Enhanced Probability Density Function Using APD in SAC-OCDMA Systems Based SPD Technique

Hamza M. R. Al-Khafaji [1*], S. A. Aljunid [1], Angela Amphawan [2,3], and Hilal A. Fadhil [1]
[1] School of Computer and Communication Engineering, University Malaysia Perlis (UniMAP), Perlis, Malaysia
[2] InterNetWorks Research Group, School of Computing, University Utara Malaysia, Kedah, Malaysia
[3] Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA, USA
[*] Corresponding author. E-mail: eng.hamza.alkhafaji@gmail.com

Abstract—This paper examines the avalanche photodiode (APD) gain impact on spectral-amplitude coding optical code-division multiple-access (SAC-OCDMA) systems based single photodiode detection (SPD) technique. Numerical results are used for inspecting the APD gain influence upon the probability density function (PDF) and signal-to-noise ratio (SNR) performance. The usage of APD over positive-intrinsic-negative (PIN) photodiode accommodates more users with improved PDF and higher SNR.

Keywords—SAC-OCDMA; SPD technique; MAI; PIIN; APD; PIN photodiode.

I. INTRODUCTION

For quite some time now, OCDMA has garnered remarkable research interests for its numerous benefits, such as asynchronism, simplified network topology, robust signal security, and flexibility in information rates [1, 2]. Nevertheless, multiple-access interference (MAI) is the main constraint of performance and capacity in conventional OCDMA systems [3]. One of the coding approaches developed for OCDMA systems is spectral-amplitude coding (SAC) which gains substantial attention because it tackles MAI problem through employing an appropriate detection technique. The majority of published work on SAC-OCDMA considers light-emitting diodes (LEDs). The key advantage of these sources is their broadband nature, which is very suitable for SAC-OCDMA operation [4]. However, they are thermal in nature and thus suffer from phase-induced intensity noise (PIIN) [5]. PIIN caused by the incoherency of broadband optical sources, limits the throughput of SAC-OCDMA systems to below 1 Gbps [6]. This noise can be modeled by a negative exponential distribution, and the PDF of the integrated intensity of an unpolarized thermal source can be approximated by a gamma density function [7, 8]. PIIN increased with a rise in the number of active users. Thus, the scalability of SAC-OCDMA systems is somewhat limited due to this noise. Of late, the SPD technique is proposed to eliminate the effects of PIIN and MAI in SAC-OCDMA systems through cancelling the interfering signals in the optical domain [9 – 11].

APDs have a high optoelectronic gain and are capable of increasing the SNR performance of OCDMA systems by amplifying the received signal photocurrent [12]. The gains that are available in the APD makes it extremely sensitive in comparison to PIN photodiode [13]. Accordingly, investigating the effect of APD gain in SAC-OCDMA system using SPD technique is important.

In this study, modified double-weight (MDW) codes are utilized as the signature sequences for SAC-OCDMA systems. MDW codes are characterized by unity cross-correlation ($\lambda = 1$), which is the ideal cross-correlation value. For a weight of four ($w = 4$), the code length is [14]:

$$L = 3K + \frac{8}{3}\left[\sin\left(\frac{K\pi}{3}\right)\right]^2 \quad (1)$$

where L is the code length, and K is the number of users.

Following the Introduction, the work is structured as follows. Section II presents the operating principles of the SPD technique. Section III provides analyses that necessary to the calculation of SNR which is used to compute the PDF at photodiode, followed by the discussion of results. In the end, the findings are concluded in Section IV.

II. SPD TECHNIQUE

The diagram of SAC-OCDMA receiver based on SPD technique is illustrated in Fig. 1. The incoming optical signal is decoded using the same spectral response as that which is intended for the encoder. The detected output from the decoder is either w power units (P.U.) for an active user or λ P.U. for interferers. The remainder of the signal from the decoder is then transmitted to the AND decoder. The AND decoder has the overlapped spectral bins from different interferers. The output of the AND decoder is either zero P.U. for an active user or λ P.U. for interferers. This technique can be realized by utilizing low-priced fiber Bragg-gratings (FBGs) to decode the incoming signal given their low insertion losses, high long-term stability, small size, and light weight. After optical subtraction, the output is either w P.U. for an active user or zero P.U. for interferers. This shows that the interfering signals are eradicated in the optical domain before their conversion to the electrical domain. As a consequence, the SPD technique mitigates both PIIN and MAI in the optical domain. Eliminating interfering signals in the optical domain enables a single photodiode to be utilized

978-1-4799-1125-7/13/$31.00 ©2013 IEEE

rather than two as in other detection techniques. After the desired signal is detected by a photodiode (PD) and low-pass filtered to reduce out-of-band high-frequency noise, the transmitted data are restored.

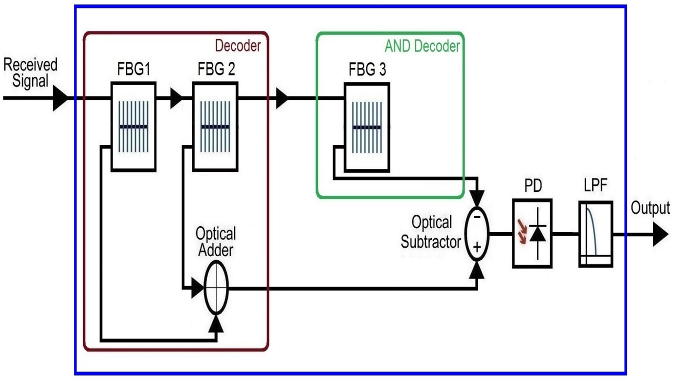

Fig. 1. Schematic diagram of SPD technique. FBG: fiber Bragg-grating; PD: photo-diode; LPF: low-pass filter.

III. PERFORMANCE ANALYSIS AND RESULTS

In this section, we present analytical expressions for the mean optical power and major noises to compute the SNR and PDF performances of SAC-OCDMA system based SPD technique with APD.

The mean optical power reaching PD when the desired user is active is given by:

$$\langle P_{User}\rangle = \frac{4SB_o}{L} \tag{2}$$

where S is the received power spectral density level at PD.

For APD, Eq. (2) can be rewritten as follows:

$$\langle P_{User,APD}\rangle = \frac{4SGB_o}{L} \tag{3}$$

where G is the APD gain.

The simplified expression of PIIN for the unpolarized thermal light source can be expressed as follows:

$$\sigma^2_{PIIN,APD} = \frac{4S^2G^2B_eB_o}{L} \tag{4}$$

where B_e is the bandpass resulting from the filtering and it is equal to 0.75 × R_B, where R_B is the data rate.

The variance of shot noise can be computed as:

$$\sigma^2_{sh,APD} = 2eB_eG^{2+x}\langle P_{User}\rangle \Re_{APD} \tag{5}$$

where the parameter x equals to 0.7 for InGaAs APD [15].

The variance of thermal noise is also given by:

$$\sigma^2_{th} = \frac{4k_BT_nB_e}{R_L} \tag{6}$$

and the SNR is thus

$$SNR = \frac{(<P_{User,APD}>)^2}{\sigma^2_{PIIN,APD} + \sigma^2_{sh,APD} + \sigma^2_{th}} \tag{7}$$

The conditional PDF $f(P)$ of the integrated optical power P for an incoherent light source obeys the Gamma probability function. For $P \geq 0$, the PDF is mathematically expressed by [16]:

$$f(P) = \left(\frac{SNR}{\langle P\rangle}\right)^{SNR} \frac{P^{SNR-1}}{\Gamma(SNR)} \exp\left(-SNR\frac{P}{\langle P\rangle}\right) \tag{8}$$

where Γ is the Gamma function.

In [16], P has units of (W/m^2). In the current analysis, the surface area is assumed to be constant. Thus, P has units of (W). Parameters are provided in Table I.

Table I. Typical Parameters.

Optical bandwidth	B_o = 3.75 TH$_z$
Received optical power	P_{User} = – 30 dBm
Electron's charge	e = 1.602 × 10^{-19} C
APD Responsivity	$\Re_{APD}$ = 0.75
Boltzmann's constant	k_B = 1.38066 × 10^{-23} JK^{-1}
Receiver noise temperature	T_n = 300 K
Receiver load resistor	R_L = 1030 Ω

The SNR versus the number of active users is given in Fig. 2 for SPD technique using APD (with G = 10, 50, and 100) and PIN photo-detectors at a transmission rate of 1.25 Gb/s. The SNR of the SAC-OCDMA system decreases when the number of active users increases, mainly due to PIIN. Remarkably, SPD technique using the APD is able to sustain better SNRs for larger number of active users compared to PIN photodiode. Moreover, Fig. 2 reveals that the SNR performance decays at high gain values (G = 50 and 100), since high APD gains induce increment in PIIN and shot noises as shown in Eq. (4) and (5).

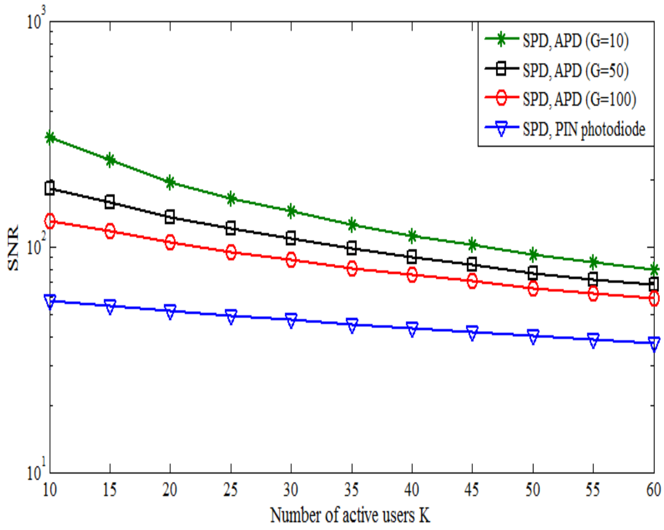

Fig. 2. SNR against number of active users using APD and PIN photodiode.

The PDF of SAC-OCDMA system based SPD technique is obtained as shown in Fig. 3 at a transmission rate of 2.5 Gb/s. Even with a high APD gain (G = 100), it can be seen from Fig. 3 that APD can achieve better PDF (higher SNR) than when using PIN photodiode. The PIN photodiode spreads the PDF, which leads to a larger standard deviation (less SNR). Thus, degrading the system performance.

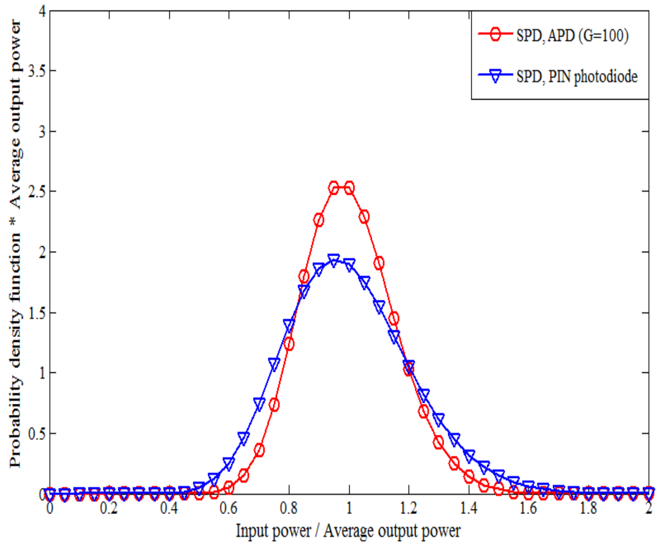

Fig. 3. PDF for APD against PIN photodiode with K=35 and R_B = 2.5 Gb/s.

IV. CONCLUSIONS

In SAC-OCDMA systems, alleviating the effects of MAI and PIIN is extremely desirable to boost the performance. The enhanced signal quality, design simplicity, and cost-effectiveness have made the SPD technique attractive for further investigation. In this paper, the SNR and PDF performance of SAC-OCDMA systems using SPD technique has been evaluated and compared using APD and PIN photodiode. It is shown that using APDs with low gain (G = 10) have enhaced the performance of SAC-OCDMA systems based SPD approach. This marks the viability of SAC-OCDMA system based on SPD technique as a capable candidate for future optical access networks.

REFERENCES

[1] S. Idris, T. Osadola, and I. Glesk , “Towards self-cloked gated OCDMA receiver,” J. Europ. Opt. Soc. Rap. Public., vol. 8, 13013, 2013.

[2] H.M.R. Al-Khafaji, S.A. Aljunid, A. Amphawan, H.A. Fadhil, and A.M. Safar “Phase-induced intensity noise reduction with improved group velocity dispersion tolerance in SAC-OCDMA systems,” International Journal of Engineering and Technology (IJET), vol. 5, No. 1, pp. 95-100, 2013.

[3] Z. Jiang, et al., “Four-user, 2.5-Gb/s, spectrally coded OCDMA system demonstration using low-power nonlinear processing,” J. Lightwave Technol., vol. 23, pp. 143-158, 2005.

[4] H.M.R. Al-Khafaji, S.A. Aljunid, and H.A. Fadhil, “Improved BER based on intensity noise alleviation using developed detection technique for incoherent SAC-OCDMA systems,” J. of Modern Optics, vol. 59, pp. 878-886, 2012.

[5] C.-T. Yen, “Optical code-division multiple-access embedded with a polarisation diversity scheme for radio-over-fibre transmissions,” IET Optoelectronics, vol. 6, pp. 131-139, 2012.

[6] M. Noshad, and K. Jamshidi, “Code family for modified spectral-amplitude-coding OCDMA systems and performance analysis,” J. Opt. Commun. Netw., vol. 2, pp. 344-354, 2010.

[7] S. Ayotte, M. Rochette, J. Magne, L.A. Rusch, and S. LaRochelle, “Experimental verification and capacity prediction of FE-OCDMA using superimposed FBG,” J. Lightwave Technol., vol. 23, pp. 724-731, 2005.

[8] M. Abtahi, S. Ayotte, J. Penon, and L.A. Rusch, “Balanced detection of correlated incoherent signals: a statistical analysis of intensity noise with experimental validation,” J. Lightwave Technol., vol. 26, pp. 1330-1338, 2008.

[9] H.M.R. Al-Khafaji, S.A. Aljunid, A. Amphawan, and H.A. Fadhil, “Improving spectral efficiency of SAC-OCDMA systems by SPD scheme,” IEICE Electron. Express, vol. 9, pp. 1829-1834, 2012.

[10] H.M.R. Al-Khafaji, S.A. Aljunid, A. Amphawan, H.A. Fadhil, and A.M. Safar, “Reducing BER of spectral-amplitude coding optical code-division multiple-access systems by single photodiode detection technique,” J. Europ. Opt. Soc. Rap. Public., vol. 8, 13022, 2013.

[11] H.M.R. Al-Khafaji, S.A. Aljunid, A. Amphawan, and H.A. Fadhil, “SOA/SPD-based incoherent SAC-OCDMA system at 9 × 5 Gbps,” IEICE Electron. Express, vol. 10, 20130044, 2013.

[12] P. Sun, M.M. Hayat, and A.K. Das, “Bit error rates for ultrafast APD based optical receivers: exact and large deviation based asymptotic approaches”, IEEE Trans. Commun., vol. 57, pp. 2763-2770, 2009.

[13] M.S. Anuar, S.A. Aljunid, A.R. Arief, M.N. Junita, and N.M. Saad, “PIN versus Avalanche photodiode gain optimization in zero cross correlation optical code division multiple access system”, Optik - International Journal for Light and Electron Optics, vol. 124, pp. 371-375, 2013.

[14] S.A. Aljunid, M. Ismail, A.R. Ramli, B.M. Ali, and M.K. Abdullah, “A new family of optical code sequences for spectral-amplitude-coding optical CDMA systems,” IEEE Photon. Technol. Lett., vol. 16, pp. 2383-2385, 2004.

[15] G. Keiser, Optical fiber communications, 4th ed., McGraw-Hill, 2010.

[16] J.W. Goodman, Statistical optics, Wiley, New York, 2000.