SPAD Receivers for Future Optical Wireless Communications

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The forthcoming sixth-generation (6G) technology is expected to provide crucial features such as ultra-high speed, subcentimetre geo-location accuracy, and global coverage [1]. To attain the envisioned KPIs, it is predicted that optical frequency bands will be thoroughly exploited in 6G. One of the main challenges of optical wireless communication (OWC) lies in the occasional outages arising from fluctuation in the received optical power, which may be introduced by numerous factors such as user mobility, beam misalignment, and atmospheric scintillation. In this paper, we explore the feasibility of leveraging single-photon avalanche diode (SPAD) based receivers to enhance OWC receiver sensitivity and mitigate the impact of received power fluctuation.

The gains of SPAD, normally on the order of millions, far surpass that of the commonly used photodiodes (PDs) in OWC. As a result, the sensitivity attainable with SPAD-based receivers is expected to well exceed that of PDs and may even approach the quantum limits. SPAD can generate a digital pulse when detecting a single photon, which eliminates the need for complex analog circuitry for signal amplification. The operation of a SPAD requires the use of a quenching circuit, which has the role of stopping the avalanche current generated by an incoming photon and preparing the avalanche diode for the next detection. During the quenching and recovery phase, the detector is blind to the incoming photon arrivals for a short period of time, also referred to as the dead time. To mitigate the effect of count loss caused by dead time, SPAD detectors are typically implemented as large arrays. Note that another key advantage of array detectors is the increase of the receiver FOV, which holds significance in laser-based communication systems where misalignment poses a considerable issue.

Dead time can result in significant nonlinear effects, imposing a fundamental limit on the achievable data rate of SPAD-based OWC systems. The primary obstacle in the extensive integration of SPAD receivers in OWC systems lies in effectively mitigating the impact of dead time. Fig. 1a presents an example of the SPAD photon detection. It is shown that due to the presence of dead time, certain incident photon arrivals are undetected if they fall within the dead time introduced by the previous photon detections. As the incident photon rate increases, the frequency of photon arrivals also increases, which exacerbates the loss of photon detection. The dead time can degrade the communication performance in two ways: nonlinear response and dead-time-induced inter-symbol-interference (ISI). If the loss of photon detections occurs within the symbol duration, it results in a receiver nonlinear response, wherein the detected photon count increases nonlinearly alongside the incident photon rate. The dead time started in a symbol may extend to the subsequent symbols. In effect, SPAD detector could be inactive at the beginning of the photon counting period (e.g., symbol 2 in Fig. 1a), leading to nonlinear dead-time-induced ISI.

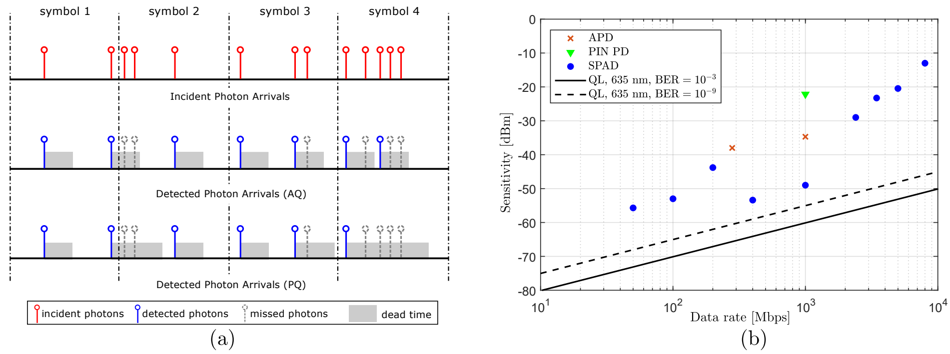

Fig. 1. (a) The dead time effects of SPAD receivers, PQ: passive quenching, AQ: active quenching; (b) The reported sensitivity versus the data rate achieved in the current literature, QL: quantum limits.

Over the last decade, there has been a substantial body of experimental research focused on exploring the potential applications of SPAD in various OWC systems. Fig. 1b shows the sensitivity of SPAD-based receivers reported in the literature versus the achievable data rate along with that for some benchmark PIN PD and APD receivers. In particular, SPAD-based OWC with a data rate of 5 Gbps was achieved through the utilization of optical OFDM [2]. More recently, 8 Gbps data transmission of SPAD OWC with wide-band VCSEL was reported in [3]. In low data rate regimes, the superiority of SPAD-based OWC over APD and PIN PD in terms of sensitivity is clearly demonstrated. In contrast, in high data rate regimes, their sensitivity levels degrade primarily due to the SPAD nonlinearity. It is anticipated that there will be a substantial enhancement in achievable data rates in the near future, facilitated by the utilization of novel modulation schemes and signal processing techniques, alongside progress in detector manufacturing methods.

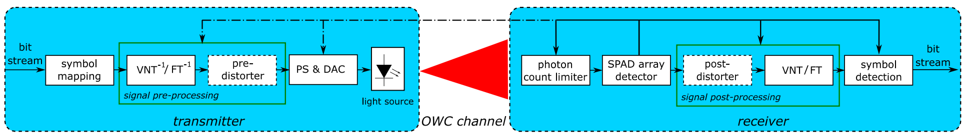

Fig. 2. Schematic diagram of the proposed SPAD-based OWC, VNT: variance normalizing transform; FT: Fourier transform; PS: pulse shaping; DAC: digital-to-analog converter.

To improve the reliability and achievable data rate of SPAD-based OWC systems and thus expand the potential of SPAD receivers in 6G networks, in this work, we propose a general framework as illustrated in Fig. 2. This framework incorporates signal pre-processing and post-processing blocks at the transmitter and receiver, respectively, as well as a photon count limiter. The pre- and post-distorter in the signal processing blocks are designed according to the SPAD's unique characteristics to alleviate the nonlinear effects caused by dead time. If nonlinearities stemming from other components, such as light source [4], prove to be significant, their mitigation can be integrated into the distorter design. SPAD-based OWC also suffers from the noise signal dependency. In contrast to conventional PDs, the noise of SPAD receivers is signal-dependent and its characteristics are notably more complex. One promising way to mitigate this effect is employing transformations that can effectively decouple signal from noise and approximately convert the signal-dependent noise channel to a signal-independent one. For single-carrier modulation, one can utilize variance normalizing transform (VNT) techniques [5]. In the case of systems with multicarrier modulation systems, the used Fourier transform (FT) inherently accomplishes the same task. Thus, in the proposed framework, noise normalization is implemented using the inverse transformation at the transmitter and the direct transformation at the receiver. The photon count limiter in the system is used to reduce the optical power when necessary to avoid excessive nonlinear effects, which may be implemented either optically using a variable optical attenuator or electrically using a gating circuit. Furthermore, the channel state information estimated by the receiver can be utilized in the key blocks to enhance the performance.

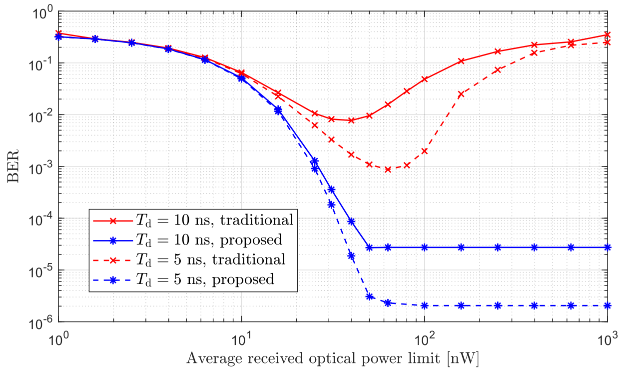

Fig. 3. Comparison of BER with the average received optical power limit for the proposed and the traditional system with different dead times.

Fig. 3 illustrates the BER performance enhancement of the proposed system over the traditional system without pre- and post-signal processing and photon count limiter. 4-PAM modulation, SPAD array with 2048 pixels, received background noise power of 10 nW, symbol duration of 5 ns, wavelength of 785 nm, and PDE of 0.18 are considered. We utilize VNT and a pre-distorter designed with the assumption of negligible dead-time-induced ISI [5], alongside a Volterra series based equalizer as a post-distorter. Note that the assumption of negligible ISI is not accurate for high-speed systems operating at high received power levels, which makes the simulated system sub-optimal. It can be observed that employing the proposed system, despite the use of sub-optimal blocks, results in a significant performance improvement. For instance, with a dead time of 10 ns, the traditional system fails to reach a BER below 10^{-3} regardless of the power level, whereas the proposed system attains this target when the power exceeds 25 nW. While the optimal design of the proposed system remains an open challenge, it is reasonable to anticipate that an optimal design will lead to additional performance enhancement.

References

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