A Survey to Optical CDMA Systems – Part II: Performance Improvement Schemes

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***Abstract*— Optical CDMA (Code Division Multiple Access) is an enhancement of wideband CDMA to access the optical communication channel having huge bandwidth. The OCDMA technique is very promising as it has the capability of transmitting data at 10–100 Gbps data rates. This survey paper describes the Optical CDMA, its advantages and disadvantage. Apart from the well known multiple access interference reduction schemes, spectral efficiency maximization techniques, and some security performance improvement methods have been also described here. These different performance improvement methods also have their limitations. There is requirement of such schemes which improve the bit error rate (BER), spectral efficiency and security performances simultaneously in the same Optical CDMA system.**

***Index Terms*— Optical CDMA (Code Division Multiple Access), Multiple access interference (MAI), spectral efficiency, security performances.**

I. Introduction

IN the present age of globalization, people are coming closer via different mediums of communications. These mediums of communications need to transfer data at high bit rates and without errors among multiple pairs of users communicating with each other. Among all the mediums of communication available to us, optical fiber is capable of providing a huge bandwidth, of the order of tens of Tera-Hertz. Because of bunching of many fibers in a cable and many cables in a conduit, and many conduit in a dig, a network span is able to provide bandwidth of the order of thousands of Tera-Hertz. This poses the challenge to research community, how to utilize this huge amount of available bandwidth ? To access the optical fiber bandwidth by multiple users, some well known multiple access schemes are (i) Wavelength Division Multiple Access (WDMA), (ii) Optical Time Division Multiple Access (OTDMA), (iii) Optical Code Division Multiple Access (OCDMA).

The Optical CDMA scheme is able to provide good results in terms of asynchronous access, bandwidth utilization, inherent security and simple network management & control. However a few shortcomings are also associated with this scheme [1]. The research community has to accept them as challenge for the success of OCDMA schemes. A few challenges are given below.

a) When multiple users access the same sub-channel using different optical orthogonal codes, due to interactions among them multiple access interference is created. This Multiple Access Interference (MAI) is unwanted at the time of extraction of desired signal from the multiplexed signal as it increases bit error rate. To reduce this MAI, many reduction schemes have already been proposed [5-15]. They reduce MAI at the cost of spectral efficiency and security performances.

b) The spectral efficiency, or the utilization factor of bandwidth offered by optical fiber, is to be maximized. Some schemes are already proposed in [16-24] to maximize the spectral efficiency, yet more research is needed to increase the spectral efficiency more than 1 b/s/Hz.

c) The inherent security of the Optical CDMA system, provided by the optical orthogonal codes, may be broken at any destination with the knowledge of some parameter of code used for encoding at OCDMA encoder. Hence the security is to be enhanced by some other techniques also so that information could not be decoded by unwanted users.

d) The requirement is to create coding schemes in such a way that it would help in reduction of MAI, help to improve the spectral efficiency and security performance.

e) The integration of OCDMA encoder and decoder on a single chip covering very small area is another issue.

f) The simplification of network management and control is also an important issue in coherent type OCDMA systems.

II. Multiple Access Interference (MAI) Reduction Schemes

First we should explore about Multiple Access Interference (MAI) in context with OCDMA system as What MAI is, Why it is present at receivers of OCDMA system and How can it be reduced. MAI is a common drawback of any CDMA system. This interference is caused in the optical channel due to simultaneous access of same channel by two or more than two optical transmitters with imperfect optical orthogonal codes as signature sequences. This MAI is caused only when at least one other transmitter is sending the imperfect optical orthogonal code for data bit ‘1’, while for data bit ‘0’ no MAI because for data bit ‘0’ no optical pulses are sent to the channel. Hence the main reason for MAI is use of imperfect orthogonal code as signature sequences to access the optical channel .

For the case of Incoherent Optical CDMA system the optical orthogonal codes are uni-polar. The uni-polar codes are formed from binary digits (0 and 1) with code length ‘n’ representing the number of bits in code-word and with code weight w representing the number of total '1' bits in the code word. By the definition of perfect orthogonal code the dot product of two or more than two perfect orthogonal code is zero. As per definition of optical orthogonal codes and its auto-correlation properties [2] the uni-polar orthogonal code and its all shifted sequence represent to same uni-polar orthogonal code word. The dot product of these shifted sequences with optical orthogonal code word should be minimized to zero for proper detection of autocorrelation peak as synchronizing pulse at receiver and detection of data bit '1'. The dot product of orthogonal code word with its shifted sequences can be constraint upto a limit called auto-correlation constraint λ_a which is not responsible for MAI but its higher value close to auto-correlation peak (amplitude w) may be responsible for wrong detection at receiver, hence it should be minimized upto zero. For the case of uni-polar orthogonal code word auto-correlation constraint λ_a can not be less than one because of binary dot product . The auto-correlation constraint λ_a has a range from 1 to w-1.

As per definition of optical orthogonal code and its cross-correlation properties [2], the maximum value of dot product of one uni-polar orthogonal code word with other orthogonal code word and its shifted sequences is called the cross correlation constraint λ_c. No uni-polar orthogonal code word pair has λ_c equals to zero because of binary dot product. This cross-correlation constraint λ_c is ranged from 1 to w-1. The non zero value of λ_c is responsible for MAI. Hence MAI is always present at the receiver in case of Incoherent optical CDMA system with uni-polar orthogonal codes. The MAI can be minimized by the use of uni-polar orthogonal codes having minimum value of λ_c i.e. one. Similarly for correct detection of auto-correlation peak and correct synchronization of bit period, minimum value of λ_a should be one. Hence we search for the code set of maximum possible optical orthogonal codes with minimum λ_a and λ_c. The maximum possible optical orthogonal code number N of code length 'n', code weight 'w' with $\lambda = \lambda_a = \lambda_c$ is given by Johnson's' bounds [2].

The Optical CDMA transmitters send the optical orthogonal encoded information for data bit '1' and no optical pulses for data bit '0' to the channel. The channel accepts such N signals to transmit them to every receiver. The receiver correlates this intermixed signal from channel with its signature sequence and separates the data intended for it. If the data intended for the receiver having a bit '0' , then no optical pulse will be sent in the bit period T_b. The receiver accepts at most N-1 encoded signal, which is correlated with already stored user's code, if it has a finite value exceeding particular threshold value, it may be detected as bit '1' which is the wrong decision by detector as bit '0' was forwarded. While there is no error if bit '1' was sent, as it is always decoded as bit '1' even in the presence of multiple access interference [3,4].

It can be estimated how the probability of error is related with the MAI and other parameters of the orthogonal code set. The probability of error for chip synchronous and noise free OCDMA [4] is calculated as

$$P(E) = \sum_{i=\mu}^{N-1} \left({}^{N-1}C_i \right) \left(\frac{w^2}{2L} \right)^i \left(1 - \frac{w^2}{2L} \right)^{N-1-i}$$

Here N is number of active user, μ is the threshold value, w is the weight of the code, L is T_b/T_c or length of the code word. The meaning of chip synchronous is that the chip period T_c is same for every user and their chips starting or chip ending time is not different with each other users.

To reduce the MAI or P(E) which is responsible for bit error, some schemes are proposed in [5-15] by Research technocrats time to time for different optical cdma systems. Some of the schemes which reduce MAI significantly are given below.

(i) There is a scheme with modified PN sequences and Fiber Bragg Grating (FBG) encoder and decoder [5]. Here the modified PN codes has equal number of '1' and '0' in the code of even length. Suppose a modified PN sequence (11100100) is assigned to one user. This user generates a optical stream of pulses with different wavelengths $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8)$ as $(\lambda_1 \lambda_2 \lambda_3 00 \lambda_6 00)$ by FBG encoder for data bit '1', and it's complement as $(000 \lambda_4 \lambda_5 0 \lambda_7 \lambda_8)$ is generated by same FBG encoder for data bit '0'.

The receiver is equipped with FBG decoder and two photo diode PD1 and PD2. The received signal is matched by FBG decoder and passes to either of photo diode. The PD1 detects the signal as data bit '1' and PD2 detects the signal as data bit '0'. This proposed system can obtain the same performance at a lower Signal to Interference Noise Ratio (SINR) by 6 dB than that of conventional system with uni-polar capacity.

(ii) The high performance optical thresholding technique is demonstrated by using super-continuum (SC) generation in normal dispersion-flattened-fiber (DFF) for reducing the MAI in high chip rate coherent OCDMA system [6]. The proposed SC is comprised of an EDFA, a 2 km long DFF, and a 5nm band pass filter (BPF). The operating principle is that the decoded optical signal is boosted by EDFA to high peak power with 2 ps pulse width which can generate SC in the DFF. The incorrectly decoded signal is spread over large time span with low peak power so that it is unable to generate SC. The BPF only allow the SC signal and rejects the otherwise so that MAI noise is suppressed.

(iii) The Adaptive Resonance Code (ARC) are generated with a given algorithm in [7] and compared with other Time Wavelength Hybrid (TWH) codes for Multiple Access Interference (MAI). The MAI is most responsible factor for Bit Error Rate (BER).

$$(MAI)_i = \sum_{j=1, j \neq i}^{N-1} \max(R_{xy}(m))$$

$(MAI)_i$ is multiple access interference at i_{th} node (for i_{th} user)
And $R_{xy}(m)$ is cross correlation of two sequences X and Y
The bit error rate at any node depends on the MAI, lower is the MAI lesser will be the bit error rate for that node. The ARC code are selected on the basis of the least value of MAI between two codes as compared with the MAI of selected codes. So that the ARC always present with lowest value of MAI as compared with other code set like OW (OOC + WDMA), PH (Prime Hop), EP (Eqc. Prime), MW (Multi Wavelength) , OC (Optimal Code). The MAI of these different coding schemes is compared in [7] and found ARC with lowest MAI i.e. with least probability of error or BER.

(iv) The Interference Avoidance for Optical CDMA system is described in two parts (i) State estimation and (ii) Transmission scheduling in [8]
In state estimation the node estimate the state of line and next the transmission scheduling decides the appropriate time to send the packet so that lower number or no collision of weighted chips occur. The packets sent between state estimation and transmission scheduling may causes interference. By the protocol Interference sensing/ Interference detection (IS/ID), the node estimate the state and schedule the transmission.
In [9,10,11,12], the estate estimation and transmission scheduling are described along with there algorithms.

(v). The serial interference cancellation with first stage in which the interference is reproduced and then subtracted from received data is described in [13]. For N number of users there are N-1 serial cancellation stages along with N-1 different optical orthogonal codes. Here first cancellation stage is described for desired user #1 with consideration of interference produced by N^{th} user with different threshold values starting from 1 to w, the weight of the code.
The BER performance of the described system is compared with conventional optical cdma system for different number of users yielding better performance as compared with others.

(vi). The parallel interference cancellation stage is described with lowest threshold value in [1. Initially BER performance of conventional OCDMA system is compared with OCDMA system with optical hard limiter before the OCDMA receiver. It reduces the effect of MAI upto some level but not the effect of other noises in the receiver at lowest threshold value. This problem can be solved by using parallel interference cancellation stages. All N-1 interference cancellation stages are connected in parallel to get the sum of all interference produced by each respective unwanted users. This complete interference is subtracted from the received signal to get the desired signal without MAI.

(vii). A simple direct detection optical PPM – CDMA system is described with interference cancellation [15]. The modified prime sequences are used as signature sequence, and at receiver the Poisson effects of photo-detection process are considered.

II. Spectral Efficiency Maximization Techniques

The spectral efficiency of Optical CDMA system is the optical fiber bandwidth utilization factor, in terms of bit/s per Hertz. This factor is equal to total bit rate through the channel divided by bandwidth offered by optical fiber. The redundancy bits added by spread spectrum modulation and/or by channel encoding to binary data, increases the requirement of bandwidth and decreases the spectral efficiency. The normal value of spectral efficiency lies around 1.0 but for CDMA system it is very less than 1.0. There are some spectral efficiency increasing techniques are described [16-24] as follows

(i). The M –ary modulation scheme is proposed in [16] to enhance the spectral efficiency of the optical cdma system. Here each user is assigned with an optical orthogonal code modulate its information with optical pulse in M-ary modulation fashion before launching the modulated information into the optical fiber. It improves the spectral efficiency i.e. the bandwidth utilization factor. For incoherent optical CDMA M-ary intensity modulation or M-ary wavelength shift keying may be utilized but for coherent OCDMA M-ary phase shift keying or wavelength shift keying may be utilized. It increase complexity at receiver and requires M number of optical wavelength pulses.

(ii). An OCDMA technology demonstrator (TD) based on a set of 32 2D OOCs is designed in [17]. The TD design has been captured in a system simulation (R_Soft LinkSIM) to explore and refine the system concept. Based on the simulation results, a guard-time is proposed to add to the 2D codes generated by combinatorics. An OHL is also incorporated the correlator (decoder). The spectral efficiencies (32/64 (=0.5 bit/s/Hz) with guard-time and OHL, and 16/64 with guard-time only) are found superior to those reported for other OCDMA 2D codes.
The added degree-of-freedom with PPM is that the autocorrelation peak can appear in any of the chip times, and this time location carries added information.
One key limitation of PPM is that optical chips are allowed to leak into the adjacent symbol times, thus changing the dynamic of the MAI produced by other users.

(iii). An analytical model is derived that provides the full statistics of the probability distribution of MAI in an O-CDMA network that uses PPM [18]. It is concluded on this basis that the effect of increased MAI in PPM is almost like MAI in conventional OCDMA with twice the number of users. Its is also observed that overall increase using PPM OCDMA is up to ~3X increase in spectral efficiency as compared to conventional OCDMA.

(iv). The authors discuss about optical amplifier and proposes to use it in experimental and simulated OCDMA systems [19]. The spectral efficiency and number of supported users (about 10 to 20) have been limited due to severe multi-user interference which degrades the transmitted information, by high transmission rates at which the signal processing has to be performed and because of limited all-optical signal processing capabilities. It shows that if with Reed-Solomon code over *GF(256)* followed by Berrou's rate 1/3 turbo code, which are separated by a user-specific interleaver (permutation). The coded data are then modulated with specific optical spreading sequences of length *N=128* before being sent through the optical channel. The used OCDMA spreading sequences are quaternary with chip intensities m = 0,1,2,3 used with near-optimal probabilities, the use of optical amplifiers allows the system to support more than 120 active users at BER=10^{-9}, where as this number limits on 70 without optical amplifier.

(v). In this scheme [20], it is supposed that number of available codes is much greater than number of active users at any given time. Each user is assigned with M number of codes such that K = Log_2M, every code word represent K- tuple of bits. It increases the overall spectral efficiency of the system but the encoding and decoding become complex.

(vi). In this scheme [21] forward error correction and dynamic threshold optimization is combined to improve spectral efficiency. Multiple pulse-per-row (MPR) codes with optimum threshold detection are used in this approach. Each user is assigned a MPR code matrix with **N,** rows, L_t, columns, and a constant weight of W= N_w R. N_w is the number of wavelength channels. R is the number of pulses per wavelength channel in the code matrix. Codes used are the flexible BCH family of codes with a block length of n=511 which allows the correction of up to 121 bit errors in each frame. With the use of BCH code, the spectral efficiency is given by:

$$\eta_{BCH} = \frac{N_{su} \cdot B \cdot R}{N_w \cdot \Omega} = \frac{R}{{p_d}^2}$$

where *R* is rate of the code. By this method spectral efficiency is increased fourfold the spectral efficiency achievable in a multi-wavelength optical code-division multiple access network.

(vii). In the proposed scheme [22], each user "occasionally" transmits error-control coded information bits directly over the channel, This approach guarantees that each sent bit is corrupted by only a few symbols from interfering users (usually less than five). Consequently, the multi-user interference is reduced at the transmitter side and the achieved spectral efficiency is significantly increased, very high spectral efficiencies of up to 0.740 bits per channel use.
Here the effects of practical, non-ideal, optical devices is determined which are used throughout the optical CDMA communication such as optical transmitters, fiber, amplifiers and photo-detectors. M-ary OCDMA transmission with ideal channel parameters are taken to evaluate the spectral efficiency limits based on channel capacity calculations. Then the effect of practical optical transmitters, optoelectronic receivers and power-limited fiber-optic transmission is evaluated on the OCDMA spectral efficiency limits. This scheme also proposes a coded M-ary OCDMA transmission with practical parameters that can practically support hundreds of active users at low bit error rates.

(viii). A universal scheme is proposed [23] to allow transmission of any bipolar code over the uni-polar optical channel while maintaining the correlation properties of the codes. The transmitter and receiver structure will accommodate any bipolar code without any modification in hardware. The ultimate BER performance and the spectral efficiency achievable using bipolar codes over the uni-polar optical channel are quantified.
The problem of lack of negative pulse in a unipolar channel, will be overcome by converting bipolar codes to unipolar codes before sending them out to the unipolar channel. Monte Carlo simulations were done using Gold codes to estimate the performance of the proposed system. The proposed system is able to achieve the same spectral efficiency as an optical bipolar base-band CDMA system for all BER levels.

(ix). A highly spectral-efficient OCDM/WDM transmission by applying the quaternary phase-shift keying (QPSK) optical encoding/decoding accompanied by ultra fast optical time-gating and optical hard thresholding is demonstrated [24]. As a result, 6.4-Tbit/s OCDM/WDM (4 OCDM X 40 WDM X 40 Gbit/s) transmission using only within the conventional band (C-band) wavelength region is experimentally demonstrated with a spectral efficiency of 1.6 bit/s/Hz.

IV. `Security Performance Improvement Methods

However, any CDMA system is with inherent security through the use of orthogonal codes to modulate the binary information of every user. The eavesdropper has developed many other techniques to get unauthorized access of user's data from code division multiplexed signal received at every receiver. There are some scheme [25-33] described to avoid any unauthorized access of user's data.

(i). The security performance of OCDMA system has been analyzed in [25]. The analysis is qualitative and theoretical in nature. The author has considered both the time spreading and the wavelength hopping. The Kerckhoffs' principle has been considered before performing the analysis i.e. eavesdropper knows every thing about algorithm the thing he doesn't know is the key. He has also assumed that eavesdropper has sufficient amount of resources and is technologically sophisticated. He has assumed OCDMA system as a LTI (Linear Time Invariant) system, so if eavesdropper knows the input signal for any particular output he will be able to find a key or code used by the system. While quantifying the security performance, he has considered both the cases when eavesdropper has single user data and when he has multiple user data. He concluded that while transmitted energy is minimum, the security performance can be maximized. He also concluded that just processing of 100 bits with SNR of 12db is sufficient for breaking the encoding of OCDMA system.

(ii) In [26] the author has again analyzed the security performance of OCDMA system. This time he has examined spectral-phase-encoded OCDMA in place of On Off Keying on theoretical basis. The author has considered Kerckhoffs' principle and also has assumed that eavesdropper has sufficient amount of resources and is technologically sophisticated. He has assumed that eavesdropper is using optical beat detector for interception. He has done simulation using MATLAB. He concluded that though eavesdropper's receiver is capable in decoding spectral phase encoding yet is better then OOK in this regard. If user code can be changed regularly, approximately at the rate of data transmission, the capability of receiver of eavesdropper will get down drastically.

(iii). The security performance of OCDMA system has been experimentally examined using a Technology Demonstrator (TD) in [27]. TD will use OOC (Optical Orthogonal Codes) and IMDD (Intensity Modulation Direct Detection) with W = 4 and n_c x n_λ = 8x8. three types of experiments are performed. The first one characterizes the performance of an O-CDMA, the second checks the susceptibility of OCDMA to eavesdropping when the MAI is severe and the third if the members of a code set can eavesdrop on each other. And finally concluded that intruder can eavesdrop if BER is good but his performance degrades as the number of users increase.
(iv) It Presents a new technique time varying phase masking in OCDMA system for enhancing the confidentiality and security of system and evaluates its performance [28]. In this scheme a new layer of phase shifting is added over the top of already present phase encoding. This new layer is termed as phase mask. This mask will be changing with time. While comparing the performance of 3types of masks 8ps,4ps and 2ps 8ps gives the best performance needing $1.6X10^{19}$ random guesses to detect. So making a change at every 1600 sec will give the probability of interception equle to 10^{-10}

(v). Simple On Off keying is more vulnerable to attacks as it can be detected using a simple energy detector. In [29] authors has examined the code switching technique (on off keying with continuously changing codes) experimentally. In this experiment .4 ps pulses at 10GHz around 1542 nm are used. In this experiment they have used 2 different codes with 31M length.

(vi). There are two things are pointed out about OCDMA system [30], first how the number of users is related with confidentiality of the system and not the number of frequency bins used. Second, even if there are a large number of users, an eavesdropper can easily destroy the confidentiality of the system. It can only be avoided if keys can be refreshed at the rate comparable to data rate of system and so key will be changed before eavesdropper will find any thing.

(vii). The feasibility and security analysis of incoherent OCDMA system have been done in [31]. They have assumed that eavesdropper is using a Band Pass Filter along with band limited photo detector. In the experiment they have used a broad band light source along with bipolar coding and modified PN codes (The '0' bits were inserted at end of PN codes to balance the number of '1's and '0's and to make even code length). They have also analyzed the change in security performance with change in spectral width of chip. The entire test is done for 1.25 Gb/s for a transmission up to 20 kms.

(viii). A testbed for incoherent OCDMA with *One-time Pad* security with a capacity of four users have been developed in [32]. The codes used are two dimensional and in both time spreading and wavelength hopping i.e. WHTS OCDMA codes. They have used a novel tunable "dual-code" OCDMA encoder and decoder with optical layer XOR capable of OCDMA codes swapping on a bit-to-bit basis to enhance security performance and to decrease cross talk between users.

(ix). A testbed with *One-time Pad* security for coherent OCDMA system for avionics applications have been developed in [33]. They have used novel tunable optical dual-code encoders/decoders with an optical layer XOR capable of swapping codes on a bit-to-bit basis. This results in enhancing the security performance and decreasing cross talk between users. As a result of experiment on this testbed they have plotted BER versus received power for the eavesdropper.

V. CONCLUSION

The Optical CDMA system needed more to work in this field to bring it out from laboratories. First of all optical orthogonal coding schemes attract to find out the upper boundaries for designing of all possible one dimensional, two dimensional and three dimensional optical orthogonal codes. So that as per requirement possible orthogonal codes could be generated. Second, a common scheme or group of schemes is needed to find, such that multiple access interference is minimized for improving bit error rate, spectral efficiency is maximized along-with improvement in security performance and simplification of network management & control. Besides of this scheme, in future, more work is needed for reduction of dispersion and attenuation effect on OCDMA signals through optical fiber. The VLSI (Very Large Scale Integration) technocrats can work for integration of Optical CDMA systems.

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