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High Performance with Avalanche Photodiode in Wavelength/Time Optical Code Division Multiple Access

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ABSTRACT

In order to increase the number of users as increasing the data rate and transmission distance, then to reduce the impact of multi-access interference (MAI) and the effect of phase-induced intensity noise (PIIN). This study proposed the utilizing of an avalanche photodiode (APD) on two-dimension optical code division multiple access (2-D OCDMA). APD detector is more sensitive than positive-intrinsic-negative (PIN) photodiode, due to its inherent gain that increases the signal to noise ratio (*SNR*) of the system by amplifying the received signal prior to proceeding to next stage. In this research, an improvement of realizable system capacity APD performance of different gain applied for Wavelength/Time modified double weight (MDW) code for cardinality, bit error rates (BER) and noise interference are analyzed. MATLAB is utilized as a software for theoretical results to study the APD gain effect upon the probability density function (PDF) and SNR performance. The results in very good approval indicate that 95.45% cardinality improvements compare to 2-D MDW code with PIN at 1.25 Gbps data bit rate. The P_{sr} = -14 dBm for 500 active users by using APDs with gain =5, but 5 dBm effective receive power for PIN error floor 10^{-9} for 500 users. The usage of APD over (PIN) photodiode provides a high performance for a long transmission distance and high data bit rate that improved in the simulation for real environment by using the Optiwave software version 11.0. Seemingly, the system supports more no. of users, less bit error rate, and large data rate transmission.

INTRODUCTION

The 2-D code has great improvements on correlation properties, BER, and maximum user number; this is why researching on the 2-D signature code. However, the 2-D code is developed from 1-D code, it is the mixture of two single 1-D codes, and the design of 1-D code with good properties is the basis for the design of 2-D code. (Zhang, 2012).

The W/T OCDMA has higher bit rates due to lower chip rates nevertheless, to the detriment of increase system complexity. Rather, by utilizing appropriate optical code sequences and right orthogonal characteristic the system performance can be improved. This indicates that the bit time or time-chip can be split into a low number of chip intervals then allow n high data rate (Tsai & Liang, 2011). Various 2-D codes have been developed. The 2-D hybrid codes with suppressed PIIN and MAI cancellation (Yeh, Lin & Wu, 2010), 2-D modified quadratic congruence (MQC) code with fixed cross-correlation resulted in the complete disposal of MAI by differential detection and suppression of PIIN (Wei, Shalaby & Ghafouri-Shiraz, 2001). 2-D perfect difference (PD) code in-

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phase and cross-correlations are exactly equal to one which has property to stifle PIIN and dispense with MAI (Lin, Wu &Yang, 2005),Recursive Combinatorial (RC) code (Nordin, 2014),the code length of this code is also shorter compared to other codes. Hence, this code could be a potential approach for greater improvement in optical communication, particularly the OCDMA network. 2-D m-sequence code extends in the wavelength domain and time domain using optical delay lines (Chang *et al.*, 2010). These 2-D codes can enhance the system capacity. The 2-D MDW code is W/T OCDMA code was developed in 2014 by brief (Arief *et al.*, 2014), this code has a good cross-correlation property, optimizing data transmission rate, equipped for stifling PIIN, wiping out MAI and improving framework performance of OCDMA system architecture. The code likewise has a preference of high cardinality, ideal information transmission rate, and low effective transmitted power. The 2-D MDW OCDMA code is derived from 1-D MDW OCDMA (Aljunid *et al.*, 2004).

2-D OCDMA framework can be enhanced to accomplish high framework limit by using avalanche photodiodes (APD). It keeps up high pick up security and substantial responsivity in the ultrafast long-haul and metro-area light wave systems (Peng *et al.*, 2009). APD is credited in high-speed receivers to their high inner optoelectronic gain. The photo created capability empower to give an electrical flag that rules the thermal without requiring for optical pre-amplification of the received optical signal (Sriwas *et al.*, 2016). The influence of the APD photodetector on the exhausted noise of an incoherent OCDMA network to mitigate systems noises and BER is considered by (Anderson *et al.*, 2009). Here the avalanche photodiode is implemented in place of PIN photodiode and evaluate performance of the 2-D MDW OCDMA codes system using avalanche photodiode with different gain 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 APD) by increasing the no. of users, but BER for APD is far better than PIN photodiode. 2-D W/T MDW codes are utilized as the signature the system. PIIN, shot noise, thermal noise, and APD are contemplated in the consideration in the performance study. The performance investigation is done cons dering the APD gain of 2-D MDW receiver systems are coincide, and no lost in transmitter and receiver splitters.

2-D MDW Code SNR Function and Noises:

There are three different sources of noises that are taken into consideration; MAI noise, which is coming from the network, Phase Induced Intensity Noise PIIN, is from the detector, and thermal and shot noise which is originated from the receiver noise (Zahang, 2012). The encoded signals arrive at the decoders and go through matched filtering to decode and recover the desired optical pulse signals (Tsai & Liang, 2011).

PIIN, a standout amongst an essential noise in SAC-OCDMA systems is PIIN, that created at the photo-detector because of the optical interference delivered in summing of the different postponed optical signs (Dar *et al.*, 2014). However, PIIN is highly proportional to the photo-detectors (Ghafouri & Karbassian, 2012) as:

$$\langle I_{PIIN} \rangle = I^2 \tau_C B_r \qquad (1)$$

Where I is the photo-detector current, τ_c is the coherence time of the source and B_r is the electrical bandwidth. A system that utilizes incoherent broadband sources is shortened by PIIN because of the thermal-like nature of incoherent light. PIIN emerges from the force commotion brought on by the phase noise is corresponding to the force of produced from photocurrent (Kumar *et al.*, 2015).

Thermal noise, in any conductor, the electrons have an irregular movement at a particular temperature. A fluctuating current is created in the heap resistor as a result of these movements regardless of the connected voltage is missing. This vacillates current will be added to the produced current of the photograph detector in the type of noise. These extra noise parts are called thermal noise or Nyquist noise (Fathallah *et al.*, 2014). The thermal noise is governed by Gaussian statistic on large-scale behavior (Dar *et al.*, 2014). Thus, the thermal noise variance is expressed as (Ghafouri-Shiraz & Karbassian, 2012; Hou *et al.*, 2015):

$$\langle I^2_{thermal} \rangle = \frac{4K_b T_n B_r}{R_L} \qquad (2)$$

Where K_b is the Boltzmann constant, T_n is the absolute temperature (in kelvin), and R_L is the load resistor.

The photodiode is the device that detects light in a discrete process. The signal emerging from detectors. The shot noise can be defined as (Clerk *et al.*, 2010).

$$\langle I^2_{shot} \rangle = 2eB_r I \qquad (3)$$

Where e is the electron charge, 1.602×10^{-19} coulomb.Thus, there is an exchange off between the transmission capacity of a recipient and its noise performance. A beneficiary is normally composed in order to have quite recently adequate transmission capacity to oblige the craved bit rate so its performance execution is enhanced.

As mention before there is three type of noise that are taken into consideration in the performance analysis. The effect of the dark current is neglected. The BER calculation is based on the Gaussian approximation. The photo-diode which is used to detect thermal lights, produces the photodiode noise that can be written as follow (Wei *et al*., 2001, Hamza., 2012):

$$\langle i \rangle = 2eIB + I^2 B\tau_c + \frac{4K_b T_n B}{R_L} \tag{4}$$

The PSD of the received optical signal is written as (Arief *et al*., 2014)

$$r(f) = \frac{P_{sr}}{\Delta f k_2} \sum_{w=1}^{W} d(w) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}(w) \left\{ u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i \right] - u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i-2 \right] \right\} \tag{5}$$

Where P_{sr} the effective power of a bandwidth source at the receiver is, Δf is the bandwidth of the source, k_2 is the code weight of the time-chip code sequence. W is the number of simultaneously active users, $d(w)$ is the data bit of the W_{th} user which can either be ‘’1’’ or ‘’0’’. M is the code length of the spectral code sequence, N is the code length of the temporal code sequence, a_{ij} is an element of W_{th} user’s code word.

Where $u(f)$ is the unit step function that can be expressed as:

$$u(f) = \begin{cases} 1, f \geq o \\ 0, f \langle 0 \end{cases} \tag{6}$$

PSD that exists at the $PD0, PD1, PD2,$ and $PD3$ of the receiver by using the cross-correlation between code-word $A_{00}^{d}, A_{g,h}$ are calculated. The PSDs for a single bit period of the optical signals at $PD0, PD1, PD2,$ and $PD3$ of the receiver was represented by (Arief *et al*., 2014).

$$G_0(f) = \frac{P_{sr}}{\Delta f k_2} \sum_{k=1}^{W} d(w) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}^{(0)} a_{ij}(w) \left\{ u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i \right] - u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i-2 \right] \right\} \tag{7}$$

$$G_1(f) = \frac{P_{sr}}{\Delta f k_2} \sum_{k=1}^{W} d(w) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}^{(1)} a_{ij}(w) \left\{ u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i \right] - u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i-2 \right] \right\} \tag{8}$$

$$G_2(f) = \frac{P_{sr}}{(k_1 - 1)\Delta f k_2} \sum_{k=1}^{W} d(w) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}^{(2)} a_{ij}(w) \left\{ u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i \right] - u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i-2 \right] \right\} \tag{9}$$

$$G_3(f) = \frac{P_{sr}}{(k_1 - 1)\Delta f k_2} \sum_{k=1}^{W} d(w) \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}^{(3)} a_{ij}(w) \left\{ u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i \right] - u\left[f - f_0 - \frac{\Delta f}{2M}(-M+2i-2 \right] \right\} \tag{10}$$

For worst situation analysis, we set $d(w)=1$. The $G_0(f), G_1(f), G_2(f)$ and $G_3(f)$ are used to obtain output current from each arm of the detector. Average output currents $PD0, PD1, PD2,$ and $PD3$ of the receiver are written as:

$$I_0(f) = \Re \int_0^{\infty} G_0(f)\,df = \frac{\Re P_{sr}}{M k_2} \left\{ k_1 k_2 + k_1 \frac{(W-1)(N-1)}{(MN-1)} + k_2 \frac{(W-1)(M-1)}{(MN-1)} + \frac{(W-1)(M-1)(N-1)}{(MN-1)} \right\} \tag{11}$$

$$I_1(f)=\Re\int_0^{\infty}G_1(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{k_1\frac{(W-1)(N-1)}{(MN-1)}+\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \tag{12}$$

$$I_2(f)=\Re\int_0^{\infty}G_2(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{k_2\frac{(W-1)(M-1)}{(MN-1)}+\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \tag{13}$$

$$I_3(f)=\Re\int_0^{\infty}G_3(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \tag{14}$$

Where $\Re$ is the responsivity of the photodiode, $\Re=\eta e/hf_0$, η is the quantum efficiency of the PD, h is the Plank's constant and f_0 is the central frequency of the incident light. The average photocurrent output from the receiver is defined as average output current of (PD0-PD1) minus (PD2-PD3) of the receiver was expressed as:

$$I_r=(I_0-I_1)-(I_2-I_3)=\frac{\Re P_{sr}k_1}{M} \tag{15}$$

PIIN is the result of mixing incoherent light field's incident, which causes intensity noise at PD output (Al-Khafaji *et al*., 2014). The power of PIIN that exists in photocurrent of the receiver can be written as:

$$\left\langle I^2{}_{PIIN}\right\rangle=B_rI_r^2\tau_r=\frac{B_r\Re^2P_{sr}^2\left\lfloor k_1k_2(MN-1)^2+\Lambda_2^2\right\rfloor}{2M\Delta fk_2^2(MN-1)^2} \tag{16}$$

The shot noises are coming from the receiver, the average output currents of the receiver are independent of each other.The power of shot noise current can represented by:

$$\begin{aligned}\left\langle I^2_{shot}\right\rangle&=2eB_r(I_0+I_1+I_2+I_3)\\&=2eB_r\frac{\Re P_{sr}}{Mk_2(MN-1)}\left\{k_1k_2(MN-1)+2k_1(W-1)(N-1)+2k_2(W-1)(M-1)+4(W-1)(M-1)(N-1)\right\}\end{aligned} \tag{17}$$

From (15) the total photocurrent output from the receiver I_r is given by:

$$I_r^2=\left[\frac{\Re P_{sr}k_1}{M}\right]^2 \tag{18}$$

2-D MDW code SNR function was developed from (16),(17),(18) and (2) as:

$$SNR=\frac{I_r^2}{\left\langle I^2_{PIIN}\right\rangle+\left\langle I^2_{shot}\right\rangle+\left\langle I^2_{thermal}\right\rangle} \tag{19}$$

BER can be expressed in terms of the signal-to-noise ratio (SNR) as:

$$BER(M)=\tfrac{1}{2}erfc(\sqrt{\frac{SNR}{8}} \tag{20}$$

The avalanche ionization coefficient ratio K_e is an important criterion affecting the performance of APD. APDs have larger values of responsivity (R) compare to PIN photodiode. The physical marvel behind the internal current gain is known as the impact ionization (Ferraro *et al*., 2016). The system performance of OCDMA systems can be enhanced using the APD instead of the PIN photodiode.

$$F_e = K_e G + (1 - K_e)(2 - G^{-1}) \tag{21}$$

Ionization ratio of the APD (Ferraro, 2016). The SNR equation of APD can expressed as:

$$SNR_{APDs} = \frac{\left[\dfrac{G\Re P_{sr}}{Mk_2(MN-1)}\left\{k_1(W-1)(N-1)-k_2(W-1)(M-1)\right\}\right]^2}{\left[\begin{array}{l}\dfrac{B_r G^2 \Re^2 P_{sr}^2}{M\Delta f k_2^2 (MN-1)^2}\left[k_1 k_2 (MN-1)^2 + \Lambda_2^2\right] + eB_r GF_e \dfrac{G\Re P_{sr}}{Mk_2(MN-1)}\left[\begin{array}{l}k_1 k_2 (MN-1) + 2k_1(W-1)(N-1) + 2k_2(W-1)(M-1)\\ +4(W-1)(M-1)(N-1)\end{array}\right]\\ + \dfrac{4K_b T_n B_r}{R_L}\end{array}\right]} \tag{22}$$

$$\Lambda_2 = k_2(W-1)(M-1) \tag{23}$$

2-D MDW OCDMA APD SNR equation can be written by:

$$SNR_{APDs} = \frac{G^2 I_r^2}{\left\langle G^2 I_{PIIN}^2 \right\rangle + \left\langle G^2 I_{shot}^2 \right\rangle + \left\langle I_{thermal}^2 \right\rangle} \tag{24}$$

G is the gain of APD.

Analysis Result:

In the theoretical calculation, the link parameter of the equation 19 that used is shown in Table 1 these parameters are the same used in (Arief & Abdullah, 2013).

The 2-D MDW OCDMA code sequence uses the nation of $(M, N, W, \lambda_a, \lambda_c)$ to denote M is a number of wavelengths, N is temporal code length, W is weight, λ_a and λ_c are auto-correlation and cross-correlation values.

Table 1: Parameters Used in Numerical Calculation (Areif, 2013)

Parameters Used in Numerical Calculation	
PD quantum efficiency	η=0.75
Spectral width of broadband light source	Δλ=30nm(Δλ=3.75THz)
Operating wavelength	λ_o=1.55μm
Electrical bandwidth	B=320 MHz
Data transmission rate	R_b =622 Mbps, 1 Gbps, 1.5 Gbps, 2 Gbps
Receiver noise temperature	T_n =300K
Receiver load resistor	R_L=1030Ω
Boltzmann’s constant	K_b=1.38×10^-23 W/K/Hz
Electron charge	e=1.60217646×10^-19 coulomb
Light velocity	C=3×10^8m/s

APD is capable of increasing the cardinality through gain optimization. The average gain of APDs is 5, excess noise factor of APD is 3.5, and the APDs’ effective ionization ratio is 0.5. Figure1 illustrates the performance of 2-D MDW code in terms of BER against the number of active users by using PIN and APD when the data bit rate is 622 Mbps and 1.25 Gbps and P_{sr} is 0 dBm. Clearly, the employment of APD is better than PIN due to the internal gain G, where the performance improves with increasing gain values. At BER of 10^{-9}, the use of APD in a receiver increased the number of active users to 900. When to increase the data bit rate to 1.25 Gbps the use of APD at the receiver is still better than PIN that can reach to 600 users even is little more PIN which reaches 480 users with data rate equal 622 Mbps.

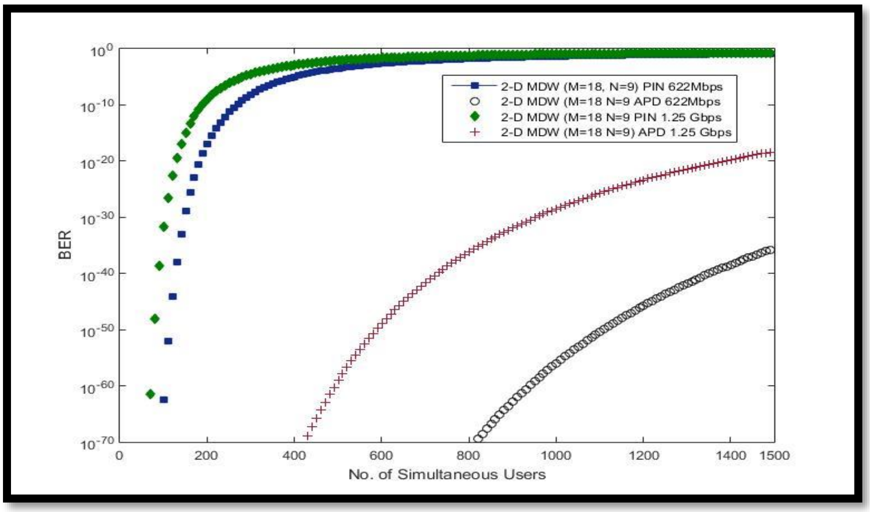

Fig. 1: BER versus Number of Active Users of 2-D MDW code with PIN and APD under different data rate

The improvement of the cardinality for using PIN and APD Photo-detector for 2-D MDW code with different data bit rate.

Table 2: The Improvement of the Cardinality with different Data Rate by Using PIN and APD

Data Rate	Cardinality	Improvement
622 Mbps APD 622 Mbps PIN	800 490	63.2%
1.25 Gbps APD 1.25 Gbps PIN	430 220	95.45%
0.622 Gbps PIN 1.25 Gbps PIN	490 220	122.7%
0.622 Gbps APD 1.25 Gbps APD	800 430	86%

In Figure 2, it is clearly observed that the performance of the OCDMA system is enhanced as the APD photo-detector gain increase. With data rate 622 Mbps the number of users can be achieved at BER 10^{-9} is more the 4000 and for APD, a gain of 2, the number of users is 1250 at BER 10^{-9}. As the data rate is increasing the system performance for APD with a gain of 5 is better at 1.25 Gbps data bit rate than the performance of APD with a gain of 2, the cardinality is 3000, and 600 respectively.

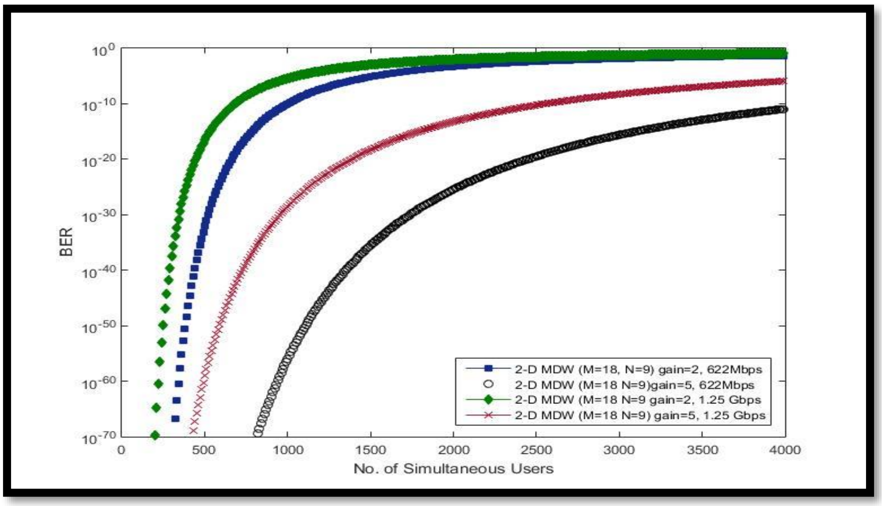

Fig. 2: BER versus Number of Users with different data rate and APD gain=2, 5

Figure 3 shows the performance of the 2-D MDW code with BER versus P_{sr} using PIN photodiode and ADP G=5 under different data bit rate of 622 Mbps and 1.25 Gbps with a number of users is 500. Clearly, the performance enhanced by the utilization of APD as opposed to PIN photodiode. The power penalties of using PIN compared to APD for gain value is 5 dBm for 622 Mbps. Therefore, the use of APD will improve the sensitivity of the receiver to receive an optical signal with low power.

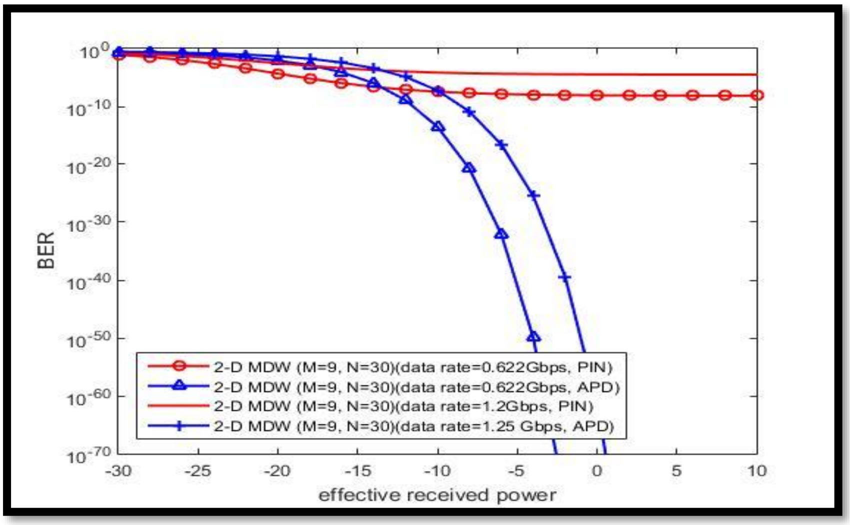

Fig. 3: BER versus Receive Power of APD and PIN Photo-Detector

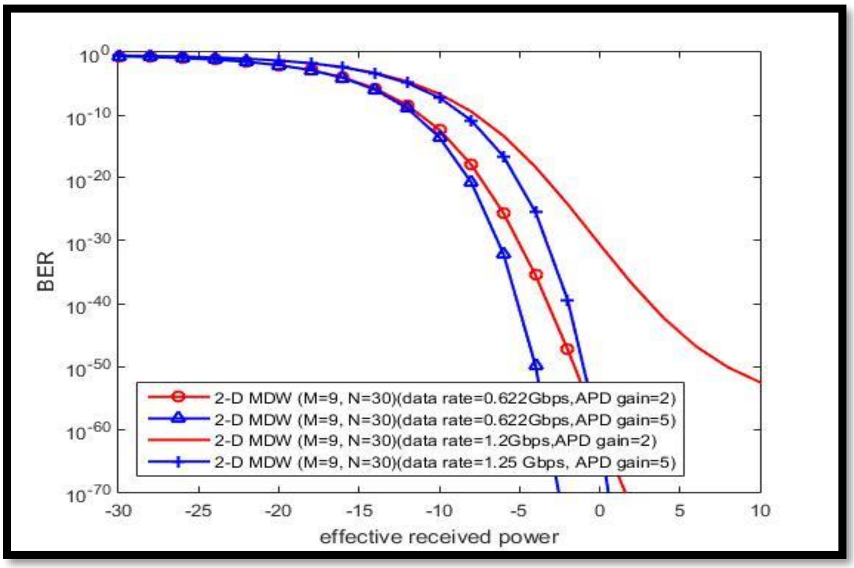

Fig. 4: performance of different gain for APDs with 60 active users with 622 Mbps and 1.25 Gbps

This section consists of the simulation results of 2-D MDW code with the incoherent system and using commercial software OptiSystem version 11.0. The simulation results were obtained from a comprehensive simulation where all factors that affect the system performance are taken into accounts such as the dispersion and nonlinear effect. The parameters used are shown in Table 3

Table 3: The parameters are used in Simulation**.**

Parameters used in the simulation	
Number of users	4
2-D MDW code length	$M = 9, N = 3,$
2-D MDW code weight	$k_1=4, k_2=2$, for spectral and temporal chip respectively
Input power for LED	16.66 dBm
WDM filters bandwidth	0.8 nm

Data format generator	NRZ, RZ
Mach-Zehnder Modulator extinction ratio	30 dB
The delay	Optical delay
Transmission multimedia	ITU-T G.652 standard single mode optical fiber
Transmission distance length	5km-40km
Attenuation	0.25 dB/km
Dispersion	16.75 Ps/nm/km
Data rate	622 Mbps, 1.25 Gbps, 1.5 Gbps, 2.5Gbps
Decoder	Rectangular Optical filters, Optical Adder, PIN Photodiode, APD Photodiodes
Dark current for the PIN , APD	10nA
Thermal noise for each photo-detector	1×10^-22 W/Hz
Detection techniques	AND-Subtract , Direct detection techniques

The values of the system parameters are adopted in this simulation based on the typical values in a real environment. The 2-D MDW code of $k_1 = 4, k_2 = 2, M = 9, N = 3$ were applied as the signature code for four users OCDMA system

The BER performance of the 2-D MDW code versus the data rate by using PIN and APD (G=5) is shown in Figure 5. Clearly using APD is better for the system performance, which can reach 19 km of 622 Mbps data bit rate, and better with high data rate 1.25 Gbps that the transmission distance is 16 km but for PIN with this data rate can only 10 km for the transmission distance.

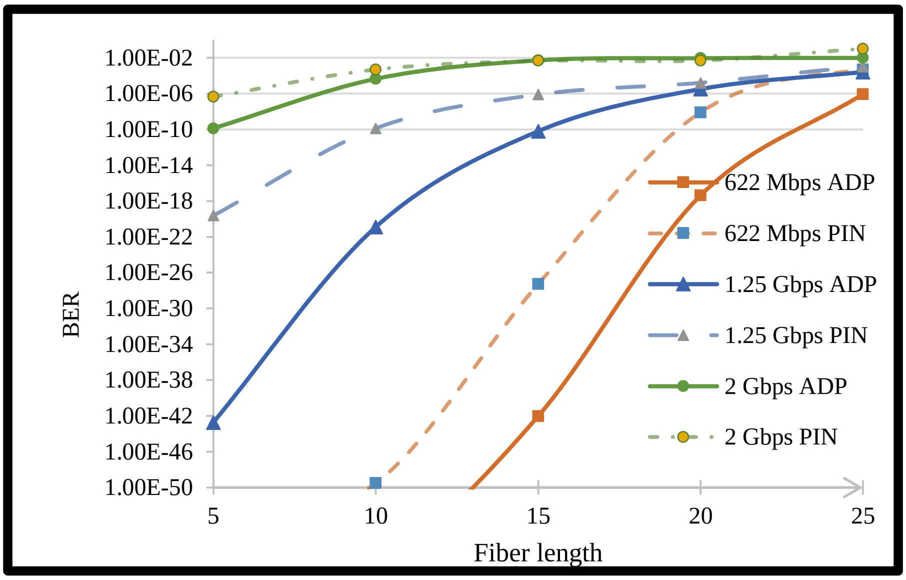

Fig. 5: BER versus optical transmission distance by using PIN and APD Photo-detector

APD appropriateness and supportiveness hold tight on numerous parameters. Two of the bigger components are quantum proficiency, which indicates how well occurrence optical photons are retained and after that used to deliver essential charge bearers; and aggregate leakage current, which is the sum of the dark current and photocurrent and noise. Electronic dark noise mechanisms are series and parallel noise. Series noise, which is the effect of shot noise, is essentially relative to the APD capacitance through the parallel clamor is connected with the varieties of the APD mass and surface dark current.

Conclusion:

The proposed networks cardinality has been increment by 63.2% based on APDs compare to PIN photo-detectors at data bit rate 622Mbps, and 95.45% for 1.25 Gbps data bit rate. The $Psr=-14$ dBm for 500 active users by using APDs with gain =5, but 5 dBm for PIN. For data bit rate 1.25 Gbps P_{sr} =-6 for APDs photo-detector using. Increase the code length and code size by making the spectral code length longer, does not improve the BER performance because the increasing of spectral length leads to spread the power on long spectral length, and increase the electrical noise bandwidth, respectively. 2-D MDW code size can be further increased and optimized to keep the BER low through increase the time code length. APD is a viable solution for a system where the power loss or thermal noise is limited. Even though APD provides high cardinality, for high bit rate and for long transmission distance, the BER performance indicates slow degradation. However, the various value of the APD gain is complemented with the penalty of shot noise present in the photo-generated electrical signal produced.

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