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Effects of the Vector Combinatorial code connection parameters on the performance of an OCDMA system for high-speed networks

Hassan Yousif Ahmed, Ibrahima Faye, N.M.Saad and S.A. Aljined

Abstract—**In this paper, we study the performance of optical code-division multiple access (OCDMA) systems using vector combinatorial (VC) code under various link parameters. The impact of the fiber dispersion effects on the multi-user interference (MUI) is reported using a commercial optical systems simulator, Virtual Instrument Photonic (VPITM). The VC code is compared mathematically with other codes which use similar techniques. We analyzed and optimized the data rate, fiber length, and channel spacing in order to reduce the BER without the need to deploy dispersion compensating devices. The performance and optimization of VC code in OCDMA system is reported. We have demonstrated that, for a high data rate (higher than 2.5 Gb/s), even if dispersion compensated devices are not deployed, the BER can be significantly improved when the VC code desired parameters are selected. We have shown that when compensation dispersion devices are not deployed in the system, there is a tradeoff between the limited dispersion effects and the MUI.**

***Index terms*—FBG, VC, SAC-OCDMA, MUI.**

I. Introduction

In the recent years, we are seeing rapidly increasing demand on optical communication systems due to the large bandwidth offered by the fiber optic. This demand is fueled by many different factors. The tremendous growth of internet has brought huge amount of users consuming large amount of bandwidth since data transfers involving video, database queries, updates and image [1-4]. To realize the demands for bandwidth and new services, a new technology must be deployed and fiber optic is one such key technology [1]. Optical spectrum code division multiple access (OSCDMA) is a multiplexing technique modified from CDMA system that was initially developed for radio frequency (RF) communication systems. In OCDMA systems, a data bit is in general encoded by split it into many smaller chip frequencies. Each user is assigned a unique signature code that specifies the chips that must contain optical power. At the receiver, the complement decoder is used to correlate the incoming chip stream, thus reproducing the original signal. The signature codes have good auto-correlation and cross-correlation properties that enable each user to distinguish its own data. Other users in the network will produce multiple-user interference (MUI), but as long as the MUI is less than the autocorrelation peak, the desired data is detected correctly [5].

Many codes have been proposed for OSCDMA [6-12].However, some of these codes have much poorer cross correlations (e.g. Hadamard code[6]), or the number of available codes is quite restricted (e.g. integer lattice codes exist for m and k where m and k need to be co-primes (it is enough if one is even and the other is odd) [7], a prime number p for modified quadratic congruence (MQC) [8], a prime power Q for modified frequency hopping (MFH) where $Q= p^n$ (p is a prime number and $n\geq 1$) [9], an even natural number for modified double code (MDW) [10], and an odd natural number for enhanced double weight (EDW) [11]) .Long code lengths are considered disadvantageous in its implementation since either very wide band sources or very narrow filter bandwidths are required. Short code length limits the free of code sequence. The main issue for VC code is to develop a code set of good system performance. The code set size dependence on the code length. For the OSCDMA scheme to be more practical, it is desired to create an optical code that can accommodate a larger number of simultaneous users with a low error probability for a given code length [1]. In this paper we examined and simulated an OCDMA system using VC code, to improve and characterize the data rate, fiber length and channel spacing, in order to minimize the BER without the need to deploy dispersion compensating devices.

Hassan Yousif Ahmed is with the Electrical & Electronic Engineering Department, Universiti Teknologi PETRONAS,Bandar Seri Iskandar, 31750 Tronoh, Perak, MALAYSIA Tel: +605-368-8000 Fax: +605-365-7443(e-mail: Hassan_uofg@yahoo.com).

Ibrahima Faye and N.M.Saad are with the Electrical & Electronic Engineering Department, Universiti Teknologi PETRONAS,Bandar Seri Iskandar, 31750 Tronoh, Perak, MALAYSIA Tel: +605-368-8000 Fax: +605-3657443(email:ibrahima_faye@petronas.com.my,naufal_saad@petronas).

S.A. Aljined is with School of computer and communication Engineering, Universiti Malaysia Perlis, Malaysia.

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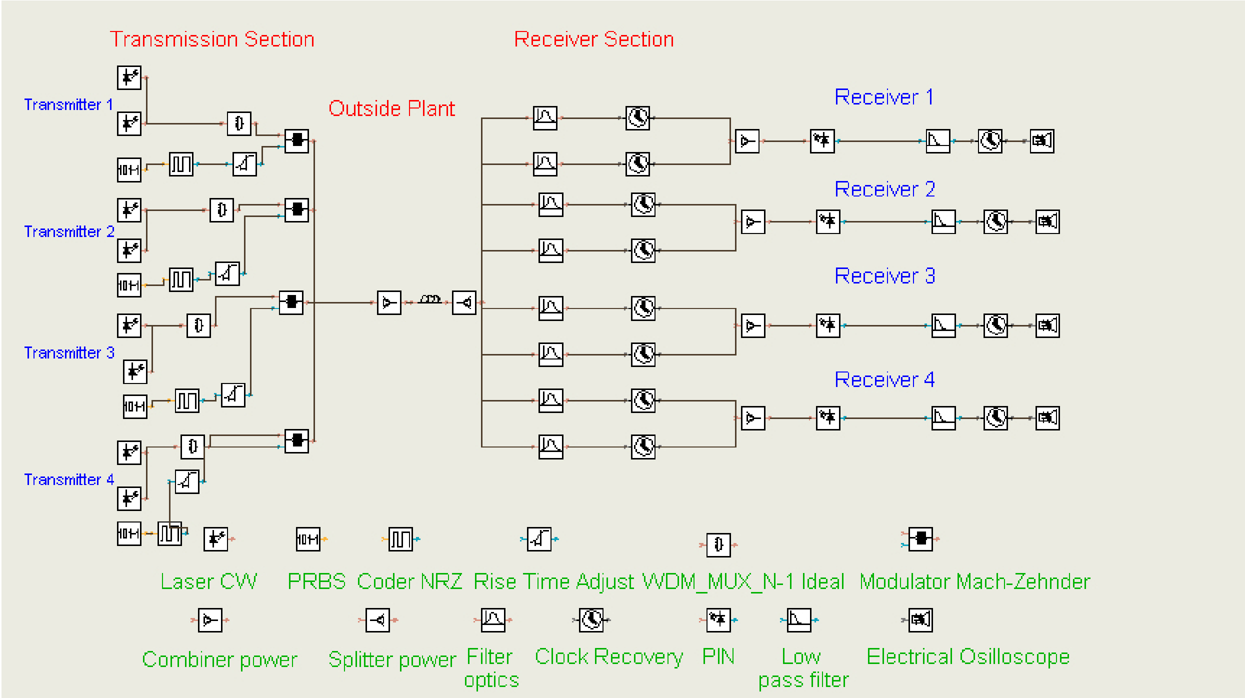

Fig. 1 Simulation setup of proposed system

For example, in the case when a Dispersion Compensated Fiber (DCF) is deployed, attenuation will be increased. Also, additional optical amplification devices are required. This might be having a negative impact on the network capacity. The paper is organized as follows. In Section II, firstly we review the system performance analysis for encoder-decoder structure using VC code. Secondly we demonstrate the BER mathematical setup for VC code taking into account the effect of different types of noise. Section III shows the simulation results. Finally, conclusions are drawn in Section IV.

II. System performance analysis

A. . Encoder–decoder structure

The setup of the proposed VC code [12] system using spectral direct detection technique with two users is shown in Fig. 1. Fig. 1 shows the setup of the proof of principle simulation for the proposed scheme. The performances of VC families, MQC, MFH are simulated by using the simulation software, Virtual Photonic Instrument (VPI) version 7.1. Each chip has a spectral width of 0.8 nm (100GHz). The tests were carried out at a data rate of 10Gb/s for 30, 40, 50km distances with the ITU-T G.652 standard single mode fiber (SMF). All the attenuation α (i.e., 16 ps/nm km) and nonlinear effects such as four-wave mixing, the cross phase modulation, and the group delay were activated and specified according to the typical industry values to simulate the real environment as close as possible.

As shown in Fig. 1 after transmission, we used a filter optics spectral phase decoder that operates to decode the coded sequence. The decoded signal was decoded by a photo-detector (PD) followed by a 0.7 GHz low pass filter (LPF) and error detector, respectively.

The transmitted power used was -10 dBm out of the broadband source. The noise generated at the receiver was set to be random and totally uncorrelated. The dark current value was 5 nA and the thermal noise coefficient was $2.5\times e^{-23}$ W/Hz for each of the photo-detectors. The light source of every user is assumed to be unpolarized and has a flat spectrum over a bandwidth ΔV Hz. The average optical power for one photo-detector per user when the desired user transmits bit "1" is

$$Psig = \frac{\Re PsrW}{L} \quad (1)$$

Where $\Re$ is the photodiode responsivity, P_{sr} is the effective power of a broad-band source at the decoder, W and L are the code weight and length respectively.

B. Performance analysis

In our analysis of the proposed system we have considered incoherent intensity noise (σ_I), as well as shot noise (σ_{sh}) and thermal noise (σ_T) in photodiode. The detection scheme for the proposed system is based on direct detection using optical filter followed by photodetecor. Gaussian approximation is used for the calculation of BER. The SNR is calculated at the receiver side and for each user there is only one photodiode, the current flow through the photodiode is denoted by *I*.

Let $C_N\ (i)$ denote the *i*th element of the *N*th VC code sequence. Assume user# (f,g) is the desired user belong to the ideal case ($N=W+1$) and user# (z,t) does not belong to ideal case ($N=P(W+1)+R$), the correlation functions of each user is given by [12]:

$$PD1_{(0)}(f,g,z,t)=\begin{cases}W, & f=z, g=t\\ 1, & f\neq z, g=t \quad For \quad N=(W+1)\\ 0, & g\neq t \quad For \quad N=P(W+1)+R\end{cases}$$

(2)

And

$$PD2_{(1)}(f,g,z,t)=\begin{cases}0, & f=z, g=t\\ W-1, & f\neq z, g=t \quad For \quad N=(W+1)\\ 0\ , & g\neq t \quad For \quad N=P(W+1)+R\end{cases}$$

(3)

Thus

$$PD1_{(0)}(f,g,z,t)-\frac{PD2_{(1)}(f,g,z,t)}{W-1}=\begin{cases}W, & f=z, g=t\\ \\ 0, & else\end{cases}$$

(4)

When a broad-band pulse is input into the group of FBGs, the incoherent light fields are mixed and incident upon a photo-detector, the phase noise of the fields causes an intensity noise term in the photo-detector output. The coherence time of a thermal source (Th_c) is given by [8]:

$$Th_c=\frac{\int_0^\infty G^2(v)\,dv}{\left[\int_0^\infty G(v)\,dv\right]^2} \quad (5)$$

Where *G(v)* is the single sideband power spectral density (PSD) of the source. The Q-factor performance provides a qualitative description of the optical receiver performance, the performance of an optical receiver depends on the signal-to-noise ratio (SNR). The Q-factor proposes the minimum SNR required to obtain a specific BER for a given signal. The SNR of an electrical signal is de-fined as the average signal power to noise power [SNR = I_2/σ_2], where $\sigma 2$ is defined as the variance of the noise source (note: the effect of the receiver's dark current and amplification noises are neglected in the analysis of the proposed system), given by $\sigma 2 = \sigma_{sh} + \sigma_I + \sigma_T$, which also can be written as:

$$Q^2 = 2eIB + I_2BTh_c + 4K_BT_nBR_L \quad (6)$$

Where

e electron's charge
I average photocurrent
I_2 the power spectral density for I
B noise-equivalent electrical bandwidth of the receiver
K_B Boltzmann's constant
Tn absolute receiver noise temperature
R_L receiver load resistor.

In Eq. (6), the first term results from the shot noise, the second term denotes the effect of Phase Intensity Induced Noise (PIIN) [8, 10], and the third term represents the effect of thermal noise. The total effect of PIIN and shot noise obeys negative binomial distribution [13]. To analyze the system with transmitter and receiver, we used the same assumptions that were used in [7–11] and are important for mathematical simplicity. Without these assumptions, it is difficult to analyze the system. We assume the following:

1. Each light source is ideally unpolarized and its spectrum is flat over the bandwidth [v_o-Δv/2, v_o+Δv/2] where v_o is the central optical frequency and Δv is the optical source bandwidth in Hertz.
2. Each power spectral component has identical spectral width.
3. Each user has equal power at the receiver.
4. Each bit stream from each user is synchronized.

The above assumption is important for mathematical simplicity. Based on the above assumptions, we can easily analyze the system performance using Gaussian approximation. The power spectral density of the received optical signals can be written as [8]:

$$r(v)=\frac{P_{sr}}{\Delta V}\sum_{N=1}^{N}d_N\sum_{i=1}^{L}c_N(i)\begin{Bmatrix}u\left[v-v_o-\frac{\Delta v}{2L}(-L+2i-2)\right]\\ -u\left[v-v_o-\frac{\Delta v}{2L}(-L+2i)\right]\end{Bmatrix} \quad (7)$$

where P_{sr} is the effective power of a broadband source at the receiver, $\boldsymbol{N}$ is the active users and $\boldsymbol{L}$ is the VC code length, d_N is the data bit of the $\boldsymbol{N}$th user that is "1" or "0", and $u(v)$ is the unit step function expressed as

$$u(v)=\begin{cases}1, & v\geq 0\\ 0, & v<0\end{cases} \quad (8)$$

Taking into consideration, we have to analysis the effects of shot and thermal noises as well as PIIN. From Equation (7), the power spectral density at photodetector 1 and photodectotor 2 of the *n*th receiver during one bit period can be written as

$$G_1(V) = \frac{P_{sr}}{\Delta V}\sum_{N=1}^{N}d_N\sum_{i=1}^{L}C_N(i)\overline{C}_{(f,g)}(i)$$
$$\{\ u\left[V-V_0-\frac{\Delta V}{2L}(-L+2i-2)\right] \quad (9)$$
$$-u\left[V-V_0-\frac{\Delta V}{2L}(-L+2i)\right]\ \}$$

$$G2(V) = \frac{P_{sr}}{\Delta V}\sum_{N=1}^{N}d_N\sum_{i=1}^{L}C_N(i)C_{(f,g)}(i)$$
$$\{\ u\left[V-V_0-\frac{\Delta V}{2L}(-L+2i-2)\right]$$
$$-u\left[V-V_0-\frac{\Delta V}{2L}(-L+2i)\right]\ \}$$

(10)

The photodetector current can be calculated by integrating:

$$I_1 = \int_0^\infty G_1(v)dv = \frac{P_{sr}}{L} \sum_{n=1 n\neq f}^{N} d_n \quad (11)$$

And

$$I_2 = \int_0^\infty G_2(v)dv = \frac{P_{sr}}{L} d_f + \frac{P_{sr}}{L} \sum_{n=1 n\neq f}^{N} d_n \quad (12)$$

The photocurrent can be expressed as:

$$\mathbf{I} = I_2 - I_1 = \Re\int_0^\infty PD_2(V)dv - \Re\int_0^\infty PD_1(V)dv \quad (13)$$

$$\mathbf{I} = \Re \frac{P_{sr}}{L} W \quad (14)$$

Here, h is the quantum efficiency, e is the electron's charge, h is the Planck's constant, and V_c is the central frequency of the original broad-band optical pulse. Since the noises in photodetector 1 and 2 are independent, the power of noise sources that exist in the photocurrent can be written as [8]

$$\langle I^2 \rangle = \langle I_1^2 \rangle + \langle I_2^2 \rangle + \langle I_{th}^2 \rangle \quad (15)$$

Where,

I^2 = Total noise power;

I_1^2 = Shot noise;

I_2^2 = Phase Induced Intensity Noise (PIIN);

I_{th}^2 = Thermal noise.

From equation (15)

$$\langle I^2 \rangle = 2eB(I_1 + I_2) + BI_1^2 t_{c1} + BI_2^2 t_{c2} + \frac{4K_b T_n B}{R_L} \quad (16)$$

Therefore

$$\langle I^2 \rangle = 2eB\Re\left[\int_0^\infty G_1(v)dv + \int_0^\infty G_2(v)dv\right] + B\Re^2\int_0^\infty G_1^2(v)dv + B\Re^2\int_0^\infty G_2^2(v)dv + \frac{4K_b T_n B}{R_L}$$

(17)

From equation (11), when all the users are transmitting bit ''1'' using the average value as $\sum_{N=1}^{N} c_N \approx \frac{NW}{L}$ and the noise power can be written as:

$$\langle I^2 \rangle = 2eB\Re\left[\frac{P_{sr}}{L}((N-1) + W + (N-1)\right] + B\Re^2\left[\frac{P_{sr}^2}{\Delta VL}\cdot\left[\frac{NW}{L}\right].\left[\begin{matrix}(N-1) + W \\ + (N-1)\end{matrix}\right]\right] + \frac{4K_b T_n B}{R_L}$$

(18)

Noting that the probability of sending bit '1' at any time for each user is a $\frac{1}{2}$ [8, 10], then Equation (20) becomes:

$$\langle I^2 \rangle = \frac{P_{sr}\, e\, B\, \Re}{L}\left[(2N-2) + W\right] + \frac{P_{sr}^2\, B\Re^2\, N\, W}{2\,\Delta V\, L^2}\left[(2N-2)/(P+R) + W\right] + \frac{4K_b T_n B}{R_L}$$

(19)

From (14) and (19), we can get the average of SNR as in (20) and (21)

$$SNR = \frac{(I_2 - I_1)^2}{\langle I^2 \rangle} \quad (20)$$

$$SNR = \frac{\frac{\Re^2 P_{sr}^2 W^2}{L^2}}{\frac{P_{sr} e B\Re}{L}\left[(N-1) + W\right] + \frac{P_{sr}^2 B\Re^2 N}{2\Delta V L^2}\left[(N-1) + W + (N-1)/P + R\right] + \frac{4K_b T_n B}{R_L}}$$

(21)

Where $\Re$ is the photodiode responsivity, P_{sr} is the effective power of a broad-band source at the receiver, e is the electronic charge, B is the electrical equivalent noise band-width of the receiver, K_B is the Boltzmann's constant, Tn the absolute receiver noise temperature, R_L is the receiver load resistor, ΔV is the optical source bandwidth, W, N, L, P and R are the code weight, the number of users, the code length, the number of mapping and the remaining of users after modulo operation respectively as being the parameters of VC itself . The Bit Error Rate (BER) is computed from the SNR using Gaussian approximation as [7-11]

$$\text{BER} = 0.5\,\text{erfc}\sqrt{SNR/8} \quad (22)$$

For numerical simulations, we used the following parameters: Psr= -10dBm is the optical received power, ΔV=3.75 THz is the line width of the broad band source, B=80 MHz is the receiver noise-equivalent electrical bandwidth, Tn = 300 K, R_L= 1030 Ω , bit-rate 155 Mb/s, h =0.6 is the photodiode quantum efficiency and λ=1550 nm is the operating of wavelength.

III. Simulation Results

Using Eq. (22), the BER of the VC code is compared mathematically with other codes which use similar techniques.

Fig. 2 shows the relation between the number of users and the BER, for VC, MFH, MQC and Hadamard codes, for different values of N (number of active users). It is shown that the performance of the VC code is better compared with the others even though the weight is far less than other codes, which are 4 in this case.

The maximum acceptable BER of 10^{-9} was achieved by the VC code with 110 active users than that for 90 by MFH code. This is good considering the small value of weight used. This is evident from the fact that VC code has a property of reducing cross-correlation with the mapping technique while Hadamard code has increasing value of cross-correlation as the number of users increase. However, a few codes with precise parameters were chosen based on the published results for these practical codes [8, 10]. The calculated BER for VC was achieved for W = 4 while for MFH, MQC and Hadamrad codes were for W = 17, W = 14, and W = 64 respectively.

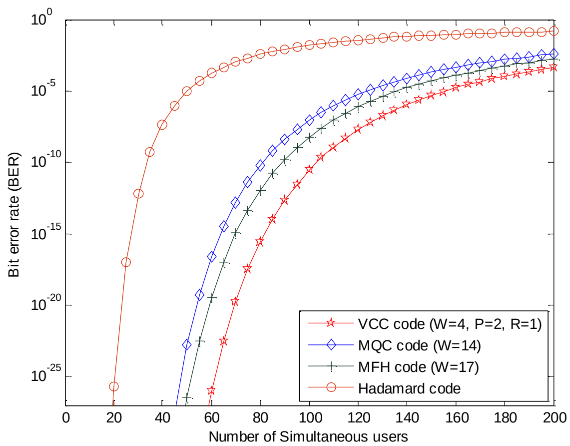

Fig. 2 BER versus the number of simultaneous users

Dispersion impact on the system performance as a function of the number of users N is illustrated in Fig. 3. In order to minimize the MUI impact, the optimum decision threshold is set to $S = 2 \times P$cen [1]. As can be seen from this figure the trend of the BERs with and without dispersion (Fig. 3) is the same. One can see that for N = 10 active users and 40 km fiber length, the MUI is low. In this case chromatic dispersion is the main limiting factor of the system performance. However, when the number of users is increased to 17, MUI is the main limiting factor, whereas the chromatic dispersion effect is very small. This is the reason why there is a difference in the value of BERs between the two cases, N = 10 and N = 17 users. Therefore, the system performance is more subject to dispersion when the number of users is reduced (i.e. low MUI). In order to upper-bound the dispersion effect, simulations for N = 10 are performed. Also it can be seen from Fig. 3 that the systems performance is deteriorated when the fiber length is increased.

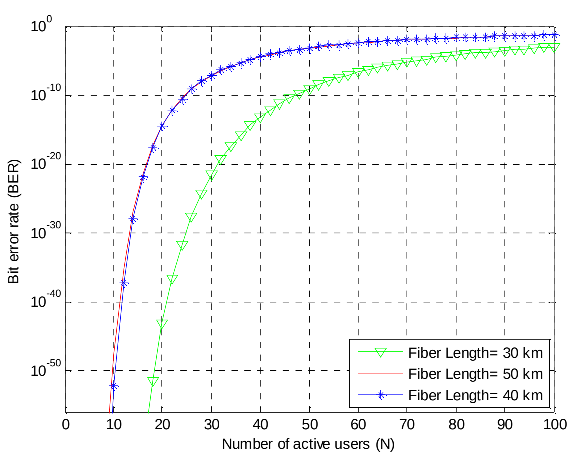

Fig. 3 Variation of BER as a function of the number of users and fiber length for VC code when *Data rate* = 10 Gbit/s.

Fig. 4 shows the variation of BER as a function of data rate for different fiber lengths, one can see that dispersion has a significant impact on the system performance when data rate increases. Our simulation results indicate that the system performance is deteriorated as the fiber length increases from 30 to 50 km. We can observe that for a 30 km long optical link, the performances of a VC (N = 30 and W = 4) are not affected by the fiber dispersion up to ***data rate*** =2.8 Gbits/s.

However, for a 50 km long optical link, the performances are degraded from a data rate 2.8 Gbits/s. In fact, when the fiber length decreases, the data rate should increase to recover a similar degradation of the signal form. Thus, in order to design and optimize link parameters, the maximum fiber length should be defined as short as possible, to obtain high data rate and to achieve a desired system performance without dispersion compensation device.

Simulation results are compared to the theoretical BER of the conventional receiver, expressed by the Eq. (22) for W = 4.

From Fig. 4 one can see that dispersion has a significant impact on the system performance when the data rate increases. According to the theory expressed by Eq. (22), when the data rate increases the BER is becomes almost three times. This is because, in the theory, the effects of attenuation, fiber non-linearity, insertion loss are not considered. However, our simulation results indicate that the system performance is deteriorated by about more than one order of magnitude, when the dispersion effect is presented in the simulation model.

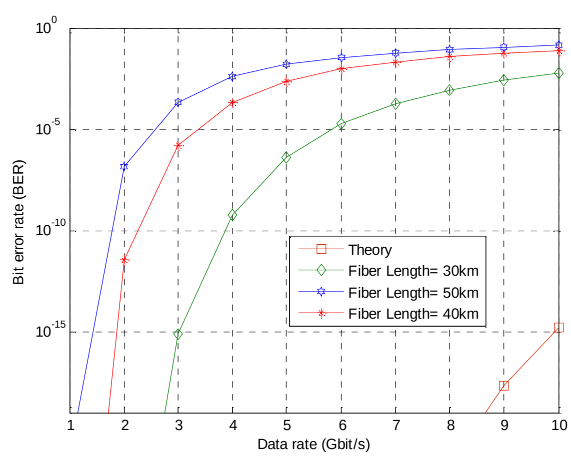

Fig. 4 Variation of BER as a function of data rate and fiber length for VC code when N = 30.

The computed BER versus channel spacing width is shown in Fig. 5 for a 50km fiber length. The pulse duration is fixed to Tc = 1/(data rate × code length). As the channel spacing width goes from very narrow to wider, the

BER decreases, best performance occurs at a spacing bandwidth between 0.8 (100 GHz) and 1.2 nm. The reason for the BER increasing after the minimum is that the SNR improvement due to the use of wider optical bandwidth is counteracted by an increased crosstalk/overlapping between adjacent frequency bins that yield MUI. Note that, decreasing channel spacing the effects of four-wave mixing on optical transmission and in single mode fiber are appeared, this is noticeable as degradation of optical SNR and the system BER performance.

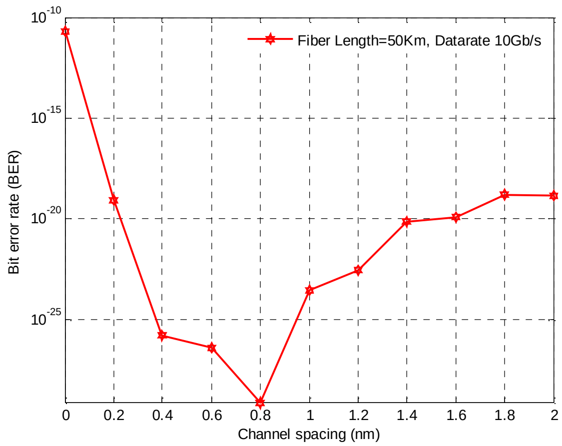

Fig. 5 Variation of BER as a function of channel spacing width for VC code when (W = 4, N = 3, and L = 6, data rate 10Gbits/s) for a 50km fiber length.

IV. Conclusion

A new variation of optical code structure for amplitude-spectral encoding OCDMA system has been successfully developed. The VC code has been proven to provide a better performance compared to the systems encoded with Hadamard, MQC and MFH codes. This code posses such a numerous advantages including the efficient and easy code construction, simple encoder/decoder design, existence for every natural number n, maximum cross correlation $\lambda = 1$, and high SNR. The developed model is used to analyze and optimize the OCDMA parameters such as data rate, optical fiber length, and code sequence parameters. It is verified that chromatic dispersion has a significant negative impact on system performance which cannot be neglected for systems with short fiber length and high data rate. It is reported that system performance can be significantly overvalued if chromatic dispersion is ignored. It is found that for a high data rate even if dispersion compensated devices are not deployed; the BER can be significantly improved when the VC optimal channel spacing width is carefully selected (even for short fiber length). Our simulations show that in order to obtain desired system performance, we can change the OCDMA system parameters, even that without the need to install compensated dispersion devices or interference cancellation receivers. In simulation, about 30 active users can be supported for error free transmission at 10 Gbit/s with data-rate detection; while by employing optical VC code to reject the MUI, the number of users could be doubled. The study reveals that the MUI noise has been eliminated effectively.

References

[1] J. A. Salehi, "Code division multiple access techniques in optical fiber network—Par I: Fundamental principles," IEEE Trans. Commun., vol.37, pp. 824–833, 1989.

[2] J. A. Salehi and C. A. Brackett, "Code division multiple access techniques in optical fiber network—Part II: System performance analysis," IEEE Trans. Commun., vol. 37, no. 8, pp. 834–842, Augst. 1989.

[3] A. Stok and E. H. Sargent, Lighting the local network: Optical code division multiple access and quality of service provisioning, IEEE Network, vol. 14, no. 6, pp. 42–46, Nov. 2000.

[4] P. R. Prucnal, M. A. Santoro, and T. R. Fan, "Spread-spectrum fiber-optic local area network using optical processing," J. Lightwave Technol. Vol. LT-4, pp. 547–554, May 1986.

[5] Vahid R. Arbab, Poorya Saghari, Narender M. Jayachandran, Alan E. Willner, "Variable Bit Rate Optical CDMA Networks Using Multiple Pulse Position Modulation"OCIS codes: (060.4510) Optical communications, (060.4250) Networks, Optical Society of America

[6] M. Kavehrad, and D. Zaccarh, "Optical Code-Division-Multiplexed Systems Based on Spectral Encoding of Noncoherent Sources," Journal ofLightwave Technology, Vol. 13, No. 3, March 1995

[7] Ivan B. Djordjevic and Bane Vasic, "Novel Combinatorial Constructions of Optical Orthogonal Codes for OCDMA Systems". Journal of Lightwave Technology, Vol. 21, September 2003

[8] Zou Wei, H. M. H. Shalaby, H. Ghafouri-Shiraz, "Modified Quadratic Congruence codes for Fiber Bragg-Grating-Based SAC-OCDMA," Journal of Lightwave Technology, Vol. 19, no. 9, pp. 1274-1281, Semptember. 2001.

[9] Zou Wei, H. Ghafouri-Shiraz, "Codes for Spectral-Amplitude- Coding Optical CDMA Systems," Journal of Lightwave Technology, Vol. 50, pp. 1209-1212, August 2002.

[10] S.A.Aljunid, ,M.Ismail, A.R.Ramli, Borhanuddin M. Ali, and Mohamad Khazani Abdullah, "A New Family of Optical Code Sequences for Spectral-Amplitude-Coding Optical CDMA Systems" IEEE Photonics Technology Letters, Vol. 16, No. 10, October 2004

[11] Mohamad Khazani Abdullah , Feras N. Hasoon , S.A. Aljunid , Sahbudin Shaari," Performance of OCDMA systems with new spectral direct detection (SDD)technique using enhanced double weight (EDW) code" ScienceDirect, Optics Communications 281 (2008) 4658–4662.

[12] Hassan Yousif Ahmed, Ibrahima Faye, N.M.Saad and S.A. Aljined, "Spectral Amplitude Coding Optical CDMA: Performance Analysis of PIIN Reduction Using VC Code Family" International Journal of Electronics, Communications and Computer Engineering, Vol. 1, No 2, June 2009, pp. 72-78.

[13] J.W. Goodman, Statistical Optics, Wiley, New York, 1985.