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The SPAD Noise effects on the performance of adaptive incremental sensor networks with the VLC technology in Mines

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***Abstract*— Noise is the main affecting parameter in the performance of the estimation and tracking systems. The problem of distributed estimation through adaptive networks has been greatly tangled with the presence of noise in the nodes and in the links that are connecting these nodes. There are various types of noises according to their different sources. Recently, by the development of the Visible light communication (VLC) systems, the implementation of wireless adaptive networks has been suggested with this technology. The VLC systems have their own noise type regarding the Single photon avalanche diodes (SPADs). The SPADs are usually used in the very weak light signal conditions that mines are very likely to one of the main places to use them due to the extra dust and dim environment. The usage of these SPADs will lead to the generation of the multiplicative sub-Poisson noise. In this paper, we examined the effects of this unique type of noise on the performance of adaptive incremental networks. Also, the effect of combined Gaussian, sub-Poisson noise model is examined and compared with Only Gaussian noise model.**

Keywords—Adaptive networks, VLC, SPAD noise, incremental strategy, distributed, Mining applications.

I. Introduction

The incremental adaptive networks are interesting tools for the monitoring and estimation of different entities in an environment when the data collection and processing power of the detecting nodes are low and we do not want to have a central processing node [1-8]. In these situations, the distributed processing is the best offer and the incremental networks are the main tools for this type of processing. The adaptive networks have been proposed in several types and the incremental, diffusion and consensus networks are the most famous of them. It has been shown in many applications that the diffusion network produces better results in different application due to their rigorous communication between the nodes. However, in some applications, we do not access to large quantities of the communication and node power and therefore we need to stick to the incremental networks where each node can only communicate with two adjacent nodes. This may cause certain disadvantages like when one of the nodes become non-operational or the link failure becomes inevitable, however, when the resources are low, we must face these problems. The best way to avoid the link failure, is to presume the link conditions and prepare our network to operate in the worst conditions. One of the main problems that have been presumed for the performance of the adaptive networks is the problem of noise [1]. Noise can affect the estimation and monitoring quality of the incremental network directly [2]. Although there are many types of noise in the communication environment, the researchers in [1] and [2] only considered the additive Gaussian white noise effect on the adaptive networks. This assumption was partly because of the partial simplicity of the calculations for the theoretical analysis of the additive Gaussian noise effects on the network performance. However, imagine that one wants to implement the adaptive incremental networks with other technologies rather than the radio frequency communication [3-8]. This novelty has been addressed through several papers by considering the free space optical [4, 8] and the visible light communication (VLC) technologies [5] for implementing the adaptive networks. Although the dominant noise is also additive white Gaussian noise, in FSO and VLC, sometimes other noise types may affect their systems. For example, in the VLC implemented systems for mining applications, the multiplicative sub-Poisson noise becomes dominant. This noise problem is happening due to the usage of Single Photon avalanche diodes (SPADs) in the VLC systems and is usually named as the SPAD noise problem [9-22].

There are two types of SPADs: The Active quenching (AQ) with lower dead time and higher count rate and the passive quenching (PQ). These two quenching types cause SPAD noises with different statistical characteristics which we will be explaining later. The usage of SPADs have been proposed in many wireless optical communication systems including [9-22]. For example, in [9], the effect of the SPAD noise has been examined on on-off keying systems.

In [18], a practical photon counting receiver in optical scattering communication with finite sampling rate, paralyzable dead time, and electrical noise is characterized where it is shown that the dead time effect leads to sub-Poisson distribution for the number of recorded pulses. The approximate photon count distribution derived in [18], is only applicable if the photon rate is sufficiently low. In [19], we studied the statistical behavior of an AQ SPAD receiver and investigated the effect of non-paralyzable dead time on the bit error performance of an optical system. We extended our approach in [20] and an array of AQ SPADs was characterized for OWC applications. We also studied the information transfer rate of an AQ SPAD in [21] where the AQ SPAD receiver was modeled as a discrete memory less channel, and the information transfer rate was studied using an information theoretic approach.

Recently, in [5] and [6] the authors have proposed the implementation of adaptive incremental networks in the underwater environments using the VLC technologies. In these references the authors thoroughly considered the effects of the underwater environment on the link conditions and the performance of the incremental networks. However, the problem of noise other than the Gaussian is still remained unhindered. In this paper, based on the research on the VLC systems, we considered the effect of the Poisson noise on the implemented incremental networks. Also, the investigation of performance in this paper is different with other papers because of the fact that the sub-Poisson SPAD noise is multiplicative and is not additive. Therefore, this noise type is affecting the network such as the turbulent link coefficients. In order to elaborate the effects of SPAD noise on the incremental network for mining applications, we neglected the turbulent channel effects on its performance.

II. THE SPAD NOISE PROPERTIES

The additive Gaussian noise problem for the adaptive networks have been fully addressed in [1] for the incremental and more completely in [2]. Also, the authors have investigated the effects of the multiplicative link turbulence coefficients in reference [3-8] for the incremental networks. However, the problem of multiplicative noise effects like the SPAD noise is yet to be addressed. The previously presented additive Gaussian noise model is applicable almost to all communication systems including the VLC system that is considered in this paper. However, in order to be more specific about the noise behavior of these systems, we must first take a look on the components of these systems. The VLC system operates with the following components in Fig. 1:

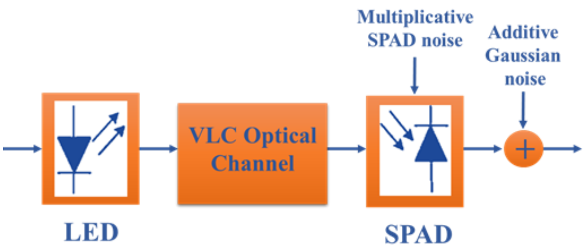

Fig. 1. The VLC communication system by considering the usage of SPADs in mining applications.

The usage of SPADs, make the problem of the multiplicative noise in VLC systems and we use them in weak signal conditions as in mining applications. If we consider the dead time to be zero, the photon detection events of a SPAD receiver are given as a Poisson process and the probability of counting k photons during a time period of $(0, T_b)$ is as follows {9]:

$$p_0(k) = \frac{(\lambda T_b)^k e^{-\lambda T_b}}{k!} \qquad (1)$$

Here, the constant λ is the average photon arrival rate (in photons/s), therefore, λT_b is the average number of photons arriving at the SPAD during the observation time of T_b seconds. The photon arrival rate λ is related to the power of the optical signal as follows [9]:

$$\lambda = \frac{\eta QE P_r}{h\nu} \qquad (2)$$

In this relation, ηQE is the quantum efficiency of the SPAD; P_r denotes the power of the incident optical signal; h is the Planck's constant; and ν represents the frequency of the optical signal. In the presence of dead time, however, the photon counts no longer follow a Poisson distribution. As we mentioned in the introduction part, The SPAD noise with the consideration of death time can be either AQ or PQ. Here, we explain these noise models in detail in mining applications [9]:

A. AQ SPAD Noise model

For AQ SPADs, after each photon detection, the detector is inactive for a constant time τ. A photon is detected if and only if no detection event has taken place during a time τ preceding it, and any photon arriving during the dead time is neither counted nor has any influence on the dead time duration. The noise distribution for AQ SPAD [9]:

$$p_k(k) = \sum_{i=0}^{k} \psi(i, \lambda_{k+1}) - \sum_{i=0}^{k-1} \psi(i, \lambda_k) \qquad (3)$$

Where $\psi(i, \lambda) = \lambda^i \frac{e^{-\lambda}}{i!}$ And $\lambda_k = \lambda(T_b - k\tau)$. It is important to mention that λ is the average photon arrival rate $\left(\frac{photon}{s}\right)$ and λT_b is the average number of photons arriving at SPAD during the observation time T_b.

The mean and variance of AQ SPAD:

$$\mu_k = (K_{max} - 1) - \sum_{k=0}^{K_{max}-2} \sum_{i=0}^{k} \psi(i, \lambda_{k+1}) \quad (4)$$

$$\sigma_k^2 = \sum_{k=0}^{K_{max}-2} \sum_{i=0}^{k} (2K_{max} - 2k - 3)\psi(i, \lambda_{k+1}) - \left(\sum_{k=0}^{K_{max}-2} \sum_{i=0}^{k} \psi(i, \lambda_{k+1})\right)^2 \qquad (5)$$

The PDFs for AQ SPAD distribution are shown in Fig. 2, for various values of $\delta = \frac{\tau}{T_b}$.

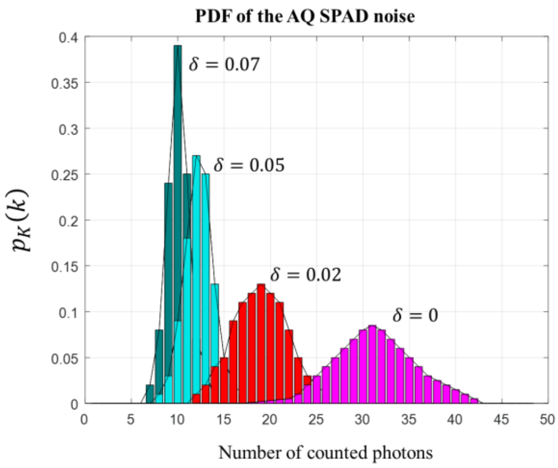

Fig. 2. PDFs of the AQ SPAD noise for $T_b = 1\mu s$ and $\lambda = 3 \times 10^7$ in mining applications.

B. PQ SPAD Noise model

The For PQ SPADs, any photon arrival is followed by dead time, and the ones occurring during the dead time of previous photons, extend the dead time duration. The noise distribution for PQ SPAD [9]:

$$p_k(k) = \sum_{i=k}^{K_{max}-1} (-1)^{i-k} \binom{i}{k} \frac{\lambda^i (T_b - i_\tau)^i}{i!} e^{-i\lambda\tau} \quad (6)$$

The mean and variance of PQ SPAD:

$$\mu_k = \lambda e^{-\lambda\tau}(T_b - \tau) \quad (7)$$

$$\sigma_k^2 = \lambda^2 e^{-2\lambda\tau}(3\tau^2 - 2T_b\tau) + \lambda e^{-\lambda\tau}(T_b - \tau) \quad (8)$$

The PDFs for PQ SPAD distribution are shown in Fig. 3, for various values of $\delta = \frac{\tau}{T_b}$.

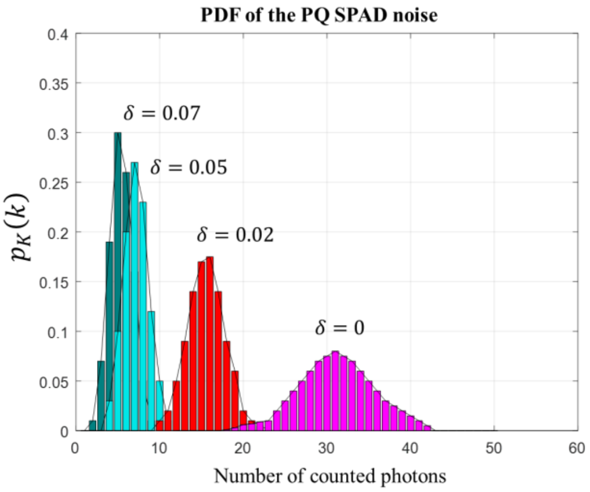

Fig. 3. PDFs of the AQ SPAD noise for $T_b = 1\mu s$ and $\lambda = 3 \times 10^7$ in mining applications.

III. THE VLC INCREMENTAL ADAPTIVE NETWORK WITH SPAD NOISY LINKS

The additive Gaussian noise comes from the thermal variations of the electrical components of the VLC system, while the source of the multiplicative noise is the single photon avalanche diode. We will apply this noise model on the incremental network to simulate its performance with the real VLC components. The incremental network that is considered in this paper is designed to estimate or track an unknown vector $\boldsymbol{w}^o$ based on the indirect input u_i and outputs (d_i) that are related to the following relation [3-8]:

$$d_k^{(i)} = \boldsymbol{u}_k^{(i)} \boldsymbol{w}^o + v_k^{(i)} \quad (9)$$

in this relation, the (i) index shows the iteration pace and the k index indicates the sensor number to show that each sensor at iteration (i) collects its own inputs and outputs, the $v_k^{(i)}$ parameter is also used to show the sensor measurement noise. The overall incremental network operation with the LMS algorithm and the ideal link conditions is as follows:

$$\begin{cases} \boldsymbol{\psi}_0^{(i)} \leftarrow \boldsymbol{w}_N^{(i-1)} \\ \boldsymbol{\psi}_k^{(i)} = \boldsymbol{\psi}_{k-1}^{(i)} + \mu_k \boldsymbol{u}_k^{(i)*}\left(d_k^{(i)} - \boldsymbol{u}_k^{(i)} \boldsymbol{\psi}_k^{(i)}\right) \end{cases} \quad (10)$$

In these equations, the μ is the step size, $\boldsymbol{\psi}_k^{(i)}$ shows the local estimation. After performing the local estimation based on these data, the sensor sends this estimation to its immediate neighbor node. However, this communication between the nodes is through VLC link and experiences noise. An incremental network in noisy conditions is depicted in Fig. 4:

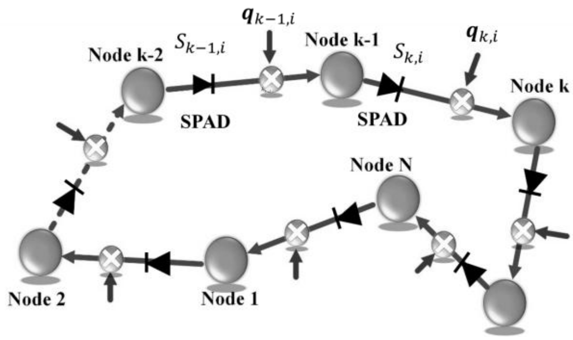

Fig. 4. The implementation of the incremental adaptive network with VLC technology and SPADs in mining applications.

In this figure, the link noise values, that follow the Gaussian distribution, are shown with the $\boldsymbol{q}_k^{(i)}$ parameter and the link turbulence coefficients are shown with the $I_k^{(i)}$. As the links between the nodes are noisy and turbulent, the received local estimation by node k would be:

$$\boldsymbol{r}_k^{(i)} = I_k^{(i)} \boldsymbol{\psi}_k^{(i)} + \boldsymbol{q}_k^{(i)} \quad (11)$$

with this assumption, the updating relation of incremental network changes to:

$$\boldsymbol{\psi}_k^{(i)} = \boldsymbol{r}_k^{(i)} + \mu_k \boldsymbol{u}_k^{(i)*}\left(d_k^{(i)} - \boldsymbol{u}_k^{(i)} \boldsymbol{r}_k^{(i)}\right) \quad (12)$$

and by replacing (5) in (6) we have:

$$\boldsymbol{\psi}_k^{(i)} = I_k^{(i)} \boldsymbol{\psi}_{k-1}^{(i)} + \boldsymbol{q}_k^{(i)} + \mu_k \boldsymbol{u}^*\big(d_k^{(i)} - \boldsymbol{u}_k^{(i)}(I_k^{(i)} \boldsymbol{\psi}_{k-1}^{(i)} + \boldsymbol{q}_k^{(i)})\big) \quad (13)$$

To evaluate the performance of the incremental network, we used the mean square deviation (MSD) and excess mean square error (EMSE) values defined as [13]:

$$MSD_k \triangleq \lim_{i\to\infty} \mathbb{E}\left[\left\|\widetilde{\boldsymbol{\psi}}_{k-1}^{(i)}\right\|_{\boldsymbol{I}}^2\right] \quad (14)$$

where $\widetilde{\boldsymbol{\psi}_k^{(i)}} \triangleq \boldsymbol{w}^o - \boldsymbol{\psi}_k^{(i)}$ is the weigh error vector at sensor k and iteration i, $\boldsymbol{I}$ is a 4×4 identity matrix. Using these values, we present the simulation performance of the incremental network.

IV. NOISE EFFECT SIMULATIONS

W surmise that the incremental network is implemented in a mine with weak light conditions with a 20 node count and apply additive and multiplicative noises on them to perform several Monte Carlo simulations. The Gaussian additive noise is assumed to have several variances and the statistical

properties of the multiplicative SPAD noise is also taken as: $T_b = 1\mu s$, $\delta = \frac{\tau}{T_b}$ and we have $\delta = 0.001$, $\delta = 0.01$ and $\delta = 0.1$. The simulation parameters of the Incremental network are given in Fig. 5:

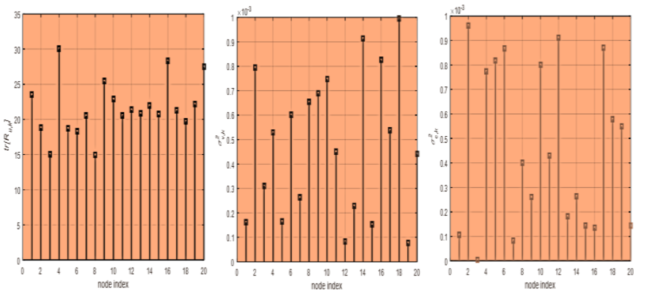

Fig. 5. The simulation parameters for implementing the incremental network in mining applications.

The simulation results are given for AQ SPAD noise condition in Fig. 6. As we can see the multiplicative SPAD noise effects can be much more degrading for the estimation performance of the incremental network than the additive Gaussian noise. This is because of the distorting effect of the multiplicative coefficients to the communicated estimations of the neighboring nodes. Also, we can see that as the values of the SPAD δ parameter rises, the distorting effect of the multiplicative noise becomes larger.

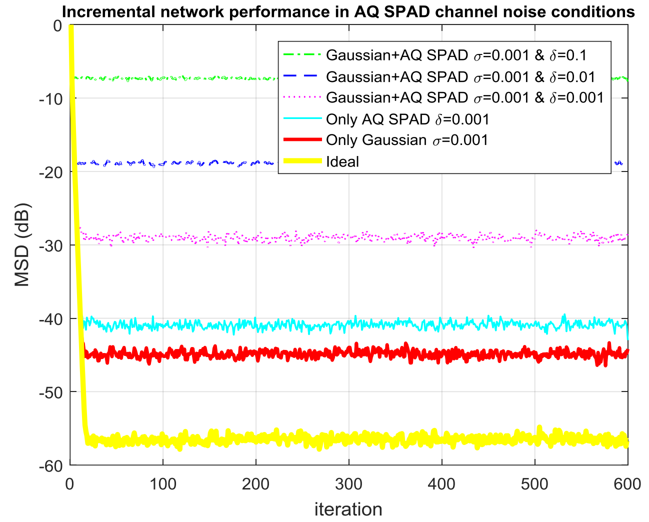

Fig. 6. The performance of the incremental adaptive networks in AQ SPAD channel noise conditions, for mining applications.

In fig. 7, we can see the effect of PQ SPAD noise on the performance of the incremental adaptive networks. As we expected, the degrading effects of the PQ SPAD noise is more than the AQ noise.

As we can see in Fig. 8, the effects of the PQ SPAD noise is slightly more degrading for the Incremental network performance than the AQ SPAD noise effects.

V. Conclusion

In this paper, for the first time we examined the effect of non-Gaussian multiplicative SPAD sub-Poisson noise on the performance of the distributed incremental adaptive networks in mining applications. In comparison of Gaussian additive and sub-Poisson multiplicative noises, it is shown that in the VLC based adaptive incremental network system, sub-Poisson noise is dominant. The exact performance results are shown in the presence of Gaussian noise, sub-Poisson noise models based on the SPAD delta values with the MSD criteria. It is demonstrated that the PQ SPAD noise model is more degrading for the incremental networks than the SPAD PQ noise model. In future works, we will examine the more detailed effects of the optical appliances on the performance of the adaptive networks. Also, the complete theoretical performance results of the incremental networks in the SPAD noise conditions will be presented.

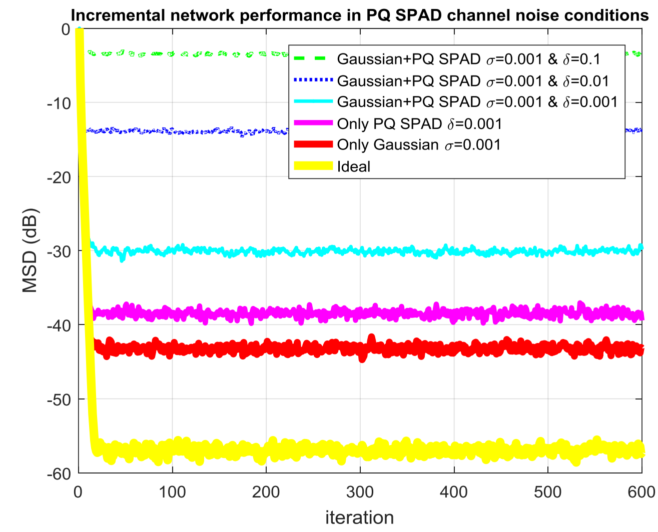

Fig. 7. The performance of the incremental adaptive networks in PQ SPAD channel noise conditions, for mining applications.

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