Optical Engineering 48(4), 045002 (April 2009)

Performance enhancement of successive interference cancellation scheme based on spectral amplitude coding for optical code-division multiple-access systems using Hadamard codes

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Abstract. A successive interference cancellation scheme is applied to optical code-division multiple-access (OCDMA) systems with spectral amplitude coding (SAC). A detailed analysis of this system, with Hadamard codes used as signature sequences, is presented. The system can easily remove the effect of the strongest signal at each stage of the cancellation process. In addition, simulation of the prose system is performed in order to validate the theoretical results. The system shows a small bit error rate at a large number of active users compared to the SAC OCDMA system. Our results reveal that the proposed system is efficient in eliminating the effect of the multiple-user interference and in the enhancement of the overall performance. *© 2009 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3119303]

Subject terms: optical code-division multiple access; multiple-access interference; spectral amplitude coding; fiber Bragg-grating; successive interference cancellation; Hadamard code.

Paper 080574RRRR received Jul. 20, 2008; revised manuscript received Jan. 24, 2009; accepted for publication Feb. 17, 2009; published online Apr. 20, 2009.

1 Introduction

One of the main advantages of optical code division multiple access (OCDMA) systems is that they allow multiple users to transmit information over the same physical channel. Meanwhile, the main disadvantages of this system are that the performance and capacity of CDMA systems are limited by multiple access interference (MAI). MAI acts as the big problem faced by the researchers in this field. Consequently, interference cancellation techniques are proposed in order to overcome MAI in optical CDMA systems. In Refs. 1 and 2 the authors have proposed some cancellation techniques for both on-off keying (OOK) and pulse-position modulation OCDMA systems. These techniques depend on estimating the interference from knowledge of some other users' code sequences. In Ref. 3 Shalaby has proposed some techniques to estimate the interference using a modified prime code. In[4] we have developed a receiver model inspired from multiuser detection, called the successive interference cancellation (SIC) technique. In Refs. 5–8, we have analyzed the SIC scheme in the OOK-CDMA system using OOC codes, and the modified prime code as signature codes. It has been found that the proposal of SIC receiver is effective in cancelling the MAI, and in turn, the bit of error (BER) performance improves at each stage of the cancellation process.

In this paper, we propose using a successive interference cancellation receiver in spectral amplitude coding optical CDMA systems to improve the system performance and increase its capacity; that is, we propose a fiber Bragg-grating (FBG)–based SAC/SIC (FBG-SAC/SIC) hybrid scheme for an optical CDMA system adopting Hadamard signature codes. Although the system is a bit complex, it can accommodate many users; thus, our system is suitable

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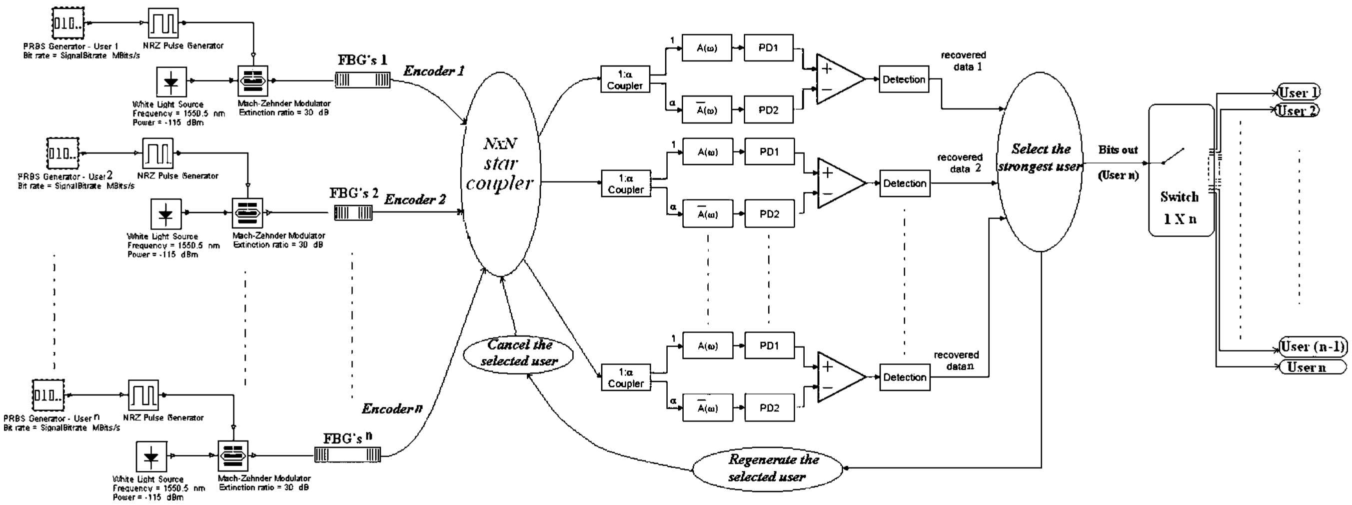

Fig. 1 SAC/SIC system block diagram.

for networks with high traffic and moderate rates (e.g., access networks) Next, we analyzed the performance of this hybrid system taking into account the effect of the phase-induced intensity noise (PIIN), shot noise, and thermal noises. Finally, we confirm the validity of our analysis with the aid of system simulation.

The rest of this paper is organized as follows. Section 2 is devoted to the description of the system architecture and the discussion of its basic principles. The analysis of our system performance is given in Section 3. In Section 4, we present our theoretical and simulation results. Finally, the conclusion is given in Section 5.

2 System Architecture and Basic principles

Figure 1 shows the hybrid architecture of our optical CDMA system. It is combined of both SIC and SAC based on FBG.

This type of CDMA system is decoded at one point, and then the signals are sent to the targeted users. Thus, the received signal is an input to a set of decoders that uses all the code set. A comparator can be used to detect the strongest signal.

We consider the proposed receiver of the hybrid architecture of our optical CDMA system for the entire system, as shown in Fig. 1. It is assumed that users are detected according to the signal strength. The SIC scheme works by first detecting and demodulating all the received signals. At this point, the strongest user is not known but will be detected from the strength of the correlation of each user chip sequence with the received signal. The correlation values are passed on to a selector, which determines the strongest correlation value and selects the corresponding user for decoding and cancellation (i.e., after the strongest user has been selected it will be regenerated to the base band and subtracted from the overall received signal producing a new base-band signal. The algorithm then repeats, except the strongest user from the new base-band signal (which has one less user signal) is detected, demodulated, regenerated, and subtracted).

The basic ideal of SIC scheme can be found, in Refs. 4–8, where the general algorithm is summarized as follows:

1. Recognize the strongest signal (the one with maximum correlation value) from the composite received signal.
2. Decode the strongest signal.
3. Regenerate the strongest signal using its chip sequence.
4. Cancel the strongest signal by subtraction from the received one.
5. Repeat the above process until all users are decoded or a permissible number of cancellations are achieved.

The concept of spectral amplitude coding scheme was introduced in Ref. 9. The receiver filters the incoming signal with the same filter [direct decoder, $A(v)$] used at the transmitter as well as its complementary filter [complementary decoder, $\bar{A}(v)$]. The outputs from the filters are detected by the two photodetectors connected in a balanced fashion. This way of detection helps in reducing the effect of MAI.[9]

3 System Performance Analysis

In this section, we analyzed our proposed SAC/SIC system with Hadamard codes used as the signature sequence codes. In our analysis, we take into account the effect of shot noise, thermal noise, and PIIN. It is known that an $(N \times N)$ Hadamard matrix of 1's and 0's has the property that any row differs from any other row in exactly $N/2$ positions. In addition $N-1$ code sequences can be constructed where each one has weight equal to the $N/2$ and a length N. If $c_n\ (i)$ denotes the i'th element of the n'th code sequence, the code properties ensure that

$$\sum_{i=1}^{N} c_n(i)c_l(i) = \begin{cases} \frac{N}{2}; & n=l \\ \frac{N}{4}; & n \neq l \end{cases} \qquad n,l \in (2,3,\ldots,N). \tag{1}$$

Assuming that each user has the same power at the receiver, the variance of the photocurrent current can be expressed as[9–11]

$$\langle i^2 \rangle = 2eIB + I^2 B\tau_c + 4K_b T_n B/R_l, \tag{2}$$

where B is noise-equivalent electrical bandwidth of the receiver; K_b is Boltzmann's constant; e, electron's charge; I, average current; T_n, absolute receiver noise temperature; R_l, receiver load resistor, and τ_c is the source coherent time, given by[10,11]

$$\tau_c = \frac{\int_{v=0}^{\infty} G^2(v)dv}{[\int_{v=0}^{\infty} G(v)dv]^2}, \tag{3}$$

where $G(v)$ is the one-sided source power spectral density.

In Eq. (3), the first term is due to the effect of shot noise, the second term is due to the effect of PIIN noise, and the third one is due to the effect of the thermal noise. The received signal is fed to a bank of receivers, one for each user. The sign of the output of the receiver is the corresponding user decision. We consider the first user as the desired user; therefore, the decoder output at the photodetectors during one bit period can be expressed as

$$\begin{aligned} G_1(v) = \frac{P_{er}}{\Delta v}\sum_{k=1}^{K} b_k \sum_{i=1}^{N} c_k(i)\bar{c}_1(i) \\ \cdot \left(u\left[v - v_o - \frac{\Delta v}{2N}(-N+2i-2) \right] \right. \\ \left. - u\left[v - v_o - \frac{\Delta v}{2N}(-N+2i) \right] \right), \end{aligned} \tag{4}$$

$$\begin{aligned} G_2(v) = \frac{P_{er}}{\Delta v}\sum_{k=1}^{K} b_k \sum_{i=1}^{N} c_k(i)c_1(i) \\ \cdot \left(u\left[v - v_o - \frac{\Delta v}{2N}(-N+2i-2) \right] \right. \\ \left. - u\left[v - v_o - \frac{\Delta v}{2N}(-N+2i) \right] \right). \end{aligned} \tag{5}$$

From Eqs. (4) and (5), we can express photocurrent for the first user as follows:

$$I_1 = \int_0^{\infty} G_1(v)dv = \frac{P_{er}}{4}(K + b_{m1}), \tag{6}$$

$$I_2 = \int_0^{\infty} G_2(v)dv = \frac{P_{er}}{4}(K - b_{m1}). \tag{7}$$

We can get integral of $G_1^2(v)$ and $G_2^2(v)$, according to Refs. 10 and 11 as follows:

$$\begin{aligned} \int_0^{\infty} G_1^2(v)dv \\ = \frac{P_{er}^2}{N\Delta v} \cdot \sum_{i=1}^{N} \left\{ \bar{c}_1(i) \cdot \left[\sum_{k=1}^{K} b_k c_k(i) \right] \cdot \left[\sum_{m=1}^{K} b_m c_m(i) \right] \right\}, \end{aligned} \tag{8}$$

$$\begin{aligned} \int_0^{\infty} G_2^2(v)dv \\ = \frac{P_{er}^2}{N\Delta v} \cdot \sum_{i=1}^{N} \left\{ c_1(i) \cdot \left[\sum_{k=1}^{K} b_k c_k(i) \right] \cdot \left[\sum_{m=1}^{K} b_m c_m(i) \right] \right\}. \end{aligned} \tag{9}$$

From Eqs. (8) and (9), we can get the signal from the desired user (i.e., first user) by the difference of the photodiode current outputs. Hence, after j'th cancellation, the decision variable for the $(j+1)$'th user takes into account the code properties indicated in Eq. (1). In general for the j'th cancellations, we get

$$r_j(t) = r_{j-1}(t) - Z_j \cdot c_j(i), \tag{10}$$

where Z_j refers to the correlation after $(j-1)$'th cancellation, and then the decision variable for the $(j+1)$'th user is

$$Z_{j+1} = \Re \frac{P_{er}}{2} b_{j+1} + \langle i_{j+1}^2 \rangle, \tag{11}$$

where the responsivity of the photodetector (PD) $\Re$ is given by $\Re = \eta e / h v_c$, where η is the quantum efficiency, e is the electron's charge, h is the Plank's constant, and v_c is the central frequency of the original broadband optical pulse. $\langle i_{j+1}^2 \rangle$ is given by

$$\begin{aligned} \langle i_{j+1}^2 \rangle = eB\Re P_{er}\left(k + \frac{1}{2}\sum_{i}^{j} \langle i_i^2 \rangle \right) \\ + \frac{B\Re^2 P_{er}^2}{4\Delta v}\left[k(k+1) - \frac{3}{4}\sum_{i}^{j} \langle i_i^2 \rangle \right] + \frac{4K_b T_n B}{R_l}. \end{aligned} \tag{12}$$

Thus, from (11) and (12) we can express the signal-to-noise ratio (SNR) as follows:

Table 1 Typical parameters used for calculation.

Parameter	Value
Operation wavelength	193.1 THz
PD quantum efficiency	0.6
Receiver noise temperature	300 k
Receiver load resistor	1030 Ω
Electrical equivalent bandwidth	80 MHz
Line width of the thermal noise	Δv=3.75 THz

$$\mathrm{SNR}_{j+1} = \frac{\Re^2 (P_{er}^2/4) b_{j+1}^2}{eB\Re P_{er}[k + (1/2)\Sigma_i^j \langle i_i^2 \rangle] + (B\Re^2 P_{er}^2/4\Delta v)[k(k+1) - (3/4)\Sigma_i^j \langle i_i^2 \rangle] + 4K_\mathrm{b} T_n B/R_1}. \tag{13}$$

Finally, the probability of error (BER) after the j'th cancellation can be estimated using the Gaussian approximation $\mathrm{BER}_{j+1} = Q(\sqrt{\mathrm{SNR}_{j+1}})$.

4 Theoretical and Simulation Results

In this section, we present some performance results for our proposed system with typical system parameters as listed in Table 1. Figure 2 shows the bit error rate performance versus the number of active users, using Hadamard code as signature sequence, the BER function of SAC system using Hadamard code is also plotted in Fig. 2 for the sake of comparison. It is clear from Fig. 2 that our proposed system significantly improves the BER performance at a large number of users. The SAC system gives a BER better than our proposed system for <40 users, but the BER is too small. In addition, our system performance has been simulated using Optisystem software, taking the Hadamard code as a sequence code. First, we used a simple schematic block diagram, which consists of three users.

The transmitter part consists of white-light sources with equal power of −115 dBm for all the users, Mach–Zehnder modulator and some uniform fiber Bragg grating with reflectivity's ~99.9%. Also, we used signature codes each with a length of $N=4$. Thus, we adopt a 4×4 Hadamard matrix codes that contain rows of (1, 1, 1, 1), (1, 0, 1, 0), (1, 1, 0, 0), and (1, 0, 0, 1). The (1, 1, 1, 1) row corresponds to OOK of all used wavelengths and is omitted. Therefore, the possible central wavelengths of the FBG coders are designed as the code vector $(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$. These selected spectral chip wavelengths are 1548.5, 1550.1, 1550.9, and 1552.5 nm. Finally, we have set up the system with a data rate of 200 Mbit/s.

The simulation results for our SAC/SIC system are presented in Figs. 3–5, which show the eye diagram for each stage of cancellation, respectively. Figure 3 shows the eye diagram of the received signal after the complete detection for all the users before any cancellation. The strongest user is selected, regenerated, and subtracted form the overall received signal. The new signal now consists of only two users and is fed back to detection again. After its complete detection, we get the eye diagram as shown in Fig. 4. Again, the strongest user is regenerated and subtracted from the overall received signal of the eye diagram of the resultant signal, which consists of only one user and is shown in Fig. 5. We note that in Fig. 3 all the users appear. In Fig. 4, however, we have only two users because the signal of one of the users is already cancelled. In Fig. 5, we have only one user, as the signals from other two have been cancelled already. The BER of this system at each stage of cancellation is listed in Table 2. It is clear from Table 2 that the BER improves at each cancellation stage.

Next, we have increased the number of users to six for our SAC/SIC system using the Hadamard code sequences with a length of $N=8$. Thus, we adopt an 8×8 Hadamard matrix that contain rows of (1, 1, 1, 1, 1, 1, 1, 1), (1, 0, 1, 0, 1, 0, 1, 0), (1, 1, 0, 0, 1, 1, 0, 0), (1, 0, 0, 1, 1, 0, 0, 1), (1, 1, 1, 1, 0, 0, 0, 0), (1, 0, 1, 0, 0, 1, 0, 1), (1, 1, 0, 0, 0, 0, 1, 1), and (1, 0, 0, 1, 0, 1, 1, 0). The first row is excluded and the possible central wavelengths of the FBG coders are designed as the code vector $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8)$. These selected spectral chip wavelengths are 1549, 1549.5, 1550, 1550.5, 1551, 1551.5, 1552, and 1552.5 nm. The noise-equivalent electrical bandwidth of the receiver depends on various transmitted data rates and in the simulation part, we have tested the system and found that our system supports up to 200 Mbps per channel. Hence, the signals can be filtered by the low-pass Bessel filter placed

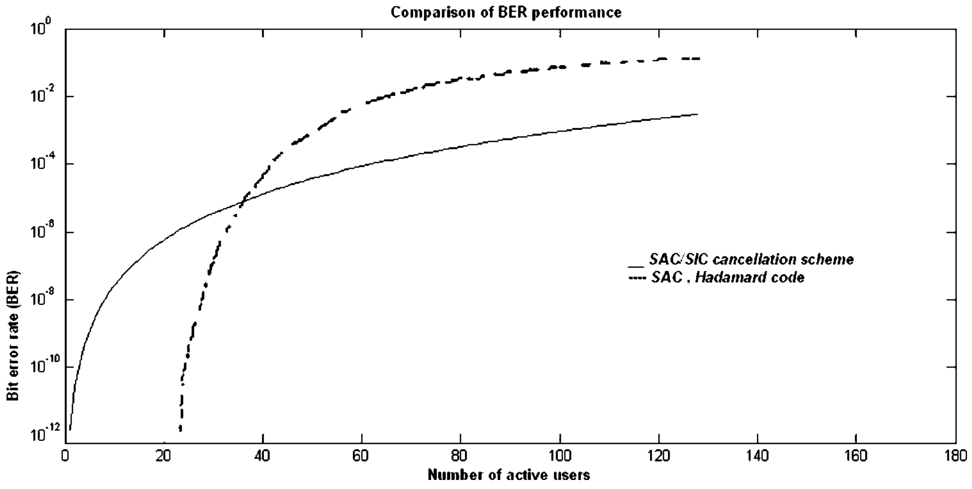

Fig. 2 Comparison of BER performance.

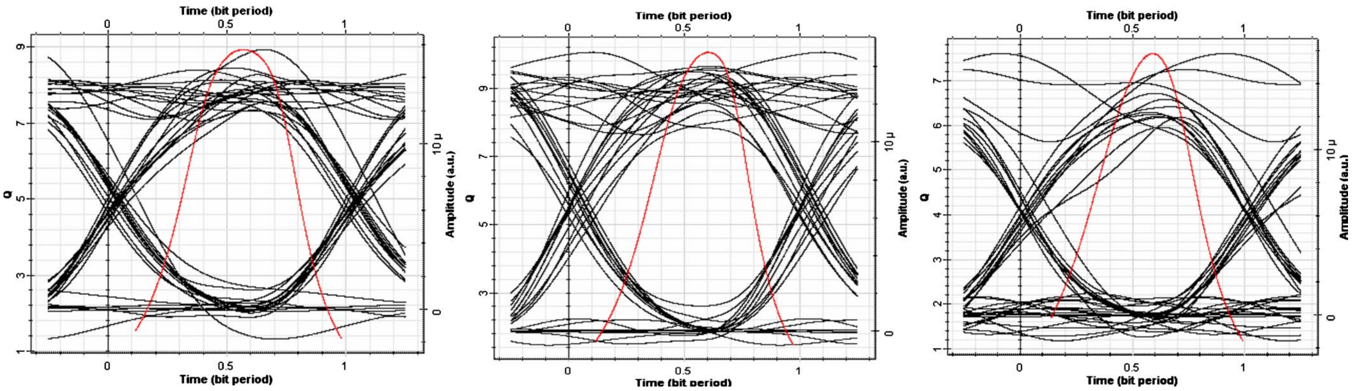

Fig. 3 Eye diagram of BER analyzer (first stage).

after photodetectors, provided that the cutoff frequency =0.65 * signal bit rate, which will be 130 MHz.

Simulation results of the system with six users have been listed in Table 3, where it is clear that at each stage of calculation one user is dropped. In the first row of Table 3, all the users' signals appear and one user's signal has been cancelled at the second row (first cancellation). This user does not appear again for any of the other cancellation stages. In the second row, one more signal has been cancelled. Then, in the last row (fifth cancellation stage), all the signals except one have been cancelled out.

From the simulation results with six users as in Table 3, the best BER has been chosen at each stage of calculation and is plotted (in Fig. 6) versus the number of active users. In Fig. 6, it is shown that the bit error rate decreases as the number of users decreases. However, there is a sudden increase in the last stage. The reason is that, in final stage of calculation, only one user is available with some noise cre-

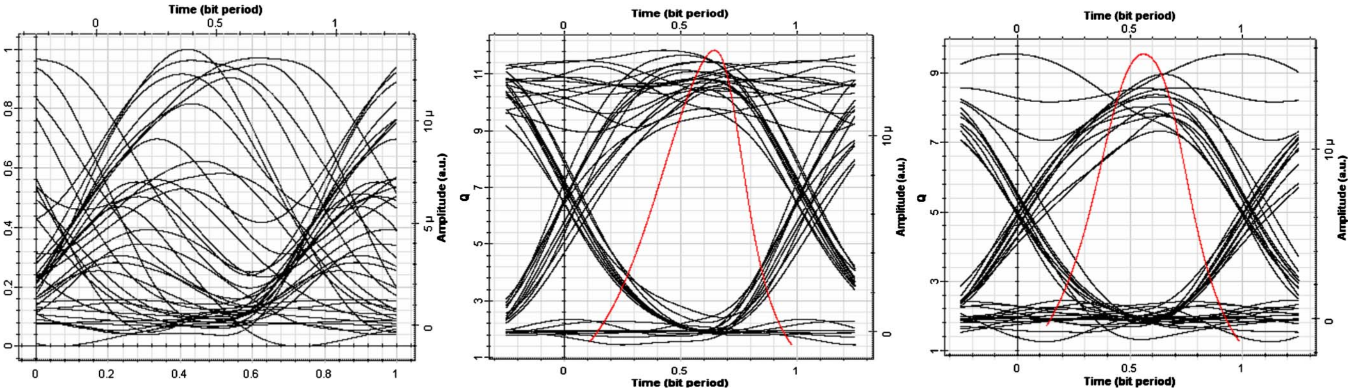

Fig. 4 Eye diagram of BER analyzer (second stage).

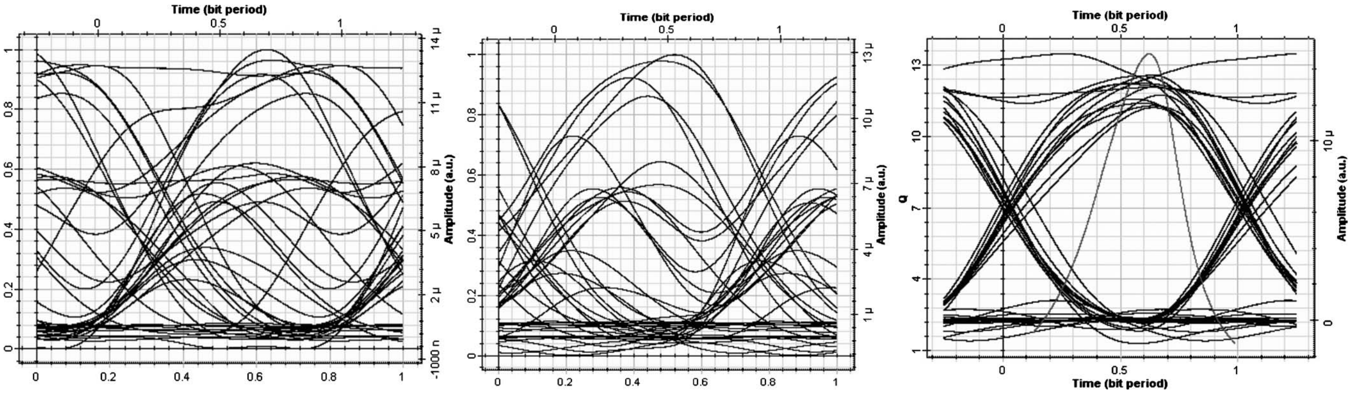

Fig. 5 Eye diagram of BER analyzer (third stage).

Table 2 BER at each stage of calculation.

	User 1	User 2	User 3
BER (no cancellation)	1.97×10^{-19}	4.28×10^{-24}	1.09×10^{-14}
BER (first cancellation)	1	1.035×10^{-32}	4.33×10^{-22}
BER (second cancellation)	1	1	9.18×10^{-42}

ated from the cancellation process. The main reasons for this are the BER user's different cause from the overlapping noise and some noise created from the cancellation process. This imperfect cancellation process increases noise increases at each stage, affects bit error rate performance, and makes it different for all the users.

5 Conclusion

In this paper, we have theoretically analyzed a SAC/SIC optical CDMA system, using Hadamard code as a signature sequence code. The system shows a small bit error rate at a large number of active users compared to the SAC OCDMA system. In addition, the system has been simulated using Optisystem software. The system can easily select the strongest user's signal at each stage of the cancellation process. The selected signal is subtracted from the overall received signal, taking into account the impact of imperfect interference cancellation. The system has been tested for both three and six users. It has been shown from the simulation results that the BER system performance improves at each stage of cancellation, where at each stage one user signal is cancelled. Currently, we are working on a SIC cancellation scheme to have it operate fast enough to avoid any tolerable delay. Therefore, presumably limiting

Table 3 BER at each stage of calculation.

	User 1	User 2	User 3	User 4	User 5	User 6
BER no cancellation	6.74×10^{-15}	4.27×10^{-14}	2.15×10^{-16}	7.83×10^{-23}	5.06×10^{-15}	1.02×10^{-21}
BER at first cancellation	5.01×10^{-13}	1.05×10^{-22}	1.85×10^{-19}	2.56×10^{-23}	1	5.34×10^{-23}
BER at second cancellation	2.98×10^{-16}	4.03×10^{-27}	1	1.84×10^{-27}	1	1.93×10^{-27}
BER third cancellation	8.29×10^{-23}	5.14×10^{-31}	1	1	1	2.67×10^{-27}
BER fourth cancellation	6.97×10^{-35}	1	1	1	1	2.33×10^{-33}
BER fifth cancellation	1.12×10^{-30}	1	1	1	1	1

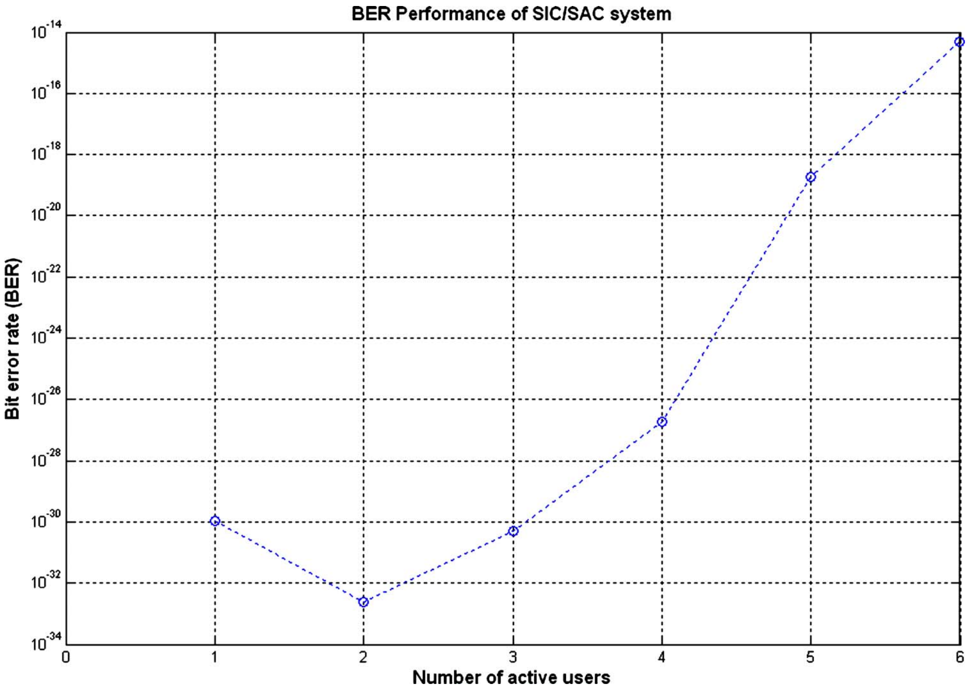

Fig. 6 BER versus number of active users.

the number of cancellation processes is the suitable way to perform that. The ability to limit the number of cancellations allows one to achieve a compromise between complexity and performance.

Acknowledgments

Tawfig Eltaif thanks Dr. Abdullatif M. Abdulla Alsharjabi of University Kebangsaan Malaysia, Bangi, Selangor Malaysia, for worthwhile ideas and useful suggestions, and Marcio Freitas, Research Scientist, Optical Systems, Optiwave, 7 Capella Court, Ottawa ON K2E 7X1, Canada, for his suggestion, discussions, and assistance to improve the system design output. This work was funded by Malaysian Ministry of Science, Technology and Environment under Project No. IRPA UKM-OUP-BTT 26/2007.

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