Coherent Optical Array Receiver Experiment: Design, Implementation and BER Performance of a Multichannel Coherent Optical Receiver for PPM Signals under Atmospheric Turbulence

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ABSTRACT

The performance of a coherent free-space optical communications system operating in the presence of turbulence is investigated. Maximum Likelihood Detection techniques are employed to optimally detect Pulse Position Modulated signals with a focal-plane detector array, and reconstruct the turbulence-degraded signals. The experimental demonstration of this project and results may be divided in three parts; two of which have already been explained in previous publications (1,2). This latest paper shows the final experimental results, including investigation of performance of the Coherent Optical Receiver Experiment (CORE) performed at the laboratory facilities at JPL. Bit Error Rate (BER) is presented for single and multichanel optical receivers, where quasi-shot noise limited performance is achieved, under simulated turbulence conditions using non-coherent post-detection processing techniques. Theoretical BER expressions are compared with experimental obtained BER results and array combining gains are presented. Receiver sensitivity in terms of photons per bit (PPB) is examined; BER results are shown as a function of signal to noise ratios, (SNR), as well as a function of photons per symbol, and photons per bit.

Keywords: photons per bit, signal to noise ratios, shot noise limited performance.

1. INTRODUCTION

The use of a laser beam as a carrier for a satellite-to-ground link enables transmission using very narrow beam divergence angles. Inhomogeneity in the temperature and pressure of the atmosphere leads to variations of the refractive index and the transmission path. Since the index of refraction of air is not uniform, it distorts the electromagnetic wave passing through it. Therefore, a laser beam traversing the atmosphere is constantly being refracted, or bent and as a result scintillation occurs [1]. This turbulence-induced fading impairs free-space optical links in much the same way that flat multipath fading impairs radio-frequency wireless links. These variations of refracted index as well as pointing vibrations can cause fluctuations in the intensity and phase of the received signal leading to an increase in link error probability.

Absorption by water vapor reduces the energy content in the communication beam, and turbulence increases the beam's divergence. The three main atmospheric processes that affect optical wave propagation are absorption, scattering, and refractive-index fluctuations. Index of refraction fluctuations lead to irradiance fluctuations, beam broadening, and loss of spatial coherence of the optical wave at the receiver. In the context of optical communications, this randomization of the optical phase-front often requires the use of larger receiver field of view, thus admitting more unwanted background radiation into the receiver. In the presence of background radiation, performance of direct detection optical receivers often degrades significantly. One way to overcome the effects of background radiation is to use coherent detection, which is generally much less sensitive to background effects than direct detection [2]. In addition, detectors used for coherent detection have higher quantum efficiency than those used for direct detection

photon-counting applications. The solution proposed here is to use focal-plane arrays to collect optical signals from different spatial modes of the received signal field simultaneously, and then recombine the signals optimally. Analysis and proof-of-concept demonstration of coherent adaptive array detection with PPM signals will be described in the following sections.

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2. Results of the Coherent Optical Receiver Experiment

The experimental setup consists of two Nd:YAG (YAG denotes yttrium aluminum garnet) lasers operating at 1064 nm, whose outputs are aligned and combined on the surface of a 4X4 Fermionics InGaAs detector array. One of the lasers serves as a local oscillator, while the other simulates the received signal. The two lasers are operated at slightly different wavelengths, yielding a relatively stable difference-frequency tone of approximately 6 MHz in the detected signal. In the presence of spatial distortions simulating atmospheric turbulence conditions, the difference-frequency tone is generally observable in several array elements simultaneously, but usually with different phases. If the detector element outputs were simply summed, the addition of out-of-phase tones could result in significant cancellation, yielding a weak signal tone at the output. Non-coherent addition of signal components from different elements of the detector array is analogous to detection with a single large detector: this is the prime reason why a single large detector is not effective for coherent detection of signal fields under turbulent conditions. However, if small areas of the detector surface over which the signal field is essentially coherent are processed separately, then the outputs can be phase-aligned prior to addition, recovering the lost signal power. Figure 1 is a photograph of the optical setup at the Jet Propulsion Laboratory where the experiments described in this thesis have taken place. This signal laser beam is focused into the photodetector via the receiver lens.

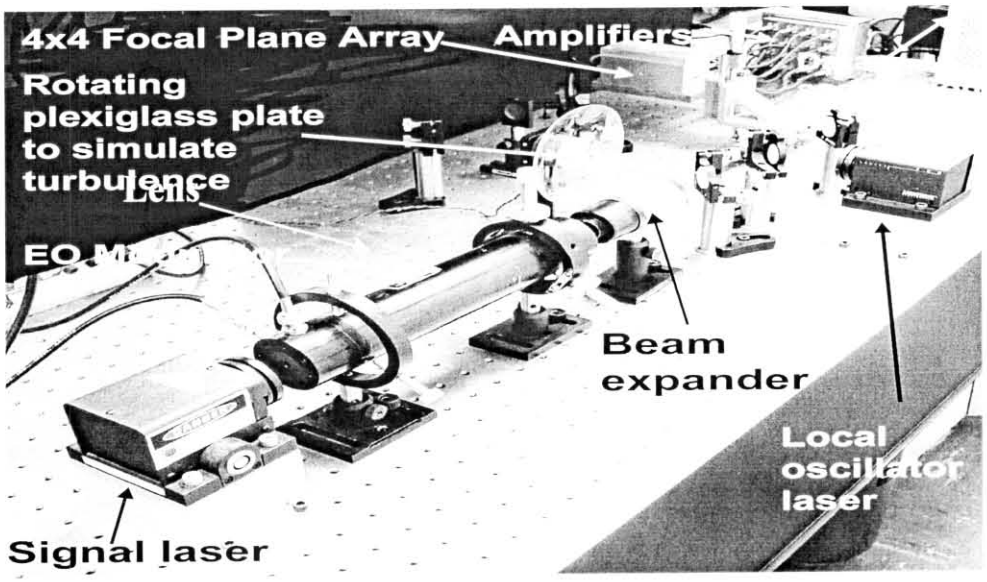

Figure 1 Coherent combining experiment at the Jet Propulsion Laboratory, NASA.

In the current coherent combining experiment, each of the 16 outputs of the detector array are amplified, and input to a 16-channel data-acquisition assembly (using GaGe data-acquisition cards). The analog signals are digitized to 8 bits at a sampling rate of 25 mega-samples per second (MSPS). The data-acquisition system is capable of synchronously recording up to 1 megabyte of data per channel (or one million 8-bit samples), however for the initial tests only 104128 samples were taken per channel for, in order to simplify the data-transfer from the data-acquisition computer to the signal-processing computer. At a sampling rate of 25 MSPS, this sample-stream represents 4.16512 ms of elapsed time. For the first results, channels that contained significant signal were identified, and at a certain time synchronously collected 104128 samples were collected from each channel (in a realistic communications scenario, the combining algorithm would automatically select the "signal" pixels for processing). The modulation format for the transmitted laser signal is PPM using an external Electro-Optic Modulator (Pockle cell). At the GaGe scope we can see the PPM modulated beatnotes at a rate of 97.65 kHz. The PPM frame period is exactly 10.24 μs. The slot width is approximately 320ns, resulting in a 32-PPM system.

A snapshot of an individual laser pulse that contains the coherently detected PPM beatnote is shown in Figure 2.

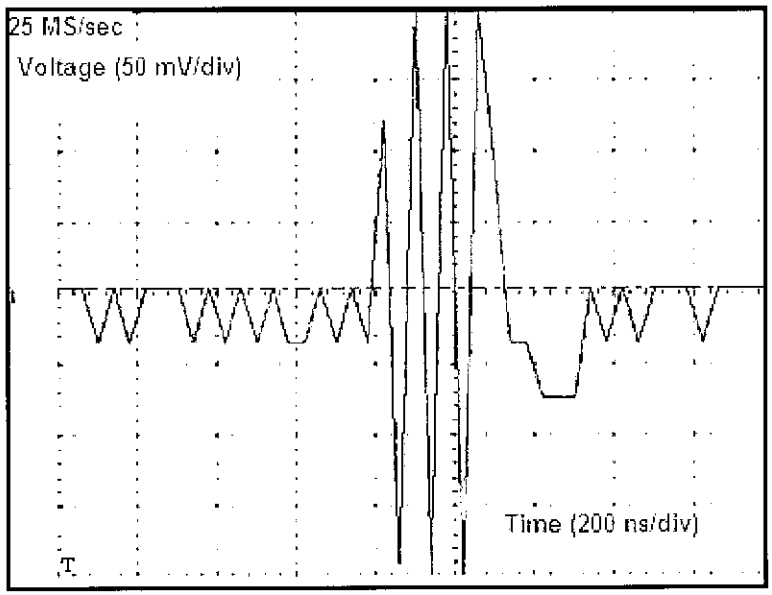

Figure 2 Snapshot of an individual PPM pulse beatnote.

The resulting sample-stream acquired with the GageScope is digitally downconverted to complex baseband. The resulting downconverted complex samples served as input to a least-mean-square (LMS) algorithm, which was used to estimate the complex weights required to reconstruct the signal. The complex-weighted samples from each channel were then combined, in order to maximize the combined signal-to-noise ratio (SNR).

A rotating pre-distorted plexiglass plate was incorporated into the experimental setup to simulate atmospheric turbulence. Intensity distributions of the signal beam obtained with a Spiricon camera at the input to the focal-plane array under ideal conditions are shown in Figure 3,

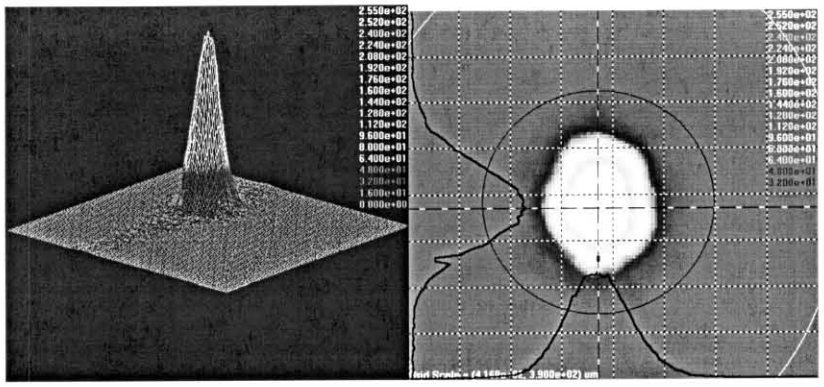

Figure 3 Intensity distribution of the signal beam under ideal conditions

While when the plexiglass plate is introduced in the signal path, as it can be observed in Figure 4, the beam is broken up into several 'hot spots' that can be captured by different detectors of the focal plane array

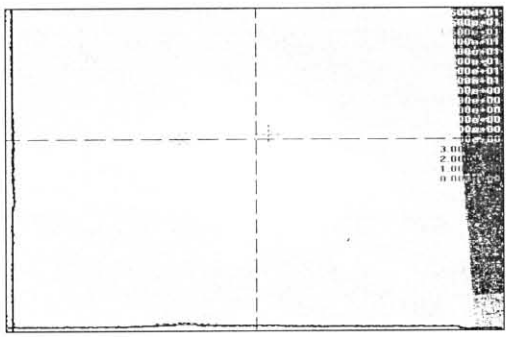

Figure 4 Beam profile under spatial distortions resembling atmospheric turbulence generated with a plexiglass plate in the laboratory

3. Adaptive combining of beatnotes using the LMS algorithm

The discrete complex version of the LMS algorithm can be described by the recursive equation [3]:

$$W_i(k+1) = W_i(k) + \mu S_i^*(k)\varepsilon(k) \tag{1}$$

The LMS is a recursive algorithm that allows the value of each weight, W_i, at the (k+1) sample to be calculated from its value at the k-th sample, using the signals at the kth sample. The sampled error signal is obtained from the sampled reference signal and array output, as follows:

$$\varepsilon(k) = d(k) - s(k) = d(k) - \sum_{i=1}^{N} W_i(k) S_i(k) \tag{2}$$

The LMS algorithm described in Eqs. (1) and (2) is complex in the sense that the input and output data as well as the weights are all complex values. In the initial simulations and experiments, the target signal used was a constant value, equal to the sum of the average magnitudes of the signals in the signal channels (Compton, 1988). Later on, a different desired signal was utilized as it will be explained later on in the chapter.

The nominally 6 MHz signal-tones were downconverted to complex baseband, and input to a least-mean-square algorithm, or LMS. This adaptive algorithm automatically estimates the complex weights required to reconstruct the signal, then it applies the weights to the complex signal in each channel, and combines the "phased-up" signals in order to maximize power, or SNR. The weights are computed from Eq. (1) starting with zero initial values. Varying the stepsize, it is possible to control the fraction of the current weight estimate applied during each update, providing a desired degree of smoothing to the weight estimates.

4. Experimental results

4.1. Results with single detector

Experiments involving a single detector were performed using both 32 PPM and 256 PPM modulation. This paper will only illustrate result for the most relevant case of 256 PPM. The purpose of these experiments was to illustrate nearly shot-noise-limited performance (shot noise 5 dB above thermal noise). Although the shot noise due to the local oscillator was greater than the thermal noise component, thermal noise was still present. Hence, the results presented here are not truly shot-noise limited.

The first set of BER curves covers the case of random 256 PPM for a single detector configuration. Figure 5 illustrates BER performance as a function of Ks, which is the number of photons per pulse. The experimental points lie close to the theoretical BER performance line, and the trend line fitted to the experimental points is seen to lie very close to the theoretical bound. The upper bound in this case, computed based on leakage statistics, is seen to be pessimistic. In Figure 6, BER is plotted against photons per bit. This figure shows a bit error rate only slightly above $3 \cdot 10^{-3}$ at 1 photon per bit, illustrating the system's performance in the presence of weak signals. A plot of BER vs. $\frac{E_S}{N_0}$ is shown in Figure 7.

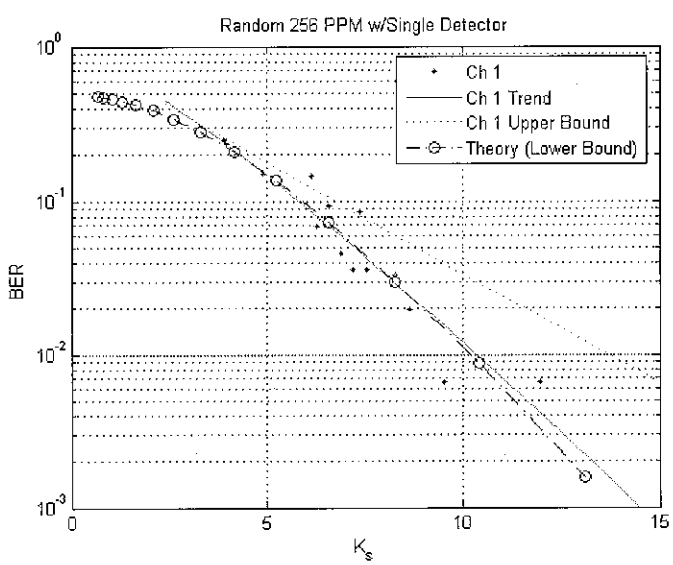

Figure 5 BER vs. photons per pulse with the single detector and 256 PPM

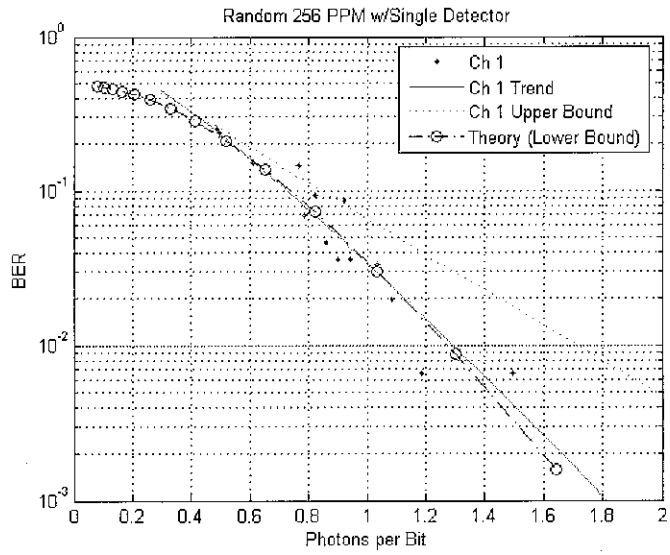

Figure 6 BER vs. photons per bit with the single detector and 256 PPM

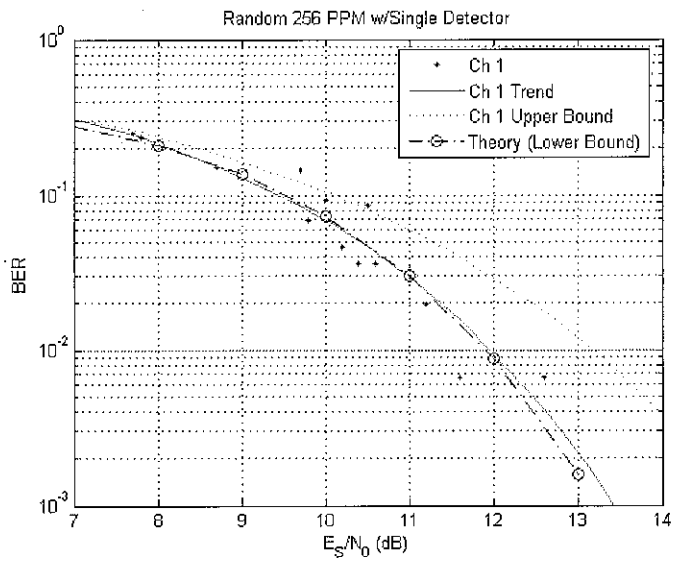

Figure 7 BER vs. Es/N0 in dB for the single detector and 256 PPM

4.1. Results with the Focal Plane Array

The objective here is to demonstrate the ability to coherently combine multiple channels in a focal plane array in order to recover the desired signal. The goal is to come as close as possible to the theoretical BER curve for BER vs. Ks or BER vs. photons per bit. The FPA, by allowing signals from different parts of the detector plane to be summed coherently, is able to come close to the level of performance that would be achieved with a single detector without any phase distortion in the aperture plane. The FPA amplifiers introduced a great deal of thermal noise into the system.

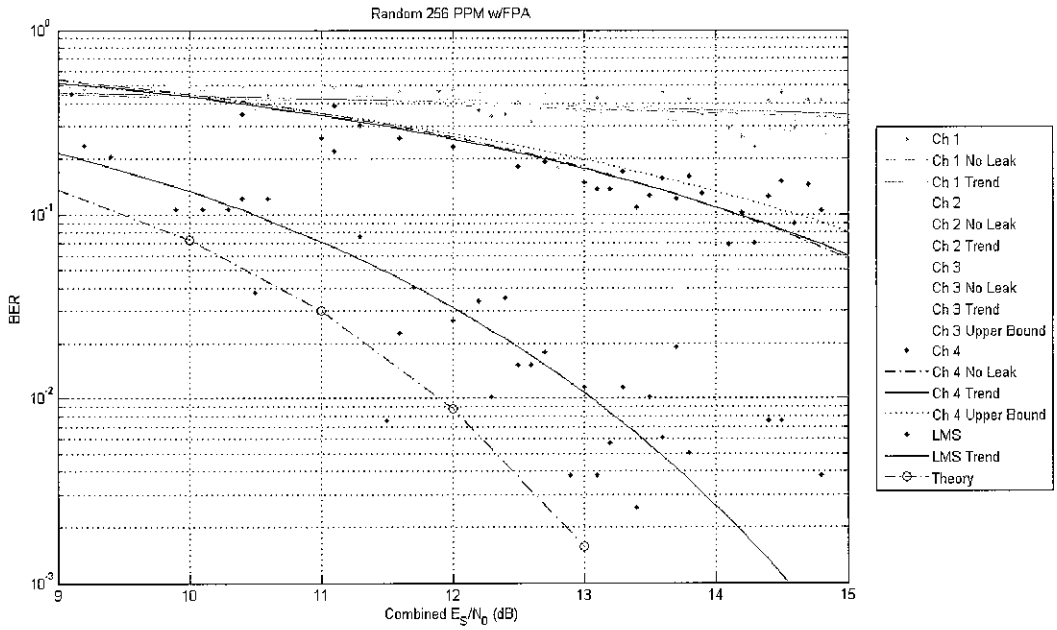

Figure 8 BER vs. Es/N0 with the FPA for 256 PPM

From Figure 8, it is seen that the combined channel within 1.0 to 1.5 dB of the theoretical curve, indicating that the FPA achieves good combining performance. It should also be noted that the FPA's combined BER curve is almost 3 dB better than the best single FPA channel. This implies that a single detection element under the best of conditions would suffer from a 2.5 to 3.0 dB loss in performance relative to the FPA.

The FPA's gain is reasonable. Four channels are being coherently combined. Channels 1 and 2 are very weak and contribute only a small amount to the total SNR. The two stronger individual channels are about 1 dB apart, and combining them coherently would lead to a gain of slightly more than 2.5 dB in theory. Given the SNR expressed as the ratio $\frac{E_S}{N_0}$, one could determine both Ks and the number of photons per bit if the FPA had been capable of shot noise limited operation. The hypothetical plots of BER vs. Ks and BER vs. photons per bit are shown in Figure 9 and 10.

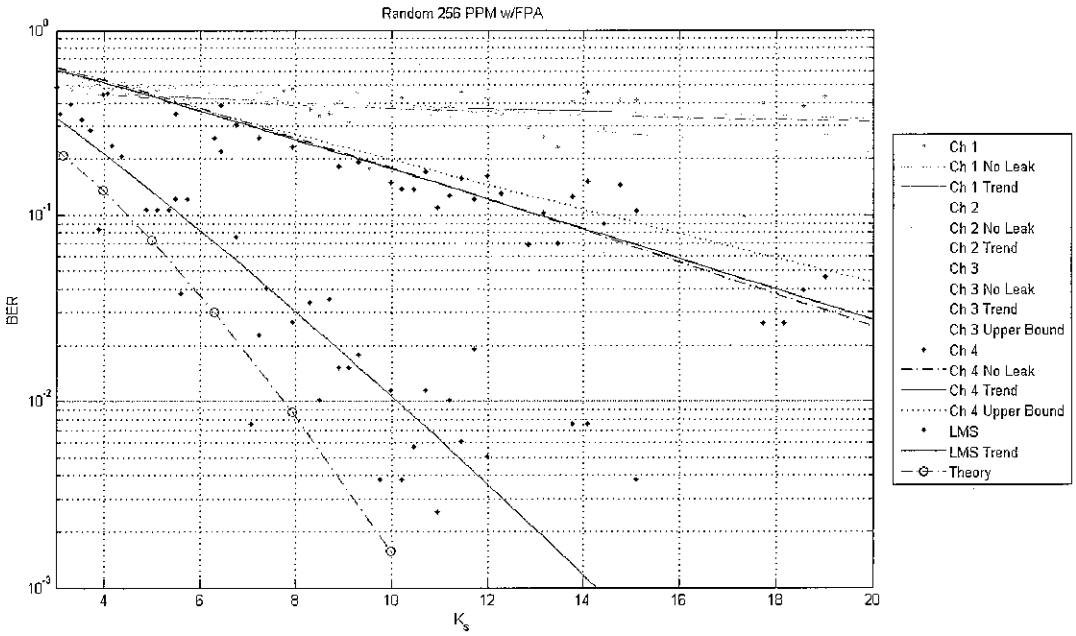

Figure 9 BER vs Ks for a shot noise limited FPA system with 256 PPM

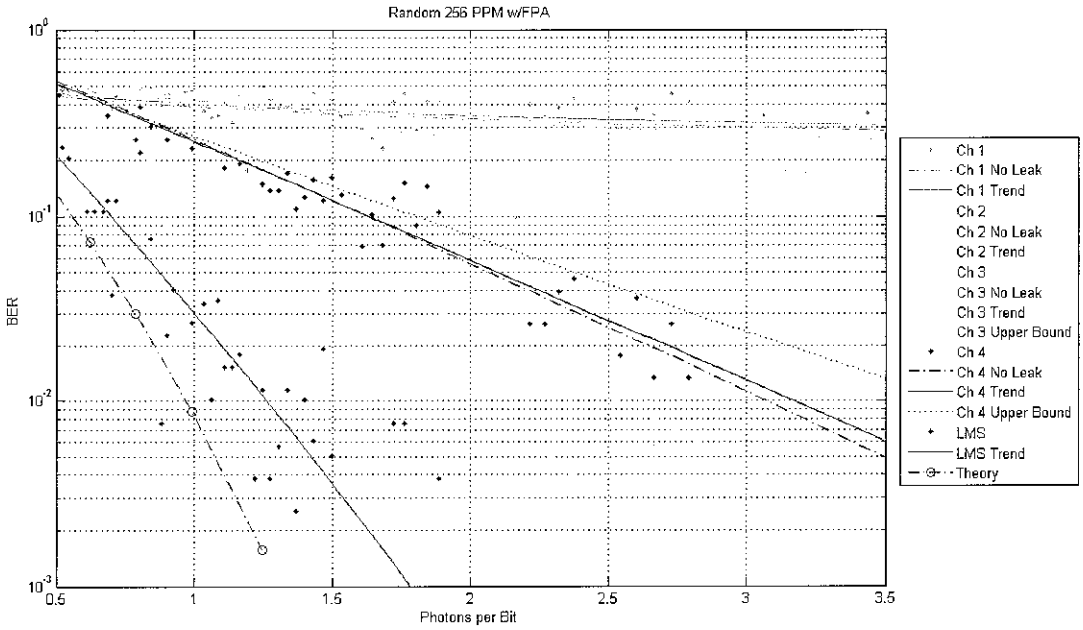

Figure 10 BER vs photons per bit for a shot noise limited FPA system with 256 PPM

The actual system suffered from high levels of thermal noise, it was necessary to determine the actual achieved performance, which is shown in Figures 10 and 11.

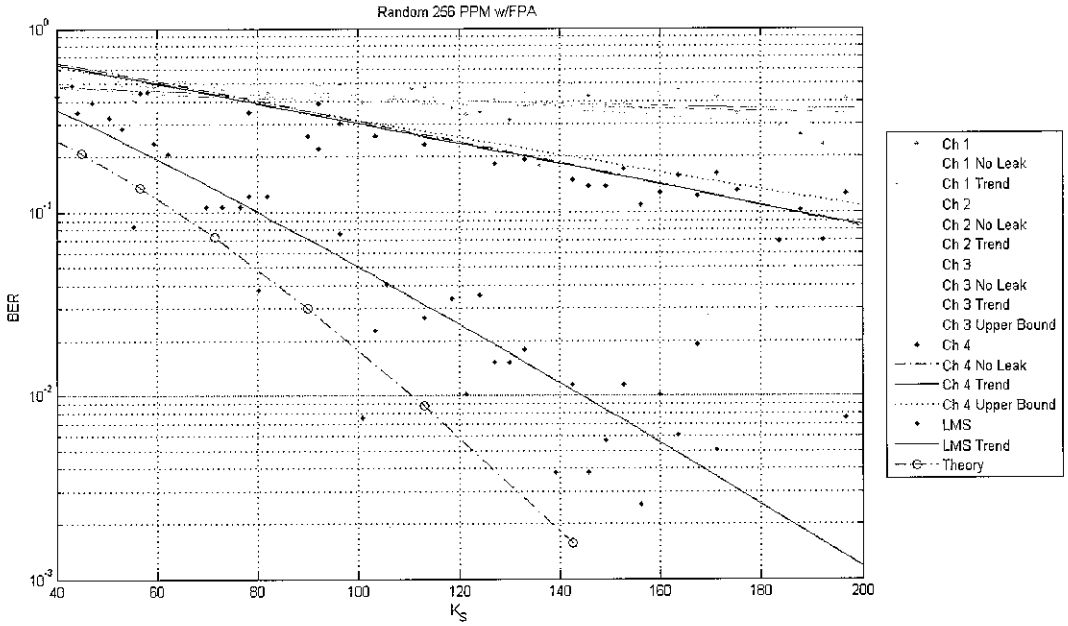

Figure 10 BER vs. Ks for 256 PPM with the FPA

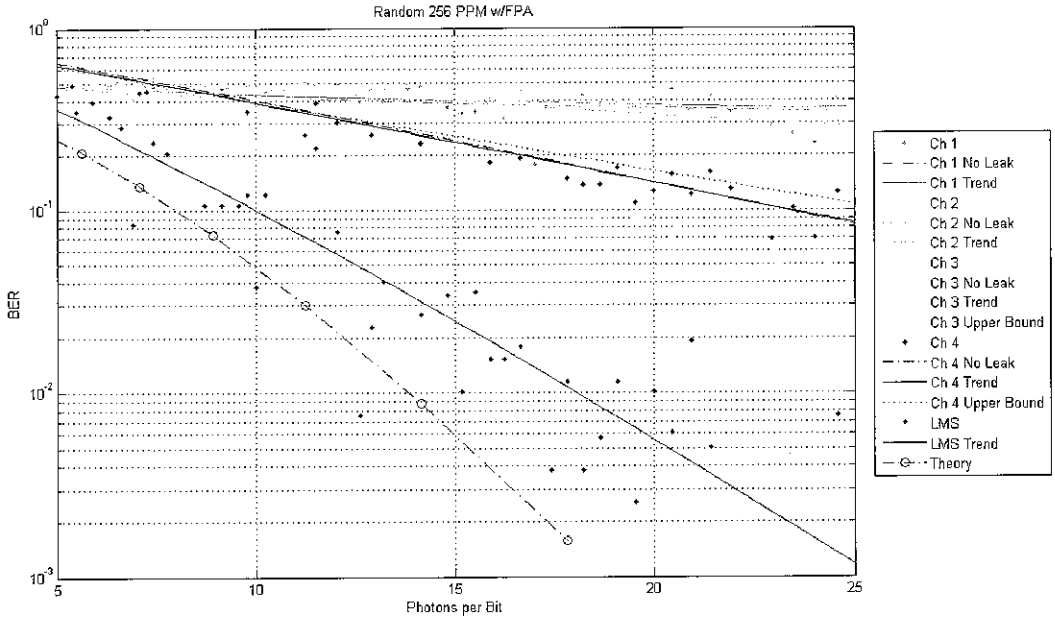

Figure 11 BER vs. photons per bit for 256 PPM with the FPA

BER performance vs. Ks was far less impressive than what was achieved with the single detector. Nevertheless, as shown in Figure 5, BER performance as a function of SNR comes within roughly 1.0 to 1.5 dB of theory. This is a strong indication that LMS combining performance is good.

The ability to coherently combine signals in the focal plane allows the system to achieve BER performance close to that achievable without atmospheric turbulence using a single detector and is a significant improvement over single detector performance in the presence of turbulence. In particular, most of the signal photon energy is successfully recovered as evidenced by the closeness of the BER curve to the theoretical curve. Performance is close to what would have been achieved if no turbulence were present and if all of the signal photons had landed on a single detector instead of on the multiple detection elements of the FPA.

These results indicate that coherently combining the outputs of the FPA channels permits very good reconstruction of the signal that would have existed if no turbulence had been present and if all photons had been hitting this detector.

Conclusions

The FPA experimental results indicate the ability of the focal plane array in conjunction with the LMS algorithm to coherently and constructively add signals together in order to achieve performance very close to that of a single detector without any atmospheric turbulence. The BER curves for the combined output of the FPA channels are close to the theoretical curves for a single channel system at the same SNR as the FPA combined channel. The spreading of signal energy in the detector focal plane caused by atmospheric turbulence can therefore be corrected by means of coherent combining of the focal plane array channels using the LMS algorithm with decision feedback. Thus, the FPA-based receiver in the laboratory achieves the goal of compensating for the phase distortions introduced at the aperture plane of the system and continues to achieve robust performance in the face of such distortions. The large improvement in BER performance of the complete FPA over even the best single channel in the detector plane

illustrates the fact that it is necessary to use spatial combining to recover from signal spreading in the focal plane induced by phase errors in the aperture plane caused by atmospheric turbulence.

The strong performance of the single detector system provides real world laboratory verification of the ability to detect weak, low SNR signals in a reliable fashion as well. Given the ability to receive such weak signals when high quality electronics are used, it is believed that the use of high quality low thermal noise amplifiers and circuits in an FPA system would yield very good results in the presence of turbulence. The plots of hypothetical FPA performance assuming noise characteristics similar to those of the single detector clearly illustrates the potential that the FPA has, although the actual FPA suffered from significant thermal noise degradation.

ACKNOWLEDGMENTS

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