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High-Speed Detection with Avalanche Photodiode in Optical Interleave Division Multiple Access Scheme

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Abstract

Objective: To execute the Avalanche photodiode instead of a PIN photodiode in Optical Interleave Division multiple Access (O-IDMA) communication system and to analyze the performance for high data rate transmission. **Methods/Statistical Analysis:** The detection of optical signal at the receiver of the O-IDMA system is an important operation and decides the performance of the system. Here the detection is done using Avalanche Photodiode for O-IDMA system and analyzed. Iterative decoder is used for decoding at the receiver using the soft decision method. MATLAB is utilized as a simulation tool. **Findings:** The simulation results have been demonstrated that Avalanche Photodiode is appropriate than PIN Photodiode. The completion and efficiency of the O-IDMA system can be ameliorated with the utilization of avalanche photo detector. **Applications/Improvements:** The completion of the O-IDMA system is ameliorated appreciably by utilizing Avalanche photodiode and system support more no. of users, less bit error rate and large data rate transmission.

Keywords: Avalanche Photodiode, Bit Error Rate, IDMA Scheme, Optical Fiber, PIN Photodiode

1. Introduction

The optical fiber is a very important medium of wired communication and can be easily employed for long distance transmission and high bandwidth. As higher data rate applications are prime requirement in communication, therefore, it is essential to utilize the efficient bandwidth of the optical fiber and multiple access technique are used for this purpose. CDMA scheme is the most popular technique[1] due to better bandwidth efficiency than WDMA (Wavelength-Division Multiple-Access) and TDMA (Time-Division Multiple-Access) schemes. Optical-CDMA is an optical processing system which allows multiple users to share the same bandwidth without interfering with each other using optical code. In O-CDMA system, the effect of ISI (inter symbol interference) and MAI (multiple access interference) is not precious at the less number of users, but these effects are irreplaceable at a huge number of users. Therefore, as number of users increases, Bit error rate (BER) increases and quality of service decreases. To overcome these effects the alternate multiple access scheme may be introduced in which the data of users are segregated by interleavers which work on the principle of interleaving mechanism and this scheme is known as IDMA. In O-IDMA[2] the data string of each user is separated by a specific interleavers and the cross correlation between them is to be modest[3-6]. Output data produced from user-specific interleavers, demonstrated better orthogonality between each other in the optical fiber channel, following less interference with each other. The O-IDMA scheme inherits the superiority of optical fiber i.e. high bandwidth and IDMA scheme, i.e. efficient utilization of bandwidth of the fiber with less interference and distortion, however its performance is affected by the detection at the receiver. Here the avalanche photodiode is implemented in place of PIN photodiode and evaluate performance of the O-IDMA system using avalanche photodiode and compare it to the PIN Photodiode. The results show clearly that Bit Error Rate (BER) or the error probability increases for both of the detector (i.e. PIN and

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APD) by increasing the no. of users, but BER for APD is far better than PIN photodiode.

In section 2, optical IDMA transmitter and receiver are presented using optical channel. Section 3 presents photo detector; section 4 presents the simulation result and discussion of optical IDMA using the avalanche photo detector and PIN Photo detector. Section 5 concludes the article.

2. Optical-IDMA System Model

The block diagram of the O-IDMA system is displayed in Figure 1. It consists of the transmitter, optical channel and receiver. The detail of the O-IDMA system is described one by one in the following sections:

2.1 Transmitter Section

The upper segment of Figure 1 displays the transmitter model of O-IDMA system in which a specific interleaver is used for each user. In O-IDMA system, the interleavers is exerted for high spectral efficiency, improved performance[7-10] and low receiver complexity. The O-IDMA scheme anticipates on interleaving mechanism to discriminate the signals of different users and resemblance between CDMA and IDMA schemes have been manifested that user-specific interleavers may anticipate better orthogonality and emanate least interference between each other in the channel[6,11].

IDMA scheme is based on implementation of user-specific interleavers $\{\pi_k\}$ which separate the user's string data and maintain the orthogonality. Generally interleavers are precipitated randomly and separately. The role of interleaver is to disperse the coded sequences and produce near to zero cross correlation between the chips, which makes chip-by-chip (CBC) detection process absolutely simple and speedy[12].

The use of IDMA in Optical domain plays an important role in enhancing the performance which can be measured in terms of BER. The application of IDMA in Optical domain[13] plays a requisite character and intensified

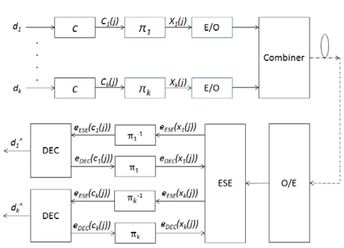

Figure 1. Block Diagram of O-IDMA System.

the performance, which is dignified by concerning the bit error rate[14] (BER).

In the transmission section of O-IDMA, it is presumed that the no. of users to be transmitted simultaneously is K and the selected coding rate to encode the input data is *c* which is modest to get the optimum output because low code rate is appropriate for non coherent transmission. The input data string d_k is applied at the input of the encoder and converted into a coding series $\boldsymbol{c}_k=[c_k(1)\ldots..c_k(j)\ldots..c_k(J)]^T$, where *J* denotes the data frame length of the user. The components of $\boldsymbol{c}_k$ denotes coding bits. Here convolutional encoder is selected and it is replaced by three parameters n, l, and k. n represents the no. of bits in coded sequence, l is the input of the encoder and m is the no. of shift registers. The selected values of these parameters are n=2, l=3,and m=2. The Coded sequence $\boldsymbol{c}_k$, is the input of user-specific interleaver π_k, permutated by the interleaver and converted into the data streams $\boldsymbol{x}_k= [x_k(1)\ldots..x_k(j)\ldots..x_k(J)]^T$. The components of $\boldsymbol{x}_k$ are known as 'chips'[12,15].

The different type of interleaving mechanism can be used in this system which followed by the interleaver, but it is important to select the appropriate interleaving mechanism to find the optimum performance. To select the appropriate interleaving mechanism, the three recent interleaving mechanism are considered for preforming the system using an avalanche photo detector at the receiver. The execution of O-IDMA with Random, Tree based and Prime interleavers[3,16,17] are shown in Figure3.

During the transmission of input data of each user through optical fiber, first, it is encoded by the encoder, secondly, pass out through the interleaver and last, converted into optical pulse by Laser. If *k* indicates the number of modes, Δw indicate the spacing between two consecutive modes in the mode locked laser then the electric field is generated by mode locked laser (MLL) and can be replaced as[2,18],

$$E_{MLL} = e^{iwot} \sum_{k=0}^{K-1} e^{ik(\Delta w)t} \quad (1)$$

OOK (on-off keying) modulation is used to modulate the output of MLL with interleaved data $x_k(j)$. The data of the users, which is transmitted through optical fiber, are stated as

$$E_{MLL} X_K(j) = X_K(j) e^{iwot} \sum_{k=0}^{K-1} e^{ik(\Delta w)t} \quad (2)$$

Where, $X_K(j) \in (1,0)$.

2.2 Communication Channel

The Nonlinear Schrodinger equation (NSE)[19,20] is used to consider the transmitting pulse in optical fiber which behaves nonlinearly. If *A(z,t)* is the envelope of slow varying pulse, propagation constants are β_1 and β_2, the transmitting distance is *z*, attenuation is denoted by α and the nonlinear coefficient is γ then the NSE can be expressed as[19-21]

$$\frac{\partial A(z,t)}{\partial z} + \beta 1 \frac{\partial A(z,t)}{\partial t} + \frac{j}{2} \beta 2 \frac{\partial^2 A(z,t)}{\partial t^2} = j\gamma A^2(z,t)A(z,t) - \frac{\alpha}{2} A(z,t) \tag{3}$$

Here, $j = \sqrt{-1}$. The transmitting pulse *A(z,t)* can be constituted as,

$$A_z = A(L+N) \tag{4}$$

The equation 4 represents a nonlinear partial differential equation which contains a linear operator *L* and a nonlinear operator *N*. The main two factors which affect the execution of the O-IDMA system are attenuation and dispersion[23] in the fiber.

The split step method is used to express the propagating pulse as[19,23]

$$A_z = -\frac{\alpha}{2}A - i\frac{\beta}{2}A_n + i\gamma|A|^2 A \tag{5}$$

The attenuation and dispersion are linear in nature. If the attenuation factor is $\boldsymbol{\alpha}$ and the split step distance is denoted by *dz*, The attenuation and dispersion can be represented as

$$\textbf{Attenuation} = e^{\frac{\alpha}{2}\times\frac{dz}{2}} \tag{6}$$

$$Dispersion = e^{\left(\beta_1 \frac{w}{2} + \beta_2 \frac{w^2}{2} + \beta_3 \frac{w^3}{2}\right)\times\frac{dz}{2}} \tag{7}$$

Dispersion is zero for single mode fiber therefore propagation constant of first derivative is zero i.e. $\beta_1 = 0$. The second and third derivative of the propagation constant is

$$\beta_2 = \frac{\lambda^2 \times D_1}{-2\pi c} \tag{8}$$

$$\beta_3 = \frac{1}{(-2\pi c)^2}\left(D_3 + \frac{2D_2}{\lambda_{ref}}\right)\lambda_{ref}{}^4 \tag{9}$$

Where, *c* characterizes as the velocity of light in free space. D_2 and D_3 characterize the second order and third order dispersion coefficient respectively.

For long distance transmission through an optical fiber, the non-linear distortion is quite crucial parameter in addition to the dispersion mechanism. As the optical signal pulse passes through the fiber it gets broaden due to dispersion and if the transmitting distance is sufficiently large the pulse may be overlap with neighboring pulse. Hence, the distortion in the signal ultimately becomes responsible for limiting the information carrying capacity of a fiber[19,24,25]. The nonlinear effects rely on the intensity of the signal and can be ignored at low power.

If the effective cross section area of the core of the fiber is A_{eff}, the nonlinear factor is denoted by n_2 and *I* can be measured by $|signal|^2$ then the nonlinear component is expressed as

$$A_z = e^{\frac{2\pi n_2 I}{\lambda A_{eff}} \times dz} \tag{10}$$

2.3 Receiver Section

In Figure 1, the receiver part of the Optical IDMA system is displayed in secondary segment. The optical receiver, is utilized to receive the original signal, consists the APDs, an elementry signal estimator (ESE), de-interleavers, interleavers and decoders. The main component of optical receiver is a photodetector which works on the principal of the photoelectric effect and used to convert the light pulse into electrical signals. At present, the PIN photodiode is used for detection and here it is replaced by avalanche photo detector (APD) to perform the operation speedily and accurately. The Bandwidth and the response time are the important parameters of Optical detectors. The range of the frequency should be high and response time should be less to get the high transmission rate which is desired by optical communication system. If the input power is denoted by P_{in} which is applied to a fiber of length *L*, the optical power at the output P_{out} can be expressed as[19]

$$P_{out} = P_{in}\exp(-\alpha L) \tag{11}$$

$\boldsymbol{\alpha}$ can be written as in dB/km

$$\alpha\left(\frac{dB}{km}\right) = -\frac{10}{L}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{12}$$

The Photo-current I_p which is produced by the detector is calculated by multiplying the responsivity R and the incident optical power P_{in} and can be stated as

$$I_p = RP_{in} \tag{13}$$

Where, *R* is in A/W. The quantum efficiency η can be expressed in term of responsivity *R* as

$$\eta = \frac{generation\ rate\ of\ electron}{incidence\ rate\ of\ photon} = \frac{\frac{I_p}{q}}{\frac{P_{in}}{hv}} = \frac{hv}{q} \quad (14)$$

The responsivity in terms of gain and quantum efficiency is

$$I_p = \frac{G\, q\, \eta}{\boldsymbol{h}\, \omega} P_{out} \quad (15)$$

Here, G indicates APD gain, η indicates the internal quantum efficiency respectively, h indicates Planck's constant ($6628*10^{-38}$J/s), ω indicates the optical frequency and q indicates the magnitude of the electron charge ($1.6*10^{-19}$C) respectively.

The Poisson distribution is used to calculate the probability of photons absorbed by incident optical field during a chip interval for a detector. If the received laser power is P_0 then the average number of photon absorption over the time interval T_C is stated as

$$\lambda_s = \frac{\eta P_0}{\boldsymbol{h} f} \quad (16)$$

Here, λ_s indicates the absorption rate of the photon, P_0 indicates the received power of the laser.

At the receiver section, the output from the optical fiber first convert into electrical form by APD and comes into the iterative decoder. The iterative decoder[4,5] has an elementary signal estimator (ESE), interleavers, de-interleavers and number of decoders (DECs) k with A Posteriori Probability (APP). The extrinsic log-likelihood ratios (LLRs) are used to relate outputs of the elementary signal estimator and decoder about $\{x_k(j)\}$ and is stated as

$$e_{ESE}\left(x_k\left(j\right)\right) \equiv iog\left(\frac{p_r(x_k\left(j\right) = +1)}{p_r(x_k\left(j\right) = -1)}\right) \quad (17)$$

For respective k, the received signal can be expressed as[3]

$$r(j) = \boldsymbol{h}_k x_k(j) + \xi_k(j) \quad (18)$$

Where, $\xi_k(j) \equiv r(j) - \boldsymbol{h}_k x_k(j)$ (19a)

$$\xi_k(j) = \sum_{k' \neq k} \boldsymbol{h}_{k'} x_{k'}(j) + n(j) \quad (19b)$$

The CBC(Chip by Chip)algorithm[3]is followed by the turbo detector and following steps are processed in it with initialization $e_{DEC}(x_k(j)) = 0, \forall\, k, j$

$$E\left(x_k\left(j\right)\right) = \tanh(e_{DEC}\left(\frac{x_k\left(j\right)}{2}\right) \quad (20)$$

$$var(x_k(j)) = 1 - \left(E(x_k(j))\right)^2 \quad (21)$$

$$E(\xi_k(j)) = \sum_{k' \neq k} \boldsymbol{h}_{k'} E\left(x_{k'}(j)\right) \quad (22)$$

$$var(\xi_k(j)) = \sum_{k' \neq k} |\boldsymbol{h}_{k'}|^2\, var(x_k(j)) + \sigma^2 \quad (23)$$

$$e_{ESE}\left(x_k\left(j\right)\right) = \frac{2hk}{\mathrm{var}\left(\xi_k\left(j\right)\right)}\left(r\left(j\right) - E\left(\xi_k\left(j\right)\right)\right) \quad (24)$$

In the completion of one iteration, LLRs $\{e_{DEC}(x_k(j)), \forall\, k, j\}$ are produced by DECs which follow the APP decoding operation and then come back to equation 20 to complete next iteration. The count of iterations in the receiver increases the certainty of recovery of user-specific data safely. However, it also increases the mathematical complexity and high power requirement. It has been observed with various simulations that, the count of 15 iterations in the receiver section, are sufficient for recovery of any user-specific data.

3. Photodetectors in O-IDMA System

The Avalanche photodiodes (APD's) are utilized in the Optical IDMA system to perform the detection with high data rate[26]. The motivation behind the use the APD's in place of PIN diode is that APD has high internal gain, larger responsivity and highly sensitive to the incoming photons while PIN diode has unity constant gain, low responsivity and less sensitive to the incoming photons. When the O-IDMA system is loss limited or thermal noise limited, APDs performed better than PIN photo diodes therefore APDs are advantageous. When the optical intensity falls at the junction of the APD, primary photoelectron-hole pairs are generated due to the absorption of incident photons. The generation of these primary photoelectron-hole pairs can be modeled by a Poisson point process of rate λ(t). Each primary pair next generates secondary electrons which are random in number at the output of APD by avalanche multiplication, which is presumed to be instantaneous. The numbers of secondary electrons$\{g_k\}$ yielded by the absorption of each primary electron and can be mentioned as the gain of APD. The number of secondary electrons is presumed as I.I.D. (independent and identically distributed) random variables.

The function of moment generation (mgf) $M_g(s)$ with APD gain (g) cab be expressed as

$$M_g(s) = E[\exp(sg)] = \sum_{n=1}^{\infty} \Pr\{g = n\}\exp(sn) \quad (25)$$

Here E[.] is used to denote the expectation operator for implicitly[27]

$$s = \ln\left[M_g(s)\right] - \frac{1}{1-k_{eff}}\ln\left[(1-a)M_g(s)+a\right], -\infty < \mathrm{Re}\{s\} < c_{\max} \quad (26)$$

Where, $a = \frac{1 + k_{eff}(G-1)}{G}$ and the gain of the APD is $G \equiv E[g]$, and $c_{\max} > 0$. The mean square value of g can be expressed as

$$v_g \equiv E[g^2] = \left[k_{eff}G + \left(2 - \frac{1}{G}\right)(1-k_{eff})\right]G^2 = FG^2 \quad (27)$$

Where, $F = \left[k_{eff}G + \left(2 - \frac{1}{G}\right)(1 - k_{eff})\right]$ states the APD excess noise factor. Here, K_{eff} is the important parameter in fabrication and theoretically it can be can be measured as

$$k_{eff} = \frac{\text{Ionization probabilities of holes per unit length}}{\text{Ionization probabilities of electrons per unit length}}$$

The value of K_{eff} should be lower for better execution. $M_g(c)$ can be calculated with the use of equation (26) and Newton's method is used to solve the equations. Here the value of c is $Re\{s\}$. If the value of K_{eff} is zero, the equation (26) provides the mgf of a geometric random variables[28]and the pdf can be denoted as[29]

$$\Pr\{g = n\} = (1 - b)b^{n-1} \quad (28)$$

Where $b = \frac{G-1}{G}$ which lie between 0 and 1, n is an integer (n = 1,2,…) and $v_g = 2G^2 - G$. This geometric distribution can be used to find the limitation of upper bounds and lower bounds on the probability of bit error (P_e)[26].

4. Results and Discussion

The simulation of the O-IDMA system has been executed with the help of MATLAB. To estimate the accomplishment of the system, bit error rate (BER) is considered.

In O-IDMA, the iterative decoder is used to get the original signal and therefore number of iteration is significant. Figure 2 reveals the variation in BER versus the number of iterations for the O-IDMA system considering APD and PIN photo detector. It is noticed from the Figure 2 that BER decreases with increase the number of iterations upto 14 and above 14 iterations the value of BER secures a constant value. Therefore the number of iterations is set to be 15 to get the efficient output. The reason behind choosing the 15 iteration is that above 15 iterations there is no change in the performance, but it produces complexity and require more power.

The execution of the O-IDMA system can be upgraded by choosing the relevant interleaves mechanism. To decide the perfect interleavers, the recent interleaving mechanisms are considered, including random interleavers[3], tree based interleavers[16] and prime interleavers[17] and the point is to be noticeable is that simulation is done using an APD detector at the receiver for high data transmission. It is clear from the Figure 3 that prime interleaves have the minimum BER and hence most suitable for the system using APD photodiode. Therefore, the Prime interleaving mechanism is selected for separating the users in the O-IDMA system. The optimum value of the parameters is selected for simulation and beyond this value the performance decreases accordingly. The important parameters are as follows: spreading length = 16, iteration number = 15. Data length of each user = 2048 bits. Wavelength of the optical fiber = 155nm. Maximum bit rate = 1 Gbps. Transmitted power = 1m W. Refractive index, which is dependent on an intensity = 2.35exp-20. Responsivity = 0.65. Efficiency = 0.80. The shape of the pulse to be transmitted in the fiber is

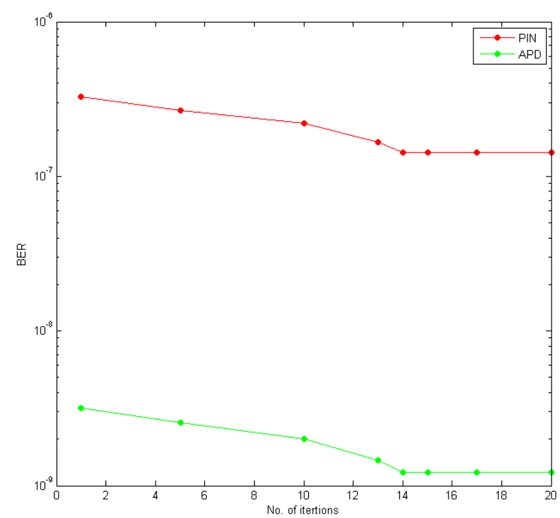

Figure 2. The BER vs. iterations for O-IDMA System with APD and PIN Photodetector.

Gaussian and ON-OFF keying (OOK) modulation is adapted for transmission of the pulse.

The typical parameters used for APD detector are the same order of magnitudeasin[26,28] that were taken to execute the O-IDMA system. The typical parameters are chosen for PIN photodetector[19]. Figure 4 reveals that as the number of users increases the BER increases and O-IDMA system degrades using both types of detectors (i.e. APD and PIN). But the accomplishment of the O-IDMA system using APD detector is much better than PIN detector; leading to desirable performance for the optical system.

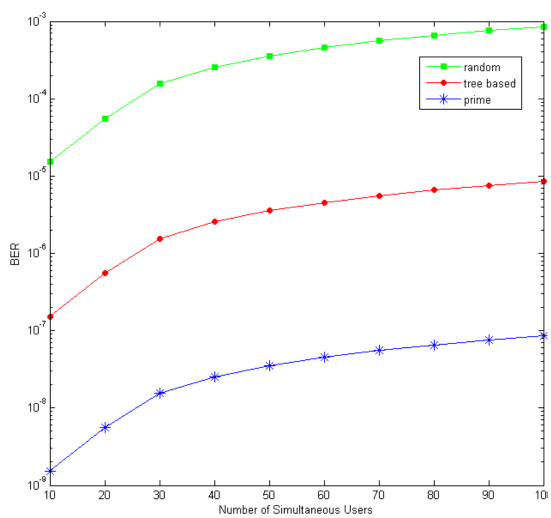

Figure 3. Performance of O-IDMA system using random, tree based and prime interleaving mechanism with APD detector.

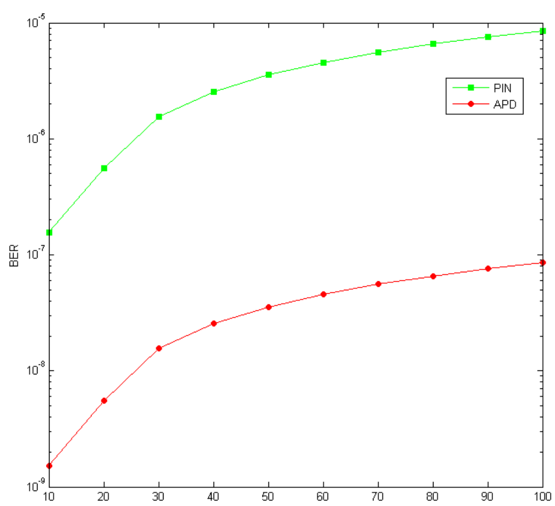

Figure 4. Performance of O-IDMA system using APD and PIN photodetector.

5. Conclusion

In this paper, the APD is implemented in place of PIN photodetector in the O-IDMA system because APD has high internal gain, larger responsivity and high sensitive to the incoming photons. The performance of the O-IDMA system using a PIN and APD detectors has been analyzed and results confirm that APD detector is a better detector for the O-IDMA system while some complexity increases in the system. The prime interleave mechanism may be preferred for user's separation with APD because it has the minimum BER. Finally, the conclusion is that the O-IDMA system can furnish an efficient and successful solution for high data rate using APD detection.

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