Impact of ADC Bandwidth and Clipping Ratio on COF-PON Systems Based on Spatial Coding and Subcarrier Multiplexing

Tianjiao Xia, Changjian Guo, and Sailing He
Center for Optical and Electromagnetic Research, Joint laboratory of Optical Communications,
Zhejiang University, Hangzhou 310058, China. Email: xiatianjiao@coer.zju.edu.cn

***Abstract*—In this paper, we analyze the impact of analog-to-digital convertor (ADC) bandwidth and clipping ratio on the performance of a 1 Gb/s × 15 user CDM-over-fiber-PON (COF-PON) system based on 16-QAM modulation, spatial coding and subcarrier multiplexing. We consider the clipping ratio, resolution and bandwidth of ADCs with fixed sampling speed in both back-to-back and 25 km standard single mode fiber (SSMF) transmission cases, taking into account nonlinear propagation effects in fiber transmission. We find that the best error vector magnitude (EVM) performance can be achieved when a clipping ratio (*CR*) of 1.5-1.8 is applied for different ADC resolutions, and that in order to achieve an EVM of smaller than 0.12, an ADC with at least 5-bit resolution should be used.**

***Keywords*—Analog-to-digital convertor (ADC), clipping ratio, code-division-multiplexing (CDM), passive optical networks (PON), subcarrier multiplexing.**

I. INTRODUCTION

Passive optical networks (PONs) have been considered a very promising solution to address the ever increasing demands for internet bandwidths. Various multiplexing techniques has been proposed for PON systems, among which optical code-division multiplexing (OCDM) has been attracted lots of research interests due to its advantages including high-speed optical processing, full asynchronous transmission, soft capacity on demand, etc [1]-[3]. All optical en/decoders used in OCDMA systems can offer chip rate of as high as 640 Gchip/s [1]. However, OCDMA systems based on optical en/decoders suffer from severe multiple access interference (MAI), which limits the number of access users [2], [3]. Additionally, expensive devices such as ultra-short pulse lasers, optical thresholders and optical time gating devices are also needed, increasing the overall cost. Fortunately, by using CDM over fiber technology, i.e., by coding and multiplexing electronically and then up converted to optical domain, MAI can be eliminated effectively [5] and can therefore increase the number of access users as well as reducing system cost.

Recently, we have proposed and experimentally demonstrated a novel CDM over fiber PON scheme based on spatial coding and subcarrier multiplexing [4], [6]. The basic concept of spatial coding and subcarrier multiplexing is depicted in Fig. 1, where 4 codes are used for illustration. In OLT, signals for each users are split into k ($k = 4$ as in Fig. 1) identical branches, each followed by a switch, whose on/off state are controlled by code word. The output signals from the switches are power combined with the counterparts of other users and then subcarrier multiplexed, using a set of frequency. The SCM signals are finally added up, forming the encoded electrical signal. As for decoding, the received signal is again split into k branches and each subcarrier is down-converted. After that, the down-converted signals are added up or subtracted according to the code word to decode the signal. Our approach offers the following advantages: 1) Spatial en/decoding and data-rate processing enables us with high capacity. 2) By using electrical en/decoding, MAI can be eliminated effectively, and therefore no optical thresholders and optical time gating devices are needed. 3) Subcarrier multiplexing increases the spectrum efficiency and avoids massive usage of optical components, as compared with [5]. More importantly, using both spatial coding and subcarrier multiplexing offers us coding gain when the number of simultaneous users is smaller than the number of subcarriers (code length) [6]. 4) Coherent detection and DSP technologies can be adopted, enabling very high receiver sensitivity, thus can support ultra long distance PON.

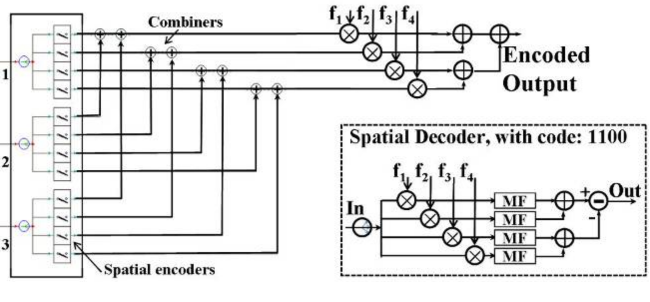

Fig. 1. Illustration for electrical spatial coding and subcarrier multiplexing.

A key aspect of our proposed CDM over fiber scheme is the analog-to-digital conversion after photo detection. It is very challenging to design ADCs with both high resolutions and high sampling rate [7], [11]. Additionally, as multiple subcarriers are used in the CDM over fiber system, the peak to average power ratio (PAPR) can be very significant [8]-[10], and therefore clipping should be used before A/D conversion to improve the performance. In this paper, we analyze the impact of analog-to-digital convertor (ADC) bandwidth and clipping ratio on the performance of a 1 Gb/s × 15 user CDM-over-fiber-PON (COF-PON) system based on 16-QAM modulation, spatial coding and subcarrier multiplexing. We consider both

978-1-4244-6554-5/11/$26.00 ©2011 IEEE

back-to-back and 25-km SSMF transmission cases, with nonlinear nonlinear propagation effects considered in fiber transmission. We show that the best error vector magnitude (EVM) performance can be achieved when a clipping ratio (*CR*) of 1.5-1.8 is applied, and that in order to achieve an EVM of smaller than 0.12 (corresponding to a BER of 1e-4), an ADC with at least 5-bit resolution should be used.

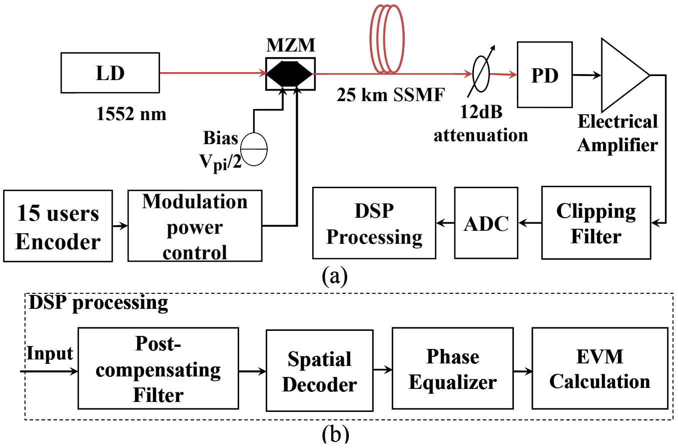

Fig. 2. (a) Layout of the 1 Gb/s × 15 user CDM-over-fiber-PON (COF-PON) system; (b) steps for DSP processing.

II. SIMULATION MODEL

Fig. 2 shows the structure of our 1 Gb/s × 15 user COF-PON system based on 16-QAM modulation, spatial coding and subcarrier multiplexing. The I and Q components of the 16-QAM signals from 15 users were spatial coded using 2^4 Walsh code separately using the same code, and subsequently subcarrier multiplexed using the same frequency with a 90 degree phase shift from each other, and then combined with all other channels. As a root-squared raised cosine filter with a roll off factor β = 0.2 was used in the transmitter for pulse shaping, the bandwidth occupied by each subcarrier f_b = 1e9 * (1 + β) / 4 = 300 (MHz). The center frequency of the first subcarrier f_c = 350 (MHz), and the other subcarriers are spaced f_s = 300 MHz away from each other. The overall bandwidth *B* of the 16 subcarriers is therefore:

$$B = (16-1) * f_s + f_c + \tfrac{1}{2} f_b = 5\times10^9 \text{ (Hz)} \qquad (1)$$

The SCM signals were then linearly modulated by a Mach-Zehnder Modulator (MZM) with an extinction ratio of 25 dB using double side-band (DSB) modulation, and fed into 25 km of SSMF without optical amplification. The optical source used in this simulation is a CW laser with a center wavelength of 1552 nm, and a line width of 100 KHz. At the remote node, the optical signals were divided into 16 parts by the power splitter, corresponding to 12dB attenuation. Finally, the optical signal was photo detected using a PIN diode with a thermal noise of 10 pA/√Hz and a dark current of 10 nA.

The received electrical signal was filtered using a clipping filter. The clipping ratio *CR* used here is defined as [8]:

$$CR = A_{\max} \Big/ \sqrt{P_{in}} \qquad (2)$$

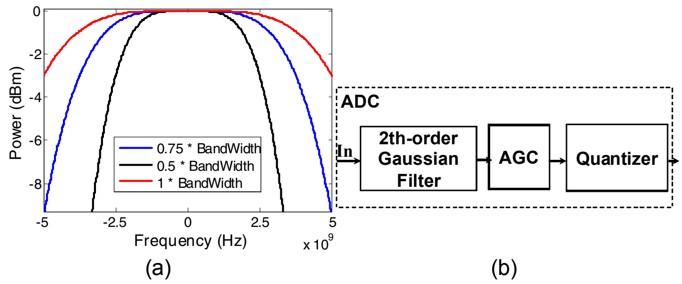

Fig. 3. (a) The power transfer function of the 2th-order Gaussian Filter at 0.75*Bandwidth, 0.5*Bandwidth and 1*Bandwidth; (b) ADC structure.

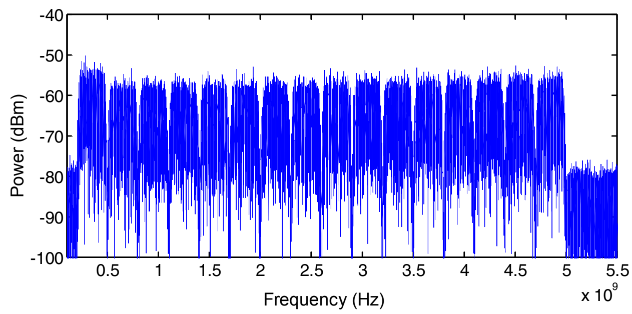

Fig. 4. Electrical spectrum after PD.

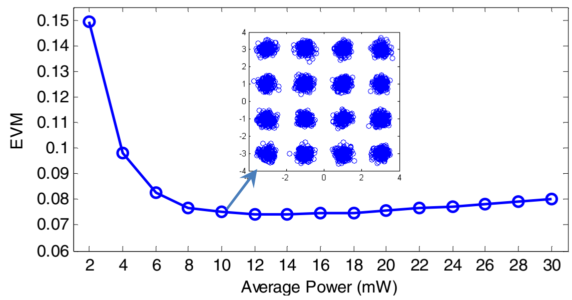

Fig. 5. EVM vs. transmitted optical power after 25 km SSMF transmission. Nonlinear effects considered.

where $A_{\max}$ is the maximum amplitude over which the signal was clipped and P_{in} is the average power of electrical signal. After clipping, the signal was fed into a 2nd order super-Gaussian low pass filter (LPF) and then sampled by an ADC operating at 10 Gs/s, i.e., two times the overall bandwidth (see Fig. 3). The power transfer functions of a set of filters with different bandwidths are shown in Fig. 3. Finally, the quantized signal was sent to a DSP unit for post amplitude compensation, spatial decoding, phase equalization and EVM calculation.

III. RESULTS AND DISCUSSIONS

In this simulation, a total number of 214 bits (4096 symbol for each user) was used for EVM calculation in each run. During all the simulations, the modulation power for E/O up-conversion was optimized. The transmitted optical power is set to 10 dBm, as further increasing the transmitted optical power would only compromise the EVM performance due to non-

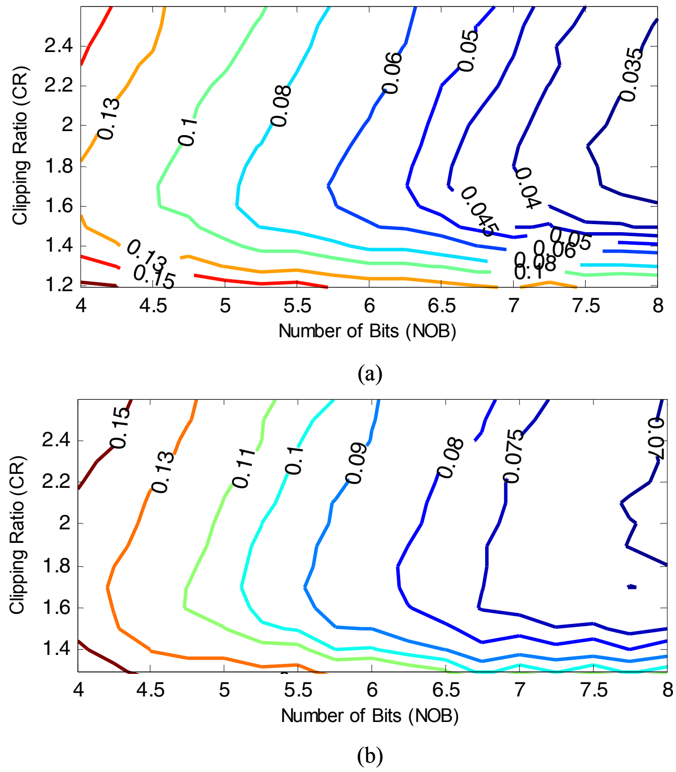

Fig. 6. Contour plot of the EVM vs. *CR* and *NOB* for (a) back to back; (b) after 25 km propagation.

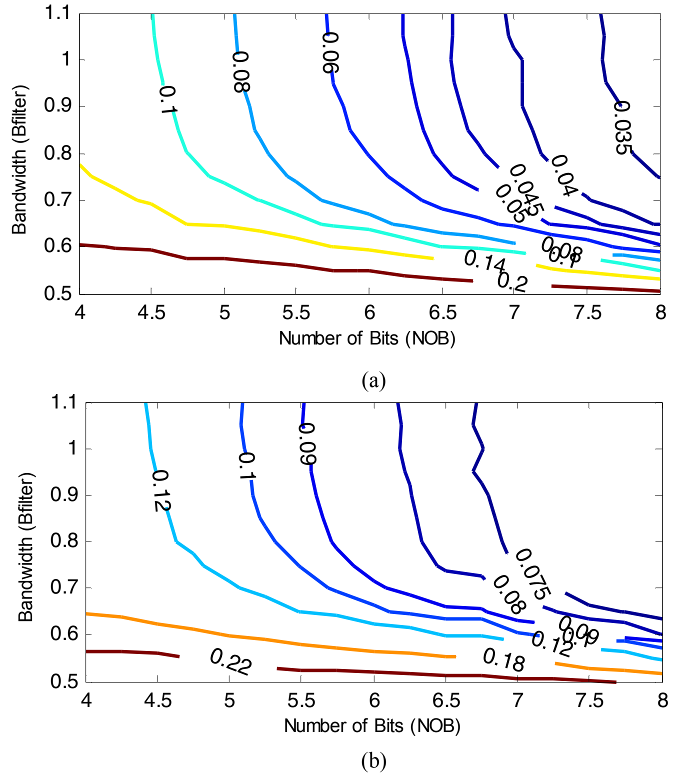

Fig. 7. Contour plot of the EVM vs. B_{filter} and *NOB* for (a) back to back; (b) after 25 km propagation.

linear propagation effects, as shown in Fig. 5. We firstly simulated the clipping impact on the EVM performance of the 15 user system. An unclipped signal in this system typically has a *CR* of around 2.6. Therefore we varied the *CR* from 2.6 down to 1.2 for ADC resolutions *NOB* from 4 bits to 8 bits. The ADC bandwidth was fixed to 1 time the overall bandwidth (5 GHz). The contour plot of the EVM versus *CR* and *NOB* was shown in Fig. 6. Both back-to-back and 25 km SSMF transmission cases are considered. It can be seen that the optimized *CR* can be found at around 1.5-1.8 for both back-to-back and 25-km SSMF transmission cases. The optimized *CR* value tends to slowly increase as the *NOB* becomes larger, from 1.5 at 4-bits resolution to 1.8 at 8-bits resolution. It should be noted that *CR* values from 1.6 to 1.8 yield similar performances for most cases, as shown in Fig. 6. At higher *CR* values, i.e., with less clipping efforts, the EVM performance gets worse, indicating that clipping is indeed useful to improve the EVM performance. On the other hand, severe clipping would cause dramatic EVM degradation, which can also be seen from Fig. 6.

For ADC bandwidth simulation, we swept the bandwidth B_{filter} from 0.5 times the overall bandwidth to 1.1 times the overall bandwidth for ADC resolutions *NOB* from 4-bits to 8-bits. The clipping ratio was fixed at 1.7, a value that yield best performance for most cases (see Fig. 6). As our proposed CDM over fiber scheme uses spectral multi-level amplitude-shift keying (M-ary ASK) based on spatial coding and subcarrier multiplexing, it is critical that the relative spectra amplitudes of all subcarriers remain unchanged. We therefore used a post amplitude compensation filter to compensate the amplitude degradation caused by the ADC pre-filter. We drew the contour plot of EVM performance versus B_{filter} and *NOB*, in both back-to-back and 25 km SSMF transmission cases, as shown in Fig. 7. One can find that the EVM always get better when B_{filter} becomes larger. This can be explains as follows. In PON systems, no optical amplifiers are used in transmission link, thus OSNR degradation is small. Therefore, noises outside the sampling band have limited influence on the EVM performance even when the sampling bandwidth is larger than the overall signal bandwidth. It can be seen from Fig. 7 that in order to get an EVM smaller than 0.12 (corresponding to a BER of 1e-4), an ADC with at least 5-bit resolution should be used.

We have also depicted the EVM performance of user #1 (code: 1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1, 1, -1) versus number of simultaneous users and *NOB*s from 4 bits to 8 bits for both back-to-back and 25 km SSMF transmission cases, shown in Fig. 8. The EVM increases monotonously with the number of simultaneous users.

IV. Conclusions

The impact of ADC resolution, bandwidth and clipping ratio on the performance of a 1 Gb/s × 15 user CDM-over-fiber-PON (COF-PON) system based on 16-QAM modulation, spatial coding and subcarrier multiplexing has been analyzed in this paper. We considered both back-to-back and 25 km SSMF transmission cases. We found that by properly clipping the input signal with a *CR* of around 1.5-1.8 for different ADC resolutions, an optimum EVM can be obtained. We also found that when the ADC bandwidth *B* is greater than 0.8, the system yields almost the same performance, as shown in Fig. 7. In order to achieve an EVM of smaller than 0.12, an ADC with at least 5-bit resolution should be used.

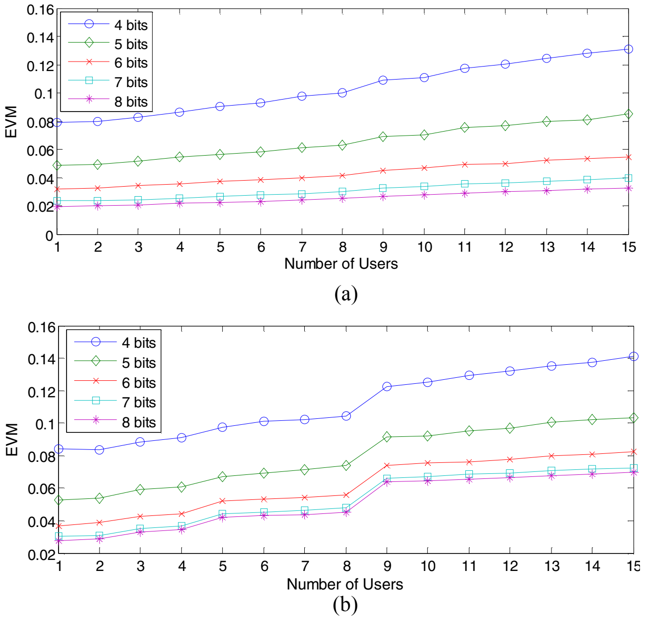

Fig. 8. EVM for user #1 vs. number of simuletaneous users for (a) back to back and (b) after 25 km propagation cases.

REFERENCES

[1] T. Hamanaka, X. Wang, N. Wada, and K. Kitayama, " 511-Chip SSFBG and DFG-Based Optical Thresholder Enabled Compound Data Rate (10Gbps~622Mbps) OCDMA Experiment for Multiple Service Provisioning Platform," in OFC'06, paper OThT4, Mar. 2006.

[2] L. Xu, I. Glesk, V. Baby, and P. R. Prucnal, "Multiple access interference (MAI) noise reduction in a 2-D opticalCDMA system using ultrafast optical thresholding," in Proc. IEEE LEOS Annu. Meeting, 2004, pp. 591–592, Paper WP4.

[3] C. Guo, X. Hong, and S. He, "Elimination of Multiple Access Interference in Ultrashort Pulse OCDMA Through Nonlinear Polarization Rotation," IEEE Photonics Technology Letters, vol. 21, issue 20, pp. 1484-1486, Oct. 2009.

[4] C. Guo; C. Luo; and S. He, "Electrically Processed OCDMA System Based on Spatial Coding and Subcarrier Multiplexing," in Photonics in Switching, OSA Technical Digest (CD) (Optical Society of America), paper JTuB43, July 25, 2010.

[5] S. Kaneko, H. Suzuki, N. Miki, H. Kimura, and K. Kumozaki, "Beat-Noise-Free OCDM Technique Employing Spectral M-ary ASK Based on Electrical-Domain Spatial Code Spreading," in OFC'09, paper OThI5, Mar. 2009.

[6] C. Guo; L. Huang; and S. He, "Demonstration of 1 Gb/s × 15-User CDM over WDM-PON Using Electrical Spatial Coding and Subcarrier Multiplexing," submitted to IEEE Photonics Technology Letters.

[7] R.H. Walden, "Analog-to-digital converter survey and analysis," IEEE Journal on Selected Areas in Communications, vol.17, no.4, pp.539-550, Apr. 1999.

[8] HidekiOchiai and HidekiImai, "Performance of the deliberate clipping with adaptive symbol selection for strictly band-limited OFDM systems," IEEE Journal on Selected Areas in Communications, vol.18, no. 11, pp. 2270 – 2277, Nov. 2000.

[9] Hua Yu; Gang Wei, "Choosing the Optimal Clipping Ratio for Clipping and Filtering PAR-Reduction Scheme in OFDM," International Conference on WiCom 2007, Shanghai, China, pp. 460 – 463, Sept. 2007.

[10] Chun-Tao Lin; Wen-Rong Wu, "Clipping ratio estimation for OFDM receivers," VTC 2005-Spring, 2005 IEEE 61st, vol. 2, pp. 797 – 800, June 2005.

[11] A. Carena, V. Curri, P. Poggiolini, G. Bosco, and F. Forghieri," Impact of ADC Sampling Speed and Resolution on Uncompensated Long-Haul 111 Gbit/s WDM PM-QPSK Systems," IEEE Photonics Technology Letters, vol. 21, no. 20, pp. 1514-1516, Oct. 2009.