Proposal of successive interference cancellation scheme in optical code-division multiple access systems

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Abstract. Proposes one of the multiuser detection schemes, a new technique that has the potential to reduce interference or suppress multiple-access interference and, therefore, increase the capacity of optical code-division multiple access (CDMA) systems. It is a successive interference cancellation (SIC) scheme known as a low-complexity multiuser detection method for direct sequence CDMA systems. A SIC scheme is analyzed using an optical orthogonal code, with a different power for each user, that takes into account the impact of imperfect interference cancellation. © *2008 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.2898642]

Subject terms: optical code-division multiple access (OCDMA); multiple-access interference (MAI); optical orthogonal codes (OOCs); successive interference cancellation (SIC).

Paper 070597R received Jul. 16, 2007; revised manuscript received Nov. 13, 2007; accepted for publication Nov. 21, 2007; published online Mar. 25, 2008.

1 Introduction

Successive interference cancellation (SIC) is a multiuser detection (MUD) technique,[1] where MUD is typically employed in optical code-division multiple access (CDMA) communication systems. The problem of demodulating a specific user signal is complicated, as the other user signals exist in the same bandwidth.[2] In conventional receivers, the presence of other signals is treated as noise. In MUD algorithms, this noise is usually referred to as multiple access interference (MAI), and it is shown that this type of noise limits direct sequence CDMA (DS-CDMA) system capacity. Any technique that can suppress (cancel) MAI will increase the system's capacity.

In recent years, MUD has become an attractive alternative to conventional spread spectrum detectors. It is well known that optimum MUD has a much better theoretical performance than conventional detection.[3,4] However, the majority of multiuser detectors have a very high complexity and, consequently, suboptimum structures have been presented.[3] In this work, we propose and analyze a SIC scheme using an optical orthogonal code (OOC) with a different power for each user, that takes into account the impact of imperfect interference cancellation.

2 Principle of the SIC Scheme

The basic idea of this scheme is simple, it detects and demodulates the strongest user signal currently present in the overall received signal. The strongest user is not known beforehand, but it is detected from the strength of the correlations of each of the user's chip sequences with the received signal. The correlation values can be found from the bank of the correlator. Figure 1 shows the block diagram of

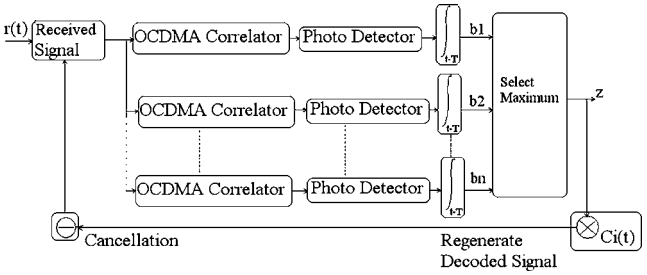

Fig. 1 The SIC receiver block diagram.

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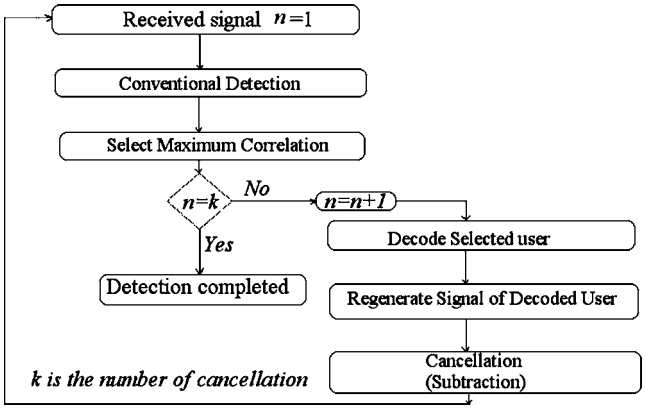

Fig. 2 Flow chart of interference cancellation schemes.

the SIC receiver. After this user has been detected and demodulated, its contribution to the original signal is regenerated and subtracted from the overall received signal to get a new received signal.

Then we can conclude that the algorithm repeats, excluding the strongest user from the new received signal, which, composed of one user signal less, is detected, demodulated, regenerated, and subtracted.[5,6] At the end, we can say that the strongest received signals are subtracted from the original signal one by one until all users have been detected and demodulated.

Figure 2 shows the flowchart of this process. In a general algorithm, the successive cancellations are carried out as follows:

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

3 SIC System Equations

In our system, we consider an incoherent, DS optical CDMA (DS-OCDMA) system. The system consists of N users, labeled by n, where $n=1,2\ldots N$. On-off keying (OOK) modulation is used to transmit binary data via an optical channel for each user with a specific sequence code for each. In particular, OOC will be used as the signature codes[7] in this paper. It is a family of (0,1) sequences of length F and weight W that satisfy the requirement that λ_a, λ_c are equal to 1. With good auto- and cross-correlation, it enables the effective detection of the desired signal. The n'th user spreading code can be represented as

$$c_n(t) = \sum_{k=-\infty}^{\infty} c_{k,n} P_{T_e}(t - kT_c). \tag{1}$$

Here, $c_{k,n} \in \{0,1\}$, T_c refers to the chip duration, and $P_\tau(t)$ is the optical rectangular pulse in $[0,\tau]$ with unit amplitude. We consider an ideal synchronous case, that is $\tau_k=0$. It has been shown in Refs. 7 and 8 that the synchronous case is the worst case. Let the binary data of the n'th user $b_n(t)$ be given by

$$b_n(t) = \sum_{i=-\infty}^{\infty} b_{i,n} P_T(t - iT), \tag{2}$$

where $b_{i,n} \in \{0,1\}$ and T is the bit duration. Then we can say that the intensity signal of the n'th user is $S_n(t) = P_n b_n(t) c_n(t)$, where P_n is the signal strength of the n'th user. Therefore, on the receiver side, we can get the signal $r(t)$ to be the sum of the user's signals as follows:

$$r(t) = \sum_{n=1}^{N} P_n b_n(t - \tau_n) \sum_{i=1}^{F} c_n^i(t - \tau_n) + n(t). \tag{3}$$

Here, τ_n is the relative delay, and we have considered an ideal synchronous case, $\tau_n=0$.

In a general case, we look for the bit error probability, which can be written as follows:

$$P_b = \frac{1}{2} P[(E/0) + (E/1)]. \tag{4}$$

As we mentioned previously, the main function of this system is based on maximum cross correlation between the users, and the effect of the n'th user's signal on the first receiver is denoted by $I_n^{(1)}$. We define the cross correlation between the i'th user and the n'th user as

$$I_{n,i}(\tau_{n,i}) = \frac{1}{T}\left[\int_0^T c_n(t - \tau_{n,i}) \times c_i(t)\mathrm{d}t\right], \tag{5}$$

where $\tau_{n,i}$ is the time delay of the n'th user relative, to the i'th user.

Hence, the first decision variable Z_1 at time T, can be written as

$$Z_1 = \frac{1}{T}\int_0^T r(t) \times c_1(t - \tau_1) \times \mathrm{d}t \tag{6}$$

$$= \frac{1}{T}\int_0^T \left[\sum_{n=1}^{N} P_n b_n(t - \tau_n) \sum_{i=1}^{F} c_n^i(t - \tau_n)\right] \sum_{i=1}^{F} c_1^i(t - \tau_n) \times \mathrm{d}t. \tag{7}$$

Then after the decoding and integration, we can get the following:

$$Z_1 = \frac{P_1 b_{(1)} W}{F} + l_1, \tag{8}$$

where the first term refers to the desired signal term of the first user, and the second term can be defined as

$$l_1 = \frac{1}{F}\sum_{n=2}^{N} P_n b_n I_{n,1}(\tau_{n,1}) + n(t). \tag{9}$$

It is assumed that users are detected in the order of decreasing signal strength such that user 1 will always corre-

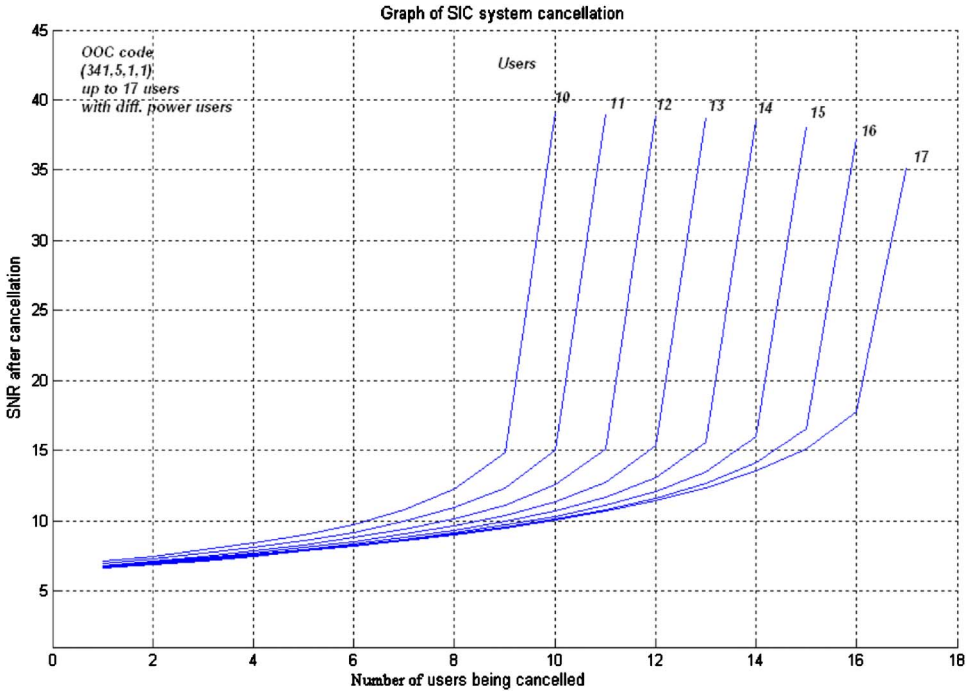

Fig. 3 The SNR after cancellation under different power OOC code (341, 5, 1, 1).

spond to the strongest user. Once this user has been detected and demodulated, the result is used to regenerate the user signal. Then the regenerated signal is subtracted from the original signal. The correlation value is used for cancellation

$$r_1(t) = r(t) - Z_1 \times c_1(t-\tau_1) \tag{10}$$

$$= \sum_{n=2}^{N} P_n b_n(t-\tau_n) \times c_n(t-\tau_n) + n(t) - l_1 \times c_1(t-\tau_1). \tag{11}$$

Now for the second strongest user, we have $(N-2)$ interfering signals and some noise due to imperfect cancellation. In following decision statistic for user 2 after canceling user 1, after decoding and integration we got

$$Z_2 = \frac{P_2 b_{(2)} W}{F} + l_2, \tag{12}$$

and l_2 is defined as

$$l_2 = \frac{1}{F}\left[\sum_{n=3}^{N} P_n b_n I_{n,2}(\tau_{n,2}) - l_1 I_{1,2}(\tau_{1,2})\right] + n(t). \tag{13}$$

In general, for the j'th, cancellations, we get

$$r_j(t) = r_{j-1}(t) - Z_j \times c_j(t-\tau_j). \tag{14}$$

Here, Z_j refers to the correlation after the j'th cancellation, then the decision variable for the $(j+1)$'th user is given by

$$Z_{j+1} = \frac{P_{j+1} b_{(j+1)} W}{F} + l_{j+1}, \tag{15}$$

where l_{j+1} are given by

$$l_{j+1} = \frac{1}{F}\left[\sum_{n=j+2}^{N} P_n b_n I_{n,j+1}(\tau_{n,j+1}) - \sum_{i=1}^{j} l_i I_{i,i+1}(\tau_{i,i+1})\right] + n(t). \tag{16}$$

In the above expression, the first term is MAI of the uncancelled users; second term is cumulative noise from imperfect cancellation, and the third term is the thermal noise.

4 SIC Interference Analysis

In this section, we consider the effect of both MAI and thermal noise; other sources of noise are neglected. Related to MAI, we can define the variance of l_{j+1} conditioned on P_n as follows:

$$\sigma_{j+1}^2|\_MAI = \frac{1}{F}\left\{\sum_{n=j+2}^{N} P_n^2 b_n^2 \operatorname{var}[I_{n,j+1}(\tau_{n,j+1})] + \sum_{i=1}^{j} \sigma_i^2 \operatorname{var}[I_{i,i+1}(\tau_{i,i+1})]\right\}. \tag{17}$$

The term $I_{n,j+1}$ is a random variable that depends on the random signature sequences. Central to the analysis is the variance of this term (for the case of $n \neq j+1$). For the synchronous case, where τ_n is zero for all n, the variance of cross correlation of Eq. (5) is given by[9,10]

$$\mathrm{var}(I_{n,j+1}) \approx \frac{1}{F}. \tag{18}$$

Substituting (18) into (17), we get the variance of the noise in the decision variable

$$\sigma^2_{j+1}|\_MAI = \frac{1}{F^2}\left[\sum_{n=j+2}^{N} P_n^2 + \sum_{i=1}^{j} \sigma_i^2\right]. \tag{19}$$

Furthermore, we consider the effect of thermal noise

$$\sigma_{th} = 4K_b T_n \frac{B}{R_L}, \tag{20}$$

where B is the noise-equivalent electrical bandwidth of the receiver in Hertz; K_b is Boltzmann's constant in joules per Kelvin $=1.38\times10^{-23}$ J/K; T_n is absolute receiver noise temperature in Kelvin; and R_l, is the receiver load resistor in ohms.

The responsivity of the PDs is given by $\Re = \eta e/hv_c$. Here, η is the quantum efficiency, e is the electron's charge, h is Plank's constant, and v_c is the central frequency of the original broadband optical pulse.

Then the signal-to-noise ratio (SNR) function of P_n is

$$SNR_{j+1} = \frac{\dfrac{\Re^2 P_{j+1}^2 W^2}{F^2}}{\dfrac{\Re^2}{F^2}\left[\sum_{n=j+2}^{N} P_n^2 + \sum_{i=1}^{j} \sigma^2 i\right] + 4K_b T_n \dfrac{B}{R_L}}. \tag{21}$$

The bit error rate (BER) is given by

$$BER_{j+1} = Q(SNR_{j+1})^{1/2}. \tag{22}$$

5 Performance Results and Discussion

In this section, we present the numerical results of SNR and BER performance of the proposed SIC scheme. The typical parameters used in the calculations are given in Table 1. In this analysis, we assume that each user had different power. Figure 3 shows the relationships between SNR and the number of users being cancelled, at various stages of cancellation using OOC[11] under different powers from −30 to −10 dBm. As we can see in the figure below, the SNR of the users increases at each stage of the cancellation process, and hence the SNR decreases when the number of users increased. In this analysis, we take in to account the possibilities of errors in previous cancellations.

Figure 4 shows a comparison of the BER under different OOC code parameters, namely different weights and lengths. We can see from the figure that an OOC with parameters (631, 6, 1, 1) gives a lower BER than that using (341, 5, 1, 1). However, when using (1365, 5, 1, 1) or (341, 5, 1, 1), we get almost the same results. We conclude from the figure that the SIC system performance depends on the code weight rather than the code length. As we can see in the figure, BER improves at each stage of the cancellation process, and we note that MAI becomes increasingly accurate as the number of users is increased. In fact, the BER performance improves as the code weight increases.

Table 1 Typical parameters in the system.

Parameter	Value
Operating frequency	193.1 THz
PD quantum efficiency	0.6
Receiver noise temperature	300 K
Receiver load resistor	1030 Ω
Noise-equivalent electrical bandwidth	80 MHz
Effective received power	−30 to −10 dBm
OOC	(1365,5,1,1)
	(631, 6, 1, 1)
	(341, 5, 1, 1)
	(63, 3, 1, 1)

In Fig. 5, we have compared the results of the system with and without cancellation for the number of active users. The BER from the obtained analysis shows that the cancellation scheme has better performance than the conventional scheme for a large number of users. However, if there is a small number of users, the system without cancellation performs better. This results from the effective power. Indeed, for the system without cancellation, the BER is independent of the effective power. However, the BER of our proposed system depends on the effective power as it is clear in Eq. (21). In our analysis, we have used different values of effective power for all users ranging from −30 to −10 dBm. It can be seen from Fig. 5 that, at an effective power of −30 dBm, the system performance with cancellation is not good; on the other hand, when the effective power is increased to −10 dBm, the system performance gives good results compared to the system without cancellation.

6 Conclusion

In this paper, a new proposal for interference cancellation of MUD has been reviewed. This new method is called successive interference cancellation (SIC), and this scheme is a simple, attractive technique to improve system capacity. In this work, we have obviously analyzed the performance of SIC. It is found from the results that the proposal SIC receiver effectively suppresses MAI and significantly improves BER performance at each stage of the cancellation process. However, the major problem with the SIC scheme is the accumulated cancellation noise; therefore, interference cancellation is not a perfect solution, and the residual cancellation errors propagate because of the successive nature of the decoding. In fact, these residual errors are the principal capacity-limiting issue in SIC systems. However, the system shows much lower BER performance with SIC cancellation compared with one without cancellation.

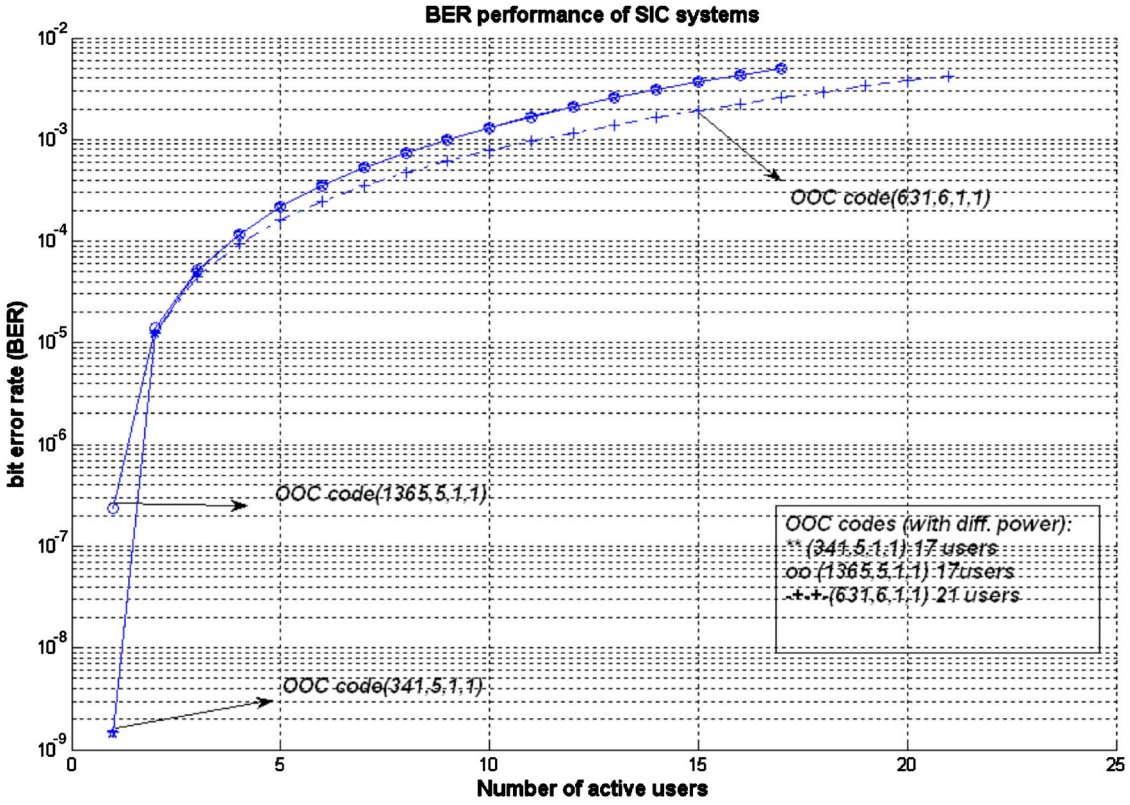

Fig. 4 Comparison of BER among different OOC codes.

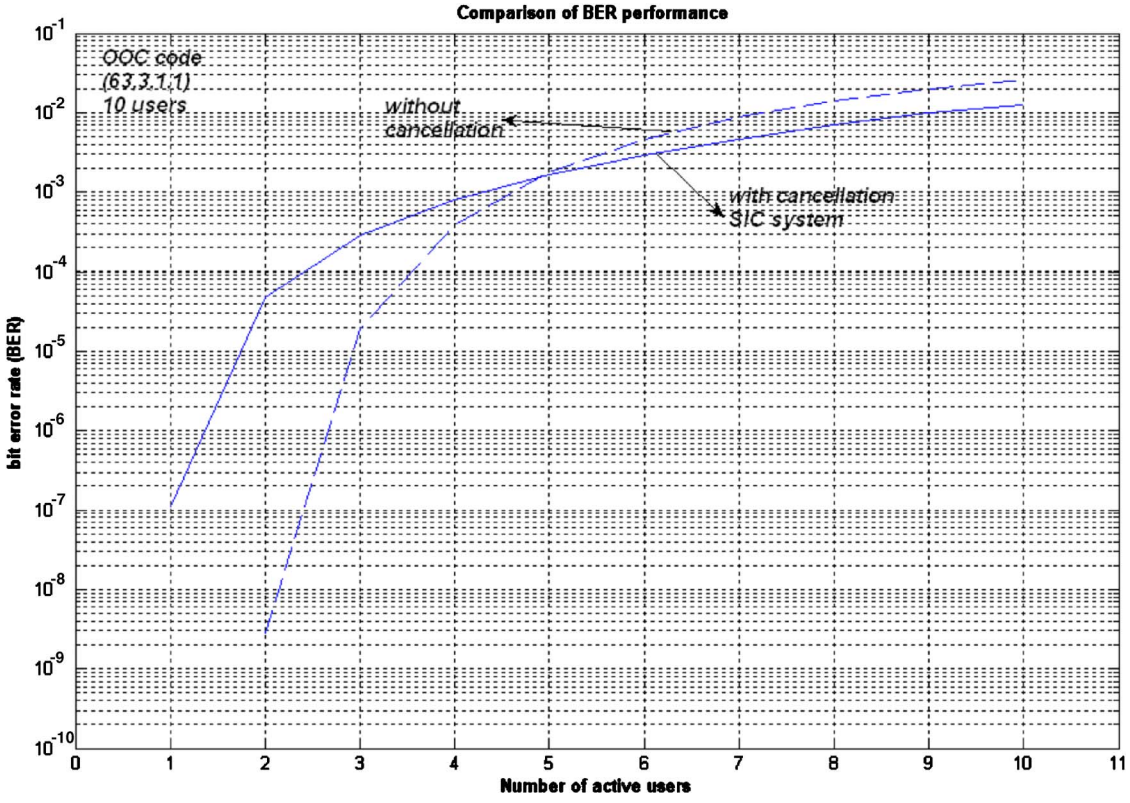

Fig. 5 Comparison of BER performance.

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