A Novel Optical CDMA Modulation Scheme: Code Cycle Modulation

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***Abstract*— Recently there has been some interest in optical CDMA (OCDMA) for optical networks. A major drawback of OCDMA systems is their low spectral efficiency. This paper explores a novel modulation scheme for OCDMA systems which increases the spectral efficiency called code-cycle modulation (CCM) which uses different cyclic shifts of the spreading sequence assigned to each user to transmit an M-ary information. While the idea of using M-ary OCDMA modulation has been proposed using other means, most of these modulation schemes need M different receiver units to recover the data which causes complexity and power issues in the receiver. The advantage of our scheme is that we propose a supporting receiver architecture which doesn't suffer from complexity and power issues as mentioned above. In the rest of the paper we analyze the performance of this modulation scheme.**

I. Introduction

Recently there has been an upsurge of interest in applying code division multiple access (CDMA) techniques to optical networks (OCDMA)[1]. Part of the revived interest in using optical-CDMA is the inherent security, flexibility and simplicity of network control that it affords.

In an OCDMA system A different users transmit their data on the same shared optical channel. Each user's data is spread by its unique spreading sequence. These sequences are unipolar $\{0,1\}$ sequences called optical orthogonal codes(OOC). At the receiver side there is a combination of all user's data on the channel, and each receiver can retrieve a specific transmitter's data by correlating the received signal with the specific transmitter's spreading sequence and then detecting the transmitted data using an optical receiver.

However, a key drawback for O-CDMA has been that for the kinds of data rates demanded by current practical applications, and the number of users desired to be supported, conventional O-CDMA systems require an excessively high chip rate. One approach towards partially alleviating the high chip rate requirement has been the introduction of two dimensional (2-D) O-CDMA architectures, in which the quasi-orthogonal spreading codes of the different users are spread over both time and wavelength [2]. However, even under the time/wavelength approach using a reasonable number of wavelengths and practical chipping rates, O-CDMA systems are still unable to accommodate an abundance of active users [3].

A variety of modulation formats (M-ary modulations) are proposed to increase the number of users(spectral efficiency) by increasing the number of bits per symbol. In [4], an OCDMA communication system with PPM signaling was introduced. In this method first each symbol is divided to its ppm positions and then each position is spread using its unique code, so the pulses are smaller than the equivalent OOK system by a factor of number of symbols so the spectrum is broadened. One problem with this approach is the need of multiple correlator in the receiver which can not scale.

In this paper, we review an existing [5] O-CDMA modulation scheme called code cycle modulation (CCM) along with a novel receiver design. We derive a performance analysis of the system using random code model and also find a close form for interference distribution by gaussian assumption in addition to a recursive formula based on random codes. CCM can be used in conjunction with either 1-D or 2-D O-CDMA systems. In this method, each cyclic shift of the spreading sequence represents a symbol enabling transmitter to send a $\log_2 T$ bits of information across the link in the time that it takes for the OOK scheme to communicate a single bit, where T denotes the length of the spreading code along the time axis. More specifically, under CCM, the transmitter selects and transmits a particular cyclic (or wrap-around) shift of the spreading code assigned to that transmitter. The relative spectral efficiency of CCM permits a vastly increased number of users to be supported. It should be noted that CCM permits the different users to operate asynchronously, in order for a particular transmitter and receiver to exchange information, a synchronous link needs to be created, usually accomplished through code acquisition at the receiver.

II. Code Cycle Modulation

Conventional OOK transmits a copy of the spreading sequence to represent 1 and nothing for 0. In CCM, we transmit $\log_2 T$ bits in each transmission as described in following:

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[2]This work was supported in part, by the DARPA OCDMA Program under Grant No. N66001-02-1-8939.

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CCM Modulation: Since the spreading sequence is of length T, and all of the T cyclic shifts of the spreading sequence are distinct instead of binary signaling we can use $\log_2 T$-ary signaling, with each of the circular shifts representing one of the T symbols. Thus we can transmit $\log_2 T$ bits in each transmission. We name this modulation scheme *Code Cycle Modulation(CCM)* [3]. In following we show an example of how to generate all symbols from a single spreading sequence:

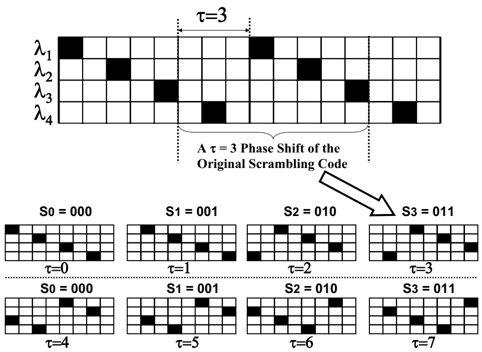

Fig. 1. Generating CCM symbols from a single spreading sequence

Now we can label different CCM symbols with all different T, $\log_2 T$ bits $\{0, 1\}$ sequences, and use them to transmit data. An example of this is shown in Fig.1 . As it can be seen in CCM in each transmission we are transmitting $\log_2 T - 1$ more bits.

Remark 1: What we are losing in CCM is the timing information. In OOK we know only one of the T circular shifts is possible, and with that we can extract timing information which is not the case in CCM.

III. Timing Issues in CCM

In a typical OCDMA system there are two separate phases in the receiver:

- **Acquisition period:** In acquisition period the receiver tries to synchronize itself with the transmitter. In this mode the receiver take advantage of the good autocorrelation property of the spreading sequence. There are different algorithms for OCDMA acquisition. At the end of acquisition period the receiver and transmitter are synchronized.
- **Tracking period:** In tracking mode the receiver and transmitter are synchronized and the receiver is receiving data from transmitter. In a classical OCDMA system each user transmits the spreading sequence to transmit 1, and transmit nothing to transmit 0, which is equivalent to on-off keying(OOK).

In the tracking mode, while the whole system is asynchronous the transmitter and receiver are synchronized. On the other hand it was mentioned as OOC properties that each sequence is distinct from all of its cyclic shifts, and that is necessary to maintain the synchronization between the receiver and transmitter. When the synchronization is established there is no need to transmit synchronization data which is hidden in each sequence.

Once we have established synchronization at the beginning of the packet, then we don't need any synchronization data within the packet. The synchronization at the beginning of the packet can be achieved using a preamble.

IV. CCM Demodulator

While CCM concept can be applied to all OOCs, from now on we focus on specific category of 2-D OOCs called at most one puls per wavelength(AM-OPPW) 2-D OOCs. This category of OOCs are the most important ones for implementation [3]. A $(\Lambda \times T, \omega, \kappa)$ 2-D OOC is an array in Λ wavelength and T chip times, Hamming weight ω and maximum correlation parameter(MCP) κ. The AM-OPPW 2-D OOC has maximal weight 1 per wavelength.

Since in CCM the data is encoded in the amount of circular shifts of the spreading sequence,τ, a CCM demodulator should detect the amount of circular shift of the received sequence in comparison to the basic sequence,τ. In following we propose a demodulation scheme in which demodulator is generating a pulse at the output with a delay relative to the amount of circular shift, τ.

In classical OCDMA demodulator the inverse of the delay patterns applied in modulator will be applied in demodulator to stack all pulses on top of each other, and then using appropriate gating, the stacked pulses are detected by the optical receiver. This demodulator can't be used for CCM since in circular shifting some of the pulse may wrap around the frame, and these pulses won't stack up with other pulses, while they stack up on the same instant of the frame one symbol time prior to the other pulses.

To solve this problem we need to delay the wrapped around pulses for one symbol time to stack all the pulses on top of each other and then detect the amount of circular shift,τ. In addition since the detection takes more than one symbol time, and can take up to two symbol times, the detection can't be done with a single receiver, and we need a dual receiver. To solve the wrap around problem we are proposing a novel Cycling Optical Shift Register(COSR):

A. Cycling Optical Shift Register

Figure 2 shows a proposed implementation for COSR. COSR essentially consists of T delay line in wavelength λ of duration T_c, where T is the number of time slots in the spreading sequence, and T_c is the chip time duration. The input to the COSR is in wavelength λ. There is a switch in COSR which can switch between the two operating modes of COSR:

- **Loop:**In the loop mode the switch is connects its input from COSR back to COSR, and creates a loop. The whole delay from input going around the loop to the output of the coupler should be equal to one symbol time. This is

[3]This idea is similar to multibits/sequence-period OOCDMA of [5] which we developed independently and named it CCM

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for the wrap around pulses, which should wait for one symbol time to be able to stack with other pulses.
- **Delay:** When the switch is connected to the output, COSR is working in delay mode, and the whole delay from input to the output should be equal to d_λ. This delay is used to stack all the pulses on top of each other. This delay is determined with the number of delay lines from input to output.

Remark 2: While it is not possible to implement COSR using discrete components for practical optical communication speeds, because of the small delay lines needed, implementing them on a chip is not far from imagination.

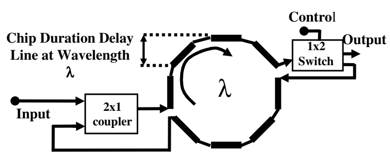

Fig. 2. Suggested implementation of COSR

B. Dual COSR Receiver

A COSR receiver module is shown in Figure 3. A COSR receiver module consists of a demultiplexer which separates the different incoming wavelengths, and a collection of COSRs working in parallel, and a multiplexer to couple different wavelengths into one output.

The number of COSRs is equal to the number of incoming wavelengths, Λ, and the delay between input and output on COSR working in wavelength λ is d_λ which is the delay needed in wavelength λ to stack up all the pulses in classical OCDMA receiver.

COSR receiver module has two different phases:

- **Buffering Phase:** In buffering phase the input port is connected to the input line and all of the COSRs are in loop mode. After T chip times all of the pulses are stacked on top of each other in some on known segment of COSR.
- **Detection Phase:** After T chip times (one symbol time)the input port will be disconnected from input line, and the COSR will go to delay mode. At this point if the stacked pulses are at the input of the switch then they will be forwarded to the output which is equivalent to $\tau = 0$. If $\tau \neq 0$ then the pulses are in some segment with distance τT_c from output, and will arrive to the output after τ chip times. So at the output we will receive a pulse with a delay relative to a reference clock which is proportional to τ. Thus COSR receiver module convert CCM to PPM.

All we need now is to parallel two COSR receiver modules to create the actual demodulator. We should arrange the two modules such that when one of them is in buffering phase, and is connected to the input, the other one is in detection phase, and is connected to the output. In this way we can retrieve all information with one symbol delay. One implementation of the dual COSR receiver is shown in Figure 4.

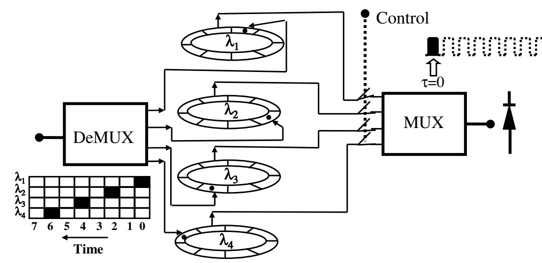

Fig. 3. COSR receiver module

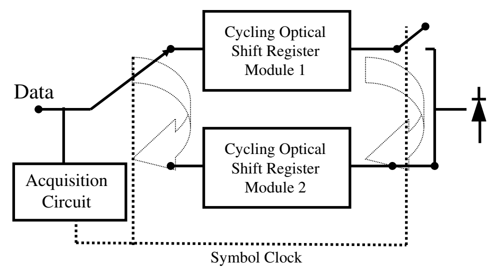

Fig. 4. Dual COSR receiver

V. Interference Model

Let's assume there are two users A and B in the system, and we need to find the pmf of multiple access interference(MAI) B creates on A. As it is shown in Figure 5, user A and B have a time shift equal to δ, where $0 \leq \delta < T$, due to asynchronism of two users . So in each time slot T some cyclic shifted version of user A's code experiences interference from two consecutive symbols of user B:

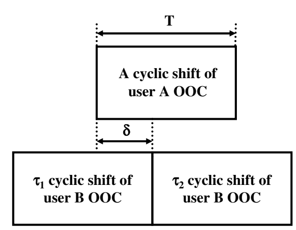

Fig. 5. Interference realization between two users A and B

- The last δ chip times of first symbol, which is a τ_1 cyclic shifted version of user B OOC.
- The first $T - \delta$ chip times of second symbol, which is a τ_2 cyclic shifted version of user B OOC.

In the conventional OCDMA, $\tau_1 = \tau_2$, so the two consecutive symbols act as a symbol which is synchronous with user A and uses a τ' cyclic shifted version of user B OOC. On the contrary in CCM τ_1 and τ_2 vary from symbol to symbol, while δ remains fixed for a specific realization of two users.

Pmf of MAI for the conventional OCDMA which is equivalent to the case of $\delta = 0$ is derived in several papers for example [3]. Let call this pmf $p_T(h) = Pr(\text{some interferer of length } T \text{ causes } h \text{ units of interference})$. Now we need to find $p_\delta(h)$. If we assume spreading sequences as random codes with maximum collision restriction as it

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is assumed in [3] then the probability of having collision equal to $h \neq 0$ scales with $\frac{\delta}{T}$, while probability of having 0 collision increases:

$$p_\delta(h) = \begin{cases} \frac{\delta}{T} p_T(h), & h \neq 0 \\ (1 - \frac{\delta}{T}) + \frac{\delta}{T} p_T(0), & h = 0 \end{cases} \quad (1)$$

Remark 3: Note that, the above formulation is true for AM-OPPW 2-D OOCs. While for general OOCs(1-D and 2-D) we need to apply an additional condition that the number of hits should be less than or equal to the δ times number of wavelength, which is always true in at most one pulse per wavelength 2-D OOCs. Since we are more interested in these type of OOCs we don't consider the other case, which is essentially the same formulation with an additional restriction.

Let's assume the interferences caused by two independent cyclic shifts of the same OOC have independent pmfs. This assumption is valid for a large number of interferes. Then we can compute the pmf of MAI of B on A as:

$$P^B_{MAI|\delta} = p_\delta * p_{T-\delta} \quad (2)$$

where $*$ is convolution operator. To compute pmf of MAI in general we should average it on δ:

$$P^B_{MAI} = \sum_{\delta=0}^{T-1} P^B_{MAI|\delta} pr(\delta) = \frac{1}{T} \sum_{\delta=0}^{T-1} P^B_{MAI|\delta} \quad (3)$$

Assuming there are S independent users $B_1, B_2, \cdots, B_S$ interfering with user A we can compute the over all pmf of MAI recursively as:

$$P^{B_1,B_2,\cdots,B_S}_{MAI} = P^{B_S}_{MAI} * P^{B_1,B_2,\cdots,B_{S-1}}_{MAI} \quad (4)$$

Let's take $p_T(h)$ equal to the pmf of single interferer for AM-OPPW 2-D OOCs developed in [3]. Figure 6 (a) shows pmf of MAI for a code with 32 wavelengths, 64 chip times, weight 20 and MCP equal to 1 for 15 and 30 interferers. As it can be seen pmf tail goes to two times MCP. In Figure (b) the same graphs are plotted against conventional OCDMA in logarithmic Y axis. In this figure solid lines show CCM model, while dotted lines show conventional OCDMA system. As it can be seen there is a significant difference between the two set of curves. This is mainly due to fact that conventional OCDMA does not transmit anything for symbol 0, hence the average traffic on the line in CCM is twice the average traffic in conventional OCDMA.

To make a comparison, we plot a conventional OCDMA which always transmit using dashed lines in Figure 6(b). It is clear that the MAI of CCM and always on conventional CDMA are not significantly different thus as a rule of thumb we can say MAI in CCM system is approximately equal to MAI in a conventional OCDMA system with half the number of interferers. The small difference between these two set of curves is in their tails, and that is because maximum MAI in CCM is potentially twice maximum MAI for always on conventional OCDMA system.

Remark 4: Note that we are only talking about MAI in this Section. The performance of the two systems depends on the receiver structure and will be discussed in Section VII.

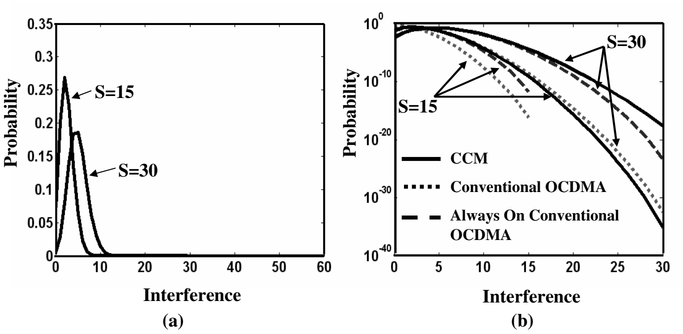

Fig. 6. Pmf of interference for code of dimension $(\Lambda \times T, \omega, \kappa)$ equal to $(32 \times 64, 20, 1)$ for S interferers:(a) CCM and (b) CCM vs. conventional OCDMA and always on conventional OCDMA

VI. Gaussian Interference Model

As Central Limit Theorem says, we expect the pmf of MAI converge to a gaussian pdf for large number of interferers . In this Section we develop a gaussian approximation model for MAI of CCM . The model we develop in this Section uses at most one pulse per wavelength 2-D OOCs. All of the results can be generalised to general OOCs with a little more details, which we omit them in this paper.

It is not possible to impose the OOC restriction in Gaussian assumption. So the Gaussian assumption is not exact in tails, but it gives a good picture of code performance. Since we are not going to impose OOC restriction, we can assume the code in each wavelength as a separate OOC of weight either 1 or 0 with probabilities $\frac{\omega}{\Lambda}$ and $1 - \frac{\omega}{\Lambda}$. For large number of interferers, this assumption is not that bad, and justifies why we can ignore the OOC restrictions.

For any two of these single wavelength OOCs in the same wavelength which both of them have a 1 in that wavelength probability of interference is $\frac{1}{T}$ for CCM and $\frac{1}{2T}$ for conventional OCDMA (OOK). Probability of interference is 0 if any of the two has no 1 in that wavelength. Since we know the ω wavelengths in which our user of interest has a 1, we will look only at these wavelengths. So :

$$p^{B_i,\lambda_j}_{MAI,CCM}(h) = \begin{cases} \frac{\omega}{\Lambda T}, & h = 1 \\ 1 - \frac{\omega}{\Lambda T}, & h = 0 \end{cases} \quad (5)$$

Where i varies over the interferers and j varies over the wavelengths which user of interest has its 1s. It is obvious if we substitute T with $2T$, we will find MAI for conventional OCDMA. So MAI for a single wavelength OOC will be a Bernoulli random variable. The mean and variance of this process is:

$$m^{B_i,\lambda_j}_{MAI,CCM} = \frac{\omega}{\Lambda T}, (\sigma^2)^{B_i,\lambda_j}_{MAI,CCM} = \frac{\omega}{\Lambda T}(1 - \frac{\omega}{\Lambda T}) \quad (6)$$

Assuming all of the ΛS single wavelength interferes to be independent, we can find the total mean and variance MAI on user of inerest as:

$$m_{MAI,CCM} = \sum_i \sum_j m^{B_i,\lambda_j}_{MAI,CCM} = \frac{\omega^2 S}{\Lambda T} \quad (7)$$

$$\sigma^2_{MAI,CCM} = \sum_i \sum_j (\sigma^2)^{B_i,\lambda_j}_{MAI,CCM} = \frac{\omega^2 S}{\Lambda T}(1 - \frac{\omega}{\Lambda T}) \quad (8)$$

Using Central Limit Theorem we can use a gaussian random variable with mean and variance as computed in Equations (7) and (8) to estimate the MAI of S interferers:

$$P^S_{MAI,CCM} = \mathcal{N}\left(\frac{\omega^2 S}{\Lambda T}, \frac{\omega^2 S}{\Lambda T}(1 - \frac{\omega}{\Lambda T})\right) \quad (9)$$

Figure 7 (a) shows the MAI for a $(32 \times 64, 20, 1)$ CCM OCDMA system for 15 and 50 interferers using random code model from last Section and Gaussian model of this Section. As it can be seen the estimations are not the same, but they are close. We believe the random code approximate is more accurate, since all the assumptions of this model are present in Gaussian model too while the OOC restrictions which are applied in random code assumption are not applied in Gaussian model. The gaussian model overestimate the MAI, but it is an easy model to work with, and can give insight in system design. Note that the tail of Gaussian interference model extends for negative interference values too which is not valid. For large enough number of interferers which is the case of our interest the probability of negative interference goes to zero.

VII. CCM Performance

CCM performance depends on the receiver structure. The receiver described in Section IV, chooses a threshold, and if finds only one peak above the threshold decodes to that data and can't decode in other cases.

Lets set threshold to less than or equal to ω. Since the only degradation assumed on the line is MAI, an error occurs only if we receive a false peak. Since the MAI distribution for all chip times(all cyclic shifts of the user of interest's OOC) is the same, probability of a false peak is given by:

$$Pr(\text{false peak on chip time } i) = \sum_{h=\lceil th \rceil}^{2S\kappa} P^S_{MAI,CCM}(h) \quad (10)$$

Using Union bound:

$$P_e \leq \sum_{i \neq \text{original signal}} Pr(\text{false peak on chip time } i)$$

$$\Rightarrow P_e \leq (T-1) \sum_{h=\lceil th \rceil}^{2S\kappa} P^S_{MAI,CCM}(h) \quad (11)$$

Remark 5: As it can be seen from P_e formulation, for CCM and conventional OCDMA systems with similar MAI distributions, the CCM perform worse in error probability for equal number of interferers by a factor of $T-1$.

Spectral efficiency η in an OCDMA system is defined as:

$$\eta = \frac{AR_b}{\text{Total bandwidth}} = \frac{Ab}{\Lambda T \alpha} \quad (12)$$

Where $A = S+1$ is the number of active users in the system, $R_b = \frac{bR_c}{T}$ is each user's data bit rate, R_c is each user's chip rate, number of chip times in OOC is shown by T, b is the number of bits per symbol and α is wavelength spacing parameter between any two consecutive wavelengths. We set $\alpha = 1$ for the rest of the paper:

$$\eta_{CCM} = \frac{A_{CCM} \log_2 T}{\Lambda T}, \eta_{OOK} = \frac{A_{OOK}}{\Lambda T} \quad (13)$$

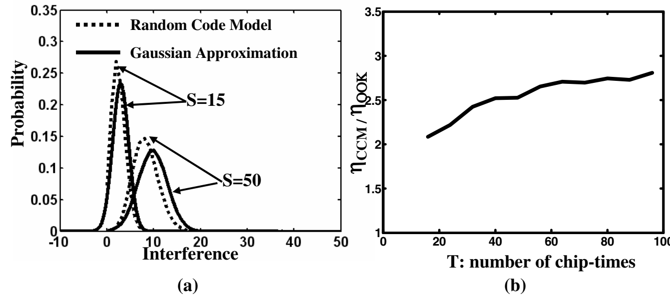

Fig. 7. (a)Pmf of interference for code of size $(\Lambda \times T, \omega, \kappa)$ equal to $(32 \times 64, 20, 1)$ for S interferers based on random code model and Gaussian model (b)CCM improvement in spectral efficiency over OOK for $(\Lambda \times T, \omega, \kappa) = (32 \times T, 20, 1)$

In Figure 7 (b) the increase in spectral efficiency of CCM over OOK is shown for sytem error fixed at 10^{-9} using random code model for MAI. It is easy to see that the increase in Spectral efficiency is almost equal to $\frac{\log_2 T}{2}$.

VIII. Conclusion

In this paper we showed an M-ary modulation scheme for OCDMA and a novel receiver design for it. Despite previously proposed M-ary OCDMA systems, our approach doesn't need M different receivers and the proposed receiver model can scale without much increase in system complexity. We analyzed the performance of the system and showed that pmf of interference in our system lies between the pmf of interference of an OOK system which always transmits 1 with the same number of interferers and an OOK system with twice the number of interferers. Although the system experience an increased probability of error in comparison to an OOK system with the same interference model because of its M-ary nature. We showed that our system increases the spectral efficiency by a factor close to $\frac{log_2 T}{2}$ over OOK system for threshold set at OOC weight ω.

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