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Full Length Research Paper

Performance improvement of SAC-OCDMA system using modified double weight (MDW) code for optical access network

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In this paper, we have extensively analyzed the SAC-OCDMA system performance using Modified Double Weight (MDW) code with NAND detection technique as newly developed by the authors. In theoretical analysis, various noises and Multiple-Access Interference (MAI) effect were taken into account. The system performance was characterized by the signal-to-noise ratio (SNR) and the Bit-Error-Rate (BER). The analysis results obtained with NAND detection technique were compared with those as obtained with complementary subtraction techniques. The comparison results revealed that the NAND detection technique with MDW code can support more number of active users and improve the system performance compared with complimentary subtraction techniques. We also ascertained by simulation experiment that the BER performance of the system with NAND detection technique is greatly improved as compared to the complementary subtraction technique.

Key words: Optical code division multiple access (OCDMA), NAND/complementary detection, modified double weight (MDW) code, multiple-access interference (MAI).

INTRODUCTION

Optical code division multiple access (OCDMA) is a promising technique for optical access network to support large number of users by utilizing available frequency with no time delay, mitigating connection and providing flexible provisioning (Castro et al., 2006; Wei and Ghafouri, 2002). The OCDMA offers many advantages over time division multiple access (TDMA) and wavelength division multiple access (WDMA) system (Salehi, 1989). However, the OCDMA system always suffers from various types of noises such as shot noise, thermal noise, dark current including the multi-access-interference (MAI) effect. Among these noises, the most dominant noise is MAI (Wei et al., 2002; and Aljunid et al., 2004) and fiber dispersion (Monga and Kaler, 2010). In order to overcome the MAI effect, a technique called Spectral-Amplitude-Coding (SAC) with ideal cross correlation was proposed (Smith et al., 1998; Kavehrad and Zaccarin, 1995; Hilal et al., 2009; Anuar et al., 2009).

The SAC-OCDMA technique increases the physical bandwidth of the channel. Due to the more number of users in a single channel, the system performance is degraded, which is called the Multi Access Interference (MAI) effect. In order to reduce the MAI effect, various detection techniques are proposed by many researchers. In SAC-OCDMA system, the detection is considered as one of the important processes to design the system transmitter and receivers for the enhancement of the system performance (Jose et al., 2006). In general, two basic known detection techniques namely coherent and incoherent are widely used (Huang et al., 2009).The knowledge of the phase information of the carriers keeps big impact when coherent detection sends the detection signal, but on the other hand incoherent detection has no such kinds of knowledge. Alternatively, the incoherent

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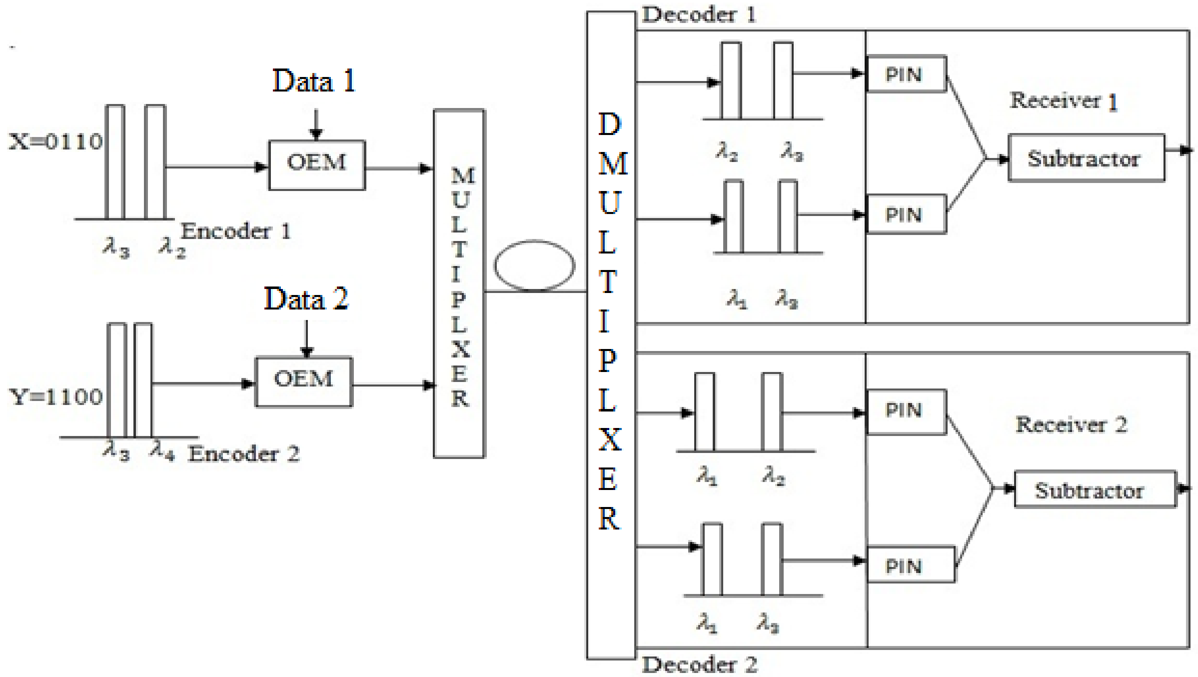


Figure 1. shows the implementation of NAND subtraction detection.

detection is performed in a unipolar approach and coherent is performed in a biopolar behavior with the coding operation. Furthermore, the incoherent detection does not need phase synchronization and complex hardware, which motivated us to choose the incoherent detection techniques. The well known incoherent detection techniques are the complimentary subtraction technique (Nguyen and Aazhang, 1995; Aljunid et al., 2004), and the spectral direct detection technique (SDD) (Abdullah et al., 2008). Although these detection techniques can suppress the MAI, but suffer from the poor signal quality, which is a big limitation of the existing detection techniques.

The Modified Double Weight (MDW) (Aljunid et al., 2004) was applied with complimentary subtraction technique and successfully reduced the MAI effect but the signal quality is still poor. Considering this limitation of MDW code with complementary detection technique, we chose the NAND subtraction detection for this study to improve the system performance. We analyzed the system performance by theoretical analysis as well as simulation experiment. The results obtained by using MDW code with NAND detection technique were compared with those as obtained with the complementary detection techniques. The comparison results ascertained that the performance of system is greatly improved by using MDW code with NAND detection technique compared to the complementary subtraction techniques. We also noticed that the NAND detection can carry better signal quality than the existing techniques.

MATERIALS AND METHODS

NAND subtraction technique

The mobility of the digital electrons in NAND gate is three times higher than AND/NOR gates (Holdsworth and Clive, 2002).This statement refers to the digital logic gates (AND, OR, NAND). However, in our proposed system the idea of NAND is used as an operation, not as a digital gate. Considering this point of view, the authors brought the concept of the NAND subtraction technique in our study. In the NAND subtraction detection technique, the cross-correlation $\theta_{\bar{X}\bar{Y}}(K)$ is substituted by $\theta_{(\overline{XY})}$, where $\theta_{(\overline{XY})}$ represents the NAND operation between X and Y sequences. For example, let $X = 1100$ and $Y = 0110$ therefore the NAND is $(\overline{XY}) = 1011$. Figure 1 shows the implementation of NAND subtraction detection technique, and Table 1 shows the comparisons between complementary, NAND subtraction detection technique using MDW codes.

Note that λ_i (where i is 1, 2.....N) is the column number of the codes which also represents the spectral position of the chips. Therefore, MAI can be cancelled using both techniques. However, NAND subtraction detection technique can generate extra weight as shown in Table 1. This is due to the fact that when the code weight is increased, the signal power increases as well; hence, increases the signal-to-noise ratio. Therefore, SAC-OCDMA system performance is improved significantly using the NAND subtraction

Table 1. Comparison of NAND, and complementary subtraction detection technique.

	Complementary subtraction				NAND subtraction			
	λ_1	λ_2	λ_3	λ_4	λ_1	λ_2	λ_3	λ_4
X	1	1	0	0	1	1	0	0
Y	0	1	1	0	0	1	1	0
	$\theta_{XY} = 1$				$\theta_{XY} = 1$			
	$\theta_{\overline{XY}} = 0011$				$\theta_{\widetilde{\overline{XY}}} = 1011$			
	$\theta_{\overline{XY}} = 1$				$\theta_{(\widetilde{\overline{XY}})Y} = 1$			
Z	$Z = \theta_{XY} - \theta_{\overline{XY}} = 0$				$Z_{NAND} = \theta_{XY} - \theta_{(\widetilde{\overline{XY}})Y} = 0$			

detection technique.

System performance analysis

In our analysis, we have considered the effect of incoherent intensity noise $\langle i_{PIIN} \rangle$ shot noise $\langle i_{shot} \rangle$ and thermal noise $\langle i_{thermal} \rangle$ as well. The detection scheme considered for the analysis is based on the NAND detection technique using Fibre Bragg Grating (FBG) followed by photo-detector. Gaussian approximation is used for the calculation of BER (Nguyen and Aazhang, 1995). When the incoherent light fields are mixed and incident upon a photo-detector, the phase noise of the fields causes an intensity noise term in the photo-detector output (Abdullah et al., 2008). The source coherence time τ_c is expressed as (Wei and Ghafouri, 2002).

$$\sigma_c = \frac{\int_0^\infty G^2(v)dv}{\left[\int_0^\infty G(v)dv\right]^2}, \quad (1)$$

Where *G (v)* denotes the single sideband power spectral density (PSD) of the thermal source. The Q-factor performance provides the qualitative description of the optical receiver performance. The performance of an optical receiver depends on the signal-to-noise ratio (SNR). The Q-factor suggests the minimum SNR required to obtain a specific BER for a given signal (Smith et al., 1998). The SNR of an electrical signal is defined as the average signal to noise power $SNR = \left[I^2/_{\sigma^2}\right]$, where σ^2 is the variance of noise source (note: the effect of the receiver's dark current and amplification noises are neglected in the analysis of the proposed system), given by:

$$\sigma^2 = \langle i^2_{Shot} \rangle + \langle i^2_{PIIN} \rangle + \langle i^2_{thermal} \rangle = 2eBI + I^2 B\sigma_c + \frac{4K_b T_n B}{R_L} \quad (2)$$

Where the symbols used in Equation 3 bear the following meaning.
E - Electron charge;
I - Average photocurrent;
I^2 -The power spectral density for *I*;
B - Electrical bandwidth;
Kb - Boltzmann Constant;
T_n - Absolute receiver noise temperature;
R_L - Receiver load resistor.

The code cross correlation properties of MDW codes using NAND operation of the detection part differs from complementary subtraction technique. In this technique, the system carried out better performance in terms of PIIN noise, shot noise, signal to noise ratio and bit-error-rate. The NAND detection scheme based on MDW code properties is explained in Equation 3. If $C_k(i)$ denotes the ith element of the K*th* MDW code sequence, the code properties G_2 can be written as shown in Equation 3.

$$\sum_{i=l}^{N} C_K \widetilde{\overline{(i)C_l}}(i) \cdot C_l(i) = \begin{cases} W, & For\ K = l \\ W-1, & For\ K \neq l \\ 0, & Else \end{cases} = \begin{cases} K+1\ if\ K < l \\ K-1\ if\ K > l \end{cases} \quad (3)$$

The system transmitter and receiver is analyzed according to the analysis. All the assumptions considered in (Aljunid et al., 2004), are important for mathematical simplicity. Therefore, the following assumptions are taken into account for analysis of the system such as: A) each light source is ideally unpolarized and its spectrum is flat over the bandwidth $\left[V_0 - \frac{\Delta V}{2}, V_0 + \Delta V/2\right]$ where V_0 the central optical frequency is and Δv is the optical source bandwidth expressed in Hertz. B) Each power spectral component has an identical spectral width. C) Each user has equal power at the receiver. D) Each bit stream from each user is synchronized. The power spectral density of the received optical signals can be written as (Wei and Ghafouri, 2002; Sahbudin et al., 2009):

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{K=1}^{K} d_K \sum_{i=1}^{N} C_K(i) rect(i), \quad (4)$$

Where P_{sr} is the effective power of a broadband source at the receiver, *K* is the active users and *N* is the MDW code length, d_K is the data bit of the *K*th user that is "1" or "0". The $rect\ (i)$ is given by:

$$rect(i) = u\left[v - v_0 - \frac{\Delta v}{2N}(-N + 2i - 2)\right] - u\left[v - v_0 - \frac{\Delta v}{2n}(-N + 2i)\right] = u\left[\frac{\Delta v}{N}\right] \quad (5)$$

Where $u(v)$ is the unit step function and can be expressed as:

Table 2. Typical system parameters used for calculation.

Parameter	Value
PD quantum efficiency	$\eta = 0.6$
Line width of the thermal source	$\Delta v = 3.75THz$
Operation wavelength	$\lambda = 1.55\mu m$
Electrical bandwidth	$B = 311\ MHz$
Receiver noise temperature	$T_r = 300\ K$
Receiver load resistor	$R_L = 1030\Omega$

$$u(v) = \begin{cases} 1, & v \geq 0, \\ 0, & v < 0. \end{cases}$$

The total incident power at the input of PIN 1 and 2 is given by:

$$\int_0^{\infty} G_1(v)\, dv = \int_0^{\infty} \left[\frac{P_{sr}}{\Delta v} \sum_{K=1}^{K} d_K \sum_{i=l}^{N} C_K(i) C_l(i) \left\{u\left[\frac{\Delta v}{N}\right]\right\}\right] dv \quad = \frac{P_{sr}}{N} \sum_{K=1}^{K} \sum_{K=l} d_K \qquad (6)$$

Now, power spectral density for photodetector 2 is given by

$$\int_0^{\infty} G_2(v) dv = \int_0^{\infty} \left[\frac{P_{sr}}{\Delta v} \sum_{K=1}^{K} d_K \sum_{i=l}^{N} \left(\overline{C_K(i)} C_l(i) \,.\, C_K(i)\right) \left\{u \left[\frac{\Delta v}{N}\right]\right\}\right] dv$$

$$\int_0^{\infty} G_2(v) dv = \frac{P_{sr}}{N} \left[W + (W-1) \sum d_K\right] \qquad (7)$$

In the above equations, d_K is the data bit of the *K*th user that carries the value of either "1" or "0". Now the photodiode current *I* can be expressed as:

$$I = I_2 - I_1 = \Re \int_0^{\infty} G_2(v) dv - \Re \int_0^{\infty} G_1(v) dv = \frac{\Re P_{sr}(2W-2)}{N} \qquad (8)$$

Where $\Re$ is the responsivity of the photo-detectors and given by $\Re = {\eta e}/{h v_c}$. Here, η is the quantum efficiency, *e* is the electron charge, *h* is the Planck's constant, and v_c is the central frequency of the original broadband optical pulse. The noise power of shot noise can be written as:

$$\langle I_{shot}^2 \rangle = 2eB\, (I_1 + I_2) = \frac{2eB\Re P_{sr}}{N}\left[\frac{4W + W^2}{2}\right] \qquad (9)$$

By using the similar methodology in (Castro et al., 2006) and approximating the summation $\sum_{K=1}^{K} C_K \approx \frac{KW}{N}$ and $\sum_{K=1}^{K} C_{KT} \approx \frac{KW}{N}$ the noise power can be written as:

$$\langle I_{PIIN}^2 \rangle = BI_1^2 \tau c_1 + BI_2^2 \tau c_2 = \frac{B\Re^2 P_{sr}^2 KW}{N^2 \Delta v}\left[\frac{4W + W^2}{2}\right] \qquad (10)$$

The thermal noise is given as (Aljunid et al., 2004; and Huang et al., 2000):

$$\langle i_{thermal}^2 \rangle = \frac{4K_b T_n B}{R_L} \qquad (11)$$

Noting that the probability of sending bit '1' at any time for each user is ½ (Wei and Ghafouri, 2002) so that the SNR of the NAND detection system can be written as:

$$SNR = \frac{I^2}{\tau^2} = \frac{\frac{\Re^2 P_{sr}^2 (2W-2)^2}{N^2}}{\frac{eB\Re P_{sr} W\left(\frac{4W + W^2}{2}\right)}{N} + \frac{B\Re^2 P_{sr}^2 KW\left(\frac{4W + W^2}{2}\right)}{N^2 \Delta v} + \frac{4K_b T_n B}{R_L}} \qquad (12)$$

Equation 12 is the general equation used to calculate the signal-to-noise ratio for the MDW code families. Using Gaussian approximation, the bit-error-rate (BER) can be expressed as (Wei and Ghafouri, 2002).

$$BER = P_e = \frac{1}{2}\, erfc\left(\sqrt{\frac{SNR}{8}}\right) \qquad (13)$$

All the theoretical results are calculated by using equations (12) and (13). The typical parameters are used for calculation is shown in Table 2.

Network simulation setup

The simulation setup of SAC-OCDMA system based on MDW code using NAND subtraction detection technique consisting of 2 users is shown in Figure 2, as an example. The simulation was carried out using simulation software, Opt system version 7.0, at 622 Mb/s bit rates. The code is used for transmitting data bit 1 and converting to data bit rate zero. The broad band light source (LED) is sliced using splitter. Each sliced chip has a spectral width of 0.8 nm which is modulated by the pseudo random bit sequence (PRBS). The multiplexer is combined the modulated signal including multiplexer insertion loss 2 dBm. The ITU-T G.652 standard single-mode optical fiber (SMF) is used to transmit signal to the receiver side. In

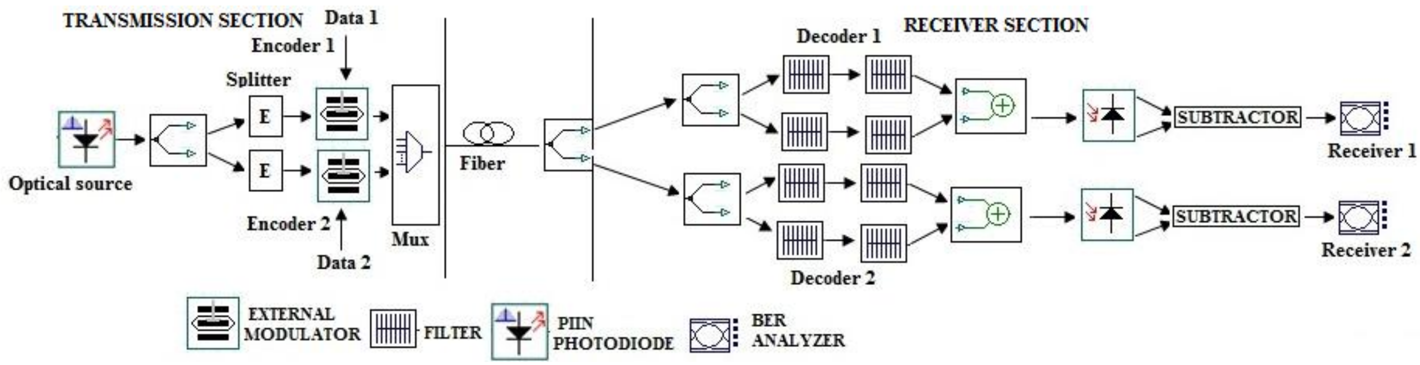


Figure 2. Simulation setup for the SAC-OCDMA system with NAND subtraction technique.

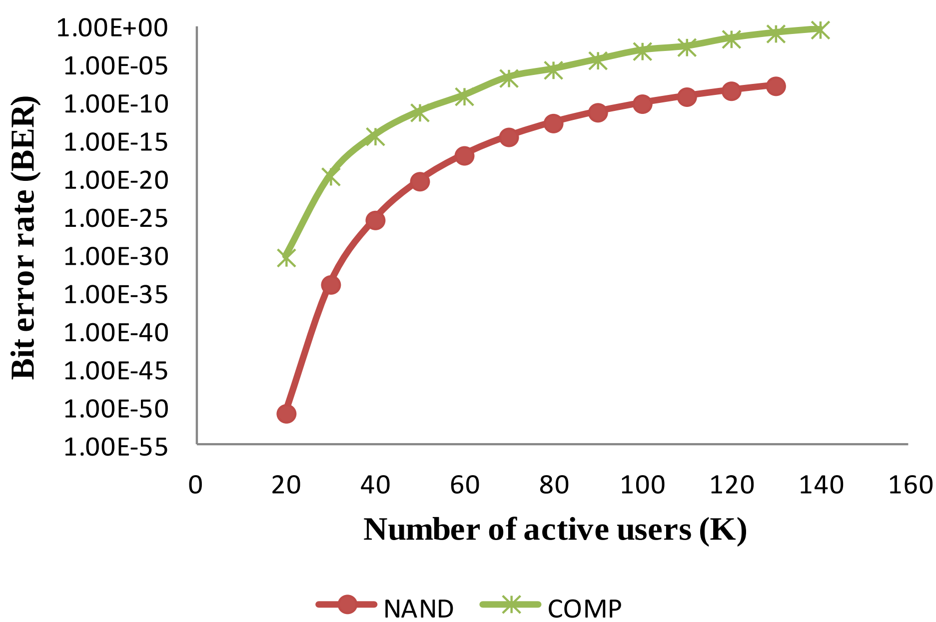


Figure 3. BER versus number of simultaneous user when $P_{sr} = -10\ dBm$.

the receiver side, the signal is filtered using fiber-bragg-gratings (FBG) and subtracted using the subtractor. The photodetector (PIN) is used to detect the signal and the signal analyzed by BER analyzer.

The fiber parameters values are taken from the data which are based on the G.652 non dispersion shifted fiber (NDSF) standard. This includes all fiber parameters such as group delay, group velocity, attenuation α (that is, 0.25 dB/km), polarization mode dispersion (PMD, that is, 18 ps/nm km). The effects of non linear such as four wave mixing (FWM) and self phase modulation (SPM), which were all wavelength dependent. All these parameters were activated during simulation. The dark current values was 5 nA and the thermal noise co-efficient was 1.8 × 10^{-23} W/Hz for each of the photodetectors. The generated noise at the receivers was set to be random and totally uncorrelated. The transmitting power 0 dBm was used out of the broad band source. The system performance is carried out by referring to the bit error rate. The whole simulation is specified according to the typical industrial values to simulate the real environment as close as possible.

RESULTS

In this section, the performance evaluation results based on theoretical analysis and simulation experiments are presented according to the typical system parameters as listed in Table 2. The bit-error- rate (BER) performance against the number of active user using complementary and NAND subtraction techniques are shown in Figure 3.

It is seen from Figure 3 that the NAND subtraction detection technique using MDW codes as a signature sequence suppressed MAI significantly, and the received

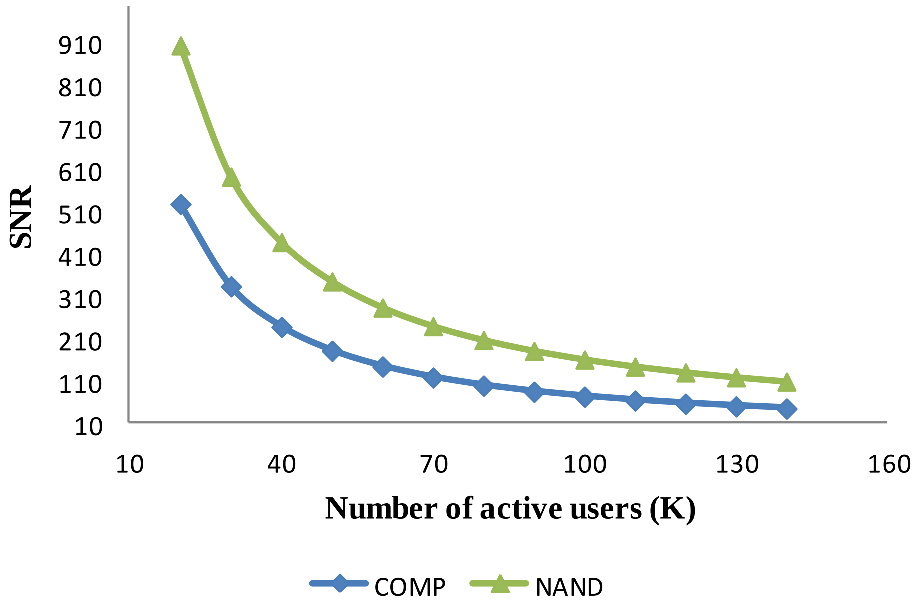


Figure 4. SNR versus number of simultaneous user when $P_{sr} = -10\ dBm$.

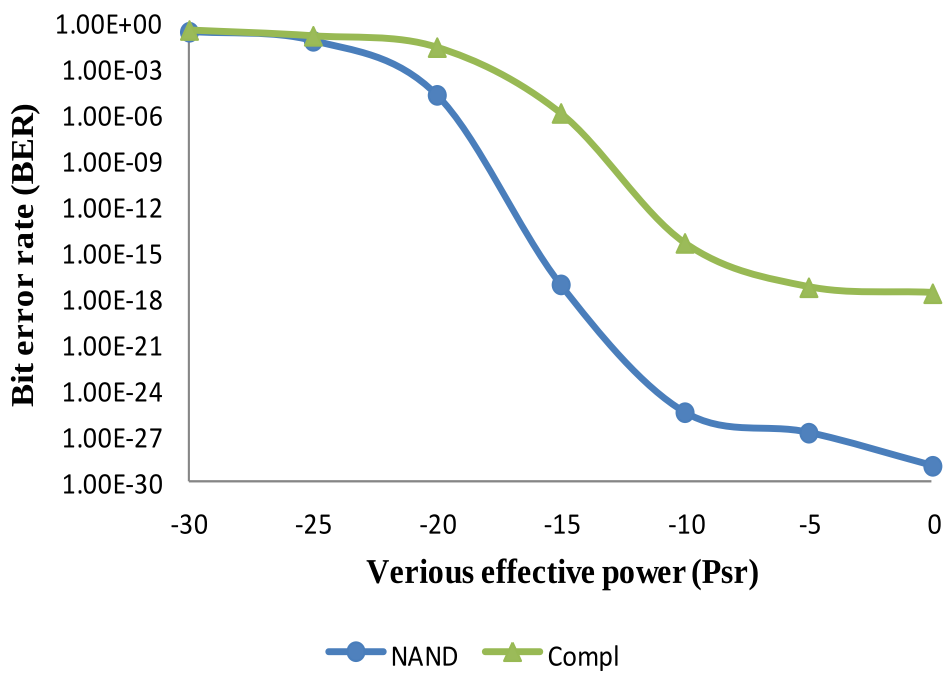


Figure 5. BER versus P_{sr} when number of simultaneous users is 40.

power (detected 1'st user) is higher than the Complementary subtraction technique. The signal to noise ratio (SNR) against the number of simultaneous user is shown in Figure 4 shows. It is seen that the MDW codes give a much higher SNR value using NAND subtraction technique compared to Complimentary subtraction techniques when the effective power is high (when $P_{sr} < -25\ dBm$). Figure 5 shows the performance

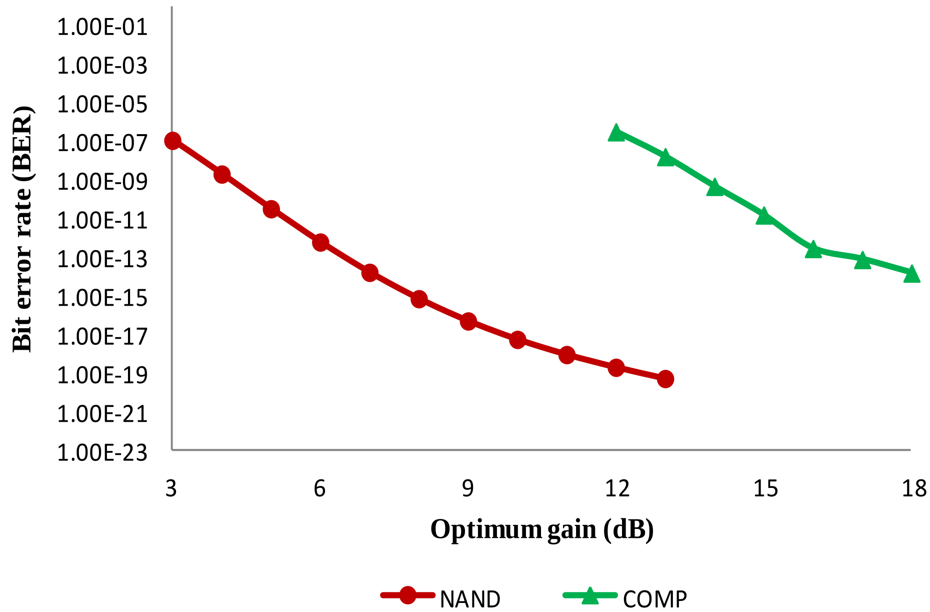


Figure 6. Measured BER values against different optimum gain.

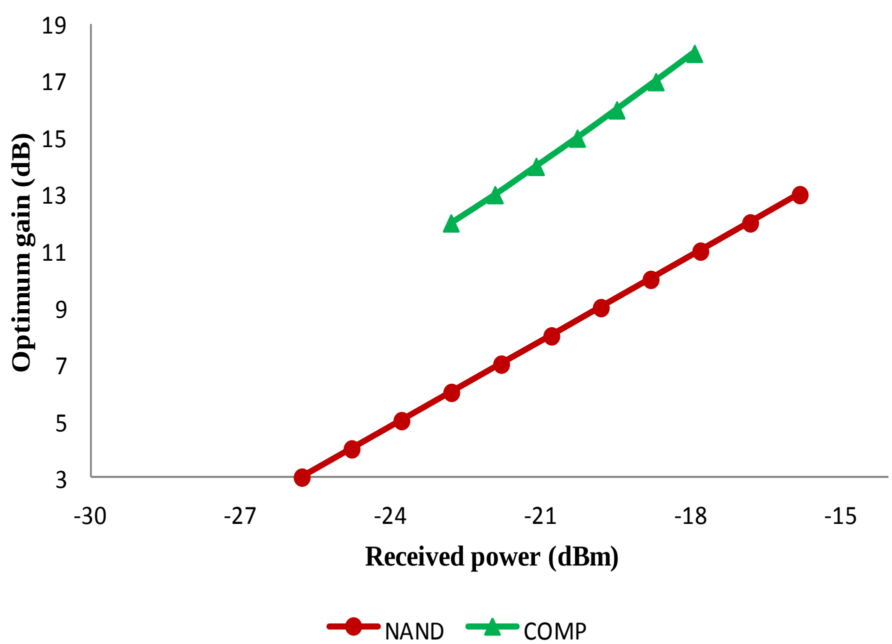
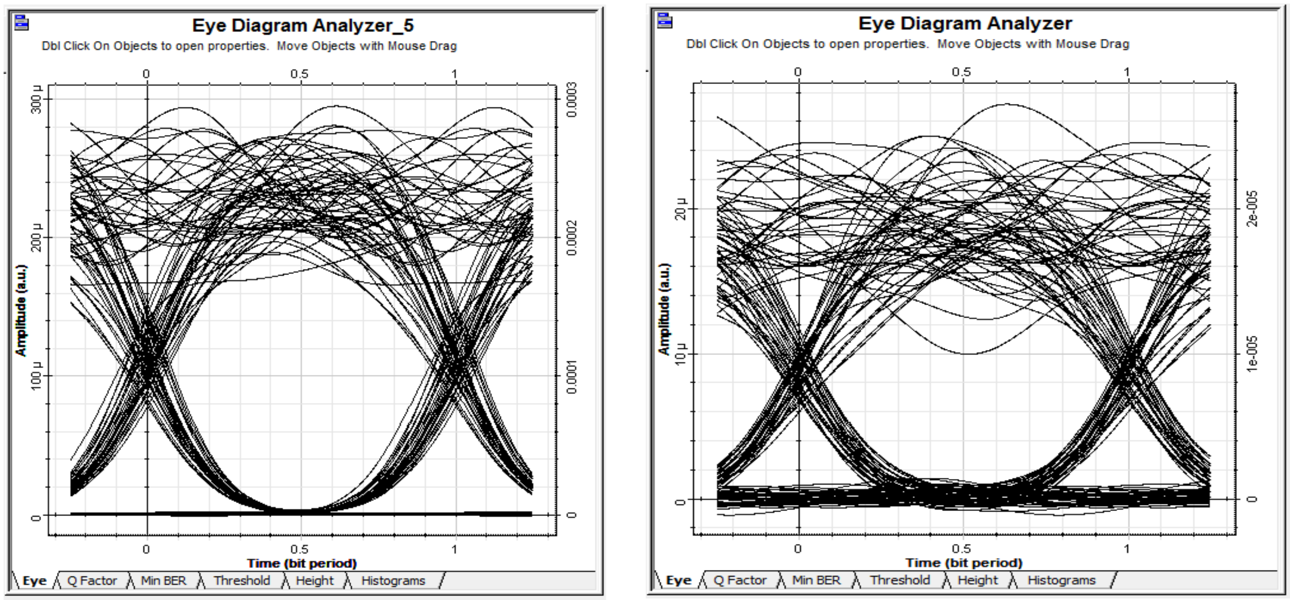


Figure 7. Measured received power against different optimum gain.

of the system using NAND and Complementary subtraction technique at various values of received power P_{sr}.

The simulation results are plotted in Figures 6 and 7. The signal is transmitted for long distance (70 km) including amplifier (EDFA). The EDFA noise figure was set in 4 dB and power 10 dBm. The analysis is carried out to find out standard optimum gain for the proposed system and compared with existing system. As seen from Figure 6 that the BER is increasing as the optimum gains



(a) NAND detection (BER 10-^{19}) (b) Complementary detection (BER 10-^{7})

Figure 8. Eye diagrams measured at 622 Mb/s on receiver side for three different detection.

is increasing for all cases. However, the system with NAND detection can produce better signal with the minimum gain value compared to complementary detection. The error free transmission (10e^{-9}) with NAND detection can be obtained at 4 dB gain. Whereas complementary detections require 10 dB and 12 dB gain respectively to satisfy the error free transmission. Figure 7 illustrates the optimum gain at various received power. It is shown that the system received power with NAND detection is higher than with complementary existing detections. As an example, it is seen from Figure 7 that the system received power is -26 dBm at 4 dB gain whereas the conventional detection required 9 dB to achieve -25 dBm receive power, which can be considered as the significant improvement of the system performance. It is also ascertained from the eye diagram of the received signal as shown in Fig.8 (a, and b).

DISCUSSION

In theoretical analysis, we do not consider any parameters such as optical fiber non-linear effects namely four wave mixing (FWM), self phase modulation (SPM), cross phase modulation (XPM) and also the dispersions namely chromatic dispersion (CD) and polarization mode dispersion (PMD). However, all these parameters will not affect the comparative analysis between the three techniques, because all the transmission conditions are same. Moreover, all these parameters are taken in to the account in the simulation.

In Figure 3, it shows clearly that the NAND subtraction technique significantly increase the BER performance and can support more number of active users (users 140 at 10^{-28}) as compared to the Complimentary subtraction technique with standard error free transmission (10e^{-9}).

The various P_{sr} distributions for the fixed number of users are shown in Figure 5. The number of active users in the system is fixed at 40. The performance of the system using NAND subtraction technique is better than complementary techniques. Although the BER goes down but the value is very negligible (for example 1^{-55}). This does not oppose the objective of the study in comparing the performance of two detection schemes. Finally, In Figure 8. Shows the simulated results where the system with NAND detection can produce significant signal quality compared to other conventional detections such as complementary when fiber optimum gain is 12 dB.

Since the main objective of this study is to improved the system performance, which has been achieved by the new detection technique. The results are obtained using theoretical and simulation analysis has been compared with existing detection technique. It is found that new detection can improve the system BER performance in a significant amount. Therefore, the proposed OCDMA system can be applicable for future optical access network.

Conclusion

In this study, we have analyzed the SAC-OCDMA system performance extensively using modified double weight (MDW) code with three detection techniques such as NAND, Complimentary subtraction techniques. In theoretical analysis, various possible noises like PIIN noise, shot noise, thermal noise and the interference like MAI effect has been considered. The analysis results obtained by NAND detection technique were compared with those as obtained by conventional techniques such as Complimentary subtraction techniques. The comparison results ascertained that the NAND detection technique with MDW code can support more number of active users and improve the system performance by reducing the MAI effect significantly. We also ascertained by simulation experiment that the BER performance of the system with NAND detection technique is greatly improved. In addition, the system with new detection requires the lower optimum gain to transmit the signal for long distance as compared to the complementary subtraction technique.

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