This paper is available online at www.praiseworthyprize.org
International Journal on Communications Antenna and Propagation (I.Re.C.A.P.), Vol. 8, N. 5
ISSN 2039 – 5086
October 2018

Performance Enhancement of Optical PPM-CDMA Using Successive Interference Cancellation Scheme

Naif Alsowaidi[1], Tawfig Eltaif[1], Mohd Ridzuan Mokhtar[2]

Abstract – *A comprehensive mathematical model of Successive Interference Cancellation (SIC) using Direct Sequence (DS) and Spectral Amplitude Coding (SAC), which is employed in incoherent optical CDMA using On-Off Keying (OOK) Pulse Position Modulation (PPM) and On-Off Keying (OOK) considering the presence of Phase–Induced Intensity Noise (PIIN), shot noise and thermal noise is presented in this work. SIC scheme has the potential to suppress Multiple Access Interference (MAI). The concept of SIC is the following: detection is taken place in successive stages where the most reliable symbols are chosen at each stage. Where the interference contributed by the already detected symbols will be removed. It has been found out that, theoretically, the size of M-ary on optical CDMA system limits the MAI effect. Thus, the system performance improves with the increasing of M-ary PPM. Hence, the system using PPM has better performances if compared to the one using OOK, due to a lower average number of interfering optical pulses. In addition, a lot of users can be accommodated with SIC/SAC-optical CDMA based PPM signaling system instead of the SIC/SAC-optical CDMA based OOK one.*
Copyright © 2018 The Authors.
Published by Praise Worthy Prize S.r.l.. This article is open access published under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

***Keywords**: Optical Code Division Multiple Access (Optical CDMA), Multiple Access Interference (MAI), Spectral Amplitude Coding (SAC), Prime Code, Successive Interference Cancellation (SIC)*

Nomenclature

T	Duration of a PPM frame with M slots, s
T_s	The pulse duration/ slot's width, s
M	Number of slots per PPM frame
R_s	Symbol rate, symbol /s
R_b	Bit rate, bit/s
p	Prime number
$f = p^2$	MPC code length
$w = p$	MPC code weight
T_c	Chip duration, s
P_p	Peak power of PPM pulse, dBm
P_a	Average laser power, dBm
P_{er}	Peak received power, dBm
L	Fiber transmission loss, dB
N	Number of users
$P_{T_c}(t)$	Optical rectangular pulse with duration T_c
$P_{T_s}(t)$	Optical rectangular pulse with duration T_s
$n(t)$	The total noise, W
t_n	Relative delay, s
$c_n(t)$	The n^{th} user signature sequence code
N_0	Total thermal and shot noises
j	Number of cancellations $j = 0,1 \ldots N-1$
$I_{n,j+1}$	The cross correlation between i^{th} user and the n^{th} user
l_{j+1}	The total signal interference
$u(v)$	Unit step function
B	Noise-equivalent electrical bandwidth of the receiver, Hz
K_b	Boltzmann's constant
e	The electron's charge, C
I	Average current, A
T_n	Absolute receiver noise temperature, K
R_l	Receiver load resistor, Ω

Greek Notations

ΔV	Optical source bandwidth, Hz
η	Quantum efficiency
$\Re$	Photodiode responsivity

I. Introduction

Optical CDMA system has attracted much attention during the last decade and it is considered as the most promising candidate for the high-speed optical networks, the next generation of PON access networks [1]-[3]; optical CDMA has been implemented and examined in the asynchronous and communications [4]-[5].

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.
This article is open access published under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/)
Available online by October 31th, 2018
https://doi.org/10.15866/irecap.v8i5.14441

PPM and OOK signaling format are used in optical CDMA systems [6]-[9]. One of the features of PPM over OOK is power efficiency.

However, besides all the features of the optical CDMA, this system suffers of Multiple Access Interference (MAI), which is due to the presence of un-orthogonal signals from other transmitters at each receiver of optical CDMA system. MAI is a common drawback of any CDMA system.

Therefore, the suppuration or cancellation of the MAI has been the focus on the study of optical CDMA system. Several methods have been introduced and proposed to suppress or cancel the MAI [10]-[13].

Interference Cancellation (IC) schemes are considered one of the best methods used to reduce the MAI. Successive interference cancellation (SIC) is a promising IC scheme in suppressing the interference affecting the users' data, which occurs due to the overlapping between the users. The main idea of the SIC, once the users are completely detected, is that the strongest and the most reliable one will be chosen and encoded by its unique signature codes, then the regenerated or the encoded user will be subtracted from the overall received signal.

Hence, a newly received signal with *N*-1 users enters the receiver, and this process will continue, so users will be eliminated after each stage of cancellation.

Designing a system that has the ability to overcome the MAI problem, improving the signal quality and increasing the system capacity as well are the proposals of this article; comprehensive theoretical analyses for optical CDMA system based SIC using DS and SAC scheme with PPM signaling to mitigate the MAI has been presented. The article has five sections, the derivation of bit error probability (BER) for optical CDMA correlator receiver with and without SIC for both DS and SAC based PPM signaling using Modified Prime Codes (MPC) is presented in section III.

Numerical results and comparison between optical PPM-CDMA system and optical OOK-CDMA system with and without SIC for both DS and SAC using MPC codes are shown in section IV. The conclusion is presented in section V

II. Performance Analysis

II.1. Theoretical Analysis of Optical PPM-CDMA System

In PPM modulation, a single pulse with duration of T_s, placed in one of *M* possible time slots, represents a symbol. Each slot has a width $T_s = \frac{T}{M}$. The performance of optical CDMA in terms of BER depends on code sequence and PPM. The bit rate can be expressed in terms of the symbol rate (R_s):

$$R_b = kR_s = \frac{\log M}{T} = \frac{\log M}{MT_s} \tag{1}$$

Using MPC codes [14], where p^2 Codes can be generated, each code has a weight equal to $(w = p)$ and a length equal to $(f = p^2)$.

T_c refers to the duration of the chip and can be expressed as $T_c = \frac{T_s}{f} = \frac{T}{Mf}$ [15]. The loss produced by the couplers during the encoding-decoding process is $\frac{L}{Nw^4}$, where *L* refers to the optical fiber losses during the transmission. The peak power of PPM pulse is $P_p = MfP_a$ where P_a is the average laser power; hence, the peak received power is [15]:

$$P_{er} = P_P\left(\frac{L}{Nw^4}\right) = \left(\frac{P_a fML}{Nw^4}\right) = P_a\frac{ML}{Np^2} \tag{2}$$

The n^{th} user signature sequence code can be written as:

$$c_n(t) = \sum_{k=1}^{f} c_{k,n} P_{T_c}(t - kT_c) \tag{3}$$

Here $c_{k,n} \in \{0,1\}$, and $P_{T_c}(t)$ is an optical rectangular pulse with duration T_c. At a time i, the *J* binary source bits of the n^{th} user is converted to an *M-ary* symbol $b_{i,n} \in (0,1,....,M-1)$. Then the PPM signal can be given by:

$$b_n(t) = \sum_{i=-\infty}^{\infty} P_{T_s}(t - b_{i,n}T_s - iT) \tag{4}$$

where T_s is the duration of the *M-ary* symbols, and a rectangular pulse with duration T_s is expressed by $P_{T_s}(t)$:

$$P_{T_s}(t) = \begin{cases} 1, & 0 < t < T_s \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Therefore, the overall received signal can be stated as:

$$r(t) = P_{er}\sum_{n=1}^{N}\sum_{k=1}^{f} b_n(t-\tau_n)c_{k,n}(t-\tau_n) + n(t) \tag{6}$$

$n(t)$, τ_n are the noise and the relative delay respectively. By using the probability of detecting a correct symbol [16]. Without loss of generality the sample $y_1 = x_1 + n_o$ was transmitted among *M* slots, where the symbol $x_m = Mp^2P_ab_m$ and n_m is the signal's noise, where $m = 1,....M$.

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.

Then:

$$P\left[\text{correct symbol}\right]= P\left[\begin{matrix} x_1+n_1>x_2+n_2, x_1+ \\ +n_1>x_3+n_3 ... x_1+n_1>x_M+n_M \end{matrix}\right] \quad (7)$$

Eq. (7) can be rewritten in terms of Q function as:

$$P\left[\text{correct sym}\right]=E\left\{\begin{matrix}\left[1-Q\left(\frac{x_1-x_2+n_1}{\sqrt{N_0}}\right).\right] \\ \left[1-Q\left(\frac{x_1-x_3+n_1}{\sqrt{N_0}}\right)\right]... \\ ...\left[1-Q\left(\frac{x_1-x_M+n_1}{\sqrt{N_0}}\right)\right]\end{matrix}\right\} \quad (8)$$

$$P\left[\text{correct symbol}\right]= E\left[\begin{matrix}1-Q\left(\frac{x_1-x_2+n_1}{\sqrt{N_0}}\right)+ \\ -Q\left(\frac{x_1-x_3+n_1}{\sqrt{N_0}}\right)\dots Q\left(\frac{x_1-x_M+n_1}{\sqrt{N_0}}\right)\end{matrix}\right] \quad (9)$$

Then, symbol error rate derived as:

$$\begin{gathered} P\left[\text{symbol error}\right]=1-P\left[\text{correct symbol}\right] \\ =Q\left(\frac{x_1-x_2+n_1}{\sqrt{N_0}}\right)+ \\ -Q\left(\frac{x_1-x_3+n_1}{\sqrt{N_0}}\right)-Q\left(\frac{x_1-x_M+n_1}{\sqrt{N_0}}\right) \\ P\left[\text{symbol error}\right]=\prod_{m=2}^{M}Q\left(\frac{S^1-S^m}{\sqrt{2N_0}}\right) \end{gathered} \quad (10)$$

where the BER of optical CDMA based PPM signaling system can be stated as:

$$P_e=\frac{M}{2(M-1)}\left[\prod_{m=2}^{M}Q\left(\frac{S_n^1(t)-S_n^m(t)}{\sqrt{2N_0}}\right)\right] \quad (11)$$

where S_n^1 and S_n^m are the first and m^{th} components of the n^{th} user.

Eq. (11) is the common BER equation for optical PPM-CDMA systems and it's also valid for our proposal system based on both DS and SAC schemes, except that the desired signal parameter (i.e., S_n^1 and S_n^m) will be totally different. The following subsections present the analysis of proposal systems in terms of S_n^1; S_n^m and the total interference, given in Eq (18) and Eq (33).

II.2. Performance Analysis of Optical CDMA System Based SIC/DS Using PPM Signaling

The receiver block diagram of Optical CDMA system Based SIC scheme for both DS and SAC detection schemes using PPM signaling is illustrated in Fig. 1.

Starting from Eq (6), the detected signals using optical CDMA based SIC with PPM signaling derives as follows; the first decision variable S_1, at time T_s, is given as:

$$S_1=\frac{1}{T_s}\int_0^{T_s} r(t)\,c_1(t-\tau_1)\,dt \quad (12)$$

$$\begin{gathered} S_1=P_{er1}\left[\int_{\tau_1+iT_s}^{\tau_1+(1+i)T_s} b_1(t-\tau_1)c_1(t-\tau_1)dt\right. \\ \left.+\sum_{n=2}^{N}\int_{\tau_n+iT_s}^{\tau_n+(1+i)T_s}(b_n(t-\tau_n)c_n(t-\tau_n)C_1(t-\tau_1)dt\right]+n(t) \end{gathered} \quad (13)$$

After decoding and integration, without loss of generality, suppose that the desired user depends only on b_0^1, then the first decision is given as:

$$S_1=P_{er}wT_cP_{1,i}+l_1 \quad (14)$$

where, l_1 corresponds to the MAI and can be expressed as:

$$\begin{gathered} l_1=\sum_{n=2}^{N}\int_{\tau_n+iT_s}^{\tau_n+(1+i)T_s}P_{er}b_n(t-\tau_n)c_n(t-\tau_n)c_1(t-\tau_1)dt \\ +n(t) \end{gathered} \quad (15)$$

The most reliable user has been chosen among all users, the selected user will be spread over the code sequence and canceled from the original received signal and a newly received signal results with only *N-1* users as:

$$\begin{gathered} r_1(t)=r(t)-S_1\,c_1(t-\tau_1) \\ r_1(t)=\sum_{n=2}^{N}\int_{\tau_n+iT_s}^{\tau_n+(1+i)T_s}P_{er}b_n(t-\tau_n)c_n(t-\tau_n)dt+ \\ +n(t)-l_1\,c_1(t-\tau_1) \end{gathered} \quad (16)$$

Generally, users can be detected one by one following the steps above, and the newly received signal after each cancellation can be given as:

$$r_j(t)=r_{j-1}(t)-S_j\,c_j(t-\tau_j) \quad (17)$$

S_j represents the signals detected of the j^{th} cancellation and the decision variable on the symbol for the $(j+1)^{th}$ user is obtained as $\left[S_{j+1,m}\right]_{\max}; m=1,....M$ is given by:

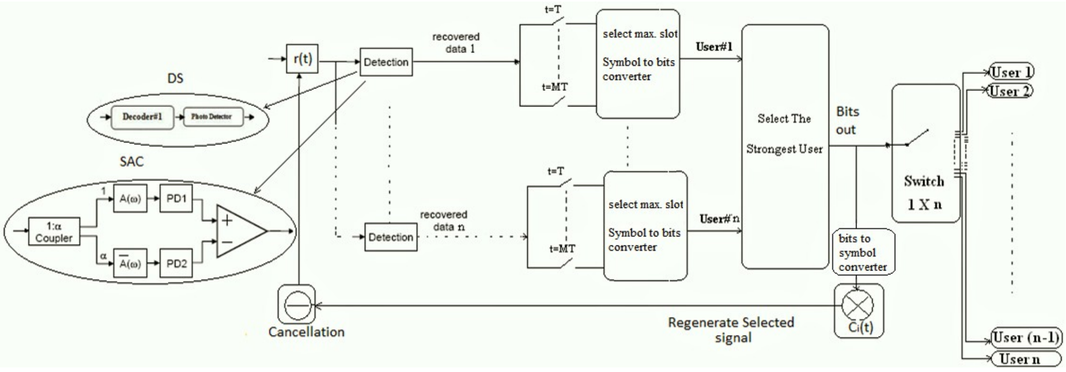

Fig. 1. Block diagram of SIC scheme (inset DS and SAC)

$$S_{j+1} = P_{er} w T_c P_{j+1,i} + l_{j+1} \tag{18}$$

where l_{j+1} is the total signal interference and can be expressed as:

$$l_{j+1} = \sum_{n=j+2}^{N} \int_{\tau_n+iT_s}^{\tau_n+(1+i)T_s} P_{er} b_n(t-\tau_n) I_{n,j+1}(\tau_{i,j+1}) dt - \sum_{i=1}^{j} l_i I_{i,j+1}(\tau_{i,j+1}) dt + n(t) \tag{19}$$

where $I_{n,j+1}$ is the cross-correlation and can be defined as $I_{n,i}(\tau_{n,i}) = \frac{1}{T}[\int_0^T c_n(t-\tau_{n,i}) c_i(t) dt]$, while the second imperfect cancellation noise and signal noise are the second and third term respectively, by substituting Eq (18) into Eq (11) the BER of system can be measured.

II.3. Performance Analysis of Optical CDMA Systems Based SIC/SAC Using PPM Signaling

Fig. 1 shows the receiver operational block diagram for optical PPM-CDMA using SAC scheme (inset), based on SIC. Due to the flat Power Spectral Density (PSD) of the source in Optical CDMA system using SAC detection, the PIIN, shot noise and thermal noise introduced significant degradation in the system performance [17], [19].

The power of each spectral chip in both arms of SAC scheme is the same at the receiver side. By having power splitted, there will be no need for power amplification. MPC with prime number p has been used as identification code for the proposed system and its properties can be expressed in Eq (20):

$$\sum_{i=1}^{f} c_k(i) c_l(i) = \begin{cases} p, & k = l \\ 1, & k \neq l \end{cases} \qquad \sum_{i=1}^{f} c_k(i) \overline{c}_l(i) = \begin{cases} 0, & k = l \\ p-1, & k \neq l \end{cases} \tag{20}$$

Since the light source has flat PSD, then the received signal is expressed as:

$$G^i(v) = \frac{P_{er}}{\Delta v} \sum_{n=1}^{N} b_n \sum_{i=1}^{f} c_n(i) \cdot \left(u\left[v - v_o - \frac{\Delta v}{2p^2}(-p^2 + 2i - 2) \right] + -u\left[v - v_o - \frac{\Delta v}{2p^2}(-p^2 + 2i) \right] \right) \tag{21}$$

The PPM signal is $b_n(t) = \sum_{i=-\infty}^{\infty} P_{T_s}(t - b_{i,n} T_s - iT)$, where P_{er}, $u(v)$ and $P_{T_s}(t)$ are the effective power including the losses occurring during the transmission, the unit step function, and a rectangular pulse of M-ary symbols with duration of respectively as shown in Eq (2). PIIN noise, thermal noise and shot noise, can be stated as follows [20]:

$$\left\langle i^2 \right\rangle = 2eIB + I^2 B \tau_c + 4K_b T_n B / R_L \tag{22}$$

The coherent time τ_c is given as [20]:

$$\tau_c = \frac{\int_{v=0}^{\infty} G^2(v) dv}{\left[\int_{v=0}^{\infty} G(v) dv \right]^2} \tag{23}$$

From Eq (21), the PSD output of upper and lower arms of SAC scheme of the first user can be expressed as:

$$G_1(v) = \frac{P_{er}}{(p-1)\Delta v} \sum_{n=1}^{N} b_n \sum_{i=1}^{f} c_n(i) \overline{c}_1(i) \cdot \left(u\left[v - v_o - \frac{\Delta v}{2p^2}(-p^2 + 2i - 2) \right] + -u\left[v - v_o - \frac{\Delta v}{2p^2}(-p^2 + 2i) \right] \right) \tag{24a}$$

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.

$$G_2(v)=\frac{P_{er}}{\Delta v}\sum_{n=1}^{N}b_n\sum_{i=1}^{f}c_n(i)c_1(i)\cdot \left(u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i-2)\right]+ -u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i)\right]\right) \quad (24b)$$

where the output of photo-detectors for the first user is given as (25a), (25b):

$$I_1=\int_0^\infty G_1(v)dv=\frac{P_{er}}{p^2}\sum_{n=2}^{N}b_n \quad (25a)$$

$$I_2=\int_0^\infty G_2(v)dv=\frac{P_{er}}{p}b_1+\frac{P_{er}}{p^2}\sum_{n=2}^{N}b_n \quad (25b)$$

Then, the subtraction of the photocurrent I_1 and I_2 will result to the desired user:

$$I=I_2-I_1=\Re\frac{P_{er}}{p}b_1 \quad (26)$$

where $\Re$ is the responsiveness of the PD's. The integration of Eq (24) can be expressed as:

$$\int_0^\infty G_1^2(v)dv=\frac{P_{er}^2}{p^2(p-1)^2\Delta v}\sum_{i=1}^{f}\left\{\overline{c_1}(i)\cdot\left[\sum_{n=1}^{N}b_nc_n(i)\right]\cdot\left[\sum_{m=1}^{N}b_mc_m(i)\right]\right\} \quad (27a)$$

$$\int_0^\infty G_2^2(v)dv=\frac{P_{er}^2}{p^2\Delta v}\sum_{i=1}^{f}\left\{c_1(i)\cdot\left[\sum_{n=1}^{N}b_nc_n(i)\right]\cdot\left[\sum_{m=1}^{N}b_mc_m(i)\right]\right\} \quad (27b)$$

Taking into account the code correlation properties, the simplified output of Eq (27) and Eq (25) can be substituted into Eq (25), then Eq (22) can be rewritten as:

$$\left\langle i_1^2\right\rangle=\frac{eB\Re P_aML}{Np^4}(2N+p-2)+\frac{B\Re^2P_a^2M^2L^2}{2Np^5\Delta v}\left[\frac{p^2-2p+pN}{p-1}\right]+ +4K_bT_nB/R_L \quad (28)$$

The desired user data alongside with the total noise is given as:

$$S_1=\Re\frac{P_aML}{Np^3}T_cwP_{1i}+\frac{eB\Re P_aML}{Np^4}(2N+p-2)+\frac{B\Re^2P_a^2M^2L^2}{2Np^5\Delta v}\left[\frac{p^2-2p+pN}{p-1}\right]+ +4K_bT_nB/R_L \quad (29)$$

By implementing the main idea of the SIC as discussed in the previous sections, for the proposed system it can be mathematically stated as:

$$G^1(v)=G(v)-S_1.\sum_{i=1}^{f}c_1(i)\cdot \left(u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i-2)\right]+ -u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i)\right]\right) \quad (30)$$

The substitution of Eq (21) and Eq (29) into Eq (30) results in a newly received signal:

$$G^1(v)=\frac{P_{er}}{\Delta v}\sum_{n=2}^{N}P_{er}b_n\sum_{i=1}^{f}c_n(i)\cdot \left(u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i-2)\right]+ -u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i)\right]\right)-\left\langle i_1^2\right\rangle\cdot\sum_{i=1}^{f}c_1(i)\cdot \left(u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i-2)\right]+ -u\left[v-v_o-\frac{\Delta v}{2p^2}(-p^2+2i)\right]\right) \quad (31)$$

In the next round, there will be only $(N-2)$ interference signals, since the first user has already been detected and removed from the total received signal.

Then, repeating steps from (24) to (28), the second user data S_2 can be obtained along with its interference and noise, thus the total interference is given as;

$$\left\langle i_2^2\right\rangle=\frac{eB\Re P_aML}{Np^4}(2N+p-2(1+\left\langle i_1^2\right\rangle))+\frac{B\Re^2P_a^2M^2L^2}{2Np^5(p-1)\Delta v}\cdot [p^2-2p+pN-(p^2-1)\left\langle i_1^2\right\rangle] +4K_bT_nB/R_L \quad (32)$$

Hence, the general formal after $(j+1)^{th}$ cancellation is:

$$S_{j+1} = \Re \frac{P_a ML}{Np^3} T_c w P_{j+1} + \left\langle i_{j+1}^2 \right\rangle \quad (33)$$

where $\left\langle i_{j+1}^2 \right\rangle$ is the total interference, and is given by:

$$\begin{aligned}\left\langle i_{j+1}^2 \right\rangle &= \frac{eB\Re P_a ML}{Np^4}\left(2N + p - 2\left(1 + \sum_i^j \left\langle i_i^2 \right\rangle\right)\right) + \\ &+ \frac{B\Re^2 P_a^2 M^2 L^2}{2Np^5 (p-1)\Delta v} \cdot \begin{bmatrix} p^2 - 2p + pN + \\ -(p^2-1)\sum_i^j \left\langle i_i^2 \right\rangle \end{bmatrix} + \\ &+ 4K_b T_n B / R_L \end{aligned} \quad (34)$$

Finally, substituting Eq (33) into Eq (11), the system performance can be measured in terms of BER.

III. Numerical Results and Discussion

The system was tested by MPC codes with 50km channel length and effective power of -11.3dBm. Fig. 2 shows that the Optical CDMA system based DS with and without SIC using PPM modulation has better performance in terms of BER and capacity than the system using OOK format, it is revealed that the system without SIC using PPM modulation can support up to 22 users while the system using OOK modulation can support only up to 14 users at BER benchmarking 10^{-9}.

However, in case of SIC receiver, although both systems have good performance, it can be clearly observed that Optical PPM- CDMA with SIC can support up to 80 users. Fig. 3 shows the comparison results of the SAC-optical PPM-CDMA system and SAC-optical OOK-CDMA system for both conventional receiver and SIC receiver [11]. It can be clearly observed that the SAC-Optical-CDMA system with and without SIC scheme using PPM modulation has better performance than the system using OOK modulation.

It was found out that in PPM modulation , any number of users can be accommodated by increasing M-ary and preserving the average laser power fixed, while in OOK modulation the maximum number of active users can’t be increased without increasing the average laser power, even if the average laser power is increased, therefore, it is possible that the system is not able to accommodate all the subscribers, because of the high average number of interfering optical pulse which is equal $(N-1)/2$, while in case of PPM signaling the average interfering pulses equals $(N-1)/M$.

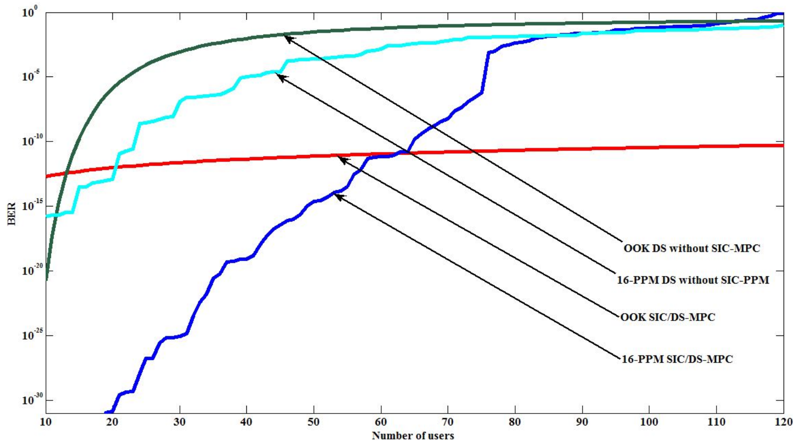

Fig. 2. DS-Optical PPM-CDMA System versus DS-Optical OOK-CDMA System with/out SIC scheme

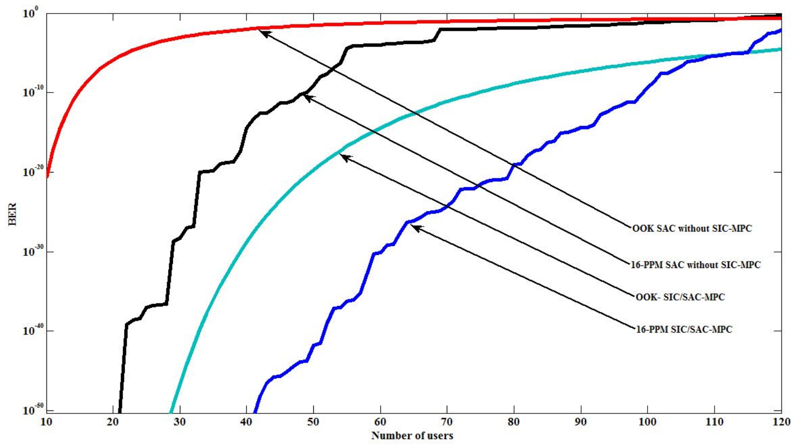

Fig. 3. SAC-Optical PPM-CDMA System Versus SAC-Optical OOK-CDMA System with/out SIC scheme

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.

IV. Conclusion

In this paper, successive interference cancellation has been used to mitigate MAI and intensity noise in both DS and SAC detection for incoherent optical CDMA systems. Two different modulation types have been used; PPM and OOK modulations. The system has been tested and analyzed by MPC, considering PIIN noise, shot noise, thermal noise, and MAI. The results show that the system using PPM modulation has better BER performance than the one using OOK modulation and this is because of a lower average number of interfering optical pulses. In addition to that optical PPM/OOK-CDMA using SAC scheme has better performance than the optical PPM/OOK-CDMA system using DS scheme for both conventional receiver and SIC receiver. Hence, more users can be supported by SIC/SAC-optical PPM-CDMA system, compared to SIC/SAC-optical OOK-CDMA system.

Acknowledgements

This works was supported by Multimedia University (Malaysia) under project MMU-GRA-IP20130621001.

References

[1] Hadi M, Pakravan M, Analysis and Design of Adaptive OCDMA Passive Optical Networks, *J. Lightwave Technol.*, Volume 35, (Issue 14), 2017, Pages 2853-2863.

[2] Chang C, Kwong W, Two New Families of Synchronous Optical Codes for CDMA-Based Passive Optical Networks. *IEEE Trans. Commun.*, Volume 62, (Issue 5), 2014, Pages 1646-1657.

[3] Abbas H, Gregory M. The next generation of passive optical networks: A review. *Journal of Network and Computer Applications,* Volume 67, 2016, Pages 53-74.

[4] Fathallah H, Seleem H, Bentrcia A, Efficient interference cancellation detector for asynchronous upstream optical code division multiple access-passive optical network with mixed Poisson–Gaussian noise. *IET Communications,* Volume 8, (Issue 13), 2014, Pages 2393-2403.

[5] Lin Y, Yang G, Chang C, Kwong W, Design and Analysis of Asynchronous Incoherent Optical-CDMA Systems Using a New Code-Shifting Technique, *IEEE Trans. Commun., Volume 63,* (Issue 7), 2015, Pages 2619-2631.

[6] Khazraei, S., Pakravan, M. Generalized OOC Assisted PPM and Overlapping PPM, Considering Thermal Noise and APD Effect. *J. Opt. Commun. Netw.* Volume 5, (Issue 7), 696. 2013, Page 696

[7] Lee, T., Shalaby, H., & Ghafouri-Shiraz, H. Interference reduction in synchronous fiber-optic PPM-CDMA systems. *Microwave and Optical Technology Letters,* Volume 30, (Issue 3), 2001, Pages 202-205.

[8] Correia D, Sales J, Pinto P, Moura L, Ferreira A, Menezes J et al, Analysis of the Performance of a PAM/PPM/OOK System Operating with OCDMA, under Nonlinear Optical Effects in Optical Fiber Propagation, *Journal of Optical Communications*., Volume 37, (Issue 2), 2015, Pages 1-14.

[9] Shalaby, H. Efficient Use of PPM in Spectral-Amplitude-Coding Optical CDMA Systems. *J. Lightwave Technol.,* Volume 30, (Issue 22), 2012, Pages 3512-3519.

[10] N. Alsowaidi, T. Eltaif, M. R. Mokhtar. A Review on Successive Interference Cancellation Scheme Based on Optical CDMA Network, *Journal of Optical Communications,* Volume 35, (Issue 4), 2014, Pages 297–304.

[11] Eltaif, T., Shalaby, H., Shaari, S., &Hamarsheh, M, Performance enhancement of successive interference cancellation scheme based on spectral amplitude coding for optical code-division multiple-access systems using Hadamard codes, *Optical Engineering,* Volume 48, (Issue 4), 2009.page 045002.

[12] Matsushima T, Kakuyama M, Murata Y, Teramachi Y, Yamasaki S, A Study on Multi-User Interference Cancellers for Synchronous Optical CDMA Systems-Decision Distance and Bit Error Rate, *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences.,* Volume E100.A, (Issue 10), 2017, Pages 2135-2145.

[13] Shi F, Ghafouri-Shiraz H, Performance Analysis of Two New Code Families for Spectral-Amplitude-Coding Optical CDMA Systems., *J. Lightwave Technol.,* Volume 34, (Issue 17), 2016, Pages 4005-4014.

[14] Zhang, J., & Kwong, W. Effective design of optical code-division multiple access networks by using the modified prime code. *Electron. Lett.,* Volume 33 (Issue 3), 1997, Page 229.

[15] Gagliardi, R., Mendez, A., Dale, M., & Park, E. Fiber-optic digital video multiplexing using optical CDMA, *J. Lightwave Technol.,* Volume 11 (Issue 1), 1993, Pages 20-26.

[16] Audeh, M., Kahn, J., & Barry, J. Performance of pulse-position modulation on measured non-directed indoor infrared channels. *IEEE Trans. Commun.,* Vol. 44 (Issue 6), 1996, Pages 654-659.

[17] A. O. Aldhaibani, T. A. Rahman, S. A. Aljunid, M. N. Hindia, and E. B. Hanafi, A new model to enhance the QoS of spectral amplitude coding-optical code division multiple access system with OFDM technique., *Optical and Quantum Electronics,* Volume 48, (Issue 10), 2016, Pages 1-12.

[18] Taiwo A, Moghaddasi M, Kuje D, Idriss Y, Mokhtar M. Practical investigation of suitable decoding techniques for spectral amplitude coding optical code division multiple access-based vibration sensing, *IET Optoelectronics.,* Volume 10, (Issue 6), 2016, Pages 227-232

[19] Shi F, Ghafouri-Shiraz H, Performance Analysis of Two New Code Families for Spectral-Amplitude-Coding Optical CDMA Systems, *J. Lightwave Technol.,* Volume 34, (Issue 17), 2016, Pages 4005-4014.

[20] Zou Wei, Shalaby, H., & Ghafouri-Shiraz, H. Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems. *J. Lightwave Technol.,* Volume 19 (Issue 9), 2001, Pages 1274-1281.

[21] Noor Mohammed, V., Mallick, P., Nithyanandan, L., Sricharan, N., MAI Mitigation Using V-BLAST and PIC Based Binary Orthogonal Code Spreaded Multi Antenna MC-CDMA System, (2015) *International Journal on Communications Antenna and Propagation (IRECAP)*, 5 (3), pp. 138-143. doi:https://doi.org/10.15866/irecap.v5i3.5907

Authors' information

[1]Faculty of Engineering &Technology, Multimedia University, 75450; Bukit Beruang, Melaka, Malaysia.

[2]Faculty of Engineering, Multimedia University, 63100, Cyberjaya, Selangor, Malaysia.

Naif Alsowaidi received his B.Eng. degree (with honors) in communication engineering from International Islamic University Malaysia (IIUM), in 2012 and the M.Sc. degree in engineering science from Multimedia University (MMU), Malaysia, in 2015. He is currently pursuing a Ph.D. degree in optical communication field at Multimedia University. His current research interests include wireless communication, Optical CDMA systems, and nonlinear optics.

Tawfig Eltaif (Corresponding author) received his BSc degree in communication engineering from University of Tripoli, Libya, 2003, and MSc degree in microelectronics and PhD degree in micro-engineering & nanoelectronics from National University of Malaysia, Malaysia, 2005, 2009, respectively.

He joined Photronix Technologies Company,

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.

2008-2011, as a product and research engineer. Since 2012 he has been a senior lecturer at Multimedia University.
His current research is focused on optical communication, optical frequency comb, FBG, and optical amplifiers.
E-mail: tefosat@ieee.org

Mohd Ridzuan Mokhtar received his PhD degree in optoelectronics from the University of Southampton, UK, in 2005. He is professor at the Faculty of Engineering, Multimedia University, Malaysia.
He became a research fellow with City University London, UK, for a year in 2009, sponsored by the Technology Strategy Board in the UK. He has been the director of research and collaboration at Multimedia University since 2011. His main research interests include fiber optic sensors and optical communications.

Copyright © 2018 The Authors. Published by Praise Worthy Prize S.r.l.