Reducing the Hardware Complexity and Processing Time of Optical Parallel Interference Cancellation

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Summary
The successful of parallel interference cancellation (PIC) to reduce the multiple access interference in wireless CDMA communication systems has motivated the communication community to investigate the potential of PIC in the optical CDMA domain. However, the drawback of PIC in optical domain is the increase in demand for hardware in each receiver. As a result, it requires more complex hardware, higher processing time and cost. The hardware complexity increases in the receiver side of Optical PIC (OPIC) when the number of transmitter (users) increases which may require the upgrade of the entire system. To overcome the mentioned problem, a new technique is proposed which is based mainly on the conventional OPIC referred as One Stage OPIC (OS-OPIC).Optical Orthogonal Code (OOC) is adopted as signature sequence for the performance analysis and new expression for the error probability is derived. The results show that the proposed method is effective to reduce the hardware complexity, processing time and cost while maintaining the same bit error probability at the cost of increasing the threshold value.
Key words:
Optical Code Division Multiple Access (OCDMA), Multiple Access Interference (MAI), Optical Parallel Interference Cancellation (OPIC), One Stage OPIC (OS-OPIC).

1. Introduction

In the past two decades, we have seen an increasing demand for networks with higher capabilities at lower cost. This demand is fueled by many different factors. The tremendous growth of the internet has brought more users online, consuming large amounts of bandwidth due to data transfers involving video and image. These factors are deriving the need for more bandwidth for networks as well as new network services. To fulfill the demands for bandwidth and to deploy new services, new technology must be deployed and fiber optic is one such key technology. Fortunately, the advanced developments in fiber optics for the past 20 years have made the use of optical fiber as transmission media in such systems possible. Optical fiber offers several advantages over the traditional media (e.g. twisted wire pair and coaxial cable). It offers virtually unlimited bandwidth and is considered as the ultimate solution to deliver broadband access to the last mile. It also offers a much lower attenuation factor where optical signals can be transmitted over very long distances without signal regeneration or amplification. In addition, many channels can be multiplexed to share the same fiber optic medium, thus reducing the number of links required and the cost to end users. To share the available bandwidth offered by fiber optic, optical multiplexing techniques have to be employed to exploit full system transmission capacity. TDMA and WDMA have been extensively used in fiber communication systems to allocate the available bandwidth among the users. However, both of them present significant drawbacks in local area systems requiring large number of users [4]. Optical Code Division Multiple Access (OCDMA) [1-4] offers an attractive alternative for local area networks where the traffic tends to be bursty. Because such system offers several advantages in local area networks. Firstly, OCDMA allows simultaneous users to send their data asynchronously with no waiting time [3] through the assignment of unique signature sequence. It also offers strong security in the physical layer. As a result, OCDMA receives substantial attention for the use in the LAN. In OCDMA systems, the Multiple Access Interferences (MAI) [2] is the ultimate limit in the system performance. MAI increases in the conventional OCDMA system with the number of the simultaneous users and severely limits the capacity of the system. It was shown that, in noncoherent optical direct detection CDMA the use of unipolar pseudo-orthogonal code that have good correlation properties (i.e. high autocorrelation peaks and low cross-correlation) are needed to reduce the effect of MAI. Research on the OCDMA systems led to the invention of a few families of code such as optical orthogonal codes (OOC) [1] and prime sequence codes [3]. However, recent studies show that, an OCDMA system cannot be designed by considering the properties of the code only, the detection

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technique also plays an important role and should be addressed. Due to this, several techniques appeared in the literature aiming at lowering the effect of MAI [2][6][7]. In particular, Optical Parallel Interference Cancellation (OPIC)[7] has been used in OCDMA systems to reduce the effect of MAI, it is well known that the latter is effective to reduce the power of MAI and upgrade the performance of the conventional OCDMA receiver[1][2]. The OPIC system is effective to mitigate the power of MAI and improve the performance of the system. However, the demand for hardware in each receiver side results in increasing the complexity, cost and processing time. The need for hardware in the receiver side increases as the number of user increases which may require the upgrading of the hardware used in each receiver of the OPIC system. Due to this, conventional OPIC system is not straightforward for heavy load local area network which includes a large number of users. To overcome these difficulties, we propose a novel technique which essentially based on the conventional OPIC namely, One Stage OPIC (OS-OPIC). The performance of the proposed method is compared to the conventional OPIC. Software simulation is used to compare the results. The results show that the proposed method manages to reduce the hardware complexity and eventually the cost while maintaining the same performance of OPIC at the cost of threshold value.
This paper is organized as follows; general information about the OCDMA system is given in section 2. Section 3 demonstrates the main concept of the conventional OPIC. Section 4 discusses the proposed method .i.e. OS-OPIC. Theoretical analysis and new expression of the probability of error is considered in Section 5. Section 6 discusses the simulation results of the conventional OPIC and OS-PIC.

2. OCDMA System

OCDMA is the technique that attracts the attention of most researchers due to the tremendous advantages offered by the system. Different schemes have been proposed since the early implementation of the OCDMA system and various families of codes have been invented due to the natural different between the Radio Frequency (RF) systems and the optical domain. In this section, general survey will be presented including the classification of OCDMA, the most studied code and the OCDMA network. Furthermore, we will focus on the techniques that we are going to consider during this work.

2.1 Synchronous OCDMA

In OCDMA systems, both synchronous and asynchronous systems have been investigated [9]. In general, synchronous accessing schemes, with rigorous transmission schedules produce more successful transmissions than asynchronous techniques where network access is random and collisions occur. However, the performance of synchronous OCDMA system is severely limited by the Multiple Access Interference (MAI) [2] originating from other users trying to use the medium simultaneously.

2.2 Incoherent OCDMA Systems

The Optical CDMA communication system can be all-optical or partly optical. In a partly optical CDMA system, at least the communication channel is an optical. There are two basic categories of optical CDMA systems, coherent and incoherent. The all-optical CDMA system is usually an incoherent system (Fig.1). In the incoherent systems, Direct Detection (DD) receiver is used. In DD systems, at the transmitter, the information signal is intensity modulated to produce a series of optical pulses. Signal detection in these systems is equivalent to power measurement, i.e. on-off keying ("full" power for transmitting a mark, zero power for space). These systems are modeled as positive systems, i.e. a system that cannot manipulate its signals to add to zero, since optical power cannot be negative. In positive systems, unipolar codes must be used. Whenever an information "1"bit is to be transmitted, a whole code sequence consisting of "0"s and "1"s is transmitted. Information "0"bit is not encoded.
At the receiver side, the received signal is detected by a photodiode which converts the optical signal into an electric baseband signal. In general, Incoherent system is the area of research that attracts the most group of researcher up to now due to ease implementation of the direct detection. In this investigation we will consider the Incoherent Direct Detection fiber optic CDMA.

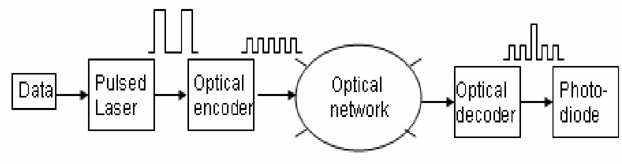

Fig. 1 Incoherent OCDMA

2.3 Optical Orthogonal Codes (OOC)

According to the natural different between wireless and optical domain, code used in wireless CDMA is inapplicable in optical CDMA. This is because the optical signal is equivalent to the instant power which is nonnegative. As a result, only unipolar sequences consisting of [0, 1] values can be used for optical CDMA systems. Due to this, research on OCDMA led to few families of codes such as Optical Orthogonal Code (OOC) [1] and prime codes [3]. The OOC will be considered throughout this paper. An optical orthogonal code (OOC) which is characterized by $(L, w, \lambda_a, \lambda_c)$ is a family of [0, 1] with length L and weight w (number of marks). It possesses good properties of autocorrelation and cross correlation (high autocorrelation and low cross correlation, the good auto-correlation ease the detection of the desired signal, and the low cross-correlation reduces MAI in the network.). In general, for $(L, w, \lambda_a, \lambda_c)$ the upper bound on the cardinality N of a set of OCDMA codes with unity autocorrelation and unity cross-correlation is given by:

$$N = \left[\frac{L-1}{w(w-1)} \right]$$

Where the brackets denote the integer portion of the real value. In this work, we will consider the OOC as signature sequence

2.4 Optical CDMA network

This part discusses the Incoherent, Synchronous Direct Sequence Optical CDMA (DS-OCDMA) employing on-off keying (OOK) as a common method of modulation to transmit independent and equiprobable binary data upon an optical channel. Assume that there are N optical encoder and decoder pairs (users) in the fiber-optic CDMA system under investigation as shown in Fig. 1. Each user in this system is assigned a unique optical signature code with desired distinguishable correlation properties, so simultaneous users are allowed to send their data asynchronously through this code. The signature sequence, $C_k(t)$ of the k^{th} user is given by:

$$c_k(t) = \sum_{j=1}^{L} d_{k,j} P(t - jT_c) \quad (1)$$

Where $P(t)$ is the unit rectangular pulse with duration T_c and $d_{k,j}$ is the k^{th} periodic sequence of binary optical pulses (0,1). Here, a data bit one is encoded at an optical encoder with intended destination signature code. Data bit zeros are not encoded.

The N output signals are combined at the coupler and are transmitted to all receivers. The received signal $r(t)$ is the sum of signals transmitted by all active users and can be expressed by:

$$r(t) = \sum_{k=1}^{N} b_k(t) c_k(t - \tau_k) \quad (2)$$

Where τ_k, with $0 \le \tau_k \le T_c$, is the time-delay associated with k^{th} user and $b_k(t)$ is the bit (0, 1) of the k^{th} user.

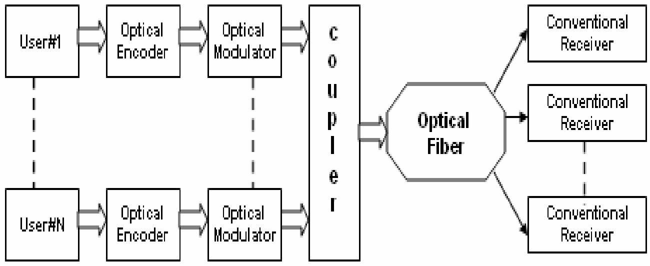

Fig. 2 Optical Code Division Multiple Access

2.5 Conventional OCDMA Receiver

Conventional OCDMA receiver or the correlation receiver (Fig. 3) has been studied in several articles in the literature [1]-[3]. It operates by enhancing the desired user while suppressing other users considered as interference. In this receiver, each optical decoder correlates its own signature code with the received optical data sequences to generate correlation functions. Optical data sequences arriving at the decoder with unmatched signature code result in cross-correlation functions which, in turn, are considered as interference. Threshold detector is used to compare the correlation value to the Th in order to extract the transmitted data. In [2] it was shown that, in the absence of thermal noise and shot noise, an error can only occur when the data bit is zero and the interference from the other users exceeds the threshold. Due to this, MAI is the major reason for the system degradation in the conventional OCDMA receiver. It is well known that, MAI severely threatens the performance of the conventional OCDMA receiver and limits the capacity of the system. In order to study the effect of MAI, we consider that all the optical and electronic components are ideal, i.e. errors are only due to MAI.

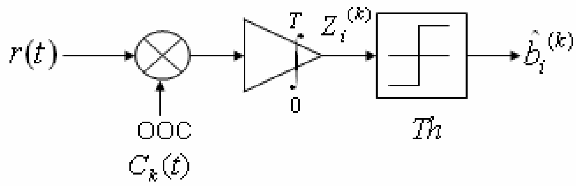

Fig. 3 Conventional OCDMA receiver

3. Optical Parallel Interference Cancellation

Parallel Interference Cancellation (PIC) has been widely deployed in the area of wireless communication systems [8]. In recent years, the use of PIC in the optical domain also has been investigated for the sake of reducing the effect of MAI [7] in the OCDMA system.

The basic idea behind OPIC (Fig.3) is to estimate the interference due to all non-desired users. Then the estimation $\hat{b}_i^{(j)}$ of the non-desired user # j is spread by the corresponding code sequence. The estimated interference is then rebuilt and removed from the received signal $r(t)$ (2).
The bit sent by the desired user is then extracted by a conventional correlation receiver. The signal applied to the entry of the desired receiver (let us assume the desired user is the user #1) can be written as follow:

$$s(t) = r(t) - \sum_{j=2}^{N} \hat{b}_i^{(j)} c_j(t)$$

(3)

Where: $\hat{b}_i^{(j)}$ and $c_j(t)$ are the estimated data and the code sequence of user # j respectively. The next step is the detection and estimation of the desired user data, by conventional correlation method. The decision variable for the desired user #1 is:

$$Z_i^{(1)} = W.b_i^{(1)} + \sum_{j=2}^{N} (b_i^{(j)} - \hat{b}_i^{(j)}) \int_0^T c_1(t).c_j(t)dt$$

(4)

In the above equation, the second term is called the interfering term and we referred to as I . Errors in the OPIC are due to this term.
Unlike the conventional OCDAM receiver, here we have errors only if the desired user sends data equal to 1 [7] and the interference due to other simultaneous user cause an error. On the other hand, I is always negative (if we have wrong detection for the non-desired user i.e. if the non-desired user sends data 0 [2]) or null (if there are no errors during the extraction of the non-desired user's data). Then, I is an integer number corresponds to the number of interfering users. Accordingly, if the number of interfering users is equivalent to W , definitely we have wrong decision on the desired user, no matter the value of threshold. So to reduce the number of errors for the desired user, one can choose the minimum threshold value. On contrary, if we set the threshold of the desired user to the maximum, one interfering user could produce error.

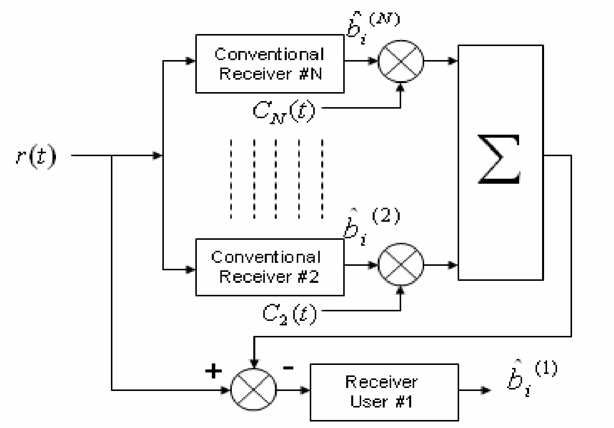

Fig. 4 Optical Parallel Interference Cancellation

4. The Proposed Method

In the previous section, the main concept of the conventional OPIC has demonstrated. OPIC is effective to reduce the effect of MAI. However, the need for a receiver with less hardware complexity is one of the main problems that hampered the implementation of OPIC in local area networks with heavy load. For instance, the previous section showed that to extract the data of user#1 we have to extract the data of $N-1$ non-desired user which is very complex and tedious in network that include large number of users. Besides, the hardware complexity increase when new users are added to the network which reveals that, OPIC is not practical in the LAN.
To overcome the stated problem One Stage Optical Parallel Interference Cancellation (OS-OPIC) which is based on the conventional OPIC is demonstrated in this section and its performance is compared to the conventional one.

The idea of OS-OPIC is quite simple and very effective in term of cost and complexity. Unlike the OPIC in which we have to extract the data of all non-desired user in order to recover the desired user's data, OS-OPIC operates by providing the estimation $\hat{b}_i^{(k)}$ of only one non-desired user referred as user # k . Then the estimated data is spread by corresponding code sequence, i.e., $c_k(t)$ and removed from the received signal $r(t)$.

The bit sent by the desired user is then extracted by a conventional correlation receiver. The signal applied to the entry of the receiver can be written as follow:

$$s(t) = r(t) - \hat{b}_i^{(k)} c_k(t)$$

(5)

Where: $\hat{b}_i^{(k)}$ and $c_k(t)$ are the estimated data and the code sequence of non-desired user $\#k$ respectively. In this method, there is probability of error in both cases i.e. if the desired user sends data "0" or sends data "1" however, from the theoretical analysis and the simulation results, we could observe that, errors could occurs mainly if the desired user sends data equivalent to "0". Still there is probability of error when the desired user sends data "1" according to specific conditions. However, the achieving of these conditions at the same time is very hard as we will see later. Due to this, to obtain better performance, threshold of the desired user should be set to the maximum contrary to the conventional OPIC but we managed to get the same Bit Error Rate (BER) as it shown in the results.

5. Theoretical Analysis

We analyze the performance of the proposed system under the following assumption: we will consider the non-coherent, synchronous Direct Sequence system employing on-off keying (OOK) as a method of modulation; OOC is considered for N simultaneous users. Moreover, user #1 is chosen to be the desired user and that user $\#k$ is the non-desired and all the users have the same transmitting energy so there is no strong interference. We consider the case of full synchronization ($\tau_k = 0$).

Furthermore, assume that the threshold level of the non-desired user receiver is given by $S_n (0 < S_n \leq w)$ and the threshold level for the desired one, i.e. user #1 is given by $S_d (0 < S_d \leq w)$.

The signal applied to the entry of the desired user can be written as follow:

$$\begin{aligned} s(t) &= r(t) - \hat{b}_i^{(k)} c_k(t) \\ &= \left[b_i^{(1)} c_1(t) + b_i^{(k)} c_k(t) + \sum_{\substack{j=2 \\ j\neq k}}^{N} b_i^{(j)} c_j(t) \right] - \hat{b}_i^{(k)} c_k(t) \\ &= b_i^{(1)} c_1(t) + \left(b_i^{(k)} - \hat{b}_i^{(k)}\right) c_k(t) + \sum_{\substack{j=2 \\ j\neq k}}^{N} b_i^{(j)} c_j(t) \end{aligned} \tag{6}$$

Before the last detection bloc, the decision variable for the desired user is:

$$\begin{aligned} Z_i^{(1)} &= w b_i^{(1)} + \left(b_i^{(k)} - \hat{b}_i^{(k)}\right) \int_0^T c_k(t) c_1(t) dt + \sum_{\substack{j=2 \\ j\neq k}}^{N} b_i^{(j)} \int_0^T c_j(t) c_1(t) dt \\ &= w b_i^{(1)} + H + I \end{aligned} \tag{7}$$

The second term appears in (7) is due to the non-desired user $\#k$ referred as H and the third term is undetected users referred as I.
We will consider 2 cases:

Case (1): If the desired user, i.e. (user #1) sends data "0"
Let P_0 be the error probability on data $b_i^{(1)} = 0$ of the desired user.
We have error if: $H + I \geq S_d$
In this case $H = -1$ (wrong decision) or $H = 0$.

If $H = -1$, then $-1 + I \geq S_d$ accordingly the probability of error if the desired user send data 0 is:

$$P_{0(H=-1)} = \frac{1}{2} \sum_{i=S_d+1}^{N-2} \binom{N-2}{i} \left(\frac{w^2}{2L}\right)^i \left(1 - \frac{w^2}{2L}\right)^{N-2-i} \tag{8}$$

If $H = 0$, then we have error on user #1 if $I \geq S_d$. We then obtain:

$$P_{0(H=0)} = \frac{1}{2} \sum_{i=S_d}^{N-2} \binom{N-2}{i} \left(\frac{w^2}{2L}\right)^i \left(1 - \frac{w^2}{2L}\right)^{N-2-i} \tag{9}$$

Then the probability of error when the desired user sends data 0 can be written as follow:

$$P_0 = \left\lfloor Q \times P_{0(H=-1)} \right\rfloor + \left\lfloor (1-Q) \times P_{0(H=0)} \right\rfloor \tag{10}$$

Where Q is the error probability on $b_i(k) = 0$ of the non-desired user and can be demonstrated from [1] [2] as follow:

$$Q = \frac{1}{2} \sum_{i=S_n}^{N-2} \binom{N-2}{i} \left(\frac{w^2}{2L}\right)^i \left(1 - \frac{w^2}{2L}\right)^{N-2-i} \tag{11}$$

Case 2: If the desired user (user #1) sends data "1":

We have error if: $w + H + I < S_d$

Let us assume that, the following conditions are verified:

- ⇨ The threshold value is equal to the weight w, i.e. $S_d = w$.
- ⇨ User k is interfering user so that $H = -1$.
- ⇨ The value of I is equal to zero.

Then, the probability of error that user # k is an interfering user can be written as follow:

$$Q^* = \frac{1}{2}\sum_{i=S_n}^{N-1}\binom{N-1}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-1-i}$$
(12)

Based on the above conditions we obtain here the error probability when the desired user sends 1:

$$P_1 = \frac{1}{2}\left[Q^* \sum_{i=S_d-1}^{N-2}\binom{N-2}{i}\left(\frac{w^2}{2L}\right)^i\left(1-\frac{w^2}{2L}\right)^{N-2-i}\right]$$
(13)

In general, the probability of error for one stage Optical PIC is:

$$P_T = P_0 + P_1 \quad (14)$$

6. Simulation Results and Performance Comparison

Fig. 5 and Fig.6 show the BER versus the threshold values for the conventional OPIC and the proposed method OS-OPIC using different number of users. The parameters of OOC are: L=341, 97 and w=5, 4 for 17 and 8 simultaneous users respectively.

From the figures, we could observe that the theoretical line of the OS-OPIC correlates with the simulation one. We could then validate the results for further study in this topic. Also observe that, by using the proposed method, a lower BER is obtained when the maximum threshold is selected. In contrast, we can obtain better performance for the conventional OPIC if we use the minimum threshold value. The BER for both receivers is almost the same but as cost of threshold.

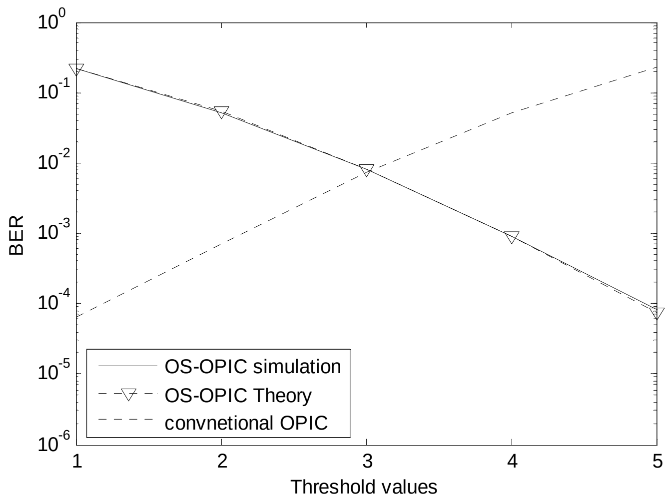

Fig. 5 BER for the OPIC and OS-OPIC for 17 users, code OOC, w=5, L=341 for different threshold values

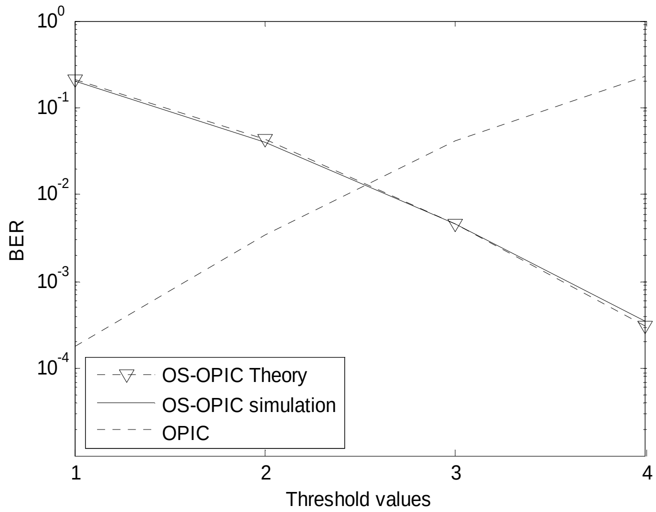

Fig. 6 BER for the OPIC and OS-OPIC for 8 users, code OOC, w=4, L=97 for different threshold values

7. Conclusion

MAI is one of the major problems that hamper the implementation of OCDMA system. OPIC is effective to mitigate the effect of MAI. However the hardware used in each receiver side makes the system indesirable which results in increase the complexity, processing time and eventually the cost. In this work, one stage Optical Parallel Interference Cancellation was proposed to alleviate the stated problems. This method is based on the conventional OPIC receiver.

A general equation for OS-OPIC receiver has been established. This equation was then validated by the simulation results.

The paper shows that, the OS-OPIC is able to reduce the hardware complexity while maintaining the same performance of the conventional OPIC receiver despite the cost of threshold value.

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