



Performance analysis of a hybrid fiber Bragg grating-based spectral-amplitude-coding/successive interference cancellation for optical CDMA systems

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ABSTRACT

Successive interference cancellation (SIC) scheme is proposed as a new technique that has the potential to reduce the interference and suppress the multiple-access interference (MAI) in spectral-amplitude-coding (SAC) optical-code-division-multiple access (OCDMA) systems. The proposed receiver-based on fiber Bragg gratings (FBGs) techniques. The performance of the proposed system is theoretically analyzed, taking into account various types of noise and interference, including both multiple-access interference (MAI) and receiver noise. Analytical results show that the proposed system offers significant improvement in terms of bit error rate and system capacity (number of users). We have tested our results with both modified prime codes (MPR) and modified quadratic congruence (MQC) codes. In addition, we have compared our proposed system with the corresponding one without cancellation. It has been shown that the proposed scheme gives a substantial increase in capacity.

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1. Introduction

Optical-code-division-multiple access (OCDMA) has emerged as a promising candidate, instead of wavelength-division multiplexing (WDM), which appears to be an attractive technique that can accommodate hundreds of ultra-high-speed users by assigning them different wavelengths. However, the deployment of WDM in the access environment is still limited because it requires expensive components. OCDMA is a multiplexing technique that uses an approach different from TDM and WDM. In OCDMA systems, the optical fiber's resources (i.e., wavelength and time) are not shared among users; instead all resources are assigned to all users. Multiplexing is achieved by use of signature-encoded signals. The advantages of OCDMA include ultra-high-speed connections, asynchronous access, scalability, security, and a potentially lower cost than WDM.

In the last two decades, many proposals have been done in optical CDMA, early ones coded the incoherent pulses in time domain using tapped delay lines [1–3]. Coherent systems have been proposed in [4–6], which can mitigate MAI. However, incoherent systems are more effective than coherent systems according to the

main reason that it does not need phase synchronization; therefore hardware complexity of the system is reduced.

With incoherent technique, Kavehrad and Zaccarin have described a technique called spectral-amplitude-coding (SAC), this system shows a good performance in suppressing or cancelling multiple-access interference (MAI) [7]. Some codes such as m-sequence and Hadamard codes have been used for this scheme in [8]. However, the system still has the phase-induced intensity noise (PIIN) as the main parameter that limits its performance. Hence, some codes have been proposed to mitigate the effect of PIIN [9]. In [10–13] we have proposed and analyzed the SIC scheme with OOC codes, and modified the prime code using OOK modulation, it is found that SIC receiver effectively cancelled MAI and BER performance significantly improves at each stage of cancellation process.

In this article, we have presented different theoretical analyses for the successive interference cancellation (SIC) scheme, which applies to optical-code-division-multiple access (O-CDMA) systems with spectral-amplitude-coding (SAC) based on fiber Bragg gratings (FBGs). A detailed analysis of this system using modified prime code (MPR) as signature sequences is presented. Therefore, compared with modified quadratic congruence (MQC) codes, it is shown that MPR codes give better results of BER. In addition, we have compared the optical CDMA system with and without cancel-

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lation scheme, and it has been shown that the SAC/SIC scheme (i.e., with cancellation) has potential to suppress the intensity noise and mitigate the multiple-access interference (MAI), giving substantial increase in capacity.

To highlight the differences in terms of work done, in previous papers [11–13] the SIC scheme has been applied to the direct sequence optical CDMA system, while in this paper the SIC scheme is applied to the SAC optical CDMA system. In [11–13] we considered only the MAI noise and thermal noise, but in this paper, we take into account various types of noise and interference such as, effect of the phase-induced intensity noise (PIIN), shot and thermal noises, and multiple-access interference (MAI). And finally the SAC/SIC cancellation scheme has been compared with the conventional scheme (without cancellation), and it is shown that the cancellation scheme has better performance than the conventional scheme.

Our contribution is five folds: the basic principle of the system description is given in Section 2. We describe the system performance analysis in Section 3. We present numerical results in Section 4. Finally, conclusions are drawn in Section 5.

2. Basic principle of an SAC/SIC system

2.1. Successive interference cancellation

The received signal is fed to the bank of convolution receivers, each signal will be correlated with the signature code sequence that characterizes the desired user. The output is then photo detected, integrated, and sampled at the end of the time frame. The next stage of this process is that all the signals will be entered to the selector, which will select the strongest signal, this strong signal will be generated and subtracted from the overall receiver signal to get a new received signal. The basic principle of the SIC scheme is based on the algorithm illustrated in [10–13]. In this system with N users, it is assumed that the cancellations are performed at baseband. (i) Recognize the strongest signal (the one with maximum correlation value); (ii) decode the strongest signal; (iii) regenerate the strongest signal using its chip sequence; (iv) cancel the strongest user signal by subtraction; and (v) repeat until all users are decoded or a permissible number of cancellations are achieved [10–13].

In electrical domain the cancellation process can be easily done. In our system the cancellation process will be done in the optical domain, theoretically the cancellation can be performed in the optical domain, as is shown in Eqs. (13) and (14). For the cancellation process to be subtracted in the optical domain, we need to have information about both the phase and amplitude (and both signals should be synchronized). In addition, we would need an

optical coupler, and the signal selected should have a phase delay of 180° compared to the original signal.

2.2. Spectral-amplitude-coding

The SAC/OCDMA technique was first described by Zaccarin and Kavehrad [7]. Fig. 1 shows the principal structure of this technique. The main concept of this scheme is the complementarity of each bit at the receiver side. The receiver filters the incoming signals 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 has shown that the MAI can be eliminated with Hadamard codes in [8]. Zou et al. in [9] have proposed a new code, modified quadratic congruence (MQC) code, and it is shown that the new code can suppress intensity noise effectively and can improve the system performance significantly.

2.3. Fiber Bragg grating-based SAC optical CDMA

Fig. 2 shows a bank of FBG based on SAC for optical CDMA. The concept of this system with FBG is simple, where the transmitter sends a pulse only when the bit is “1”, otherwise no optical pulse is sent. In the transmitter side we need two FBGs as shown in the regeneration signal part in Fig. 2, where the optical pulse passes through the first FBGs groups and the correspondent spectral components are reflected. Hence the second FBGs groups are used to compensate the round trip delay of different spectral components. The received signal will be reflected back from the FBG's $A(v)$, and its complementary $\bar{A}(v)$ will be getting out from the other end of the grating group. More details of this proposal can be found in [9].

2.4. Hybrid of SAC–SIC optical CDMA

Fig. 2 shows our proposed receiver structure for optical CDMA, combining both FBG/SAC and SIC, more details of the structure of the SAC system are given in [7–9], FBG structure given in [14], and structure of SIC given in [10–13]. We consider the proposed receiver for the entire system, and just send the detected signal to each receiver. In this case we would not need power amplification, since we have power splitting once.

In this system we need N components of FBG/SAC, which should be equal to the number of cancellation processes. At the receiver side, the received signals will be fed into the bank of the FBG/SAC optical CDMA system. Each bit of data received will be split with bit complementary and each one will be detected by photode-

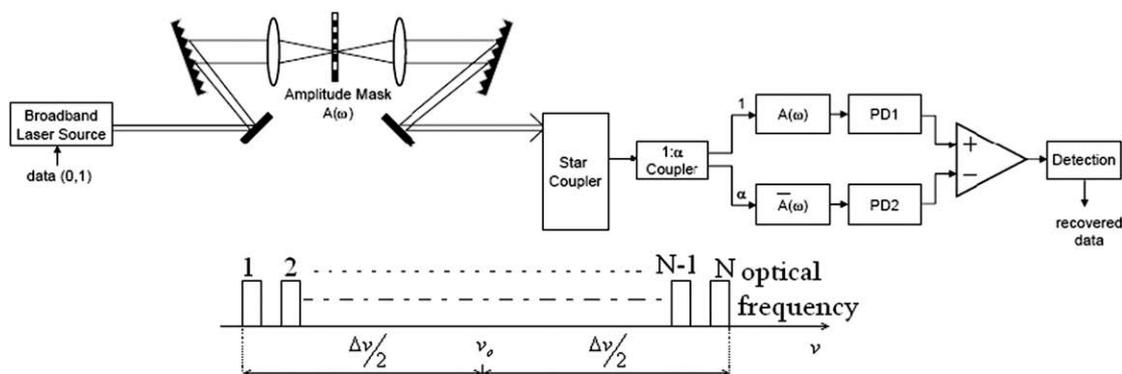


Fig. 1. Block diagram of SAC optical CDMA system.

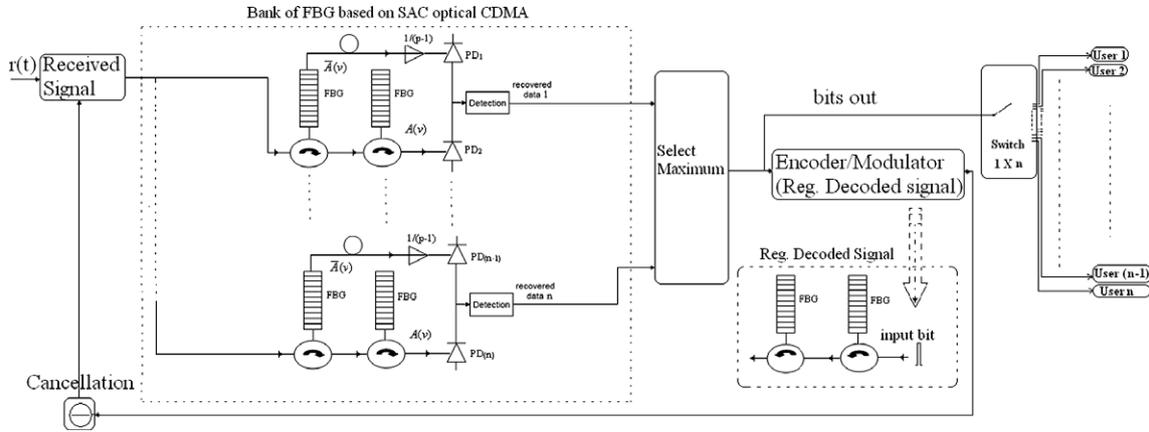


Fig. 2. Block diagram of SAC/SIC receiver.

tectors. Then after detection and modulation, the strongest user will be selected, regenerated and subtracted from the original received signal to get a new received signal.

In the ideal spectral-amplitude-coding some assumption should be made, source spectrum is ideally flat over a bandwidth of $\nu_o + \Delta\nu/2$, where ν_o is the central optical frequency and $\Delta\nu$ is the optical source bandwidth in hertz (spectral width), and should be identical for each user as shown in Fig. 1. All the users have the same power at the receiver side. In the next section, we present our analyzed performance system using modified prime code.

3. Theoretical analysis

Optical CDMA system can be viewed as a multiple-channel system, with each channel corresponding to a CDMA code. In our system we used modified prime code as our signature sequence, considering N active users equal to p^2 , each code with length $F = p^2$. The modified prime code properties expressed as

$$\sum_{i=1}^F c_k(i)c_l(i) = \begin{cases} p, & k = l \\ 1, & k \neq l \end{cases} \quad (1a)$$

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

Let $G(v)$ be the single sideband power spectral density (PSD) of the source, expressed as a function of receiver input signals as sum of the user's signals as follows:

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

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

$$u(v) = \begin{cases} 0; & v \geq 0 \\ 1; & v \leq 0 \end{cases} \quad (3)$$

In this section, we analyze the proposed system, considering incoherent intensity noise, shot noise as well as thermal noise as well, neglecting any other sources of noise. And under some assumptions such as, taking the ideal synchronous case, i.e., $\tau_n = 0$ [3], and ideal power for all the users. The original prime code is analyzed by using a Gaussian approximation, and we can express photocurrent variance as follows [8,9]:

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

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

In the above equation, the first term is due to shot noise, the second is related to effect of PIIN noise, and the third one is the thermal noise effect. The source coherent time τ_c can be expressed as [8,9]

$$\tau_c = \frac{\int_{\nu=0}^{\infty} G^2(\nu) d\nu}{\left[\int_{\nu=0}^{\infty} G(\nu) d\nu \right]^2} \quad (5)$$

We consider the first user as the desired user; therefore the decoder output at the photo detectors during one bit period can be expressed as

$$G_1(v) = \frac{P_{er}}{(p-1)\Delta\nu} \sum_{n=1}^{N=p^2} b_n \sum_{i=1}^{F=p^2} c_n(i)\bar{c}_1(i) \cdot \left(u \left[v - \nu_o - \frac{\Delta\nu}{2p^2}(-P^2 + 2i - 2) \right] - u \left[v - \nu_o - \frac{\Delta\nu}{2p^2}(-P^2 + 2i) \right] \right) \quad (6a)$$

$$G_2(v) = \frac{P_{er}}{\Delta\nu} \sum_{n=1}^{N=p^2} b_n \sum_{i=1}^{F=p^2} c_n(i)c_1(i) \cdot \left(u \left[v - \nu_o - \frac{\Delta\nu}{2p^2}(-P^2 + 2i - 2) \right] - u \left[v - \nu_o - \frac{\Delta\nu}{2p^2}(-P^2 + 2i) \right] \right) \quad (6b)$$

And the photocurrent at each PD1 and PD2 for the first user is given by ((7a) and (7b))

$$I_1 = \int_0^{\infty} G_1(v) dv = \frac{P_{er}}{p^2} \sum_{n=2}^N b_n \quad (7a)$$

$$I_2 = \int_0^{\infty} G_2(v) dv = \frac{P_{er}}{p} b_1 + \frac{P_{er}}{p^2} \sum_{n=2}^N b_n \quad (7b)$$

We can get integral of $G_1^2(v)$ and $G_2^2(v)$ referring to Fig. 1, according to [9] as follows:

$$\int_0^{\infty} G^2(v) dv = \frac{\Delta\nu}{p^2} \sum_{i=1}^{p^2} a^2(i) \quad (8)$$

$$\int_0^{\infty} G_1^2(v) dv = \frac{P_{er}^2}{p^2(p-1)^2 \Delta\nu} \cdot \sum_{i=1}^{p^2} \left\{ \bar{c}_1(i) \cdot \left[\sum_{n=1}^{N=p^2} b_n c_n(i) \right] \cdot \left[\sum_{m=1}^{N=p^2} b_m c_m(i) \right] \right\} \quad (9a)$$

$$\int_0^\infty G_2^2(v)dv = \frac{P_{er}^2}{p^2\Delta v} \cdot \sum_{i=1}^{p^2} \left\{ c_1(i) \cdot \left[\sum_{n=1}^{N-p^2} b_n c_n(i) \right] \cdot \left[\sum_{m=1}^{N-p^2} b_m c_m(i) \right] \right\} \quad (9b)$$

From the above results, we can calculate the signal from the desired user (i.e., first user) by the difference of the photodiode current outputs, which can be expressed as

$$I = I_1 - I_2 = \Re \frac{P_{er}}{p} b_1 \quad (10)$$

The responsivity of the PDs is given by $\Re = \eta e/h\nu_c$. Here, η is the quantum efficiency, e is electron's charge, h is Plank's constant, and ν_c is the central frequency of the original broadband optical pulse. Now considering some of correlation properties, the variance of the noise power according to (4) can be found as

$$\langle i_1^2 \rangle = \frac{eB\Re P_{er}}{p^2} (2N + p - 2) + \frac{NP_{er}^2}{p^3\Delta v} \left[\frac{p^2 - 2p + pN}{p - 1} \right] + 4K_b T_n B/R_L \quad (11)$$

From (10) and (11), we can get the desired signal of user 1 (Z_1) with all noise, which can be expressed as follows:

$$Z_1 = \Re \frac{P_{er}}{p} b_1 + \frac{eB\Re P_{er}}{p^2} (2N + p - 2) + \frac{NP_{er}^2}{p^3\Delta v} \left[\frac{p^2 - 2p + pN}{p - 1} \right] + 4K_b T_n B/R_L \quad (12)$$

$$SNR_{j+1} = \frac{\Re^2 \frac{P_{er}^2}{p} b_{j+1}^2}{\frac{eB\Re P_{er}}{p^2} (2N + p - 2(1 + \sum_i^j \langle i_i^2 \rangle)) + \frac{B\Re^2 NP_{er}^2}{2p^3(p-1)\Delta v} [p^2 - 2p + pN - (p^2 - 1) \sum_i^j \langle i_i^2 \rangle] + 4K_b T_n B/R_L} \quad (18)$$

The second part of the analysis focuses on SIC, after all the users detect and recover the data, the system will select one of the users as a function of maximum correlation to regenerate and encode it again, then this signal will be subtracted from the overall received signal to make the new received signal, and cancellation of the users will be one by one till the cancellation process is finished and the detection of all the users is completed.

$$G^1(v) = G(v) - Z_1 \cdot \sum_{i=1}^{F=p^2} c_1(i) \left(u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i - 2) \right] - u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i) \right] \right) \quad (13)$$

Substituting (2) and (12) into (13) we can get the new received signal

$$G^1(v) = \frac{P_{er}}{\Delta v} \sum_{n=2}^{N-p^2} P_{er} b_n \sum_{i=1}^{F=p^2} c_n(i) \cdot \left(u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i - 2) \right] - u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i) \right] \right) - \langle i_1^2 \rangle \cdot \sum_{i=1}^{F=p^2} c_1(i) \cdot \left(u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i - 2) \right] - u \left[v - v_o - \frac{\Delta v}{2P^2} (-P^2 + 2i) \right] \right) \quad (14)$$

Similarly, followin the same steps from (6) to (9), we can get the output Z_2 of the first cancellation. After detection and integration of the second part of the above equation, the interference can be expressed as

$$\langle i_2^2 \rangle = \frac{eB\Re P_{er}}{p^2} (2N + p - 2(1 + \langle i_1^2 \rangle)) + \frac{B\Re^2 NP_{er}^2}{2p^3(p-1)\Delta v} [p^2 - 2p + pN - (p^2 - 1) \langle i_1^2 \rangle] + 4K_b T_n B/R_L \quad (15)$$

In the next stage the system has only $(N - 2)$ interference signals. Moreover there is some noise due to imperfect cancellation. Hence we can express the $(j + 1)$ th decision variable as follows:

$$Z_{j+1} = \Re \frac{P_{er}}{p} b_{j+1} + \langle i_{j+1}^2 \rangle \quad (16)$$

and $\langle i_{j+1}^2 \rangle$ is given by

$$\langle i_{j+1}^2 \rangle = \frac{eB\Re P_{er}}{p^2} (2N + p - 2(1 + \sum_i^j \langle i_i^2 \rangle)) + \frac{B\Re^2 NP_{er}^2}{2p^3(p-1)\Delta v} [p^2 - 2p + pN - (p^2 - 1) \sum_i^j \langle i_i^2 \rangle] + 4K_b T_n B/R_L \quad (17)$$

From (16) and (17) the SNR was found as

Therefore, the probability of error BER after the j th cancellation can be estimated using the Gaussian approximation

$$BER_{j+1} = Q(\sqrt{SNR_{j+1}}) \quad (19)$$

4. Numerical results

The results obtained are shown in Figs. 4–6. We have tested the system by the modified prime codes and the modified quadratic

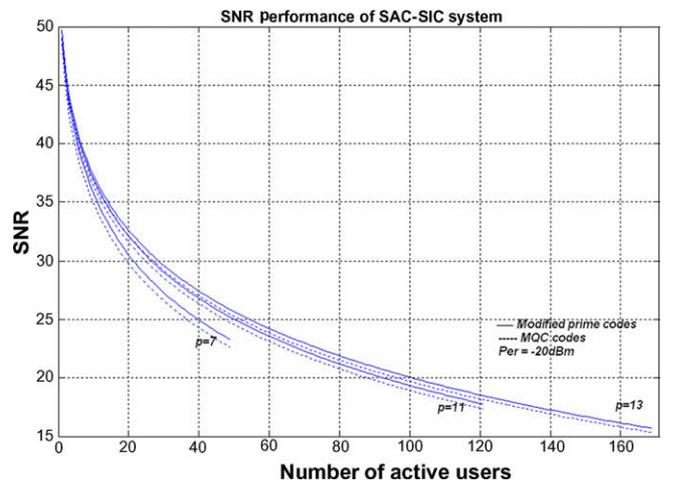


Fig. 3. SNR versus number of active users with received power (–20 dBm).

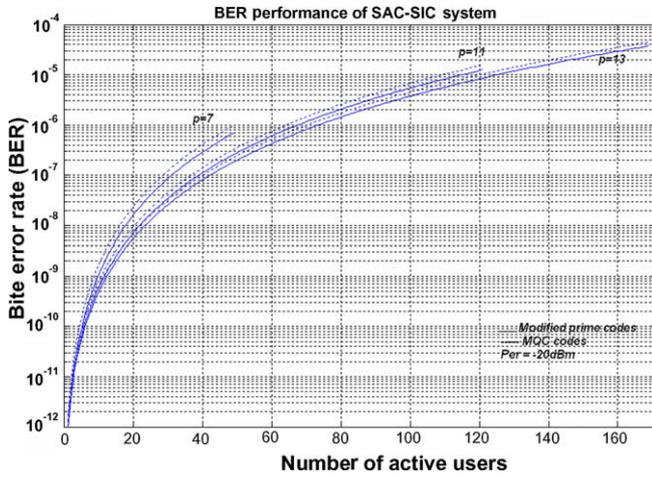


Fig. 4. BER versus number of active users under ideal power (–20 dBm).

congruence (MQC) codes, when the prime number sets as $p = 7$, $p = 11$, and $p = 13$, respectively. Fig. 3 shows the system’s SNR versus the number of active users when the effective power is –20 dBm. It has been shown that the modified prime codes give a higher SNR with bigger prime codes than MQC codes. Fig. 4 shows the bit error probability performance versus the number of active users at (–20 dBm). The performance of the proposed system is derived using (18) and (19) under the constraint on the bit error rate listed in Table 1.

Fig. 5 shows the variations of the BER versus the number of active users, using modified prime code $p = 11$, with different effective power (–20, –30, –40 dBm). Clearly the SIC system with prime codes is improved significantly with low power P_{er} , where BER performance increases with large power P_{er} .

Table 1
Typical parameters used for the 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	$\Delta\nu = 3.75$ THz

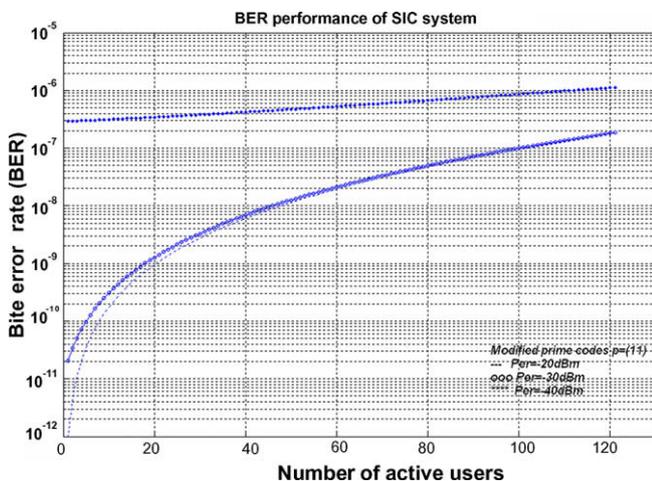


Fig. 5. BER versus number of active users under different power (–20, –30, –40 dBm).

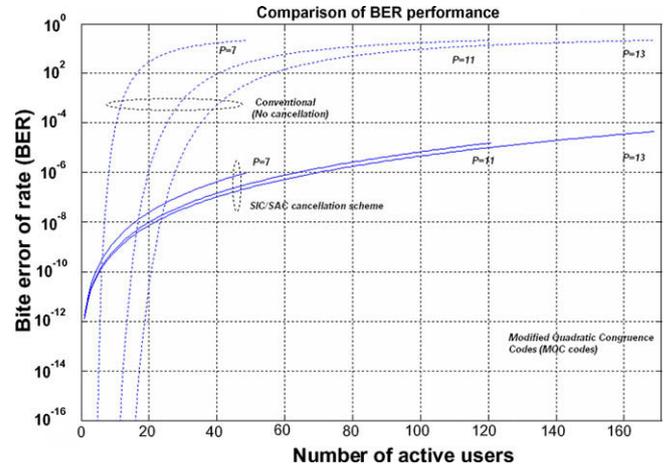


Fig. 6. Comparison of BER performance.

Fig. 6 shows the BER performance comparison of the system with and without cancellation, for number of active users. The bit error rate from the analysis obtained shows that the cancellation scheme has better performance than the conventional scheme. Assuming that the prime number set as a length 11, we can notice that for similar BER performance (10^{-6}), less than 20 users can be active with the conventional scheme, which can be increased to 60 users with the SAC/SIC cancellation scheme, giving substantial increase in capacity.

5. Conclusion

We have proposed a SAC/SIC optical CDMA system based on FBGs. The system performance has been theoretically analyzed taking into account various types of noise and interference, such as PIIN noise, shot noise, thermal noise, and MAI. Family prime codes have been considered, including the modified prime codes and modified quadratic congruence (MQC) codes. We have compared the BER performance of the proposed system for both codes. It has been shown that the proposed system can suppress the noise and improve the system performance significantly. Additionally, it is shown that modified prime codes give better results of BER as compared to MQC codes. Therefore, using the modified prime codes for the proposed system can effectively suppress the effect of multiple-access interference (MAI), and increase the system capacity. Further, with SAC/SIC cancellation we can accommodate much more number of users as compared to the system without cancellation.

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