Demonstration of 1 Gb/s × 15-User CDM Over WDM-PON Using Electrical Spatial Coding and Subcarrier Multiplexing

Changjian Guo, *Student Member, IEEE*, Lingchen Huang, and Sailing He, *Senior Member, IEEE*

Abstract—The downlink transmission of a 1 Gb/s × 15-user code-division multiplexing (CDM) over wavelength-division-multiplexing passive optical network (WDM-PON) based on electrical spatial coding and subcarrier multiplexing is experimentally demonstrated. Two wavelengths with 100-GHz spacing are used to carry the 15 spatial encoded subcarriers generated by an arbitrary waveform generator. Our results show that error-free operation can be achieved after 20-km standard single-mode fiber (SSMF) transmission when 15 simultaneous users are present assuming that forward-error correction coding is used.

Index Terms—Code-division multiplexing (CDM), digital signal processing (DSP), passive optical network (PON), subcarrier multiplexing.

I. INTRODUCTION

PASSIVE optical networks (PON) is one important solution to address the ever increasing demands for bandwidths. Various PON solutions have been proposed so far, among which optical code division multiple access (OCDMA) [1] is considered as one of the attractive access technologies due to its advantages including high capacity, flexible network management, and the potential of security enhancement for the physical layer, etc. Several all-optical en/decoders have been used in OCDMA systems [2]–[4], which can offer chip rates as high as 640 Gchip/s [3]. However, OCDMA systems based on all-optical en/decoders suffer from severe beat noise and multiple access interference (MAI). Additionally, practical deployment of OCDMA systems typically faces the challenges of high system cost due to the adoption of expensive optical units, including ultrashort pulse lasers, optical thresholders and optical time gating devices. Electrically processed OCDMA systems, or code division multiplexing (CDM) over fiber systems based on charge-coupled devices (CCDs) [5], transversal filters [6], etc., have been proposed recently. As electrical

processing at chip rate is used in those systems, the electrical processing speed poses a bottleneck, limiting the data rate and the number of access users. Shin Kaneko, *et al.* [7] proposed a CDM over fiber system based on electrical spatial coding to avoid chip-rate processing and therefore can achieve a data rate of 1.5 Gb/s. However, the number of optical devices used in this scheme increases linearly with the code length, which may lead to high cost when long codes are used.

Recently, we have proposed an CDM over fiber system based on spatial coding and subcarrier multiplexing (SCM) [8]. The concept of electrical spatial encoding/decoding and SCM is illustrated in Fig. 1(a) and (b). The signal of each user is split into k parts (k is the code length. In this example, $k = 4$.) and followed by k switches through which the signals are encoded by controlling their on/off states. The total number of switches used in the optical line terminal (OLT) is k times the number of users. The output signals of the same user after the switches are synchronized, combined with the corresponding tributaries of other users and multiplexed with a set of subcarriers with different frequencies, as shown in Fig. 1(a). The decoding process is the inverse operation. The received signals are firstly down-converted and each subcarrier is extracted. As a square-root raised-cosine filter is usually used in the transmitter side, a matched filter (MF) is used before decoding. Subcarriers are then added or subtracted according to the code to recover the signal, as shown in Fig. 1(b). The proposed scheme has the following advantages: 1) electrical en/decoding enables us to be beat noise free, and suppresses the MAI noise effectively, thus no need for optical thresholders or optical time gating devices; 2) subcarrier multiplexing avoids intensive use of optical devices; 3) coherent detection and digital signal processing (DSP) technologies can be adopted, enabling very high receiver sensitivity, and can therefore support long distance PON systems. In this letter, we demonstrate the downlink transmission of a CDM over wavelength division multiplexed (WDM)-PON based on our proposed scheme with experiments. By employing CDM techniques over WDM-PON architecture, multiple users can use the same wavelength(s) without sharing the bandwidth, thus fewer wavelengths are needed compared to conventional WDM-PONs when the same number of users is considered for both architectures. The downstream configuration is shown in Fig. 1(c), where two wavelengths are used to transmit the 15 subcarriers after spatial encoding and subcarrier multiplexing. It should be noted that the users inside each optical network unit (ONU) shown in Fig. 1(c) can actually be used as independent ONUs, or several users can be assigned to one ONU. Therefore, Fig. 1(c) is just
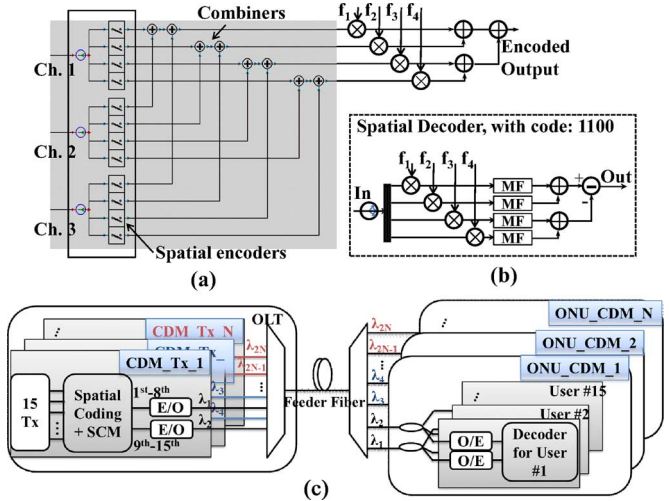
(a) **(b)** **(c)**

Fig. 1. Illustration for electrical spatial coding and subcarrier multiplexing; (a) spatial encoding and subcarrier multiplexing; (b) spatial decoding and (c) system configuration for downstream transmission. MF: matched filter.
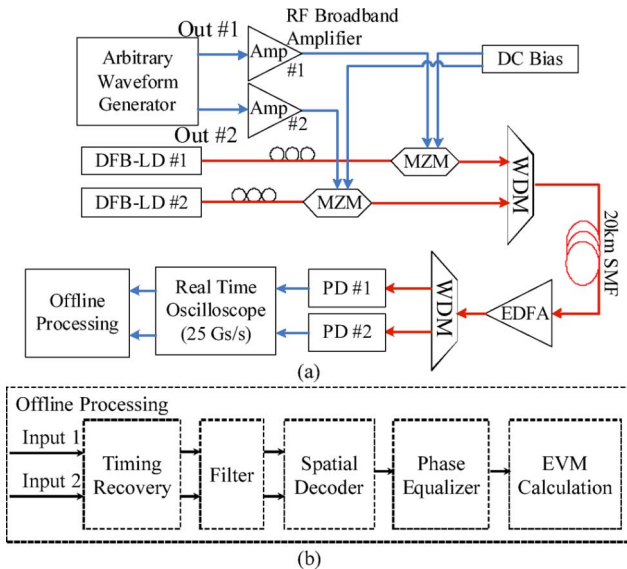

Fig. 2. (a) Experimental setup. (b) Steps for offline processing algorithms.

one example of the possible system configurations. The codes used in the experiment has a length of 15, supporting at most 15 users, each with a data rate of 1 Gb/s. We show that error free operation assuming forward error correction (FEC) coding can be achieved after 20 km standard single mode fiber (SSMF) transmission when 15 users are present.

II. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup of the CDM over WDM-PON system. In this experiment, the bit rate for each user is 1-Gb/s, and the data stream is 16-QAM modulated. As a root-squared raised cosine filter with roll-off factor $\beta = 0.18$ is used in the signal generation, the bandwidth for each subcarrier is $1e9 * (1 + \beta)/4 = 295$ (MHz). PN codes with length of $2^4 - 1$ are used in spatial encoding (see Fig. 1(a)). The center frequency of the first subcarrier is 190 MHz, and the other subcarriers are spaced 320 MHz away from each other. The encoded SCM signals were generated using VPI software and then resampled and downloaded into an arbitrary waveform
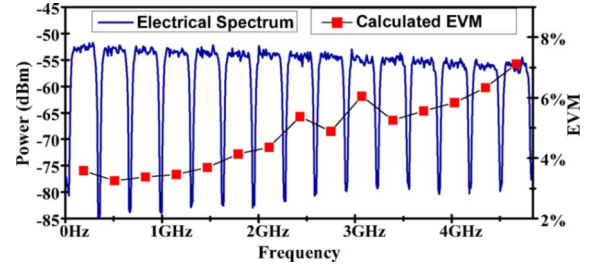

Fig. 3. Uncoded SCM spectrum (left axis) generated by the AWG. Each subcarrier is a 1-Gb/s 16-QAM modulated signal. The red squared dots are for the calculated EVM performance of the corresponding subcarriers (right axis).
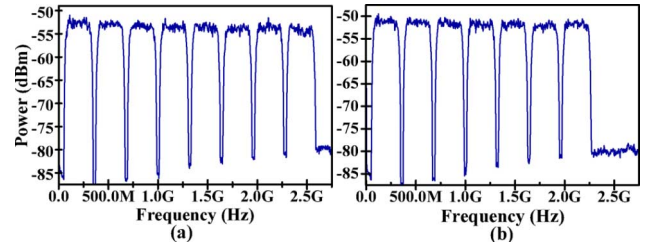

Fig. 4. Encoded SCM spectrum. The 15 subcarries were split into two groups, (a) 1st–8th, and (b) 9th–15th. The first subcarrier frequency and the subcarrier spacing are the same for both groups.

generator (AWG, sampling at 12 Gs/s) to produce electrical signals. To evaluate the limitation of the instrument, 15 uncoded subcarries using the same parameters as mentioned above were generated at sample rate of 12 Gs/s, and sent directly to a real-time oscilloscope. The error vector magnitude (EVM) performance of each subcarrier, which is shown in Fig. 3, indicates that the performance of the subcarriers deteriorates as the frequency increases. Therefore, the 15 subcarriers were split into two groups and generated separately by the two output ports of the AWG in order to ensure that the generated electrical signal has an EVM of below 5.3% corresponding to a bit error ratio (BER) of 1E-9 [10]. The spectra of the two output electrical signals are shown in Fig. 4. The SCM signals were then applied to two broadband amplifiers. Electrical attenuators were used after the amplifiers in order to optimize the EVM. Two laser diodes (LDs) with wavelength of 1548.5 nm and 1549.3 nm were used as the optical sources. Double sideband (DSB) optical modulation was used here. After that, the signals were coupled into a 100-GHz spaced WDM multiplexer and sent into 20-km SSMF. The transmitted optical power is around −1 dBm. At the receiver, the two optical signals were amplified, separated by a WDM demultiplexer, direct-detected using two 43-GHz photodetectors (PDs) and then recorded using a 25 Gs/s real-time oscilloscope for offline DSP processing, which contains 5 steps: timing recovery, matched filtering, spatial decoding, phase equalization, and finally EVM evaluation, as shown in Fig. 2(b). It should be noted that coherent detection can also be used here, in which case about 16 dB margin could be added to the theoretical sensitivity limit[12], enabling long-reach, high splitting ratio PONs without amplifiers. DSP processing can then be applied for impairments compensation and FEC decoding.

III. RESULTS AND DISCUSSION

In our experiment, 65536 bits (2^{16}, or 16384 symbols) were recorded each run. The optical signal-to-noise ratio (OSNR)
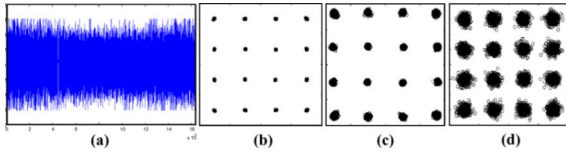
Fig. 5. (a) Received signal waveforms and (b) recovered constellations for 1 user, back-to-back, without optical modulation; (c) 1 user, after 20-km SSMF transmission; (d) 15 users, after 20-km SSMF transmission.
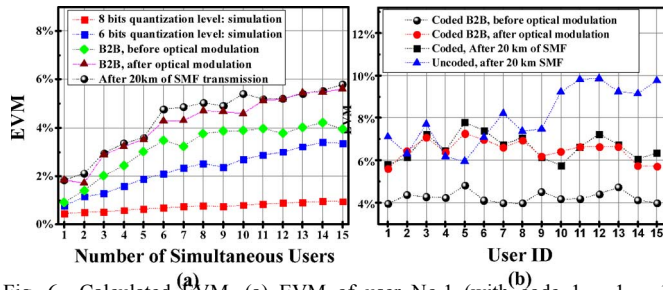

Fig. 6. Calculated EVM. (a) EVM of user No.1 (with code 1, -1, -1, $-1,1,1,1,1$, $-1,1$, $-1,1,1$, -1, -1) versus number of simultaneous users. (b) EVM performance of each users when all 15 users are present.

after the optical amplifier was 42 dB. Fig. 5 shows the received waveforms (a) and constellations of the recovered signals: Fig. 5(b) for the AWG generated single user electrical signals; Fig. 5(c) for single user signals after 20 km SSMF transmission and Fig. 5(d) for 15 simultaneous users after 20 km SSMF transmission. The EVM performance of user No.1 (with code:1, -1, -1, $-1,1,1,1,1$, $-1,1$, $-1,1,1$, -1, -1) as the number of simultaneous users increases is depicted in Fig. 6(a). The two simulation curves were calculated after the original software generated signals were quantized using 6-bit (blue squares) and 8-bit (red squares) ideal analog-to-digital converter (ADC). Note that the resolution of the digital-to-analog converter (DAC) of the AWG was set to 10, and the effective number of bits (ENOB) of the real-time oscilloscope we used in this experiment is typically smaller than 6[11]. We also evaluated the EVM performance of user No.1 for cases of both before (green diamonds) and after optical modulation (brown triangles) and after 20 km SSMF transmission (black spheres). Both cases show similar EVM performance because of relatively small cumulated chromatic dispersion (340 ps/nm), and narrow bandwidth occupied by both SCM signals (each less than 2.6 GHz). It can be seen from Fig. 6(a) that three factors can be considered concerning the degradation of the system performance: 1) insufficient DAC resolution of the AWG, which can be seen from the blue squares curve and the green diamonds curve; 2) modulation nonlinearity, which can be seen from the green diamonds curve and the brown triangles curve; 3) insufficient ADC resolution, which can be seen from the two simulation curves. These three factors caused the signal distortion during signal generation, modulation and reception, respectively, which result in residual MAI, degrading the performance as the number of users increases. We also evaluated the EVMs for all users when 15 users were transmitted, as shown in Fig. 6(b). The EVMs of the back-to-back electrical signal for all 15 users (black spheres) are between 4% – 4.8%, which is comparable to that of the 6th and 7th subcarrier in uncoded case shown in Fig. 3. The EVMs for signals after optical modulation (red circles) and 20 km SSMF transmission (black squares) are all below 8%, which is also comparable to that of the lower

frequency uncoded subcarriers after 20 km SSMF transmission (blue squares). The worst case EVM of the deocded signal was found to be 7.8%, which is within the correction capability of the common FEC techniques [9], [10]. One can see from Fig. 6 that coding gain, also called processing gain defined as the ratio of transmission and information bandwith, can be observed when the number of simultaneous users are smaller than the code length, which agrees with some earlier observation [13].

IV. CONCLUSION

We have experimentally demonstrated the downlink transmission of a 1 Gb/s × 15-User CDM over WDM-PON based on our proposed scheme. We have shown that error free transmission can be achieved for 15 users after 20 km SSMF transmission over single wavelength band (assuming common FEC techniques). We have also observed the coding gain over uncoded subcarrier multiplexing when the number of transmitted users are smaller than the code length. This feature, together with the other advantages including beat noise free, adoption of coherent detection and DSP processing, etc., makes this scheme very attractive for PON solutions.

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