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HYBRID MULTI USER DETECTION FOR DS-OPTICAL CDMA

[1]ADIL EL KABLI, [2]MY AHMED FAQIHI, [3]AHMED HAMMOUCH

[1]PhD student, Department of Telecommunication and Networks Engineering, University of Mohamed V

[2]Assoc. Prof., Associate member of LRIT, Telecom Engineering and Networks, University of Mohamed V

[3]Assoc. Prof., ENSET, University of Mohamed V

E-mail: [1]adil.elkabli@um5s.net.ma, [2]faqihi@ensias.ma, [3]a.hammouch@um5s.ac.ma

ABSTRACT

OCDMA multiplexing technique has gained increasing interest from researchers and has made great progress due to its easy access and flexible network structure.

DS-OCDMA systems suffer however from many noises, the most serious is multiple access interferences (MAI), in order to mitigate the effect of MAI, codes offering high performances in term of auto-correlation and cross-correlation like Optical Orthogonal Codes (OOC) or Prime Codes (PC) have been proposed but as the entire burden of performances could not be placed on code design only, numerous detection strategies have been developed to help increase the system performances.

In this paper, we present a statistical based method that uses both conventional detection and non linear detection in an efficient way. The results show that we can reduce by 24\% up to 60\% the detection complexity while keeping the BER at the same level.

Keywords: *Optical Orthogonal Code (OOC), Optical CDMA (OCDMA), Multiple Access Interferences (MAI), Direct Sequence OCDMA (DS-OCDMA), Single User Detection.*

1. INTRODUCTION

End-user demand for broadband services is unstoppable, resulting in high pressure on operators to upgrade their access networks. Most operators agree that fibre is the end-game and fibre deployments are already happening all over the world. In this context optical CDMA can help bring solution to the increasing demand for broadband access.

CDMA technique has proven its success and strength in radio frequencies domain, this success has encouraged engineers and researchers to design CDMA based optical systems [1].

The performances of optical CDMA systems are like other CDMA systems, limited by the MAI [1]-[3]. MAI gives rise of irreducible errors even in absence of thermal noise. The use of orthogonal codes improves notably the performances but the delay between users destroys the orthogonality, moreover, the system capacity is limited by the theoretical limit of the number of codes given a defined spreading factor [1],[5]. In order to overcome these shortcomings an appropriate detection strategy should be applied.

We found generally two detections families: Single-user detection and Multi-user detection. [10], [11].

The single user detector treats the signals of all the other users as noise and tries to suppress it. Thus, conventional decoding requires that the interference from other users should be minimal. However, the interferences suppression capability of such system deteriorates as the number of users grows in the system.

A better detection strategy is to jointly detect multiple users, where the additional structure of the MAI is exploited rather than considered as noise. Multi-user Detection deals with the demodulation of the digitally modulated signals in the presence of MAI [10], [11]

The use of conventional detection is not sufficient to reach high performances, for this reason a statistical based technique that combines conventional and non-linear detections is described and analyzed.

Section II describes the single-user detection technique and its performance in term of BER.

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Section III introduces the newly proposed method whereas the obtained results are evaluated in section IV. The conclusion and the recommendations are discussed in section V.

2. SINGLE-USER DETECTION

In single-user detection strategy, each user is detected independently from the others through the use of a bank of correlators (matched filters)

2.1 System Model

In the DS-OCDMA system involved in this paper the following assumptions are considered:

- For the sake of simplified analysis, the effects of quantum noise and thermal noise in the system are neglected and consequently, the performance degradation is caused only by the presence of other users interferences.
- The used multiple-access channel is an asynchronous incoherent additive channel.
- OCDMA system in this paper uses Optical orthogonal codes

The output from one encoder under the assumptions listed above could be expressed as [1]

$$s_k(t) = A_k c_k(t) d_k(t) \quad (1)$$

Where A_k, c_k, d_k are the amplitude, signature code waveform and modulation of the k^{th} user respectively.

The codeword $c_k(t)$ could be expressed as [1]

$$c_k(t) = \sum_{i=\infty}^{\infty} c_{i,k} p_{T_c}(t - iT_c) \quad 0 \le t \le T_b \quad (2)$$

Where $c_{i,k} \in (0,1)$ is the i^{th} chip of the k^{th} address codeword, T_c is the width of one chip, T_b is the time bit and p_{T_c} is a rectangular pulse of duration T_c.

The modulation of the k^{th} user data bit using on-off keying (OOK) could be expressed as :

$$d_k(t) = \sum_{i=\infty}^{\infty} d_{i,k} p_{T_b}(t - iT_b) \quad (3)$$

Where $d_{i,k} \in (0,1)$ is i^{th} bit of the k^{th} user, T_b is the time bit and p_{T_b} is a rectangular pulse of duration T_b.

The resulted signal $r(t)$ from K users in the system is expressed as the sum of K superimposing signals [1]:

$$r(t) = \sum_{k=1}^{K} s_k(t - \tau_k) = \sum_{k=1}^{K} A_k c_k(t - \tau_k) d_k(t - \tau_k) \quad (4)$$

Where τ_k is the delay for user k. τ_k is uniformly distributed over $[0\ T_b]$

2.2 Conventional detection

The conventional detection for the received signal expressed by equation (1) is done through a bank of $\boldsymbol{K}$collerators as shown in Figure 2, the received signal is correlated with each branch code sequence using a matched filter. The output from each correlator is then sampled during the interval $\boldsymbol{T_b}$a decision is finally made based on a threshold $\boldsymbol{T_h}$. Figure 1 shows a receiver block diagram. [10],[11].

2.3 Performance analysis of DS CDMA using OOCs

This section evaluates DS-OCDMA system based on Binary Error Rate (BER), indeed multiple access interferences is the main component impacting the BER. The system BER should be less than $\mathbf{10^{-9}}$.

The probability of error in case of chip synchronous case is given by [3]:

$$P_{err} = \frac{1}{2}\sum_{i=T_h}^{N-1} \binom{N-1}{i} \left(\frac{w^2}{2n}\right)^i \left(1 - \frac{w^2}{2n}\right)^{N-1-i} \quad (5)$$

Where $\boldsymbol{w}$ is the code weight, $\boldsymbol{n}$ is the code length, $\boldsymbol{N}$ is the number of subscribers and $\boldsymbol{T_h}$ is the decision threshold. It is important to choose $\boldsymbol{T_h}$that permits the minimal number of errors, hence choosing $\boldsymbol{T_h}$ too high will lead to some 1s taken for 0s whereas a too low value of $\boldsymbol{T_h}$causes some 0s to be taken for 1s.

One approach to decrease the number of errors is to place an optical hard limiter before the correlator of the receiver. An ideal Optical Hard Limiter (OHL) is a device that has an output $\boldsymbol{g(x)}$ as bellow:[1],[3],[10]

$$\boldsymbol{g(x)} = \begin{cases} \mathbf{1}, & \boldsymbol{x} \ge \mathbf{1} \\ \mathbf{0}, & \boldsymbol{x} < \mathbf{1} \end{cases} \quad (6)$$

The usage of an optical hard limiter mitigates the multi user interferences; the probability of errors is reduced in this case. Figure 3 shows the gain if an OHL is used.

The probability of error if an OHL is used could be expressed by [1],[3],[10]:

$$P_{err-OHL} = \frac{1}{2}\binom{W}{T_h}\prod_{m=0}^{T_h-1}(1 - q^{N-1-m}) \quad (7)$$

Where $q = 1 - \frac{w}{2N}$

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The binary error rate increases with the number of simultaneous users as it can be seen in Figure 3, the performance degradation of the system is due mainly to the effect of multiple access interferences. For this reason codes with good cross-correlation and anto-correlation values should be used to mitigate the effect of multiple access interferences (MAI).

Figure 4 shows that the lowest BER is obtained for threshold value equal to w, and in Figure 5 we can see that the BER decreases with the code weight, and in all cases the system performs better with an OHL.

The biggest limitation of one dimensional incoherent OCDMA codes is that the code cardinality is proportional to the length of frequency spreading (the length of the code). Due to the limitation of current technology it is difficult to make the width of chip optical pulses narrower than the order of magnitude of ps (pico second) from the practical point of view in optical communication systems. Furthermore, even if it is possible to make an optical pulse narrower, it is difficult for it to be transmitted a long distance because of existing limitations in the fiber-optic, such as non-linearity, dispersion, etc [10].

It is obvious that the entire burden of performance of OCDMA systems could not be placed on optical codes performances only, indeed detection and interferences cancellation methods contribute greatly to improve OCDMA performances as well.

3. SMART DETECTION METHOD

In this section we describe how it is possible to apply an interferences cancellation technique like parallel interference cancellation (PIC) with high efficiency.

3.1 Description of PIC

PIC detector subtracts out interferences from undesired users in the same time using conventional detection scheme.

The initial bit estimates are done using conventional detection, these bits are then spread using codes, and a summer finally sums up all signals except the one that will be cleaned hence the summed signal represents the MAI from all interfering users. The MAI is finally subtracted for the user k as bellow [11],[12]:

$$r_k(t) = r(t) - \sum_{\substack{i=1 \\ i \neq k}}^{N} \widehat{b_\iota}\, c_i(t) \qquad (8)$$

Where $\widehat{b_\iota}$ is the estimated bit for the user i obtained by the conventional detector, N is the number of simultaneous users.

It is possible to repeat this process a certain number of times (stages) till obtaining a satisfying level of performances.

Figure 6 shows an example of PIC detector for 5 users and one stage. The input of the desired user detector is a cleaned signal if the previous conventional detections are successful. [3]

3.2 Auxiliary Threshold Decision Variable

Let X_k^i be the variables defined as:

$$X_k^i = \int_{iT_b}^{(i+1)T_b} r(t)dt$$

Where T_b is the time bit, i is the i^{th} bit and $r(t)$ is the received signal from all users.

X_k^i is a random variables that represent the sum of data and MAI from all users received by the user k during T_b.

Let S_k^i the variable defined as:

$$S_k^i = \frac{1}{K}\sum_{j=1}^{K} X_j^i$$

Where K is the number of active users during the interval T_b $(K \leq N)$ and i is the i^{th} bit transmitted by the j^{th} user.

For the sake of simplicity, and without lost of generality we consider the first bit transmitted $(i = 1)$ and we note S_K^1 as S_K.

S_K is also a random variable that represents the mean amount of data and interferences received by the K active users during T_b. Based on the Theorem of Central Limit (TCL) we can assume that the variable $\overline{S_K}$ follows a normal distribution; Figure 8 shows a comparison of the distribution of variable $\overline{S_K}$ obtained by simulation and calculated using the normal distribution, the graph shows that the normal approximation is valid.

3.3 Learning phase and PIC processing decision

The learning phase consist of constructing the values of $\overline{S_K}$ in the context of a transmission without errors, these values will be compared with the real values obtained after the detection phase.

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At the received end, we first calculate the value of $\overline{S_K}$ and then estimate the number of bits ”1”.
if the estimated value of the number of bits ”1” is equal to the number of detected bits ”1” obtained by conventional detection then we assume that there is no need to use a nonlinear detection method like PIC. On the other hand, if the comparison results in a mismatch between the estimated number of bits ”1” and the number of ”1” really obtained by conventional detection, then we conclude that there is likely an error in this case a non linear detection method should be applied.

4. RESULTS

In this paragraph we present the results of different simulations done using MATLAB program.
We consider only the case where $6 \leq K \leq 15$ because when $K \leq W$ or all users are active no errors occurred. We repeat the experience of K users sending with equal probability bit ”1” or bit ”0” and we note the number of errors, Based on the approximation of the variable $\overline{S_K}$ we can consider only the values of $\overline{S_K}$ that fall in the interval $\left[\mu_K - \frac{\sigma_K}{\gamma} \quad \mu_K + \frac{\sigma_K}{\gamma}\right]$
The figure 9 shows that by lowering the value of γ the number of unnecessary interferences cancellations (a method of interferences cancellation is applied whereas it is not needed) decreases which is a an improvement of the system efficiency, the number of detected errors improves significantly for $\gamma \geq 1$ but the number of estimation errors (i.e decision to perform only a conventional detection whereas a method of interferences cancellation is needed) remains high for $\gamma \leq 1$.

We can see that for $\gamma = 2$ we have a good trade-off between system efficiency and Binary Error Rate (BER)

5. CONCLUSION

In this paper I tried to propose an enhancement to the DS-OCDMA system by reducing the number of expensive interferences cancellation operations given the fact that the most serious limitation of DS OCDMA is the multi user interferences which prevent this system from being deployed in larger networks. This system simplification will keep DS-OCDMA on the course among other all optical technologies given its simple configuration and lower cost. I suggest for future work to improve the decision model in order to perform interferences cancellation only when it is needed meaning that for a system with N users using OOC of weight W the rate of interferences cancellation is approximately:

$$r = \frac{1}{2}\binom{W}{T_h}\prod_{m=0}^{T_h-1}(1 - q^{N-1-m})$$

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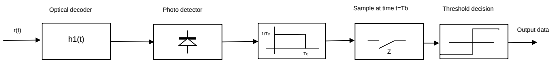

Fig. 1 OCDMA system receiver block diagram

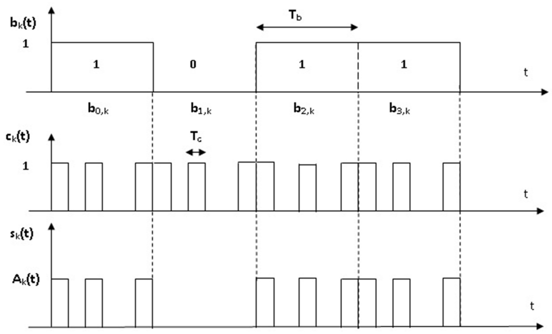

Fig. 2 User Data $b_k(t)$, Code Waveform $c_k(t)$, And OCDMA Encoder Output $s_k(t)$

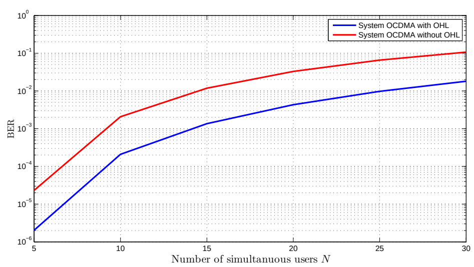

Fig. 3 Bit Error Rate Performance For The Two Cases With And Without An Ideal Optical Hard-Limiter Versus The Number Of Simultaneous Users N When $n = 97$ And $Th = w = 4$

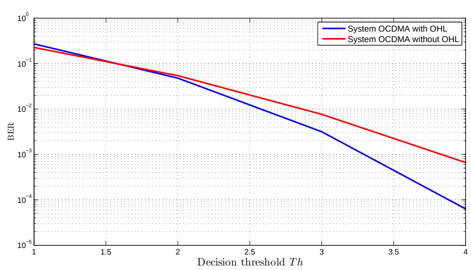

Fig. 4 Bit Error Rate Performance For The Two Cases With And Without An Ideal Optical Hard-Limiter Versus The Decision Threshold Th When $n = 97$ And $N = 8$

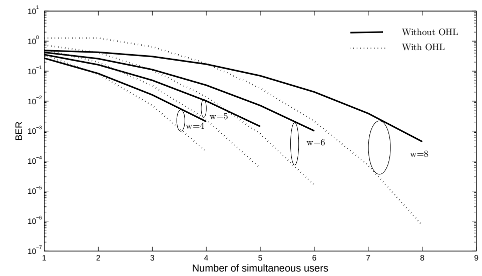

Fig. 5 Bit Error Rate Performance For The Two Cases With And Without An Ideal Optical Hard-Limiter Versus The Decision Threshold Th And The Code Weight w When $n = 97$ And $N = 10$

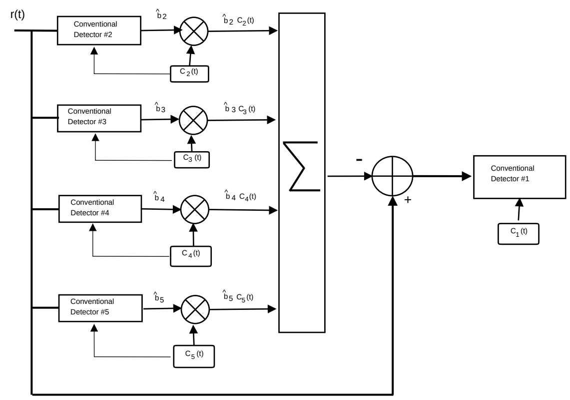

Fig. 6 Parallel Interference Cancellation Detector

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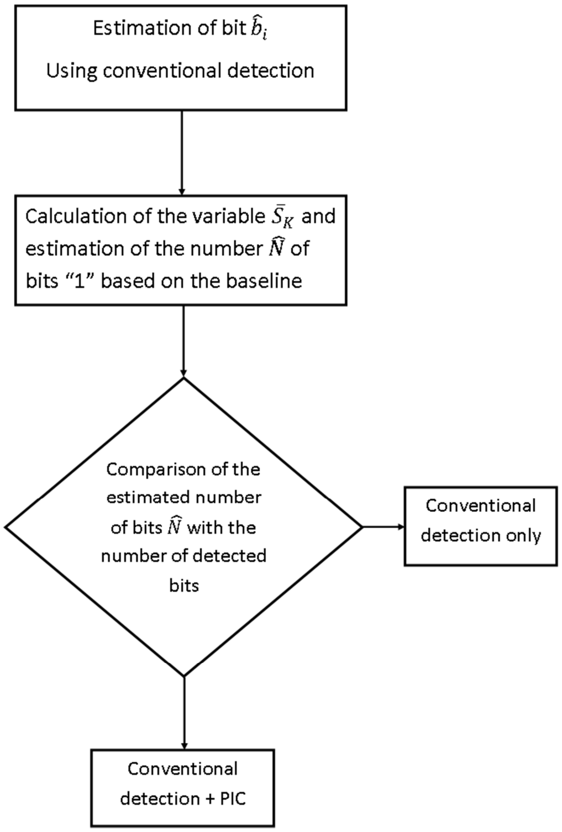

Fig. 7 Schematic Diagram Of The Proposed Enhancement Algorithm For User Detection

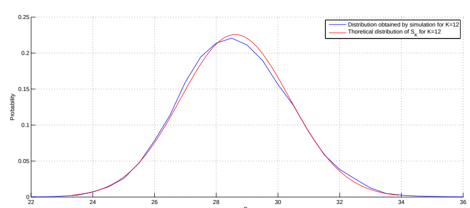

Fig. 8 Distribution Of The Variable S_K For $K = 12$ And $N = 16$

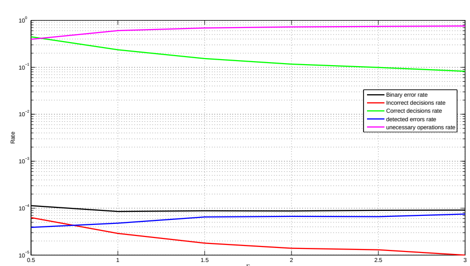

Fig. 9 Comparison Between The Binary Error Rate, Incorrect Decisions, Detected Errors And Unnecessary Operations Rates Versus γ For DS-OCDMA With 16 Users And Using OOC (217,4,1,1)