

Performance Analysis of SAC/Optical CDMA and WDM under a Hybrid Overlay Scheme

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Abstract- This paper presents a performance analysis of both optical code-division multiple-access (OCDMA) and wavelength division multiplexing (WDM) in an overlay hybrid scheme. Modified quadratic congruence (MQC) code pulses of spectral amplitude coding (SAC) for optical CDMA is utilized as the signature address codes. This hybrid system is described, and its performance is analyzed, taking into account interferences and some types of noises. It is shown that the performance results in terms of both the bit-error rate (BER) and signal-to-noise and interference ratio (SNIR) are accepted in optical communication networks.

Keywords: Optical code division multiple access (OCDMA), spectral amplitude coding (SAC), wavelength division multiplexing (WDM).

I. INTRODUCTION

Recently, Optical CDMA systems have an important role in optical networks because these systems provide the users simultaneous and asynchronous access to the network with high security [1, 2]. SAC/OCDMA spectrum can be in-band transmitted with multichannels of WDM system to get some advantages of transmission capacity and data confidentiality enhancement [3, 4]. Modified quadratic convergence (MQC) code is used as a signature address code for SAC/OCDMA system. This scheme has features such as a significant reduction in the effects of multiple access interference (MAI) and attenuation in the effects of phase induced intensity noise (PIIN) [5].

In previous studies, The WDM and SAC/OCDMA hybrid overlay system have been studied in [6, 7], where each WDM channel can employ the same set of SAC/OCDMA systems. In [3] we have investigated the feasibility of transmitting both OCDMA and WDM users on the same spectrum band. Both hybrid and non-hybrid systems have been simulated and the performance comparison is presented. Our results in [3] indicate that it is possible to achieve an acceptable performance with good data confidentiality under the hybrid scheme. The results in [3] have been only demonstrated by simulation. Theoretical analysis of the performance, however, has not been demonstrated yet for this system.

In this paper, we analyze the performance of both SAC/OCDMA-WDM systems under hybrid overlay system theoretically. Hence, the overall signal-to-noise and interference ratio (SNIR) is derived and the corresponding bit-error rate (BER), taking into consideration various types

of noises and interferences. In addition, we obtain the numerical results with the effects of system parameters. The remainder of this paper is organized as follows: In Section 2 we describe the proposed system. In Section 3 we analyze the performance of the hybrid system. In Section 4, numerical results are presented for both sub-systems (SAC/OCDMA and WDM). Finally the conclusion of the paper is provided in Section 5.

II. SYSTEM DESCRIPTION

In the proposed system [3, 4], narrow-band WDM signals and optical broadband CDMA signals are in-band transmitted over the same spectral region. A block diagram of the hybrid WDM-SAC/OCDMA system is shown in Fig. 1. Fig. 2 (a) illustrates that the CDMA signals are spread over a band of $\Delta\nu$, whereas each WDM signal covers a band of B_w . In addition, the frequency spacing between WDM signals is 100 GHz as the ITU standards [10]. So that, the maximum number of WDM channels, N_w is $\Delta\nu / 100GHz$. At the OCDMA receiver side, the WDM interferences can be attenuated by using notch filters. Fig. 2 (b) shows the function of an ideal notch filter that is utilized in the proposed system.

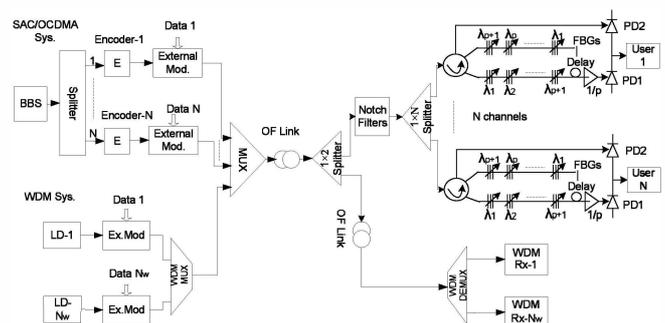
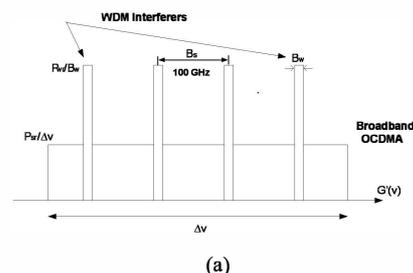


Figure 1. Block-diagram of the hybrid system.



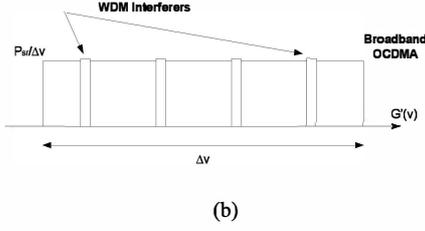


Figure 2. SAC/OCDMA and WDM- overlay signals. (a) Narrow-band signals of WDM and broad-band signals of OCDMA. (b) Function of an ideal notch filter.

The SAC/OCDMA system consists of a broadband source and point-to-point transmission channels by using star coupler. The data of each user is encoded by MQC code families $(p^2 + p, p + 1, 1)$ with p a prime number. The properties of MQC codes are mentioned in [5], where an MQC code is denoted by (N, w, λ) , where N is the number of code words, w is the code weight, and λ is the cross-correlation. In this code the optimal number of users K equals p^2 . The public WDM system setup consists of CW laser sources for some channels that are modulated at specific data rate for each user. The two systems are using on-off keying modulation and are combined together over a single fiber link. At the receiver side of the system, the WDM receiver consists of a narrow band-pass filter followed by O/E conversion. The SAC/OCDMA receiver is based on the complementary detection scheme [5], following a notch filter designed for the hybrid system.

III. PERFORMANCE ANALYSIS

The signals from both WDM and OCDMA channels are independently combined into the optical fiber link. The performance of both systems is limited by the multi-access interference in addition to the phase-induced intensity noise (PIIN), shot noise, and thermal noise. In this section we develop a theoretical analysis of the system under consideration.

A. SAC/OCDMA Subsystem Analysis

In this subsystem with ideal broadband light source (BLS), the assumptions and symbol definitions follow that of previous studies [5, 8-9]. In addition, the chip width B_c of an MQC code of SAC/OCDMA is equal to the bandwidth of a WDM channel B_w . That is, $B_c = B_w$.

The received SAC/OCDMA signal, before the notch filters and OCDMA decoders, $r(v)$, is a sum of the transmitted signal, $s(v)$ and the WDM interferers, $w(v)$.

$$r(v) = s(v) + w(v) \quad (1)$$

$$s(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k \sum_{i=1}^N c_k(i) \{rect(i)\} \quad (2)$$

$$w(v) = \frac{P_{wr}}{B_w} \sum_{i=1}^N A_i \{rect(i)\} \quad (3)$$

where P_{sr} is the effective power of a broad-band source at the receiver (there is power loss due to transmission and star coupler), $c_k(i)$ denotes the i th element of the k th MQC code sequence, K is the number of CDMA users, and d_k is the

data bit of the k th-user, $d_k \in \{0, 1\}$. P_{wr} is the effective power of WDM pulses at the receiver and for each $i \in \{1, 2, \dots, N\}$

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

Notice that $\sum_{i=1}^N A_i = N_w$, where N_w is the number of WDM users.

The $u\{v\}$ is the unit step function and $rect(i)$ is given by

$$rect(i) = u \left[v - v_0 - \frac{\Delta v}{2N} (-N + 2i - 2) \right] - u \left[v - v_0 - \frac{\Delta v}{2N} (-N + 2i) \right] \quad (4)$$

Therefore, equation (1) can be rewritten as follows:

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k \sum_{i=1}^N c_k(i) \{rect(i)\} + \frac{P_{wr}}{B_w} \sum_{i=1}^N A_i \{rect(i)\} \quad (5)$$

As mentioned above, the function of the notch filters is to reject the high power of WDM interference. We suppose that the notch filters are ideal attenuated the WDM power to the level of an OCDMA signal, Fig. 2(b). That is the power spectral density (PSD) of the attenuated WDM signal equals $P_{sr} / \Delta v$. The effect of the notch filter on the OCDMA chips can be neglected as long as $N \gg N_w$. Therefore, the PSD of the receiving signals at PD1 and PD2 of user $l \in \{1, 2, \dots, K\}$, during one bit period can be expressed as

$$G_1(v) = \frac{1}{p} \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k \sum_{i=1}^N c_k(i) \bar{c}_l(i) \{rect(i)\} + \frac{1}{p} \frac{P_{sr}}{\Delta v} \sum_{i=1}^N A_i \bar{c}_l(i) \{rect(i)\} \quad (6)$$

$$G_2(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k \sum_{i=1}^N c_k(i) c_l(i) \{rect(i)\} + \frac{P_{sr}}{\Delta v} \sum_{i=1}^N A_i c_l(i) \{rect(i)\} \quad (7)$$

Considering incoherent intensity noise, shot noise, and thermal noise, the combined 3 noises can be expressed as

$$\langle N_{Noise}^2 \rangle = \langle i_{PIIN}^2 \rangle + \langle i_{Shot}^2 \rangle + \langle i_{Th}^2 \rangle \quad (8)$$

The average interference photocurrent due to WDM signals

$$\langle Interf.^2 \rangle = \left(\Re \frac{P_{sr} N_w}{N^2} \left(1 + \frac{1}{p} \right) \right)^2 \quad (9)$$

Then the signal-to-noise and interference ratio (SNIR) is

$$SNIR = \frac{(\Re P_{sr} / 2p)^2}{\langle N_{Noise}^2 \rangle + \langle Interf.^2 \rangle} \quad (10)$$

B. WDM Subsystem Analysis

The second part of the analysis focuses on the WDM system performance under the hybrid scheme. Each WDM signal performance strongly depends on the peak power ratio used between WDM users and SAC/OCDMA users. We assume that the receiving peak power for all WDM users is equal. The receiving signal at a WDM demultiplexer can be written as

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k \sum_{i=1}^N c_k(i) \{rect(i)\} + \frac{P_{wr}}{B_w} \sum_{i=1}^N A_i \{rect(i)\} \quad (11)$$

the PSD of the PD at the l th WDM receiver during one bit period can be written as

$$f_l(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^K d_k c_k(i) \{rect(i)\} + \frac{P_{wr}}{B_w} rect(i) \quad (12)$$

the total average noise and interference, respectively:

$$(WDM \text{ noise})^2 = B_{ew} \Re^2 \left[\frac{P_{wr}^2 N}{\Delta v} + \frac{P_{sr}^2 K}{N \Delta v 2p} + \frac{P_{sr} P_{wr} K}{p \Delta v} \right] \quad (13)$$

$$+ 2eB_{ew} \Re \left[P_{wr} + \frac{P_{sr} K}{2Np} \right] + (4K_b T_n B_{ew} / R_L) \quad (14)$$

$$(\text{Interf}_{WDM})^2 = \left(\frac{\Re P_{sr} K}{2pN} \right)^2 \quad (14)$$

and the average WDM signal:

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

Hence, using (13), (14) and (15), we have

$$SNIR_{WDM} = \frac{(WDM \text{ signal})^2}{(WDM \text{ noise})^2 + (\text{Interf}_{WDM})^2} \quad (16)$$

IV. NUMERICAL RESULTS

The typical parameters used for the performance of hybrid system calculation are illustrated in Table I. We have employed this expression $BER = 0.5 \text{erfc}(\sqrt{SNIR}/2)$ to obtain the performance of SAC/OCDMA subsystem in the hybrid system. Fig.3 shows the relation between bit-error rate (BER) and the number of active users for various number of WDM channels (N_w), with using $p=9$, the effective power is -10 dBm and the bit rates are 622 Mbps. The performance of this system reduces when the number of active users increases due to PIIN. It is also noticed that the performance decays with rising of WDM channels due to the effects of interferences. Therefore, as long as $N \gg N_w$ the effects of WDM interferences can be neglected. This paper emphasizes on the performance analysis of the hybrid system. The complete description of the increment in confidentiality of the hybrid system as compared to non-hybrid system has been published in [3].

The results of WDM system performance under the hybrid scheme is shown in Fig. 4, whereas the WDM system's SNIR is versus the received power, P_{wr} , when the effective power of SAC/OCDMA, P_{sr} , starts at -20 dBm, using various values of bit rates for WDM. We can clearly see that the WDM SNIR decreases with decreasing received power and with increasing bit rates. These results show that the performance of WDM users is accepted in spite of the hybrid scheme.

TABLE I
TYPICAL PARAMETERS USED FOR CALCULATION

Responsivity of the PDs	$\Re = 0.75$
Electron's charge	$e = 1.6 \times 10^{-19}$
Boltzmann's constant	$K_b = 1.38 \times 10^{-23}$

Receiver noise temperature	$T_n = 300 \text{ K}$
Receiver load resistor	$R_L = 1030 \Omega$
Line-width of the thermal source	$\Delta v = 3.75 \text{ THz}$
Electrical bandwidth (for SAC/OCDMA)	$B_{ec} = 320 \text{ MHz}$
Electrical bandwidth (for WDM)	$B_{ew} = 1.29 \text{ GHz}$
Data bit rate	622 Mbps and 2.5 Gbps
Operating wavelength	$\lambda_0 = 1.55 \mu\text{m}$

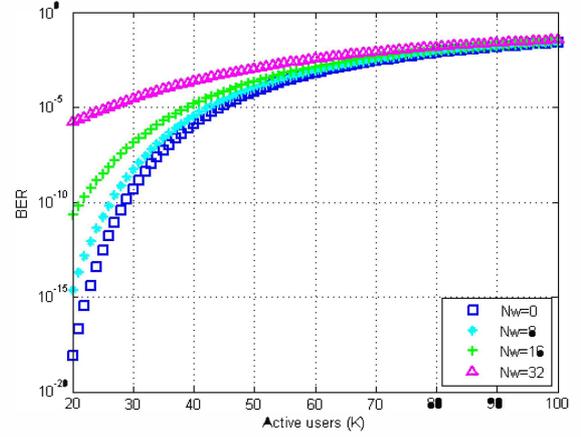


Figure 3. Number of active users versus BER at $p = 9$, $P_{sr} = -10$ (dBm) and various N_w values.

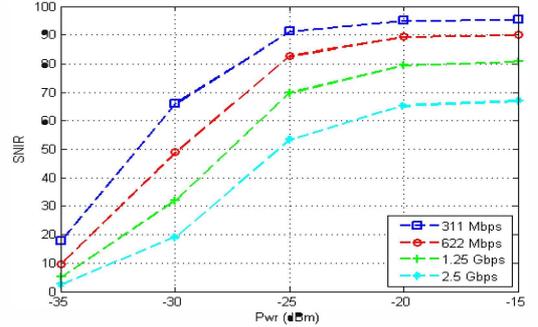


Figure 4. SNIR of hybrid WDM system vs. various received power, P_{wr}

V. CONCLUSION

We have analyzed the performance of both SAC/Optical CDMA and WDM systems in a hybrid scheme, considering the effects of intensity noise, interference, thermal noise and shot noise. The intensity noise and the interference are the main factors that limit the system performance. However, the proposed hybrid scheme makes an eavesdropper to face another challenge for intercepting and decoding the coded signal hence improving the overall security of OCDMA systems.

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