Architectures and Key DSP Techniques of Next Generation Passive Optical Network (PON)

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Abstract: Passive optical network (PON) is continuously explored for new architectures and effective DSP techniques to adapt to the next generation communication. In this paper, we summarize our work and discuss the challenges and potential solutions for the next-generation PON.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems

1. Introduction

With the rapid growth of emerging technologies, such as virtual reality (VR), cloud services, and peer-to-peer multimedia services, the bandwidth demand of access network has been constantly booming [1]. As one of the most promising candidates, passive optical network (PON) technology is rapidly evolving to adapt to the development of future access networks. The present commercial 10 Gb/s/λ PON is developing towards the next-generation PON (NG-PON) with a capacity of 100 Gb/s/λ to satisfy the ever-increasing bandwidth demand. In the literature, various PON architectures have been proposed, but the common point of these schemes is that the evolution of NG-PON will pursue the goals of low cost, high transmission rate, flexible access and effective digital signal process (DSP) techniques [2-3]. Our group is committed to exploring the new network architecture of the NG-PON, and also puts forward some possible key DSP techniques to realize the next stage deployment of NG-PON.

In this paper, we review the main results of our work that focused on the promising solution for NG-PON, and we also discuss challenges and potential solutions for the uplink of access networks. We have discussed the following key DSP techniques: 1) a low cost and power consumption noise shaping technology, which can effectively reduce the quantization bits of a digital-to-analog converter (DAC); 2) a sub-Nyquist sampling reception technique, which enables optical network units(ONUs) to receive high-rata aggregated data with a low-speed analog-to-digital converter (ADC); 3) a flexible PON uplink scheme based on filter bank multicarrier (FBMC), which can achieve higher spectrum efficiency with better robustness against time synchronization errors.

2. Low-cost Noise Shaping Technique

At present, high-resolution DACs are widely adopted in the current PON to support high capacity of network [4]. To meet the low-cost and low-power requirements of the NG-PON, the signal generated by the low-resolution DAC is an effective and feasible solution. However, high quantization noise caused by conventional DAC with 4-bit resolution will seriously degrade the system performance. To solve this problem, Li H. et al. proposed a delta-sigma modulation technique, in which the noise transfer function is designed to reduce the quantization noise within the signal bandwidth [5]. The disadvantage of delta-sigma modulation technique is that it requires an ultra-high oversampling rate. A novel noise shaping scheme with low computational complexity was proposed in Ref. [6]. Similar to delta-sigma modulation, the operation principle of the noise shaping scheme is to push the quantization noise out of the signal band and increase the signal-to-noise ratio (SNR) of the signal band, while the required sampling rate is far less than delta-sigma modulation. In our previous work, we studied the simplified noise shaping technology in over 100 Gb/s/λ DMT and PAM transmission systems [7-8]. The experiment results show that the noise shaping technique can effectively eliminate quantization both for PAM and DMT signal and is not sensitive to the modulation format.

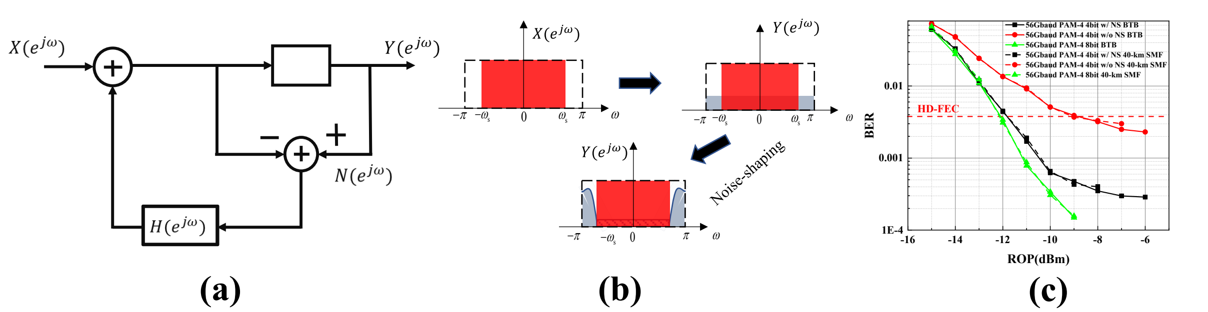

Fig. 1. (a) Linear models of noise shaping technique. (b) Operating principle of noise shaping technique in frequency-domain. (c) BER versus ROP of 56 Gbaud PAM-4 in OBTB and 40 km SMF transmission.

Fig. 1(a) illustrates the linear model of noise shaping technique, and $H(e^{j\omega})$ is realized by finite impulse response (FIR) filter. The architecture of noise shaping technique is a kind of feedback filter whose transfer function is similar to a high pass filter. It is used to reshape the white quantization noise to an irregular spectrum, where the quantization noise within the signal band is pushed to the higher frequency band without signal, as shown in Fig. 1(b). We have experimentally demonstrated the transmission of a 56 Gbaud PAM-4 signal over 40-km single-mode fiber (SMF) in the O-band utilizing a 4-bit resolution DAC [8]. The BER performance of signal over OBTB and 40-km SMF transmission is given in Fig. 1(c). With the help of noise shaping, the BER performance of 56 Gbaud PAM-4 signal generated by 4-bit resolution DAC can approximately approach the signal generated by 8-bit resolution DAC both in OBTB and 40-km SMF transmission. Besides, the 4-bit quantization signal with noise shaping achieves 2.8 dB received optical power (ROP) sensitivity improvement compared with the 4-bit quantization signal without noise shaping at the BER of 3.8×10^{-3}. The experimental demonstration [8] shows that the noise shaping technique can effectively reduce DAC quantization bits, and is a practical low-cost solution for future access networks.

3. Sub-Nyquist Sampling Reception Technique

Compared to TDMA-PON based single carrier technique, frequency division multiple access (FDMA) has the advantage of dynamic bandwidth allocation. Therefore, orthogonal frequency division multiplexing (OFDM) as a mature multicarrier technology has been extensively studied in FDM-PONs. However, in OFDM-PON, the data shared to multiple ONUs are aggregated in the optical line terminal (OLT), and the data rate is very high. According to the Nyquist sampling theorem, the sampling rate needs to be at least twice the signal bandwidth to prevent signal aliasing. As a result, the sampling rate of the ADC at each ONU is required to be high, even though only a small part of the subcarriers is needed. With increasing bandwidth requirements, it will be more difficult for each ONU to receive the required data. Under such a background, Cheng L. et al proposed a channel-characteristic-division multiplexing (CCDM) scheme to realize the sub-Nyquist sampling reception of ONUs [9]. In CCDM OFDM-PON, different electrical filters placed in front of the ADCs are designed to provide unique channel characteristics for ONUs. As a special form of CCDM, the delay-division multiplexing (DDM) scheme distinguishes the channel phase response by controlling the sampling delay of the ADC. Nevertheless, these traditional sub-Nyquist sampling reception schemes reduce the requirement of sampling rate but do not reduce the analog bandwidth of an ADC, because all the transmitted subcarriers must be reserved before the spectrum aliasing. Based on Ref. [10], we have investigated an improved optical shaping technique based on Mach-Zehnder modulator (MZM), which can effectively lower the required analog bandwidth of ADC in these sub-Nyquist sampling reception systems.

In sub-Nyquist sampling reception schemes, ONUs are divided into M groups, and each ONU only requires a 1/M Nyquist sampling rate and 1/M FFT size in demodulation. The principle of the sub-Nyquist sampling reception is to generate different channel responses to each ONUs before sub-Nyquist sampling. In this way, different ONUs will receive different aliased signals. By preprocessing the aggregated OFDM signal at the OLT, each ONU can detect the demanded data after corresponding transmission, which is called predictable aliasing. Thus, in traditional schemes, the analog bandwidth of the ADC must be sufficient to achieve spectral aliasing of all transmitted sub-carriers. The idea of optical shaping technique is to perform spectrum aliasing before photoelectric conversion, as shown in Fig. 2(a). Because the periodic pulse signal has harmonic components in the frequency domain, when the OFDM signal is convolved with the periodic pulse signal, sufficient spectrum overlapping can be achieved. Different optical shaping pulses have different transmission performances. We have proposed an improved optical shaping pulse. With the aid of improved shaping pulse, 10-GHz/38-Gb/s DDM OFDM-PON employing 2.5 GHz and 5 GSa/s ADC has been demonstrated [11]. As shown in Fig. 2(b), the simulation result indicated that the proposed scheme is about 0.5 dB penalty in receiver sensitivity at the HD-FEC threshold compared to the traditional DDM scheme. These studies show that the sub-Nyquist sampling reception scheme is a promising way to break the bottleneck of high-speed PON.

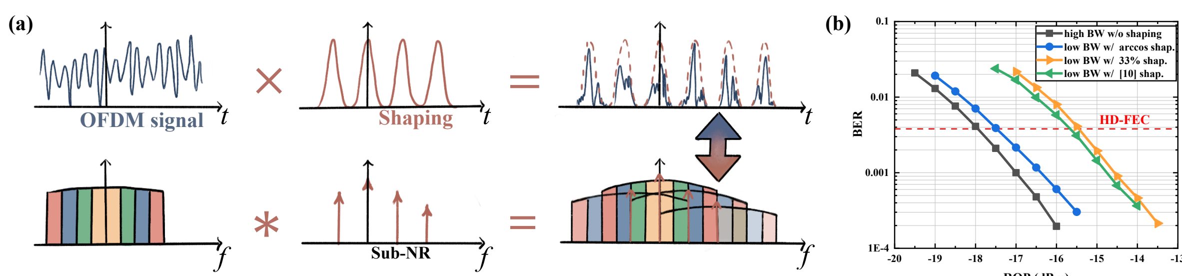

Fig. 2. (a) BER of 50 Gb/s PAM-4 signal versus SOA bias current. (b) BER versus ROP for 50 Gb/s PAM-4 signal over 20-km SMF transmission.

4. Flexible uplink scheme based on FBMC

OFDM stands out from other multicarrier technology because of its dispersion tolerance and equalization simplicity. However, in the uplink direction of the PON network, signals are usually heterogeneous and aggregated with different spectrum occupations. The strict time and frequency requirement of OFDM signals is a major burden on hardware and power consumption. Without synchronization, large guard intervals are required between the adjacent frequency bands, which will significantly reduce the spectrum efficiency. For example, Ref. [12] demonstrates that in the uplink OFDM system with two asynchronous ONUs using 128-IFFT and QPSK modulation formats, a guard interval of up to 25% of the signal bandwidth is required to compensate for the multiple access interference between them. In the real-time implementation, it is also difficult to reduce the out-of-band leakage of OFDM by increasing the IFFT size, which will increase the computational complexity of the hardware and require a larger computation latency.

In this case, non-orthogonal multicarrier technologies such as FBMC are being studied for future PON uplink transmission. The principle of FBMC scheme is to perform a filter-bank with time-frequency well-localized prototype filters to pulse shape the subcarriers [13-14]. As a result, the power of FBMC signal is better concentrated on the subcarrier positions, reducing out-of-band leakage. Compared with OFDM scheme, the guard intervals of FBMC scheme are not necessarily integral multiples of subcarrier spacing, and only a very narrow guard band is needed to avoid multiple access interference between asynchronous ONUs. In addition, FBMC scheme has better robustness against time synchronization errors, which relaxes the synchronization requirements. Due to the requirements of future communications for low power consumption, flexibility in frequency band allocation, low latency and high spectrum efficiency, the uplink scheme based on FBMC and improved network structure will be an important research topic. As shown in Fig. 3, a laser sharing structure combined with FBMC signal can have the characteristics of low cost, good flexibility and backward compatibility.

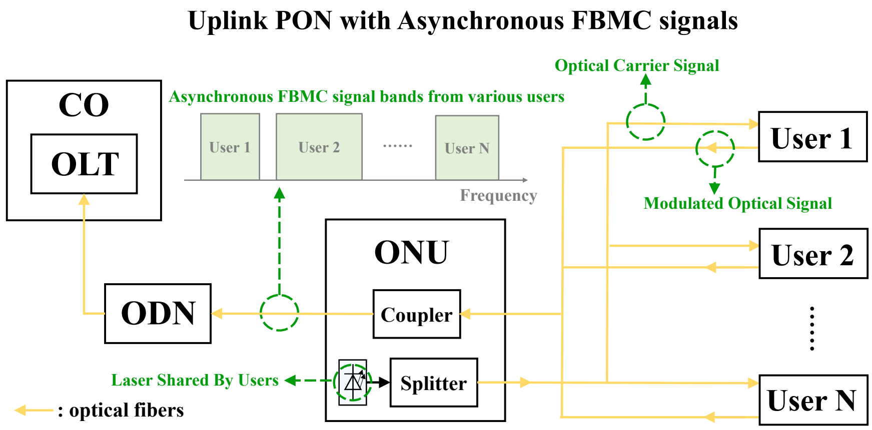

Fig. 3. A flexible laser sharing PON uplink scheme based on FBMC.

5. Conclusion

In conclusion, it has been seen that NG-PON is evolving continuously in the direction of lower cost, higher transmission capacity, and more flexible access. Our research results indicate that the noise shaping technique and sub-Nyquist sampling reception technique may be the promising solution for the next generation access network. In addition, with the tremendous increase in bandwidth demand, an aggregated data rate of 100 Gb/s with a single wavelength will be the goal of NG-PON uplink direction. According to existing research results, FBMC-based PON with large bandwidth is viewed as one of the outstanding uplink strategies.

This work is partly supported by the National Key R&D Program of China (2018YFB1801301); Open Fund of IPOC (BUPT) (IPOC2020A010); Fundamental and Applied Basic Research Project of Guangzhou City (202002030326).

6. Reference

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