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Nonlinear Array Detection Strategies for Optical Beams in Long Range Free-Space Optics Channels

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ABSTRACT

In this study, we examine the problem of array detectors for free-space optical (FSO) communication systems when the optical field is detected using an array of detectors in the presence of large background noise and non-negligible pointing error. It is assumed that the spatial pointing errors are due to beam tilt and/or platform vibration. We propose and study a nonlinear detection mechanism for processing the outputs of the photodetectors (PD). The proposed strategy performs photodetector array combining that favors the PDs with non-negligible signal strengths, which are proportional to the spatial characteristics of the beam. Provided that the spatial profiles of the optical beams in single and multiple-spatial-mode scenarios are non-uniform, uniform aperture detector arrays will provide only a suboptimal performance. That is, the spatial feature of the detector is assumed to match the spatial feature of the received beam. This principle mirrors the concept of matched filtering in time domain for the detection of signals buried in additive white Gaussian noise. Performance in this paper is established in terms of the overall bit error rate for direct-detection receivers. It is shown that the proposed detection strategy results in a sizeable gain in performance in terms of reducing the bit error rate by an order of magnitude for all conditions, including when the pointing error is substantial.

Keywords: Array, Detectors, FSO,

1. INTRODUCTION

The use of array of detectors has been subject of a number of studies for deep-space applications[1-8]. Array detection has also been proposed for FSO communications in urban arenas in the presence of turbulence[4-7,9]. In general, the use of arrays enables one to compensate for the misalignment at the receiver, to capture the received optical beams that are subjected to the atmosphere-induced tilt and wander, and to capture optical fields that have been extended beyond the diffraction-limited field of view of the receiver due to atmospheric effects. To achieve the benefits stated above, the receiver must consider the outputs of the PDs and combines them to achieve the desired performance. A simple combining involves the sum of the detected signals. Such an approach is reasonable when a small number of detectors are utilizing. For large number of detectors, one is faced with the problem of taking into account the output of PDs that are exposed only to the background radiation. In near-earth applications, when the optical receiver may face the "hot" earth, the background radiation may hamper the performance of such an approach. For this reason, a more intelligent approach to combining the output of PDs in detector arrays may be considered. One approach is to estimate the presence of the desired optical field in one or several PDs and only consider the outputs of such detectors[3]. However, such a technique requires that one performs estimation of the signal level[4,5,7]. Such estimation techniques are prohibitively complex and can lead to an unacceptable level of complexity in multi gigabit per second (Gbps) optical communication link when a large number of array elements are brought to bear. Given the uncertainties in the reception of the optical field in a long range FSO system, the use of large number of array elements is desirable. Hence, one must consider novel strategies other than a simple combining of the detected signals that are generated by the array elements.

In this paper, we propose a simple and yet effective means for combining the detected signals. In this strategy, we emphasize the output of the photodetectors which are receiving the desired optical field while deemphasizing the photodetector outputs that are exposed to the background noise only using a nonlinear process. It is shown that this technique will enhance the performance of a PD array by a sizeable margin. Given that no signal estimation is required, the proposed technique is well-suited for deployment in practical FSO systems operating in harsh environments.

This paper is organized as follows. In Section 2, we present a system model and describe the optical detection mechanism. Furthermore, the propose method for combining the outputs of the photodetectors is introduced in this section. In Section 3, with the aid of simulation, we present the performance of the standard receiver with array detectors. We compare the performance of the standard receiver with that of the proposed receiver in this section under variety of conditions, including when a substantial pointing error is present at the receiver.

Finally, in Section 4, we present the concluding remarks.

2. SYSTEM MODEL

2.1 Optical Receiver

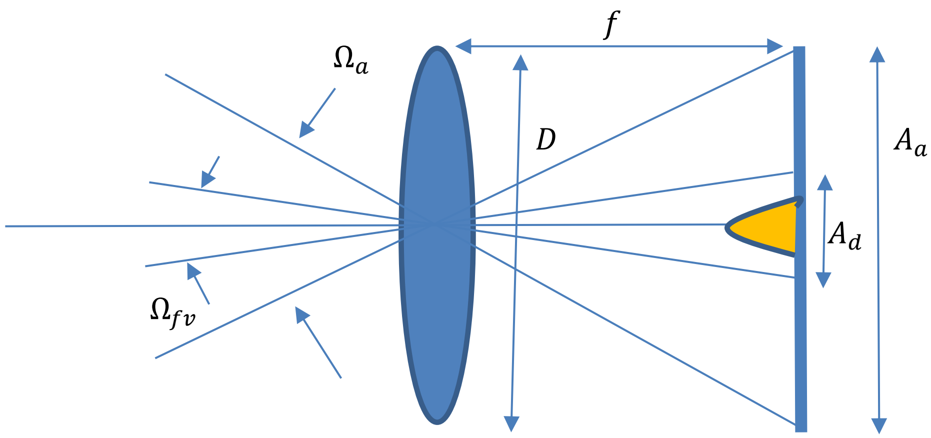

Fig. 1. Focal plane detector array.

In this study, we assume a direct-detection receiver with binary pulse-position modulation (BPPM). The optical signal is detected using an optical assembly followed by an array of PDs. As shown in Fig. 1, the optical assembly offers a field of view $\Omega_a = \frac{A_a}{f^2}$, where $A_a$denotes the area of the optical reception, consisting of N^2photodetectors, each with an area of A_a. Furthermore, $f$denotes the focal distance of the focusing lens. It is further assumed that the diffraction limited optics focuses each mode of the incident light onto only one photodetector with an area of A_d. The diffraction limited field of view of the receiver, then, is given by

$$\Omega_{fv} = \frac{A_d}{f^2} . \tag{1}$$

Hence, N must satisfy the following:

$$N^2 = \frac{A_a}{A_d} = \frac{\Omega_a}{\Omega_{fv}}. \tag{2}$$

As can be seen, this optical assembly is capable of receiving N^2 spatial modes. This allows for a wide variation in the direction of arrival as well as pointing jitter and uncertainly. This also allows for beam broadening that will happen in a long distance optical propagation, such as ground to space or space to ground laser communications.

2.2 Detection Mechanism

For the problem at hand, the detectors produce independent signals. Let r_{ij}^{+} denote the photon count for the ijth PD over the 1st slot duration of the BPPM symbol. Furthermore, let r_{ij}^{-}denote the similar count for the 2nd time slot of the BPPM signal. Then, the following decision variables are formed:

$$\Lambda_1 = \sum_{i=1}^{N} \sum_{j=1}^{N} r_{ij}^{+} \tag{3}$$

and

$$\Lambda_2 = \sum_{i=1}^{N} \sum_{j=1}^{N} r_{ij}^{-} \ . \tag{4}$$

Then, the optimum receiver is given by

$$\hat{d} = \arg\max\{\Lambda_j\}\ ; j = 1{,}2\ , \tag{5}$$

where $\hat{d}$ denotes the estimate of the transmitted binary data $d \in [0{,}1]$. One main disadvantage of this method is that, among the N^2 photodetectors, it is possible that only one PD is receiving the desired signal while others are merely collecting background radiation. Hence, a strategy that amplifies the desired PD output while suppressing the noise generating PDs will invariably yield a superior performance when compared to the strategy outlined by (5). Note that such a strategy must consider all possible spatial modes of the signal. That is, more than one PD may be receiving signal, which may very well not be centered about the center of the detector array.

We propose a new detection strategy, given by

$$\hat{d} = \arg\max\{\Lambda_j^{\mathrm{p}}\}\ ; j = 1{,}2 \tag{6}$$

where

$$\Lambda_1^{+} = \sum_{ij=1}^{N} g(\, r_{ij}^{+}) \tag{7}$$

and

$$\Lambda_2^{-} = \sum_{ij=1}^{N} g(\, r_{ij}^{-}). \tag{8}$$

In the above, $g(x)$ is a nonlinear function to be determined. One key factor about this function is that it must be a monotonically increasing function of its argument. This is due to the fact that when a PD is illuminated over a given time slot by the desired signal, it will yield a strong response, whereas the response from background noise illuminated PDs is weak. In that case, such a function will emphasize the decision variable corresponding to the correct time slot and PD while de-emphasizing a similar metric for the empty time slot of the other PDs. In this paper, we consider power of n type nonlinearity. That is, without the loss of generality, we consider

$$g(x) = x^n \tag{9}$$

for some n. In this paper, via simulation, we study the performance of the array for $n = 2\ and\ 3$. Note that this receiver does not require an estimation of the signal level and is relatively simple to operate with the use of nonlinear devices (if digital signal processing is not possible due to high-speed signaling). This is critical as multi-Gbps systems with a large number of detectors can put a serious burden on the complexity of the signal processing systems that follow the optical detection.

2.3 Detection Statistics

As noted above, we have a direct-detection receiver, which is operating under the impact of a non-negligible background radiation. Hence, we assume that the detector operates under a background noise-limited scenario, which will yield Gaussian statistics for the detected signal. We assume a scenario where the output current of the PD is integrated for the two consecutive time slots of the BPPM symbol to form r_{ij}^+ and r_{ij}^-, respectively. Assuming that the ijth PD is the recipient of the signal, then for a direct-detection receiver, subject to background noise and thermal noise, the expected value of the observed photon count (integrated over a slot duration of a BPPM symbol) when conditioned on the data is given by[10]

$$\chi_{ij}^+ = E\{r_{ij}^+|d\} = g(dK_s + K_b) \tag{10}$$

and

$$\chi_{ij}^- = E\{r_{ij}^-|d\} = gR\left(\bar{d}P_s + P_b\right)T_s \tag{11}$$

where that data bit $d \in [0,1]$ and $\bar{d}$ is the complement of d. Furthermore, $K_s, K_b,\ and\ g$ denote the photon count of the signal in the BPPM slot, the background photon count over the BPPM slot, and the average gain of the PD (this includes the amplifier gain that will be used to amplify the detected signal). Furthermore, variances of r_{ij}^+ and r_{ij}^- , respectively, are given by[10]

$$\sigma_{+,ij}^2 = Fg^2(dK_s + K_b) + \sigma_n^2 \tag{12}$$

and

$$\sigma_{-,ij}^2 = Fg^2\left(\bar{d}K_s + K_b\right) + \sigma_n^2 \tag{13}$$

where F denotes the PD's excess noise factor. For p-i-n PDs, typically $F = 1$. For avalanche PD, however, $F > 1$. In the above equations[10],

$$\sigma_n^2 = \frac{2kT_0}{e^2 R_L} T_s \tag{14}$$

is the variance of the thermal noise contribution to the photon count where $k, T_0, and\ R_L$ denote the Boltzmann's constant, the operating temperature of the receiver in Kelvin, and the load resistance of the detector. Furthermore, $e\ and\ T_s$ denote the charge of an electron and the BPPM slot duration in sec. Note that the presence of a signal in a given PD impacts the desired PPM slot substantially when the received signal power is not negligible. It is then justifiable to consider a scenario where the receiver emphasizes such PD outputs while suppressing the other PDs, which are simply receiving background and thermal noise contributions. For the PDs that are not in receipt of any signal, we have

$$\chi_{nm}^+ = \chi_{nm}^- = gK_b; nm \neq ij \tag{15}$$

and

$$\sigma_{+,nm}^2 = \sigma_{-,nm}^2 = Fg^2K_b + \sigma_n^2\ ; nm \neq ij. \tag{16}$$

Finally, we are interested in the statistics of $\Lambda_{1,2}^{\pm}$. There are two key assumptions that are made here. First, as noted earlier, we assume a background noise limited scenario, leading to a Gaussian statistic for the detected signal. Furthermore, given that we assume a large number of detectors, such as $16\ (4 \times 4),\ 36(6 \times 6),\ or\ 64(8 \times 8)$ detector arrays, $\Lambda_{1,2}^{\pm}$ may also assume a Gaussian statistics as well due to the central limit theorem even though the nonlinearity that is applied, *i.e., $g(x)$,* will alter the statistics of the detected signal from Gaussian to non-Gaussian.

To gain insight, in the ensuing section, we use simulation to gain an understanding of the potential of the proposed method in enhancing the performance of array detectors in the presence of large background noise and when large pointing error may be present.

3. SIMULATION RESULTS

Without the loss of generality, we consider a 8×8 detector array. We consider two scenarios of $K_b = 10$ & 20 to account for various background noise levels. We also consider thermal noise level at room temperature ($T_0 = 300\ k$) and when a large level of thermal noise is present (*i.e.*, when $T_0 = 338\ K$). Three types of receivers are considered; the standard receiver, the squaring received ($n = 2$), and cubic receiver ($n = 3$).

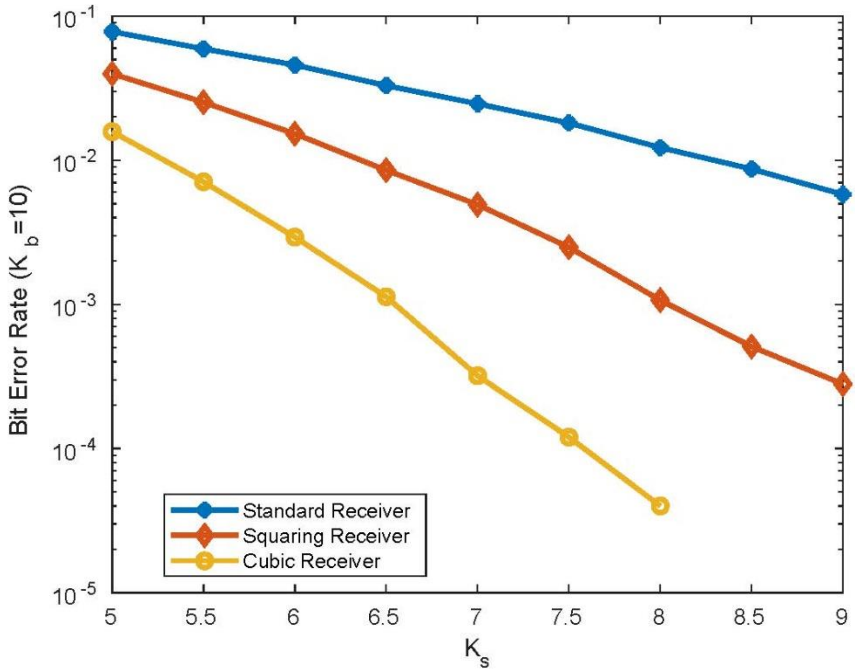

Fig. 2. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 10, T_0 = 300K, \bar{g} = 3500, F = 1$.

In Fig. 2., we are presenting the performance of the three receivers. As can be seen, the proposed receivers outperform the standard receiver by significant margin. We note that the use of 64 PDs reaffirms the Gaussian statistics as all receivers studied here combine 64 random variables regardless of the level of the background or signal processes.

We assume that the received signal impinges upon only one PD while the other PDs are collecting background noise. Since we are considering the bit error rate of an uncoded system, we target the error rate of $10^{-4} - 10^{-2}$. With advanced coding techniques, one can expect error rates less than 10^{-6}. As can be seen, the standard receiver yields an unacceptable performance. The enhancement in performance using the proposed receivers is in the range of several orders of magnitude. This is expected as a simple combining takes into account 63 photodetector outputs that are due to background noise only. In contrast, the proposed receivers substantially reduce the output of PDs that are exposed to noise only.

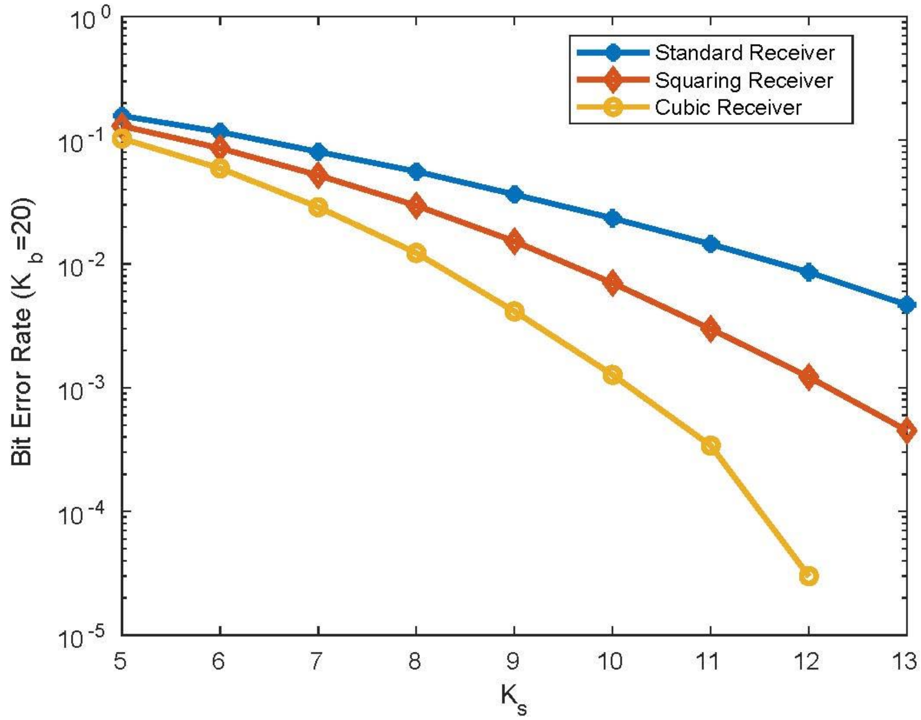

Fig. 3. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 20, T_0 = 300K$, $\bar{g} = 3500$, $F = 1$.

Fig. 3 depicts the performances of the receivers considered here when the background noise level is increased to 20. A similar set of results is observed. However, the gap in performance becomes less pronounced. This is due to the fact that with a large background noise level, the power of n receiver begins to take the output of the noise detectors into account. Nonetheless, the gain in performance is substantial. In Figs. 4&5, we consider performance of the above receivers when a large thermal noise level is present. A similar set of results are also observed here. That is, the power of n receivers offer a substantial gain in performance and that the gain in performance becomes less pronounced as the noise levels due to background and/or thermal effects increase.

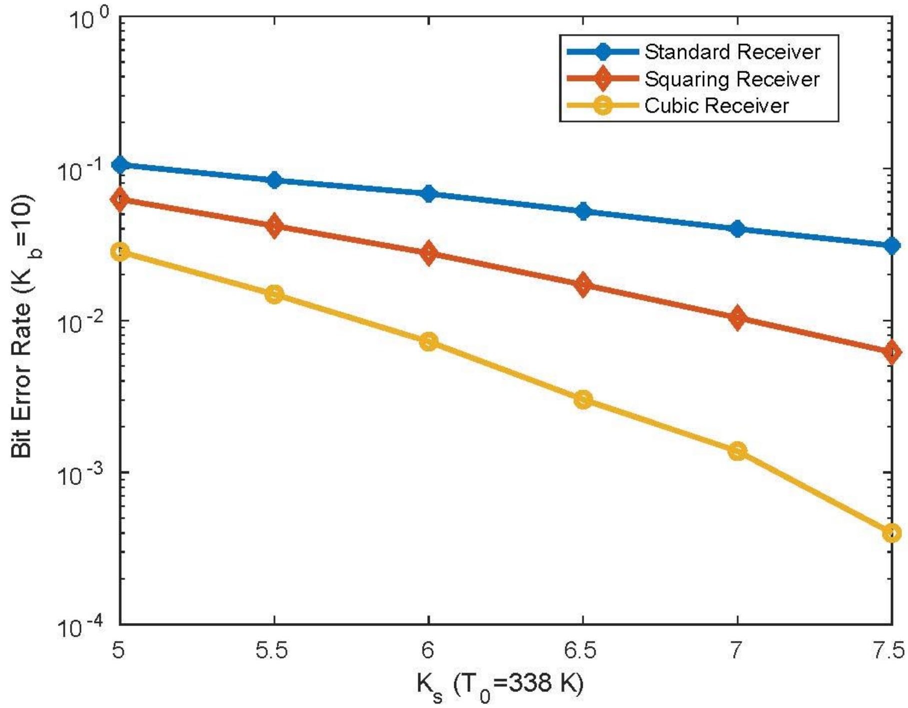

Fig. 4. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 10, T_0 = 338K, \bar{g} = 3500, F = 1$.

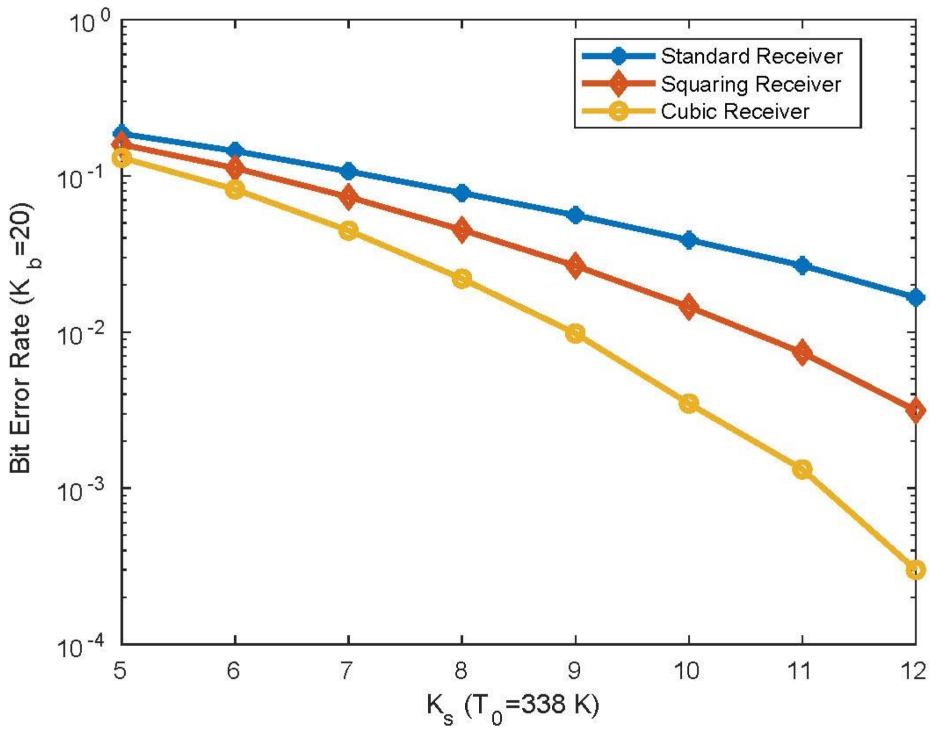

Fig. 5. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 20, T_0 = 338K, \bar{g} = 3500, F = 1$.

Finally, in Figs. 6 & 7, we consider the impact of pointing error for two conditions. That is, when background and thermal noise processes are small ($K_b = 10$ and $T_0 = 300K$) and when large background and thermal noise levels are present (*i.e.*, when $K_b = 20$ and $T_0 = 338K$). In these figures, we assume that the pointing error is large enough to cause 50% of the signal power to fall onto the adjacent PD. Comparing Figs. 2 and 6 confirms our understanding of the manner by which the array detector operates. That is, although the pointing error has caused a significant change in the received signal, causing 50% of the signal power to fall onto the adjacent PD, the performance of the standard receiver remains the same. Although the use of the power of n receiver results in a substantial gain in performance, the presence of spatial error diminishes the gain of the proposed receivers when compared with the standard receiver. That is, the adjacent PD which is in receipt of the signal is also emphasized by the proposed receivers, resulting in additional errors. Nonetheless, the proposed receivers outperform the standard receiver by a sizeable margin.

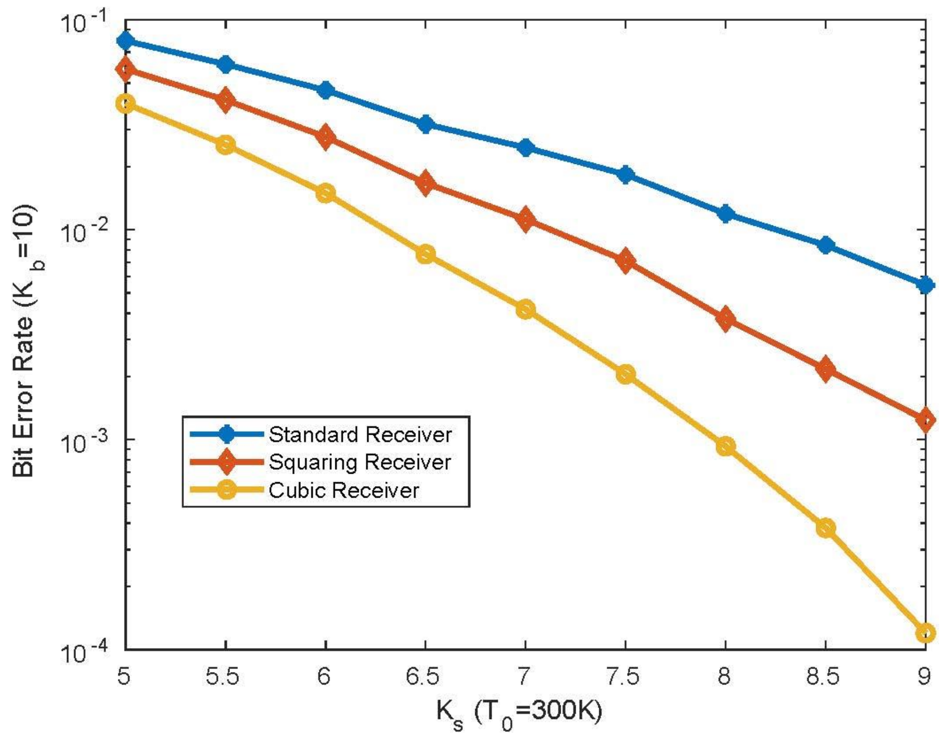

Fig. 6. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 10, T_0 = 300K$, $\bar{g} = 3500, F = 1$. It is further assumed that the pointing error has caused 50% of the signal power impinge upon an adjacent detector.

A similar set of conclusions can be made about the performances of the proposed receivers when Figs. 5 and 7 are compared. That is, although the performance of the standard receiver is not impacted by the pointing error, the performance gains of the power of n receivers becomes less pronounced with an increase in noise levels when pointing error is present. Moreover, although the combined impact of pointing error, thermal noise, and background noise pushes the performance of the standard receiver to an acceptable level, the use of cubic receiver results in an acceptable performance for an uncoded system.

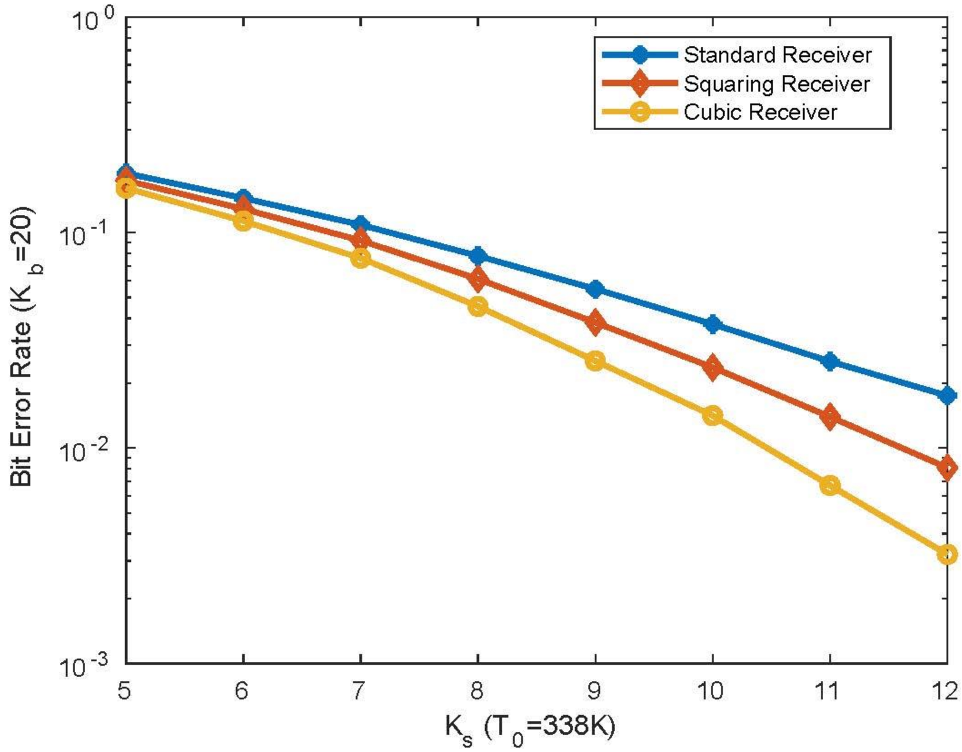

Fig. 7. Bit error rate of the standard, squaring, and cubic receivers. It is assumed that $K_b = 20, T_0 = 338K, \bar{g} = 3500, F = 1$. It is further assumed that the pointing error has caused 50% of the signal power impinge upon an adjacent detector.

4. CONCLUDING REMARKS

In this paper, it was demonstrated that a simple, yet effective nonlinear operation of the detected optical signal in a large array detector system can yield a performance far superior to that of the standard linear receiver. It was shown that the gain in performance, although substantial, is dependent upon the strength of the thermal and background noise processes. Furthermore, in the presence of large pointing errors, the performance gain was shown to suffer. Nonetheless, it was concluded that the use of power of n nonlinearity can result in a significant improvement in performance for a wide range of thermal noise, background noise, and point errors.

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