Efficient 2D NZCC/MD code for SAC-OCDMA systems based on direct spectral/spatial dimension detection and WF

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ABSTRACT

One dimensional (1D) spectral amplitude coding-optical code division multiple access (SAC-OCDMA) systems are generally known by a strict limitation in the number of users that can simultaneously connect. A main solution to overcome this drawback consists of constructing a two-dimensional (2D) structure using a new hybrid spectral/spatial code through combining a one dimensional new zero cross correlation code (NZCC) to a one dimensional multi-diagonal code (1D MD) to easily provide null cross-correlation properties and totally remove the multiple access interferences. Accordingly, this research paper describes an easy and fast technique to construct a hybrid two-dimensional NZCC-MD code based on a non diagonal matrix for SAC-OCDMA systems with direct spectral/spatial dimension (SDD) detection technique and water-filling (WF) optimization. The novel code presents many advantages such as less complex structure, acceptable code length as well as the possibility to construct it for any weight value. The proposed code demonstrates a very good performance for systems with high debit and high simultaneous user number keeps a less complex structure.

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1. INTRODUCTION

Communication systems that use optical fibers (optical communication systems) offer many advantages such as fast transmitting, wide ranging and multiplexing several users in the same medium with the same security level [1]. Today, such a kind of systems increases in speed in order to widen the exploited channel bandwidth by the same users which constitute main topic for many research studies. Different techniques of channel accessing are nowadays largely employed to respond the previous requirements, among them all-optical CDMA namely optical code division multiple access (OCDMA) technique is used for transmitting big data within optical signal super-positioning. Such a system can be divided into two main categories: coherent OCDMA and incoherent OCDAM [2].

Generally, coherent OCDMA systems [3] use unipolar codes to enhance transmitting performance. Specifically, it mentions the application of the spectral amplitude coding (SAC) technique, which utilizes fixed cross-correlation (CC) codes to mitigate the detrimental effects of multiple access interference (MAI) in the optical link. Additionally, the use of SAC helps minimize system performance degradation caused by firing noise, thermal noise, and phase-induced noise (PIIN). Coherent OCDMA systems employ unipolar codes, which are codes that manipulate the amplitude of the optical signal in a specific way to achieve optimal transmission performance. The SAC technique is a particularly promising approach for OCDMA systems.

SAC utilizes fixed CC codes [4] which are predetermined codes that possess specific properties when correlated with each other. The primary objective of SAC is to minimize or reduce the interference caused by multiple users accessing the optical link simultaneously, which is known as multiple access interference (MAI). By employing fixed cross-correlation codes, SAC allows for better management of MAI, resulting in improved system performance [5].

Subtractive detection technique [6] is an efficient method that eliminates the MAI using a zero cross correlation (ZCC) making possible the MAI cancelation as well as the enhancing the system performance [7], [8]. However, the structure complexity of the system stills important and becomes inacceptable because of the high values of the code weight and length, so that using a two-dimensional (2D) code structure that is one of the effective techniques used to surpass such a shortcoming [9], [10]. It consists of a main alternative method providing a high cardinality, keeping always the MAI cancellation property based on time/wavelength, space/wavelength or polarization/wavelength filed [11], [12]. 2D codes can be constructed based on the combination of two 1D codes to increase the user number using the same code length [13]-[15]. Accordingly, this research study develops an effective hybrid 2D NZCC MD for SAC-OCDMA systems, using a specific direct spectral/spatial dimension detection [16] technique and water-filling optimization method to improve the system performance in terms of big data rate, good broadband performance, high number of simultaneous users, low structure complexity and total cancellation of the MAI effects.

2. CONSTRUCING STEPS OF THE TWO DIMENTIONAL CODE

2D NZCC MD a hybrid code that can be constructed by combining a 1D NZCC code to 1D MD code based on a spectral/spatial dimension detection technique for which the NZCC code is implemented by a spectral spreading however the MD code is implemented by a spatial spreading [17]. The 2D NZCC MD code operates in a system where optical fibers are connected to couplers in a star-shaped configuration. Figure 1 displays a visual representation of this configuration. In this system, the goal is to establish simultaneous connections for multiple users. The length of the codes used in the system determines the proportion of users that can be accommodated simultaneously, with the spatial code length being a critical factor. The NZCC component of the hybrid code is responsible for spectral spreading. It is designed to minimize cross-correlation between different users' codes, thereby reducing interference. By spreading the spectral components of the code, the NZCC technique enhances the system's ability to distinguish between different users' signals [18], [19].

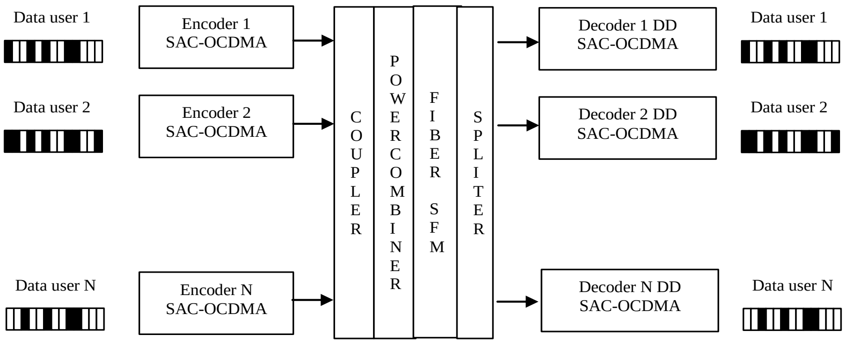


Figure 1. 2D SAC-OCDMA system with SDD

According to Shi and Shiraz [20], using a combine power at the level of the output coupler leads to create a phase-induced noise that arises optical systems due to fluctuations in the phase of a signal. It can be caused by various factors, including thermal effects, interference, or imperfections in the transmission medium or components of the system. These factors can introduce random phase variations, resulting in phase noise. For this, each coupler must be connected to a single photo detector through a fiber. The system schematics can be developed as in the following Figure 2.

Wavelengths are multiplexed by a multiplexer (MUX) depending on the NZCC code sequence, from which each MUX receives a wavelength. The coupler output signals are emitted in optical fibers that can be reduced in terms of numbers using single $(N \times 1)$ outputs as shown in Figure 3(a). At the level of the reception block, each coupler receives a single signal from one branch to be connected to a direct detection block consisting of a splitter. The received optical power (from each fiber) is injected into optical filter than a photo detector followed by a lowpass electrical filter as presents Figure 3(b).

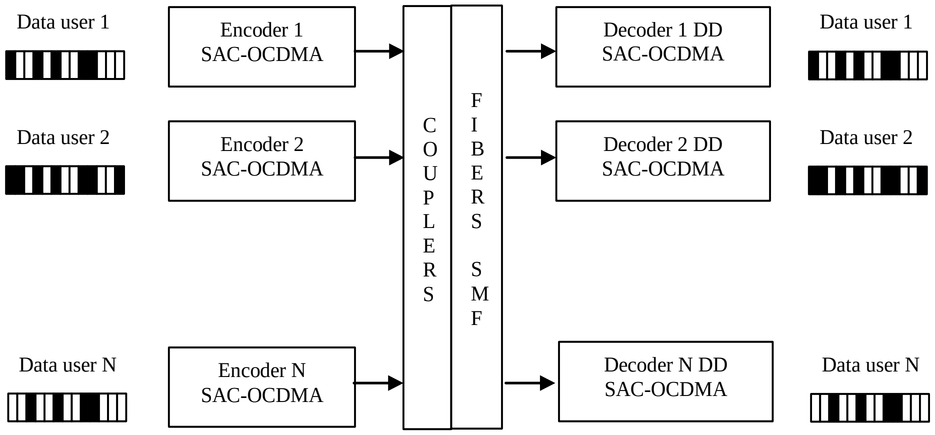
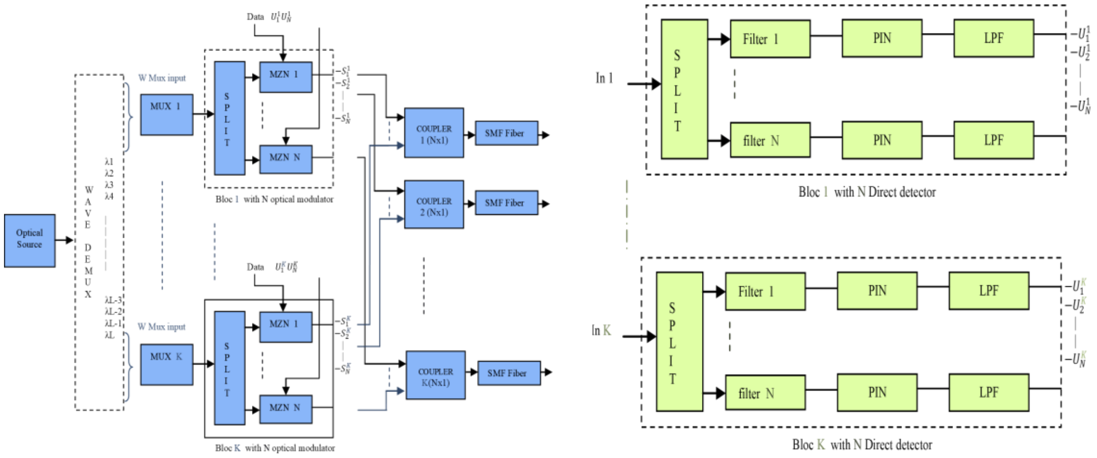


Figure 2. 2D SAC-OCDMA system with SDD without combine power and splitter



(a) (b)

Figure 3. 2D SAC-OCDMA diagram with N couplers: (a) transmitter and (b) receptor

3. PERFORMANCE DETERMINATION OF THE 2D NZCC/MD CODE BASED DIRECT SSD

The 2D code permits a total PIIN cancellation. The Gaussian approximation is applied to the bit error rate (BER) calculation. When all users transmit bit “1”, for a direct detection the NZCC code property is written as:

$$\sum_{i=1}^{L} C_f(i)C_x(i) = \begin{cases} W_2 \; when \; f = x \\ 0 \; else \end{cases} \tag{1}$$

The system will have a capacity of K_{2d} equals to $K \times N$ and a code length L_{2d} equals $W \times K$ (K and N present the line numbers of spectral and spatial codes respectively). Using NZCC properties leads to obtain a pure photo current after a direct detection. The signal to noise rate (SNR) and BER can be calculated by [21], [22].

$$SNR = \frac{I^2}{\langle I_{tot}^2 \rangle} = \frac{\left(\frac{N\mathcal{R}P_{sr}}{K_{2d}}\right)^2}{\frac{2e\,B\,N\,\mathcal{R}P_{sr}}{K_{2d}} + \frac{4K_B T_n B}{R_L}} \tag{2}$$

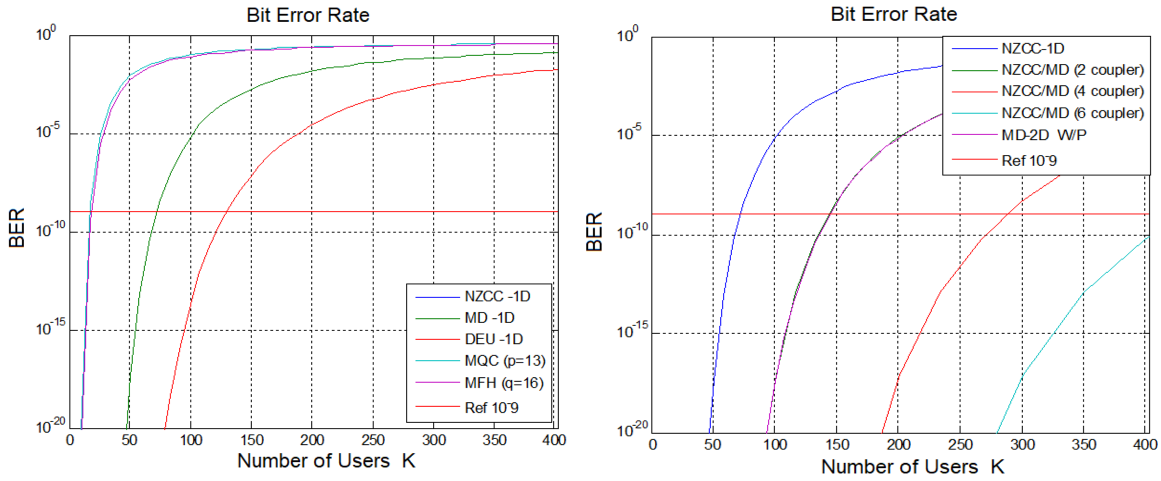
$$BER = \frac{1}{2} erfc\sqrt{SNR/8} \tag{3}$$

Table 1 presents BER numerical calculating parameters to measure the accuracy or reliability of the communication system. BER represents the percentage or fraction of bits that are received incorrectly or corrupted during transmission. To calculate the BER numerically, these parameters are typically used to compare the transmitted bits with the received bits and counting the number of discrepancies or errors. This comparison can be done using error-detection techniques or by utilizing known patterns within the transmitted data. In practice, calculating the BER numerically involves conducting experiments or simulations where known data patterns are transmitted over the communication channel. Lower BER values indicate better transmission quality, while higher BER values indicate a higher error rate and poorer performance of the communication system. The BER is an essential metric for evaluating and optimizing the performance of the system, ensuring reliable and accurate data transmission. Here, the developed hybrid 2D NZCC MD code is evaluated using OptiSystem (V.15) to be proved. The SDD technique [23] is easily applied to the proposed code within the SAC-OCDMA system whose performance is compared to previous system performances using 2D NZCC MD code and 2D MD wave-length/polarization (W/P) code. The results of simulation are displayed in the following figures considering the parameters set in Table 1 to calculate the BER values.

Table 1. BER numerical calculating parameters

Parameter	Symbol	Value
NZCC code weight	w	3
MD code length	L'	2
User number	K	4
Bandwidth	BP	6 nm (1552–1558)
Central frequency	V	194 THz (1555 nm)
Transmitting power	Psr	$-10\ dBm\ (10^{-4}\ W)$
Electrical receiver bandwidth	B	466.5 MHz for 622 Mbps
Quantum yield	$\mathcal{R}$	0.6
Thermal noise at the receiver	T_n	300 K
Load resistance	R_L	1030 Ω
Electron charge	E	1.6×10^{-19} C
Constant of Boltzmann	K_B	$1.3806503 \times 10^{-23}$ J. K^{-1}
Constant plank	h	6.62×10^{-34} m^{2}kg/s

Figure 4(a) shows the BER variation as a function of the simultaneous user number for a SAC-OCDMA system based on 1D coding. It is clearly observed that the 1D NZCC capacity ($w = 2$) is fair to the 1D MD capacity. MD tends to be better than MQC ($p = 13$) and MFH ($q = 16$) for the same code length. In Figure 4(b), it is demonstrated that the system using hybrid 2D NZCC MD code functions well than with 1D NZCC MD code for the same weight and length that leads to improve the system performance basing on the added couplers number. The comparison is made with other coding schemes demonstrates superior performance in terms of achieving lower BER values for the proposed code which indicates better performance and improved reliability in data transmission. This observation serves as validation for the high performance of the SAC-OCDMA system utilizing the developed 2D NZCC MD code. The results suggest that the proposed code is effective in minimizing errors and improving the overall transmission quality in the system.

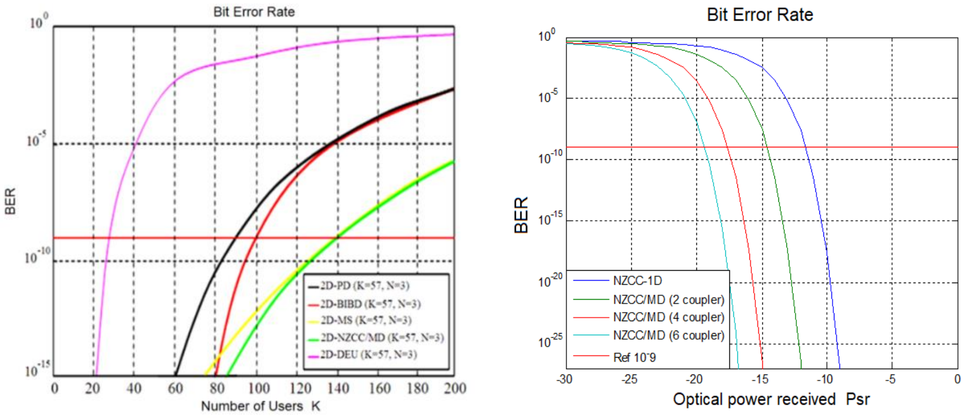


(a) (b)

Figure 4. BER comparison for the different 1D code systems in (a) 2D system performance comparison and (b) different numbers of couplers

Table 2. BER and users' number according to the couplers' number

State/cases	BER	Coupler number	User number
Case 1	10	2	145
Case 2	10	4	187
Case 3	10	6	430



(a) (b)

Figure. 5 2D system performance comparison for different numbers of users in (a) BER and (b) Psr

Upon analyzing the graph, several observations can also be made. As the number of added couplers increases, the performance of both coding schemes improves. This improvement is expected as more couplers allow for better signal distribution and improved system performance. However, a crucial finding from Figure 4(b) is that the system utilizing the hybrid 2D NZCC MD code consistently outperforms the system using the 1D NZCC MD code. This superiority is demonstrated by the higher position of the curve representing the hybrid code, indicating lower BER values or better performance for the same weight and length conditions. Accordingly, Table 2 presents the achieved BER values in function of the different numbers of couplers added to the system in relation to the allowed number of users.

It is clearly observed from Figure 5(a) that BER values in SAC-OCDMA system based on of the proposed code reaches good values comparing to systems employing other codes including diagonal eigenvalue unity (2D-DEU), perfect difference (2D-PD) and balanced incomplete block design (2D-BIBD) code for a number of users greater than 100. This validates a high performance for the system using the developed 2D NZCC MD code. In addition, 2D-DEU, 2D-PD, 2D-BIBD, "2D-MS" multi-service code and 2D NZCC MD codes allow a user number of 27, 90, 100, 138 and 140 respectively for a minimum value of BER equals to 10^{-9} as displayed in graph. This demonstrates the efficiency of the proposed code in permitting a high number of simultaneous users comparing to the other codes. Finally, Figure 5(b) presents the BER values of the hybrid SAC-OCDMA system for a received optical power range from -30 dBm to 0 dBm. Adding couplers allows detecting low optical powers and leads realizing a good transmission process for long distances.

4. WATER-FILLING SOLUTION

When a channel is damaged by severe fading, adapting the signal to the channel during the transmission generally brings a great improvement to the process speed. The aim then is to allocate an optimal power by maximizing the capacity for a limited global transmission power. This can be achieved using complicated optimization algorithms known as water-filling [24], [25] technique that permits good adaptation and increases the channel capacity. Two channel states can be observed:

a. Channel known to transmitter: the necessary return channel with slowly varying channel.
b. Channel unknown to transmitter: channel estimation is performed by periodically inserting training symbols, a training sequence sent periodically.

Water-filling is an accurate technique that examine per-tone SNR results in per-tone bits number and energy levels that must be optimally exploited. To maximize the data rate given by $R = b/T$ for a set of parallel sub-channels with a fixed symbol rate that equals to $1/T$, it is necessary to maximize the achievable value of $b = \sum_n b_n$ over b under a given total input energy and a target probability of error. Specifically, the number of bits allocated to the n^{th} sub-channels is:

$$b_n = log_2\left(1+\frac{\varepsilon_n g_n}{\Gamma}\right) \text{ with } g_n = \frac{|H_n|^2}{2\delta_n^2} \qquad (4)$$

where g_n represents the sub-channel SNR when the transmitter applies an energy unit to that sub-channel. The ratio g_n (channel coefficient) is a fixed function of the channel, but ε_n denotes the 2D sub-symbol energy allotted to the n^{th} sub-channel that can be optimized to maximized b, subject to a total transmit energy constraint of:

$$\sum_{n=1}^{N} \varepsilon_n \leq \varepsilon_x \qquad (5)$$

Thus, the aggregate bit rate in b is maximized when the optimum sub-channel transmit energies satisfy:

$$E_n + \frac{\Gamma}{g_n} = K = cte \qquad (6)$$

K is chosen such that the total energy constraint given by the equation is met. In fact, the procedures of calculation by water-filling solution can be resumed as:

- Ranking of g_n in descending order.
- Choosing the number of the used sub-carriers (fixed for all sub-channels).
- Calculating K level (shown in red line in Figure 6); the threshold which makes it possible to choose the sub-channels so as to respect the constraint of total transmitted energy.
- Eliminating sub-channels with negative energy.
- Calculating the energy and bits number assigned to each sub-channel.

From Figure 6, positive energies found for sub-channels indicate that the water-filling solution has been found. The algorithm assigns greater transmit power to channels with high SNR (and vice versa). The number of bits to be added by each sub-channel can be calculated and the capacity can be increased. To combat attenuation and dispersion problems existing in the optical fiber links for long distances, a new technique involves inserting orthogonal frequency division modulation (OFDM) in SAC-OCDMA systems leading to hybrid OFDM /SAC-OCDMA systems [16].

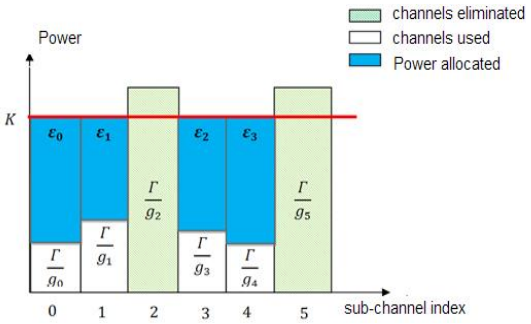
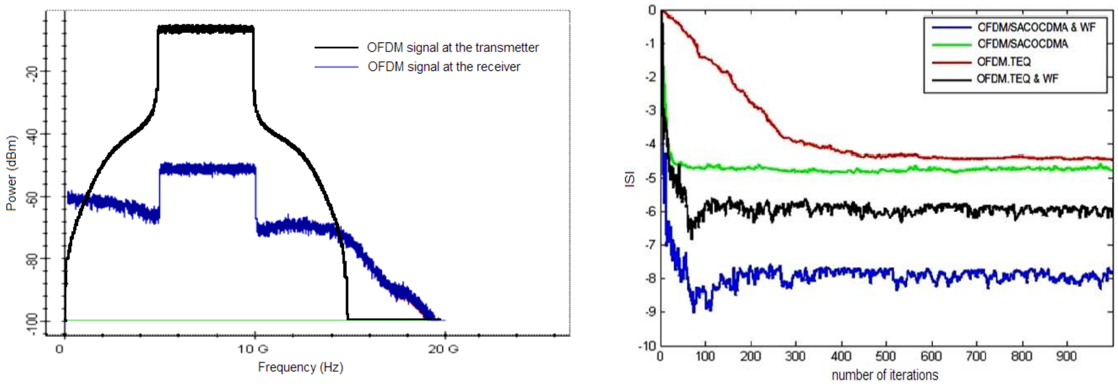


Figure 6. Water-filling solution

The performance of the hybrid OFDM/SAC-OCDMA based on the proposed 2D NZCC MD code system is evaluated by simulation via MATLAB and OptiSystem by evaluating BER values as a function of the user number taking into account DD-OFDM detection processing as displayed in have been performed and presented in Figure 7(a). It is transmitted to an OFDM demodulator with the same specifications as the OFDM modulator. The output obtained from a quadrature amplitude modulation (QAM) sequence decoder maps symbols to bits is used for BER values analysis. Numerical simulation results of inter symbol interference (ISI) have been performed and presented in Figure 7(b). The evolution of the ISI as a function of the number of iterations allows to know how to evaluate and compare the performances of the systems in terms of their speed of convergence. The ISI is obtained by varying the number of iterations (the number of symbols) that is equal to 1000. Simulation results use water-filling as a standard test channel. The FFT size is of 512, the cyclic prefix (CP) length is of 32, the time-domain equalizer (TEQ) has 16 taps and the SNR is of 40 dB. The curves of the OFDM/SACOCDMA system using water-filling solution are much better than the other curves, the system converge rapidly which makes water-filling efficient technique to significantly improve the system performance.



(a) (b)

Figure 7. OFDM signal transmitter versus OFDM signal receiver in (a) performance comparison of hybrid OFDM/SAC-OCDMA system based on develop 2D NZCC MD code with and (b) without WF solution

5. CONCLUSION

This paper presents a high efficiency 2D NZCC MD code based on a non diagonal matrix and direct spectral/spatial dimension detection for SAC-OCDMA systems using water-filling technique as a effective optimization solution to solve the problem of power allocation. The initiative to integrate OFDM into SAC-OCDMA system makes possible to obtain a hybrid OFDM/SAC-OCDMA system which has the possibility of increasing the multiplexing capacity and the number of users simultaneously connected. Results derived from both calculation and simulation demonstrate that the constructed hybrid 2D NZCC MD code permits a total elimination of the MAI and PIIN noise and outperforms 1D NZCC and 2D MD (W/P) codes already developed based on BER values related to the simultaneous user number. The code construction method is less complex for a high number of simultaneous users and big data rate that offers good characteristics and high performance for SAC-OCDMA systems taking into consideration the good broadband performance of the proposed code that stills robust for high debit and high user number using couplers and direct detection. It is very important to suggest that applying water-filling technique makes also possible to overcome many restrictions of optical fiber and to have important data rates and high spectral efficiency. Simulation result comparison with and without water-filling confirm the effectiveness of the channel; such a solution is unique because the rate function being maximized is concave. Therefore, there is a unique optimum energy distribution referring to the specific distribution of energy across different channels that maximizes the overall system performance. The goal is achieved by allocating available energy resources in an optimal way leading to maximizing data rates, minimizing error rates and optimizing other system metrics.

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