New Receiver Architecture Based on Optical Parallel Interference Cancellation for the Optical CDMA

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Abstract—**Optical Code Division Multiple Access (OCDMA) is considered as the strongest candidates for the future high speed optical networks due to the large bandwidth offered by the system, Based on the vast amount of bandwidth, OCDMA systems have received much attention in fiber optic Local Area Networks where the traffic is typically bursty. However, Multiple Access Interference (MAI), which is originated from other simultaneous users, severely limits the capacity of the system. Optical Parallel Interference Cancellation (OPIC) has been used to reduce the effect of MAI. However, the usage of OPIC in OCDMA systems will increase the demand for hardware complexity which results in higher processing time and cost. The hardware complexity increases in the receiver side of OPIC when the number of transmitter (users) increases. To overcome these difficulties, an efficient method is presented in this paper called, One Stage Optical Parallel Interference Cancellation (OS-OPIC) which is based mainly on the OPIC. Optical Orthogonal Code (OOC) is adopted as a signature sequence for the performance analysis and a new expression for the error probability is derived. It is shown 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 threshold value.**

Index Terms—**OCDMA, MAI, OPIC, OS-OPIC.**

I.INTRODUCTION

There has been growing interest in using the Optical Code Division Multiple Access (OCDMA) technique for the next generation high-speed optical fiber networks [1-4]. OCDMA is attractive technology because optical fiber provides huge a mount of bandwidth and Code Division Multiple Access (CDMA) offers the flexibility needed in the bursty environment. Moreover, 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 allocate the available bandwidth offered by fiber optic, multiplexing techniques should be used. Traditional fiber optic communication systems use either TDMA or WDMA schemes to allocate bandwidth among multiple users. Unfortunately, both present significant drawbacks in local area systems requiring large number of users [4]. In contrast, OCDMA offers an interesting alternative to frequency and time based multiple access methods for the next generation high-speed optical fiber networks. Optical CDMA can operate asynchronously, without centralized control and it does not suffer from packet collisions. In fact, OCDMA system offers several advantages in local area networks. First of all, 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 because OCDMA schemes do not achieve their multiple access property by division of the transmission of different users in either time or frequency, but instead make a division by assigning each user a different code. An OCDMA user inserts its code or address in each data bit and asynchronously initiates transmission. Thus, this modifies its spectrum appearance in a way recognizable only by the intended receiver. Otherwise, only noise-like bursts are observed.

However, Multiple Access Interferences (MAI) [2] is the ultimate limit in the system performance. MAI 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. Researches on the OCDMA systems have 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 technique also plays an important role and should be addressed as well. Due to this, several techniques appeared in the literature aiming at lowering the effect of MAI [2][5-7]. In particular, Optical Parallel Interference Cancellation (OPIC)[7] has been used in OCDMA systems to reduce the effect of MAI. The latter is effective to reduce the power of MAI and upgrade the performance of the CCR. The drawback of OPIC is that, it increases the demand for hardware, resulting into more complexity and higher processing time. The need for hardware in the receiver side increases as the number of user increases which may require the upgrading of the entire 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, a new technique is proposed in this letter which is based on the conventional OPIC namely, One Stage OPIC (OS-OPIC). The expression of error probability for the new design is derived and the software simulation is used to evaluate and verify the performance. In addition, the performance of the proposed method is compared to the conventional OPIC. The results reveal that, the proposed method is effective to reduce the hardware complexity, processing time and eventually the cost while maintaining the same performance of OPIC at the cost of increasing the threshold value.

This paper is organized as follows: a general background 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.

II.BACKGROUND

Code Division Multiple Access (CDMA) is the most recent multiple accessing technique in the optical domain. The key advantage of using CDMA is that, CDMA can be encoded and decoded in the optical domain without converting the signal to electronic unless it is desired. This is extremely important because the electronic processing is much slower than the optical transmission rate. Accordingly, OCDMA is the technique that attracts the attention of the most research group up to now. In this section, general survey will be presented including the detection of OCDMA, the OCDMA code and the OCDMA network.

increases in the Conventional Correlation Receiver (CCR) with the number of the simultaneous users and severely limits the capacity of the system. It was shown

A. Detection Schemes of OCDMA:

In OCDMA systems, the detection schemes affect the design of transmitters and receivers. In general, there are two basic detection techniques namely coherent [10] and incoherent [9].

Optical CDMA communication system can be all-optical or partly optical. The information bits may be originally optical or electrical. The all-optical CDMA system is usually an incoherent system. On the other hand, a system consisting of unipolar sequences in the signature code is called incoherent system. A system that uses bipolar codeword is called a coherent system. Since coherent is phase sensitive, the use of such techniques will of course be more difficult than that of incoherent ones. In this work, the incoherent OCDMA system will be considered.

B. Incoherent OCDMA Systems:

Incoherent OCDMA (Figure 1) [9] is the area of research that has attracted the attention of most research groups up to now due to the practical ease of implementing direct optical detection based systems. In these systems, Direct Detection (DD) receiver is used. At the transmitter part, the information signal is intensity modulated to produce a series of optical pulses. 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.

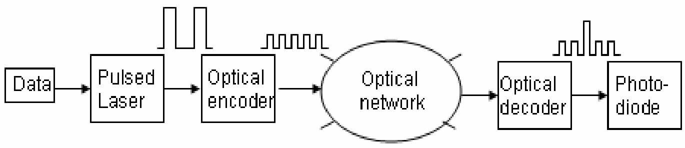

Figure1. Incoherent OCDMA system

C. Synchronous and Asynchronous OCDMA:

OCDMA system may be Synchronous (S-OCDMA) or Asynchronous [11]. In a Synchronous system the bits and chips are synchronized. In the Asynchronous system the bits are not synchronized but the chips may be transmitted synchronously.

Both Asynchronous and Synchronous OCDMA techniques have been examined. Each of which has its strengths and limitations. In general, since synchronous accessing schemes follow rigorous transmission schedules, they produce more successful transmissions (higher throughputs) than asynchronous methods where network access is random and collision between users can occur. It is shown that, in application that requires real time transmission, such as voice or interactive video, synchronous accessing techniques are most efficient. When the traffic tends to be bursty in nature or when real time communication requirements are relaxed, such as in data transmission or file transfers, asynchronous multiplexing schemes are more efficient than synchronous multiplexing.

D. Optical Orthogonal Code (OOC):

OCDMA systems like wireless CDMA in which, each user is assigned with unique signature sequence called codeword. The choice of the codewords, the signature sequence, is a key to any successful CDMA scheme, either electrical or optical. However, codes based on [–1, +1] signals, which are used in wireless CDMA system, cannot be applied in optical system 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 OCDMA systems. Researches on OCDMA have led to few families of codes such as Optical Orthogonal Code (OOC) [1] and prime codes [3]. 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) and good properties of autocorrelation and cross-correlation (high autocorrelation and low cross correlation). The good auto-correlation facilitates the detection of the desired signal, and the low cross-correlation reduces MAI in the network.

The maximum number of users 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. The OOC will be considered as a signature sequence.

E .Optical CDMA Network:

Assume that there are N optical encoder and decoder pairs (users) in the fiber-optic CDMA system under investigation (Figure 2). 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:

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

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).

In the transmitting side, a data bit one is encoded at an optical encoder with intended destination signature code. Data bit zeros are not encoded. The encoded data code is then superimposed with the encoded data codes from other users and coupled into the fiber channel. At the other end of the fiber, the optical data sequences from all simultaneous users are distributed to all optical decoders via an optical star coupler. At the receiver side the desired signal along with the interference from all other $N-1$ users will be received. The receiver has to be able to decide which bit of the desired user has been sent. The received signal $r(t)$ 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.

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. The threshold detector compares the correlation value to a threshold Th so as to extract the transmitted data.

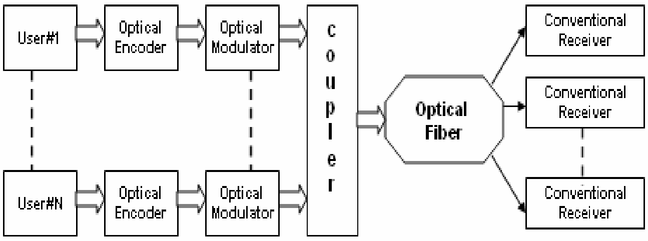

Figure 2. Optical Code Division Multiple Access

F. Conventional Correlation Receiver (CCR):

The Conventional Correlation Receiver (CCR) (Figure 3) operates by enhancing a desired user while suppressing other users considered as interference. In the CCR, errors occur only if the desired user sends data “0” and the interference from other users exceeds the threshold level. It is well known that, MAI threatens the performance of the CCR and limits the maximum number of simultaneous users. An Optical Hard Limiter (OHL) has been placed in front of the receiver in order to improve the performance (Figure 4) [2] [6]. While a receiver with hard limiter is called a hard limiting receiver, a soft limiting receiver simply refers to one without. An ideal optical hard limiter is defined as follows [2]:

$$g(x) = \begin{cases} 1, & x \geq 1 \\ 0, & 0 \leq x < 1 \end{cases}$$

Where 1 is the normalized optical light intensity. Therefore, if an optical light intensity is bigger than or equal to one, the optical hard limiter would clip the intensity to one and if the optical light intensity is smaller than one, the output of the OHL would be zero. The OHL clips the incoming light power, resulting in a performance improvement because it is able to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of the non-zero positions of signature codes. However the improvement is not considerable in the presence of thermal noise and avalanche photodiode.

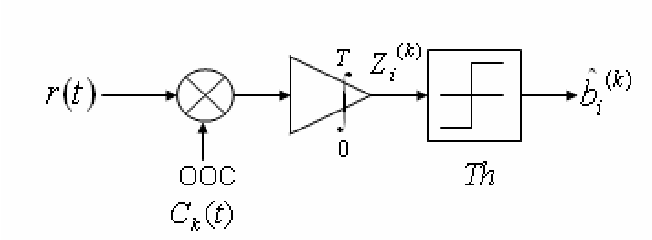

Figure 3. Conventional Correlation Receiver

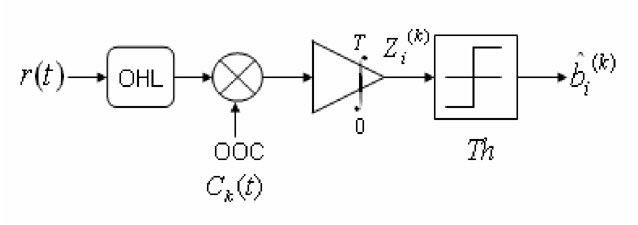

Figure 4. Conventional Correlation Receiver with Optical Hard Limiter

G. Multi-User Interference Cancellation:

The principle of multi-user interference cancellation is relying on the estimation and reconstruction of the MAI seen by each user with the objective of canceling it from the received signal.

The basic idea of the multi-user detection is different from the single user detection. Here, we first enhance the non-desired users, extract their data and remove it from the received signal. The receivers have the knowledge of all the active users' codes patterns and we assume that all the users have the same transmitting energy. So, there are no strongest interfering signals.

The multi-user technique considered in this letter is referred as, Optical Parallel Interference Cancellation (OPIC). In the next section, the main concept of OPIC receiver will be considered. This technique is more complex than the conventional techniques but it is more efficient.

III. OPTICAL PARALLEL INTERFERENCE CANCELLATION (OPIC)

Parallel Interference Cancellation (PIC) [8] has been widely deployed in the wireless communication systems to mitigate the effect of MAI and improve the system performance. In the recent years, the use of PIC in the optical domain also has been investigated to reduce the MAI or improve the system performance in the present of MAI [7].

The basic idea behind Optical Parallel Interference Cancellation (OPIC) (Figure 5) 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 its 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 the CCR. The signal applied to the entry of the receiver is:

$$S(t)=r(t)-\sum_{j=2}^{N}\hat{b}_i^{(j)}c_j(t)=b_i^{(1)}c_1(t)+\sum_{j=2}^{N}(b_i^{(j)}-\hat{b}_i^{(j)})c_j(t) \quad (3)$$

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:

$$Z_i^{(1)} = wb_i^{(1)} + \sum_{j=2}^{N}(b_i^{(j)} - \hat{b}_i^{(j)})\int_0^T c_1(t)c_j(t)dt \quad (4)$$

In the above equation, the second term is called the interfering term and we referred as I . Errors in the OPIC are due to this term.

It is important to know that in OPIC system, errors only happen if the desired user sends data equal to 1 [7]. On the other hand, I is always negative (if we have wrong detection for the non-desired user i.e. in the case of sending data equal to 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 , regardless the values of threshold we still have an error. Therefore, in order to reduce the number of errors for the desired user, one can choose the minimum threshold value. Otherwise, one interfering user can contribute to the error if maximum threshold value is selected [12]. To improve the OPIC receiver efficiency by the simplest way, Optical Hard Limiter (OHL) has been placed in front of the receiver side (Figure 6). OPIC with OHL is managed to improve the performance of OCDMA system. The function of the OHL is to lessen the localization of strong interference and equalize the interference strength at all nonempty pulse positions. OPIC with OHL is quite effective in term of MAI suppression because OHL has the potential to exclude some combinations of interference patterns from becoming heavily localized in a smaller part of the non-zero positions of signature codes and OPIC has the capability to remove the contribution of the non-desired users.

Generally, OPIC is attractive technology to reduce the non-desired user's signals. However, the usage of PIC in optical domain will increase the demand for hardware complexity which results in higher processing time and cost. The hardware complexity increases in the receiver side of Optical PIC (OPIC) when the number of transmitter (users) increases. To overcome these difficulties, an efficient method is presented called One Stage Optical Parallel Interference Cancellation (OS-OPIC) which is based mainly on the OPIC. 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 threshold value.

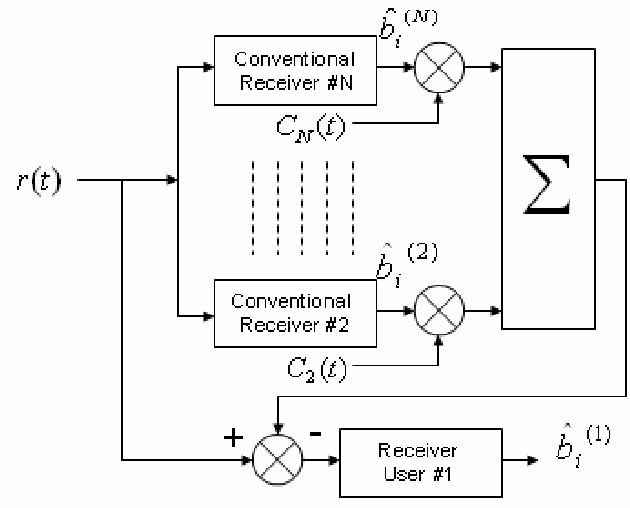

Figure 5. Optical Parallel Interference Cancellation

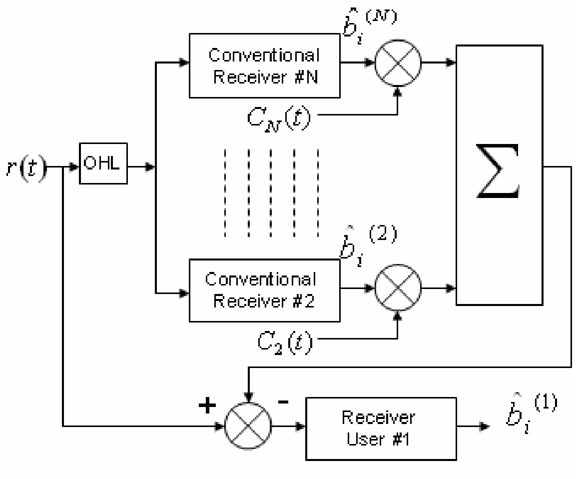

Figure 6. Optical Parallel Interference Cancellation with OHL

IV.ONE STAGE OPTICAL PARALLEL INTERFERENCE CANCELLATION (OS-OPIC):

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 hamper 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:

$$S(t) = r(t) - \hat{b}_i^{(k)} c_k(t) \qquad (5)$$

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 "0". Still there is probability of error when the desired user sends data "1" but according to specific conditions.

V.THEORETICAL ANALYSIS

This section discusses: a non-coherent, synchronous Direct Sequence OCDMA with On-Off Keying (OOK) as a method of modulation and employing Optical Orthogonal Code (OOC) as signature sequence with length L, weight w and the auto-and cross-correlations bounded by 1, so that, for sending "1" bit a user sends its signature code and for "0" bit it sends nothing.

The performance of the proposed system will be analyzed under the following assumption:

- User #1 is chosen to be the desired user with the threshold level given by $S_d (0 < S_d \le w)$.
- User #k is the non-desired with the threshold level given by $S_n (0 < S_n \le w)$.
- All the users have the same transmitting energy so there is no strong interference.
- The case of full synchronization $(\tau_k = 0)$ is considered.

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

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

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

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

The second term appears in the above equation is the non-desired user #k detected by the OS-OPIC receiver referred as H and the third term is due to the undetected users referred as I. Two cases will be considered:

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:

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

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

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

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

$$P_0 = \left[Q \times P_{0(H=-1)} \right] + \left[(1-Q) \times P_{0(H=0)} \right] \qquad (10)$$

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:

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

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:

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

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

$$P_1 = \frac{1}{2} \left[Q^* \sum_{i=S_d-1}^{N-2} \binom{N-2}{i} \left(\frac{w^2}{2L} \right)^i \left(1 - \frac{w^2}{2L} \right)^{N-2-i} \right] \qquad (11)$$

In general, the probability of error for One Stage OPIC is:

$$P_T = P_0 + P_1 \qquad (12)$$

VI. SIMULATION RESULTS AND PERFORMANCE COMPARISON

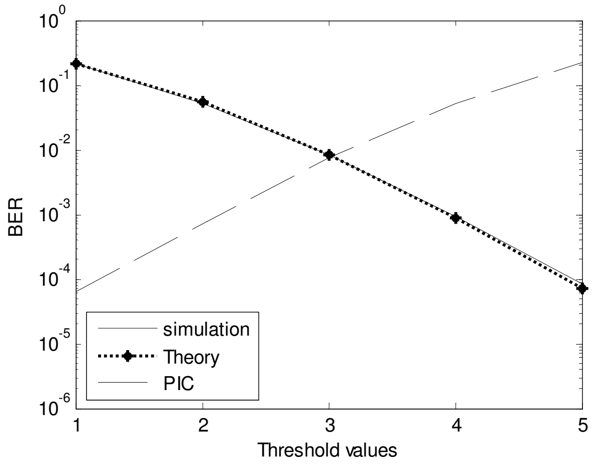

Figure 7. BER for the OPIC and OS-OPIC for 17 users, code OOC, W=5, F=341 for different threshold values

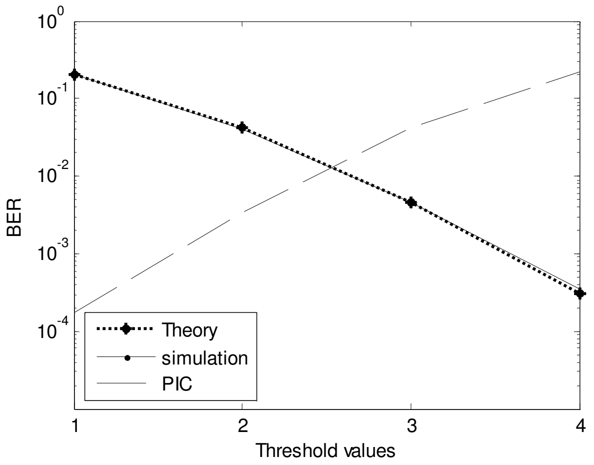

Figure 8. BER for the OPIC and OS-OPIC for 8 users, code OOC, W=4, F=97 for different threshold values

Figure 7 and Figure 8 show the BER versus the threshold value for OPIC and the proposed method OS-OPIC using different number of users. OOC is adopted with parameter: L=341, 97 and w=5, 4 for 17 and 8 simultaneous users respectively.

From the figures, we can observe that the theoretical line of the OS-OPIC correlates with the simulation one. We can then validate the results for further study in this topic. We can see that by using the proposed method, a lower BER is obtained when we set the threshold value to a higher value. In contrast, we can obtain better performance for the OPIC if we use the minimum threshold value.

CONCLUSION

MAI is the major problem that hampers the implementation of OCDMA system. OPIC is shown to be effective to mitigate the effect of MAI. However the hardware used in each receiver side makes the system unpractical which results in the increase of processing time and the cost. In this paper, One Stage OPIC was proposed to reduce the hardware complexity and cost. 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 value of the threshold.

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