 Bureau Drive, Gaithersburg, MD 20899, USA
[e] Joint Quantum Institute, University of Maryland, College Park, MD, 20742, USA
[f] School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel

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ABSTRACT

We explore the use of a switchable single-photon detector (SPD) array scheme to reduce the effect of a detector's deadtime for a multi-bit/photon quantum link. The case of data encoding using M possible orbital-angular-momentum (OAM) states is specifically studied in this paper. Our method uses N SPDs with a controllable $M \times N$ optical switch and we use a Monte Carlo-based method to simulate the quantum detection process. The simulation results show that with the use of the switchable SPD array, the detection system can allow a higher incident photon rate than what might otherwise be limited by detectors' deadtime. For the case of $M = 4$, $N = 20$, a 50-ns deadtime for the individual SPDs, an average photon number per pulse of 0.1, and under the limit that at most 10 % of the photon-containing pulses are missed, the switchable SPD array will allow an incident photon rate of 2250 million counts/s (Mcts/s). This is 25 times the 90 Mcts/s incident photon rate that a non-switchable, 4-SPD array will allow. The increase in incident photon rate is more than the 5 times increase, which is the simple increase in the number of SPDs and the number of OAM encoding states (e.g., $N/M = 20/4$).

1. Introduction

Quantum information systems have the ability to protect the information channels against eavesdropping [1,2]. This security is derived from the quantum non-cloning theorem that any eavesdropping made by a third party would inevitably leads to errors that can be detected by the sending and receiving parties [3,4]. Typical qubits encoding on photon's two polarizations can provide one bit/photon of information [5,6]. However, since each photon has only two orthogonal polarizations, quantum system capacity might be increased if a basis set having more than two orthogonal states is used for data encoding. One example may be through the use of a set of orthogonal spatial modes, for which the photon can occupy one of the many states at a given time [7]. A potential spatial basis set that has recently received increasing interest is the orbital-angular-momentum (OAM) mode set, which is a subset of Laguerre Gaussian (LG) modes [8–14].

A light beam's phasefront that has an azimuthal (ϕ) dependence of $\exp(i\ell\phi)$ will "twist" in a helical fashion as it propagates. Such a beam carries OAM corresponding to $\ell\hbar$ per photon, in which the OAM charge ℓ represents the number of 2π phase shifts in the azimuthal direction. An OAM beam will be orthogonal to other OAM beams depending on its ℓ value. Since a single photon can carry a distinct OAM charge, photons can be encoded on more orthogonal OAM states than those provided by polarization states [15–18]. Typically, a quantum system encoded in M OAM states ($M = 1, 2, 3, \ldots$) of photons could transmit up to $\log_2 M$ quantum bits per photon [14].

A key limitation for the incident photon rate in a quantum system is the deadtime of a single photon detector (SPD). This deadtime is defined as the length of time that the detector must recover after "firing" from one detected photon before it is ready to detect and accurately register another incoming photon. This limitation on incident photon rate would be present to a larger or smaller extent depending on the

* Corresponding author at: Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA.
E-mail address: liucong@usc.edu (C. Liu).

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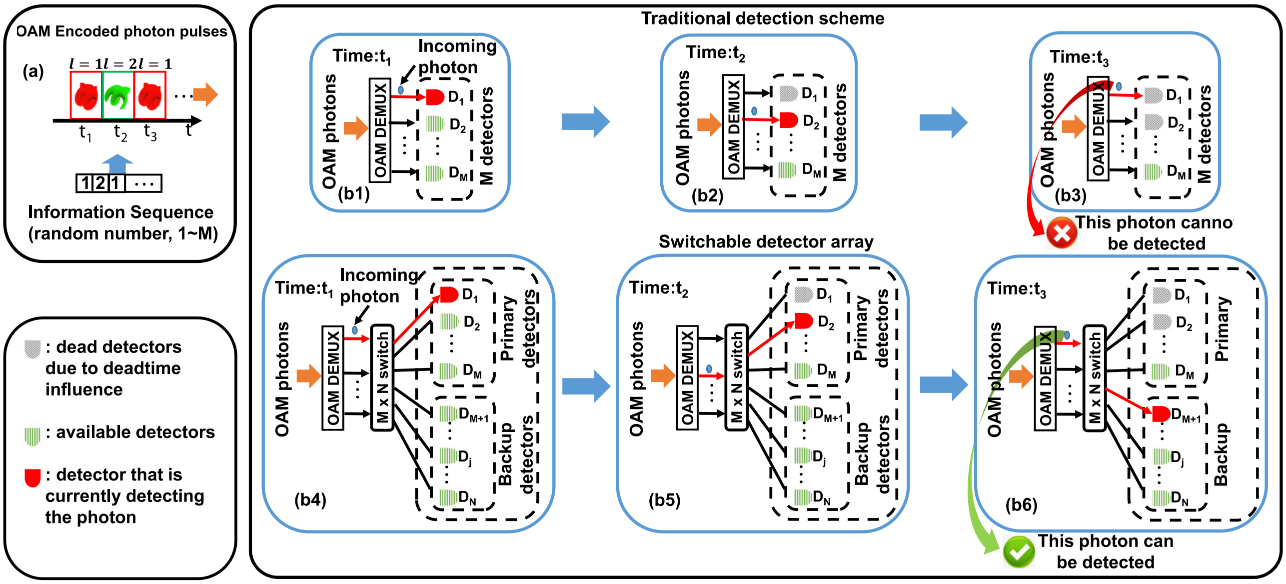


Fig. 1. Concept of the detection schemes for a multi-bit/photon quantum link. (a) The M-OAM-state-encoding; (b1–b3) the traditional detection scheme; (b4–b6) the switchable SPD array scheme. In the traditional detection scheme, the incoming photon would be ignored when it arrives during the deadtime of the SPD. In the switchable SPD array, the controllable $M \times N$ switch routes the incoming photon to the first available fresh backup SPD when its primary SPD is dead, and routes the incoming photon back to its primary SPD once it becomes fresh.

deadtime of different SPDs. In typical avalanche photodiode (APD) based SPDs, the deadtime ranges from ~50 ns for actively quenched APDs to ~10 μs for passively quenched ones [19]. Gated APD based SPDs have the potential to be operated at higher incident photon rate because their deadtimes only exist in some of the clock cycles [20]. Some free-running superconducting single-photon detectors could also achieve a shorter deadtime (about tens of picosecond) with a reduced dark count rate than the APD-based SPDs [21–23].

For two-polarization-state quantum encoding systems, the deadtime limitation on the incident photon rate of SPDs could be reduced by using a switchable detection scheme [19,24]. In this approach, more SPDs are used in the receiver than are strictly necessary, and a controllable optical switch routes an incoming photon away from an SPD that is still within its deadtime to a "fresh" SPD.

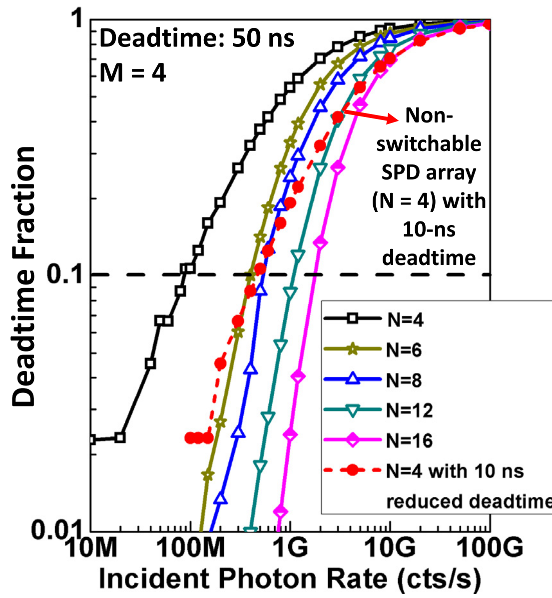
Previous reports have shown that a switchable SPD array with N SPDs can potentially operate at more than N times the incident photon rate that a single SPD can achieve for a single quantum channel [19, 24]; we note that this result was for a goal of missing no more than 10% of photon-containing incident pulses, which could be considered as a limit for some quantum detection applications. In addition, they show that a switchable N-SPD array can potentially operate at a higher incident photon rate than that of a single SPD that has a deadtime reduced to $1/N$.

In this paper, we extend the previous work using SPD arrays in polarization-encoded quantum systems to investigate the use of a switchable SPD array in a multi-bit/photon quantum link where bits are encoded on M OAM states. Our method uses N SPDs with a controllable $M \times N$ optical switch to route the incoming photon from an SPD within its deadtime to a fresh active SPD awaiting a new photon. Our Monte Carlo-based simulation results show that the switchable SPD array scheme with N SPDs could operate at an increased incident photon rate under the same deadtime when the same detection limitation is applied. For the case of $M = 4$, $N = 20$, the SPDs' individual deadtime of 50 ns, an average photon number per pulse of 0.1, and under the limitation that missing at most 10% of the photon-containing pulses, the switchable SPD array can operate at an incident photon rate of 2250 million counts/s (Mcts/s). This is 25 times the 90 Mcts/s incident photon rate that a non-switchable, 4-SPD array will allow. The increase in incident photon rate is more than the 5 times, which is the simple increase in the number of SPDs (N) over the number of OAM encoding states (M).

2. Concept

Fig. 1 illustrates the concept of the switchable detection scheme. The photons are generated by an attenuated, pulsed, weak-coherent-state laser source, encoded in M OAM states according to the information sequence. The transmitted information, which is a sequence of integers ranging from 1 to M, is created using a random number generator with each number having an equal probability of $1/M$. Without loss of generality in the analysis, we ignore channel loss between the sending and receiving parties in our model, as channel loss and detection efficiency always appear as a product and are thus indistinguishable. Based on this assumption, the incident photon rate at the receiving party equals the pulse frequency of the single photon source (e.g., attenuated laser source) at the sending party. The pulse frequency is varied in our simulation by varying the incident photon rate to show its influence to the detection system. The amount of photons coming to the detection array in a certain time period would be determined by the pulse frequency and the average photon number per pulse of the single photon source (μ).

At the receiver part, an incoming photon having an OAM charge of ℓ will be demultiplexed and sent to the corresponding ℓth SPD. The photon would be ignored if it arrived during the SPD's deadtime and the information it carries would be lost, as shown in Fig. 1. (b1–b3). To achieve a higher information efficiency, we use a switchable SPD array with N SPDs and an $M \times N$ optical switch ($N > M$). Among the N-SPD pool, the first M SPDs work as primary SPDs corresponding to each of the M OAM states, and the remaining $N - M$ SPDs work as backups. The switch dynamically routes incoming photons from a dead SPD to the next available fresh backup SPD, as shown in Fig. 1. (b4–b6). At the start of the operation all SPDs are fresh and ready to detect photons. The optical switch is set to route the first incoming photon to its primary SPD. The control electronics monitors the output of every SPD to check whether it fires. Once an SPD fires, the switching algorithm searches for the first available fresh backup SPD and the switch routes the incoming photon(s) to this backup SPD. By doing this, during the deadtime of the primary SPD, the assigned backup SPD



N	Incident photon rate at 10 % DTF (cts/s)	Improve-ment
4	≈ 9.1*10^7	--
4 (10-ns deadtime)	≈ 4.7*10^8	≈ 5.2X
6	≈ 4.1*10^8	≈ 4.5X
8	≈ 5.5*10^8	≈ 6X
12	≈ 1.1*10^9	≈ 12X
16	≈ 1.8*10^9	≈ 20X

Fig. 2. Simulation results of DTF versus the incident photon rate of different SPD arrays for a 4-OAM-encoded quantum link. The dashed black horizontal line shows the 10% DTF level. The DTF curve for a non-switchable detection scheme (4 SPDs for 4 OAM states, no optical switch) with 10-ns deadtime is also shown for comparison (red dashed line).

can replace it. If an SPD does not fire, then the switch state remains unchanged. The input is always switched back to its corresponding primary SPD when the latter becomes available. This process repeats for every pulse. The switching algorithm is computer-programming based, so the search-and-route time could be small compared to the switching time of the optical switch. In addition, the switching time of a given optical switch could be described as constant in the scheme. Therefore, this effect might be mitigated by using an offline digital signal processing method after the detection process if the switching time is shorter than the time period between two incoming photons. When working at high incident photon rates, multiple SPDs might fire in a short time period and subsequently go into their "dead" states. However, if enough backup SPDs are available, the detection system can always detect the incoming photons with an acceptable percentage of missed photon-containing pulses. This also allows for optimum use of an array of SPDs having different deadtimes.

3. Simulation results and discussion

The received photon number per pulse follows a Poisson distribution model with the average photon number per pulse of μ [25]. That distribution gives a probability of having more than zero photons in a pulse as p:

$$p = P(x \geq 0) = 1 - P(x = 0) = 1 - e^{-\mu} \tag{1}$$

where:

$$P(x\ photons\ in\ a\ pulse) = e^{-\mu} \cdot \frac{\mu^x}{x!}, x = 0, 1, 2, \ldots \tag{2}$$

We assume that for each OAM state, the probability of having more than zero photons in a single pulse period is q:

$$q = 1 - \left(\frac{M-1}{M} + \frac{1}{M} \cdot e^{-\mu}\right) = \frac{p}{M} \tag{3}$$

We use a Monte Carlo-based simulation to determine the performance of our switchable SPD array scheme, which is employed to obtain numerical estimations of the photon detection events. To describe the ratio of missed photon-containing pulses to all photon-containing pulses, a deadtime fraction (DTF) is defined as [19]:

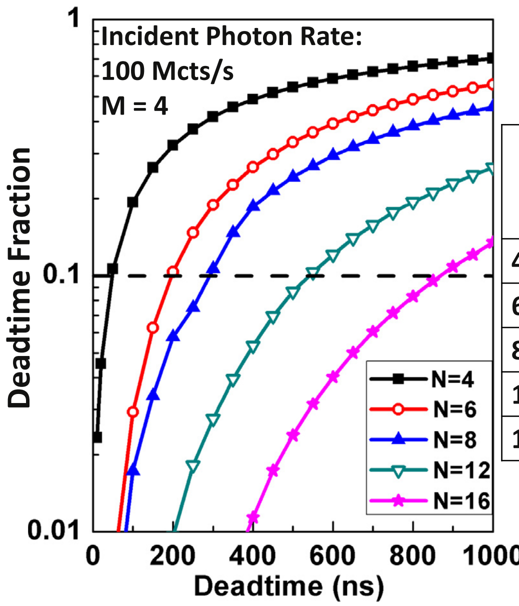
$$DTF = \frac{Missed\ pulses\ containing\ photons}{Total\ pulses\ containing\ photons} \tag{4}$$

Our simulation also assumes that: (i) the detector has 100% detection efficiency and no afterpulsing or dark counts; (ii) in a typical faint laser-based single-photon source, μ is selected to be 0.1 to reduce the multiple-photon emissions [26]; (iii) an upper detection limit in some detection applications is 10% DTF [19].

As shown in Fig. 2, when $M = 4$ with individual SPD deadtime of 50 ns, to maintain the 10% DTF level, a switchable 16-SPD array can work at ≈ 20 times the incident photon rate of that for a non-switchable SPD array. The achieved gain in speed is significantly more than the 4 times (where $N/M = 16/4$) increase in the number of SPDs. Comparing with the non-switchable detection scheme whose SPDs' deadtime is reduced 5-fold to 10 ns, the switchable SPD array still offers higher performance, as measured by the allowed incident photon rate when the number of SPDs exceeds 7, while keeping the 10% DTF upper limit. We note that for a non-switchable SPD array, if the incident photon rate increases from 10 Mcts/s to 50 Mcts/s, 100 Mcts/s, 500 Mcts/s and 1 Gcts/s, to keep the same DTF performance with that under a 10 Mcts/s incident photon rate, the SPD deadtime need to be reduced inversely from 50 ns to 10 ns, 5 ns, 1 ns, and 0.5 ns, respectively. However, when applying the switchable SPD array with the number of SPDs to be 5, 6, 12, and 16 under the incident photon rate of 50 Mcts/s, 100 Mcts/s, 500 Mcts/s and 1 Gcts/s, respectively, the DTF performance could be comparable with that under an incident photon rate of 10 Mcts/s, while still using 50-ns-deadtime SPDs.

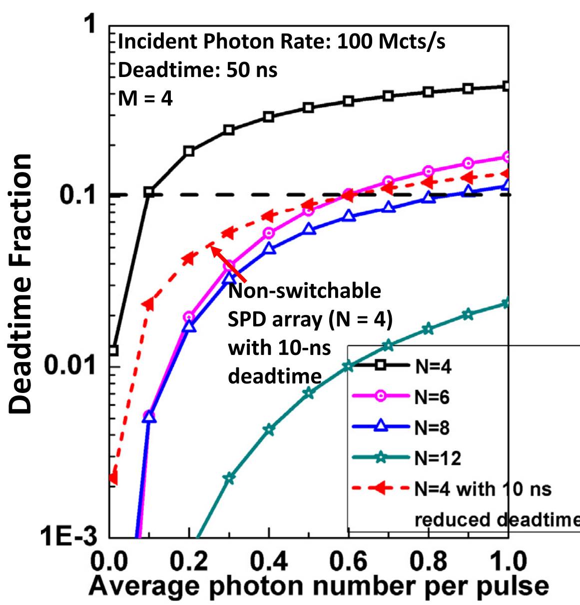
Fig. 3 shows the DTF performance with different SPD arrays for various deadtimes. We could see that when $M = 4$ and under a 100 Mcts/s incident photon rate, a switchable 16-SPD array can have SPDs with deadtime as large as ≈ 870 ns to achieve a 10% DTF. However, for a non-switchable SPD array, SPD deadtime of ≈ 50 ns are required to achieve the same level of performance. This increase of allowed deadtime is more than the 4 times increase in the number of SPDs where $N/M = 16/4$. We note that if the incident photon rate is > 100 Mcts/s, the tolerance of SPD deadtime might be less than that under 100 Mcts/s incident photon rate, and we could use more SPDs in the switchable SPD array to get a suitable tolerance of SPD deadtime.

In some applications, $\mu > 0.1$ might be needed for a multiple-photon quantum system [27,28]. When $\mu > 0.1$, the probability of detecting an event for each SPD becomes larger so that SPDs are more likely to become "dead". In this case, a switchable SPD array with more SPDs is needed. Fig. 4 shows that, when $M = 4$, operating at an incident



N	Deadtime at 10 % DTF (ns)	Improve-ment
4	≈ 50	--
6	≈ 200	≈ 4X
8	≈ 300	≈ 6X
12	≈ 550	≈ 11X
16	≈ 870	≈ 17.4X

Fig. 3. Simulation results of DTF versus SPDs' deadtimes for different SPD arrays for a 4-OAM-encoded quantum link operating at a 100 Mcts/s incident photon rate. The dashed black horizontal line shows the 10% DTF level.



N	Average photon number per pulse	Improve-ment
4	≈ 0.1	--
4 (10-ns deadtime)	≈ 0.6	≈ 6X
6	≈ 0.6	≈ 6X
8	≈ 0.85	≈ 8.5X
≥ 12	> 1	> 10X

Fig. 4. Simulation results of DTF versus μ for different SPD arrays in a 4-OAM-encoded quantum link. The dashed black horizontal line shows the 10% DTF level. The DTF curve for a non-switchable detection scheme (4 SPDs for 4 OAM states, no optical switch) with a 10-ns deadtime is also shown for comparison (red dashed line).

photon rate of 100 Mcts/s with individual SPD deadtime of 50 ns, and the 10% DTF limit is applied, the tolerance to μ could reach ≈ 0.6 or ≈ 0.85 with a switchable SPD array having 6 or 8 SPDs. By implementing a switchable SPD array with > 12 SPDs, μ could be increased to > 1. In addition, when working at an incident photon rate of 100 Mcts/s, a non-switchable SPD scheme with its SPDs' deadtime reduced to 10 ns has a tolerance of $\mu \approx 0.6$, while a switchable SPD scheme with individual deadtime of 50 ns and containing 6 or more SPDs could tolerate a larger μ under the same 10% DTF limit.

$R_{\mathrm{DTF}=10\%}$ is defined as the incident photon rate that results in a DTF of 10% [19]. It can be seen from Fig. 5 that when M = 4 and with SPDs' individual deadtime of 50 ns, increasing the number of SPDs from 4 to 20 improves the $R_{\mathrm{DTF}=10\%}$ from ≈ 90 Mcts/s to ≈ 2250 Mcts/s. This improvement in $R_{\mathrm{DTF}=10\%}$ is significantly more than the 5 times increase in the number of SPDs where N/M = 20/4. We could infer from Fig. 5 that if the SPD deadtime is limited, we could still operate at a higher incident photon rate with more number of SPDs in a switchable SPD array to maintain a DTF upper limitation of 10%. We note that our simulation indicates an ≈ 90 Mcts/s incident photon rate is allowed under the 10% DTF limit when using 4 SPDs for 4 channels (the non-switchable SPD array case). This allowed incident photon rate is larger than the estimation given in [29]. We believe this is because under the $\mu = 0.1$ assumption in our simulation model, there are some "empty" pulses that the amount of incident photons at the receiver will be less than that in [29] at the same incident photon rate. Thus a larger incident photon rate could be allowed than that in [29] under the same condition.

Clearly, the inevitable optical loss added by the switch needs to be kept to a minimum, because as the switch loss increasing, more photons would be lost and the DTF would increase. Fig. 6 shows the DTF versus the switch loss for a 4-OAM-encoded quantum link with different switchable SPD arrays. One can see that, with individual SPD

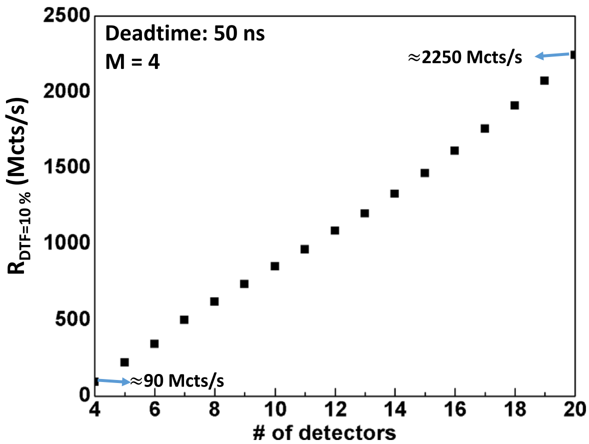


Fig. 5. Simulation results of $R_{DTF=10\%}$ versus the number of detectors for a 4-OAM-encoded quantum link.

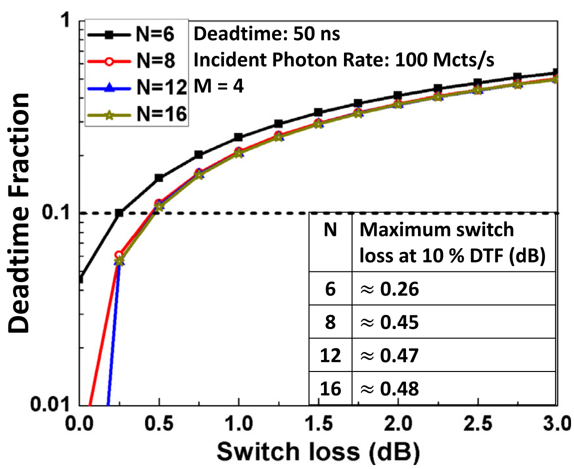


Fig. 6. Simulation results of DTF versus switch loss for different SPD arrays for a 4-OAM-encoded quantum link operating at an incident photon rate of 100 Mcts/s. The dashed black horizontal line shows the 10% DTF level.

deadtime of 50 ns and an incident photon rate of 100 Mcts/s, in order to keep within the DTF upper limit of 10%, a switchable SPD array with 6, 8, 12, 16 SPDs could tolerate a switch loss of ≈ 0.26 dB, ≈ 0.45 dB, ≈ 0.47 dB, and ≈ 0.48 dB, respectively. We could also see from Fig. 6 that if the switch loss is > 2 dB, the loss would be the major factor for the increased DTF, thereby diminishing the advantage of using switchable SPD arrays. Moreover, there are reports showing potential methods for low-loss, fast optical switches, like photonic crystal, quantum dot, and silicon photonic based Mach–Zehnder type optical switches [30,31]. This might open the possibility for future applications of the switchable SPD array to reduce the deadtime effects.

In a quantum information system, the effects of detector dark counts must also be considered, as it introduces additional errors. While passive beam-splitter tree detection schemes have also been employed as an approach to reduce the effect of the SPDs' deadtime [19], the effects of detector dark counts in this approach have a larger impact than the switchable SPD array scheme. This is because all SPDs in the beam-splitter tree scheme are "turned on" for each incident photon pulse, the system dark count rate is the sum of all the individual SPD dark count rates. However, for an actively switchable scheme the system dark count rate is just the dark count rate of the single SPD turned on by the control algorithm.

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