Projected Parallel Interference Cancellation Multi-user Detector for Asynchronous Upstream OCDMA-PON

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***Abstract*—OCDMA is a promising candidate for Next Generation Passive Optical Networks (NG-PON). OCDMA-PON can potentially provide all customers with a Gb/s-class bandwidth upstream with inherent flexibility. Unfortunately OCDMA suffers from Multiple Access Interference (MAI) and various detection noises. To mitigate MAI we propose a novel parallel interference cancellation technique for incoherent DS-OCDMA that better exploits the positivity of the solution. The proposed PIC scheme incorporates this additional information into its structure. The proposed PIC detector is shown to outperform the conventional correlator detector, the decorrelator detector, the Linear Parallel Interference Cancellation (LPIC) detector and even the Linear Minimum Mean Square Error (LMMSE) detector. As a matter of fact, our detector achieves more than 1 dB enhancement in SNR at 10^{-3} average BER for 32 active users compared to the LMMSE detector. This gain can be used to reduce the code length required to support a higher number of users.**

Keywords-Optical Code Division Multiple Access (OCDMA); Parallel Interference Cancellation (PIC); Passive Optical Network (PON); Multiuser Detector (MUD).

I. Introduction

Demand for broadband services has been promoting the rapid growth of optical access systems. PON provides a solution for optical access networks and thus makes it possible to share a part of the infrastructure across multiple users [1, 2]. PON architecture is based on sharing the time of a single wavelength among multiple users.

OCDMA is a multiple access technique, in which the signal is coded in optical domain. It provides sharing a wavelength between multiple users by creating multiple sub-channels. This is very appropriate for access and metro networks. OCMDA-PON provides a large dedicated bandwidth to each user and asynchronous transmissions where synchronization between OLT and ONU and between ONUs themselves is avoided. OCDMA reduces the packet delay observed in Long Reach PON (LR-PON) over 100 km and more because of the tell and go inherent protocol [3]. Furthermore, burst and packetized traffic give advantages to OCDMA.

In OCDMA systems, there are two basic detection schemes namely coherent and incoherent. In coherent detection, the codes are bipolar and the system is phase sensitive. On the other hand, in incoherent systems the codes are unipolar; and therefore the system is phase insensitive and consequently detection requires less complexity. This is in addition to the fact that unipolar codes were intensively studied in the literature and widely used in practice. However, unipolar codes are quasi orthogonal codes and their performance can be significantly reduced by MAI as the number of user increases.

MAI is an important factor in the system performance and restricts the system capacity [4]. In practice, MAI is introduced in multi-access systems due to the inability to maintain complete orthogonally between users' signature sequences. The Conventional Correlation Receiver (CCR) is optimal only for the single user case in Additive White Gaussian Noise (AWGN) channel. One advantage of the correlation receiver is that it allows the possibility of all-optical processing and simple implementation. But on the other hand, it does not make use of the information about other users to reduce the disastrous effect of MAI. As a result, the performance of the system deteriorates rapidly with increasing number of users [5].

To support many simultaneous users with good performance, a low MAI is needed. This can be done using very long optical codes, that can be obtained through the use of ultra-short pulses and therefore a very large bandwidth is required. This imposes a real challenge to the speed of encoding and decoding hardware. To alleviate such challenge and maintain good performance, one solution is to mitigate MAI with Interference Cancellation (IC) techniques. The simplest IC detector consists of putting an Optical Hard Limiter (OHL) in front of the CCR [6]. The OHL is a nonlinear fundamental technique for upstream traffic in PON. The main problem with the OHLs is that, once the received energy for single chip duration is limited, the assumption of a linear signal model becomes inappropriate and therefore the possibility of using interference cancellation becomes more tedious.

Multiuser Detection (MUD) or joint detection is any method or technique that exploits the knowledge of the spreading codes of users other than the desired user to enhance the quality of its data estimates [7].The best solution in terms of performance is achieved by the Maximum Likelihood (ML) detector. However, the computational complexity of the ML detector is exponential in the number of users and it is known to be NP-hard [7]. Hence, suboptimal detectors such as the decorrelator and the LMMSE detectors have been proposed [8]. These detectors exhibit a computational complexity in the order of $O(K^3)$, where K is the number of active users. Other suboptimum multiuser detectors that operate on the output of

CCR and exhibit less computational complexity (typically $O(K^2)$) such as the Parallel Interference Cancellation (PIC) and Serial Interference Cancellation (SIC) detectors have been proposed [3, 9].

One of the deficiencies of the current IC detectors proposed in the literature is that they neglect the presence of the AWGN and therefore they may not work properly in practice. As far as we know the only PIC detector that takes into consideration the AWGN is the one proposed in [10]. However, the optimal weight used in [10] to correct the bias is not trivial to calculate, which renders this scheme impractical.

In this work, we propose a novel PIC detector that takes into consideration the background AWGN and exploits the positivity of both the solution and the spreading codes to enhance the BER performance of the asynchronous OCDMA-PON. This PIC detector, that we call here the Projected PIC (PPIC), forces the positivity of the solution at each stage by projecting the solution onto the subspace defined by the positivity constraint. This approach enables correcting most of the errors that are caused by violating the positivity constraint, i.e. due for example to the negative values of the AWGN. As it will be shown in the simulation results, this detector considerably improves the system performance compared to the CCR, decorrelator detector, the LPIC detector and even the LMMSE detector that is considered as the optimal linear detector.

The rest of this paper is organized as follows. Section II describes the system model for the OCDMA-PON. Section III introduces the PPIC detector, and finally, numerical results are presented in section V, and conclusions are then given in section VI.

II. System Model

An OCDMA system with K users is considered as shown in Fig.1, with user 1 arbitrarily chosen as the desired user. In OCDMA transmission system model, each user encodes the laser pulses to transmit one of the predetermined sequences. The signal processing at the receiver depends on the type of detection used. We consider an incoherent, DS-OCDMA system, in which users apply On-Off Keying (OOK) modulation to transmit binary upstream data via optical fiber tree. The PON, which possesses a physical point to multipoint topology, has many benefits stemming from its passive power

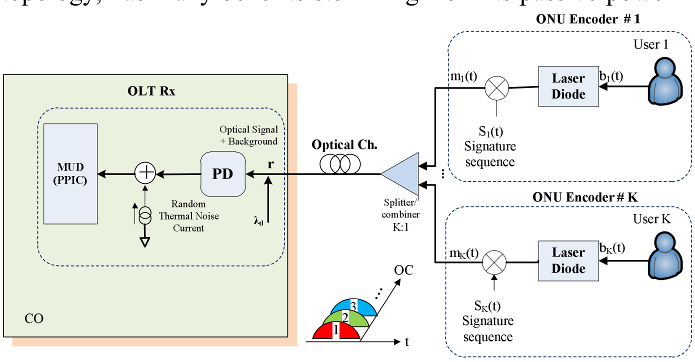

Fig. 1: System model for the Asynchronous upstream OCDMA-PON

splitter based Optical Distribution Network (ODN) [1]. For K users, a PON requires a single transceiver at the Central Office (CO).

At the OLT receiver, information is converted into electrical signals by employing a photo-detector. In Fig. 1, each user transmits binary information $b_k \in \{0,1\}$ for $k = 1,2,...,K$. by either transmitting nothing $b_k = 0$ or transmitting a signature sequence $S_k(b_k = 1)$. Each active user will be identified by one of the OOC sequence codes. The latter have good auto- and cross correlation properties which enables effective detection.

Considering Optical Code family as Φ ($N, w, \lambda_a, \lambda_c$), where N is the code length, w is the code weight (i.e. the number of "1"s in a block of length N), and they satisfy the correlation properties for any code sequence $S_i S_j \in \Phi$. Cross-correlation between the codes is defined as:

$$R_{ij} = \sum_{u=1}^{N} S_i(u) S_j(u+k) \leq \lambda_c \,, \qquad (1)$$

for any integer $k \in [0, N]$ where S_i and S_j are members of the code family and $i \neq j$. The autocorrelation is given by:

$$R_{ii} = \sum_{u=1}^{N} S_i(u) S_i(u+k) \begin{cases} = w & \ldots \quad k = 0 \\ \leq \lambda_a & \ldots \quad k \neq 0 \end{cases}, \qquad (2)$$

for any integer $k \in [1, N]$, where λ_a is the maximum out of phase autocorrelation of a code sequence, and λ_c is the maximum cross-correlation of a code sequence with any other code in the set.

The bit period is denoted by T_b, the chip period is T_c with the relation $N = T_b/T_c$ called the spreading gain. If $b_k^{(l)}$ is the binary data of the k^{th} user for l^{th} bit in the frame, then the symbols' sequence of the k^{th} user; b_k that we assume independent and identically distributed (iid) can be written as:

$$b_k(t) = \sum_{l=-\infty}^{\infty} b_k^{(l)} \prod\nolimits_{T_b} (t - lT_b) \,, \qquad (3)$$

Moreover, the spreading waveform can be written as:

$$s_k = \sum_{j=-\infty}^{\infty} s_k(l) \psi(t - jT_c) \,, \qquad (4)$$

where $\psi(t)$ is the chip pulse shape of duration T_c with $\|\psi(t)\| = 1$. For simplicity, we consider rectangular pulse shapes with unit $\prod_{T_c}(t)$ amplitude, that is:

$$s_k(t) = \sum_{j=-\infty}^{\infty} s_k^{(l)} \prod\nolimits_{T_c} (t - jT_c) \,. \qquad (5)$$

Its discrete form is denoted by $\{s_k(l)\}_{l=0}^{N-1}$, where $s_k(l) \in \{0,1\}$. The modulated signal of the k^{th} user is

$$m_k(t) = \sum_{k=1}^{K} A_k b_k(t) s_k(t) \,, \qquad (6)$$

where the signal amplitude for user k is A_k . Finally, the baseband representation of the received OCDMA signal after incoherent reception is given by:

$$r(t)=\sum_{k=1}^{K} m_k(t-\tau^k)+n(t)$$
$$=\sum_{k=1}^{K}\sum_{l=-\infty}^{\infty}\sum_{j=-\infty}^{\infty} A_k b_k^{(l)} m_k^{(l)} \prod_{T_c}(t-jT_c-\tau^k)\prod_{T_b}(t-lT-\tau^k)+n(t) \quad (7)$$

where τ^k : is the relative delay of the k^{th} user and *n(t)* is AWGN with zero-mean and variance σ^2.

As the OCDMA channel introduces MAI, different techniques of mitigating the effect of MAI result in different multiuser structures. In this paper, we address symbol asynchronous system in which all delays are multiple of the chip period.

In order to simulate our proposed interference cancellation technique for upstream OCMDA-PON system, we introduce the discrete time model for the asynchronous CDMA AWGN channel as:

$$r=\sum_{k=1}^{K} A_k b(k) s_k + n = \boldsymbol{SAb}+\boldsymbol{n}, \quad (8)$$

where $\boldsymbol{b}$ is the $\{MK\text{-by-}1\}$ vector of 0 and 1 symbols formed by users' data. $\boldsymbol{S}$ is the $\{(MN+\max_{1\le k\le K}(\tau^k))-by-MK\}$ matrix of the spreading codes. M is the number of symbols. s_k : is the $\{N\text{-by-}1\}$ spreading code sequence of the k^{th} user. $\boldsymbol{A}$ is the $\{MK\text{-by-}MK\}$ matrix of received amplitudes obtained at the output of the asynchronous channel. Matrix A is a diagonal matrix of received signal amplitudes. $\boldsymbol{n}$ is the $\{(MN+\max_{1\le k\le K}(\tau^k))-by-1\}$ vector of i.i.d AWGN. To get more insight about the structure of these matrices, see [11].

In a purely asynchronous CDMA system, the number of symbols M within one data packet is very large. Actually, each user activates and deactivates its terminal independently from each other. Thus, it is not practical to assume that the whole received signal **r** would be processed in a receiver. Therefore, a finite sliding processing (observation) window model will be developed. The received signal will be processed using a sliding window of length PW chips and overlap V chips where PW and V are defined as: $PW = WN+\max_{1\le k\le K}(\tau^k)$ and $V=\max_{1\le k\le K}(\tau^k)$ where W is the number of symbols within the processing window (the length of the processing window counted in terms of number of symbols). In doing so, it is better to buffer the received signal **r** in a matrix Q, where $\mathbf{Q}=[\mathbf{q}_1\mathbf{q}_2 \;\dots\; \mathbf{q}_b \;\dots\; \mathbf{q}_B]$ of dimension $\{PW\text{-by-}B\}$ where $\mathbf{q}_b$ is a $\{PW\text{-by-}1\}$ column of **Q**. For simplicity and without loss of generality, we use **r** instead of $\mathbf{q}_b$ in all subsequent equations.

OOC can be generated using optical delay lines or optical switches [12, 13]. For the most widely used case of $\lambda_a=\lambda_c=1$, the number of codes in the set is upper bounded by:

$$\lfloor\lfloor(N-1)(w-1)\rfloor/w\rfloor. \quad (9)$$

III. Statistical Approach to Signal Detection

As accurate information about statistical properties of the noise is available, ML method can be easily applied. A particular case is the Least Square (LS) method which is the traditional starting point of the classical estimation and detection theory [14].

The problem of optimal MUD can be stated as follows: given the statistic $\mathbf{y}_{\text{MF}}$ from the output of the CCR, also known as the Matched Filter (MF) detector,

$$\mathbf{y}_{MF}=\mathbf{S}^{\text{T}}(\mathbf{SAb}+\mathbf{n})=\mathbf{RAb}+\mathbf{z}, \quad \mathbf{(10)}$$

Find an estimate of the transmitted bit vector **b** that minimizes the probability of error, where **R** is the correlation matrix and **z** is the noise at the output of the MF.

The probability of error is chosen as the optimization criterion since it is the most important criterion for measuring the efficiency of digital communication system. Assuming that the occurrence of 0 and 1 is equi-probable, the optimal detector is the ML detector. It is well known that the set of MF outputs given by the vector $\mathbf{y}_{\text{MF}}$ is a sufficient set of statistics for the detection problem. The ML detector decides based on the following rule:

$$\hat{\mathbf{b}}=\arg\max_{\mathbf{b}\in\{0,1\}^K} L_{\mathbf{y}_{MF}}(\mathbf{b}), \quad (11)$$

where $L_{\mathbf{y}_{MF}}(\mathbf{b})=f(\mathbf{y}_{MF}/\mathbf{b})$ represent the likelihood function and $f(\mathbf{y}_{MF}/\mathbf{b})$ denotes the density function of $\mathbf{y}_{\mathbf{MF}}$ conditioned on **b**. As the likelihood function is the product of a very large number of factors, so that it is convenient to take the logarithm of this function; moreover, if we consider the negative logarithm (the so-called neglog) the maximization problem is transformed into a minimization one. Therefore we introduce the functional [14]:

$$J_{\mathbf{y}_{MF}}(\mathbf{b})=-A\ln\; L_{\mathbf{y}_{MF}}(\mathbf{b})+B \quad (12)$$

where A, B are suitable constants that can be introduced in order to simplify the expression of the functional. Since the neglog function is strictly convex, the problem is equivalent to the following one:

$$\hat{\mathbf{b}}=\arg\max_{\mathbf{b}\in\{0,1\}^K} J_{\mathbf{y}_{MF}}(\mathbf{b}) \quad (13)$$

In the case of additive white Gaussian noise, with statistically independent components, all having the same Gaussian distribution, with zero mean and variance σ^2, that is:

$$p(\mathbf{n})=(\frac{1}{\sqrt{2\pi\sigma^2}})^N e^{(-\frac{n^2}{2\sigma^2})} \quad (14)$$

the statistical model of the detected data is given by:

$$p(\mathbf{r};\mathbf{b})=(\frac{1}{\sqrt{2\pi\sigma^2}})^N e^{(-\frac{(\mathbf{r}-\mathbf{SAb})^2}{2\sigma^2})} \quad (15)$$

And expected value for MF output is given by:

$$E(\mathbf{r}) = \int \mathbf{r}\, p(\mathbf{r};\mathbf{b})\, dy = \mathbf{SAb} \quad (16)$$

The ML criterion is based on selecting the input bit vector that minimizes the Euclidean distance between the transmitted vector and the received vector, that is [15]- [16]:

$$\begin{aligned} &Minimize \quad J_{\mathbf{r}}(\mathbf{b}) = \frac{1}{2}\|\mathbf{SAb}-\mathbf{r}\|^2 \\ &subject \quad to, \ \mathbf{b} \in \Omega \end{aligned} \quad (17)$$

where $\|.\|^2$ denotes the usual 2-norm and Ω denotes a set that can be convex or nonconvex. For example, in the conventional ML detector Ω is nonconvex and defined as $\Omega = \{0,1\}^K$ however, for the decorrelator detector, Ω is convex and defined as $\Omega = R^K$.

IV. Projected PIC

Non-coherent systems have the property that all signals are positive. This information can be incorporated into the ML problem above by adding this information as a constraint, that is setting $\Omega = R_+^K$. the problem is reduced to the following convex optimization problem:

$$\begin{aligned} &Minimize \quad J_{\mathbf{r}}(\mathbf{b}) = \frac{1}{2}\|\mathbf{SAb}-\mathbf{r}\|^2 \\ &subject \quad to, \ \mathbf{b} \geq 0 \end{aligned} \quad (18)$$

The Projected PIC iteration (p+1) is defined by:

$$\mathbf{b}^{\mathbf{p}+1} = P_\Omega[\mathbf{b}^{\mathbf{p}} + \alpha\{\mathbf{y}_{MF} - \mathbf{R}\mathbf{b}^{\mathbf{p}}\}], \quad (19)$$

where P_Ω is the projection onto R_+^K and α is defined as a fixed step-length in the descent direction:

$$-\nabla J_y(\mathbf{b}^P) = \mathbf{y}_{MF} - \mathbf{R}\mathbf{b}^P, \quad (20)$$

It is provided that, if $\mathbf{b}^0 \in R_+^K$ and α satisfies the condition

$$0 < \alpha < \frac{2}{\lambda_{\max}(\mathbf{R})}, \quad (21)$$

where $\lambda_{\max}$ is the maximum eigenvalue. Then, for any initial guess $\mathbf{b}^0 \in R_+^K$, the estimated data $\mathbf{b}^p$ converges to a solution within the convex set R_+^K.

The received signal is first applied to a bank of MFs and then passed through a set of IC units. The PPIC detector is similar to the LPIC detector except that a projection operator defined by:

$$P_\Omega(x) = \max\{0, x\}, \quad (22)$$

is applied to the solution vector component-wise at each stage.

V. Numerical Results and Discussion

In our numerical simulation, OOCs of the set Φ (511, 3, 1, 1) are used. There are 85 distinct codes available in this set. The impairments considered here are MAI and thermal noise. Other types of noises like Poisson and dark current are ignored.

Five different receiver structures are considered. These are the CCR, decorrelator receiver, the LMMSE receiver, the LPIC receiver and the PPIC receiver. More details about these detectors can be found in [17].

All these detectors are simulated in asynchronous Optical CDMA system. We consider perfect power control with an optical intensity equal to 110. The last stage is hard limiter with threshold value equal half.

First, we investigate the effect of increasing SNR on the BER performance and depict the results in Fig. 2. As expected, the LMMSE detector achieves the best performance while the CCR achieves the worst. The reason is that the CCR performs no MAI reduction while the LMMSE reduces MAI but at the same time reduces the noise enhancement effect.

The performance of the decorrelator is close to that of the LMMSE detector however it is slightly worse due to the noise enhancement effect.

It can be easily seen that the PPIC detector performs better than all other detectors especially at high SNRs which is due to the non-negativity projection embedded within the PIC detector. It is quite surprising that the proposed detector performed better than the LMMSE detector though it does not need the noise information like the LMMSE detector.

Next, we investigate the average BER versus the number of PPIC stages and depict the results in Fig. 3. Both the PPIC and LPIC detectors need around 5 stages to converge, however, the PPIC detector converges to a BER level that is below that of the decorelator and LMMSE detectors. As it is shown in Fig. 3, the PPIC detector inherits the slow convergence behavior from the LPIC detector, and therefore it needs the introduction of a relaxation parameter to accelerate its convergence speed. This issue will be tackled in future papers.

Finally, the system capacity expressed as the average BER versus the number of users is depicted in Fig. 4.

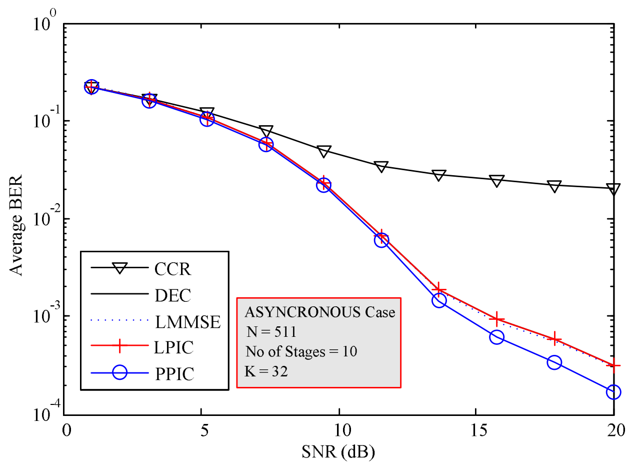

Fig. 2 Averaged BER vs. SNR

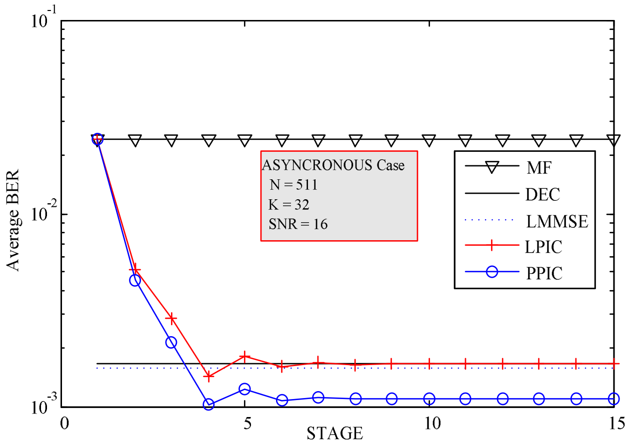

Fig. 3 Averaged BER vs. number of stages

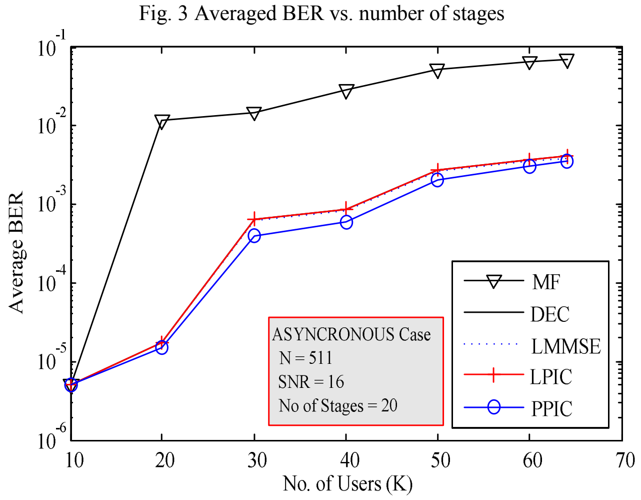

Fig. 4 Averaged BER vs. number of users

The average BER for CCR deteriorates very fast as the number of users increases. Here as well, it is clear that the average BER performance of the PPIC is better than that of the other detectors.

VI. CONCLUSION

OCDMA is one promising candidate for the NG-PON and will provide a lager dedicated bandwidth to each user. However, its performance is severely limited by MAI. Therefore, efficient interference cancellation detectors are needed to alleviate the undesirable effect of MAI. A new improved PIC detector that exploits the positivity of the system is proposed to mitigate the MAI. Simulation results indicate that the proposed PIC detector outperforms the conventional correlation receiver, the decorrelator detector, the linear PIC detector and surprisingly the LMMSE detector. Future work includes investigating relaxed versions of the proposed PIC detector and testing other coding schemes.

VII. AKNOWLEDGEMENT

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