OFDM Remodulation for 10-Gb/s/channel WDM-PON with Simple Carrier Extraction and Enhanced Tolerance to Rayleigh Noise

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Abstract: A novel OFDM-remodulation scheme for 10-Gb/s/channel WDM-PON is proposed and numerically investigated. Negative remodulation penalty is achieved without using any ultra-narrow filter or coherent detection. 40-km single-fiber bidirectional transmission is confirmed with 7-dB power margin.
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1. Introduction

Foreseeing the rapidly growing demand for multimedia services and the trend of service convergence, optical access network is an ultimate solution to break the last-mile bottleneck imposed by the 100-year-old copper network. Compared to other optical access architectures that employ power splitting at the remote node (RN), the wavelength-division-multiplexed passive optical network (WDM-PON) is a promising solution for the next-generation optical broadband access that requires large dedicated and symmetric bandwidth, data privacy, and upgrade flexibility. Remodulating downstream signal to generate upstream signal is an attractive solution for low-cost implementation of WDM-PON, as it halves the required wavelengths and eliminates the need of wavelength-specific transmitters and wavelength management at the optical network unit (ONU). Two dominant limiting factors exist in such a wavelength-reused WDM-PON: the remodulation crosstalk and the intrinsic Rayleigh backscattering (RB) noise in single-fiber bidirectional systems [1,2]. Very intensive studies have been carried out to tackle both challenging issues. A number of schemes that can effectively mitigate the remodulation crosstalk by using different modulation formats in downstream and upstream are still vulnerable to RB noise, and thus need dual feeder fibers in [3,4]. Only a few reported schemes are robust to both, remodulation crosstalk and RB noise, by using subcarrier modulation or optical phase remodulation [5,6]. However, these approaches are constrained by poor dispersion tolerance and/or asymmetric bit rates. Orthogonal frequency-division multiplexing (OFDM) with high spectrum efficiency and resistance to linear dispersion has been widely incorporated in commercial copper-based digital subscriber line (DSL) systems, and now is being considered as a strong candidate for optical access networks [7,8]. In particular, it offers new opportunities to reduce the remodulation crosstalk in WDM-PON, by either ONU-side carrier extraction using ultra-narrow filter [9] or OLT-side signal extraction using coherent detection [7]. However, the RB-induced problem yet has not been solved in both schemes.

In this contribution, we propose a novel OFDM remodulation-based WDM-PON architecture that can simultaneously circumvent both, remodulation crosstalk and RB noise, without using any ultra-narrow filter or coherent detection. The upper and lower single-sideband (SSB) OFDM signals are used in downstream and upstream, respectively, resulting in reduced spectral overlap between signal and RB noise. Thus the RB noise can be significantly mitigated by an offset filter that coincides with the desired signal. In addition, very high-quality optical carrier for upstream remodulation can be extracted from the downstream SSB OFDM signal at ONU by a normal 20-GHz bandpass filter (BPF) with 10-GHz center offset. Interestingly, we even observe a negative remodulation penalty due to laser noise reduction during carrier extraction. Complicated modulators to generate single-carrier SSB signal for RB noise suppression as in [10] are not needed in the proposed scheme.

2. Proposed OFDM remodulation-based WDM-PON architecture

Fig. 1 illustrates the proposed lightwave-centralized WDM-PON architecture using SSB OFDM signal in both downstream and upstream. The roles played by four BPFs (BPF1 – BPF4) are essential in understanding the operation principle of the proposed scheme. BPF1 and BPF2 are identical and are upper offset, whereas BPF3 and BPF4 are identical and are lower offset. BPF1 is used to form the upper-SSB downstream OFDM signal from the generated double-sideband (DSB) signal by a Mach-Zehnder modulator (MZM). BPF2 and BPF4 are used to remove the RB noise from the desired signal, which is enabled by using different sidebands in downstream and upstream, respectively. BPF3 is simultaneously used to extract the optical carrier from the downstream SSB OFDM

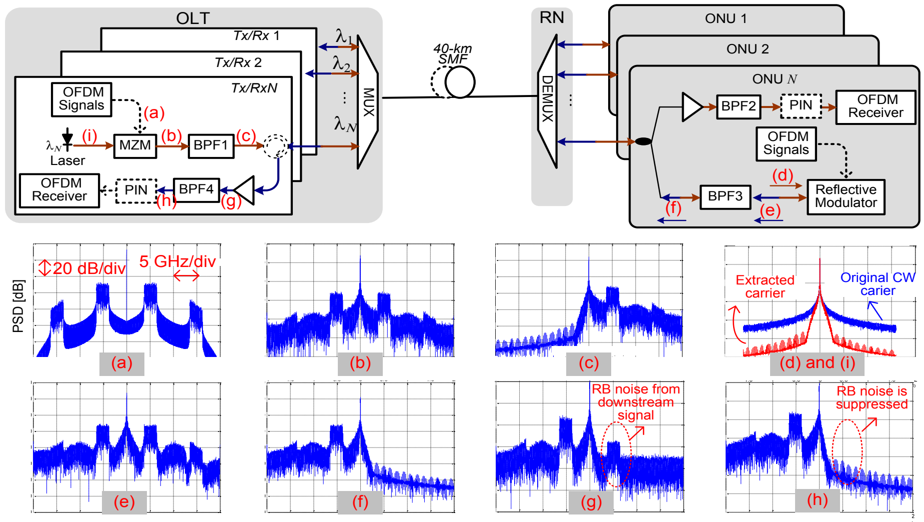

Fig. 1: Proposed lightwave centralized WDM-PON architecture using upper and lower sideband OFDM signal in downstream and upstream, respectively. Insets (a)-(h): simulated power spectral density (PSD) corresponding to point (a)-(h) marked in the architecture.

signal and to form the lower-SSB upstream OFDM signal. Unlike the ultra-narrow filters (sophisticated wave shaper or wavelength selective switch) used in previous schemes for carrier extraction [8,9], the BPF3 here is not necessarily narrower than the frequency gap between the two sidebands. Actually, the narrow BPF required for carrier extraction in the proposed scheme is logically performed by the pass-band intersection between BPF1 and BPF3. For BPF2 and BPF3, BPFs with periodic frequency response are desirable to assure a colorless ONU. Note that it is possible to replace ONU splitter, BPF2 together with BPF3 with an optical interleaver to further simplify the ONU structure. Similarly, the OLT circulator, BPF1 and BPF4 could also be replaced by an optical interleaver.

3. Performance on carrier extraction and RB noise suppression

We have numerically investigated one channel of the proposed scheme based on the architecture shown in Fig. 1. At the OLT, 1550-nm continuous-wave (CW) light with a linewidth of 5 MHz is coupled into a MZM driven by a real valued 16-QAM OFDM signal, which is generated by using a complex conjugate extension for the input to IFFT. The parameters of the OFDM signal as shown in inset (a) of Fig.1 are: input data stream of PRBS 2^{16}-1, bit rate of 10.7 Gb/s including 7% overhead for FEC, IFFT size of 2048, subcarrier number of N=256, frequency gap of 3.75 GHz. An RLC BPF (natural frequency=6 GHz, Q=1) is used after the DAC to suppress aliasing spectra. The MZM is biased at 0.5 $V\pi$ and the driving OFDM signal has a peak-to-peak amplitude of around 0.7 $V\pi$. Inset (b) of Fig.1 shows the power spectral density (PSD) of the DSB output from the MZM, which is further reshaped by BPF1 to form a SSB OFDM signal as shown in inset (c) of Fig.1. Four 20-GHz fifth-order Gaussian BPFs (insertion loss of around 3 dB) are used as BPF1-BPF4. The frequency offset of BPF1 and BPF2 is 10 GHz relative to the carrier frequency whereas the center frequency offset of BPF3 and BPF4 is -10 GHz. 40-km bidirectional transmission over single fiber, involving RB noise, is emulated by transmitting bidirectional signals in two fibers respectively and adding RB noise in each direction. At ONU, the bidirectional BPF3 and the following reflective transmitter that generally can provide simultaneous signal modulation and amplification, are emulated by an erbium-doped fiber amplifier (EDFA) and a MZM which is sandwiched between two identical BPFs (same as BPF3). The extracted carrier by the former BPF, as shown in inset (d), is modulated by the MZM to generate a double-sideband OFDM signal in inset (e). The upstream electrical OFDM signal has the same property as the downstream one and the upstream MZM is also biased at 0.5 $V\pi$. The later BPF selects the lower sideband as the upstream signal shown in inset (f). As the downstream transmission is straightforward and has the same principle in RB noise reduction, we focus our investigation on the upstream transmission. To investigate the performance on carrier extraction, first the RB noise is not involved. Noise-related parameters for EDFAs and positive-intrinsic-negative (PIN) receivers are involved in simulation according to common commercial products. Fig. 2 shows the BER results for the upstream signal measured by Monte-Carlo simulation using 10^6 bit. Compared with the back-to-back (B2B) case, 2-dB power penalty is observed after 40-km transmission in single mode fiber (SMF). The power penalty can be further reduced by using cyclic prefix and channel equalization that are not involved in the simulation. An interesting point is that compared with using an additional ONU laser (same as the OLT laser) as the upstream source, a negative power penalty (-2 dB at BER=10^{-3}) is observed for the upstream signal modulated on the extracted carrier in B2B case, as

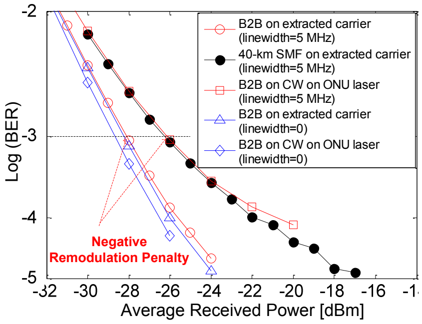

Fig. 2: BER for the upstream signal.

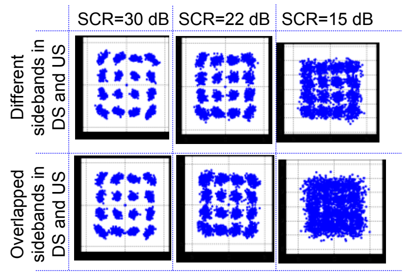

Fig. 3: Upstream constellations under different SCR levels. DS: downstream. US: upstream.

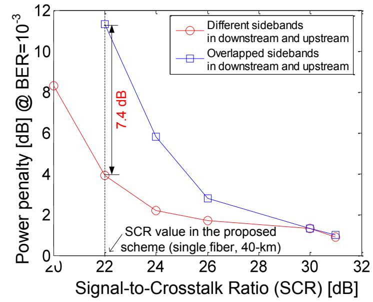

Fig. 4: Upstream power penalty ($BER=10^{-3}$) as a function of SCR

shown in Fig. 2. It attributes to the reduction of laser's white frequency noise by the optical filtering for carrier extraction [11]. Compared with the original CW light at OLT, noise reduction in the extracted carrier (with identical power as the OLT laser for fair comparison) at ONU is clearly illustrated in insets (d) and (i) of Fig.1. To confirm this explanation, we set the linewidth to be zero for the CW light at OLT. In this case the remodulation-induced power penalty is changed from -2-dB to +0.3 dB. We then investigate the RB-noise tolerance of the proposed scheme. Part of the downstream (upstream) signal is decorelated and used as the RB noise in the upstream (downstream) signal, which yields a worst-case estimation on the impact of RB noise [12]. In the proposed scheme RB noise resides in a different sideband from signal and thus can be significantly reduced by a BPF that coincides with the desired signal, as shown in insets (g) and (h) of Fig.1. Compared with using overlapped sidebands in downstream and upstream, the enhanced tolerance of the proposed scheme is apparently observed in Fig.3, which depicts the upstream constellations when the signal-to-crosstalk ratio (SCR) varies. The upstream power penalty ($BER=10^{-3}$) at different SCR levels is shown in Fig. 4. In this study we assume the lengths of feeder and distribution fibers are 35 km and 5 km, respectively. Then the RB reflection coefficients of the downstream and upstream signals can be calculated as -31.7 dB and -35.9 dB, respectively, with the difference being induced by the insertion loss of RN. In simulation, the downstream and upstream feeding powers (to fiber) are set to be -1dBm and 1 dBm, respectively, implying an around 22-dB SCR in both directions with considering the 3.5-dB loss at RN and 8-dB fiber loss. According to Fig. 4, this SCR level will induce 4-dB power penalty using the proposed scheme, which is improved by 7.4 dB compared with that using overlapped sidebands in downstream and upstream. The minimum required power for a BER lower than the FEC threshold is -26 dBm according to Fig. 2 and the received power before the upstream receiver module is around -15 dBm, implying a 7-dB system margin with RB noise being taken into account.

4. Conclusions

We propose a novel OFDM remodulation scheme that can simultaneously circumvent both remodulation crosstalk and RB noise in lightwave centralized WDM-PON. High-quality optical carrier, enabling a negative remodulation penalty (-2dB), is extracted without using any ultra-narrow filter or coherent detection. Single-fiber bidirectional transmission at 10-Gb/s is confirmed with a 40-km reach and 7-dB power margin without dispersion compensation.

5. References

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