20-Gb/s, 20-km WDM-PON Upstream Transmission using 4-PAM Modulated Free-Running 1550 nm VCSEL and Adaptive SC-FDE

Hongguang Zhang, Xiaofei Cheng, Zhaowen Xu
Institute for Infocomm Research, Agency for Science, Technology and Research, Singapore, 138632.
E-mail: zhhg@semi.ac.cn

Abstract: We propose a novel 20Gb/s WDM-PON upstream transmission scheme using 4-PAM modulated free-running 1550nm VCSEL and adaptive Single-Carrier Frequency-Domain Equalization (SC-FDE). A transmission distance of 20km is achieved in direct detection system.

OCIS codes: (140.7260) Vertical surface cavity emitting diodes; (060.4510) Optical communications

1. Introduction

Vertical Cavity Surface Emitting Laser (VCSEL) is an attractive candidate for low-cost, low power consumption, high-speed optical source, and it can be potentially applied in Wavelength-division-multiplexed passive optical network (WDM-PON). However, chromatic dispersion (CD) limits the transmission distance of VCSEL at bit rates of 10-Gb/s and above [1]. Inverse-dispersion fiber [2], optical injection locking [3] and optical filter [4] are always used to mitigate the degrading effects of CD, and short PRBS word length (2^7-1) is used in testing to get longer transmission distance [2]. DSP algorithms can also be used to mitigate the degradation caused by CD. In [5], Single-Carrier Frequency-Domain Equalization (SC-FDE) is proposed to compensate chromatic dispersion (CD) impairments in coherent optical transmission systems. However, it is ineffective for direct detection systems since signal phase information is not preserved in square-law detection [6]. To solve this problem, we propose to use adaptive SC-FDE to compensate for CD distortion in direct detection systems.

In order to improve spectral efficiency, multilevel modulation such as four-level pulse amplitude modulation (4-PAM) is introduced in optical communication [7]. In this paper, we propose and demonstrate a novel 20-Gb/s upstream transmission scheme for WDM-PON by using SC-FDE and 4-PAM modulated 1550nm VCSEL. 4-PAM is applied to modulate the VCSEL at a symbol rate of 10 Gbaud, and thus 20Gbit/s IM-DD transmission system is realized. Experiment results show that a transmission distance of 20km can be achieved after applying the adaptive SC-FDE algorithm.

Figure 1: WDM-PON upstream transmission scheme using 4-PAM signal modulated VCSEL and adaptive SC-FDE. RN: remote node; A/D: analog-to-digital conversion; Syl.: synchronization; S/P: series to parallel conversion; Rem. CP: CP removal; P/S: parallel-to-serial conversion; Demo.: demodulation.

2. WDM-PON upstream transmission scheme

Fig. 1 illustrates the proposed WDM-PON upstream transmission scheme using 4-PAM signal modulated VCSEL and adaptive SC-FDE. The 1550-nm VCSELS are deployed at the ONU as low-cost, low power consumption, high-speed upstream optical sources. 4-PAM signal with cyclic prefix (CP) and preamble inserted is directly modulated onto the VCSEL. After transmission over fiber, uplink signals are sent to the receivers via a DEMUX in the central office (CO), and then post-processed offline with the adaptive SC-FDE algorithm. As an alternative to OFDM, SC-FDE has similar performance and the same DSP complexity, but suffers less nonlinear impairments due to its lower peak-to-average power ratio [8]. In addition, because both the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) are processed at the receiver, the transmitter of SC-FDE system is simpler than that of OFDM, and therefore it is more suitable to be implemented in the ONU of WDM-PON systems.
The DSP block structure of the adaptive FDE is also shown in Fig. 1. Received signal is digitized and synchronized, and then it is framed into blocks by S/P convertor. Data sequence is transformed into frequency domain by FFT, and equalized block-by-block, while feed forward filter deals with the major inter-symbol interference (ISI) and feedback filter handle the residual. Both filters are adaptively updated based on low computational frequency domain least-mean-square (LMS) algorithm [9]. The equalization undergoes training stage in the preamble period and decision-directed stage in the data period. In the processing, overlap-save method is used to perform linear convolution effectively and fractional spaced equalization (FSE) with 2 samples per symbol is used to avoid aliasing. After removing CP, the equalized blocks are changed back to a serial symbol stream by the P/S convertor and then demodulated to binary signal. In our proposed scheme, no injection locking or dispersion compensation fiber is used. Because most of the complex DSP is performed at the receiver, the transmitter can be kept very simple and doesn’t require high-speed digital-to-analog converters (DAC). Thus, the ONUs in SC-FDE system can be significantly less expensive than that of OFDM.

3. Experiment Setup

The experiment setup is shown in Fig. 2. At the transmitter, the 4-PAM signal was generated by combining two binary pseudo-random bit sequence (PRBS) data signals from a pulse pattern generator (PPG). Using MATLAB, a PRBS sequence with word length of $2^{10}$ was generated and grouped into blocks, and CP was inserted at the end of each block. The Preamble sequence was composed of 8 random binary sequences with word length of 1024 for each sequence. The preamble sequence was also grouped into blocks with CP inserted. After preamble insertion, the binary data sequence was loaded into the PPG. The differential outputs of the PPG were combined with an RF power combiner and one output was delayed by a tunable phase-shifter. By adjusting the delay time and the amplitude of differential outputs precisely, optimized 4-PAM signal with block size of 256 bit (16-bit CP was inserted in each block) is generated from the output of RF power combiner.

An un-cooled free-running 10-Gb/s VCSEL was biased at 9.3 mA with launching power of -5.6 dBm and wavelength of 1544.66 nm. The generated 4-PAM signal was intensity modulated onto the VCSEL at a symbol rate of 10 Gbaud, and transmitted over single mode fiber (SMF) with dispersion coefficient of 17 ps/(nm•km) at 1550 nm. At the receiver, a tunable Gaussian optical filter (OTF1) with 3-dB bandwidth of 0.3 nm was used to mitigate the degrading effects of CD. It can also represent the AWG in WDM-PON system [4]. For BER measurements, an erbium doped fiber amplifier (EDFA) was used as a pre-amplifier in the receiver and it is followed by a flat-top tunable optical filter (OTF2) with 3-dB bandwidth of 0.58 nm to suppress the EDFA noise. A variable optical attenuator was used before the photodetector (PD) to adjust the optical power for BER measurement. The optical signal was detected by the PD and sampled by a 50 GS/s digital oscilloscope (Tek DSA72004B). The digitized signal was post-processed offline where adaptive FDE, 4-PAM signal demodulation and BER calculations were carried out.

4. Experiment results and discussion

Fig. 3 gives the generated 4-PAM signal at the output of RF power combiner and optical back-to-back (BTB) eye diagram. Because the amplitude of combiner output is larger than the measurement range of oscilloscope, a 3-dB RF attenuator was used before the oscilloscope. The optical spectra for these two optical filters are also shown in Fig. 3.
Fig. 3 gives the BER results before and after adaptive FDE with different transmission distance. If we use the Forward Error Correction (FEC) threshold $\left(2 \times 10^{-3}\right)$ as the criterion to analyze the system performance, it can be seen that without equalization, the BER can't reach the FEC threshold when the transmission length is 10 km. In contrast, after equalization, the BER is below FEC threshold even when the transmission distance is 20 km with optical power of -13 dBm.

5. Conclusions

We proposed and demonstrated a novel 20-Gb/s WDM-PON upstream transmission scheme using 4-PAM modulated free-running VCSEL and adaptive SC-FDE in IM-DD system. In the scheme, adaptive FDE is applied at post-processing stage to compensate CD, and no injection locking or dispersion compensation fibre is used. The transmission distance for 4-PAM modulated VCSEL is extended to 20 km with our adaptive FDE algorithm. Due to the simplicity of the intensity modulation used at the transmitter which can result in low cost ONUs, this scheme is suitable for upstream transmission in WDM-PON systems.

6. Reference