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Efficient carrier-reuse for intensity modulation and direct detection passive optical networks with Rayleigh backscattering noise circumvention

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Abstract. We propose an efficient carrier-reuse scheme for intensity modulation and direct detection (IM/DD) passive optical networks (PONs) with Rayleigh backscattering (RB) noise circumvention. In our proposed system, the number of light sources is halved since no extra light sources are required for the upstream (US) transmission, and the RB noise is eliminated without using any high cost ultra-narrow filter or coherent detection. The proposed scheme efficiently utilizes orthogonal frequency division multiplexing-based carrierless amplitude and phase modulation in the downstream, where signal multiplexing and demultiplexing are performed by digital filtering. Meanwhile, the high spectrum efficiency optical single-side band (SSB) Nyquist pulse-shaped pulse amplitude modulation-4 signal is generated by utilizing dual-drive Mach-Zehnder modulator in the US. In addition, the effect of phase-to-intensity conversion of the laser phase noise on bidirectional SSB systems over 25-km standard single-mode fiber on bit error rate performance is evaluated. Results successfully verify the feasibility of our proposed efficient carrier-reuse scheme for IM/DD PONs. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.57.6.066113](https://doi.org/10.1117/1.OE.57.6.066113)]

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1 Introduction

Compared with coherent detection, direct detection (DD) has many advantages, such as lower cost and easier integration; thus, it is more attractive for cost-sensitive passive optical networks (PONs). Recently, the orthogonal frequency division multiplexing-based carrierless amplitude and phase (OFDM-CAP) modulation technique has been widely proposed for PONs based on intensity modulation (IM) and DD,^{1–4} due to its potential of not only providing the next generation PONs with excellent network operation reconfigurability, flexibility, elasticity, and adaptability but also offering highly desirable backward compatibility with current PON standards. In addition, the pulse amplitude modulation (PAM) technique has the advantages of easy implementation, low cost, and high power efficiency, which is preferred to be implemented in the optical access network systems.^{5–8} Moreover, with the fifth-generation (5G) mobile being the most disruptive technology that might drive the future PON system standard, next-generation optical access networks are not all about bandwidth, and the requirements on future access networks for 5G wireless communication after long-term evolution advanced (LTE-A) are currently being discussed. Future generation of broadband optical access is expected to support a diversity of customers, including residential, enterprise/community, and 5G mobile networks. To meet the increasing bandwidth demands, several techniques have been proposed to enable higher data

rate in PONs, such as wavelength division multiplexing (WDM)-PONs⁹ and OFDM-based PONs.^{10,11}

So far, there have been many efforts paid for exploring more-advanced low-cost PON architectures with source-free optical network units (ONUs) utilizing lightwave centralization or signal remodulation approaches. However, single-fiber bidirectional PON systems have two critical issues: the intrinsic Rayleigh backscattering (RB) noise and the signal remodulation crosstalk. In Refs. 12–14, DD is used for downstream (DS) and coherent detection is considered for upstream (US) so as to mitigate the impact of RB and remodulation crosstalk. In Ref. 15, simulation study has demonstrated the effectiveness of high speed bidirectional signal transmission in a WDM-PON system with upper sideband for DS transmission and lower sideband for US transmission, but such a system employs a traditional gain-saturated reflective semiconductor optical amplifier at ONU to realize the US transmission, which requires high received power in the ONU and will shrink the power margin. In Refs. 16 and 17, two colorless ONUs have been proposed, in which an extra centralized continuous wave (CW) light source transmitted from the optical line terminal (OLT) is utilized as a seed light of US data. However, the employment of the extra CW light source in OLT introduces the extra cost.

In view of all these works, we propose and demonstrate an efficient carrier-reuse scheme in cost-effective IM/DD PON systems with RB noise circumvention. In our proposed PON system, OFDM-CAP modulation is employed in the DS,

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where signal multiplexing and demultiplexing are performed by digital filtering. Meanwhile, optical single-side band (SSB) Nyquist pulse-shaped PAM-4 (NPAM-4) signal is generated with a low cost dual-drive Mach-Zehnder modulator (DDMZM) in the US. Compared with the ordinary SSB signal generation process using an amplitude modulator (e.g., electro absorption modulator) and an optical filter, it is more efficient to use a single DDMZM. The DS and US signals are transmitted by the lower and upper sidebands of the SSB signal, respectively. Moreover, the RB noise and the signal remodulation crosstalk are circumvented without using any expensive ultra-narrow optical filters. Since RB component and the US signal occupy different spectral regions, the RB noise can be significantly reduced by using the tunable filter in the OLT. Moreover, the impact of phase-to-intensity conversion of the laser phase noise on the performance of this IM/DD carrier-reuse PON is also evaluated.

2 Principle

The schematic diagram of the proposed efficient carrier-reuse scheme for IM/DD PON systems with RB noise circumvention is depicted in Fig. 1. At the OLT, two OFDM channels are multiplexed/demultiplexed in the digital domain by using a pair of orthogonal digital filters, and thus, these two signals occupy the same spectral region. For each channel, an independent OFDM signal is first upsampled ($M \uparrow$) by a factor M by inserting $M - 1$ zeros between two consecutive samples, and subsequently passes through a digital shaping filter,¹ which, in time domain, can be expressed as follows:

$$h_I^i(t) = g(t) \cos(2\pi f_i t), \quad (1)$$

$$h_Q^i(t) = g(t) \sin(2\pi f_i t), \quad (2)$$

where f_i is the central frequency of the digital filters, $g(t)$ is the baseband pulse with the square-root raised-cosine (SRRC) function, which can be expressed as follows:

$$g(t) = \frac{\sin\left[\pi(1-\beta)\frac{t}{T_s}\right] + 4\beta\frac{t}{T_s}\cos\left[\pi(1+\beta)\frac{t}{T_s}\right]}{\pi\frac{t}{T_s}\left[1 - \left(4\beta\frac{t}{T_s}\right)^2\right]}, \quad (3)$$

where T_s is the sampling period prior to oversampling and β is the parameter that controls the excess of bandwidth of the SRRC function.

After being digitally filtered, the two independent OFDM-CAP signals are generated at the outputs of the SFs, which are then added together in the digital domain and delivered to a single digital-to-analog converter (DAC). An intensity modulator biased at the quadrature point is used to perform the electrical-to-optical conversion. The SSB signal is produced via a lower offset filter (filter 1), which removes the upper side-band of the generated double side-band signal. Then, the optical SSB signal passes through a WDM multiplexer before it is launched into the standard single-mode fiber (SSMF).

At the ONU side, the signal is demultiplexed via a WDM demultiplexer after the transmission over the SSMF. In each ONU, the received DS SSB signal is divided into two identical parts. One part is detected by a photodetector (PD), which transforms the optical signal into an electrical signal. After that, two corresponding matching filters with their impulse response satisfying $\{m_I(t) = h_I(-t)$ and $m_Q(t) = h_Q(-t)\}$ are used to digitally demultiplex the two OFDM signals, and subsequently, the digitally filtered signal is downsampled ($M \downarrow$) and demodulated in digital signal processors (DSPs). The other part of the optical SSB signal is used to extract the optical carrier by passing through an upper offset filter (filter2), which is not necessarily narrower than the frequency gap between the two sidebands. Then, the extracted optical carrier is reused as the US optical source and fed into the DDMZM to perform the US signal modulation. The DDMZM is biased at quadrature point and its two driving signals are a pair of Hilbert signals coded with NPAM-4 signal.¹⁸ Therefore, the SSB NPAM-4 signal is produced, which can be approximated as follows:

Fig. 1 Block diagram of the proposed source-free ONUs in IM/DD PONs with simple RB noise circumvention. (a)–(f) The corresponding optical spectra.

$$E_{T,US}(t) = \frac{E_{in}(t)}{2} \left[1 - j + \frac{\pi}{V_{\pi}} (s(t) + j\hat{s}(t)) \right], \quad (4)$$

where $E_{in}(t)$ denotes the extracted optical carrier, $s(t)$ is the electrical baseband NPAM-4 signal, $\hat{s}(t)$ is its Hilbert transform, and V_{π} is the half-wave voltage of the DDMZM. In the bidirectional PON system, both DS and US signals are affected by the RB. The received DS signal can thus be represented by

$$E_{R,DS}(t) = E_{T,DS}(t) + K_{US}E_{T,US}(t), \quad (5)$$

where K_{US} and $E_{T,DS}(t)$ are the RB coefficients of the US signals and the DS transmitted signals, respectively.

Meanwhile, at the OLT, when ignoring the signal transmission impairments, the received SSB signal with the RB interference can be written as follows:

$$E_{R,US}(t) = \frac{E_{in}(t)}{2} \left[1 - j + \frac{\pi}{V_{\pi}} (s(t) + j\hat{s}(t)) \right] + K_{DS}E_{T,DS}(t), \quad (6)$$

where K_{DS} is the RB coefficient of the DS signals. Since the US and DS signals occupy different frequency components, the second term in Eq. (6) can be partially removed via the tunable Gaussian bandpass filter (BPF; filter3). After optically filtered by filter3, only a single PD can be utilized to transform the optical NPAM-4 signal into electrical NPAM-4 signal. Therefore, our proposed PON architecture uses a simplified transceiver in both ONU and OLT. In addition, the signal multiplexing and demultiplexing are executed in DSPs, resulting in significant complexity reduction, which is valuable for cost-sensitive PON systems. Nevertheless, the phase noise introduced by the CW laser will affect the system performance due to the combining effect of the chromatic dispersion and the spectrum boarding, which can be modeled by a Wiener process^{19,20} with zero mean and variance of $t\Delta\nu/(2\pi)$, where t represents the time and $\Delta\nu$ is the laser linewidth.

3 Simulation Results and Discussion

We first perform a simulation demonstration to verify the feasibility of the proposed efficient carrier-reuse scheme for IM/DD PON systems with RB noise circumvention, by using Virtual Photonics Incorporated Transmission Maker (VPI TM 9.0) cosimulated with MATLAB software. First, in the OLT, two independent real-valued OFDM baseband signals are generated using 16-QAM and the total number of data-bearing subcarriers is 127, while the FFT size of 256 is adopted. The cyclic prefix of 0.125 is inserted into each of the OFDM signals. The sampling rate $f_{DAC/ADC}$ and the resolution of DAC/ADC are 12 GSa/s and 7 bits, respectively. The data rates of the DS and US signals are 5.3 and 11.04 Gb/s, respectively. The laser at 1553.6 nm is used in the OLT as a light source. An oversampling factor $M = 8$ is considered in this paper to evaluate the impact of the overall system performance. For this adopted oversampling factor, the digital filter tap count $L = 32$ is employed. The central frequency of the digital orthogonal filters equals to $f_i = 5 \times f_{DAC}/2/M$. The optical power launched in the OLT is fixed at 10 dBm to reserve the optical power for US transmission. At the ONU, a pseudorandom bit sequence

with 2^{20} bits is used for PAM-4 modulation, which is upsampled to 2 sample per-symbol. The Nyquist filter with a roll-off factor of 0.01 is applied to generate the NPAM-4 sequence and its Hilbert term is generated by the Hilbert transform. The PDs have a responsivity of 0.8 A/W and a thermal noise of $10 \text{ pA}/(\text{Hz})^{0.5}$. Both filter1 and filter2 are Gaussian BPFs with 16-GHz bandwidth and a filter order of 5. The center frequency offsets of filter1 and filter2 are 7 GHz relative to the carrier frequency.

First, to study the impact of nonlinearities introduced by the DDMZM in the DS traffic, we consider the modulation index (MI) of the SSB-OFDM-CAP signal applied to the DDMZM arms. The MI is defined as follows:

$$\text{DDMZM}_{MI} = \frac{\pi V}{2V_{\pi}}, V = \max\{|d(t)|\}, \quad (7)$$

where $d(t)$ is the voltage of the OFDM-CAP signal. The BER performance of signal employing filter $h_i(t)$ as the function of MI is shown in Fig. 2. Among all these results, the MI of ~ 0.44 shows the best performance. It should be emphasized that different MIs are considered mainly to identify the range of the MI that leads to relatively small modulator distortion. In the following simulations, the MI of the DS traffic is set at 0.44 and the MI of the US traffic is also optimized.

Figure 3(a) shows the spectrum for a $\Delta\nu = 0$ at the position (c), as indicated in Fig. 1. The filter2 detuning is defined as $\Delta d = f_c - f_B$, where f_c and f_B are the central frequency of the carrier and the frequency of the low-pass equivalent of the filter2, respectively. Figure 3(b) shows the performance of the US signal after 25-km SSMF transmission concerning the filter detuning and bandwidth. The system performance is affected by the bandwidth of the filter2. For the bandwidth of 16 GHz, the optimum detuning is around 1 GHz. For the bandwidth of 15 GHz, the optimum detuning increases to the values around 1.5 GHz. In addition, for a fixed bandwidth (such as 15 GHz), the $\log_{10}(\text{BER})$ tolerance to the Δd variation is very high, and it can be seen that a Δd variation higher than 1.5 GHz leads to a $\log_{10}(\text{BER})$ degradation less than 0.8.

Figure 4 shows the BER performance as a function of the received optical power. Figure 4(a) illustrates the US transmission performances for different $\Delta\nu$ with/without filter3. It indicates that: (i) the transmission performance variation with/without filter3 is negligible for $\Delta\nu$ of 1 or 20 MHz,

Fig. 2 BER performances as a function of MIs, the received optical power is fixed at -10 dBm .

Fig. 3 (a) Spectrum for a $\Delta\nu = 0$ at the position (c), as indicated in Fig. 1, after 25-km SSMF transmission. (b) Optimum filter2 detuning as a function of the bandwidth for a $\Delta\nu = 0$. Vertical lines represent ranges of the optimum filter detuning that lead to the $\log_{10}(\text{BER})$ degradation relative to the optimum $\log_{10}(\text{BER})$ not exceeding 0.8.

Fig. 4 BER performance as a function of the received optical power: (a) US transmission for different $\Delta\nu$ with/without filter3 and (b) DS transmission for different $\Delta\nu$.

which implies that the impact of the RB noise after 25 km transmission is not very noticeable and (ii) due to the laser phase noise effect, 1-dB power penalty is observed at the BER of 1×10^{-3} for the case excluding the filter3 when $\Delta\nu = 1$ MHz and $\Delta\nu = 20$ MHz. As can be seen in Fig. 4(b), for the DS signals adopting the filter of $h_I(t)$ after being transmitted over 25-km SSMF, the receiver sensitivities at the forward-error-correction (FEC) limit of $\text{BER} = 3.8 \times 10^{-3}$ are approximately -15.8, -15.5 and -14 dBm, when $\Delta\nu = 1, 2$, and 5 MHz, respectively. The

differences of receiver sensitivity for DS data are mainly because of the laser phase noise. Next, the CW with line-width of 2 MHz is employed in the following simulations to evaluate the performance of system.

Figure 5(a) shows the calculated BER performance against the received optical power for the DS signal. As expected, the BER performance improves with increasing of the received optical power and a received optical power of about -15.4 dBm is efficient to reach the FEC threshold. The differences of BER performance for DS data with filter

Fig. 5 BER performance versus the received optical power (a) for DS signal with different number of digital filter taps and (b) for US signal with different optical filter orders.

h_I and h_Q are mainly attributed to the imperfect frequency response of the employed filters.¹ The BER performance can be further improved when increasing the number of the filter's taps because of the large tap count-induced flatness of the channel frequency response. Figure 5(b) depicts the BER performance versus the received optical power of US signal with different optical filter orders K . The BER performance improves obviously when increasing the optical filter order, due to the flattened optical filter frequency response. The power penalty for optical filter order $K = 4$ and 7 is about 0.5 dB at a BER of 3.8×10^{-3} .

4 Experimental Results and Discussion

We also conduct an experiment to test the system performance of the proposed efficient carrier-reuse scheme for IM/DD PON systems with RB noise circumvention. Figure 6 depicts the experimental setup. At both the OLT and ONU, independent US and DS signals are generated offline by MATLAB. The parameters used for OFDM-CAP signals and NPAM-4 signals are the same to those in the previous simulations. The external cavity lasers at 1550 nm are employed as the light sources. Two arbitrary waveform generators (AWG700002A) operating at 12 GSa/s (the highest sample rate of 25 GSa/s) to generate 5.3 Gb/s (11.04 Gb/s) for DS and 12 Gb/s (25 Gb/s) for US. At the OLT, the electrical signal from AWG1 is modulated by an MZM biased at its quadrature point, and an optical SSB filter with 15-GHz bandwidth and the center frequency offset of 5 GHz relative to the carrier frequency are employed to remove one sideband. Before being launched into standard SSMF, the optical signal is boosted by an erbium-doped fiber amplifier to reach

the optical power of 10 dBm. After fiber transmission, one part of the DS signal is first detected by a commercial PD with 10 GHz 3-dB bandwidth and subsequently sampled by a digital processing oscilloscope at a sampling rate of 50 GSa/s and finally processed offline by MATLAB while the other part is first fed into an optical band-pass filter (OBPF) with 15-GHz bandwidth and an offset of 5 GHz relative to the carrier frequency, and then fed to the DDMZM to generate the SSB NPAM-4 US signal. The generated US SSB NPAM-4 signal is amplified and its optical launched power is -3 dBm. At the OLT receiver, the channel is first optically filtered by an OBPF. After DD, the electrical signals are sampled by a digital scope at 50-GSa/s for offline processing.

Figure 7 shows the measured BER versus received optical power after 25-km SSMF transmission. As we can see, the minimum received optical power of about -10 dBm is required to reach the FEC limit at a bit rate of 11.04 Gb/s for the DS transmission signal. The insets of Fig. 7(a) show the corresponding 16-QAM constellations for 11.04 Gb/s DS signal. For the US transmission, the received optical power of approximately -14 dBm is needed to reach the FEC limit at a bit rate of 25 Gb/s. Moreover, the power penalty for US transmissions of 12 and 25 Gb/s is about 1 dB at a BER of 3.8×10^{-3} . Hence, these results show that the US/DS communications have been realized successfully in the proposed system. It can also be found from Figs. (5) and (7) that, compared with the simulation results, power penalties of about 2.5 and 3.5 dB are obtained in the experimental measurements for DS and US transmissions respectively, which is mainly due to the inherent hardware impairments, such as the modulator and the detector.

Fig. 6 Experiment setup of the source-free ONUs in IM/DD PONs with simple RB noise circumvention.

Fig. 7 BER performance versus the received optical power for: (a) DS and (b) US.

5 Conclusions

We have proposed and demonstrated a carrier-reuse based IM/DD PON system together with RB noise mitigation, where the DS signal multiplexing and demultiplexing are performed by digital filtering, while the US effectively employs the SSB PAM4 modulation. Moreover, RB noise and remodulation interference have been circumvented without using any ultra-narrow filters. In addition, the effect of the laser phase noise resulting in the performance penalty of the proposed system has been evaluated for different laser linewidths. Both the DS and US BERs, even with inexpensive lasers with a linewidth of 2 MHz, are still below the FEC threshold when the received optical power is more than -15 dBm, which implies that the proposed system is a potential candidate for next-generation broadband optical access networks.

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Biographies for the authors are not available.