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# Bidirectional SSB modulation for Hybrid-PON with source-free optical network units

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**Abstract:** A bidirectional single-side band (SSB) modulation based passive optical network (PON) with source-free optical network units (ONUs) is proposed, where orthogonal frequency division multiple based carrierless amplitude and phase (OFDM-CAP) is employed in the downstream while wavelength division multiplexing (WDM) is utilized in the upstream.
**OCIS codes:** (060.2330) Fiber optics communications; (060.4250) Networks.

## 1. Introduction

Enabled by the next generation vision: work with heterogeneous requirements, effective techniques achieving high data rate connectivity, high flexibility, low cost and low power budget in passive optical network (PON)-based access networks are needed. Orthogonal frequency-division multiple access (OFDMA) [1, 2] thanks to its great flexibility of dynamic bandwidth allocation and its easy upgrade of end users, has been considered as a promising candidate for PONs. In an intensity modulation/direct detection (IM/DD) PON system, OFDMA can be used in the downstream broadcasting channels to achieve good performance with low cost. However, for the upstream, due to each ONU passes through different optical paths, which causes timing offset and optical beating interference [1]. Therefore, WDM are attractive for the upstream. Moreover, to reduce the costs of operation, ease the system installation and maintenance functions, there have been many efforts paid for the optically source-free feature of ONUs in PON systems. The scheme proposed in [3] utilizes an advanced tunable optical frequency comb (OFC) generator to efficiently provide multiple radio-frequency (RF) sources to up-convert the upstream signals. However, the performance of the upstream signal would be decreased due to RF power fading. In [4], a colorless OFDM wavelength division multiplexing passive optical network (WDM-PON) system is proposed, but bias control of the optical external modulator is required to eliminate the unwanted Rayleigh scattering induced noise.

In this paper, we propose a cost-effective bidirectional SSB modulation for Hybrid-PON with source-free ONUs. Orthogonal frequency division multiple based carrierless amplitude and phase (OFDM-CAP) is employed in the downstream, which can effectively support multiusers downstream transmission over a single fiber. In the upstream transmission, the OFC is generated at remote-node (RN) as the upstream source. Moreover, due to the Nyquist pulse-shaped four-level pulse amplitude modulation (NPAM-4) signal has advantages of easy implementation, free of digital-to-analog converter (DAC) and low cost which is employed in the upstream.

## 2. Principles of bidirectional SSB passive optical network architecture

The schematic diagram of the proposed bidirectional SSB modulation for Hybrid-PON with source-free ONUs is shown in Fig. 1. In the optical line terminal (OLT), each independent OFDM signal is first up-sampled (M↑) by a factor M by inserting M-1 zeros between two consecutive samples, and subsequently passes through a digital shaping filter (SF) which property is software reconfigurable. All the generated signals are added together in the

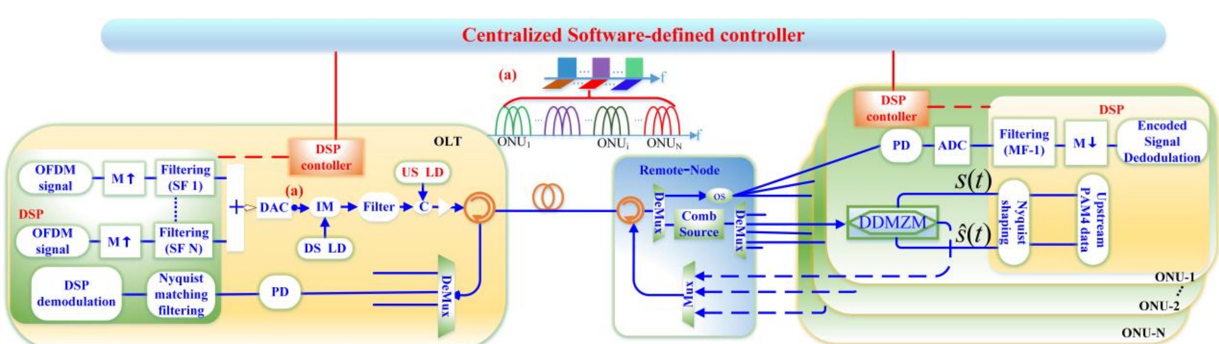


Fig. 1. Bidirectional SSB modulation for WDM-PON with source-free ONUs.

digital domain, thus multi OFDM-CAP are generated which identical to those published in [5]. And input to a single DAC, then fed into an optical intensity modulator (IM), where a continuous wave (CW) laser sources $\lambda_1$ with the frequency of 193.1 THz is used as downstream optical source. Fig. 1 (a) describes the configuration of the combined OFDM-CAP signals, the digital filters and the subcarriers can be dynamically and adaptively allocated to ONUs via SDN-controllable. Next the modulated signal is launched into an optical band-pass filter (OBPF) to generate the downstream SSB signal. After that combined another laser sources $\lambda_2$ with the frequency of 193.2THz is fed into the SSMF and directly transmitted to RN. At the RN, to reduce the cost of WDM-PON system, the $\lambda_2$ is demultiplexed by a WDM de-multiplexer (DEMUX), and a commercial available dual-driver Mach-Zehnder modulator (DDMZM) with a single RF source is utilized to generate the optical frequency comb (OFC) as upstream source as shown in Fig. 2 (a).

At the ONU, the received downstream signal is detected by a photodiode (PD) which transforms the optical signal into an electrical signal. And after optical-to-electrical conversion, a corresponding matching filter (MF) which has the inverse impulse responses of the SF is used, and the signal is further down-sampled (M↓) and de-multiplexed in digital signal processors (DSPs). The two discrete impulse responses of the SF forming a Hilbert-pair are given by

$$h_I(t)=\frac{\sin[\pi(1-\beta)\frac{t}{T_s}]+4\beta\frac{t}{T_s}\cos[\pi(1+\beta)\frac{t}{T_s}]}{\pi\frac{t}{T_s}[1-(4\beta\frac{t}{T_s})^2]}\cos(2\pi f_i t) \tag{1}$$

$$h_Q(t)=\frac{\sin[\pi(1-\beta)\frac{t}{T_s}]+4\beta\frac{t}{T_s}\cos[\pi(1+\beta)\frac{t}{T_s}]}{\pi\frac{t}{T_s}[1-(4\beta\frac{t}{T_s})^2]}\sin(2\pi f_i t) \tag{2}$$

Meanwhile, NPAM-4 signal and its Hilbert transform term with small amplitude are used to drive the DDMZM which is biased at its quadrature point to generate the optical SSB NPAM-4 upstream signal [6]. Then the upstream signal is transmitted back to the OLT for performance evaluation.

### 3. Simulation setup and results

We perform a simulation demonstration to verify the feasibility of the bidirectional SSB modulation for Hybrid-PON with source-free ONU, by using Virtual Photonics Incorporated Transmission Maker (VPI TM 9.0) with co-simulations of Matlab. Firstly, in the OLT, two independent real-valued OFDM baseband signals are generated with modulation formats of 16-QAM and the total number of data-bearing subcarriers is 127, while FFT size of 256 is used. The cyclic prefix (CP) of 0.125 is inserted into each of OFDM signals. The central frequency of SF pair $f_i = 3\times f_{DAC}/2/M$ is employed. An oversampling factor of $M = 8$ is considered to evaluate the impact of the overall system performance. For this adopted oversampling factor, the digital filter length of L= 32 is employed. The each channel optical power launched in the OLT node is fixed at 8 dBm. The two light sources with linewidth of 2 MHz are used. The PD has a responsivity of 0.8 A/W and a thermal noise of 20 pA/(Hz)$^{0.5}$. The sampling rate $f_{DAC}$ and the resolution of DAC are 12 GSa/s and 7 bits, respectively. The 12 GHz RF signals are utilized to drive DDMZM. Then, the five optical frequency combs with 12 GHz spacing and 2 dB flatness is illustrated in Fig. 2(b).

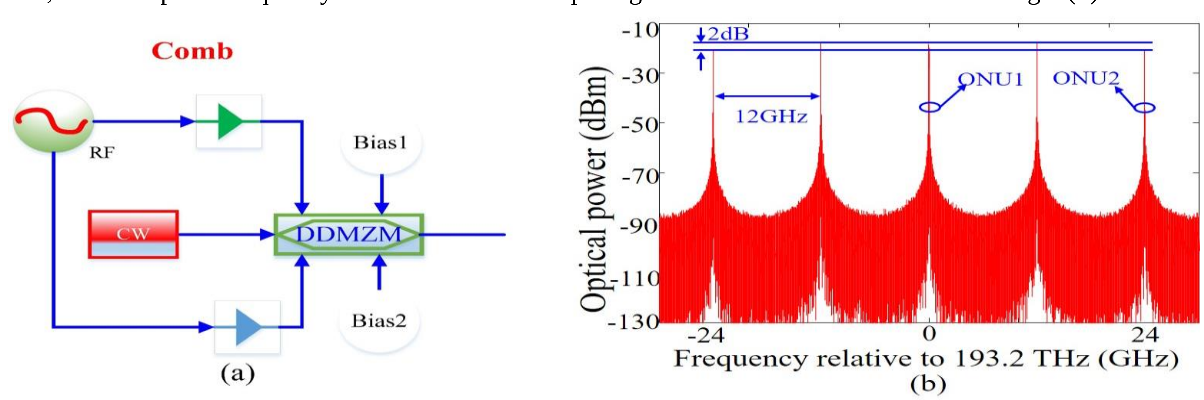


Fig. 2. (a) The schematic diagram of generating OFC with DDMZM; (b) the generated OFC with a frequency separation of 12 GHz.

Moreover, in the practical access networks, the filters and the subcarriers allocation can be adjusted dynamically and adaptively via SDN-controllable according to the traffic and actual transmission link characteristics of users, and bit loading technique can also be employed to increase the transmission throughout [7].

Fig. 3(a) shows the bit-error-rate (BER) performance against the received optical power for the downstream signal. As expected, the BER decreases with an increase of the received optical power and a received optical power of -16 dBm is needed to reach the hard-decision forward-error-correction (HD-FEC) threshold (BER = $3.8\times10^{-3}$) in the downstream signal. The differences of BER performance for downstream data to ONU-1 and ONU-2 are mainly attributed to frequency response of the employed filters [5]. And after 40 km SSMF, the received 16QAM constellations have been effectively recovered

Fig. 3(b) depicts the BER performance versus the received optical power of upstream signal after 25km and 40km SSMF transmission, respectively. Here, the receiver sensitivities for data from ONU-1 and ONU-2 are -17.5 and -17 dBm at the BER of $10^{-3}$ at 25km fiber transmissions, respectively. And the power penalty for 25km and 40 km transmissions is less than 0.7 dB at a BER of $10^{-3}$.

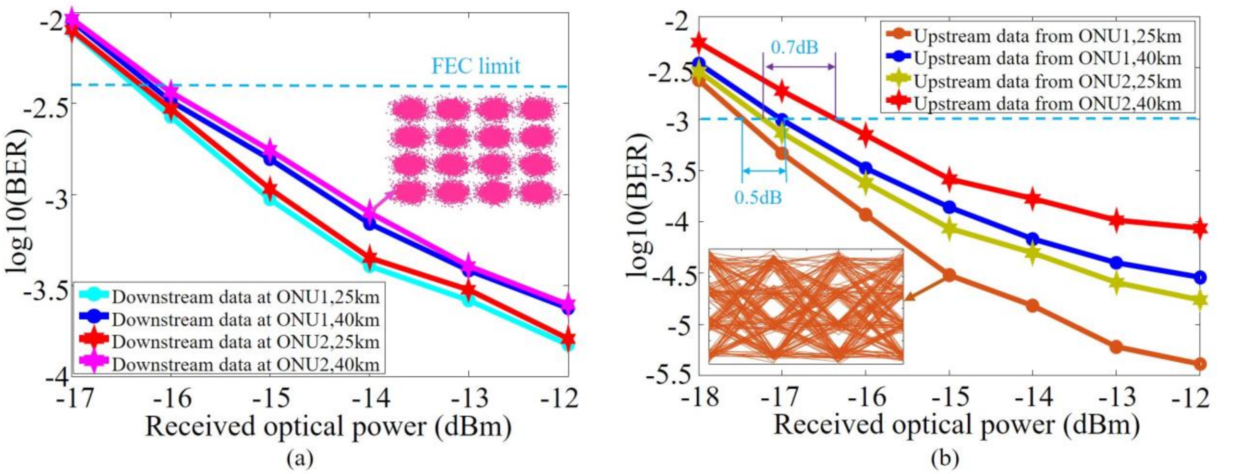


Fig.4. BER performance versus the received optical power; (a) for downstream signal, (b) for upstream signal.

## 4. Conclusions

We have proposed and investigated bidirectional SSB modulation for Hybrid-PON with source-free ONUs, in which the SSB modulation is employed to both downstream and upstream_transmissions, and the cost-effective OFC was generated at RN as the upstream source. In addition, the results indicated that power penalty of upstream signal for 25 km and 40 km transmissions is less than 0.7 dB at a BER of $10^{-3}$. Consequently, the proposed bidirectional SSB modulation for Hybrid-PON with source-free ONUs is cost-effective, and can reduce the complexity of the ONUs. It is promising for application in the next generation broadband optical access networks.

## 5. Acknowledgement

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