All-Optical Carrier Recovery with Periodic Optical Filtering for Wavelength Reuse in RSOA-based Colorless Optical Network Units in Full-Duplex 10Gbps WDM-PONs

Efstratios Kehayas[1]*, Bernhard Schrenk[2], Paraskevas Bakopoulos[1], Jose A. Lazaro[2], Alexandros Maziotis[1], Josep Prat[2] and Hercules Avramopoulos[1]

[1]School of Electrical & Computer Engineering, National Technical University of Athens,
9 Iroon Polytechniou Street, Zografou, 15773, Athens, Greece
[2]Department of Signal Theory and Communications, Universitat Politecnica de Catalunya,
Jordi Girona 1, 08034 Barcelona, Spain (Tel. +34-93-401-7179 / Fax 7200)
**Corresponding author: ekeha@mail.ntua.gr*

Abstract: Optically assisted downstream cancellation for wavelength reuse in WDM-PONs is demonstrated, allowing downstream extinction ratios up to 9dB for symmetrical full-duplex data transmission at 10Gbps with RSOA-based ONUs. PON budgets of ~20dB can be reached.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation; (230.1150) All-optical devices

1. Introduction

The emerging need for high bandwidth services is pushing the development of access solutions such as robust passive optical networks (PON), which are also scalable when extended by means of wavelength division multiplexing [1,2]. Cost-effectiveness is provided by wavelength reuse at colorless optical network units (ONU), the latter supposed to perform full-duplex data transmission at rates as high as 10 Gbps. Despite the problem of remodulation, intensity modulation is chosen for down- and upstream due to its simplicity [3], implying also simplicity and low cost at the subsystems of the customer premises equipment.

The extinction ratio (ER) of the downstream is thereby reduced to leave residual optical power, also during spaces in the bit stream, for upstream modulation. The ER becomes apparently a critical parameter of optimization and features the downstream once it is expanded to high values: while the sensitivity of typical ONU receivers is limited, receivers used in the optical line terminal (OLT) allow also for optical preamplifiers such as Erbium-doped fiber amplifiers (EDFA) due to cost sharing among customers. Although attractive low-cost modulators, such as the reflective semiconductor optical amplifier (RSOA), have been shown in their ability to modulate at high bit rates [4], their inherently low electro-optical bandwidth is compromising feed-forward cancellation approaches [5] in their efficiency, thus also restricting the use of high downstream ERs and the reach of high PON budgets.

For the first time, we perform this downstream cancellation optically, by a spectral periodic filter at the ONU. A comparison with a conventional transmitter is shown, proving that the penalty due to residual downstream pattern in the upstream is ~3.5dB even for high initial downstream ERs of 9 dB that in turn allows higher PON budgets.

2. Carrier Recovery by Spectral Periodical Filtering

The proposed solution derives from the envelope detection used in optical packet switching [6], which also aims in recovering a carrier out of a bit stream. For this purpose, a periodic filter, here from Fabry-Pérot type (FPF), is included in the ONU (Fig. 1a). The principle relies on the optical memory effect of this filter, which in the time domain translates to light addition of the signal, filling the spaces in the incident bit stream, so that the envelope of the carrier is recovered. In the frequency domain, the narrow filter bandwidth recovers the carrier of the downstream, while the periodic transfer function allows operation independent of the wavelength. The penalty for the reception of the upstream, given by an unsuppressed downstream pattern, is therefore drastically reduced.

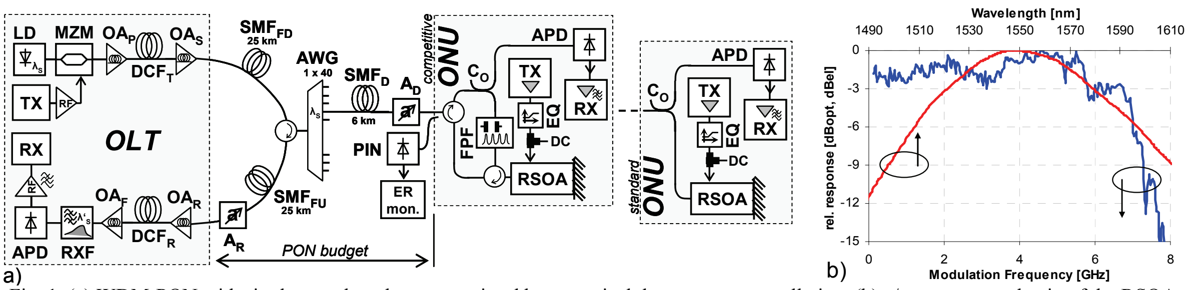

Fig. 1. (a) WDM-PON with single wavelength reuse, assisted by an optical downstream cancellation. (b) e/o response and gain of the RSOA.

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The results for the proof of concept in the back-to-back configuration with a downstream of 10 Gbps are shown in Fig. 2, where the remaining downstream ER and the cancellation efficiency, defined as the reduction of the ER in reference to its initial value, are presented. A FPF with a free spectral range of 10 GHz and a finesse of 40 was used as periodic filter. The RSOA was biased at 60 mA, giving a small signal gain of 13 dB. Its gain spectrum had a 3 dB bandwidth of 58 nm, centered at 1550 nm (Fig. 1b). The ONU input signal at 1551.72 nm was fixed to -7.5 dBm. Compared to the standard ONU (see Fig. 1a), which takes only advantage of the gain saturation of the RSOA, the proposed ONU increases the efficiency by 43% and 47% for a pseudo-random bit sequence (PRBS) of length 2^{31}-1 and an ER of 3 and 6 dB, respectively (Fig. 2a), and reaches values close to the theoretical limit of 100% cancellation. The remaining ER is as low as 1 dB even for an initial value of 9 dB, leaving an optical carrier that is suitable for remodulation with upstream data (Fig. 2b). While the gain saturation efficiency does not depend on the PRBS, the filter-assisted carrier recovery does due to the finite finesse of the FPF, leading to a fading impulse response that is sensible to sequences with consecutive spaces. A short PRBS with length 2^7-1 benefits: only 0.75 out of 9 dB remain. At lower ERs, the difference vanishes as also the spaces contribute to fill the FPF with light.

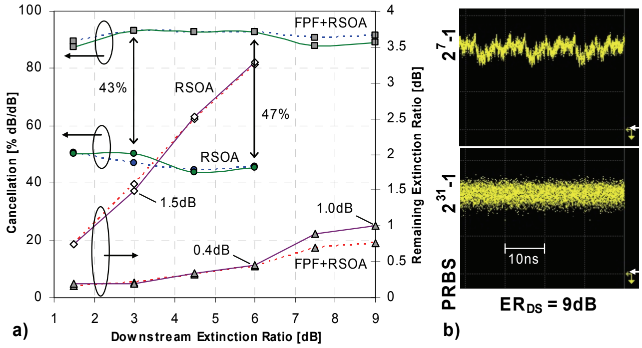

Fig. 2. (a) Cancellation efficiency and remaining ER for the standard ONU with a RSOA and for the competitive ONU with additional FPF. Solid lines indicate a PRBS length of 2^{31}-1 (for which values are mentioned), and dashed lines a length of 2^7-1. (b) Recovered optical carriers, acquired with 50 Gb/s oscilloscope. The arrows on the right side indicate the reference level.

3. Full-Duplex WDM-PON with Wavelength Reuse

The ONU was embedded in a WDM-PON, comprising a dual feeder and a drop standard single-mode fiber (SMF) with 25 and 6 km of length. A 1x40 arrayed waveguide grating (AWG) was used as distribution node. Dispersion compensating fibers (DCF) at the OLT cope for dispersive effects in the transmission, while their loss was compensated by preceding EDFAs. A Mach-Zehnder modulator (MZM) imprints the downstream, while remodulation occurs with an RSOA at the ONU, which was modulated with 60 mA_{pp}. The upstream ER of 6.4 dB at 10 Gbps is compromised by the need for electro-optical bandwidth. The latter is limited by the TO-can package and can be partially extended by optical offset filtering (RXF in Fig. 1a) at the OLT receiver with a detuned 100 GHz bandpass filter [7] and by equalization of the RSOA response. The phase modulation, introduced by the chirp of the RSOA ($\alpha = 7.7$), is converted into supportive amplitude modulation when the RXF is properly blue-shifted, leading to a bandwidth up to 5.8 GHz for the mentioned bias point of the RSOA and an ONU input power around -10 dBm (Fig. 1b). The electro-optical bandwidth had no strong dependence on the optical input power into the RSOA, so that a different filtering loss of the FPF due to a change in the ER of the downstream will not cause an additional limitation in the modulator bandwidth. Though the obtained bandwidth is not enough, penalized transmission at 10 Gbps should be possible at least at the forward error correction (FEC) level, without additional cost deriving from electronic equalization at the electrical OLT receiver.

The FPF was aligned with the downstream to obtain optimal suppression. The residual polarization sensitivity afforded controllers to optimize the response. However, with an integrated design where the FPF can be replaced by e.g. non-reflective ring resonators, not only the polarization controllers but also the circulators can be avoided.

The ratio of the optical coupler (C_O) of the ONU was chosen with 10/90 to favor the upstream branch with a higher optical power, preventing OSNR degradation during remodulation, while a sensitive avalanche photodiode (APD) is used for detection.

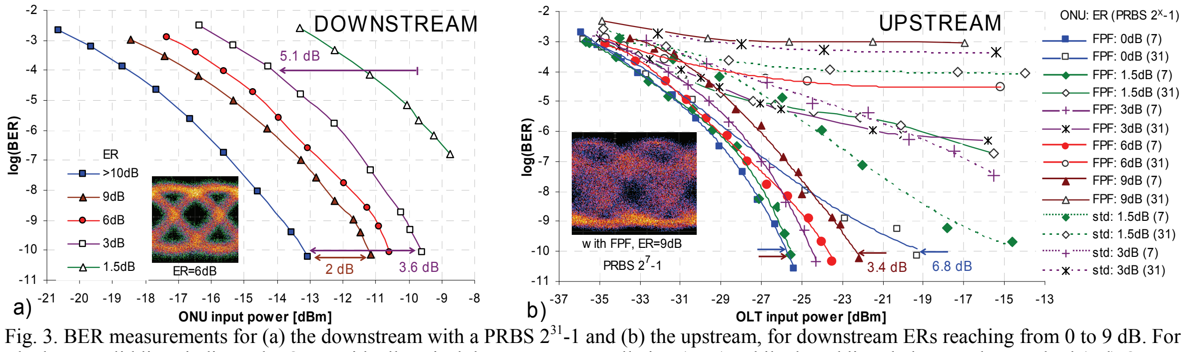

Fig. 3. BER measurements for (a) the downstream with a PRBS 2^{31}-1 and (b) the upstream, for downstream ERs reaching from 0 to 9 dB. For the latter, solid lines indicate the ONU with all-optical downstream cancellation (FPF), while dotted lines belong to the standard (std) ONU; filled markers correspond to a PRBS 2^7-1, hollow markers to a PRBS 2^{31}-1.

The downstream was launched with 6 dBm from the OLT. For an ER of 3 dB, the optical signal-to-noise ratio (OSNR) was 46.8 dB after the OLT booster and 40 dB after remodulation with the RSOA at the ONU, which net gain is limited to 5.8 dB due to the low small signal gain of the RSOA. The optical signal-to-Rayleigh-backscattering ratio was >29 dB for down- and upstream, thus no degradation is expected to arise from the drop fiber.

4. Results and Discussion

For the competitive ONU, featuring the optical downstream cancellation, the downstream penalty due to a reduced ER, referenced to a downstream ER >10 dB is 3.6 dB for an ER of 3 dB, where the FEC gain, defined as the difference in the sensitivities between a bit error ratio (BER) level of 10^{-10} and 10^{-4}, is 5.1 dB (Fig. 3a). The BER performance for the standard ONU (not shown) benefits by the missing circulator loss; however, ERs higher than 3 dB are not compatible with upstream modulation for the standard ONU (Fig. 3b).

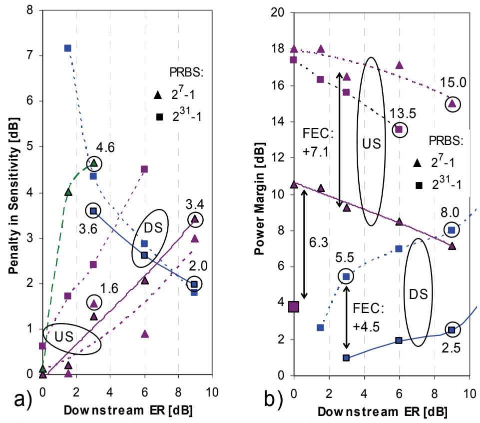

Fig. 4. (a) Penalties in sensitivity, referenced to an ER of >10 dB for the downstream and to an ER of 0 dB with a PRBS of 2^7-1 for the upstream, (b) power margins for the ONU with the FPF (solid lines: BER of 10^{-10}, dotted lines: BER of 10^{-4}, dashed lines: standard ONU, BER of 10^{-4}).

On the contrary, the competitive ONU allows downstream ERs up to 6 dB for upstream transmission at the FEC level and a PRBS of 2^{31}-1. With an ER of 9 dB, there is only a penalty of 3.4 dB at a BER of 10^{-10} for a PRBS of 2^7-1, when compared to the downstream-less (ER of 0 dB) case. The penalty suffered from a long PRBS of 2^{31}-1 is at an ER of 0 dB already 6.8 dB at a BER of 10^{-10}. As can be seen from the measurements with the standard ONU, this dependence on the PRBS is not caused by the FPF but due to patterning effects in the RSOA, enhanced by higher optical input power, when changes in the carrier density cause gain transients and therefore distortions in the upstream pattern. The FEC gain for the upstream with the competitive ONU is 7.5 and 7.9 dB for an ER of 0 and 9 dB, respectively, at a PRBS 2^7-1.

The penalties in the sensitivity are shown in Fig. 4a. The standard ONU suffers from a strong penalty once the ERs is increased, already causing 4.6 dB at an ER of 3 dB for the short PRBS while the competitive ONU is penalized with only 1.6 dB. For an ER of 9 dB, the penalty for the same PRBS is 2 and 3.4 dB for down- and upstream, respectively. This results in an extended and optimized power margin, defined as the difference between available optical power at the OLT/ONU input and its reception sensitivity, at this ER (Fig. 4b). Once FEC is included in the more critical downstream reception, the margins are balanced with a higher ER of 9 dB to 8 and 7.2 dB for down- and upstream, leading to maximum PON budgets (see Fig. 1a for definition) of 21.5 and 20.7 dB. Compared to a typically chosen ER of 3 dB, where the margins are 5.5 and 9.3 dB, additional improvement is achieved next to a significant reduction of the reception penalty of the standard ONU. If FEC is also used for the upstream, its margin raises to 15 dB at an ER of 9 dB, leaving the downstream margin of 8 dB as the limiting factor.

5. Conclusion

An all-optical approach for downstream cancellation in PONs with wavelength reuse was demonstrated, suffering only from a penalty of 3.4 dB for a downstream ER as high as 9 dB, where no full-duplex transmission is possible with the standard ONU. Next to providing a "greener" solution at the ONU, also the penalty is much lower than for the standard ONU, where it is reduced for an ER of 3 dB from 4.6 to 1.3 dB at the FEC level. The margins in a full-duplex 10 Gbps WDM-PON have been found to be >7 dB when applying FEC for the more critical downstream reception. Further improvement is expected with electronic equalization at the OLT receiver.

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