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# Variable Weight Multi-Service OCDMA Code for Optical Domain Prioritization

Saleh Seyedzadeh<sup>a</sup>, Farzad Pour Rahimian<sup>a</sup>, Ivan Glesk<sup>a</sup>, Majid H. Kakaee<sup>b</sup>

<sup>a</sup>*Faculty of Engineering, University of Strathclyde, Glasgow G1 1XW, UK.*

<sup>b</sup>*Department of Computer and Communication Systems, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.*

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## Abstract

The emergence of heterogeneous applications such as internet data, video streaming, and online gaming, brings in a demand for a network environments with capability of supporting diverse Quality of Services (QoS). Prioritizing the services is essential to ensure the delivery of information is at their best. This paper proposes a new code family to support optical domain service differentiation using spectral amplitude coding techniques within an optical code division multiple access (OCDMA) scenario. A particular user or service has a varying weight applied in order to obtain the desired signal quality. The proposed variable-weight code (VW-code) is constructed based on basic multi-service (MS) code. Mathematical model is developed to for performance evaluation of VW-MS code. In addition, the properties of proposed code is compared with other VW-OCDMA codes. It is shown that the proposed VW-MS provide an optimal code length with minimum cross-correlation compared to other VW-codes. Performance of VW-MS designed for triple-play services operating at bit rates of 0.622, 1.25 and 2.5 Gbps is demonstrated.

*Keywords:*

Variable weight code, optical code-division-multiple-access, QoS differentiation, optical fibre communication, Spectral amplitude coding.

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## 1. Introduction

Future Internet consists of wide spectrum of applications with different bit rates and quality of service (QoS) requirement. Optical-code division

multiple access (CDMA) was emerged as a solution for providing QoS differentiation in physical layer [1]. Hence, OCDMA received great attention in metro networks where heterogeneous applications require for different qualities. Realization of QoS using OCDMA system was carried out by varying the code weight [2]. Later, two dimensional code families was proposed to support multiple services in optical networks [3]. Further, multilevel OCDMA system was intruded in which high and low weight users transmit their signal at a lower and higher power levels, respectively [4]. OCDMA systems have also received attention in last mile access networks [5], optical sensor networks [6, 7] and free space optical communication [8].

Spectral Amplitude Coding (SAC) is one of several techniques developed for OCDMA systems which attracts much attention due to the reduction of the Multiple Access Interference (MAI) effects [9, 10], simplicity and lower cost of system components [11]. In variable weight SAC-OCDMA, higher quality services received more weights (more wavelengths). VW-Code was first developed using optical orthogonal code (OOC) family [2] and followed by other codes such as IL-OOC [12], VW-OOC [13] and VW-KS [14]. Providing service differentiation have been also achieved using fixed weight but varying the number of users in basic matrix [15, 16]. QoS differentiation using SAC-OCDMA system for multimedia application have been experimentally demonstrated [17].

In this paper, a new VW-code family for SAC-OCDMA system based on basic matrix construction has been proposed. Despite of VW-codes based on double weight code family, VW-MS support any integer as code weight and maintain an optimal code length in comparison with other counterparts. The rest of this paper is organized as follows. Section 2, describe and explains MS and VW-MS code design and construction and gives example codes. In section 3, a comparison of VW-MS and four other VW-codes in terms of maximum cross-correlation and code length is presented. Section 4 presents the mathematical analysis of VW-MS code employing AND detection scheme to support multimedia services. Section 5 discusses the results of VW-MS code performance. Finally, Section 6 concludes the findings of the study.

## 2. Design and Development of VW-MS Code

A VW-MS code is an enhanced version of the existing single weight MS [15], that allows users of different weight or priority to co-exist in a single system while maintaining the cross-correlation value of one.

### 2.1. Construction of MS Basic Matrix

MS code for SAC-OCDMA system is matrix based and characterized by  $(L_B, W_B, N_B, \lambda_c)$  where  $W_B = 2, 3, \dots$  is the code weight and the number of users in basic matrix,  $N_B$  is equal to  $W_B$ .  $\lambda_c$  denotes the cross-correlation between each pair of codewords in OCDMA, and due to the structure of MS code, the ideal cross-correlation of  $\lambda_c \leq 1$  is maintained in order to eliminate MAI. The length of code ( $L_B$ ) for basic matrix can be calculated as

$$L_B = \sum_{i=1}^{W_B} (i) \quad (1)$$

In case the number of users in the basic matrix  $N_B$  is less than  $W_B$ , the code length of constructed matrix is as:

$$L_B = \sum_{i=1}^W i - \sum_{i=1}^{W-N_B} i \quad (2)$$

The basic matrix for MS code consists of a  $N_B \times L_B$  matrix, where elements taking the value of either '0' or '1' representing the spectral chips. Unlike most OCDMA codes, MS code is constructed using mathematical equation and can be easily implemented using software programming. The following steps explain how the code is constructed:

**Step 1:** Let  $P_w$  be the position of  $w$ th '1' in the code where  $w = \{1, 2, \dots, W\}$ , then  $P_w$  for the first codeword is defined as

$$P_w = \begin{cases} 1, & w = 1 \\ P_{(w-1)} + (w - 1), & w > 1 \end{cases} \quad (3)$$

**Step 2:** Let  $C_{ij} \in \{0, 1\}$  be a position in  $i$ th code, where  $i = \{1, 2, \dots, N_B\}$  and  $j = \{1, 2, \dots, L_B\}$ . Thus,  $C_i$  is defined as  $C_i = \{C_{i1}, C_{i2}, C_{i3}, \dots, C_{iL_B}\}$  and assume that  $\{C_1, C_2, \dots, C_{i-2}, C_{i-1}\}$  be previous codewords.

To construct the subsequent code,  $C_i$ , starting from first code find the first '1' in previous codeword that has no overlapping with any of other generated codewords, and place '1' in this position to get the cross-correlation of one with that code. Let this position be  $C_{ij}$ . Subsequently, the bit values for the rest positions of  $\{C_{i(j+2)}, C_{i(j+3)}, \dots, C_{iL_B}\}$  are obtained by shifting the bits of previous code, [i.e.  $\{C_{(i-1)(j+1)}, C_{(i-1)(j+2)}, \dots, C_{(i-1)(L_B-j)}\}$ ] one unit to the right.

**Step 3:** Repeat step 2 for the subsequent codes until the basic code sequence  $C_B$  generated which is equal to the maximum number of basic users,  $N_B$ .

**Step 4:** Fill empty spaces with ‘0’.

Fig. 1(a) to (d) demonstrates an example of MS code basic matrix construction for  $W_B = 3$  for steps 1 to 4, respectively. The length of code calculated by (1) is 6 and there are  $N_B = 3$  users which makes a  $6 \times 3$  matrix.

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

(a)

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

(b)

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

(c)

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

(d)

Figure 1: Construction of MS code basic matrix  $C_B$  for  $W = 3$ , with steps (a)1 to (d)4.

## 2.2. Mapping Technique for Larger Number of Subscribers

In order to increase the number of users from the basic matrix,  $C_B$ , a mapping technique can be utilized. If we assume the total number of required users is  $N$ , the basic matrix repeated by  $M = N/N_B$  times, where  $N_B$  is the number of users in  $C_B$ , as the following matrix:

$$C(M) = \begin{bmatrix} C_B(1) & 0 & 0 & 0 & 0 \\ 0 & C_B(2) & 0 & 0 & 0 \\ 0 & 0 & C_B(3) & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & C_B(M) \end{bmatrix}$$

here  $C_B(m)$  is the  $m$ th mapping sequence where  $m = 1, 2, \dots, M$ . Each '0' in mapping matrix is a sequence of zeros with same size of  $C_B$ . The maximum cross-correlation  $\lambda_c$  between users in the same matrix is one and between users from different mappings is zero, hence; using mapping technique the  $\lambda_c = 1$  is obtained for all users.

Assuming the total required number of users is  $N_{max}$  with code weight of  $W$ , then the number of mapping  $M$  can be calculated as:

$$M = \left\lceil \frac{N_{max}}{W} \right\rceil \quad (4)$$

If result of division expression  $N_{max}/W$  is an integer then there will be  $M$  mapping of basic matrix with  $N_B = W$ , otherwise the number of mappings for such matrix will be  $\lfloor \frac{N_{max}}{W} \rfloor$  and there will be one matrix with following number of users

$$N_{Br} = N_{max} - W \times \left\lfloor \frac{N_{max}}{W} \right\rfloor \quad (5)$$

where  $N_{Br}$  is the number of users for the last remaining mapping matrix.

## 2.3. Variable Weight Code Construction using MS Code

Construction of variable weight code for service differentiation in optical domain using MS code is described here. In VW-OCDMA system higher weights are allocated to services which demand for higher QoS. In this study, the VW-codes is developed for triple-play service in which video-on-demand (VOD), internet data and voice over IP (VoIP) services require different QoS.

It must be noted that for each service code weight can be chosen independently in a way to satisfy the required quality. Here, the weights of 5, 4 and 2 are chosen for video, data and voice, respectively.

Construction of VW-code, is based on mapping technique so that code weight of mapping matrices are different from each other. Services are grouped based on the quality they demand and a matrix with suitable code weight is assigned for them. If the number of subscribers is higher than one basic matrix, using (4) and (5) more number of mapping is assigned to the group to support all users. Fig. 2, illustrates the structure of VW-code construction to support  $J$  number of multiple services using MS code.  $C_{BW_j}(m)$  shows the  $m$ th mapping basic matrix for  $j$ th service which is appointed with weight of  $W_j$ . In this technique, the  $\lambda_c = 1$  between all users with different weight is sustained.

$$\begin{bmatrix} \begin{bmatrix} C_{BW_1}(1) & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & C_{BW_1}(M_1) \end{bmatrix} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \begin{bmatrix} C_{BW_2}(1) & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & C_{BW_2}(M_2) \end{bmatrix} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \begin{bmatrix} C_{BW_j}(1) & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & C_{BW_j}(M_j) \end{bmatrix} \end{bmatrix}$$

Figure 2: General structure of VW-Code construction using MS code family.

The total code length of VW-MS code,  $L$ , can be derived from (1), (2), (4) and (5) and is expressed as

$$L = \sum_{j=1}^J \left( \left( M_j \times \sum_{i=1}^{W_j} i \right) - \sum_{i=1}^{W-N_{Br_j}} i \right) \quad (6)$$

For triple-play services, assuming total 13 subscribers with 5 users of VOD, 4 internet data users and 4 users of VoIP, then the VW-MS-code for this system is as the matrix depicted in Fig. 3. The total length of code is 31 and can be calculated from (6). It can be seen that in order to support 4 users with weight 2, two matrices with  $W_B = 2$  are used.

VOD	1 1 0 1 0 0 1 0 0 0 1 0 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 1 0 0 0 1 0 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 0 0 1 0 0	0 0 0 0 0 0 0 0 0 0 0	0 0 0 0 0 0
	0 0 0 1 1 1 0 0 0 1 0 0 0 1 0	0 0 0 0 0 0 0 0 0 0 0	0 0 0 0 0 0
	0 0 0 0 0 0 1 1 1 1 0 0 0 0 1	0 0 0 0 0 0 0 0 0 0 0	0 0 0 0 0 0
Data	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	1 1 0 1 0 0 1 0 0 0	0 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 1 0 0	0 0 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	0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 0 0 1 1 1 0 0 0 1	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	1 1 0 0 0 0
VoIP M=2	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	1 0 1 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 1 1 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 1 0 1

Figure 3: Generated VW-MS code for 13 number of subscriber with different weights of 5,4 and 2.

### 3. Code Evaluation and Comparison

In every code family developed for OCDMA system, the cross-correlation property plays significant role in MAI cancellation ability of that code. In the proposed VW-MS, codes are categorized into  $J$  different code weights having the same code length,  $L_B$ . Therefore, an interference at a user node can be triggered by cross-correlation between other users with any code weights. In order to demonstrate the cross-correlation property of VW-MS, a code analysis similar to [13, 18, 15] is performed.

Let  $J$  be the different code weights in a system with  $w_1 > \dots > w_j > \dots > w_J$ , and the number of users in the  $j$ th code weights is  $N_{B_j}$ . The final generated code can be presented as  $C = \{C_{W_1}, C_{W_2}, \dots, C_{W_j}, \dots, C_{W_J}\}$  where  $C_{W_j}$  is the matrix code related to particular code weight,  $j$ . The exact value of maximum cross-correlation property of VW-MS code can be expressed as

$$\lambda = \begin{bmatrix} \lambda_{W_1, W_1} & \lambda_{W_1, W_2} & \dots & \lambda_{W_1, W_J} \\ \lambda_{W_2, W_1} & \lambda_{W_2, W_2} & \dots & \lambda_{W_2, W_J} \\ \vdots & \vdots & \ddots & \vdots \\ \lambda_{W_J, W_1} & \lambda_{W_J, W_2} & \dots & \lambda_{W_J, W_J} \end{bmatrix} \quad (7)$$

where  $\lambda_{W_j, W_{j'}}$  indicates the correlation value between code weights  $W_j$  and  $W_{j'}$ . Intra-weight correlation falls out when  $j = j'$ , means the cross-correlation between codes with same code weight. Inter-weight correlation is present when  $j \neq j'$  (codes with different weight and mapping). For VW-MS code, as the mapping number of each weight is greater than one, the intra-



Table 1: Comparison of different variable weight codes properties

Codes	Code length	Code weights	Total users	$\lambda_{max}$
VW-OOC	427	4{5, 4, 3, 2}	50	1
IL-OOC	25	4{5, 4, 3, 1}	49	7
VW-KS	170	4{8, 6, 4, 2}	50	1
MW-RD	75	4 4{6, 5, 4, 3}	50	5
VW-MS	108	4{5, 4, 3, 2}	50	1

weight correlation can be either 0 or 1, while inter-weight correlation is 0 due to the code design.

For comparison purposes, four other codes are evaluated in terms of their code properties including cross-correlation value,  $\lambda_{max}$ , code length, number of supportable users and number of different code weights. The four codes are VW-OOC [13], IL-OOC [12], Multiple Weight Random Diagonal (MW-RD) [19] and hybrid dynamic VW-KS [20]. Table 1 presents code properties comparison of these code with VW-MS.

The four variable weight codes in Table 1 are chosen to support about 50 users of 4 different code weights. It is shown that VW-OOC has a very long code length which is not desirable in OCDMA code design, but with ideal  $\lambda_{max}$  of one. IL-OOC and MW-RD have the shortest code length; however, their  $\lambda_{max}$  can reach as high as seven and five, respectively which might lead to poor MAI cancellation during photodetection. Although, VW-KS provides  $\lambda_{max} = 1$ , the generated code length is not promising which suffers from higher weights selection due to the nature of the code family. Even though the proposed VW-MS has longer code length than IL-OOC and MW-RD,  $\lambda_{max}$  is maintained at one and is much ideal for MAI cancellation.

#### 4. Mathematical Analysis of VW-MS Code

In this section mathematical model for VW-MS is developed considering major performance degradation factors in SAC-OCDMA including MAI and photodetection noises. In this study three noises are taken into account which are shot noise, thermal noise and phase induced intensity noise (PIIN). Fur-

thermore, the VW-MS performance is analysed employing AND subtraction technique [21] which is based on balanced detection.

#### 4.1. VW-OCDMA System description

The general architecture of a VW-SAC-OCDMA system with AND detection is depicted in Fig. 4. For simplification purpose, only a pair of transmitter and receiver for  $n$  user with weight of  $W_j$  is shown in the figure.

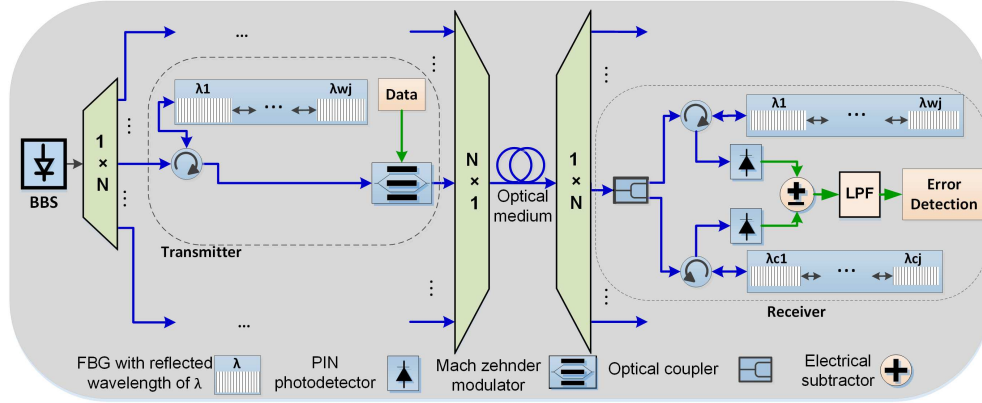


Figure 4: Architecture of a VW-SAC-OCDMA system.

At the transmitter side, power from a broad band source spectrum is split among  $K$  users. A series of fibre Bragg Gratings filter different wavelengths of  $\lambda_1, \dots, \lambda_w$  from the spectrum to form the different signature code with weight of  $w$ . Users' binary data is then modulated, which formed as Non-Return-to-Zero (NRZ) signal to the optical carrier. Modulated signals from all users are then combined using a power combiner, and transmitted over the optical medium. At the receiver part, two decoders are required in a single receiver which are the upper and lower decoders. The upper decoder detects the desired code,  $x(\lambda)$  while the lower decoder detects binary logical AND of desired and interfering code,  $x(\lambda) \cap y(\lambda)$ , with  $y(\lambda)$  being the interferer signal of other codes having overlapping chip with desired user.

#### 4.2. Development of Mathematical Model for VW-MS

In the mathematical analysis of VW-MS code, an incoherent broadband thermal source is assumed. The noise variance of a photocurrent due to the detection of an ideally unpolarised thermal light, which is generated by spontaneous emission, can be expressed as [1]

$$\langle I^2 \rangle = \langle I_{shot}^2 \rangle + \langle I_{PIIN}^2 \rangle + \langle I_{thermal}^2 \rangle \quad (8)$$

Where  $I_{shot}$  denotes the shot noise,  $I_{PIIN}$  represent the PIIN and  $I_{thermal}$  is thermal noise. The coherence time of the thermal source,  $\tau_c$  is given by [22]

$$\tau_c = \frac{\int_0^\infty G^2(v)dv}{\left[\int_0^\infty G^2(v)dv\right]^2} \quad (9)$$

Where  $G(v)$  is the source power spectral density (PSD). An ideal SAC-OCDMA system is assumed with ideally flat source spectra over the bandwidth,  $\Delta v$ , and ideal rectangular spectrum of each chip. For development of mathematical model some assumptions are considered [23, 24, 25] as the light source spectra is ideally unpolarised and its spectrum is flat over the bandwidth  $[v_0 - \Delta v/2 + \Delta v/2]$ , where  $v_0$  is the optical centre frequency and  $\Delta v$  is the bandwidth of the optical source in hertz, each power spectral component has identical spectral width, each user has equal power at the receiver and bit stream from all users is synchronized.

The PSD of the received signals can be written as [18]

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{n=1}^{N_{Bj}} d_n \sum_{l=1}^L c_n(l) \Pi(l) \quad (10)$$

Where  $P_{sr}$  is the effective power of broadband source at receiver,  $N$  and  $L$  are number of users and code length respectively,  $d_n$  is the information bit of  $n$ th active user which is either '1' or '0' ( $d_n \in \{0, 1\}$ ) and  $c_n(l)$  is the  $l$ th element of the  $n$ th MS code sequence.  $\Pi(l)$  is a function defined as

$$\begin{aligned} \Pi(i) &= u \left[ v - v_0 - \frac{\Delta v}{2L}(-L + 2l - 2) \right] - \\ &\quad u \left[ v - v_0 - \frac{\Delta v}{2N_{Bj}}(-L + 2l) \right] \\ &= u \left[ \frac{\Delta v}{2L} \right] \end{aligned} \quad (11)$$

and  $u[v]$  is the unit step function expressed as

$$u[v] = \begin{cases} 1, & v \geq 0 \\ 0, & v < 0 \end{cases} \quad (12)$$

Suppose  $C_n(l)$  is the  $l$ th element of the  $n$ th new code sequence, and the properties of the proposed VW-code at upper and lower arm of AND balanced receiver can be defined as:

$$\sum_{l=1}^L C_n(l)C_m(l) = \begin{cases} W_j, & n = m \\ 1, & n \neq m \end{cases} \quad \begin{array}{l} \text{Same mapping matrix} \\ \text{Different mapping matrix} \end{array} \quad (13)$$

and

$$\begin{aligned} \sum_{l=1}^L C_n(l) (C_m(l) \bullet C_n(l)) \\ = \begin{cases} N_{B_j} - 1, & n = m \\ 1, & n \neq m \\ 0, & n \neq m \end{cases} \quad \begin{array}{l} \text{Same mapping matrix} \\ \text{Different mapping matrix} \end{array} \end{aligned} \quad (14)$$

In this analysis, the AND operation of  $[C_m(l) \cdot C_n(l)]$  is valid for  $n \neq m$  only,  $n, m \in \{1, 2, \dots, N\}$ . However, the cross correlation of  $C_n(l)[C_m(l) \bullet C_n(l)]$  is valid for  $n = m$  and  $n \neq m$ , while the cross-correlation of  $C_n(l)C_m(l)$  is  $W_j$  for  $n = l$ .  $W_j$  is the weight assigned for service  $j$ , where  $N_{B_j}$  denotes the number of users in basic matrix of that service and  $N$  is the total number of subscribers.

Substituting (13) and (14) in (10) and integrating them results into the total power incident at the upper and lower photodetectors, PIN 1 and PIN 2, respectively which can be written as:

$$\begin{aligned} \int_0^\infty G_1(v)dv &= \int_0^\infty \left[ \frac{P_{sr}}{\Delta v} \sum_{n=1}^{N_{B_j}} d_n \sum_{l=1}^L C_n(l)C_m(l) \left\{ u \left[ \frac{\Delta v}{L} \right] \right\} \right] dv \\ &= \frac{P_{sr}}{\Delta v} \frac{\Delta v}{L} \sum_{n=1}^{N_{B_j}} d_n \sum_{l=1}^L C_n(l)C_m(l) \\ &= \frac{P_{sr}W_j}{L}d_l + \frac{P_{sr}}{L} \sum_{n=1, n \neq m}^{N_B} d_n \end{aligned} \quad (15)$$

and

$$\begin{aligned}
\int_0^\infty G_2(v)dv &= \int_0^\infty \left[ \frac{P_{sr}}{\Delta v} \sum_{n=1}^{N_{B_j}} d_n \sum_{l=1}^L C_n(l)(C_m(l) \bullet C_n(l)) \left\{ u \left[ \frac{\Delta v}{L} \right] \right\} \right] dv \\
&= \frac{P_{sr}}{\Delta v} \frac{\Delta v}{L} \sum_{n=1}^{N_{B_j}} d_n \sum_{l=1}^L C_n(l)(C_m(l) \bullet C_n(l)) \\
&= \frac{P_{sr}(N_{B_j} - 1)}{L} d_l + \frac{P_{sr}}{L} \sum_{n=1, n \neq m}^{N_{B_j}} d_n
\end{aligned} \tag{16}$$

Let  $I_1$  and  $I_2$  be the photocurrent at PIN 1 and PIN 2, respectively. The photocurrent  $I$ , therefore, is given by:

$$\begin{aligned}
I = I_1 - I_2 &= \Re \left[ \int_0^\infty G_1(v) - \int_0^\infty G_2(v) \right] \\
&= \frac{\Re P_{sr}(W_j - N_{B_j} + 1)}{L}
\end{aligned} \tag{17}$$

Where  $R = \eta e/hv$  is the photodiode responsivity,  $\eta$  is quantum efficiency,  $e$  is the electron charge,  $h$  is Planck's constant, and  $v$  is the central frequency of optical source's spectra.

The variance of shot noise in the photocurrent can be expressed as

$$\begin{aligned}
\langle I_{shot}^2 \rangle &= 2eB(I_1 + I_2) \\
&= 2eB \Re \left( \int_0^\infty G_1(v) + \int_0^\infty G_2(v) \right) \\
&= \frac{2eB \Re P_{sr}(W_j + 3N_{B_j} - 3)}{L}
\end{aligned} \tag{18}$$

Where  $B$  is half of the bit rate, denotes the noise-equivalent electrical bandwidth of the receiver.

The mean squared power of both upper and lower photodetectors is first obtained by integrating  $G_1^2(v)$  and  $G_2^2(v)$  to calculate the noise variance of PIIN, such as [22, 26, 23]

$$\int_0^\infty G_1^2(v)dv = \frac{P_{sr}^2}{\Delta v L} \sum_{l=1}^L \left\{ c_n(l) \left[ \sum_{n=1}^N d_n c_n(l) \right] \left[ \sum_{m=1}^N d_m c_m(l) \right] \right\} \quad (19)$$

and

$$\int_0^\infty G_2^2(v)dv = \frac{P_{sr}^2}{(W_j - 1)^2 \Delta v L} \sum_{l=1}^L \left\{ \bar{c}_n(l) \left[ \sum_{n=1}^N d_n c_n(l) \right] \left[ \sum_{m=1}^N d_m c_m(l) \right] \right\} \quad (20)$$

Using similar method as [26, 23] and approximation  $\sum_{n=1}^N C_n \approx \frac{NW}{L}$  [27], the variance of PIIN can be written as

$$\begin{aligned} \langle I_{PIIN}^2 \rangle &= B\Re \left( \int_0^\infty G_1^2(v) + \int_0^\infty G_2^2(v) \right) \\ &\cong \frac{B\Re^2 P_{sr}^2}{L\Delta v} \sum_{l=1}^L \left\{ C_n(l) \frac{NW}{L} \cdot \left[ \sum_{n=1}^{N_{B_j}} C_n(l) \right] \right\} \\ &+ \frac{B\Re^2 P_{sr}^2}{L\Delta v} \sum_{l=1}^L \left\{ (C_n(l) \bullet C_n(l)) \frac{NW_j}{L} \cdot \left[ \sum_{n=1}^{N_{B_j}} C_n(l) \right] \right\} \\ &= \frac{B\Re^2 P_{sr}^2 NW_j}{L^2 \Delta v} [W_j + 3N_{B_j} - 3] \end{aligned} \quad (21)$$

The thermal noise is given as

$$\langle I_{thermal}^2 \rangle = \frac{4K_b T_n B}{R_L} \quad (22)$$

Noting that the probability of sending bit '1' at any time for each user is 1/2, SNR of VW-MS system using AND detection can be written as

$$\begin{aligned}
SNR_k &= \frac{(I_1 - I_2)^2}{\langle I^2 \rangle} = \\
&= \frac{\frac{\Re^2 P_{sr}^2 (W - N_B + 1)^2}{L^2}}{\frac{eB\Re P_{sr} (W + 3N_B - 3)}{L} + \frac{B\Re^2 P_{sr}^2 NW}{2L^2 \Delta v} [W + 3N_B - 3] + \frac{4K_b T_n B}{R_L}}
\end{aligned} \tag{23}$$

Therefore, using Gaussian approximation, the probability of error for users of particular weight of interest,  $W_j$  of a multiple weight system,  $P_{e,k}$  is given by [26]

$$P_{e_k} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{SNR}{8}} \right) \tag{24}$$

It should be noted that the proposed model provide an upper bound approximation for BER of user, The proof of this method using experimental as well as simulation analysis is presented by [17].

## 5. Theoretical Results and Discussion

The parameters used in the analysis are listed in Table 2. These parameters were chosen to provide a fair comparison with other published works [18, 22, 20]. In this work, it is assumed that the number of subscribers in each service ( $W_j$ ) is almost equal.

Fig. 5 shows the probability of errors for users with different weights versus number of active users, when  $P_{sr}$  is -10 dBm and bit rate is set to 633 Mbps (ITU-T STM-4 standard). With reference to the BER of  $10^{-3}$ ,  $10^{-9}$  and  $10^{-12}$  for voice, data and video, respectively, the maximum number of active users that can be supported in a VW-OCDMA with proposed VW-MS code is 46.

Fig. 6 demonstrate the probability of error against the received optical power (ROP) per chip in presence of different noises, when the total number of active users is 36. It can be seen that when  $P_{sr}$  is high ( $P_{sr} > -6$  dBm), the effect of shot and thermal noise is negligibly small compared to PIIN, which is the main limitation factor of the system performance. However, when  $P_{sr}$  is low ( $P_{sr} < -6$  dBm), the PIIN effect is minimal and thermal noise becomes the main factor in performance degradation. It is also shown that thermal noise is more significant than shot noise. The  $P_e$  of large weight users

**Table 2: Typical parameters used in the analysis**

Symbol	Parameter	Value
$\eta$	Photodetector quantum efficiency	0.6
$\Delta\nu$	Linewidth of broadband source	3.75 THz
$\lambda_0$	Operating wavelength	1550 nm
$P_{sr}$	Received optical power	-10 dBm
$B$	Electrical bandwidth	311 MHz
$T_n$	Receiver noise temperature	300 K
$R_L$	Receiver load resistor	1030 $\Omega$
$e$	Electron charge	$1.6 \times 10^{-19}$ C
$h$	Planck's constant	$6.66 \times 10^{-34}$ Js
$K_b$	Boltzmann's constant	$1.38 \times 10^{-23}$ J/K

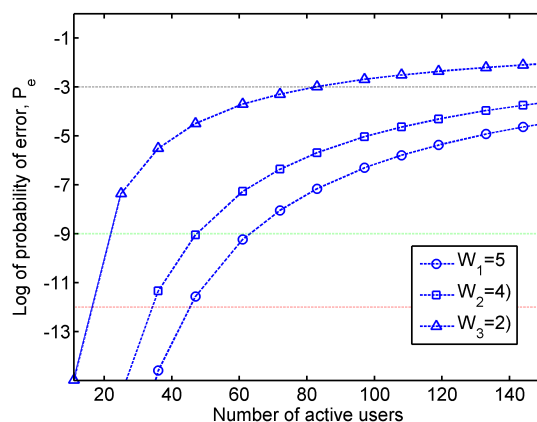


Figure 5: Probability of error versus number of total users with weight 5, 4 and 2.

saturates at  $10^{-15}$  at -5 dBm, which is better than users of smaller weights, where  $P_e$  of weight 4 and 2 saturates at  $10^{-1}$  and  $10^{-5}$ , with  $P_{sr}$  equals to -6 dBm, respectively. It can be observed that even by increasing transmitted power therewith the received power it is not possible to improve the quality of signals in presence of PIIN.

Fig. 7 depicts the plot of probability of error for the system operating at



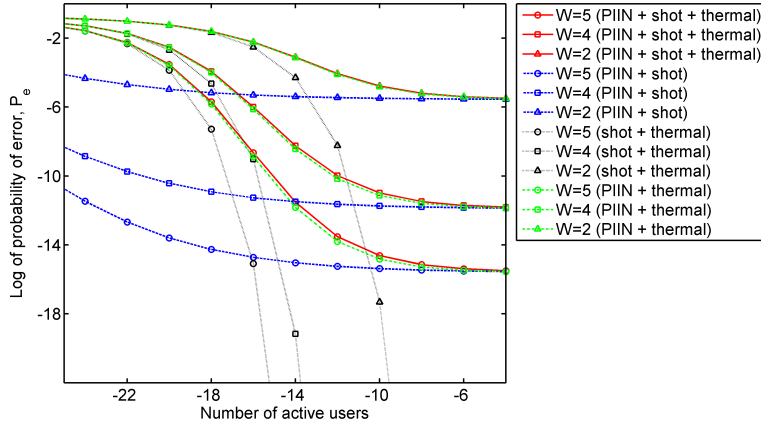


Figure 6: Probability of error against effective received power,  $P_{sr}$ , considering different noise contribution with number of active users is 36.

data rates of 1.25 and 2.5 Gbps, where  $P_{sr}$  is -10 dBm. It can be seen that the number of supportable users for OCDMA system with VW-MS is 23 and 13 for bit rates of 1.25, 2.5 respectively, regard to the acceptable error rate for triple services.

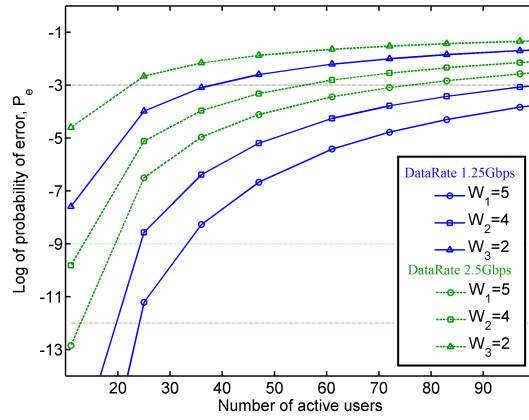


Figure 7: Probability of error versus number of active users for different bit rates of 1.25 and 2.5 Gbps.

Due to the flexible nature of MS code in constructing code, performance of services could be further improved by either assigning higher weights for

services or reducing the  $N_{B_j}$  for basic matrix. Fig. 8 illustrate the performance of system when number of users in basic matrix is reduced for weight of 5 and 4. Using this configuration, number of supported subscribers is increased from 13 to 20. The performance degradation which is observed in service with weight 2 is due to the increment of total code length as a results of higher number of mapping matrices. It should be considered that  $N_B$  for weight 2 is not reduced as the quality of service with total number of 20 is already in acceptable area. If the number of required subscribers for each service is not equal, then a weight optimization could be conducted to get the acceptable quality for all services, while keeping minimum value for the code weights as well as code length.

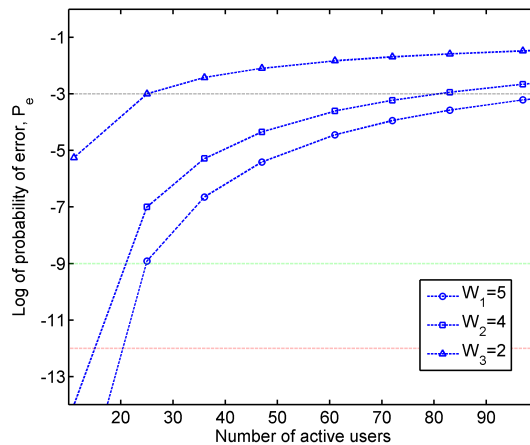


Figure 8: Probability of error versus number of active users with data rate of 2.5 Gbps and  $N_B$  is 3,2 and 2 for weights of 5, 4 and 2, respectively.

## 6. Conclusions

This paper presented a newly proposed code, VW-MS to support differentiating services directly in optical domain using SAC-OCDMA technique. The code design and construction as well as featured properties was elaborated, with code properties comparison against other similar codes, VW-OOC, IL-OOC, VW-KS and MW-RD. It was shown that the VW-MS code obtains maximum cross-correlation of one while maintaining lower code length comparing to its counterpart codes. The OCDMA system deploying

proposed code and AND detection was mathematically modelled and the performance analysed for triple-play system. With regard to BER of  $10^{-12}$ ,  $10^{-9}$  and  $10^{-3}$  for video ( $W_j = 5$ ), data ( $W_j = 4$ ) and voice ( $W_j = 2$ ) services, it was demonstrated that VW-MS with supports 46, 24 and 13 simultaneous subscribers in OCDMA system with data rate of 0.622, 1.25 and 2.5 Gbps, respectively. Further service quality improvement using variation of number of users in basic matrix was demonstrated. In conclusion, the overall results prove the suitability and flexibility of VW-MS code for integrated multi-service optical networks.

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