

# Reduction of Multiple User Interference for Optical CDMA Systems Using Successive Interference Cancellation Scheme

Tawfig Eltaif, Hesham A. Bakarman, N. Alsowaidi, M. R. Mokhtar, Malek Harbawi

**Abstract**—Multiple User Interference (MUI) considers the primary problem in Optical Code-Division Multiple Access (OCDMA), which resulting from the overlapping among the users. In this article we aim to mitigate this problem by studying an interference cancellation scheme called successive interference cancellation (SIC) scheme. This scheme will be tested on two different detection schemes, spectral amplitude coding (SAC) and direct detection systems (DS), using partial modified prime (PMP) as the signature codes. It was found that SIC scheme based on both SAC and DS methods had a potential to suppress the intensity noise, that is to say it can mitigate MUI noise. Furthermore, SIC/DS scheme showed much lower bit error rate (BER) performance relative to SIC/SAC scheme for different magnitude of effective power. Hence, many more users can be supported by SIC/DS receiver system.

**Keywords**—Multiple User Interference (MUI), Optical Code-Division Multiple Access (OCDMA), Partial Modified Prime Code (PMP), Spectral Amplitude Coding (SAC), Successive Interference Cancellation (SIC).

## I. INTRODUCTION

ONE of the optical CDMA system advantages, is the ability to allow multiple users to share a common optical channel simultaneously and asynchronously. Along with other advantages such capability, flexibility of user allocation, high spectral efficiency and security against eavesdropper, this technique considered as one of the most promising multiplexing technologies for the next generation broadband access network [1], [2].

Two important criteria must be achieved to have a high performance optical CDMA system. Firstly, recovering back the desired user signals in the presence of the other interfering users' signals, and secondly, the system should be able to accommodate more subscribers. To achieve these criteria, the degradation of signals due to the channel interference should be suppressed. Therefore, interference cancellation schemes should be applied. Intensity noise and interference cancellation has been popular areas among many researchers,

whereby various techniques to mitigate the cross correlation problem have been reported. Salehi & Brackett utilized an optical hard limiter [3].

Double optical hard limiters placed on both sides of the optical correlator were also proposed by [4]. Lin and Wu later proposed a synchronous OCDMA system with the correlator receiver placed before an adaptive optical hard limiter [5]. They found that the performance can be improved, compared with systems based on a double hard limiter. Other cancellation techniques were presented for both ON-OFF keying (OOK) and pulse-position modulation (PPM) CDMA systems [6], [7].

Recently, multi-user detection (MUD) scheme has been employed in optical CDMA system [8], and theoretically, it was found that such schemes perform much better than that of the conventional detection [9]. Another technique inspired from radio frequency called successive interference cancellation (SIC) has been employed in optical CDMA using on-off keying modulation. It was found that the proposed scheme effectively suppresses MUI and significantly improves BER performance compared with the one without cancellation [10], [11].

In this article, different theoretical analyses for the SIC scheme are performed, which are applied to OCDMA network that employs both direct sequence and balanced detection approaches. A comprehensive analysis of this system implementing partial modified prime code (PMP) as signature sequences is presented. Hadamard codes are used for comparison, which shows that PMP codes improve the system performance significantly compared with Hadamard codes. In addition, SIC OCDMA system exhibits much poorer BER performance with respect to SIC/spectral amplitude coding (SAC) operating under an ideal effective power.

## II. SYSTEM DESCRIPTION

Fig. 1 shows the hybrid receiver structure for OCDMA, combining fiber Bragg grating (FBG)/SAC encoder with SIC schemes. It can be observed from Fig. 1 that a signal pulse is sent by the user's transmitter only when the bit is "1"; else optical signal pulse is not produced. At the transmitter, two groups of FBGs are used in encoding stage. The first FBGs group reflects the corresponding spectral wavelengths of the propagating optical pulse, while the second FBGs group compensates the round trip delay of various spectral wavelengths.

At the receiver side, the FBGs will reflect the received

Tawfig Eltaif, N. Alsowaidi are with Faculty of Engineering & Technology, Multimedia University, 75450, Bukit Beruang, Melaka, Malaysia (e-mail: nas\_201013@yahoo.com).

Hesham A. Bakarman is with PTL, Institute of Microengineering and Nanoelectronics, National University of Malaysia (UKM) 43600; Bangi, Selangor, Malaysia

M. R. Mokhtar is with Faculty of Engineering, Multimedia University, 63100, Cyberjaya, Selangor, Malaysia

Malek Harbawi is with Software Engineering Department, Technology Faculty, Firat University, 23119, Elazig-Turkey.

signal, and its complementary will be generated from the opposite end of the second grating group [12]-[14]. The bank of FBG/SAC OCDMA decoders will receive the incoming signals, matching the number of cancellation processes. Subsequent to detection and demodulation, the processes of selection, regeneration and subtraction from the original received signal will be executed on the strongest user signal to conjure a new received signal. These are repeated until the decoding process for every user is completed, or achieving a permissible number of cancellations [10], [11]. Theoretically,

the cancellation can be performed in optical domain, as shown in (15).

Some assumptions should be taken into account for an optimum SAC scheme. The spectrum of an optical source is ideally constant within a bandwidth of  $[\nu_0 - \Delta\nu/2; \nu_0 + \Delta\nu/2]$ , where  $\nu_0$  is the central optical frequency and  $\Delta\nu$  is the bandwidth of the optical source (spectral width) in the unit of Hertz, which is presumed identical for all users as shown in Fig. 1.

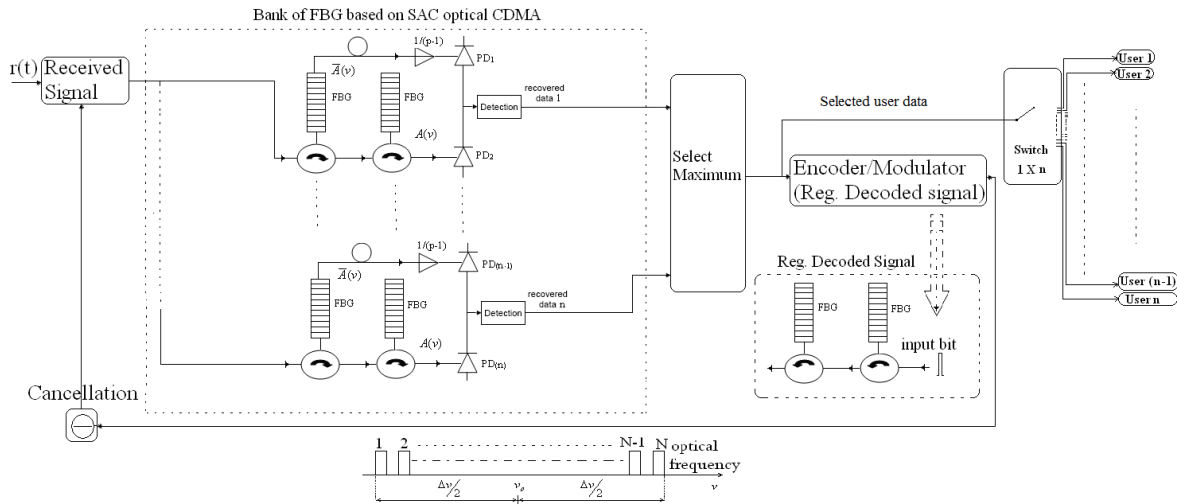


Fig. 1 Block diagram of SIC/SAC receiver

### III. PERFORMANCE ANALYSIS

This paper presents and theoretically analyses the SIC scheme based on SAC OCDMA systems with PMP code. PMP code, which is originally from the modified prime code, was chosen as a signature sequence. In this code,  $M$  new sequences are generated from each of the modified prime sequence. On the other hand,  $M$  times expansion of the size of each group of the modified prime codes is expected, whereby more details about this code can be found in [15], [16]. Considering  $N$  as active users, the code size of the PMP codes is equal to  $MP^2$  each code with length  $F=P^2$  and code weight is  $(P-1)/M$ .

In SIC/DS OCDMA system analysis, some assumption will be taken into account, such as  $\tau_n = 0$  for all users ( $n$ ) in worst case, synchronized condition [17], and ideal effective power. For a pair of code sequences  $x$  and  $y$ , the cross correlation function  $I_{xy}$  can be expressed as;

$$I_{x,y} = \begin{cases} \frac{P-1}{M}; & x = y \\ 0; & x \text{ and } y \text{ are in the same group} \\ \leq 1; & x \text{ and } y \text{ are in different groups} \end{cases} \quad (1)$$

The received signal at the receiver can be written as:

$$r(t) = \sum_{n=1}^{N=MP^2} P_{er} b_n(t - \tau_n) \sum_{i=1}^F c_n^i(t - \tau_n) + n(t) \quad (2)$$

where;  $P_{er}$  is the signal strength of the  $n^{\text{th}}$  user;  $b_n(t)$  is the bit sequence of  $n^{\text{th}}$  user;  $c_n(t)$  is the spreading chip sequence of the  $n^{\text{th}}$  user;  $n(t)$  is the noise signal (thermal noise); and  $\tau_n$  is the time delay of the  $n^{\text{th}}$  user. The bits and chips are rectangular. Their values are independent and identically distributed (i.i.d.) random values with probability 0.5 of 0/1.

Signal regeneration of the strongest user's signal will commence once the received signal has undergone detection and demodulation. Subsequently, subtraction from the original signal is performed on the regenerated signal. Generally, the  $j^{\text{th}}$  cancellations will result in,

$$r_j(t) = r_{j-1}(t) - Z_j \cdot \sum_{i=1}^F c_j^i(t) \quad (3)$$

Once the detection process is completed for all users, the  $(j+1)^{\text{th}}$  user will be assigned a decision variable parameter, which is given by:

$$Z_{j+1} = P_{er} b_{(j+1)} \left( \frac{P-1}{M} \right) +_{I_{j+1}} \quad (4)$$

where;

$$l_{j+1} = \frac{1}{P^2} \left[ \sum_{n=j+2}^{N=MP^2} P_{er} b_n I_{n,j+1}(\tau_{n,j+1}) - \sum_{i=1}^j l_i I_{i,i+1}(\tau_{i,i+1}) \right] + n_{j+1}(t) \quad (5)$$

is the total noise.

In (4), the desired user is represented by the first term, while the non-cancelled users will produce MUI that will be represented by the second term. Lastly, imperfect cancellation will contribute to the cumulative noise that is characterized by the third term. The effect of interference (i.e., MUI), created by other simultaneous users can be focused by disregarding the shot noise, the receiver's dark current, and other sources of noise. Detailed analysis of the SIC scheme can be found in [10], [11].

In SIC/SAC OCDMA system, a pair of code sequences  $x$  and  $y$  will yield a cross correlation function  $I_{xy}$  as given by:

$$\sum_{i=1}^F c_k(i) c_l(i) = \begin{cases} \frac{P-1}{M}, & k=l \\ \leq 1, & k \neq l \end{cases} \quad (6a)$$

$$\sum_{i=1}^F c_k(i) \bar{c}_l(i) = \begin{cases} 0, & k=l \\ M, & k \neq l \end{cases} \quad (6b)$$

The single sideband power spectral density (PSD) of the source is denoted by  $G(v)$ , which can be written in terms of receiver user's signal as:

$$G^i(v) = \frac{P_{er}}{\Delta v} \sum_{n=1}^{N=MP^2} b_n \sum_{i=1}^{F=MP^2} c_n(i) \cdot \left( u \left[ v - v_o - \frac{\Delta v}{2F} (-F + 2i - 2) \right] - u \left[ v - v_o - \frac{\Delta v}{2F} (-F + 2i) \right] \right) \quad (7)$$

where  $P_{er}$  is the effective power at the receiver side, including some losses related to transmission and coupler,  $b_n$  is the bit value of user  $n$ , and  $u(v)$  is the unit step function expressed as:

$$u(v) = \begin{cases} 1; & v \geq 0 \\ 0; & v < 0 \end{cases} \quad (8)$$

The proposed system will be analyzed considering major noises such as incoherent intensity noise, effect of phase-induced intensity noise (PIIN) noise, which is the dominated noise in SAC techniques, shot noise, and thermal noise for synchronous case, i.e.  $t = 0$  [17], and ideal power for all users. The PMP code is analyzed using a Gaussian approximation. The general form of the photocurrent noise caused by using a photodiode to detect a thermal light can be expressed as [12]-[14]:

$$\langle i^2 \rangle = 2eIB + I^2 B \tau_c + 4K_b T_n B / R_L \quad (9)$$

where:  $B$  is the noise-equivalent electrical bandwidth of the receiver;  $K_b$  is the Boltzmann's constant;  $e$  is the electron's charge;  $I$  is the average current;  $T_n$  is the absolute receiver noise temperature;  $R_L$  is the receiver load resistor. The shot

noise is characterized by the first term, the effect of PIIN noise is embodied by the second term, and the thermal noise effect is represented by the third term. The coherent time  $t_c$  of the source is written as [13]-[16], [18]:

$$\tau_c = \frac{\int_{v=0}^{\infty} G^2(v) dv}{\left[ \int_{v=0}^{\infty} G(v) dv \right]^2} \quad (10)$$

The first user is considered to be the desired user. Therefore, during one-bit period, the decoder output at the photo detectors can be expressed as:

$$G_1(v) = \frac{P_{er}}{M \Delta v} \sum_{n=1}^{N=MP^2} b_n \sum_{i=1}^F c_n(i) \bar{c}_1(i) \cdot \Gamma(i) \quad (11a)$$

$$G_2(v) = \frac{P_{er}}{\Delta v} \sum_{n=1}^{N=MP^2} b_n \sum_{i=1}^F c_n(i) c_1(i) \cdot \Gamma(i) \quad (11b)$$

$$\Gamma(i) = u \left[ v - v_o - \frac{\Delta v}{2F} (-F + 2i - 2) \right] - u \left[ v - v_o - \frac{\Delta v}{2F} (-F + 2i) \right] \quad (12)$$

Taking into account the PMP code properties in (6), then, the first user's photocurrent at both photodiodes (PDs), PD1 and PD2 can be expressed as:

$$I_1 = \Re \int_0^{\infty} G_1(v) dv = \frac{P_{er}}{F} \sum_{n=2}^N b_n \quad (13a)$$

$$I_2 = \Re \int_0^{\infty} G_2(v) dv = \frac{P_{er}}{F} \left( \frac{P-1}{M} \right) b_1 + \frac{P_{er}}{F} \sum_{n=2}^N b_n \quad (13b)$$

From (13), the photodiode current outputs (the signal from the desired user), can be expressed as;

$$I = I_2 - I_1 = \Re \frac{P_{er}}{F} \left( \frac{P-1}{M} \right) b_1 \quad (14)$$

where;  $\Re$  is the responsivity of the PD's,

The integral of  $G_1^2(v)$  and  $G_2^2(v)$  referring to Fig. 1 and according to [14] can be calculated as:

$$\int_0^{\infty} G^2(v) dv = \frac{\Delta v}{F} \sum_{i=1}^F a^2(i) \quad (15)$$

$$\int_0^{\infty} G_1^2(v) dv = \frac{P_{er}^2}{FM^2 \Delta v} \cdot \sum_{i=1}^F \left\{ \bar{c}_1(i) \cdot \left[ \sum_{n=1}^{N=MP^2} b_n c_n(i) \right] \cdot \left[ \sum_{m=1}^{N=MP^2} b_m c_m(i) \right] \right\} \quad (16a)$$

$$\int_0^{\infty} G_2^2(v) dv = \frac{P_{er}^2}{F \Delta v} \cdot \sum_{i=1}^F \left\{ c_1(i) \cdot \left[ \sum_{n=1}^{N=MP^2} b_n c_n(i) \right] \cdot \left[ \sum_{m=1}^{N=MP^2} b_m c_m(i) \right] \right\} \quad (16b)$$

Once the detection process of all the users is completed, the proposed system will select one of the users' signals. This selection is a procedure of maximizing correlation to regenerate and re-encode the optical spectral components again. Subsequently, the overall received signal will subtract this correlated signal, producing a new received signal. The cancellation of the users will then be performed sequentially until it completes the entire cancellation process and accomplishes the detection of every user.

After  $j^{th}$  cancellation, the decision variable parameter for the  $(j+1)^{th}$  user taking into account the code properties indicated in (5). Then, for the  $j^{th}$  cancellations, we get [10], [11]:

$$G_j(v) = G_{j-1}(v) - Z_j \cdot \sum_{i=1}^F c_j(i) \Gamma(i) \quad (17)$$

where;  $Z_j$  refers to the correlation after  $(j-1)^{th}$  cancellation, and it consists of the desired user signal according to (14) and some noise according to (9). In addition, the imperfect cancellation contributes to some noises. Therefore, the  $(j+1)^{th}$  decision variable can be expressed as [10], [11]:

$$Z_{j+1} = \frac{\Re P_{er}}{F} \left( \frac{P-1}{M} \right) b_{j+1} + \langle i_{j+1}^2 \rangle \quad (18)$$

and  $\langle i_{j+1}^2 \rangle$  is referring to the total noise at each stage of the cancellation process, taking into account the probability of sending bit "1" at any time for each user is 1/2. In addition, it can be given by:

$$\langle i_{j+1}^2 \rangle = \frac{eB\Re P_{er}}{MF} \left( 2M(N-1) + (P-1) - 2 \sum_i^j \langle i_i^2 \rangle \right) + \frac{B\Re^2 NP_{er}^2}{2MF^2 \Delta v} \left( M(N-1) + \left( P + N - 2 \left( 1 + \sum_i^j \langle i_i^2 \rangle \right) \right) \right) + 4K_b T_n B / R_L \quad (19)$$

Then, both SIC/DS and SIC/SAC systems will show the signal-to-noise ratio (SNR) as follows; consequently, by using the Gaussian approximation of  $BER_{j+1} = Q(\sqrt{SNR_{j+1}})$  the probability of error after the cancellation can be estimated.

For SIC scheme the SNR equations is;

$$SNR_{j+1} = \frac{\Re^2 P_{er}^2 \left( \frac{P-1}{M} \right)^2}{\Re^2 \left( \Gamma^2_{j+1} | MAI \right) + 4K_b T_n B / R_L} \quad (20)$$

For SIC/SAC scheme the SNR equations is;

$$SNR_{j+1} = \frac{\Re^2 \frac{P_{er}^2}{F^2} \left( \frac{P-1}{M} \right)^2 b_{j+1}^2}{\frac{eB\Re P_{er}}{MF} \left( 2M(N-1) + (P-1) - 2 \sum_i^j \langle i_i^2 \rangle \right) + k} \quad (21)$$

$$k = \frac{B\Re^2 NP_{er}^2}{2MF^2 \Delta v} \left( M(N-1) + \left( P + N - 2 \left( 1 + \sum_i^j \langle i_i^2 \rangle \right) \right) \right) + 4K_b T_n B / R_L \quad (22)$$

$$\Gamma^2_{j+1} |_{MAI} = \frac{1}{P^2} \left[ \sum_{n=j+2}^{N=P^2} P_{er}^2 b_n^2 \cdot \text{var}[I_{n,j+1}(\tau_{n,j+1})] + \sum_{i=1}^j \Gamma^2_i \cdot \text{var}[I_{i,j+1}(\tau_{i,j+1})] \right] \quad (23)$$

$\Gamma^2_{j+1} |_{MAI}$  is the variance of combination of the MUI of the non-cancelled users and cumulative noise from imperfect cancellation.

#### IV. NUMERICAL RESULTS

Using the typical system parameters as itemized in Table I, our proposed system produces results as show in Figs. 2-5. The system was tested by PMP codes as the prime number is configured at,  $P = 7$ ,  $P = 11$ , and  $P = 13$ , respectively. The performance of the proposed system was derived with SNR in (18) and (19). Fig. 2 shows the bit error probability performance versus the number of simultaneous users at  $M = 2; 5$ . The advantages of PMP code comes from the code size, as M increases the number of simultaneous users increases. Clearly, due to PMP code properties, the code weight (i.e., number of one's) decreases as M increase and the bit error probability increases. For comparison, the Hadamard code was used, and it was found that the proposed system had better performance with PMP code compared with Hadamard code.

TABLE I  
PARAMETERS USED IN THE CALCULATION

parameter	value
operation Wavelength	193.1 THz
PD quantum efficiency	0.6
receiver noise temperature	300 k
receiver load resistor	1030 $\Omega$
electrical equivalent bandwidth	80 MHz
line-width of the thermal noise	$\Delta v = 3.75$ THz
effective power	-20dBm

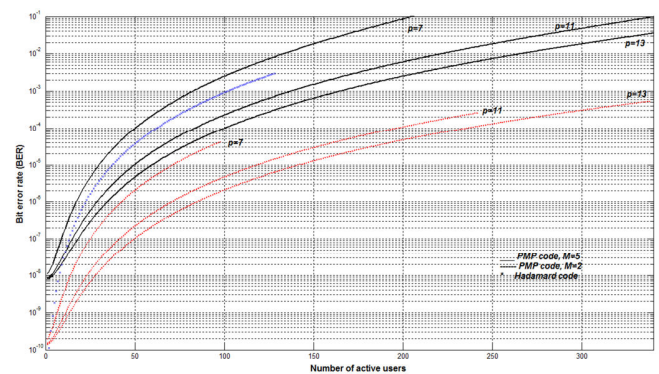


Fig. 2 BER versus number of active users at  $P_{er} = -20$ dBm

Fig. 3 shows variation of the bit error rate (BER) versus number of active users for different values of the effective power ( $P_{er}$ ), using PMP codes at  $P = 7$  and  $P = 11$ . In addition,  $M = 2, 5$ , all the noise sources were taken into account. The minimum effective power for OCDMA system based on SIC scheme is -10dBm. Fig. 4 shows the BER variations with



effective power when the total number of active users is 98 ( $P=7$ ) and  $M=2$  and 5. The Hadamard codes were used for performance comparison. The figure shows that PMP codes can provide better performance than the system using the Hadamard codes. In addition, as expected the BER is more affected by the receiver sensitivity, and the system performance also decreases as  $M$  increases. This is because the large value of  $M$  causes large power loss in the transmitter.

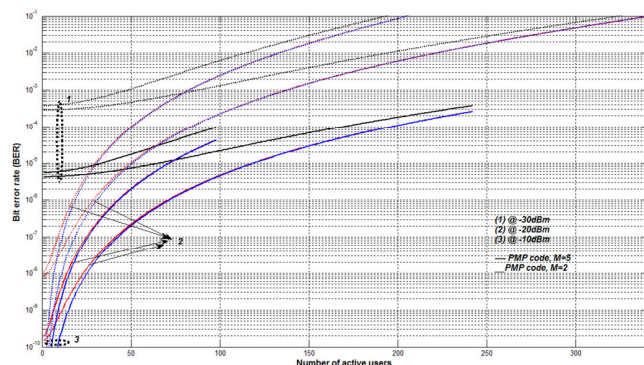


Fig. 3 BER versus number of active users at different  $P_{er}$

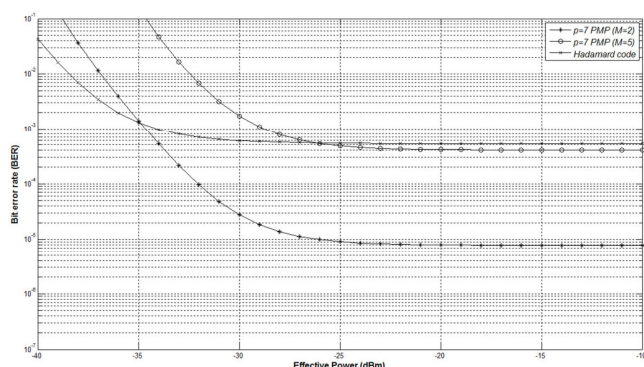


Fig. 4 BER versus effective power  $P_{er}$

Fig. 5 shows the comparison of BER performances between the systems with and without cancellation using PMP code, and effective power  $P_{er} = -20dBm$ . It can be clearly observed that SIC/SAC OCDMA system exhibits improved BER performance, achieved through PIIN noise suppression. The same figure also shows that the cancellation effect makes the SIC/SAC receiver system has a superior performance than the conventional system (i.e. without cancellation). It is also revealed that the SIC/SAC and conventional schemes, however, exhibits poorer performance when compared to SIC/DS scheme. As an example, both conventional and SIC/SAC schemes can only have active users of less than 10 within the particular network to achieve  $BER=10^{-9}$  when the prime number is set to 7. On the contrary, the number of users can be dramatically increased up to 80 users with SIC/DS cancellation scheme, especially at  $M=2$ , where the BER is slightly less than  $10^{-9}$ , giving substantial increase in the system capacity.

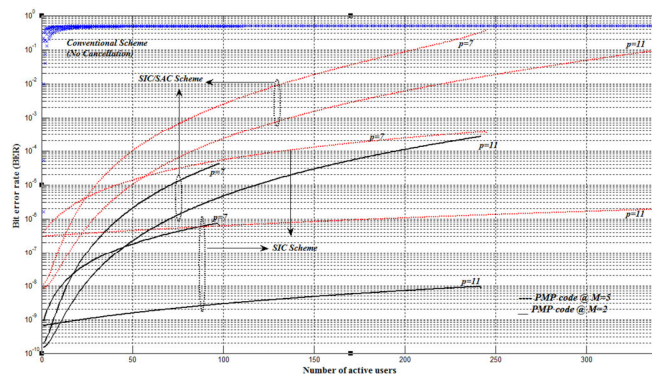


Fig. 5 Comparison of BER performances under ideal effective power

## V.CONCLUSION

This article presents theoretical analysis of SIC based on both direct sequence and SAC detection methods for OCDMA systems using PMP codes as a signature sequence codes, and considering the contribution of main noise and interference, namely shot noise, PIIN noise, thermal noise, and MUI. The Hadamard code has also been implemented for comparison. SIC scheme has been demonstrated to be able to suppress the noise, and thus improving the optical CDMA system performance. Moreover, it was also shown that PMP codes produce better BER performance relative to Hadamard codes. Hence, when the effective optical power is sufficient, the number of subscribers of the proposed system can be increased with the factor  $M$ . Furthermore, it is found that a SIC/DS scheme has a much lower BER performance compared with both the convolution and the SIC/SAC cancellation schemes. Hence, much more number of users can be accommodated by a SIC/DS system.

## ACKNOWLEDGMENT

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

## REFERENCES

- [1] Shake T H. Security performance of optical CDMA against eavesdropping. *Journal of Lightwave Technology*, 2005, 23(2), 655-670.
- [2] Jyoti V, Kaler R S. Novel virtual user scheme to increase data confidentiality against eavesdropping in OCDMA network. *Chin. Opt. Lett.* 2011, 9(12), 120602.
- [3] Salehi J A, Brackett C A. Code division multiple-access techniques in optical fiber networks-Part II: Systems performance analysis. *IEEE Transactions on Communications*, 1989, 37(8), 834-842.
- [4] Ohtsuki T, Sato K., Sasase I, Mori S. Direct-detection optical synchronous CDMA systems with double optical hard-limiters using modified prime sequence codes. *IEEE Journal on Selected Areas in Communications*, 1996, 14(9), 1879-1887.
- [5] Lin Che-Li, Wu J. A synchronous fiber-optic CDMA system using adaptive optical hardlimiter. *Journal of Lightwave Technology*, 1998, 16(8), 1393-1403.
- [6] Shalaby H M H, Sourour E A. Co-channel interference cancellation in optical synchronous CDMA communication systems. *IEEE Third International Symposium on Spread Spectrum Techniques and Applications*, 1994, 579-583.
- [7] Shalaby H M H. Cochannel interference reduction in optical PPM-CDMA systems. *IEEE Transactions on Communications*, 1998, 46(6), 799-805.

- [8] Brandt-Pearce M, Aazhang B. Multiuser detection for optical code division multiple access systems. *IEEE Transactions on Communications*, 1994, 42(2/3/4), 1801-1810.
- [9] Verdu S. Adaptive multiuser detection. *IEEE Third International Symposium on Spread Spectrum Techniques and Applications*, 1994, 43-50.
- [10] Eltaif T, Shalaby H M H, Shaari S, Hamarsheh M M N. A proposal of successive interference cancellation scheme in optical CDMA systems. *Optic. Eng.*, 2008, 47(3): 035006 (1-6).
- [11] Eltaif T, Shalaby H M H, Shaari S, Hamarsheh M M N. Analytical comparison of optical CDMA system with and without successive interference cancellation scheme using modified prime sequence codes. *Optic. Eng.* 2008, 47(9), 1-6.
- [12] Kavehrad M, Zaccarin D. Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources. *Journal of Lightwave Technology*, 1995, 13(3), 534-545.
- [13] Smith E D J, Blaikie R J, Taylor D P. Performance enhancement of spectral-amplitude-coding optical CDMA using pulse-position modulation. *IEEE Transactions on Communications*, 1998, 46(9), 1176-1185.
- [14] Zou W, Shalaby H M H, Ghafouri-Shiraz H. Modified quadratic congruence codes for fiber Bragg-grating-based spectral-amplitude-coding optical CDMA systems. *Journal of Lightwave Technology*, 2001, 19(9), 1274-1281.
- [15] Cheing-Hong L, Jingshown W, Hen-Wai T, Chun-Liang Y. Spectral amplitude-coding optical CDMA system using Mach-Zehnder Interferometers. *Journal of Lightwave Technology*, 2005, 23(4), 1543-1555.
- [16] Wen-Jeng H, Chun-Tao N, Cheing-Hong L, Jingshown W. Spatial/Spectral OCDMA System Using Partial Modified Prime Codes and Error-Correction Codes. *Journal of Lightwave Technology*, 2008, 26(17), 3030-3040.
- [17] Salehi J A. Code division multiple-access techniques in optical fiber networks-Part I: Fundamental principles. *IEEE Transactions on Communications*, 1989, 37(8), 824-833.
- [18] Goodman J W. *Statistical Optics*. Classics Edition: Wiley, New York, 1985.