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A new clipped PIC detector for asynchronous upstream OCDMA-PON

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ABSTRACT

Optimization-based approaches have been used to develop several interference cancellation detectors for incoherent direct access OCDMA systems. Some of these interference cancellation detectors exploit the non-negativity of the solution, while other detectors exploit in addition to the non-negativity constraint, the noise variance information. In this paper, we devise a new PIC detector that exploits not only the aforementioned information but also the fact that the amplitude of the solution is confined to a unit hypercube. Up to our knowledge, no such detector exists in the literature. After analyzing the convergence behavior and evaluating the computational complexity of the novel PIC detector, extensive simulations are conducted to assess the performance of the proposed PIC detector. Numerical results show that the proposed PIC significantly outperforms other PIC detectors in terms of both BER and convergence speed.

1. Introduction

A Passive Optical Network (PON) makes use of passive components such as splitters and combiners in order to reduce the complexity and the cost of the network. Combined with Optical Code Division Multiple Access (OCDMA), OCDMA-PON provides the opportunity for several users to share the same network without any additional infrastructure. Additionally, OCDMA-PONs provide users with several merits such as asynchronous transmission, large bandwidth and the support of multi-rate traffic with different QoS requirements [1]. However, these merits do not come for free, as the OCDMA technique, whether in wireless or in optical, suffers from what is known as Multi-Access Interference (MAI) [2]. The latter results from the non-orthogonality of the code sequences used in spreading the data of users in the upstream link.

Alleviating the effect of the MAI on the OCDMA systems is one of the main research streams since the early times of OCDMA, giving rise to what is known as Multi-User Detection (MUD) and Interference Cancellation (IC). The MAI problem worsens if the spreading codes are unipolar (such as in incoherent OCDMA) because of their limited orthogonality. The most common multiuser detectors dedicated to tackle the MAI problem in OCDMA are the Parallel Interference Cancellation (PIC) detector and the Successive Interference Cancellation (SIC) detector [3]. The linear SIC and linear PIC detectors in particular are used to approximate the performance of the decorrelator and the Linear Minimum Mean Square Error (LMMSE) Detectors but with less complexity (one order of magnitude less) [4].

In [5], a new approach to obtain the analytical expression of error probability in chip synchronous case for PIC detectors with Optical Orthogonal Codes (OOC) is developed whereas the performance of the PIC detector combined with the hard limiter in OCDMA is evaluated in [6]. The performance of the PIC detector has been also assessed using Prime codes [7] and 2-D codes [8]. A PIC detector that makes use of bias compensation technique is devised in [9] whereas another one making use of the lowest threshold value method is studied in [10].

Exploiting system properties such sparseness of data, statistical information of noise…etc. is one approach to develop efficient IC detectors with good performance. One example of making use of system properties is the projected PIC (PPIC) detector proposed in [11], which exploits the non-negativity of the data and the spreading codes in order to enhance the PIC detector's performance. Further extensions to the PPIC detector such are the projected SIC (PSIC), the doubly penalized PIC (DPPIC) detector and the doubly penalized SIC (DPSIC) detector are detailed in [12]. All these detectors have shown performance improvement compared to most of the standard linear MUD schemes such as the decorrelator and the LMMSE detectors.

Building upon these results, we take a step further and introduce a new clipped PIC (CPIC) detector that outperforms PIC detectors proposed in [12]. This clipped PIC detector adds another constraint that tightens the constraint subspace and improves performance, yet preserves convexity, which ensures the uniqueness of the solution. Also, results of nonlinear interference cancellation obtained for wireless CDMA systems [4], show that clipped PIC detection (different from the one developed here) performs better than the decorrelator detector and all other linear and non-linear PIC detectors if the load factor K/N, where K is the number of users and N is the spreading factor, is less than 0.35. In our case, the maximum load factor using Optical Orthogonal Codes (OOCs) is less

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than 0.35 [13] and therefore, it is expected that the performance of the proposed CPIC detector will also be better than that of the decorrelator and also better than all PIC detection schemes in [12].

The rest of the paper is organized as follows. Section 2 describes the system model for the OCDMA-PON. Section 3 provides an optimization framework for clipped detection while Section 4 introduces a PIC implementation of the proposed clipped detector. Section 5 evaluates the computational complexity of the proposed detector. Finally, Sections 6 and 7 present simulation results and concluding remarks, respectively.

2. System model

The OCDMA simulation model used in this work is the same as that in [12] and [11]. We consider an incoherent asynchronous Direct Sequence Optical Code Division Multiple Access (DS-OCDMA) system where users send their on-off keying (OOK) modulated uplink data to the Optical Line Terminal (OLT). Before sending their data, each user uses a prescribed spreading code $\mathbf{s}_k$ to spread its data $b_k \in \{0, 1\}$ for $k = 1, 2, \ldots, K$, where k is the user index and K is the total number of users. At the OLT, the same code is used for the decoding process. As in [11] and [12], we use Optical Orthogonal Codes (OOC) for spreading and dispreading of data. The received signal can be written in discrete-time form as:

$$\mathbf{r} = \mathbf{SAb} + \mathbf{n} = \bar{\mathbf{S}}\mathbf{b} + \mathbf{n} \tag{1}$$

where:

- $\mathbf{S}$ is the matrix of the spreading codes of dimension $\{(MN + \max_{1\le k\le K}(\tau^k)) - by - MK\}$, where M is the total number of transmitted bits, N is the length of the spreading code vector $\mathbf{s}_k$ and τ^k is the relative delay of the kth user with respect to the first user.
- $\mathbf{b}$ is the vector of the users' data and it is of dimension $\{MK$-by-$1\}$.
- $\mathbf{A}$ is the diagonal matrix of received signal amplitudes and it is of dimension $\{MK$-by-$MK\}$.
- $\mathbf{n}$ is the vector of i.i.d AWGN with zero-mean and variance σ^2 and it is of dimension $\{(MN + \max_{1\le k\le K}(\tau^k)) - by - 1\}$.
- $\bar{\mathbf{S}}$ is an $\{(MN + \max_{1\le k\le K}(\tau^k)) - by - MK\}$ matrix of the unnormalized spreading codes resulting from multiplying $\mathbf{S}$ and $\mathbf{A}$.

Due to space limitation, we will not provide the detailed structure of these matrices in this paper. For more information about the structure of these matrices and the signal model used in this work, readers can refer to [14].

Practical asynchronous OCDMA systems make use of a finite sliding detection window and do not process the whole received signal $\mathbf{r}$ all at once due the fact that its length M is huge. As illustrated in Fig. 1(a), the received signal $\mathbf{r}$ is processed using a sliding detection 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 $V = \max_{1\le k\le K}(\tau^k)$, respectively; here W is the number of data symbols within the processing window [14]. As shown in Fig. 1(b), the received signal $\mathbf{r}$ is buffered into a matrix $\mathbf{Q}$ of dimension $\{PW$-by-$B\}$, where B is the number of windows processed by the receiver. Q can be decomposed column-wise as $\mathbf{Q} = [\mathbf{q}_1\mathbf{q}_2 \ldots \mathbf{q}_b \ldots \quad \mathbf{q}_B]$ where the column $\mathbf{q}_b$ is of dimension $\{PW$-by-$1\}$. For simplicity and without loss of generality, we use $\mathbf{r}$ instead of $\mathbf{q}_b$ in all subsequent equations.

The Conventional Correlation Receiver (CCR) consists of a K Matched Filters (MFs); each filter is matched to the spreading code of one user. The CCR's output is:

$$\begin{aligned}\mathbf{y}_{CCR} &= \bar{\mathbf{S}}^T\mathbf{r} \\ &= \bar{\mathbf{S}}^T\bar{\mathbf{S}}\mathbf{b} + \bar{\mathbf{S}}^T\mathbf{n} \\ &= \bar{\mathbf{R}}\mathbf{b} + \mathbf{z}\end{aligned} \tag{2}$$

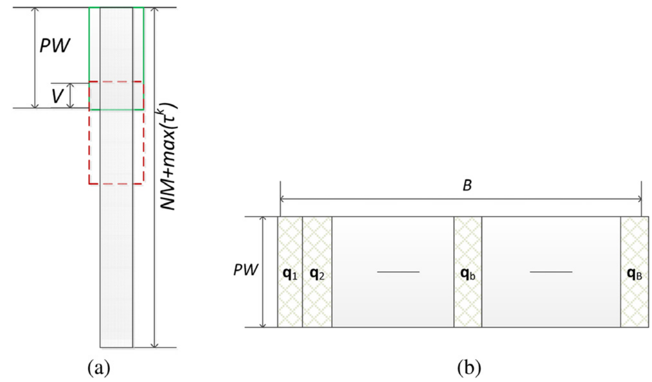

Fig. 1. (a) The vector $\mathbf{r}$ and the sliding window of length PW chips and overlap V chips. (b) The matrix $\mathbf{Q}$.

where $\bar{\mathbf{R}} = \bar{\mathbf{S}}^T\bar{\mathbf{S}}$ is the un-normalized code cross-correlation matrix, and $\mathbf{z}$ is the vector of colored Gaussian noise samples resulting from the correlation process, with $E(\mathbf{zz}^T) = \sigma^2\bar{\mathbf{R}}$. The vector $\mathbf{y}_{CCR}$ and also all is then passed through a decision device:

$$\widehat{\mathbf{b}}_{CCR} = slice(\mathbf{y}_{CCR}) \tag{3}$$

where $slice\,(.)$ operation is a decision rule that acts on the vector $\mathbf{y}_{CCR}$ element-wise as follows:

$$slice(x) = \begin{cases} 1 & if \quad x \ge 0.5 \\ 0 & if \quad x < 0.5 \end{cases} \tag{4}$$

As it is known, the CCR is optimum only for an AWGN channel and for a single user or for perfectly orthogonal users. Since this not the case in practice due to the asynchronousity of the users' data, the CCR suffers from accumulating levels of interference as the number of users increases, which necessitates the use of more advanced multiuser detectors that take into consideration the MAI.

3. Optimization framework for clipped detection

Multiuser detection in upstream OCDMA-PON is in fact a Maximum Likelihood (ML) detection problem where the ML solution corresponds to the data vector $\mathbf{y}$ that minimizes the following objective function:

$$\mathbf{y}_{ML} = \arg\min_{\mathbf{y}\in\{0,1\}^K} \frac{1}{2}\left\|\bar{\mathbf{S}}\mathbf{y} - \mathbf{r}\right\|^2 \tag{5}$$

where $\|.\|$ stand for the L_2-norm. It has been shown that this problem is NP-hard [15], which means that there is no algorithm with polynomial time complexity that can solve the abovementioned optimization problem. Hence, suboptimal detectors that exhibit less complexity were investigated. Linear multiuser detectors such as the decorrelator and the LMMSE are two examples of suboptimal detectors.

The decorrelator detector is a basic suboptimal detector and it is obtained by simply relaxing the constraints on the solution vector $\mathbf{y}$ from $\mathbf{y} \in \{0, 1\}^K$ to $\mathbf{y} \in \mathbb{R}^K$; hence, the optimization problem in (5) becomes [12]:

$$\mathbf{y}_{DEC} = \arg\min_{\mathbf{y}\in\mathbb{R}^K} \frac{1}{2}\left\|\bar{\mathbf{S}}\mathbf{y} - \mathbf{r}\right\|^2 \tag{6}$$

Solving this optimization problem yields:

$$\mathbf{y}_{DEC} = \left(\bar{\mathbf{S}}^T\bar{\mathbf{S}}\right)^{-1}\bar{\mathbf{S}}^T\mathbf{r} = \bar{\mathbf{R}}^{-1}\mathbf{y}_{CCR} \tag{7}$$

Although it completely removes the MAI, its performance however is considerably reduced especially at low Signal-to-Noise Ratios (SNRs) and if $\bar{\mathbf{R}}$ is ill-conditioned due to noise amplification.