A Comparative Study of Asynchronous and Synchronous OCDMA Systems

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***Abstract*—This paper presents a detailed survey on both asynchronous and synchronous Optical Code-Division Multiple-Access (OCDMA) systems based on one dimensional (1-D), two dimensional (2-D), and three dimensional (3-D) codes, distinctively. Accordingly, different coding schemes along with their multiplexing capacity, correlation features, advantages and drawbacks are addressed and benchmarked. Additionally, different detection techniques such as direct and coherent detection and their capability to handle Multiple Access-Interference (MAI) are also discussed. Furthermore, the most pertinent OCDMA systems from the last two decades are summarized considering their coding schemes, performance, device components and applications. Therefore, a new comparative study in terms of spectral efficiency and system performance assuming both the binomial approach and Gaussian approach for 1-D, 2-D, 3-D asynchronous and synchronous OCDMA systems is carried out. On the one hand, numerical results shown that the asynchronous 3-D modified quadratic congruence/prime hop code (3D-MQC/PHC) stands out among the codes with superior spectral efficiency up to 24%. On the other hand, 3D-MD synchronous code outperforms both 3D-PD and 3D-MD/PD codes in terms of allowed bit rate by a percentage of 59% at 300 simultaneous network subscribers.**

***Index Terms*—Optical fiber communication; Asynchronous; Synchronous; Code division multiplexing; MAI.**

I. Introduction

Nowadays, multiple access has become a key technique for modern communication systems to be used to optimize network resources and provide access to the medium while supporting large capacity. Different multiple access techniques such as Time-Division Multiple-Access (TDMA), Wavelength-Division Multiple-Access (WDMA), and Code-Division Multiple-Access (CDMA) can be found in the state-of-the-art literature [1]. On the first hand, TDMA allocates an exclusive time slot for data channel transmissions, but its synchronization requirement imposes high complexity to the technology. On the second hand, in WDMA technique, the wavelength band is divided among all users, where each user uses a dedicated wavelength for data transmission; this leads to spectrum misusage due to the wavelength guard employed to differentiate between the users' frequencies. On the last hand, CDMA technique assigns for each user a specific code for data transmission. In fact, CDMA has many advantages comparing to TDMA and WDMA techniques, such as efficient bandwidth usage, data confidentiality, low interception probability and effective network control design. Furthermore, CDMA can be applied in various distinct domains such as military satellite communication systems [2], optical CDMA (OCDMA) systems [3], cellular underwater OCDMA network [5], and Multiple Input Multiple Output (MIMO) radar [6]. Finally, Orthogonal Frequency-Division Multiplexing (OFDM) has become a promising technique to improve system performance and spectral efficiency by using the high order modulation schemes. Its benefits can be applied to OCDMA leading to a hybrid OFDM-OCDMA systems with increased capacity [10-11, 27,57-58]. OFDM-OCDMA systems are not benchmarked in this paper for the sake of conciseness.

OCDMA systems can be classified into two categories: synchronous and asynchronous. Synchronous systems have higher capacity but at the cost of being more complex systems [7], whereas asynchronous systems support a limited number of users but do not require any sort of synchronization. In fact, asynchronism is one of the most interesting feature of OCDMA. Asynchronous OCDMA systems can be applied to different network scenarios like for example local area network (LAN) [7-8,13], multimedia systems [46-54], Free-Space Optical (FSO) link [55,85-86], Passive Optical Networks (PONs) [11,67-69] and Long-Reach PONs (LR-PONs) [9,10].

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The capacity of asynchronous systems can be increased with the help of two-dimensional (2-D) and three-dimensional (3-D) codes. For instance, it is possible to use 2-D coding schemes based on a combination of time, space, or wavelength spreading to increase the system's performance without additional complexity. Moreover, 3- Dcoding can accommodate even more users by exploiting light polarization states [8].

In this paper, a detailed comparative study and analysis of synchronous and asynchronous OCDMA systems are carried out. A new analysis based on the performance evaluation of 1-D, 2-D, and 3-D code schemes is addressed. The study accounts for the different coding schemes and their features such as cardinality, design requirements, and correlation properties. Several distinct detection techniques such as direct and coherent detection and their capability to handle Multiple Access-Interference (MAI) are also discussed. The most important OCDMA systems from the last two decades are highlighted and summarized. A new numerical investigation for both asynchronous and synchronous OCDMA systems and for many different 1-D, 2-D, 3-D code schemes is carried out. Results shown that the spectral efficiency of asynchronous 3-D codes stand out among several codes and is a prospective coding technique for future networks where larger capacity will be a paramount system requirement.

To the best of our knowledge, this paper is the first survey carried out in the literature considering both asynchronous and synchronous OCDMA systems as well as different family of 1-D, 2-D, and 3-D codes. Likewise, the comparison is addressed as function of relevant system features, detection technique, spectral efficiency and BER performance.

This paper is organized as follows; Section 2 lays out the description of asynchronous OCDMA systems and 1-D, 2-D, and 3-D codes. Section 2 presents the synchronous OCDMA system and highlights the system configuration, different coding schemes and receiver technique. Section 3 presents a comparison between asynchronous and synchronous OCDMA systems considering cardinality, benefits and limitations. A numerical analysis of system performance is investigated in terms of spectral efficiency and BER is presented in Section 4. Finally, the last Section presents some concluding remarks.

II. ASYNCHRONOUS OCDMA SYSTEMS

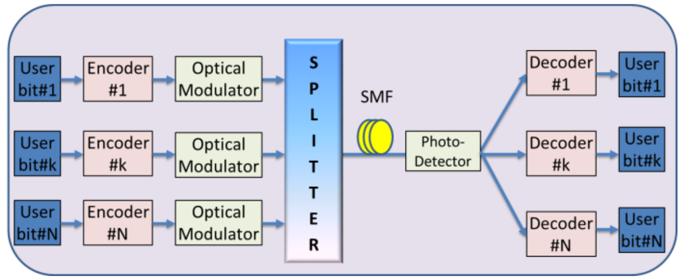


Fig. 1. Asynchronous OCDMA system architecture

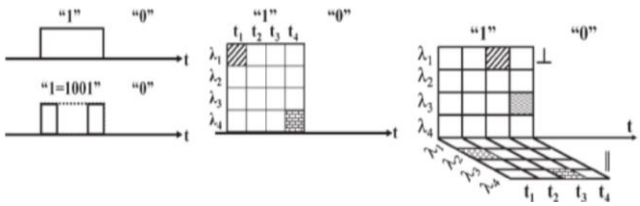
In asynchronous OCDMA system, the information bits to be sent are spread using the code signature generated by the OCDMA encoder then modulated by an optical modulator as illustrated in Fig. 1. The contribution of all users are then summed using a coupler and then signal is propagating into an optical channel. A photodetector is used to convert the optical signal into optical one. Finally, an OCDMA decoder is used to recover the data transmitted by the user. It is shown from the Fig. 1 that OCDMA encoder and decoder are the main important parts in the OCDMA architecture.

Fig. 2 presents a 1-D OCDMA code (time spreading), 2-D OCDMA code (time and wavelength spreading) and 3-D OCDMA codes (time, wavelength and polarization spreading), respectively [22].

Table 1.Asynchronous OCDMA codes features.

Family	Codes	Weight	Length	Multiplexing capacity	Auto-correlation	Cross-correlation
1D	1D-PC[83]	P	P^2	P	[0,P]	[0,2]
	1D-OOC [78]	W	P	$\frac{L-1}{W(W-1)}$	[0,P]	[0,P]
	1D-ML[47]	$2^{m-1}-1$	2^m-1	2^m-1	[-1,2^m-1]	-1
2D	2D-OOC [82]	W	T	$\frac{\Delta(\Delta T-1)}{W(W-1)}$	[0,W]	[0,1]
	2D-PHS [14]	P	P^2	P(P-1)	[0,P]	[0,1]
	2D-HC [14]	$\frac{P+1}{2}$	P^2	P^2	[0,P]	[0,1]
3D	3D-OOC [8]	W	P	$\frac{lm(lmn-1)\ldots(lmn}{W(W-1)\ldots(W-}$	[0,W]	[0,1]
	MPR[23]	W	L_T	$2RL_T$	[0,1]	[0,1]
	MQC/MP [59]	W	P^2+ P	P(P^2-1)	[0,1]	[0,1]
	MQC/PHC [77]	W	P^2+ P	P^2 (P-1)	[0,1]	[0,1]

Three categories of asynchronous OCDMA systems including 1-D, 2-D and 3-D codes are defined in Table 1. Prime code (PC), optical orthogonal codes (OOC) and maximum-length (ML) sequence are examples of 1-D OCDMA codes based on time domain coding schemes. Different schemes are employed to build 2-D coding covering time-space and time-wavelength 2D-OOC, two dimensional prime hop system (2D-PHS) and two dimensional hybrid code (2D-HC) are examples of 2-D OCDMA asynchronous codes. 3D-OOC, 3D-MPR and 3D-MQC/MP OCDMA codes are based on time/space/wavelength [22], time/wavelength/polarization [23] and phase/wavelength/time spreading [24], respectively.



(a) (b) (c)

Fig.2 Comparison of OCDMA codes, 1-D code (a), 2-D code (b) and 3-D code (c)

Table 2 highlights and summarized the key asynchronous OCDMA systems found in the literature. The different asynchronous OCDMA systems as function of the coding scheme, cardinality, performance measured metrics, system components and the different applications. As shown in Table 2, various asynchronous OCDMA coding schemes are proposed such as optical orthogonal codes (1D-OOC) [78-79], multi-wavelengths optical orthogonal codes (MW-OOC) [17], WDM-OOC codes [18], multi-length generalized OOC (ML G-OOC) codes [19], 2D-PHS [9,11,13] and 2D-HC codes [10,12, 13]. Also, various OCDMA systems based on 3-D codes are proposed in literature like time, wavelength, and polarization code set (3D-T/W/P) [8], 3D-MQC/MP [59] and 3D-MQC/PHC [77] for LAN and PON applications. According to table 2, the most important applications of asynchronous OCDMA systems are LAN over multimode fiber (MMF), PON, fault monitoring of PON and LR-PON over single mode fiber (SMF) for the uplink connection with a flexible bit rate in the range of [40-100] Gb/s. Additionally, the PON components are optical line terminal (OLT), optical fiber, splitter and optical network unit (ONU).

Table 2.Relevant asynchronous OCDMA systems.

System	**Coding scheme**	**Cardinality (Number of users)**	**Performance Measured metrics**	**System components**	**Application**
1D-OOC [78-79]	OOC	10	BER≤10E-9	Encoder-Star Coupler-Decoder	Optical Fiber Networks
2D-Optical Coding monitoring [17]	MW-OOC	64	SNIR≥10dB	Laser+ SMF+APD	Fault monitoring of PON
Hybrid WDM/OOC based OCDMA [18]	WDM-OOC	72	BER ≤10E-9	ONU-OLT	PON
Multiclass OCDMA [19]	ML Generalized-OOC	60	BER ≤10E-7	ONU-OLT	Adaptive OCDMA-PON
OCDMA with star channel [13]	2D-PHS 2D-HC	120 150	BER ≤10E-9	VCSEL+MMF+PIN	LAN
2D-OCDMA-WDM [12]	2D-HC	524	BER ≤10E-10	VCSEL+SMF +APD	40G PON
IMDD OOFDM-CDMA [11]	2D-PHS	5	BER ≤FEC limit	VCSEL+SMF+ APD	100G PON
AO-OFDM-CDMA [10]	2D-HC	45	BER ≤FEC limit	DFB+SMF+ APD	40G LR-PON
2D-OCDMA [9]	2D-PHS 2D-HC	190 120	Q-factor=6	DFB+SMF+ APD	40G LR-PON
3D-T/W/P [8]	Time, Wavelength, and Polarization codeset	49	BER ≤10E-9	Encoder-Star Coupler-Decoder	LAN

3D-MQC/MP [59]	2D-MQC 1D-MP	100	BER ≤10E-9	Laser+SMF+PD	PON
3D-MQC/PHS [77]	2D-MQC 1D-PHC	450	BER ≤10E-9	Laser+SMF+PD	PON

MAI is the most important noise source in OCDMA systems leading to a degradation of performance [14]. After the transmission of the users' signals through an OCDMA system, the desired user’s signal arrives with MAI at the receiver side. The simple superposition of the users’ signals in the star coupler used to couple all signals before transmission generates MAI, which is delivered to each user at the receiver side. This is due to the non-orthogonality of optical CDMA codes. Hence, MAI is considered as one of the main deleterious sources of noise in OCDMA systems [52,54,80,81].

In order to mitigate the MAI effects, several different techniques have been developed such as multi user detection (MUD), conventional correlation receiver (CCR) [14], hard limiter (HL) [20], serial interference cancellation (SIC) [16] and parallel interference cancellation (PIC) receiver [21]. In the optical hard limiter the amplitude contribution on a chip, due to unwanted users whose codes have the chip considered in common with the desired user, will be reduced to unit value [57].

As shown in Fig. 3 (a), the OCDMA SIC receiver uses a maximum function to determine the higher power level of the user signal that causes the noise to eliminate the highest interference contribution [12-16]. According to the Fig.3 (a), the SIC receiver components are optical demodulator, CCR#N for the undesired user N with high interference and CCR#1 for the desired user 1. Hence, the aim of using SIC receiver with one stage cancellation is to detect the bit sent by the desired user by using CCR#1 after deducing the undesired signal with the help of CCR#N. Also, r1(t) is defined as the demodulated optical signal minus the detected undesired bit user multiplied by the undesired user signature CN(t). Then, the result signal will be sent to the CCR 1 in order to detect the desired user bit bi(1).On the other hand, a sum function is used in the OCDMA PIC receiver to tackle the contribution of the undesired users [21]. In order to address the performance of asynchronous systems using the CCR, two approaches are considered, i.e., binomial distribution [14] and Gaussian distribution approach [65].

The error probability of asynchronous OCDMA systems considering the CCR receiver and ideal optical channel is given by [14]:

$$\mathrm{P_e} = \frac{1}{2}\sum_{\mathrm{i=Th}}^{\mathrm{N-1}} \binom{\mathrm{N-1}}{\mathrm{i}} (\mathrm{Pr_I})^{\mathrm{i}} (1-\mathrm{Pr_I})^{\mathrm{N-1-i}} \tag{1}$$

where Pr_I, Th are the probability of the chip overlap between two signatures and the receiver threshold. This can be further developed as [9]:

$$\mathrm{P_e} = \frac{1}{2}\int_{\mathrm{H}} \sum_{\mathrm{i=Th}}^{\mathrm{N-1}} \binom{\mathrm{N-1}}{\mathrm{i}} (\mathrm{Pr_I})^{\mathrm{i}} (1-\mathrm{Pr_I})^{\mathrm{N-1-i}}\, \mathrm{H_f dH} \tag{2}$$

where H_f is the transfer function of the optical channel.

On the other hand, when the Gaussian approach is considered, the probability of error of the OCDMA asynchronous receiver is given as follows [62-65]:

$$\mathrm{P_e} = \frac{1}{4}\sum_{\mathrm{i=0}}^{\mathrm{N-1}} \binom{\mathrm{N-1}}{\mathrm{i}} \left(\frac{\mathrm{Pr_I}}{4}\right)^{\mathrm{i}} \left(1-\frac{\mathrm{Pr_I}}{4}\right)^{\mathrm{N-1-i}} \left[\mathrm{erfc}\left(\frac{\mathrm{Th-i}}{\sqrt{2}\sigma_{\mathrm{n}}}\right) + \mathrm{erfc}\left(\frac{\mathrm{w-Th+i}}{\sqrt{2}\sigma_{\mathrm{n}}}\right)\right] \tag{3}$$

where σ_n defined as the variance of the Gaussian noise.

This can be further developed as [62-65]:

$$\mathrm{P_e} = \frac{1}{4}\sum_{\mathrm{i=0}}^{\mathrm{N-1}} \binom{\mathrm{N-1}}{\mathrm{i}} \left(\frac{\mathrm{Pr_I}}{2}\right)^{\mathrm{i}} \left(1-\frac{\mathrm{Pr_I}}{2}\right)^{\mathrm{N-1-i}} \left[\mathrm{erfc}\left(\frac{\mathrm{Th-i}}{\sqrt{2}\sigma_{\mathrm{n}}}\right) + \mathrm{erfc}\left(\frac{\mathrm{w-Th+i}}{\sqrt{2}\sigma_{\mathrm{n}}}\right)\right] \tag{4}$$

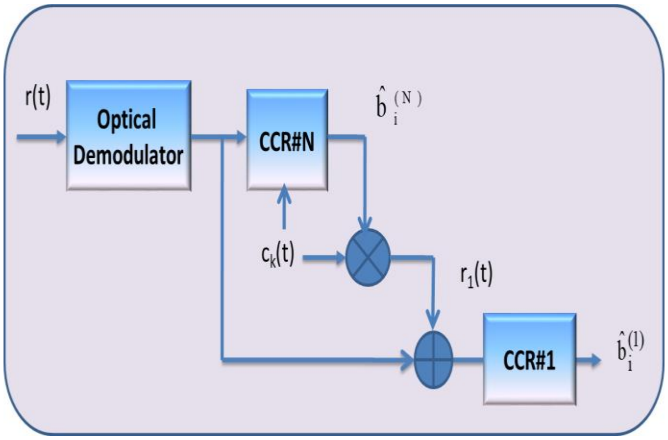
where erfc(x) is defined as the complementary error function.

Next, the bit-error-rate (BER) is described as function of signal-to-noise-rate (SNR) as follows [12]:

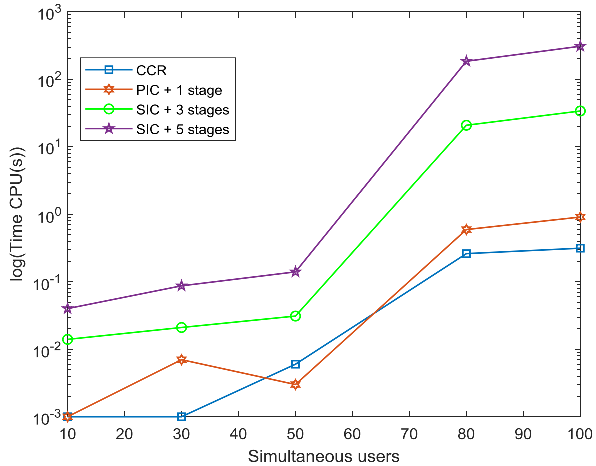
$$\mathrm{BER} = \frac{\mathrm{erfc}\left(\sqrt{\mathrm{SNR}/8}\right)}{2} \tag{5}$$

Q-factor is described as function of BER as follows [19]:

$$\mathrm{Q_{dB}} = 20\log_{10}\left(\sqrt{2}\,\mathrm{erfc}^{-1}(2\mathrm{BER})\right) \tag{6}$$



(a)



(b)

Fig.3 OCDMA SIC receiver architecture (a), CDMA receivers complexity comparison for 2D-PHS code (b) [9].

In the following paragraph, we present an OCDMA receiver complexity comparison for 2D-PHS and 2D-HC when a CCR, PIC and SIC receivers are employed, respectively.

Fig. 3 (b) presents a comparison of the different OCDMA asynchronous receiver in terms of CPU time (second) versus the number of simultaneous users when 2D-PHS is employed. However, we will present a comparison between 2D-PHS and 2D-HC in terms of time CPU when the number of receiver stages are raised from 1 to 5. It is shown from Fig.3 (b) that a SIC receiver consume more time CPU compared to CCR and PIC receivers due to the fact that it performs more sequential interference cancellation. However, when a SIC receiver with five stages is employed with 2D-HC spend more CPU time compared to 2D-PHS for a number of users less than 50 [9]. In contrary, 2D-PHS with five stages consume more CPU time compared to 2D-HC for a number of users greater than 50. As a result, 2D-HC outperforms 2D-PHS when SIC receiver with five stages is employed and when raising the number of simultaneous users due to the reduced code weight leading to a reduced time CPU and a better system performance. A tradeoff is observed between the increasing of the number of cancellation stage in the PIC/SIC receiver structure and it complexity that becomes worst. In addition, the raising of the stage in the receiver is leading to a better system performance. However, the receiver performs more operation, consumes more time CPU and becomes more complex.

III. SYNCHRONOUS OCDMA SYSTEMS

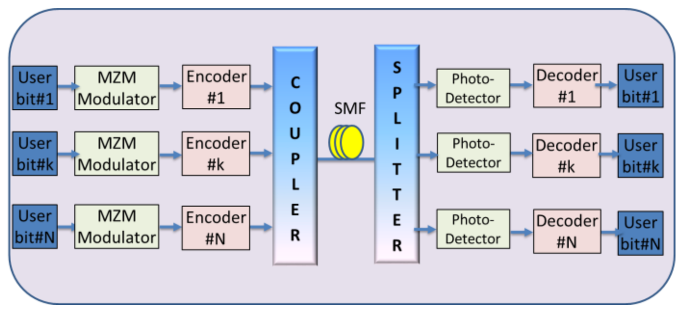


Fig. 4. Synchronous OCDMA system architecture.

In synchronous OCDMA systems all users access to the network in a synchronous way. Fig. 4 depicts the synchronous OCDMA system architecture in which a synchronous source is used to generate various wavelength, a PBRS is employed to generate the user bit randomly. A Mach-Zehnder modulator (MZM) is used to modulate the user data in the optical carrier. Then, a power combiner is used to sum the different user's data in one signal. After the propagation of the multiplexed signal through the optical fiber a PIN detector and a low pass Bassel filter is used to detect the received signal [59].

Table 3. Features of synchronous OCDMA codes.

Family	**Codes**	**Weight**	**Length**	**Multiplexing capacity**	**Auto-correlation**	**Cross-correlation**
1D	1D-PD [37]	k	$k^2 - k + 1$	W	k	$[0, k-1]$
	1D-FCC[84]	w	$w.K - (k-1)$	K	w	[0,w-1]
	1D-MD[71]	w	$w.K$	K	w	0

	1D-ZCC [87]	w	$w(w-1)$	K	w	0
2D	2D-PD [37]	k	k^2-k+1	MN	$k_1.k_2$	$[0,k_1]$
	2D-DCS [29]	p	$M.N$	$M.N$	$p_1.p_2$	[0,1]
	2D-MD [30,34]	w	$w.K$	$K_1.K_2$	$w_1.w_2$	w_1
3D	3D-PD/MD [75]	w	k^2-k+1	$K_1.K_2.K_3$	$w_1.w_2.w_3$	w_1
	3D-PD [74]	k	k^2-k+1	MNP	$k_1.k_2.(k_3-1)$	$[0,k_1]$
	3D-MD [43]	w	$w.K$	$K_1.K_2.K_3$	$w_1.w_2.w_3$	w_1

Three different families of synchronous OCDMA systems as summarized in Table 3. Perfect difference (PD), flexible cross correlation (FCC), multi diagonal (MD) and zero cross correlation (ZCC) are examples of 1-D OCDMA codes for spectral encoding scheme [25,28]. In addition, there are multiple codes which are constructed for 2-D (spectral and spatial) encoding such as 2D-PD and 2D-MD. Similarly, these codes are used for encoding 3-D spectral, time and spatial encoding domains and also combining 2D-PD and 1D-MD codes for 3D-OCDMA system.

Symbol (k) is used to express the code weight (number of ones in each code word sequence) in 2D-PD, 3D-PD and 3D-PD/MD codes so that k_1, k_2 and k_3 express the code weight for spectral, time and spatial encoding respectively. Meanwhile, it is expressed to the system capacity in other codes and k_1, k_2 and k_3 refers to number of users for spectral, time and spatial encoding, respectively.

Several codes have been proposed for synchronous OCDMA systems [25]-[33]. Each of them has its own advantage. For example, both perfect difference (PD) and flexible cross correlation (FCC) codes can eliminate the MAI which in turn works to minimize the phase induced intensity noise (PIIN) but its influence stays existing in case 1-D encoding.

In contrast, multi diagonal (MD) code is considered as one of the zero cross correlation (ZCC) codes [25, 37, 40] that is distinct by its non-overlapping between different codes (i.e., cross correlation value equal to zero). Therefore, this permits to minimize the MAI and PIIN effects to zero in 1-D encoding. In short, it can be said that it is better to construct a new code for OCDMA systems by such type of ZCC.

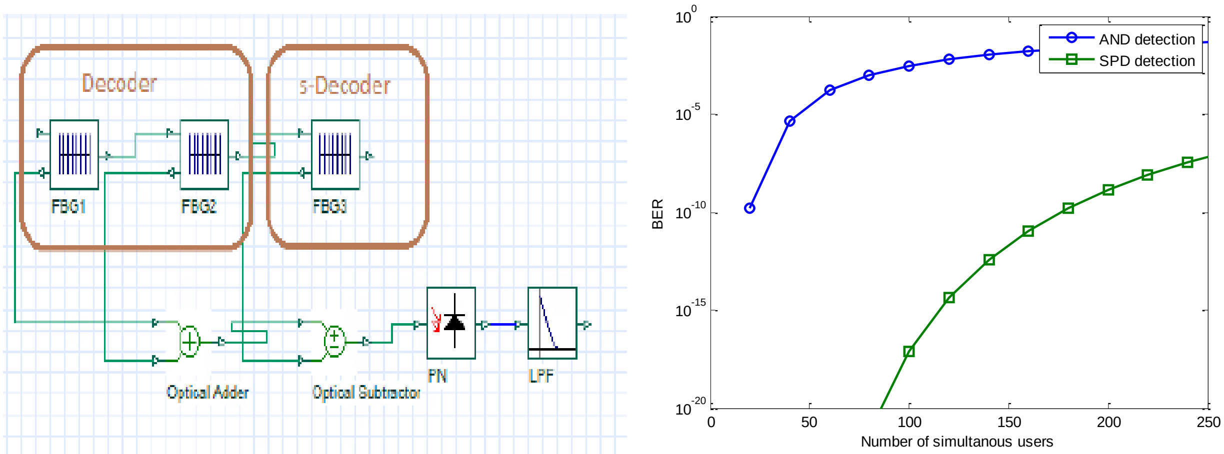
Although 2-D or 3-D encoding arise the PIIN using ZCC, they make the system performance better than 1-D because in this case there are a lot of user that requires increasing the code length that decreases the system performance [28, 29, 31, 33, 35, 36]. To overcome this shortcoming, researchers proposed to combine two domains for coding such as spectral/time (S/T), spectral/polarization (W/P), and spectral/spatial (S/S)[26]. In this way, new 2-D codes were developed like for instance 2D-PD and 2D-MD. In contrast, 3D-PD, 3D-PD/MD and 3D-MD codes are proposed for (S/T/S) encoding [36, 28, 40, and 42]. Finally, current efforts on four dimensional (4-D) (S/T/S/P) encoding are going on to further increase system performance [43-45].

Table 4 summarizes some of the most relevant synchronous OCDMA systems. Briefly, they are 1-D spectral amplitude coding OCDMA (1D-SAC-OCDMA), 2D-OCDMA and 3D-OCDMA systems. For example, both multi diagonal (MD) and dynamic cyclic shift (DCS) are proposed for SAC-OCDMA system. Meanwhile, 2D-MD, 2D-PD and 2D-DCS and 3D-MD, 3D-PD and 3D-PD/MD are proposed for 2D-OCDMA and 3D-OCDMA respectively [30-34, 43,45]. In addition, according to table 4, the most important applications of synchronous OCDMA systems are fiber to the home (FTTH), PON and next generation PON (NG-PON) over SMF and operating at 40 and 100 Gb/s.

Table 4. The most important synchronous OCDMA proposed systems.

System	Coding schema	Cardinality	Performance	System Components	Application
1D	1D-MD [71]	71	BER$\leq 10^{-9}$	DFB+ SMF +APD	OCDMA-PON
	1D-DCS [72]	33	BER$\leq 10^{-9}$	DFB+ SMF+ APD	OCDMA-PON
2D	2D-MD [30]	132	BER$\leq 10^{-9}$	Laser DFB+SMF+APD	NGPON+40G PON

	2D-PD [37]	65	BER≤ 10^{-9}	Laser DFB+SMF+APD	NGPON 100 G PON+ FTTH
	2D-DCS [29]	93	BER≤ 10^{-9}	Laser DFB +SMF+APD	NGPON 100 G PON+ FTTH
3D	3D-MD [43]	322	BER≤ 10^{-9}	Laser DFB+SMF+APD	NGPON+100G PON+FTTH
	3D-PD [74]	96	BER≤ 10^{-9}	DFB+SMF+APD	NGPON 100 G PON+ FTTH
	3D-PD/MD [75]	119	BER≤ 10^{-9}	Laser DFB+SMF+APD	NGPON 100 G PON+ FTTH



(a) (b)

Fig.5 SAC-OCDMA SPD detector structure (a), comparison between SPD and AND detector (b).

In SAC-OCDMA system, different detection techniques are used to surpass different impairments such as AND detection, modified AND detection [56], single photo-diode detection (SPD) [73], and recursive interference cancellation (RIC) [88]. Authors in [28,60] propose SPD detection to tackle MAI and PIIN showing a large PON subscribers, high spectral efficiency and a high data rate.

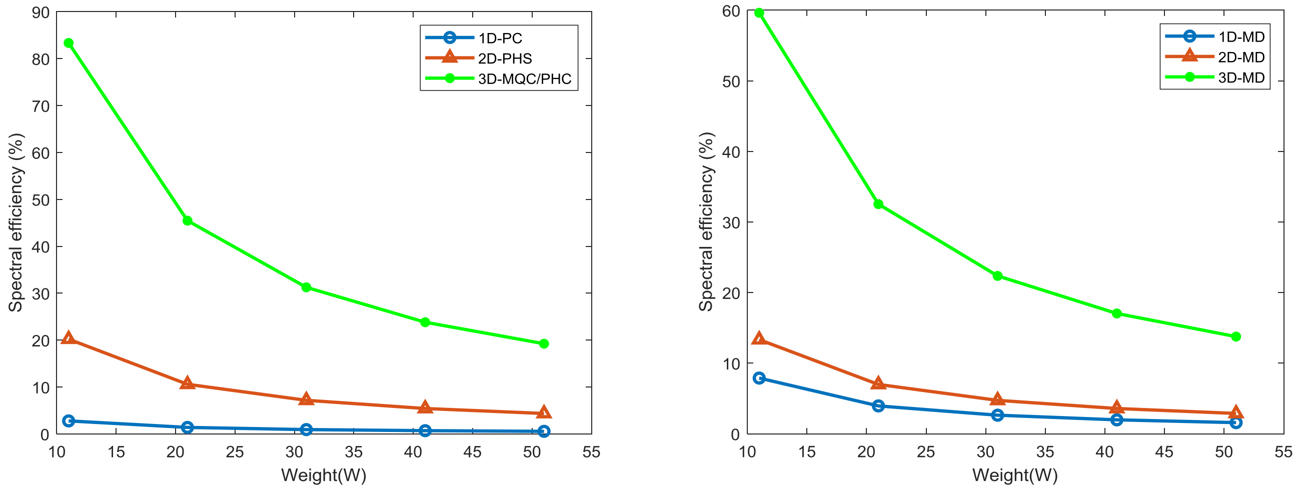
As shown from Fig.5 (a), SPD receiver is based on three FBG decoder. Two FBG filters at the decoder for transmission and refection and one FBG filter at the subtractive decoder (S-decoder) to cancel PIIN noise in optical domain due to the broadband light source incoherence. At the end of the SPD detector one PIN photodiode is used to convert optical signal to electrical one. According to Fig.5 (b), it is noted that the SAC-OCDMA system performance based on DCS code has been enhanced in terms of capacity using SPD technique rather than AND subtraction technique. In addition to that, the capacity of SAC-OCDMA technique based on AND cannot cross 20 users whereas it can go up to 197 users at 10^{-9} BER while using SPD technique. The difference between the two techniques in not limited to an increment in performance but extended to a reduction in system complexity as well [42]. Since the SPD and RIC detection perform the mitigation of the MAI and PIIN noise in optical domain leading to better performance compared to AND detection and modified AND detection. For instance, SPD detector provides match better spectral efficiency compared to AND detector and the modified AND detector [60]. On the other hand, RIC and SPD detector are more effective against PIIN and leading to an increment in the bit rate. For example, SAC OCDMA system based on enhanced multi diagonal code with SPD detector accommodates 64 users operating at 1.5 Gb/s [28]. Likewise, SAC-OCDMA system based on M-sequence with RIC detector provides access to 20 subscribers operating at 5.2 Gb/s [88].

IV. NUMERICAL ANALYSIS

In order to compare the performance of the 1-D/2-D/3-D OCDMA asynchronous and synchronous codes in terms of spectral efficiency, we introduce a Spectral Efficiency (SE) expression which is defined as follows [65,66]:

$$\mathrm{SE} = \frac{\text{Aggregate Information Rate}}{\text{Total Spectral Bandwidth}} = \frac{\mathrm{K}_{\mathrm{BER}=10^{-9}}}{\mathrm{N_w}\Delta\vartheta} \tag{7}$$

where $K_{BER}=10^{-9}$, R_b, N_w and $\Delta\vartheta$ are the number of simultaneous users at a BER of 10^{-9}, the bit rate for each user, the number of wavelength hopping and the bandwidth of each optical wavelength, respectively. In the numerical simulation, the bit rate for each user and the bandwidth of each wavelength are taken equal to $R_b = 1$ Gbps and $\Delta\vartheta$=90 nm, respectively.



(a) (b)

Fig.6 Spectral efficiency for asynchronous (a) versus synchronous (b) OCDMA 1D/2D/3D codes.

Table 5. Spectral efficiency comparison for 3D-MQC/PHC and 3D-MD versus weight.

Weight	**11**	**21**	**31**	**41**	**51**
3D-MQC/PHC	83.3	45.4	31.2	23.8	19.2
3D-MD	59.6	32.5	22.3	17.0	13.7

As shown in Fig.6 (a), 3D-MQC/PHC codes have the highest spectral efficiency compared to 2D-PHS and 1D-PC for up to a P of 51. Also, it is noticed that when the weight increased the spectral efficiency decreased. On the other hand, the spectral efficiency percentage of synchronous MD code is in the range of [8-60] % according to Fig.6 (b).

Table 5 presents the spectral efficiency comparison for 3D-MQC/PHC asynchronous code and 3D-MD synchronous code versus the code weight. As a result, the asynchronous 3D-MQC/PHC code outperforms the 3D-MD code in terms of spectral efficiency percentage by means of 23.7%, 12.9%, 8.9%, 6.8% and 5.5% at a weight code equal to 11, 21, 31, 41 and 51, respectively. The latter result is due to the fact that the 3D-MQC/PHC supports 450 users compared to 322 users supported by the 3D-MD codes at a BER equal to 10E-9 when we consider the assumption of the same number of wavelength hopping for both codes.

For numerical analysis purpose, this section will develop the SNR and BER expression for SAC-OCDMA systems. To estimate the OCDMA system performance in different encoding cases, firstly, it should to take a consideration four assumptions to make the system analysis easy which are [25-26]: i) Flat broadband light source and it is over $\left[v_0 - \frac{\Delta v}{2}, v_0 - \frac{\Delta v}{2}\right]$ where v_0 and Δv are the central frequency and optical bandwidth respectively which are estimated in Hertz. ii) Same spectral width for each power component. iii) At receiver level, each user has the same power. iv) Synchronization in each bit stream from each user.

The SNR can be defined [25, 27]:

$$SNR = \frac{I_r^2}{I_{noise}^2} \tag{8}$$

Where I_r and I_{noise}^2 denotes the output current of photo-diode (PD) and the current dark noise respectively where I_{noise}^2 can be expressed as:

$$I_{noise}^2 = I_{shot}^2 + I_{PIIN}^2 + I_{th}^2 \tag{9}$$

$$I_{noise}^2 = 2eB_rI_r + I_r^2B_r\tau_c + \frac{4K_bT_nB_r}{R_l} \tag{10}$$

where e, B_r, τ_c, K_b, T_n and R_l present the electron charge, electrical bandwidth, coherence time, Boltzmann's constant, receiver noise power and receiver load resistor respectively. In case one dimensional (1D) with codes have zero cross correlation property the PIIN is neglected so OCDMA system just suffers from two noise sources: shot noise and thermal noise. According to [30,37,43,67-71], the SNR of each cited code above can be written as:

$$\mathrm{SNR}_{1D-MD} = \frac{[\mathrm{RP_{sr}w/L}]^2}{\frac{\mathrm{eB_rRP_{sr}w}}{\mathrm{L}} + \frac{\mathrm{4K_bT_nB_r}}{\mathrm{R_l}}} \tag{11}$$

$$\mathrm{SNR}_{1D-DCS} = \frac{[\mathrm{RP_{sr}(w-1)/L}]^2}{\frac{\mathrm{eB_rRP_{sr}(w+3)}}{\mathrm{L}} + \frac{\mathrm{B_r(RP_{sr})^2Kw(w+3)}}{\mathrm{\Delta vK^2}} + \frac{\mathrm{4K_bT_nB_r}}{\mathrm{R_l}}} \tag{12}$$

$$\mathrm{SNR}_{2D-MD} = \frac{[\mathrm{RP_{sr}K_2/K}]^2}{\frac{\mathrm{eB_rRP_{sr}}}{\mathrm{L}} + \frac{\mathrm{(RP_{sr})^2B_rw_1K_2}}{\mathrm{2\Delta vK}} + \frac{\mathrm{4K_bT_nB_r}}{\mathrm{R_l}}} \tag{13}$$

$$\mathrm{SNR}_{2D-PD\,\&\,2D-DCS} = \frac{[\mathrm{I_0 + I_3 - I_1 - I_2}]^2}{\mathrm{eB_r[I_0 + I_1 + I_2 + I_3]} + \frac{\mathrm{MB_r}}{\mathrm{2\Delta v}}\left[\frac{\mathrm{(I_0 - I_2)^2}}{\mathrm{w_1}} + \frac{\mathrm{(I_1 - I_3)^2}}{\mathrm{(w_1 - 1)^2}}\right] + \frac{\mathrm{4K_bT_nB_r}}{\mathrm{R_l}}} \tag{14}$$

$$SNR_{3D-PD} = [(I_0 - I_3) - (I_1 - I_3) - (I_4 - I_6) - (I_5 - I_7)]^2 / [eB_r[I_0 + I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7] + \frac{MB_r}{2\Delta v}\left[\frac{(I_0 - I_1 - I_4 + I_5)^2}{w_1} + \frac{(I_2 - I_3 - I_6 + I_7)^2}{(w_1 - 1)^2}\right] + \frac{4K_bT_nB_r}{R_l}] \quad (15)$$

$$SNR_{3D-PD/MD} = \frac{[RP_{sr}w_1/M]^2}{eB_r[I_0 + I_1 + I_2 + I_3] + \frac{MB_r}{2\Delta v}\left[\frac{(I_0 - I_1)^2}{w_1} + \frac{(I_2 - I_3)^2}{(w_1 - 1)^2}\right] + \frac{4K_bT_nB_r}{R_l}} \quad (16)$$

$$SNR_{3D-MD} = \frac{[RP_{sr}K_2K_3/K]^2}{\frac{eB_rRP_{sr}K_2K_3}{K} + \frac{(RP_{sr})^2B_rw_1K_2K_3}{2\Delta vK} + \frac{4K_bT_nB_r}{R_l}} \quad (17)$$

The BER based on the Gaussian approach can be defined as:

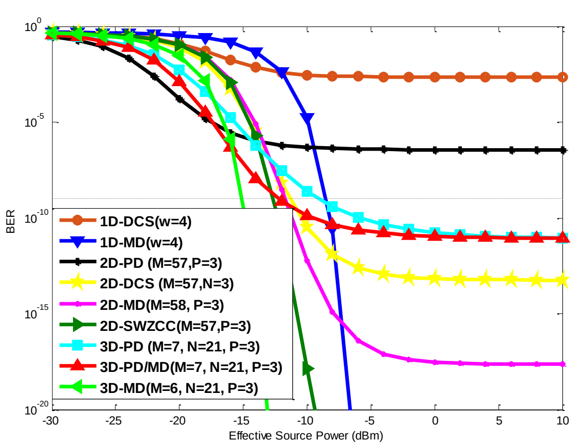
$$BER = 0.5\,\mathrm{erfc}\sqrt{SNR/8} \quad (18)$$

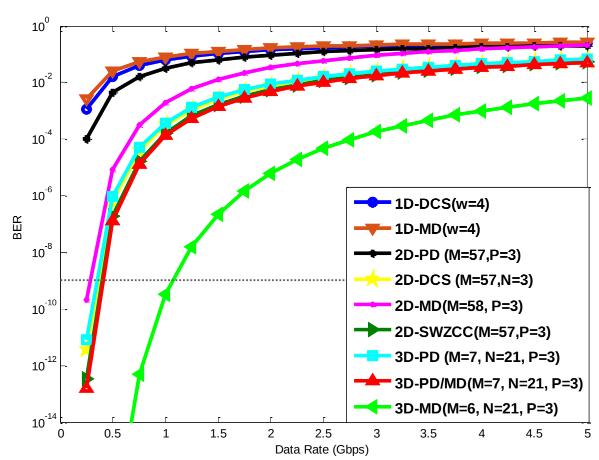
According to the above SNR expressions, both 2D-PD and 2D-DCS codes have the same SNR expression but it is not necessary that OCDMA system with these codes has the same performance because it depends on the properties of the implemented code. In the case of 3D encoding, the electrical bandwidth is equal to ''$0.5NR_b$'' in contrast to 1D and 2D encoding cases is equal to ''$0.5R_b$'' where N is the spatial code length and R_b is the data rate. It has been chosen M=7, N=21 and P=3 for spectral, time and spatial encoding respectively for 3D-PD and 3D-PD/MD codes but in case of 3D-MD code, M is chosen to be equal to 6. For 2D codes, it has been chosen M=57 and N=3 for spectral and spatial encoding respectively. Finally, for 1D-MD and 1D-DCS, the code weight equal to 4.
The parameters used in the system performance investigation are listed in Table 6.

Table 6. System parameters.

Parameter	Symbol	Value
Photo diode responsivity	$\Re$	0.75
Electrical bandwidth	B_r	500Mbps
Light spectral width	Δv	5 THz
Effective source power	P_{sr}	-10 dBm
Receiver load resistor	R_L	1030 Ω
Receiver noise temperature	T_n	300 K
Electron charge	E	$1.6{*}10^{-19}$c
Data bit rate	R_b	1 Gbps

In the next section, a comparative system performance for asynchronous OCDMA systems based on 1-D, 2-D and 3-D coding schemes, separately, is addressed. The system performance is considered as function of BER by taking into consideration the number of simultaneous users, the effective source power, the data rate and the spectral width.
For Fig. 7(a), it presents the BER variation with effective source power for 1 Gbps of data rate and for a user's number equal to 45. For an acceptable BER, both 1D-DCS and 2D-PD codes couldn't achieve required BER value due to the high PIIN effect which degrades the system performance. Whereas, using 1-D, 2-D and 3D-MD codes need around -8.5, -11.75 and -15.12 dBm effective source power, respectively. Likewise, for 2D-DCS, 3D-PD and 3D-PD/MD codes need around -11.3, -9 and -12.25 dBm, respectively. In this case, it is noted that the received power using 2D-DCS and 2D-MD codes is minor than using 3D-PD code although we can say that 3-D case provide better performance compared to 2-D case but this depends on the properties of implemented code in OCDMA system. Overall, when we pass from 1-D to 2-D or from 2-D to 3-D, the upgrading process contributes to minimize the power at receiver level and what is proved in the above results and it is observed in 1D-DCS to 2D-DCS, 1D-MD and 2D-MD to 3D-MD and 2D-PD to 3D-PD, respectively.





(a) (b)

Fig.7 BER versus the effective source power for K = 45(a), BER versus the data rate for K=300(b)

As depicted in Fig. 7(b), the BER variation is represented versus the data rate for a number of users equal to 300. Indeed, it is shown that 1D-DCS, 1D-MD and 2D-PD codes couldn't satisfy the optical communication requirements due to the poor performance of BER under 10E-9. Additionally, for 2D-MD, 2D-DCS, 3D-PD, 3D-PD/MD and 3D-MD, the acceptable BER can be achieved for date rates equal to 0.29, 0.37, 0.35, 0.41 and 1 Gbps, respectively. As a result, each user in OCDMA system can reach 1 Gbps by using 3D-MD code where it is very high compared with other codes which is limited to 0.41 Gbps of data rate.

V. Conclusion

In this paper, a detailed study and comparison between asynchronous and synchronous OCDMA systems in terms of coding schemes, architecture, applications and figure of merits have been addressed. Different coding schemes such as 1-D, 2-D, and 3-D codes for both asynchronous and synchronous OCDMA systems were analyzed separately. The main asynchronous and synchronous OCDMA systems from the last two decades were considered and presented. This paper is the first survey regarding both asynchronous and synchronous OCDMA systems as well as different family of 1-D, 2-D, and 3-D codes. Additionally, distinct multi user detection techniques were discussed in terms of receiver complexity and coding schemes. Moreover, a numerical analysis for both asynchronous and synchronous systems based on 1-D, 2-D, 3-D codes in terms of spectral efficiency and system performance were carried out. On the one hand, results shown that the spectral efficiency of asynchronous 3D-MQC/PHC code outperforms the synchronous 3D-MD code by means of 23.7%, 12.9%, 8.9%, 6.8% and 5.5% at a weight code equal to 11, 21, 31, 41 and 51, respectively. On the other hand, a system performance comparison was performed for synchronous 1D-DCS, 2D-PD, 2D-DCS, 2D-MD and 3D-PD, 3D-PD/MD and 3D-MD codes as function of simultaneous user number, bit rate, effective source power and spectral width. It is further shown that 3D-MD code outperforms 3D-PD, 3D-PD/MD codes in terms of reachable bit rate, BER and spectral width. Therefore, at a number of users equal to 300 and a BER value of 10E-9, 3D-MD code provides 59% enhancement of allowed bit rate compared to 3D-PD and 3D-MD/PD.

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