Construction and performance analysis of variable weight zero cross correlation Latin square code for spectral amplitude coding OCDMA systems*

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The selection of appropriate codes for an optical code division multiple access (OCDMA) network, which determines the maximum number of users and bit error rate (*BER*) supported by the system, is crucial. This study proposed a variable weight zero cross-correlation Latin square (VW-ZLS) code for spectral amplitude coding (SAC)-OCDMA systems, which offers high autocorrelation and zero cross-correlation, while providing differentiated quality of service (QoS) features. Using direct detection (DD) technology, the data rate of the proposed VW-ZLS code reached 4.8 Gbit/s under the condition that *BER* does not exceed 10^{-9}. This was 0.5 Gbit/s higher than that of zero cross-correlation magic square variable weight optical orthogonal code (ZMS-VWOOC) with the same cross-correlation characteristics. Further, simulation results showed that in SAC-OCDMA system, the VW-ZLS code was better than ZMS-VWOOC and exhibited excellent performance.

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Optical code division multiple access (OCDMA) is a multiplexing technology, which can asynchronously share the entire channel between different users, while providing certain data transmission confidentiality and high quality of service (QoS). It is an alternative solution for the next generation of access networks[1,2]. In recent years, OCDMA technology has been widely used. It can improve the physical layer security of free optical communication[3], be used in optical sensors to monitor the health of large urban facilities[4], and overcome the imaging speed and resolution of traditional imaging lidar[5]. However, OCDMA system encounters various challenges that limit its performance. Generally, it is affected by five noise sources, including multiple access interference (MAI), phase induced intensity noise (PIIN) usually accompanied by MAI, dark current, shot noise, and thermal noise[6-8]. Among these, the most influential is MAI.

Spectral amplitude coding (SAC) has garnered attention owing to its ability to reduce MAI[9,10], requiring simple system components and incurring low cost[11]. In the OCDMA system, the choice of codes is crucial. Thus, several codes based on SAC-OCDMA system coding have been proposed, such as modified quadratic congruence (MQC) code[12], optical orthogonal code (OOC)[13-15], fixed right shift (FRS) code[16], Latin square code (LSC)[17], and zero cross-correlation code (ZCC)[18]. However, the code weights of the above-mentioned codes are fixed, which cannot satisfy the requirements of current multimedia services, such as simultaneous transmission of voice, data, and video.

To improve the performance of SAC-OCDMA system, variable weight (VW) codes have been proposed, which support high QoS. YANG et al[19] first proposed variable weight optical orthogonal code (VWOOC), which was useful for OCDMA networks with various performance requirements. However, its construction was complicated and the code length was quite long. Later, ANAS et al[20] designed variable weight Khazani-Syed (VW-KS) with multiple QoS. However, only even integers can be selected as the code weight, which limits the choice of code weight. KUMAWAT et al[21] proposed a VW code algorithm based on enhanced and modified double weight codes to handle multimedia services. However, its cross-correlation value was not optimal and the bit error rate (*BER*) was not ideal. Recently, LU et al[22] constructed a zero cross-correlation magic square variable weight optical orthogonal code (ZMS-VWOOC) that supports different services. Compared with previous codes, it offers the advantages of simple construction,

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flexible code weight selection, and zero cross-correlation value. However, its construction method is only based on traditional mapping technology, and its code performance can be further improved.

Based on the standard Latin square matrix and a new algorithm, this study directly constructed a variable weight code with double code weight, and used the mapping technology to obtain a multi-code weight VW code according to user requirements. Thus, a variable weight zero cross-correlation Latin square (VW-ZLS) code that exhibited better performance for SAC-OCDMA system was proposed. It offers the advantages of simple and diverse structure, flexible code weight selection, zero cross-correlation, and differentiated QoS. This study focused on code construction and mathematical analysis, and the mathematical analysis was verified via Matlab and Optisystem simulations.

The VW-ZLS code is characterized by the following parameters (L, $\boldsymbol{W}$, $\boldsymbol{\Lambda}$, λ_c, $\boldsymbol{Q}$), where $\boldsymbol{W}$, $\boldsymbol{\Lambda}$ and $\boldsymbol{Q}$ represent the sets $\{\omega_1, \omega_2,..., \omega_i\}$,$\{\lambda_a^1, \lambda_a^2,..., \lambda_a^i\}$, and $\{q_1, q_2,..., q_i\}$, respectively. Here, L denotes the code length, $\boldsymbol{W}$ denotes the code weight set, $\boldsymbol{\Lambda}$ denotes the auto-correlation, λ_c denotes the cross-correlation, and q_i denotes the ratio of the code capacity of different code weights to the total capacity.

For any two codes $\boldsymbol{X}$=(x_0, x_1,..., x_{L-1}) and $\boldsymbol{Y}$=(y_0, y_1,..., y_{L-1}) with code weight ω_i, the following expressions can be obtained[19]

Auto-correlation function:

$$\sum_{j=0}^{L-1} x_j x_{j\oplus\tau} \le \lambda_a^{\ i}, \quad 1 \le \tau \le L-1, \tag{1}$$

Cross-correlation function:

$$\sum_{j=0}^{L-1} x_j y_{j\oplus\tau} \le \lambda_c, \quad 1 \le \tau \le L-1, X \ne Y, \tag{2}$$

where $\oplus$ represents all modulo-L.

The VW-ZLS code was constructed according to the following steps.

Step 1: A standard Latin square matrix $\boldsymbol{M}$ of order A (A≥3) was constructed. $\boldsymbol{M}$ is a matrix of dimensions A×A, with exactly A different elements (0 to A−1). Each different element only appeared once in the same row or column, and the elements in the first row and column were arranged in order. Each element of $\boldsymbol{M}$ can be obtained using the following formula:

$$\boldsymbol{M}(i,j) = (i+j) \bmod A, \tag{3}$$

where $0 \le i \le (A-1), 0 \le j \le (A-1)$.

For example, when A=4, $\boldsymbol{M}$ is expressed as

$$\boldsymbol{M} = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 1 & 2 & 3 & 0 \\ 2 & 3 & 0 & 1 \\ 3 & 0 & 1 & 2 \end{bmatrix}. \tag{4}$$

Step 2: Let the required new code sequence be $B(i, t)$. When $t = \boldsymbol{M}(i,j) + j(A-1), 0 \le i \le (A-1), 0 \le j \le (A-1)$, $B(i,t)$ is 1, otherwise it is 0.

Step 3: Using Eqs.(1) and (2), the cross-correlation of the VW-ZLS code is λ_c=0, and the autocorrelation is expressed as

$$\boldsymbol{R}_x(n) = \begin{cases} \{A-1, A-2\}, & n=1 \\ \{A_n-1, A_n-2, \cdots, A_1-1, A_1-2\}, & n>1 \end{cases}, \tag{5}$$

where n represents the number of different A values.

Step 4: (1) When A acquires a fixed value, the code $\boldsymbol{B}$ with two code weights is obtained.

For A=4, the following is obtained

$$\boldsymbol{B} = \begin{bmatrix} 1000100010001 \\ 0100010001000 \\ 0010001000100 \\ 0001000100010 \end{bmatrix}. \tag{6}$$

From the new sequence $\boldsymbol{B}$, it is evident that when A=4, the sequence with different code weights, ω_1=4 and ω_2=3 are obtained. Simultaneously, the minimum code length is $L_{\boldsymbol{B}}$=13 and the number of users is $N_{\boldsymbol{B}}$=4. The relationship between variable A, code weights ω_1 and ω_2, minimum code length $L_{\boldsymbol{B}}$, code capacity $\Phi_{\boldsymbol{B}}$, and the number of users $N_{\boldsymbol{B}}$ is as follows

$$\begin{cases} \omega_1 = A \\ \omega_2 = A-1 \end{cases}, \tag{7}$$

$$L_{\boldsymbol{B}} = A^2 - A + 1, \tag{8}$$

$$\Phi_{\boldsymbol{B}} = N_{\boldsymbol{B}} = A. \tag{9}$$

(2) When A takes n variables, the sequence with multiple code weights can be obtained.

The relationship between variable A and code weight ω_i is presented in Tab.1, when A acquires values in the range from 3 to 10.

Tab.1 Correspondence between code weight *ωᵢ* and variable *A*

A	3	4	5	6	7	8	9	10
ω_i	3 2	4 3	5 4	6 5	7 6	8 7	9 8	10 9

It is evident from Tab.1 that the code with multiple code weights can be obtained by considering different A values, that is, ω_i=2, 3, 4, 5, 6, 7, 8, 9, 10. When the variable A takes n values, namely A_1, A_2,..., A_n, the relationship between the minimum code length $L_{\boldsymbol{B}}$, code capacity $\Phi_{\boldsymbol{B}}$, and the number of users $N_{\boldsymbol{B}}$ is as follows.

$$L_{\boldsymbol{B}} = (A_1^2 + A_2^2 + \cdots + A_n^2) - (A_1 + A_2 + \cdots + A_n) + n, \tag{10}$$

$$\Phi_{\boldsymbol{B}} = N_{\boldsymbol{B}} = A_1 + A_2 + \cdots + A_n. \tag{11}$$

Step 5: Code capacity Φ is expressed as

$$\Phi = \begin{cases} mA, & n=1 \\ m\sum_{i=1}^{n} A_i, & n>1 \end{cases}, \tag{12}$$

where m represents the mapping times, n represents the number of different A values, and i represents a positive integer.

Step 6: Mapping technology was used to satisfy user needs and attain high QoS.

(1) When A takes a fixed value, the mapping technology increases the number of users while ensuring λ_c=0 for the obtained code.

$$\boldsymbol{C_B}=\begin{bmatrix} \boldsymbol{B}^{(1)} & 0 & 0 & 0 \\ 0 & \boldsymbol{B}^{(2)} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \boldsymbol{B}^{(m)} \end{bmatrix}. \tag{13}$$

Assuming A=4 and the mapping times m=2, we obtain

$$\boldsymbol{C_B}=\begin{bmatrix} 10001000100010000000000000 \\ 01000100010000000000000000 \\ 00100010001000000000000000 \\ 00010001000100000000000000 \\ 00000000000001000100010001 \\ 00000000000000100010001000 \\ 00000000000000010001000100 \\ 00000000000000001000100010 \end{bmatrix}. \tag{14}$$

The code $\boldsymbol{C_B}(26,\{4,3\},\{3,2\},0,\{1/4,3/4\})$ is obtained. By changing the variable A and mapping times m, the needs of the user can be met.

(2) When A takes n variables, first, mapping technology is used to increase the number of code weights, which is then used to achieve high QoS.

$$\boldsymbol{C}=\begin{bmatrix} \boldsymbol{C_B}^{(1)} & 0 & 0 & 0 \\ 0 & \boldsymbol{C_B}^{(2)} & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \boldsymbol{C_B}^{(m)} \end{bmatrix}. \tag{15}$$

Assuming A=3, 4 and the mapping times m=2, we obtain

$$\boldsymbol{C}=\begin{bmatrix} \boldsymbol{C_B}^{(1)} & 0 \\ 0 & \boldsymbol{C_B}^{(2)} \end{bmatrix}, \tag{16}$$

$$\boldsymbol{C_B}=\begin{bmatrix} \begin{bmatrix} 1001001 \\ 0100100 \\ 0010010 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1000100010001 \\ 0100010001000 \\ 0010001000100 \\ 0001000100010 \end{bmatrix} \end{bmatrix}. \tag{17}$$

The code $\boldsymbol{C}\{40,\{4,3,2\},\{3,2,1\},0,\{1/7,4/7,2/7\}\}$ is obtained, and high QoS can be achieved by changing the variable A and mapping times m.

To exploit the bandwidth of the SAC-OCDMA system based on the largest number of active users, the code length must be as short as possible. Tab.2 shows the comparison of four variable weight codes under the same code weight and number of users. It is evident that the code length of VWOOC is excessively long, which is not ideal for an SAC-OCDMA system. VW-KS code has shorter code length. However, its λ_{cmax}=1, which results in the system being affected by MAI. The code lengths of ZMS-VWOOC and the proposed VW-ZLS code are short and λ_{cmax}=0. However, that of the latter is smaller.

The cross-correlation of the proposed VW-ZLS code is zero, with no overlap in the frequency spectrum between codes. Therefore, direct detection (DD) technology was used to analyze the performance of this code. The DD technology contains a single decoder, which is very simple and low cost. Moreover, it can support more users than complementary subtraction (CS) and subtraction detection technologies[23,24].

Tab.2 Comparison of different variable weight code properties

Code	Code weight	Total users	Code length	λ_{cmax}
VWOOC	4{5,4,3,2}	50	427	1
VW-KS	4{8,6,4,2}	50	170	1
ZMS-VWOOC	4{5,4,3,2}	48	168	0
VW-ZLS	4{5,4,3,2}	48	164	0

Fig.1 shows the architecture of SAC-OCDMA system based on VW-ZLS code. It consists of a transmitter and a receiver. The transmitter includes a broadband light source (BBS), an encoder, user data, and a modulator. The receiver includes a filter, photo-detector, and low-pass filter (LPF). At the transmitting end, for each coding sequence, the corresponding wavelengths are combined via an optical coupler, modulated by a Mach-Zehnder modulator (MZM), and then the modulated signals of all users are multiplexed together and sent through a single mode fiber (SMF). At the receiving end, the DD technology is used to segment and decode the received combined optical signal according to the code, and the photodetector and LPF are used to recover the information.

To analyze the system, the following conditions need to be assumed[25-27].

1. Each user has the same received power.
2. Each power spectrum component has the same spectrum width.
3. Assuming that the light source is ideally unpolarized, its spectrum is flat at a given bandwidth $[v_0-\Delta v/2, v_0+\Delta v/2]$, where v_0 denotes the central light frequency, and $\Delta v/2$ denotes the light source bandwidth.
4. Each bit stream of each user is synchronized.

In an SAC-OCDMA system based on the power spectral density (PSD) of broadband light source, thermal noise, PIIN, and shot noise are the main factors that affect the system performance. To remove the influence of PIIN, the cross-correlation value should be as small as possible[28].

Since the cross-correlation value of VW-ZLS is zero, the influence of MAI and PIIN was eliminated. The performance of the receiver depends on the signal-to-noise ratio (SNR) as $SNR=I^2/\sigma^2$, where I denotes the average photo-current and σ^2 denotes the variance of different noise sources. For VW-ZLS code, σ^2 can be written as the sum of the shot (σ_{shot}^2) and thermal ($\sigma_{\text{thermal}}^2$) noises[29].

$$\sigma^2=\sigma_{\text{shot}}^2+\sigma_{\text{thermal}}^2=2eIB+\frac{4K_B T_n B}{R_L}, \tag{18}$$

where e represents the electronic charge, B represents the electrical bandwidth of the receiver, K_B represents the Boltzmann's constant, T_n represents the absolute receiver noise temperature, and R_L represents the receiver load resistance.

According to the nature of the VW-ZLS code, using DD technology, the relevant attributes of the ith user whose code weight is W can be expressed as

$$\sum_{i=1}^{L} C_k(i)C_l(i) = \begin{cases} W_j, k=l, \text{The same mapping matrix} \\ 0, k \neq l, \text{The same mapping matrix} \\ 0, k \neq l, \text{Different mapping matrix} \end{cases}. \quad (19)$$

The Gaussian approximation was used to calculate the BER. The PSD of the received optical signal can be expressed as[30]

$$G(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^{N_{B_j}} d_k \sum_{i=1}^{L} C_k(i) \prod(i) , \quad (20)$$

where P_{sr} denotes the effective power at the receiver, d_k denotes the data sent by the kth user and is "1" or "0", and $C_k(i)$ denotes the ith element of the kth code sequence.

$\prod(i)$ can be expressed as

$$\prod(i) = u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i-2) \right], \quad (21)$$

where $u(v)$ represents the unit step function, and is expressed as

$$u(v) = \begin{cases} 1, & v \geq 0 \\ 0, & v < 0 \end{cases}. \quad (22)$$

Using Eq.(18), the sum of the PSD at the photodetector of the lth receiver in a period can be expressed as

$$\int_0^{+\infty} G(v) \mathrm{d}v = \int_0^{+\infty} \frac{P_{sr}}{\Delta v} \sum_{k=1}^{N_{B_j}} d_k \sum_{i=1}^{L} C_k(i) C_l(i) u\left[\frac{\Delta v}{L} \right] \mathrm{d}v = \frac{P_{sr}}{\Delta v} \frac{\Delta v}{L} \sum_{k=1}^{N_{B_j}} d_k \sum_{i=1}^{L} C_k(i) C_l(i) = . \frac{P_{sr} W_j}{L} d_i + \frac{P_{sr}}{L} \sum_{k=1, k\neq l}^{N_{Bj}} d_k = \frac{P_{sr} W_j}{L}. \quad (23)$$

The photocurrent I at the output of the photodetector is expressed as

$$I = R\int_0^{+\infty} G(v) \mathrm{d}v = \frac{RP_{sr}W_j}{L}, \quad (24)$$

where R is the responsivity of the photodetector, with $R=\eta e/hv$, where η denotes quantum efficiency, h represents Planck constant, v represents the center frequency of the original broadband light pulse, and e represents the electronic charge.

Substituting Eq.(22) into Eq.(13), the noise variance is expressed as

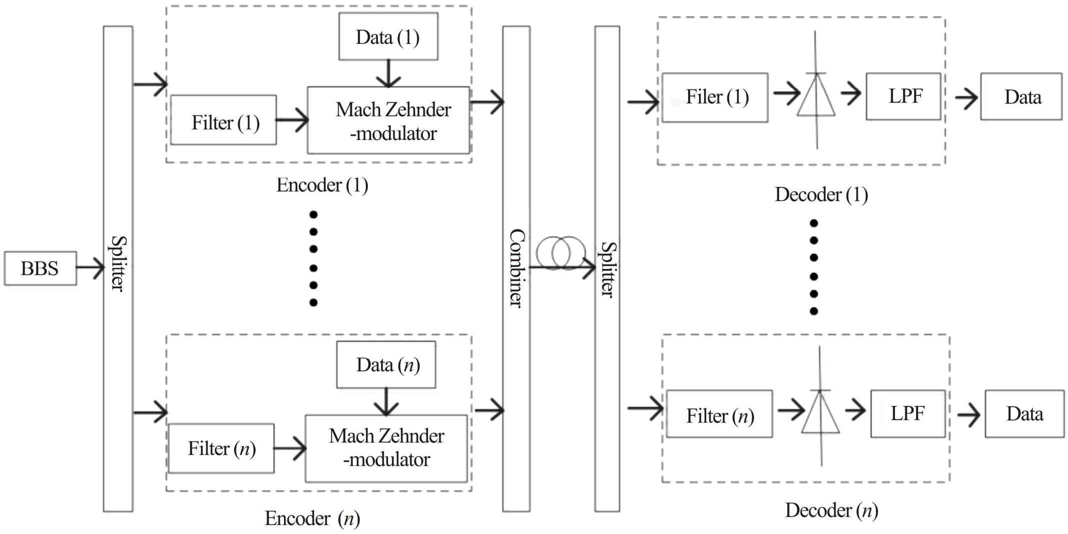

Fig.1 Block diagram of the SAC-OCDMA system using the VW-ZLS code

$$\sigma^2 = 2\frac{eBRP_{sr}W_j}{L} + 4\frac{K_B T_n B}{R_L}. \quad (25)$$

Considering that the probability of each user sending a "1" bit at any time is 1⁄2, the average SNR of each user is

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{RP_{sr}W_j}{L} \right)^2}{\frac{eBRP_{sr}W_j}{L} + \frac{4K_B T_n B}{R_L}}. \quad (26)$$

Using non-return-to-zero on-off keying (NRZ-OOK) as modulation mode, the BER can be calculated as follows[17,31]

$$BER = P_e = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{8}} \right), \quad (27)$$

where $erfc$ denotes a complementary error function.

The performances of VW-ZLS code and ZMS-VWOOC, which have the same correlation characteristics (λ_c=0), were compared numerically. The BER was calculated using Matlab. Tab.3 summarizes the parameters used in the calculation.

Figs.2 and 3 show the relationship between the number of users and BER of VW-ZLS code and ZMS-VWOOC with code weights of 6, 5, and 4, when the received power of the signal was −10 dBm and the data transmission rates were 622 Mbit/s and 2 Gbit/s, respectively. As seen from Fig.2, when W=6, the maximum numbers of users that VW-ZLS and ZMS-VWOOC can accommodate (BER=10^{-9}) are 112 and 105, respectively. Similarly, when the code weights are 5 and 4, the maximum numbers of users of VW-ZLS code are 93 and 74, respectively, and those of ZMS-VWOOC are 88 and 70, respectively. Thus, VW-ZLS code can accommodate more users than ZMS-VWOOC. Further, the results showed that the BER increased with the number of users. At the same number of users, the larger the code weight, the higher the BER of the code. Fig.3 shows that with the increase in data rate, the maximum number of users decreased. When R_b=2 Gbit/s, VW-ZLS code still exhibited good performance.

Tab.3 Typical parameters used in the calculation

Symbol	Parameter	Value
η	Photodetector quantum efficiency	0.6
B	Electrical bandwidth	311 MHz
R_L	Receiver load resistor	1 030 Ω
λ	Operating wavelength	1 550 nm
P_{sr}	Received optical power	−10 dBm
T_n	Receiver noise temperature	300 K
e	Electron charge	1.6×10^{-19} C
h	Planck's constant	6.63×10^{-34} Js
K_b	Boltzmann's constant	1.38×10^{-23} J/K

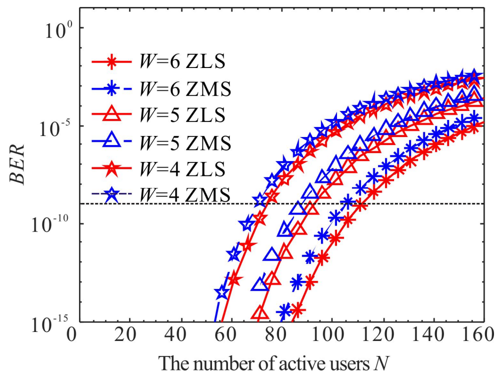

Fig.2 *BER* versus the number of active users for the VW-ZLS code and ZMS-VWOOC (R_b=622 Mbit/s)

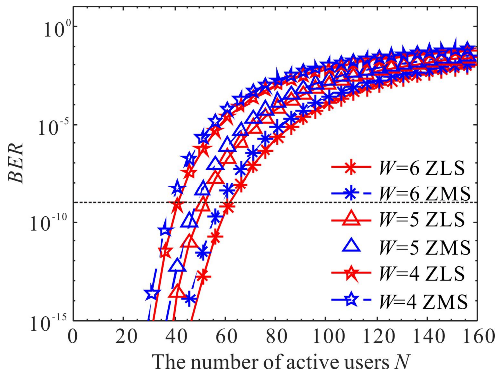

Fig.3 *BER* versus the number of active users for the VW-ZLS code and ZMS-VWOOC (R_b=2 Gbit/s)

Figs.4 and 5 show the relationship between BER and the effective power of the VW-ZLS code and ZMS-VWOOC with 40 users, when the code weights are 6, 5, and 4, and the data transmission rates are 622 Mbit/s and 2 Gbit/s, respectively. It is evident that compared with ZMS-VWOOC, the SAC-OCDMA system using VW-ZLS required less power under the same conditions. In addition, when the data rate increased, the required power increased.

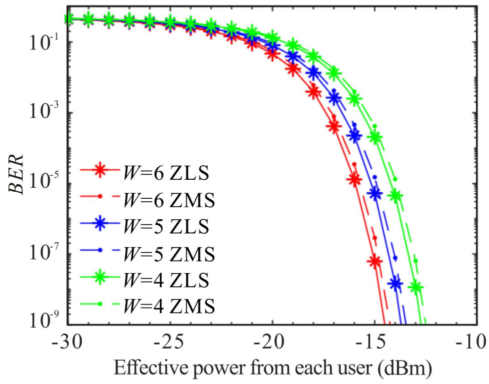

Fig.4 *BER* versus the effective received power from every user for the VW-ZLS code and ZMS-VWOOC employing the SAC-OCDMA technique (R_b=622 Mbit/s)

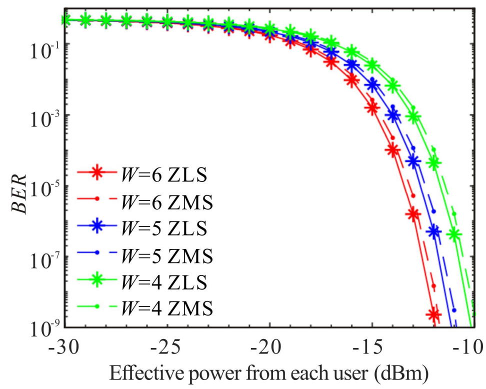

Fig.5 *BER* versus the effective received power from every user for the VW-ZLS code and ZMS-VWOOC employing the SAC-OCDMA technique (R_b=2 Gbit/s)

Fig.6 shows the performance of 40 online users with a received power of −10 dBm at different data rates. With the increase in data rate, the BER of code increased gradually, and the performance of the code decreased. For the same code, the larger the code weight, the lower the BER at the same data rate. When the acceptable BER of the system is 10^{-9}, the data rates of the VW-ZLS code with code weights of 6, 5, and 4 are 4.8 Gbit/s, 3.4 Gbit/s, and 2.2 Gbit/s, respectively, and those of ZMS-VWOOC are 4.3 Gbit/s, 3.0 Gbit/s, and 1.9 Gbit/s, respectively. Thus, VW-ZLS code can support a faster transmission rate and the code performance is better.

Fig.7 shows the relationship between the number of users and BER under different code weights at data rates of 1.8 Gbit/s and 2.3 Gbit/s. It is evident from Fig.7 that when W=4, the numbers of users supporting 10^{-3} error-free voice applications are 86 and 75, respectively. When W=5, the numbers of users supporting 10^{-9} error-free data applications are 55 and 48, respectively. When W=6, the numbers of users supporting 10^{-12} error-free video applications reach 56 and 49, respectively. Thus, the code weight can be chosen flexibly according to different service needs to satisfy the needs of users.

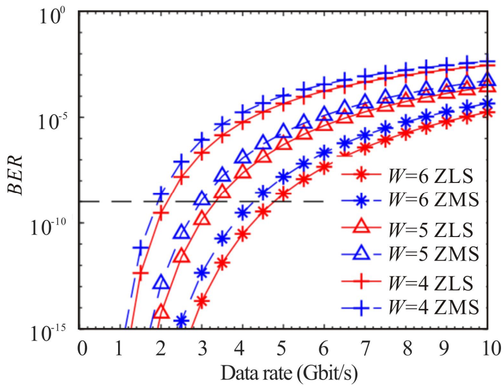

Fig.6 *BER* versus the data rate for the VW-ZLS code and ZMS-VWOOC employing the SAC-OCDMA technique

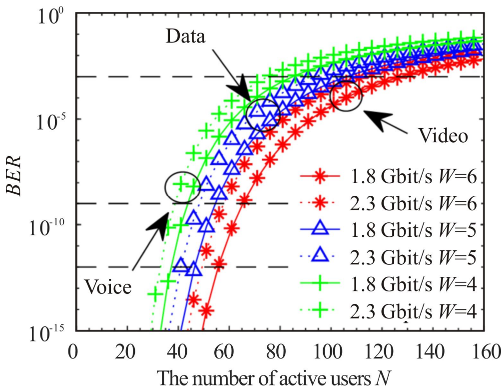

Fig.7 *BER* versus the number of active users of the VW-ZLS code with transmission data rates of 1.8 Gbit/s and 2.3 Gbit/s

Fig.8 shows the performance of the system based on *BER* and data rate. It can be observed that for VW-ZLS code with W=6, 5, and 4, the *BER* increased with the increase in data rate. In addition, as expected, the VM-ZLS code with large code weight is more effective than that with small code weight, which can be attributed to relatively large power units received at the PIIN photodiode associated with the codes of large weight. Therefore, the analysis indicates that the proposed model can provide different QoS. The VW-ZLS code with larger code weights can be used for services with higher data rate requirements, whereas that with smaller code weights exhibited relatively better performance at low data rates.

To enrich the research conducted, an SAC-OCDMA system with VW-ZLS code for four users was simulated using Optisystem system software, as shown in Fig.9. The simulation was conducted for a distance of 25 km. The attenuation of the optical fiber was 0.2 dB/km and the dispersion was 16.75 ps/(nm·km). The noise at the receiver was considered to be randomly generated and completely uncorrelated. The dark current value of each photodetector was 5 nA and the thermal noise coefficient was 1.8×10^{-23} W/Hz.

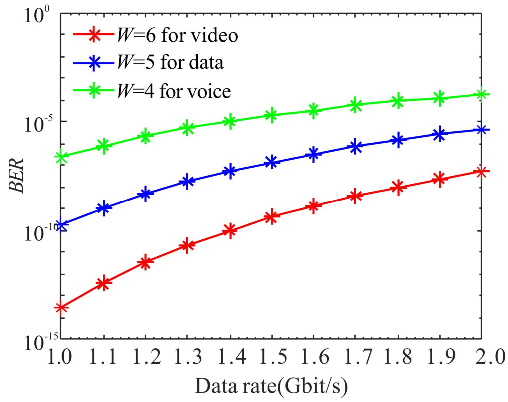

Fig.8 *BER* versus data rate of the VW-ZLS code

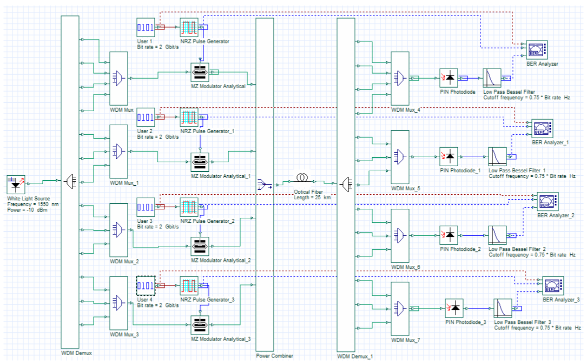

Fig.9 Simulation model of the VW-ZLS code for four users at 2 Gbit/s and −10 dBm input power

As shown in Figs.10 and 11, when the user rate is 2 Gbit/s, the *BER* of the user with W=4 is 10^{-11}, and that of the user with W=3 is 10^{-9}. Thus, the larger the code weight, the smaller the *BER*. However, when the user rate is lower than 2 Gbit/s or the transmission distance is less than 25 km, the system can support more users.

This study proposed a VW-ZLS code based on the standard Latin square matrix, and its design, structure and characteristics were introduced. The numerical results showed that when the data transmission rates were 622 Mbit/s, 1.8 Gbit/s and 2.3 Gbit/s, the maximum numbers of users supported by the SAC-OCDMA system using VW-ZLS code were 112, 66 and 58, respectively, indicating good performance. Further, compared with similar variable weight codes, VWOOC, VW-KS, and ZMS-VWOOC, the cross-correlation value of the VW-ZLS code was 0 and the code length was reduced. In addition, using DD technology to eliminate MAI and PIIN, it was verified via experiments that the performance of the

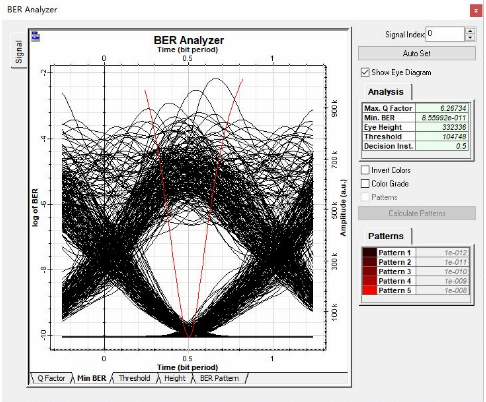

Fig.10 Eye diagram indicating the performance of four users with weight 4 using the VW-ZLS code at 25 km

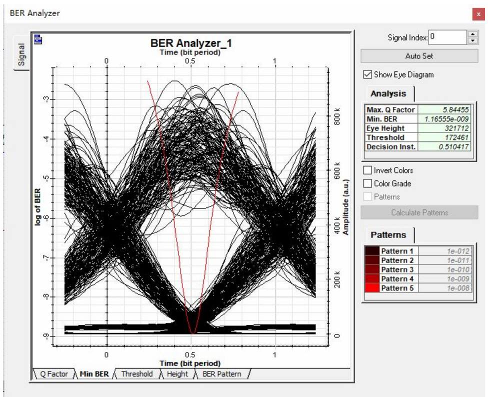

Fig.11 Eye diagram indicating the performance of four users with weight 3 using the VW-ZLS code at 25 km

VW-ZLS code was better than that of ZMS-VWOOC. Furthermore, for the same codeword, the larger the code weight, the lower the *BER* and the less the power required.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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