A Normally-Distributed Crosstalk Model for Silicon Photomultipliers

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Abstract

Optical crosstalk (OCT) in silicon photomultipliers (SiPM) occurs when photon detection in a microcell leads to the production of further photons that are also detected. Various models have been considered to predict experimental data with varying degrees of success. In this paper, we introduce the Normally-Distributed Crosstalk Model (NDCM), where the probability of triggering additional microcells is given by a 2-d normal distribution with a standard deviation of σ : a device-specific parameter representing OCT photon propagation path length in terms of microcell pitch. Monte Carlo (MC) simulations of NDCM are compared to existing models and experimental data from the CHEC-S camera developed for the Cherenkov Telescope Array, which suggests that OCT occurs with a $\sigma \approx 5$ microcells in this device.

Keywords: Silicon photomultiplier, SiPM, Optical crosstalk

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1. Introduction

Silicon photomultipliers (SiPMs) are solid state, low voltage, optical photon-counting photodetectors [1] comprising an array of Geiger-mode avalanche photodiode microcells. When a photon is detected on a SiPM biased above its characteristic breakdown voltage, a Geiger breakdown occurs via impact ionisation in a single microcell. Typically, 3 photons are generated for every 10^5 avalanche electrons [2]. These can trigger further Geiger avalanches in other microcells, a process known as optical crosstalk. Once a microcell is triggered it is effectively disabled during its recharge time constant, typically ≈ 50 ns. The number of photoelectrons (PE) measured for an incident photon indicates the number of microcells that are triggered.

OCT can occur via reflections off different surfaces such as the protective resin input window or the back of the device and its probability is related to operational and architectural parameters, such as SiPM over-voltage, presence of trenches, and window thickness[3]. OCT is quantified in terms of the number of excess microcells that are triggered.

Crosstalk has been modeled in several different ways, including the analytical Borel [4][5] and the nearest-neighbour/Gallego (NN) [2] models. The Borel model is equivalent

Figure 1: Different models for considering OCT. In a), a single triggered event in the Borel model can lead to several additional events, shown in b) on a pixel where secondary microcells are independent of the initial triggered microcell. c) shows the NN model, where only the nearest microcells to a triggered microcell can be triggered due to OCT photons.

alent to a chain of events, with a probability P_k of k PE given by $P_k = (\lambda k)^{(k-1)} e^{-\lambda k} / k!$, where λ is the crosstalk probability. It represents a microcell triggering due to initial photon detection, giving rise to OCT on any other microcell without spatial constraints, effectively using an infinite-sized SiPM, figure 1a–b.

The NN model [2], allows only microcells closest to a triggered microcell to be triggered by OCT photons. This model incorporates a fixed spatial distribution, as shown in figure 1c.

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Figure 2: a) PE probability ($\Sigma P_k=1$) against the distribution width σ . For larger σ , P_{NDCM} tends towards the values predicted by Borel, until it is affected by the size of the pixel. b) Experimental data obtained from the CHEC-S camera, with $P_k=1$ normalised to 1 (shown on the right axis), and how the experimental data compares to probabilities from different models for $\lambda=0.5$ (shown on the left axis). The model shows the best agreement for a larger sigma value over a larger pixel size, suggesting that OCT photons propagate a long distance.

Both the Borel and NN models can demonstrate good agreement with experimental data depending on the SiPM configuration. The Normally-Distributed Crosstalk Model (NDCM) has been developed to improve the all-round fit to experimental data. We introduce the NDCM and compare outputs from Monte Carlo (MC) simulations to experimental data from the CHEC-S camera [6] being developed for the Cherenkov Telescope Array (CTA) [7] and the analytical Borel and NN models.

2. The Normally-Distributed Crosstalk Model (NDCM)

The NDCM uses a 2-d normal distribution (ND) centered on the initial triggered cell, with a width σ to weight the probability of an individual pixel being triggered due to OCT. σ is a parameter that describes how far an OCT photon can propagate from the triggered cell, and therefore controls how many microcells are available to be triggered.

MC simulations were developed to investigate the NDCM behaviour at different values of σ and λ . At small σ , NDCM predicts a k PE probability $P_{\text{NDCM}}(\lambda = 0.5, \sigma, PE = k)$ greater than the P_k predicted by Borel for $k \leq 2$, and lower for $k \geq 3$, as shown in figure 2a. This is because the number of microcells that are available to be triggered, $N \approx 9\pi\sigma^2$, is constrained by the small σ . For $\sigma \approx 3$ microcells, the width of the distribution is such that $P_{\text{NDCM}}(\lambda, \sigma \approx 3, PE) \approx P_k$. At $\sigma > 5$ microcells,

the $P_{\text{NDCM}}(\lambda, \sigma > 3, PE)$ decreases as the secondary microcells are triggered further from the original microcell and are increasingly likely to be located outside the finite SiPM boundary. The decrease in $P_{\text{NDCM}}(\lambda, \sigma, PE)$ is faster for a smaller SiPM size.

The NDCM was compared to an experimental pulse height distribution (PHD) from the CHEC-S camera. The PHD parameters were used to generate the equivalent PHD for 1PE, and indicated $\lambda=0.5$. PE probabilities from the Borel and NN models were calculated for $\lambda=0.5$, $P_{\text{NDCM}}(\lambda = 0.5, \sigma, PE)$ was found for different σ values, and the 1PE probabilities were normalised to 1. The CHEC-S data is approximated well by the Borel model due to the high λ , as shown in figure 2b. Although each pixel is 120x120 microcells [6], the best NDCM fitting is given for $\sigma=5$ across 600x600 microcells. The large σ suggests that OCT photons propagate far from the original microcell; given the high λ , this is compatible with the Borel model prediction. The wider area allows for more of the tail of the ND to be measured, increasing probability of higher PE events as observed in the CHEC-S camera. This suggests a ND alone does not model the OCT close to the original microcell ideally, with further analysis required to improve understanding of the distribution.

3. Conclusion

The Normally Distributed Crosstalk Model (NDCM) gives $P_{\text{NDCM}}(\lambda = 0.5, \sigma, PE)$ related to device architectural parameters such as the pixel and cell sizes, and comparable to other analytical models. σ is proposed as a device specific parameter related to possible OCT propagation paths. A small σ constrains the number of available microcells, and hence λ . Initial analysis for the CHEC-S camera gives $\sigma \approx 5$ microcells for $\lambda=0.5$. Ongoing work is considering how σ is related to architectural parameters, and introducing further mechanisms into NDCM.

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