Hybrid WDM/Optical CDMA System Based on Hybrid Spectral/Spatial Coding Scheme

Isaac A. M. Ashour[1], Sahbudin Shaari[1], P Susthitha Menon[1], Hesham A. Bakarman[1], Hossam M. H. Shalaby[2]

[1]Institute of Microengineering and Nanoelectronics(IMEN), Universiti Kebangsaan Malaysia,
43600 UKM Bangi, Selangor, Malaysia
[2]Department of Electronics and Communications Engineering, School of Electronics, Communications, and Computer Engineering,
Egypt–Japan University of Science and Technology (E-JUST), Alexandria 21934, Egypt

The purpose of this paper is to present the hybrid WDM/optical CDMA system based on a hybrid spectral/spatial (S/S) coding scheme. The proposed hybrid system enhances the optical CDMA system performance by overcoming the main limitations of the hybrid WDM/optical CDMA system that is based on spectral-amplitude coding (SAC) alone. These limitations are the WDM interference noise and intensity noise. We have applied modified quadratic congruence (MQC) code matrices as the signature codes for Optical CDMA users based on the S/S coding scheme. In addition, WDM channels have been integrated to optical CDMA signals over the same spectral band. The significance of this integration is to make the system more immune against eavesdroppers. This is because WDM signals act as a partial masking over encoded optical CDMA pulses.

Keywords: Optical code-division multiple-access (optical CDMA), spectral-amplitude coding (SAC), wavelength-division multiplexing (WDM), modified quadratic congruence (MQC) code.

1. INTRODUCTION

The optical CDMA and WDM systems have been of widespread implementation for local and metro access network. This is because optical CDMA systems provide users both simultaneous and asynchronous access to networks with high security [1], and WDM systems provide a relatively high transmission capacity [2]. In addition, optical CDMA can be overlaid onto existing WDM networks in order to enhance the network security [3-6]. These hybrid systems prompt high service differentiation in future access networks, where various bit rates and quality of service are simultaneously joined.

Recently, hybrid WDM/optical CDMA systems have been proposed for network security and demonstrations of WDM/ optical CDMA transmission have been performed [6, 7]. Our previous approach has been simulated for optical CDMA security enhancement, which is based on hybrid SAC/optical CDMA-WDM overlay scheme [4]. In addition, in-band transmission of both optical CDMA and WDM signals have been investigated [5]. The results indicate that, on the one hand, the proposed hybrid scheme can achieve acceptable performance with good data confidentiality. The performance of the proposed system, on the other hand, was limited due to the interference of WDM signals.

Several two-dimensional codes have been utilized for hybrid spectral/spatial schemes [8, 9]. In this paper, the Modified quadratic congruence (MQC) codes were used as the signature codes for optical CDMA in the spectral/spatial hybrid system [5, 10]. Furthermore, the WDM channels share optical CDMA signals in one hybrid system based on the hybrid S/S coding scheme. The code family in this scheme represented as 2-dimensional codes can improve the system performance for the hybrid WDM/optical CDMA system. This proposed system can overcome the limitation of WDM interference and intensity noise of SAC optical CDMA, in addition to increasing the security level due to

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*Email Address: isaacash@eng.ukm.my

implementing the partial mask by WDM signals, which has been reported in several recent papers [4-7].

The following sections of this paper are well-organized to fulfill its main purpose. The second section presents the system description for a hybrid WDM/Optical CDMA system based on spectral/spatial coding. The third section proposes the structure of the transmitter and receiver of the hybrid scheme. The fourth section provides a brief performance analysis for both sub-systems in a hybrid scheme, taking into account the effects of various types of noises and multi-access interference. In section V and VI, we have attempted to show the numerical results and the conclusion of this paper, respectively.

2. SYSTEM DESCRIPTION

The block diagram of hybrid WDM/optical CDMA system using 2-D spectral/spatial codes is shown in Fig.1. The family of spectral/spatial codes is constructed as similar in [8], where the MQC code sequences is utilized in the spectral domain. The code properties is found in [5, 10], where an MQC code family is denoted by (N , w , λ), where, p is for a given prime number, $N = p^2 + p$ is the code length, $w = p+1$ is the code weight, and $\lambda = 1$ is the cross-correlation. The optimal number of available code sequences is p^2 . Whereas the spatial domain is represented as the row has only one nonzero element that is a represented central wavelength [10]. Figure 1 also shows the spatial network that consists of $(p+1)M \times M$ star couplers, which is used to connect between spectral transmitters and receivers.

The MQC code matrices can be represented as C^k and C^l . To show three different codewords for three users as example, Table I in [10] illustrates a binary sequence number $s_{\alpha,\beta}(i)$ is given when $p = 5$:

$$\lambda: 12345\ 67\quad \ldots\quad \ldots\quad \ldots\quad 30$$

$$\begin{bmatrix} 10000\ 01000\ 00001\ 00001\ 01000\ 00100 \\ 01000\ 00001\ 00001\ 01000\ 10000\ 00010 \\ 01000\ 10000\ 01000\ 00001\ 00001\ 01000 \end{bmatrix} \begin{matrix} \text{Code Seq. } \neq 1 \\ \text{Code Seq. } \neq 2 \\ \text{Code Seq. } \neq 3 \end{matrix}$$

In each binary code sequence, we have $(p+1)$ groups, whereas each group has one nonzero only. Hence, each group can represent one row for the code matrices. For example:

$$\text{User 1:}\begin{bmatrix} 10000 \\ 01000 \\ 00001 \\ 00001 \\ 01000 \\ 00100 \end{bmatrix},\ \text{User 2:}\begin{bmatrix} 01000 \\ 00001 \\ 00001 \\ 01000 \\ 10000 \\ 00010 \end{bmatrix},\ \text{User 3:}\begin{bmatrix} 01000 \\ 10000 \\ 01000 \\ 00001 \\ 00001 \\ 01000 \end{bmatrix}$$

These code matrices are required to design encoders and decoders for optical CDMA system under the hybrid S/S coding scheme. C^k is in in-phase cross-correlation, and C^l is the complementary code sequence of C^k . They are written as

$$C^k_{i,j} = \begin{cases} 1, & \text{if } i = k \text{ and } j = y_{\alpha,\beta}(k) \\ 0, & \text{otherwise} \end{cases} \qquad (1)$$

where $y_{\alpha,\beta}(k)$ is expressed in [10]. The C^k and C^l represented in the same code matrices family.

$$A_{C^k C^l} = \sum_{i=1}^{p+1} \sum_{j=1}^{p} c^k_{i,j} c^l_{i,j} = \begin{cases} p+1; & k = l \\ 1; & k \neq l \end{cases}, \qquad (2)$$

and,

$$A_{C^k \overline{C^l}} = \sum_{i=1}^{p+1} \sum_{j=1}^{p} c^k_{i,j} \overline{c^l_{i,j}} = \begin{cases} 0; & k = l \\ p; & k \neq l \end{cases}. \qquad (3)$$

where $c^k_{i,j}$ or $c^l_{i,j}$ denotes the element of the *k*,*l*th MQC code, and $\overline{c^l_{i,j}}$ is equal $1 - c^l_{i,j}$.

In WDM/Optical CDMA hybrid scheme, M encoders/decoders pairs of Optical CDMA are based on weight $(p+1)$ of spectral MQC code matrices [5, 8, 10]. The details of these en/decoders function will be mentioned later in this paper. For a WDM system, the channels 1-to-N_w can be combined to one encoder of optical CDMA, and hence, they are transferred to all optical CDMA decoders via spatial technique. At the receiver, the different signals are split and filtered for users for both optical CDMA and WDM system.

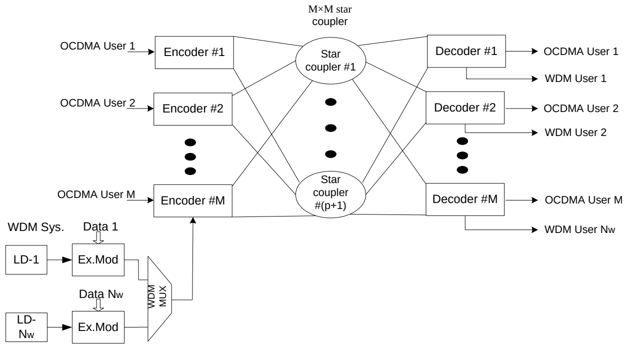

Fig.1. Hybrid WDM/Optical CDMA system based on Spectral/Spatial coding

3. TRANSMITTER/RECEIVER STRUCTURE

The transmitter/receiver structure of hybrid WDM/Optical CDMA system based on spectral/spatial coding is depicted in Fig. 2 and 3. The main method of the system architecture was mentioned in [8] without considering the hybridization of WDM system. The optical CDMA transmitter includes an unpolarized broadband light source (BLS), an electrical/optical modulator (EOM), an optical $1 \times (p+1)$ splitter, fiber bragg gratings (FBGs); and $(p+1)$ circulators, in addition to an optical combiner to feed WDM channels with optical CDMA signals into the spatial domain.

The optical pulses are produced by modulating binary data with on-off keying. The data of each optical CDMA user is encoded by the MQC codes matrices, which are prepared for being used in the spectral/spatial scheme. The row and column of the MQC codes are represented by the spectral and spatial domain, respectively. In corresponding of the MQC code properties, employing the $1\times(p+1)$ splitter is to split $(p+1)$ components of the modulating signal to achieve each row of the spatial domain. That means, in each spatial row (or dimension), a FBG can filter a specific wavelength from an BLS optical source when data bit is "1", and each filtered wavelength is transmitted to a particular star coupler. The combined signal from all optical CDMA and WDM signals that are gathered via star couplers is transmitted to each decoder. Different values of WDM channels N_w have been considered in this paper.

In Fig. 3, the optical CDMA interceptor consists of $(p+1)$ number for circulators and FBGs, two couplers with $(p+1)\times 1$ size, complementary photo-diodes (PDs), a decision device, a 2×1 splitter and notch filters. The output from a particular FBG filter is the specific wavelength from the encoded signal of each $(p+1)\times 1$ coupler. The function of these couplers in this process is to achieve the internal summation of Eq. (2). To accomplish the second part of balance detection as in Eq. (2), FBG filters transmit all spectral parts to other $(p+1)\times 1$ circulator except the specific reflected wavelengths, as illustrated in Fig.3. The received signals from FBG filters match up the internal summation of Eq. (3), and use the $(p+1)\times 1$ coupler to fulfill the result of Eq. (3). Figure 3 also shows notch filters that are used to suppress the effect of WDM interference. According to Eq. (3), the $1/p$ attenuator and differential detectors are utilized to carry out this equation for optical CDMA receiver. It is worth mentioning that the WDM system here can be an access system, or metro with using optical amplifiers. The dispersion compensating fiber (DCF) is provided to compensate the dispersion effect to the system.

At the balance detectors, we can have Eq. (4) that can be derived by the subtraction from Eq. (2) to $1/p$ multiply by Eq. (3). This technique is to cancel the multiple access interference (MAI) that is due to optical CDMA spectral elements.

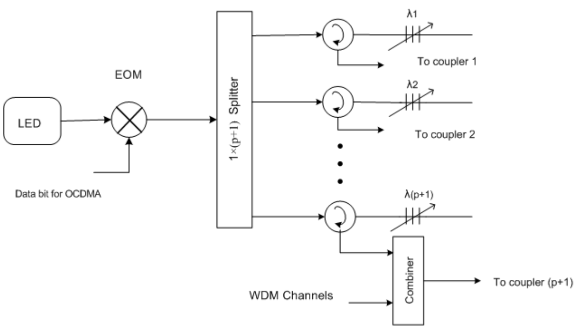

Fig.2. Hybrid WDM/optical CDMA system with optical CDMA network encoder

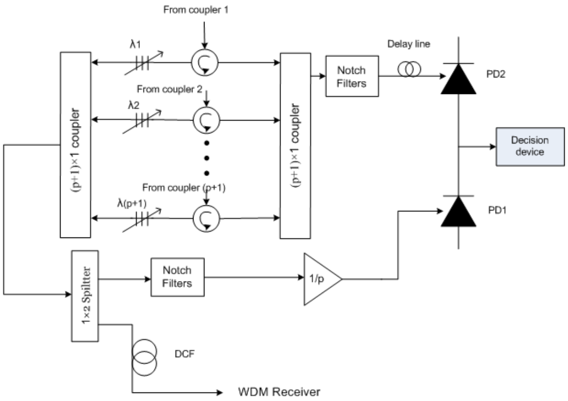

Fig.3. Hybrid WDM/optical CDMA system with Optical CDMA network decoder

$$A_{C^k C^l} - \frac{1}{p} A_{C^k \overline{C^1}} = \begin{cases} p+1; & k = l \\ 0; & k \neq l \end{cases}, \tag{4}$$

We can obtain this Equation at $p+1$ if and only if the code matrix is matched. Otherwise, the weight will be zero.

4. PERFORMANCE ANALYSES

The nature of SAC optical CDMA system is affected by three main noises; the phase-induced intensity noise (PIIN), shot noise, and thermal noise. The hybridization of two multiplexing techniques on the same spectrum band will increase the co-channel interference, which limits the performance for both subsystems. However, the DCF fiber is added as we assume that the dispersion effect is properly compensated, as well as the effect of nonlinearity is negligible because the peak power of the signals is small [7]. In addition, channel synchronization of spatial systems is a critical issue. To overcome this issue, employing a technique of utilizing two orthogonal polarization states to attenuate space asynchronously has been performed [11]. In this paper, the balance detector is used to remove the effect of MAI, and hence, synchronization for the spatial channels is achieved.

4.1 Optical CDMA Subsystem Analysis

The photocurrent variance resulting from an ideal broadband light source (BLS) can be written as follows [5, 10]:

$$\begin{aligned}\left\langle N_{Noise}^2 \right\rangle &= \left\langle i_{PIIN}^2 \right\rangle + \left\langle i_{Shot}^2 \right\rangle + \left\langle i_{Th}^2 \right\rangle \\ &= I^2 B \tau_c + 2eIB + 4K_b T_n B / R_L ,\end{aligned} \tag{5}$$

where I is the average current, B is the noise-equivalent electrical bandwidth of the receiver, e is electron's charge, K_b is Boltzmann's constant, T_n is the absolute receiver noise temperature, R_L is the receiver load resistor, and τ_c is the coherence time of the source. The coherence time can be expressed as [5, 10]

$$\tau_c = \int_0^\infty G^2(v)dv \bigg/ \left(\int_0^\infty G(v)dv\right)^2 , \qquad (6)$$

where $G(v)$ is the single sided power spectral density (PSD) of the source.

The system assumptions and symbol definitions follow that of previous studies [5, 10], that is: Each light source is unpolarized and its spectrum is ideally flat over a bandwidth of $[v_0 - \Delta v/2, v_0 + \Delta v/2]$, where v_0 is the central optical frequency and Δv is the optical source bandwidth, all users have the same power at the receiver, the spectral width is identical for each user, and the bit stream is synchronized for all users. For the sake of mathematical convenience, we suppose, without loss of generality, that the bandwidth of a WDM channel B_w is a multiple of the chip width $B_c = \Delta \nu / N$ of the MQC code sequences. That is, $B_w = \ell B_c$ with ℓ an integer. The received SAC optical CDMA signal $r(\nu)$, before the notch filters and optical CDMA decoders, is a sum of the transmitted signal $s(\nu)$ and the WDM interferers $w(\nu)$.

$$r(v) = s(v) + w(v). \qquad (7)$$

As mentioned earlier, the notch filters can suppress the high power of WDM interference. We assume that the notch filters ideally attenuate the WDM power to the level of an optical CDMA signal. The average desired signal power and interference can be expressed as follows

$$\left\langle S^2 \right\rangle = \left(\Re \frac{P_{sr}(p+1)}{2p} \right)^2 , \qquad (8)$$

$$\left\langle \text{Interf}^2 \right\rangle = \left(2\Re \frac{P_{sr} \ell N_w}{N^2} \right)^2 (p+1)^2 \left(2 - \frac{1}{p} \right), \qquad (9)$$

The intensity and shot noises also increase due to $(p+1)$ star couplers. And then, the bit-error rate (BER) is given by

$$BER = \frac{1}{2} \text{erfc}\left(\sqrt{\frac{SNIR}{2}} \right). \qquad (10)$$

4.2 WDM Sub-system Analysis

In the second part of the analysis, we have focused on the WDM system performance under the hybrid scheme. We have utilized the WDM system which has uniform channel wavelengths on a 100-GHz grid in the frequency range of 186–196 THz [2]. The WDM signals enter the system straight forward by optical combiner, $w(\nu)$ can be expressed as

$$w(\nu) = \frac{P_{wr}}{B_w} \sum_{i=1}^{p(p+1)} A_i \{rect(i)\}, \qquad (11)$$

where P_{wr} is the effective power of WDM pulses at the receiver and for each $i \in \{1, 2, \ldots, N\}$

$$A_i = \begin{cases} 1; \text{ if a WDM signal exists at the } i\text{th chip} \\ 0; \text{ else} \end{cases}. \qquad (12)$$

The WDM receiver consists of a demultiplexer which has narrow band-pass filters followed by optical-to-electrical (O/E) conversions. Each filter is centered at a selective WDM wavelength. The photocurrent I_l of each WDM signal is as follows:

$$I_l = \Re P_{wr} + \frac{\Re P_{sr}}{N} \frac{K \ell}{2p}. \qquad (13)$$

The total average noise power is:

$$(\text{WDM noise})^2 = \left\langle i_{PIIN}^2 \right\rangle + \left\langle i_{Shot}^2 \right\rangle + \left\langle i_{Th}^2 \right\rangle. \qquad (14)$$

the average WDM signal power and interference power are:

$$(\text{WDM signal})^2 = (\Re P_{wr})^2 , \qquad (15)$$

$$\left\langle \text{Interf}^2 \right\rangle = \left(\frac{\Re P_{sr} K \ell}{2pN} \right)^2 . \qquad (16)$$

Finally, using Eqs. (14-16), we have

$$BER_{WDM} = \frac{1}{2} \text{erfc}\left(\sqrt{\frac{SNIR_{WDM}}{2}} \right). \qquad (17)$$

5. NUMERICAL RESULTS

In this section, the performance results of both SAC optical CDMA and WDM sub-system under the hybrid spectral/spatial coding scheme are presented. The typical system parameters, considered for the mathematical model, are illustrated in Table I.

Table1. Typical Parameters Used for Our Calculations.

Responsivity of the PDs	$\Re$ =0.75
Electron's charge	e =1.6×10^{-19} C
Boltzmann's constant	K_b =1.38×10^{-23} J K^{-1}
Receiver noise temperature	T_n =300 K
Receiver load resistor	R_L =1030 Ω
Thermal source Line-width	$\Delta\nu$ =3.75 THz
Electrical bandwidth (OCDMA)	B_{ec} = 320 MHz for 622 Mbps data rates
Electrical bandwidth (WDM)	B_{ew} =645 MHz for 1.25 Gbps data rates
WDM channel bandwidth	B_w = 40 GHz
Operating wavelength	λ_0 =1.55 μm

Figure 4 shows the changes of the optical CDMA BER values versus the number of simultaneous users at p = 11, ℓ = 3, and with different values of WDM channels N_w for optical power of -15 dBm and 622 Mbps data rates. The BER performance of this system rises when the number of active users increases mostly due to PIIN noise. It is also clear that this subsystem performance decays with the rising number of WDM channels due to the effects of in-band interferences. For example, at K = 40, the BER is about 1×10^{-29} and 1×10^{-9} for N_w = 8 and N_w = 16, respectively. We also noticed that with increasing number of simultaneous users, the increment rate of the BER at N_w = 8 is faster than that at N_w = 16 or above. This is because the effect of multi-access interference is to be seen at low number of WDM channels.

The comparison of optical CDMA BER between spectral coding and spectral/spatial coding schemes versus number of simultaneous users is shown in Fig. 5. The different received power at both schemes has been considered; whereas P_{sr} for optical CDMA users at spectral and spectral/spatial coding schemes are -10 dBm and -15 dBm, respectively. At p = 9, ℓ = 4, and with different N_w values, the optical CDMA performance in hybrid S/S scheme is better than that in the spectral scheme alone. Therefore, a lower optical CDMA BER can be obtained with using the hybrid coding system.

Figure 6 shows the BER of the WDM subsystem versus received power, P_{wr}, for different values of ℓ, at p = 9, K = 30, and 1.25 Gbps data rate. It is noticed that the BER increases with decreasing received power due to the receiver sensitivity. It is also obvious that BER performance decays with decreasing the value of ℓ. This is because that the number of optical CDMA chips as wide noise like decreases under the WDM signal.

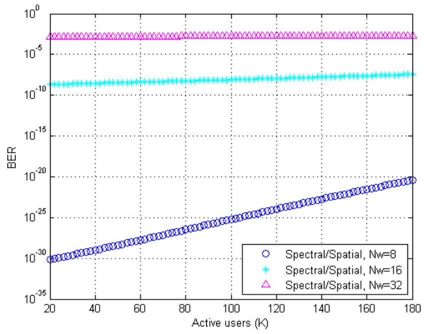

Fig.4. Optical CDMA BER versus number of active users at P_{sr} = -15 dBm, p = 11, and ℓ = 3, for different values of N_w.

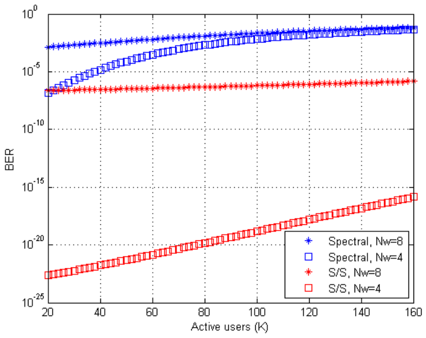

Fig.5. Optical CDMA BER comparison between spectral coding and S/S coding scheme versus number of active users.

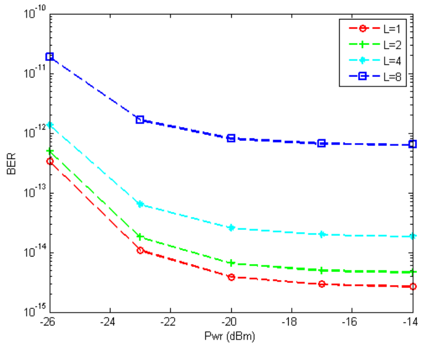

Fig.6. WDM BER versus received power, P_{wr} for different values of ℓ, at p = 9, K = 30, and 1.25 Gbps data rate.

6. CONCLUSION

MQC codes of optical CDMA in the spectral/spatial hybrid scheme have been proposed under a hybrid optical CDMA-WDM overlay system. The BER performance of both subsystems of this scheme has been presented, in addition to a comparison of optical CDMA BER between spectral coding and spectral/spatial coding schemes. It is concluded that optical CDMA system performance in the proposed scheme is better than that in spectral coding scheme alone. The proposed system is one of potential system for future compact optical networks.

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