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Eradication of Multiple Access Interference Using a Modified Multi-service Code for SAC–OCDMA

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Abstract Phase induced intensity noise (PIIN) and multiple access interference (MAI) are the main parameters that affect the performance of optical code division multiple access (OCDMA) systems, leading to degradations in system performance and reduction in the number of active users. So, this paper presents an efficient modified multi-service (MMS) code that can be used for encoding the spectral amplitude of the optical source in OCDMA systems to avoid these limitations. The proposed code disposes the effect of MAI, PIIN, and gives better performance than the other traditional codes. It can support a large number of active users (80 at bit error rate of 10^{-9}) with a small code weight ($w = 4$). Also, it achieves a practical code length with a simple receiver structure.

Keywords Multiple access interference (MAI) · Phase induced intensity noise (PIIN) · Multi-service (MS) code · Spectral amplitude coding (SAC)

1 Introduction

An optical code division multiple access (OCDMA) system has several advantages such as supporting asynchronous access to the networks, enabling multiple users to use the same

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overlapping spectral range without interference, and enhancing information security. So, it has attracted the attention of researchers recently. An incoherent OCDMA system has less hardware complexity than a coherent system because it is not necessary to know the phase information, only the signal amplitude. So, we will use it in this paper. multiple access interference (MAI) introduced from users transmitting simultaneously limits the performance of the system and reduces the number of active users. Also, the phase induced intensity noise (PIIN) is correlated to the MAI because of the spectral duplication from various users when inconsistent optical fields are combined and directed on a photo detector. The phase noise fields produce intensity noise in the photo detector output marked as PIIN [1].

Several methods have been introduced to reduce MAI depending on receiver design such as suppressing it by complementary [2], AND [3], NAND [4] or XOR [5] subtraction techniques, but in these schemes, the PIIN remains in the system. Also, these techniques increase the number of filters at the receiver and the signals endure poor quality in complementary and AND subtraction. Another method was based on using successive or parallel interference cancellation (SIC or PIC) schemes, but using these schemes, the receiver complexity and system cost increased dramatically [6, 7]. A third method depends on using the spectral direct detection (SDD) [8] technique where only clean chips are detected. This scheme provides a simpler receiver, but provides poor treatment to the MAI problem [9].

Recently, the spectral amplitude coding (SAC–OCDMA) system has been launched to dispose of the MAI effect and to ensure orthogonality between signature codes of users. The SAC–OCDMA allocates a unique spectral amplitude codeword to every user in the network to encode the light source spectral amplitude. Families of codes have been introduced for SAC–OCDMA including an optical orthogonal code (OOC) [10], modified quadratic congruence (MQC) [2], Hadamard, modified frequency hopping (MFH) [11, 12], multi-service (MS) code [13] and so on to solve the MAI and PIIN problems by designing codes with an ideal in-phase cross correlation $0 \leq \lambda c \leq 1$. Although these codes can reduce MAI, they cannot remove PIIN, which degrades system performance and reduces the number of active users. Also, each code is restricted in some way as will be discussed in Sect. 5.

In order to realize an efficient OCDMA system, signature codes must have a zero cross correlation. So codewords can be distinguished from each other. Codes with a zero cross correlation completely eliminate MAI and PIIN because there is no overlapping between codes, which means that a better BER can be obtained, the number of active users can be increased and that there is no need to build a complex receiver structure. Some existing codes have a cross correlation equal to zero ($\lambda c = 0$) such as the zero cross correlation (ZCC) code [1] and the single weight zero cross correlation (SW-ZCC) code [14]. These codes completely eliminate MAI and PIIN. The first one has flexibility in choosing the code weight, but when the code weight is increased, the code length also increases to maintain $\lambda c = 0$. The long code length needs extremely wide band sources or very narrow filter bands. The (SW-ZCC) [14] has a simple construction, but no flexibility in choosing the code weight; it's always equal to one. The variable weight is required for triple-play services, and also the code length equals the number of users, which makes this code impractical when the number of users increases.

The contributions of this paper can be summarized as follows. A modification is made in the MS code [13], which has an ideal cross correlation ($0 \leq \lambda c \leq 1$), using a spreading technique [14] to present a modified MS code with the zero cross-correlation property, a practical code length, and a smaller weight leading to a simple receiver structure as shown in Sects. 2 and 3. The mathematical analysis of the proposed modified code is derived in Sect. 4. A comparison between the proposed modified code and various traditional codes is given in Sect. 5. The discussion of the simulation results using MATLAB is given in Sect. 6. A simulation using optiwave.13 is presented in Sect. 7. Finally, the conclusion is given in Sect. 8.

2 Modified Code Construction

Assume we have two different code sequences $p_i = \{p_1, p_2, p_3, \ldots p_L\}$ and $q_i = \{q_1, q_2, q_3, \ldots q_L\}$ $p_i = \{p_1, p_2, p_3, \ldots p_L\}$ and $q_i = \{q_1, q_2, q_3, \ldots q_L\}$. The cross-correlation between these two codes is written as [13]

$$\lambda_C = \sum_{i=1}^{L} p_i \, q_i \tag{1}$$

The proposed modified code for the SAC–OCDMA system can be characterized by *(L_B, w, N_B, λc)*, where L_B is the code length in the basic matrix, *w* is the weight of the code, N_B is the number of users in the basic code matrix where

$$N_B = 2 \times w, \tag{2}$$

and

$$L_B = N_B \times w \tag{3}$$

The construction of code consists of generating two matrices Y_1 and Y_2 that have a dimension's $w \times 2w$ and $\lambda c = 1$, and then the spreading technique is used to decrease λc *to zero.*

2.1 The Construction of the Proposed Modified Code is as Follows [13]

Step 1 Generate Y_1, let P_w be the positions of ones in the code sequence calculated as

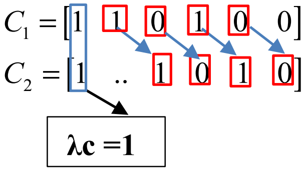
$$P_w = \begin{cases} 1, & w = 1 \\ P_{(w-1)} + (w-1), & w > 1 \end{cases}, \tag{4}$$

and the remaining positions in the code sequence filled by zeros.

For $w = 3$, Y_1 has a dimension $w \times 2w$ (3×6) P_w for the first code sequence C_1 are $\{1, 2, 4\}$, $C_1 = [1 \quad 1 \quad .. \quad 1 \quad .. \quad ..]$ and the empty spaces are filled with zeros, then $C_1 = [1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0]$.

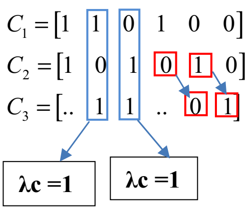
Step 2 Construct the subsequent codes C_i by starting from the first code. Find the first '1' in previous generated codes that has no overlapping with other codes, and put '1' into this position to get the cross-correlation = 1. Obtain the rest of the code sequence by shifting the bits of the previous code one unit to the right, and fill in the empty spaces with '0'.

To construct C_2, put bit '1' at the position that has no overlapping with C_1. This is found at C_{21} (first position of the second code). The rest of the code sequence positions are filled by bit shifting of C_1 by one bit to the right, and by filling empty spaces with zeros, so that the second code sequence is



$$C_1 = [1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0]$$
$$C_2 = [1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0]$$

Step 3 Repeat step 2 for the subsequent codes until the matrix Y_1 has been generated. To construct C_3, put bit '1' at the positions that have no overlapping which are C_{32} and C_{33} obtain the rest of C_3 by shifting C_2 bits one unit to the right and fill the empty spaces with zero.



$$C_1 = [1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0]$$
$$C_2 = [1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0]$$
$$C_3 = [0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1]$$

The matri

$$Y_1 = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Step 4 Create Y_2 by replacing each one in Y_1 with zero and each zero with one

$$Y_2 = \begin{bmatrix} 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Step 5 Use a code spreading technique [14] to decrease the correlation value from one to zero. For that, generate two zero matrices $w \times 2w^2$ (3×18) and then arrange the rows of Y_1 on the diagonal of the first zero matrix. Similarly, arrange the rows of Y_2 on the diagonal of the second zero matrix. Finally, the basic matrix is generated.

$$C_B = \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$

λc = 0 λc = 0

$$C_B = \begin{bmatrix} 1&1&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&1&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&0&0&1 \\ 0&0&1&0&1&1&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&1&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&1&1&0 \end{bmatrix}$$

To increase the number of users, use the mapping technique

$$m = N/N_B \tag{5}$$

$$L = m \times L_B, \tag{6}$$

where m is the mapping number, N is the total number of users in the system, and L is the total code length in the system

$$C_B(m) = \begin{bmatrix} C_B(m) & 0 & 0 & 0 \\ 0 & C_B(m) & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & C_B(m) \end{bmatrix}$$

3 System Architecture

Figure 1 shows the modified multi-service (MMS) code system with the direct detection technique, where an encoder at the transmitter side is used to encode the optical pulses corresponding to the desired code sequence to produce a unique codeword for every user. Then, data is modulated with codewords using an external-modulator and combined together before sending via the optical media. At the receiver side, a splitter is used to split encoded data, and then decoding and detection are performed. In the direct detection technique, one branch of the decoder and detector is needed at the receiver compared to other codes that need two branches at the receiver inputs, one for the code and the other for the complementary of the code as in the complementary subtraction technique [2]. Because there is no overlapping in MMS codes, the receiver is simpler and has a lower cost.

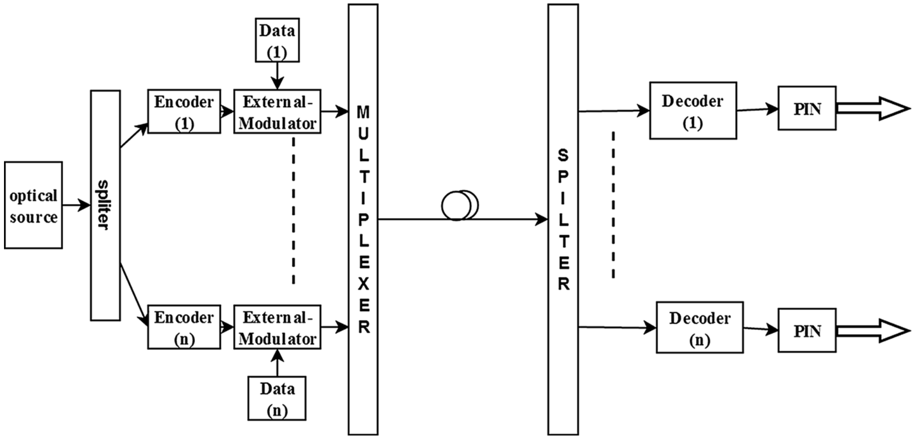


Fig. 1 Block diagram of MMS code system using direct detection technique [8]

4 Mathematical Analysis of the Proposed Modified Code

To facilitate our analysis, a Gaussian approach is used in the computation of the bit error rate for performance evaluation of the proposed modified code. In our analysis, only the impacts of shot noise and thermal noise are considered. The cross correlation value of the proposed modified code is always zero $\lambda c = 0$, which completely removes the impact of PIIN as there is no duplication of spectra from various users.

Let $C_N(i)$ indicate the ith item of the Nth MMS code sequence. For a code with the direct detection technique, the code properties are expressed as [1]:

$$\sum_{i=1}^{L} C_N(i) C_l(i) = \begin{cases} w, & for\ N = 1 \\ 0, & else \end{cases} \tag{7}$$

To parse the system we assume the following as in [1, 2]

(a) Each source of light is perfectly unpolarized and spectrum over the bandwidth $\left[v_o - \frac{\Delta v}{2}, \quad v_o + \frac{\Delta v}{2}\right]$ is flat, where v_0 is the central optical frequency and Δv is the light source bandwidth (Hz).
(b) Each power spectral component has the same spectral width.
(c) Each user has the same power at the receiver.
(d) Each bit stream from every user is synced.

The Power Spectral Density (PSD) for the optical signals received can be written as [1, 2]

$$r(v) = \frac{P_{sr}}{\Delta V} \sum_{N=1}^{N} d_N \sum_{i=1}^{L} C_N(i) \left\{ u\left[v - v_o - \frac{\Delta v}{2L}(-L + 2i - 2)\right] - u\left[v - v_o - \frac{\Delta v}{2L}(-L + 2i)\right] \right\}. \tag{8}$$

where P_{sr}, the effective power of a broadband source at the receiver; d_N, data bit of the *Nth* user which is ‘‘1” or ‘‘0”; u(v), unit step function.

$$u(v) = \begin{cases} 1, & v \geq 0 \\ 0, & v < 0 \end{cases} \quad (9)$$

The photocurrent I can be written as [1]

$$I = r \int_{0}^{\infty} G_d(v) dv \quad (10)$$

where $G_d(v)$ is the PSD at the photo-diode

$$I = R \int_{0}^{\infty} \frac{P_{SR}}{\Delta V} \sum_{N=1}^{N} d_N \sum_{i=1}^{L} C_N(i) C_l(i) u\left[\frac{\Delta v}{L}\right] dv \quad (11)$$

$$= R \frac{P_{SR}}{\Delta V} w \frac{\Delta v}{L} d_l = R \frac{P_{SR} w}{L} d_l \quad (12)$$

The power of noise in photocurrent can be expressed as [1]

$$\langle I^2 \rangle = I_{shot} + I_{theraml} \quad (13)$$

$$\langle I^2 \rangle = 2eBI_{dd} + \frac{4K_B T_n B}{R_L} \quad (14)$$

$$I_{dd} = R \int_{0}^{\infty} \frac{P_{sr}}{\Delta V} \sum_{N=1}^{N} d_N \sum_{i=1}^{L} C_N(i) C_l(i) u\left[\frac{\Delta v}{L} dv\right] \quad (15)$$

As in [2], when the users are transmitting bit "1", $\sum_{t=1}^{N} d_N \approx (K/(W-1))$

$$\langle I^2 \rangle = 2eBR + \frac{P_{sr}(k)w}{L(W-1)} + \frac{4K_B T_n B}{R_L} \quad (16)$$

When all the users are sending bit "1" and the probability of sending bit '1' at any time for every user is 50 %, the previous equation becomes [1, 2]

$$SNR = \frac{(I)^2}{\langle I^2 \rangle} = \frac{\left(R \frac{P_{sr} w}{L}\right)^2}{eBR \frac{P_{sr} K w}{(W-1)L} + \frac{4K_B T_n B}{R_L}} \quad (17)$$

BER is expressed by [1, 2]

$$\text{BER} = .5\ erfc\left(\sqrt{SNR/8}\right) \quad (18)$$

where, erfc, a complementary error function; K_B, Boltzmann's constant; R, the responsivity of the photodiode R = ηe/hf_c (Table 1).

5 Code Comparison

Several codes have been offered for SAC–OCDMA, but theses codes suffer from some limitation such as OOC [10], which has a complex code construction and a very long code

Table 1 System parameters [2]

η: quantum efficiency	=6
Δv: broadband source line width	=3.75 THz
P_{sr}: effective power	=−10 dBm
B: electrical equivalent noise band-width of the receiver	=311 MHz
λ: operating wavelength	=1550 nm
e: charge of electron	$=1.602 \times 10^{-19}$ C
h: Planks' constant	$=6.626 \times 10^{-34}$ JS
T_n: Receiver noise temperature	=300 K

Table 2 Comparison between different codes [14, 16]

Codes name	Users number	Code weight	Length of code	Cross-correlation
OOC	30	4	364	≤1
Hadamard	30	16	32	8
MFH	30	7	42	1
MQC	30	7	49	1
KS	30	4	81	1
ZCC code	30	4	120	0
SW-ZCC-code	30	1	30	0
MS	30	4	75	≤1
MMS (Modified Multi-Service)	**30**	**3**	**90**	**0**

MMS this is our proposed code

length. Also, Hadamard code does not have an ideal cross correlation and exists for the matrix sequence m only, where m ≥ 2. MQC code is limited to a prime number (P) and $P > 2$, which means minimum weight w = 4. So, the free cardinality of code selection is restricted and exists only for a prime number of users. Khazani-Syed (KS) [15] code has a simple construction and reduces the number of filters at the receiver because ones are always present in pairs, so only one filter is used for both, but there is an overlap between codes in the same section, and λc = 1 which causes MAI that reduces the number of active users, and a weight limited to even numbers only. In addition, MFH code construction is complicated and MS code [13] performance is worse than KS and MFH, as PIIN degrades the system performance. Table 2 [14, 16] shows the code length needed by the various codes to support 30 users. Modified multi-service code (MMS) can provide the same number of active users with a smaller weight, a zero cross correlation and a practical code length.

6 Results and Discussion

SNR determines the quality of the signals in the system. BER and SNR are interconnected, improved SNR provides a better BER. In this part, the analysis of the numerical results obtained by MATLAB will be based on the SNR, BER, bitrates and effective power received from each user.

6.1 SNR Versus Number of Active Users (N)

Figure 2 shows that the MMS code provides better SNR when the weight is equal to 4 than MFH (q = 16), KS (w = 6), MQC ($p = 13$) and MS (w = 4 $N_B = 2$) at the same power received ($P_{sr} = -10$ dBm), because the PIIN is completely eliminated with the MMS code due to the zero cross correlation property, while with other codes, the PIIN is still present in the system, which degrades performance. Moreover, MMS code performance is close to KS code with a high number of users, but with a smaller weight. So, the MMS code can provide better SNR values with a smaller weight than that of the other codes.

Figure 3 shows that the MMS code provides better SNR values when the weight is 4 than ZCC (w = 4), SW-ZCC (w = 1) at the same power received $P_{sr} = -10$ dBm. Although the PIIN is completely eliminated in the three codes, the MMS code can still provide better SNR values, because MMS can provide the same number of users as ZCC with smaller weight and code length. Also, the property of the SW-ZCC code that the code length is always equal to the number of users degrades its performance. When the number of active users increases, code length required for SW-ZCC becomes larger than needed for the MMS code which makes MMS gives better performance.

6.2 BER Versus Number of Active Users (N)

Figure 4 shows that at a BER = 10^{-9}, the MMS code supports 80 simultaneous users for w = 4, while MFH, KS, MS and MQC support 60, 61, 40 and 32 active users respectively, because a better BER is associated with a better SNR. Also in Fig. 5, ZCC and SW-ZCC support 68 and 55 active users respectively. So, MMS code gives a better performance and supports larger numbers of users than other codes with the same weight. Figure 6 shows that the MMS code with weight = 2 provides the same performance of the ZCC code with weight = 4. So, the MMS code can provide the same performance with half the weight

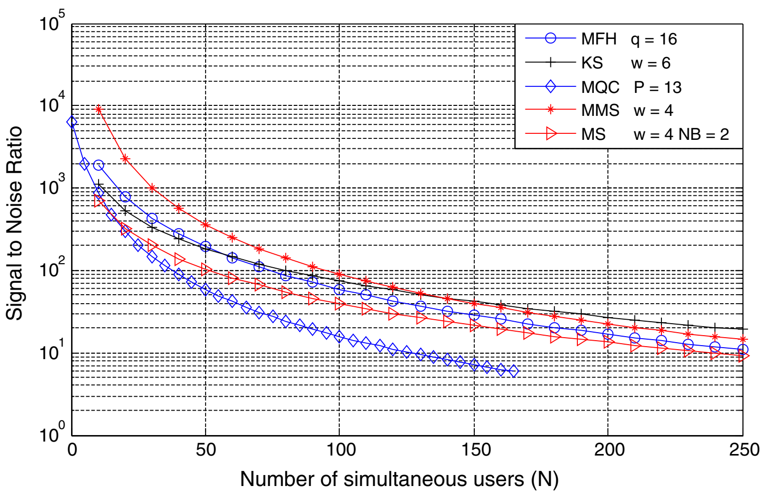


Fig. 2 SNR versus number of active users, $P_{sr} = -10$ dBm for MMS, MFH, KS, MQC, MS

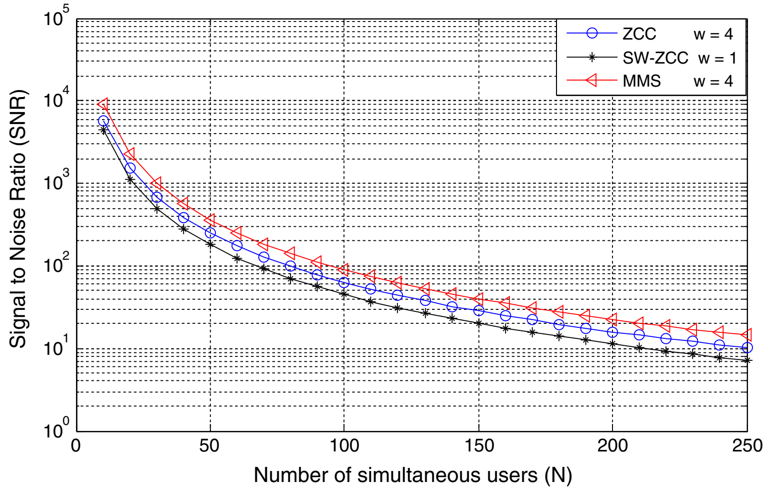


Fig. 3 SNR versus number of active users, $P_{sr} = -10$ dBm for MMS, ZCC, SW-ZCC

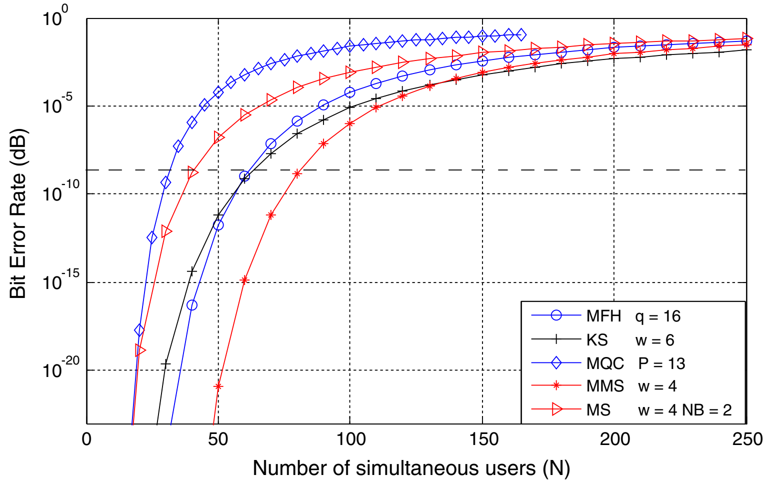


Fig. 4 BER versus number of simultaneous users (N) for MMS, MFH, KS, MQC, MS

used with the ZCC, which reduces the number of encoders and decoders to half, and decreases the system cost.

6.3 Effect of Power Received P_{sr} on System Performance

Figures 7 and 8 show the BER variation with the effective power, when the number of active users is 60. These figures show that the effective power P_{sr} at the accepted BER of 10^{-9} for MMS code with (w = 4) is ($P_{sr} \approx -12$ dBm,) lower than that for other codes KS ($P_{sr} \approx -10$ dBm), ZCC ($P_{sr} \approx -11.5$ dBm) for the same number of active

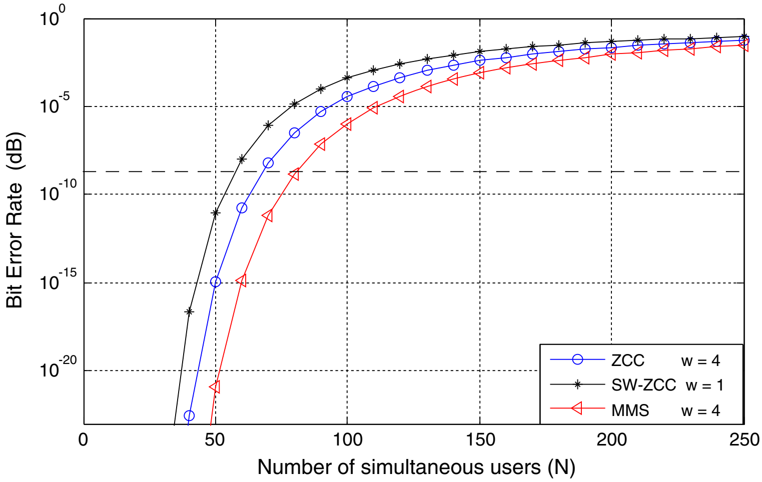


Fig. 5 BER versus number of simultaneous users (N) for MMS, ZCC, SW-ZCC

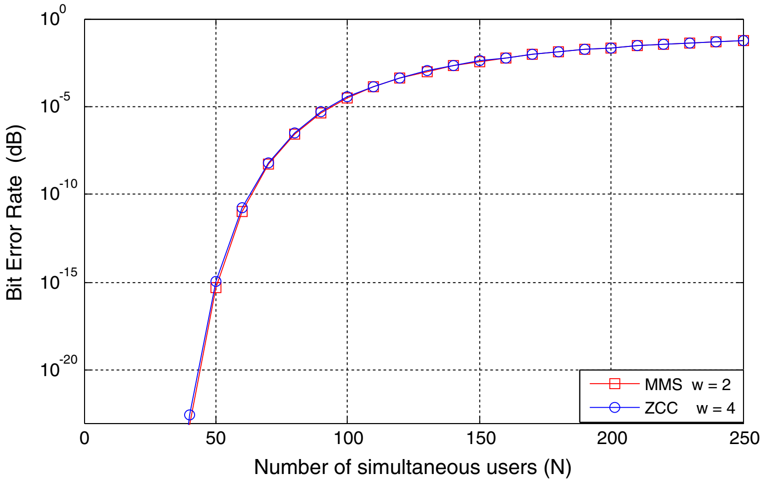


Fig. 6 BER versus number of active users, $P_{sr} = -10$ dBm for MMS (w = 2), ZCC (w = 4)

users as the interference from other users is decreased. So MMS code can provide the required system performance with power (≈ -2 dBm) lower than that required by other codes.

6.4 SNR Versus Bit Rates

Figures 9 and 10 show BER variation with different bit rates for 60 users with received power -10 dBm for various codes. It can be seen that MMS code shows the best

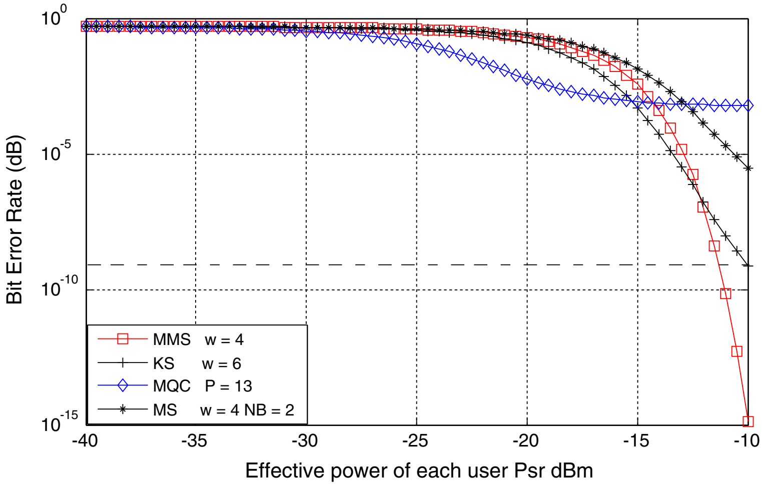


Fig. 7 BER variation with the effective power, when the number of active users is 60

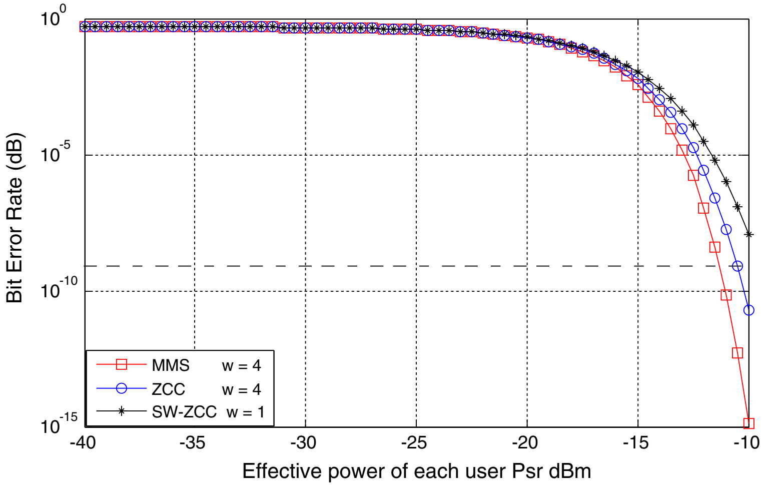


Fig. 8 BER variation with the effective power when the number of active users is 60 for MMS, SW-ZCC, ZCC

performance compered to other codes with weight 4. When the bitrate increases, the performance of the system degrades. Because when the bitrate increases, the pulse width size decreases. So, the system performance becomes susceptible to the dispersion effect [9].

6.5 BER Versus Bit Rates

Figures 11 and 12 show the BER versus bitrates for various codes. MMS gives better performance than other codes at weight 4. Another factor that effects on overall system

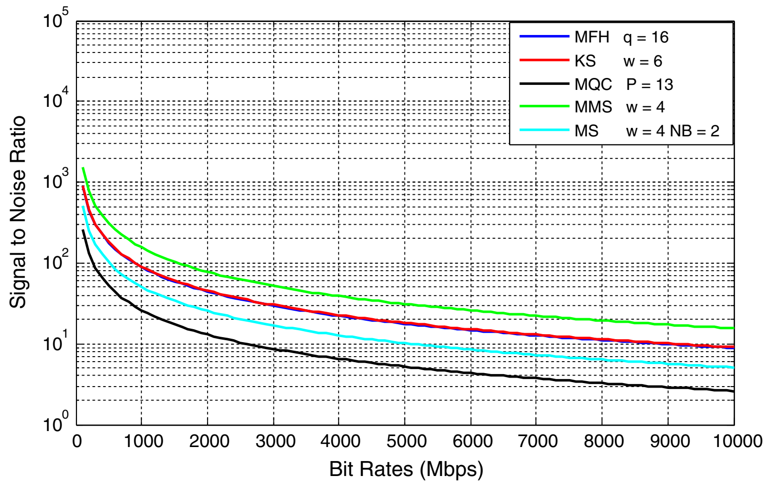


Fig. 9 SNR versus bit rates, $P_{sr} = -10$ dBm, N = 60 for MMS, MFH, KS, MQC, MS

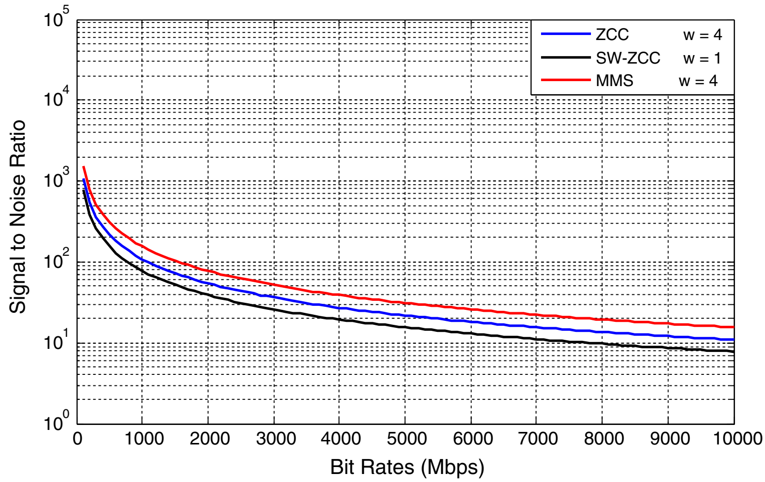


Fig. 10 SNR versus bit rates, $P_{sr} = -10$ dBm, N = 60 for MMS, ZCC, SW-ZCC

performance and causes degradation is the code length. Because it relates to the slicing of the spectrum, small code length means the number of chips in a codeword is small. So, when pulse width decreases, the dispersion effect increases [9].

7 Network Simulation

Optisystem version 13 is used to simulate the performance analysis of Modified Multi-Service (MMS) code. A simple schematic of 6 users is shown in Fig. 13. Tests

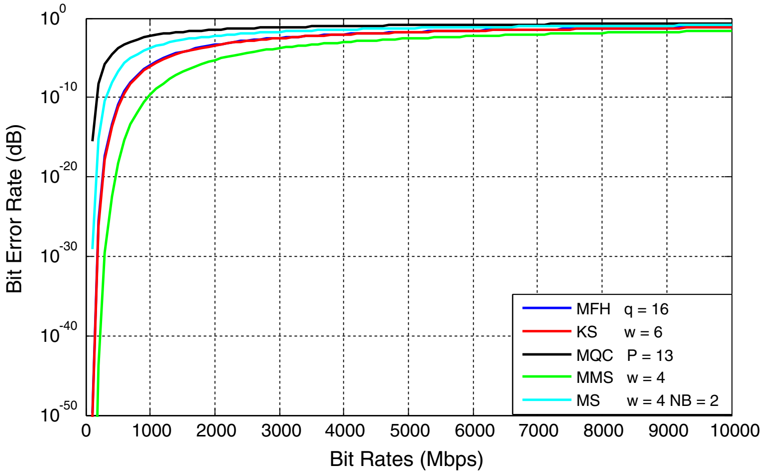


Fig. 11 SNR versus bit rates, $P_{sr} = -10$ dBm, N = 60 for MMS, MFH, KS, MQC, MS

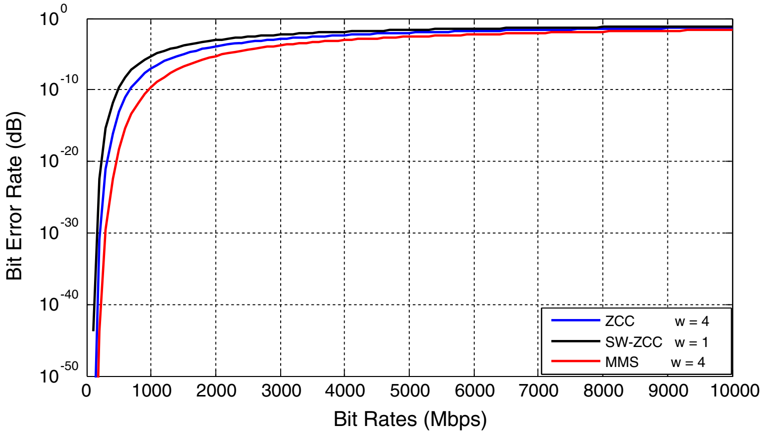


Fig. 12 SNR versus bit rates, $P_{sr} = -10$ dBm, N = 60 for MMS, ZCC, SW-ZCC

carried out using parameters in Table 3 with ITU-T G.652 standard single-mode optical fiber (SMF) and nonlinear effects were enabled and set according to the typical industry values. The bit error rate (BER) and eye pattern were used to characterize the system performance. Figure 14 shows that MMS code gives BER 10^{-24} in a back-to-back case. Then, Fig. 15 clarifies the performance of MMS code at 40 km, where the BER is reduced to 10^{-19}. So, MMS code can provide high performance reaches to 10^{-19}.

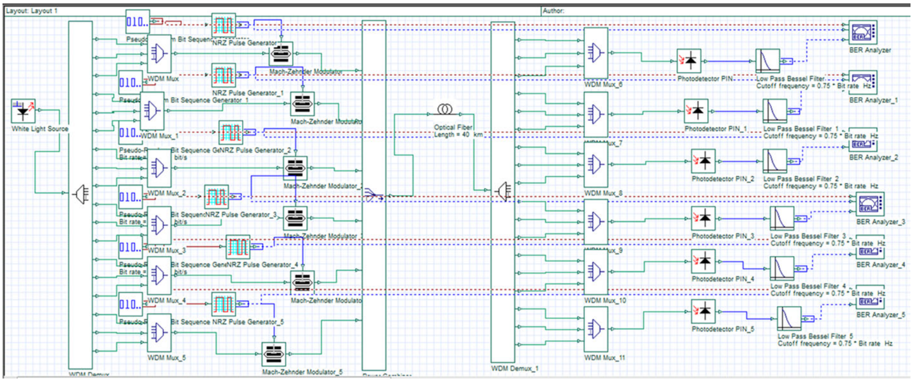


Fig. 13 MMS code schematic block diagram for 6 users

Table 3 The parameters used in optic system simulation test

Each chip spectral width	8 nm	Dispersion	16.75 ps/nm km
Data rate	622 Mbps	Dark current	5 nA
Distance (SMF)	40 km	Thermal noise coefficient	1.8×10^{-23} W/Hz
Attenuation	.25 dB/km	Low pass filter	.75 GHZ

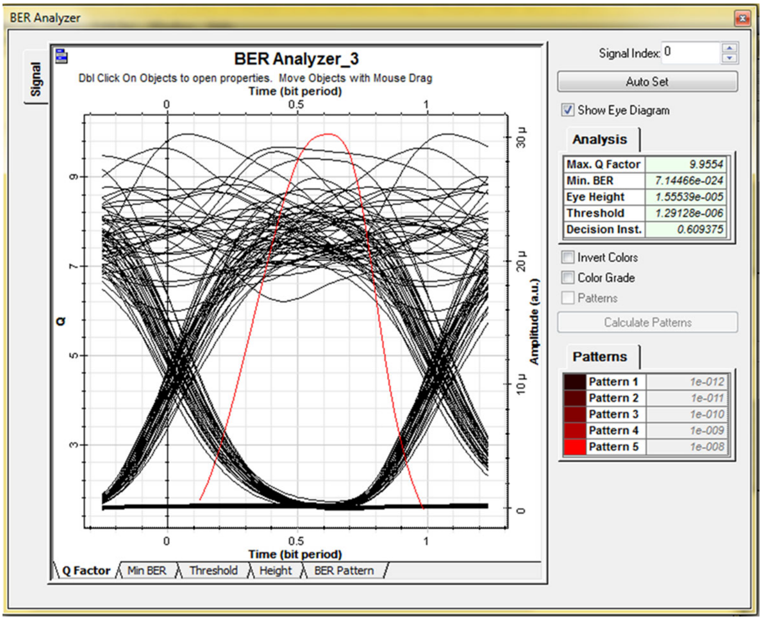


Fig. 14 Eye diagram indicating performance of 6 users with weight three using MMS code in back-to-back case

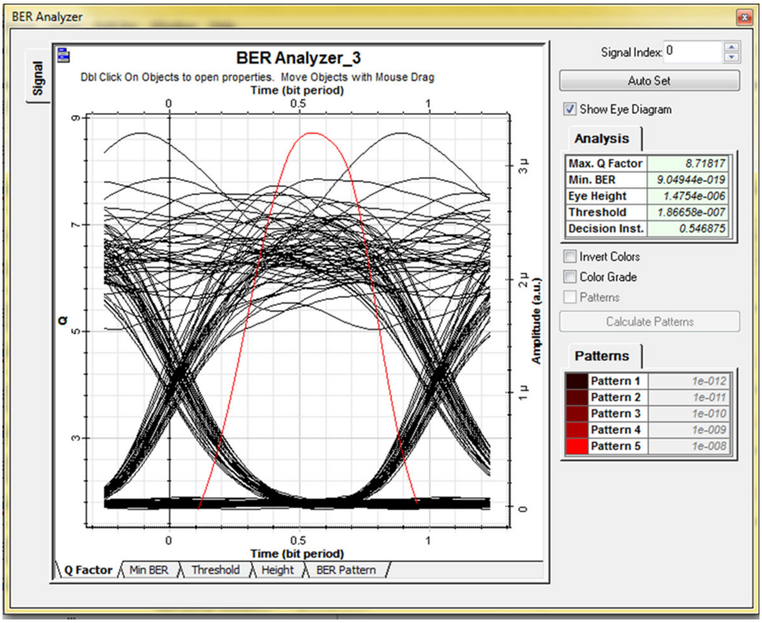


Fig. 15 Eye diagram indicating the performance of MMS code for 6 users with weight three at 40 km

8 Conclusion

The design of codes in the SAC–OCDMA system is the critical parameter to overcome the drawbacks in the system. Codes with the zero cross correlation property, simple construction, practical code length and flexibility in weight choice are desperately needed. This paper presented an MMS code with zero cross correlation. This code completely eliminates the MAI and PIIN. Also, the proposed code provided better performance than other codes which have an ideal or zero cross correlation and supported a larger number of users with practical code length and smaller weight.

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