Interference Cancellation in Optical CDMA Systems via Advanced Binary Optical Logic Gate Elements

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ABSTRACT

In this article we present an all passive optical iterative interference cancellation method for optical CDMA. We propose the receiver structure based on advanced binary optical logic gates (ABOLGs). Since the performance bottleneck in optical communication systems is the conversion from optical to electronic domains for optical detectors, the interference cancellation has been performed in the optical domain. In incoherent optical communication systems, we have only the positive values for the optical signals. In the proposed system, we bypass the negative values using logic arrays. In the simulations we consider multiple access interference and neglect other sources of noise. Simulation results show that in the future optical systems, the interference can be eliminated completely using iterative methods in the optical domains.

INTRODUCTION

The recent developments in the worldwide web Internet and communication networks have widely increased data traffic. Moreover, they have increased the user demand for high-speed high-quality services with lower costs. In order to resolve the need for high data rates, optical networks have become efficient alternatives. This is due to the superior properties of optical fiber and possible high-speed optical signal processing.

In spite of the advantages of optical fiber, one of the important issues that limit the maximum achievable data rate in optical communication networks is converting optical data to the field of electronics in optical receivers. As the electronic devices are quite limited in maximum achievable data rate, the conversion from the optical to the electronic domain for optical detectors becomes the performance bottleneck in optical communication systems. In order to solve these problems and achieve higher data rates, an all-optical implementation of communication networks has become a challenging topic [1–3].

Some of the important multiple access approaches in optical fibers are wavelength-division multiple access (WDMA), time-division multiple sccess (TDMA), and optical code-division multiple access (OCDMA). In OCDMA, encoding involves multiplying the data bit by a code sequence in either the time domain, the wavelength domain, or a combination of both. The latter method is called two-dimensional coding [4]. Time domain encoding represents each bit as a spreading sequence of short pulses. In the wavelength domain, the spectrum of the light pulse is multiplied by the pseudorandom code. This method is applied for both coherent [3] and incoherent optical sources. Further discussions about OCDMA systems can be found in [5]. As our work is mainly about OCDMA in the time domain, in this article OCDMA refers to time domain CDMA.

OCDMA systems have many advantages. In OCDMA, there is no need to synchronize the users; also, the structure of the encoder and decoder is rather simple. There is another advantage of OCDMA compared to the WDMA and TDMA technologies: we can overload the multiaccess system, which improves the spectral efficiency. Also, differential quality of service (QoS) for multimedia applications can be achieved by using multilength and multiweight codes [6, 7]. Thus, the OCDMA scheme is suitable for passive optical networks (PONs) where more bandwidth and QoS will be needed. However, multiple access interference (MAI) is the dominant noise in OCDMA systems and is the limiting factor to system performance. In OCDMA, signals from different encoders are coupled, and a decoder receives the sum of encoded signals. If a given encoder transmits a signal, only the decoder with the same code is capable of receiving it. Undesired signals appear as noise to the decoder and is called MAI.

There are many research papers on reducing or eliminating the effects of MAI for OCDMA systems. Verdu [8] proposed and analyzed an optimum multiuser detector, which is a maximum-likelihood detector for an equiprobable channel input data. This optimum detector is too complex for practical OCDMA systems. In order to reduce the complexity of the optimum receiv-

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er, significant research efforts have been devoted to developing suboptimum receivers. Brandt-Pearce and Aazhang [9] proposed a multistage detector where at each stage the interference from the previous stage is estimated, and then a new decision for current stage is made. In [10], two blind and unblind multiuser detectors for OCDMA systems based on an expectation-maximization algorithm are proposed. These detectors have two stages; at the first stage, a soft estimation of the interference is obtained, and at the second stage, by knowing the interference, the input bit is detected. Interference cancellation schemes constitute another variant of multiuser detection that is used in OCDMA systems [14]. In this article, we demonstrate that by using an iterative approach in the optical domain, the MAI issue can be completely eliminated. Moreover, in order to have an optical interference cancellation, we make use of advanced binary optical logic gates (ABOLGs), which may be the future technology for optical computing.

The rest of this article is organized as follows. In the next section we introduce a typical OCDMA system that uses optical orthogonal codes (OOCs) as the signature sequence. We describe the iterative method for interference cancellation. The system that mitigates the MAI in the optical domain is then presented. We include simulation results. The article is concluded in the final section.

System Model

Since the incoherent fiber optic communication systems and fiber optic signal processors are modeled as positive signals, they use OCDMA with on–off pulses as signature sequences. In general, an $(L, w, \lambda_a, \lambda_c)$ optical orthogonal code (OOC) C is a family of (0, 1) sequences [3] of length L and weight w (number of 1s in the code) with auto and cross correlation constraints λ_a, and λ_c. For these codes, the *Johnson bound* states that [3]

$$(K+1) \le \frac{(L-1)(L-2)\ldots(L-\lambda)}{w(w-1)(w-2)\ldots(w-\lambda)}, \qquad (1)$$

where K is the number of user codes that can be produced, and $\lambda = \max\{\lambda_a, \lambda_c\}$. It is important to mention here that by increasing the cross-correlation value, the number of active users and thus the interference will be increased.

The OCDMA system considered in this article consists of N users communicating synchronously through the shared ideal channel using OOC codes and on-off keying (OOK) signaling. In this system, for transmitting bit 1, the corresponding OOC code is sent in the bit duration, and for transmitting bit 0, no pulse is sent in the bit duration. In a bit synchronous OCDMA, the received signal can be written as,

$$\mathbf{r} = \mathbf{bC}, \qquad (2)$$

where C is a matrix with signature columns with elements {0,1}, $\mathbf{b}$ is the user data vector as $\mathbf{b} = [b_1, b_2, \ldots, b_N]^T$, and $\mathbf{r}$ is the received signal in each chip.

The transmitted bits can be extracted at the receiver by using a correlator receiver. The vector $\mathbf{Y}$ that represents the output of the N correlator receivers can be written as

$$\mathbf{Y} = \mathbf{rC}^T = \mathbf{bCC}^T = \overbrace{w.\mathbf{b}.\mathbf{I}_N}^{\text{Desired term}} + \mathbf{b}\overbrace{\begin{bmatrix} 0 & \rho_{12} & \cdots & \rho_{1(N-1)} & \rho_{1N} \\ \rho_{21} & 0 & \cdots & \rho_{2(N-1)} & \rho_{2N} \\ \vdots & \vdots & & \vdots & \vdots \\ \rho_{N1} & \rho_{N2} & \cdots & \rho_{N(N-1)} & 0 \end{bmatrix}}^{\text{Multiple Access Interference term}}, \qquad (3)$$

where $\mathbf{I_N}$ is the identity matrix and ρ_{nm} is the cross correlation of the nth and mth codes.

For fiber optic signal processing, the OOC encoder and decoder can be established easily by an all-optical passive fiber tapped delay line [3]. In the OOC encoder, the input pulse is divided by w branches, and each pulse appears at the output at different times as depicted in Fig. 1a. The receiver structure is an all-optical implementation of a correlator receiver as shown in Fig. 1b. The delay amount in the decoder in each branch is the complementary value of the corresponding branch in the encoder.

In the following section, it is shown that by using an iterative method, we can remove the multiuser interference from the OCDMA system very effectively.

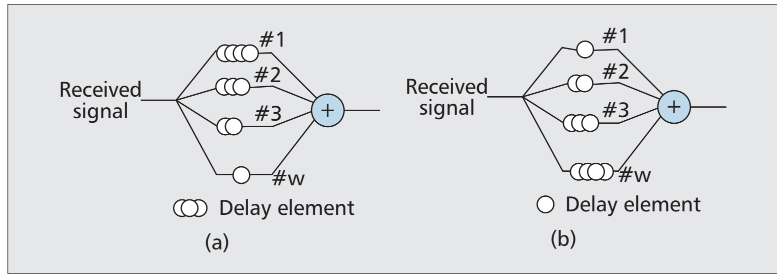

Figure 1. *a) An all-optical encoder; b) An all-optical decoder.*

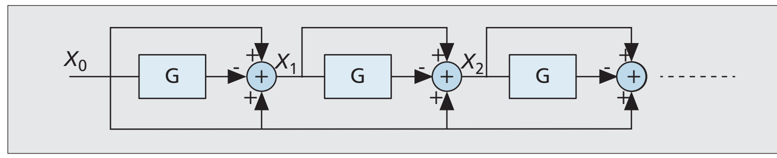

Figure 2. *The configuration of an iterative method.*

The Iterative Method for Interference Cancellation

For any system, the input and output signals are related as $\boldsymbol{y} = G\boldsymbol{x}$, where G is a known operator, $\boldsymbol{x}$ is the input data vector, and $\boldsymbol{y}$ is the output vector. At the receiver end we would like to reconstruct $\boldsymbol{x}$ from $\boldsymbol{y}$. This is possible if the inverse of G is known. Often it is difficult to find the inverse of the operator G. An iterative method can be used to approximate the inverse of G [11, 12]. The iterative method utilizes the operator G in each iteration and is given in the block diagram shown in Fig. 2.

If the input signs are the same, the absolute value of the sum is calculated from the adder unit while the output of the subtractor is zero. On the other hand, if the inputs have different signs, the output of the subtractor will be the absolute value of their difference while the output of the adder is zero.

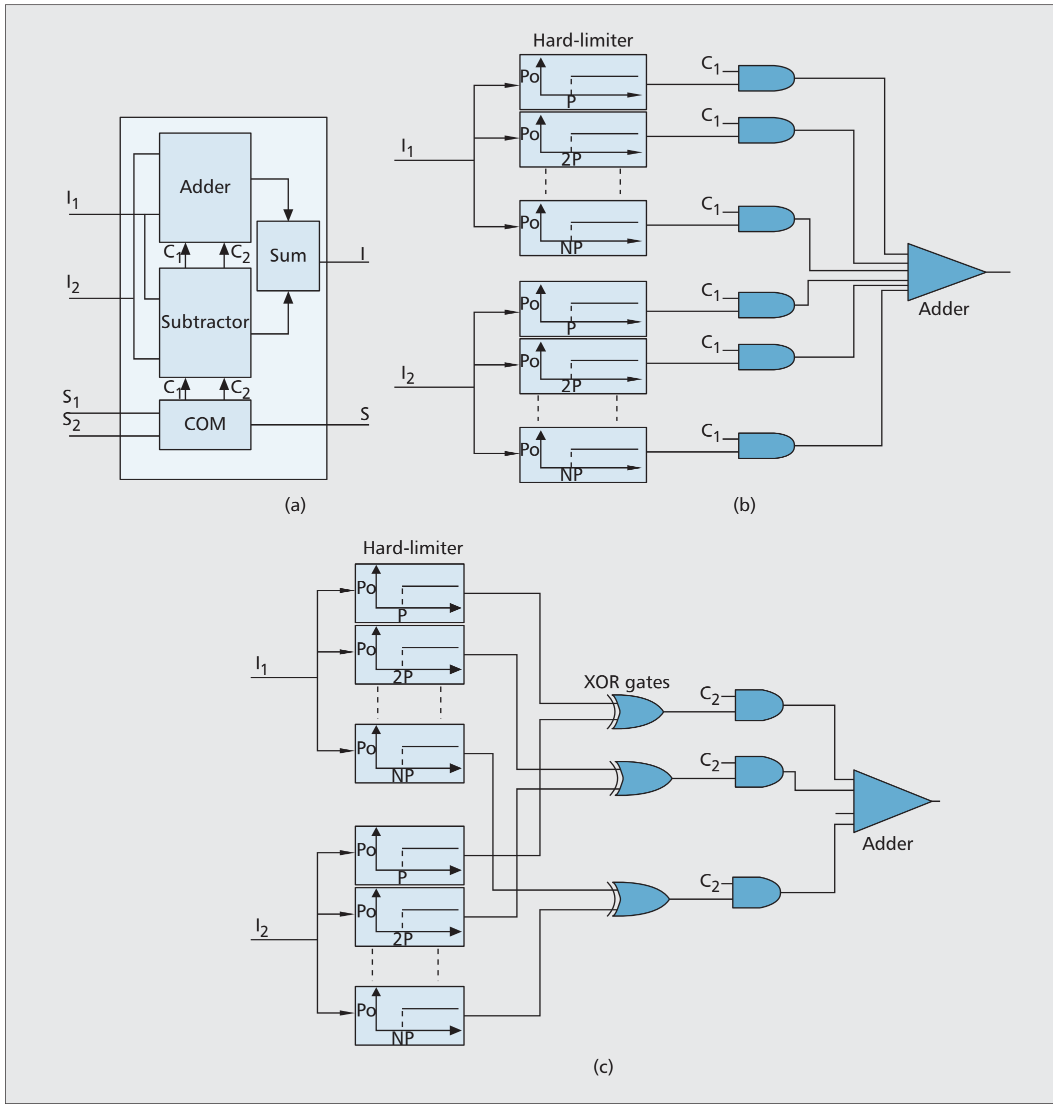

Figure 3. *a) The block diagram of the adder/subtractor; b) the block diagram of an all-passive optical adder; c) the block diagram of an all-passive optical subtractor.*

In a synchronous OCDMA system, the G operator is $\boldsymbol{C}.\boldsymbol{C}^T$, which consists of the signature encoder and the correlator decoder. In the following section, a new structure is proposed for the implementation of the iterative algorithm using optical logic gates.

Optical Implementation of the Iterative Method

In any incoherent optical processing, we have to make sure that we only process 1 and 0, and there are no negative numbers. Thus, for any processing, we need to discuss optical adders and subtractors. Consequently, we present the all-optical implementation of the iterative method for interference cancellation.

Optical Adder/Subtractor

The optical adder/subtractor in which we are interested is a block with four input and two output ports. Two of the four input ports (I_1, I_2) show absolute values of inputs, and the other two ports (S_1, S_2) are used to show the corresponding sign of the inputs. As shown in Fig. 3a, I_1 and I_2 are connected to an adder and a subtractor unit simultaneously, and the other two inputs (S_1, S_2) are connected to the comparator block (COM). If the input signs are the same, the absolute value of the sum is calculated from the adder unit, while the output of the subtractor is zero. On the other hand, if the inputs have different signs, the output of the subtractor will be the absolute value of their difference, while the output of the adder is zero. The activation and deactivation of the adder and subtractor units are done using two control signals (C_1, C_2). These signals are calculated using the following equations:

$$\begin{cases} C_1 = S_1^c.S_2^c + S_1.S_2 \\ C_2 = S_1.S_2^c + S_2.S_1^c \end{cases} \quad (4)$$

where ^{c} is the complement operator. Obviously, if the signs are the same, C_1 becomes 1; otherwise, it is 0. On the contrary, C_2 becomes active when the inputs have different signs and inactive

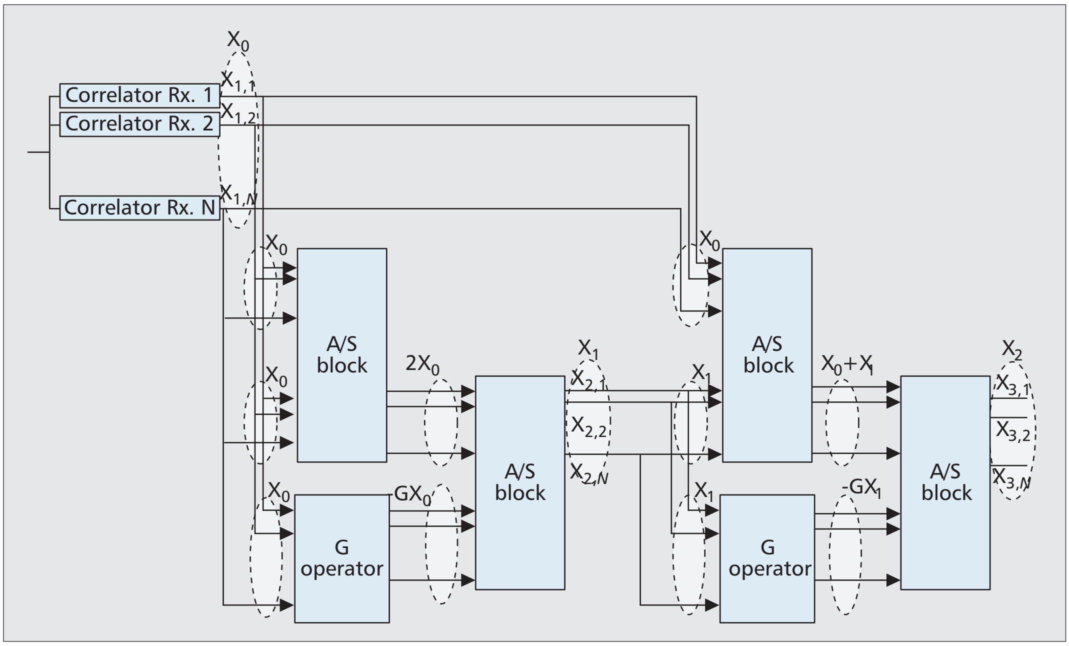

Figure 4. *The block diagram of the proposed system.*

From simulation results, we have shown that the proposed scheme can cancel the interference completely. After a sufficient number of iterations, the error probability is zero and the system is multiple access interference free.

when the signs are the same. Now we can discuss the details of the adder and the subtractor:

The adder block diagram is shown in Fig. 3b. In the first stage, the inputs go through N hard limiters. The characteristic functions of these hard limiters are shown in their blocks in Fig. 3b. In order to clarify the procedure, consider that the first input I_1 is equal to n_1P and the other input I_2 is equal to n_2P, where P is the received power of OOC pulses, and n_1 and n_2 are integers. Obviously, the first n_1 outputs of the first branch are equal to P_0 while the other outputs of this branch are zero. Similarly, the first n_2 inputs of the second branch are equal to P_0 while the rest of them are zero. The outputs of this stage are given to the optical AND gate, and if C_1 is equal to 1, the output of this stage will be the same as the output of the last stage. However, if C_1 is equal to 0, the output of this stage will be 0. Finally, the output of the AND gates are added together to yield the output.

The subtractor structure is shown in Fig. 3c. The first stage is the same as the adder. Assume that the input of the first branch I_1 is equal to n_1P and the input of the second branch I_2 is equal to n_2P. The outputs of the first stage are the same as the output of the first stage in the adder block. In the second stage, the corresponding outputs of the first and second branches are XORed. In this example, the outputs of $|n_1 - n_2|$ XOR gates are P_0 and the rest are zero. The outputs then go through the AND gates with C_2 in order to activate or deactivate this block. If C_2 is equal to 1, this block is active; otherwise, it is inactive. Finally, the outputs are added together to yield the output.

Now, we must calculate the sign of the output signal. If both inputs are positive or negative, the sign must be the same as the input sign. Otherwise, we must compare the absolute values. If the first input signal is higher than the second one, the sign must be the same as the sign of the first input. Otherwise, the sign value is the same as the sign value of the second input. In order to compute the sign bit of the subtractor, we make use of a bitwise AND between the comparator output and the output results obtained by the XOR gates.

Block Diagram of the Optical Iterative System

The system shown in Fig. 2 is implemented optically as shown in the block diagram of Fig. 4. The output of the decoders are $x_{i,j}$ where i and j represent the decoder and the iteration numbers, respectively. X_i is the vector that represents the outputs of all decoders and is defined as $\mathbf{X_i} = [x_{1,i}, x_{2,i}, \ldots, x_{N,i}]^T$, where N is the number of users. It should be noted that the decoder output consists of two parts, the absolute value and the sign parts. The outputs of the decoders enter the adder/subtractor and the G operator. The A/S block consists of N adder/subtractor blocks.

As shown in Fig. 5, the G operator is a N-input/N-output structure that consists of OOC encoders and decoders. For the optical implementation, the input signal in each branch passes through a hard-limiter. The output of the ideal hard-limiter is equal to 1 if the input is greater or equal to the code weight. Otherwise, the output of the ideal hard-limiter is equal to '0'. The outputs of the hard limiters are multiplied by the corresponding signature codes and then they are added up. The output of the adder is again multiplied by C^T. The outputs of the correlator are then inverted; this inversion is performed in order to implement the subtraction in the iterative method.

Simulation Results

This section is devoted to simulation results, which show the interference cancellation using the iterative method implemented optically.

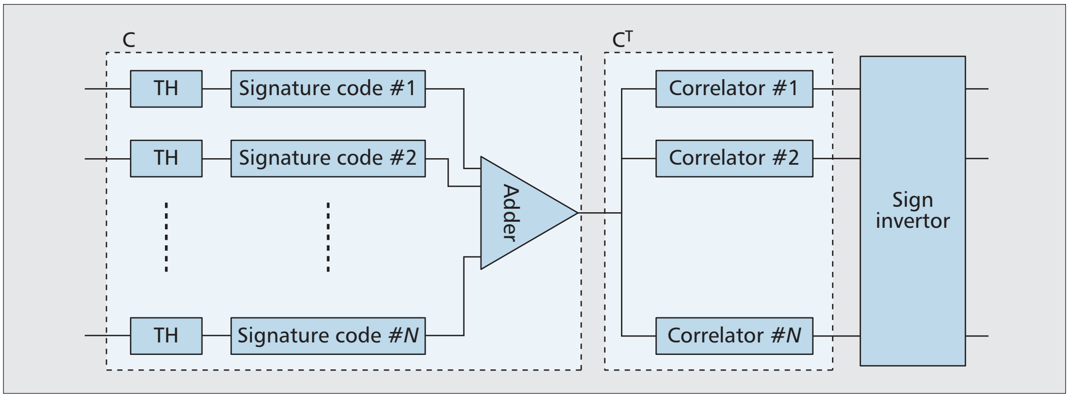

Figure 5. *The G operator block diagram.*

Figure 6a shows the bit error rate (BER) vs. the iteration number for the OOC codes with the length $L = 32$ and weight $w = 4$. Fig. 6b shows the BER, obtained by simulations, due to the proposed receiver vs. the number of users and number of iterations. We can verify that the BER decreases when either the number of users N decreases or the number of iterations increases. Moreover, Fig. 6b shows that the BER strictly decreases by increasing the number of iterations. Hence, the MAI noise is cancelled completely after sufficient number of iterations.

Conclusions

An iterative interference cancellation system based on all-passive optical processing is proposed in this article. We introduce a new adder/subtractor structure that add and subtract two signals optically using ABOLG, which may be part of the future all-optical networks. Using this structure, we can implement an iterative method for interference cancellation in optical domain. From simulation results, we have shown that the proposed scheme can cancel the interference completely. After a sufficient number of iterations, the error probability is zero and the system is multiple access interference free. Moreover, we can apply this method in multiclass OCDMA systems [6, 13] to mitigate interference and enhance the capacity of such systems.

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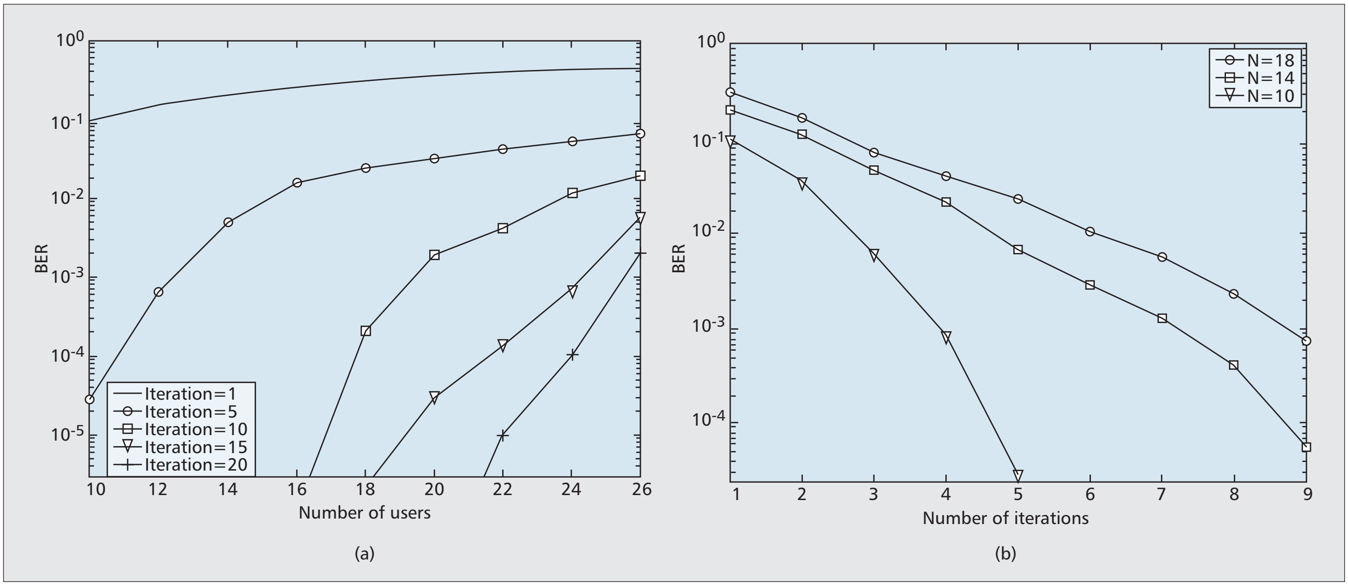

Figure 6. *a) The error probability vs. the iteration number for OOC codes (*L = 32, w = 4*); b) The error probability vs. the number of users and the number of iterations.*

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Biographies

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