Bandwidth efficient bidirectional 5 Gb/s overlapped-SCM WDM PON with electronic equalization and forward-error correction

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Abstract: We demonstrate an improved overlapped-subcarrier multiplexed (O-SCM) WDM PON architecture transmitting over a single feeder using cost sensitive intensity modulation/direct detection transceivers, data re-modulation and simple electronics. Incorporating electronic equalization and Reed-Solomon forward-error correction codes helps to overcome the bandwidth limitation of a remotely seeded reflective semiconductor optical amplifier (RSOA)-based ONU transmitter. The O-SCM architecture yields greater spectral efficiency and higher bit rates than many other SCM techniques while maintaining resilience to upstream impairments. We demonstrate full-duplex 5 Gb/s transmission over 20 km and analyze BER performance as a function of transmitted and received power. The architecture provides flexibility to network operators by relaxing common design constraints and enabling full-duplex operation at BER $\sim 10^{-10}$ over a wide range of OLT launch powers from 3.5 to 8 dBm.

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1. Introduction

The demand for Internet bandwidth is growing at an unprecedented rate, with global IP traffic expected to increase fourfold between 2010 and 2015 [1]. One driving force is the rapidly increasing consumer appetite for high-bandwidth applications such as 3-D television, high-definition video-on-demand services, video conferencing and cloud-based services. Indeed, by 2015 the traffic generated by Internet video delivered to television is expected to increase 17-fold and approximately 90% of global consumer traffic is expected to be consumed by various Internet video services [1].

The consumer demand for these data intensive services will drive the need for greater capacity on access networks, upwards of 1 Gb/s per user, motivating the adoption and deployment of fiber-to-the-home (FTTH) networks by carriers. Currently deployed passive optical networks (PONs), such as gigabit-capable PON (G-PON) and Ethernet PON (EPON), share the aggregate bandwidth by using time-division multiple-access (TDMA) which effectively limits subscribers to peak bandwidths less than 100 Mbit/s. New standards such as 10G-EPON and XG-PON will provide an upgrade pathway for operators to increase the total shared bandwidth available to users, but scaling these TDMA networks beyond 10 Gb/s is expected to be difficult [2].

Wavelength-division multiplexing (WDM), where each user is assigned a dedicated wavelength, is considered the most promising step for next-generation PONs in green-field deployments. Although limited primarily by economic factors, WDM PONs aim to provide higher capacity and security compared to current systems. A single feeder fiber will be required to provide an upgrade path for the existing infrastructure. Colourless optical network units (ONUs) will ensure the success of WDM on PONs by reducing the cost and complexity of transceivers at the customer premises [3, 4]. The reflective semiconductor optical amplifier (RSOA) is one of the most investigated candidates for this purpose, boasting a low manufacturing cost, easy integration, small form factor and wide wavelength operating range [5].

The primary drawback of RSOAs as ONU transmitters is that their modulation bandwidth is limited to ~ 2 GHz by packaging electronics and the carrier lifetime of the gain medium [6]. A number of techniques have proven successful at further increasing the transmission bit rate, such as the use of higher order modulation formats, delay interferometers, narrow optical filters, device structure and packaging optimization, integrated modulators, and electronic equalization [6–13]. Employing some of these techniques has enabled the direct modulation of a RSOA at 25.78 Gb/s [12].

In a single feeder WDM PON architecture where the same wavelength is used for full-duplex communication, in-band crosstalk due to Rayleigh backscattering (RB) and reflections impose severe limitations on uplink performance [14, 15]. Several architectural, optical, electrical and signal processing techniques have been proposed to mitigate the impact of RB [16–20]. Interest has also been shown toward using radio frequency (RF) subcarrier multiplexing (SCM) as a simple and low cost means to reduce these effects [21–24].

Many previous SCM implementations have generally been limited to asymmetric and/or sub-gigabit data rates by the RSOA's bandwidth and the use of guard bands to separate the uplink and downlink RF spectra and facilitate electrical filtering [22, 23, 25]. Recently, the authors demonstrated a novel overlapped-SCM (O-SCM) architecture that permits up to 2.5 Gb/s symmetric data rates by reducing the guard band and introducing an overlap between the received uplink and residual downlink spectra [26, 27].

In this paper we demonstrate an improved O-SCM architecture where the downlink is placed on a RF subcarrier and the uplink transmitted at baseband. Placing the downlink on a subcarrier instead of the uplink simplifies the ONU design and alleviates some of the previously encountered bandwidth effects of the RSOA [26], thus further improving spectral efficiency and enabling the data rates to be doubled.

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The O-SCM architecture focuses on the use of simple optics and cost sensitive electronics coupled with standard DSP techniques to provide an attractive solution for network operators. Symmetric data rates of 5 Gb/s are demonstrated over 20 km in a bidirectional WDM PON using electronic equalization and Reed-Solomon (RS) FEC codes. In an effort to reduce the cost and complexity of the ONU receiver, only FEC decoding is used on the downlink data. The minimum launch power to achieve full-duplex operation was 3.5 dBm, which to the best of our knowledge is one of the lowest reported for SCM systems operating at this bit rate.

2. Overlapped-subcarrier multiplexing WDM PON

2.1. Physical architecture

The bidirectional WDM PON architecture used existing infrastructure constraints, and is illustrated in Fig. 1(a). The optical line terminal (OLT) transmitter consisted of an electro-absorption modulated laser (EML) centred at 1549.36 nm. The EML was driven by a 5 Gb/s nonreturn-to-zero (NRZ) $2^{15}-1$ PRBS-based data sequence up-converted on a 5 GHz subcarrier frequency. The EML's output extinction ratio (ER) was minimized to $ER_{down} = 5.1$ dB in order to provide sufficiently reliable downlink transmission and to favour the uplink transmission by ensuring adequate data erasure during re-modulation at the ONU. Figure 1(b) demonstrates that the up-converted spectra spans the entire 10 GHz modulation bandwidth of the EML.

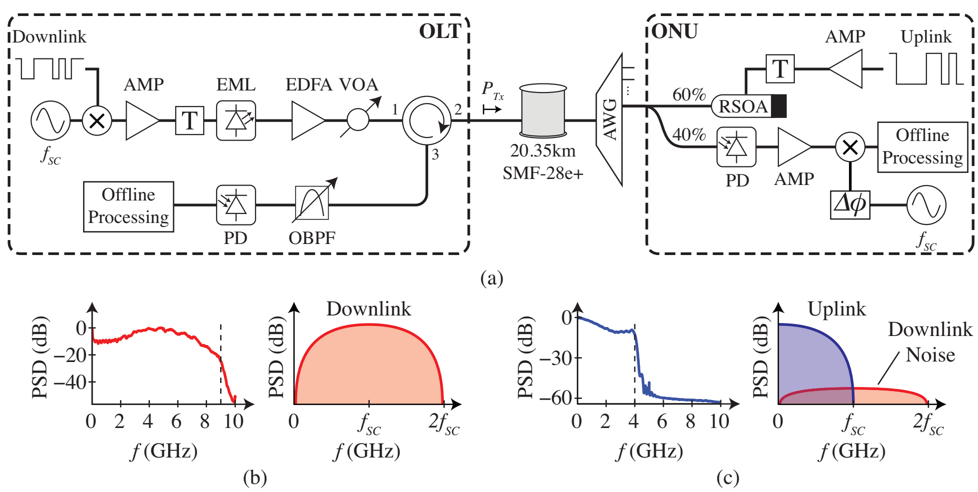

Fig. 1. (a) Experimental setup of the proposed O-SCM WDM PON. Measurements and illustrations of the received (b) up-converted downstream and (c) baseband upstream signal spectra, where the dashed vertical lines indicate that the measurement bandwidth was limited to 9 GHz and 4 GHz respectively. $\Delta\phi$: electrical phase delay, AMP: RF amplifier, AWG: arrayed waveguide grating (100 GHz), EDFA: erbium-doped fiber amplifier, EML: electro-absorption modulated laser (CyOptics E4560), f_{SC}: subcarrier frequency, Mixers: Marki Microwave (M1-0412MP), OBPF: 0.25 nm optical band-pass filter, OLT: optical line terminal, ONU: optical network unit, PD: p-i-n photoreceiver (10 GHz bandwidth), P_{Tx}: OLT transmitted power, PSD: power spectral density, RSOA: reflective semiconductor optical amplifier (CIP SOA-RL-OEC-1550), T: RF bias-tee, VOA: variable optical attenuator.

Following the EML, an EDFA and a VOA controlled the launch power for the subsequent measurements. In a realistic deployment this EDFA would be used to simultaneously amplify many user wavelengths, sharing the investment costs among the customer base. The optical

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distribution network (ODN) comprises a 20.35 km feeder of standard single mode fiber (SMF-28e+) and a 100 GHz arrayed waveguide grating (AWG).

At the ONU, a coupler tapped off 40% of the downstream signal to the receiver composed of a commercial p-i-n photoreceiver and RF down-conversion circuit. The remaining 60% seeded the RSOA with enough input power to operate in gain saturation. The uplink transmitter was designed using a butterfly packaged RSOA directly modulated with a $2^{23}-1$ PRBS-based bit sequence at 4 $V_{p\text{-}p}$ and biased at 80 mA, with peak gain from 1530 nm to 1570 nm. This resulted in an optical output with $ER_{up} \sim 9.5\,\text{dB} \gg ER_{down}$ to ensure sufficient downlink data erasure and therefore data re-modulation. The unamplified OLT receiver comprises an optical band-pass filter and a commercial p-i-n photoreceiver. Illustrated in Fig. 1(c), the baseband upstream signal is 100% overlapped [26] with the residual downstream consisting primarily of RB, reflections and re-modulation noise [16]. The measured RF spectrum in Fig. 1(c) demonstrates that limiting the acquisition bandwidth to 4 GHz greatly suppresses the out-of-band noise.

2.2. *Data frame structure*

The data sequences transmitted by the pulse pattern generator (PPG) were created offline using a custom frame-based data structure, illustrated in Fig. 2. At onset, a standard PRBS pattern (downstream: $2^{15}-1$, upstream: $2^{23}-1$) was generated and encoded with RS(255,239) FEC which is compatible with current G-PON deployments [28] and has previously been shown to provide an optimized level of redundancy for bandwidth limited RSOAs [29].

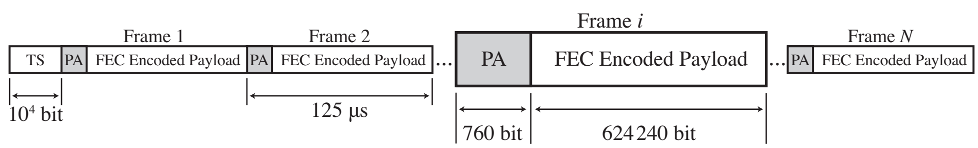

Fig. 2. Illustration of the data structure transmitted at 5 Gb/s. The sequence begins with a 10^4 bit training sequence (TS) followed by a series of N data frames. Each frame is composed of a 760 bit preamble (PA) and a 624 240 bit RS(255,239) FEC encoded payload.

The encoded sequence was then segmented into 624 240 bit frames. A 760 bit preamble was appended to the beginning of each frame to provide a unique signature for processing at the receiver, adding a negligible $\sim 0.1\%$ to the total overhead. This results in 625 000 bit frames, which at 5 Gb/s are compatible with the 125 µs upstream frame duration in existing G-PON standards [28]. The total overhead for this system is $\sim 6.4\%$ including the data frame preamble and RS(255,239) parity bits. The 10^4 bit training sequence (TS) placed before the data frames was only used to initialize the equalizer taps at the OLT receiver on system start-up and therefore is not considered to be part of the operating overhead.

This frame-based technique provides three main advantages: (1) each frame is uniquely identifiable and extractable from the received data sequence to facilitate training symbols during equalization and bit error rate (BER) calculations; (2) each frame's start can be resynchronized to account for sampling drift, analogous to clock-synchronization in deployed G-PON systems; (3) frame equalization can be efficiently computed in parallel.

Using these techniques, the BER can be reasonably calculated down to 10^{-6} because of the $\sim 4.5 \times 10^6$ bit capture length. Although the oscilloscope was capable of recording longer sequences, this length was found to be sufficient to achieve the desired BER level while remaining computationally feasible for the analysis.

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2.3. *Offline analysis & electronic equalization*

Prior to analysis, cross-correlation techniques were used to extract the data frames from the recorded sequence. The 760 bit preambles along with any incomplete frames were then removed to maintain the statistical integrity of the PRBS payload. The BER of the unequalized data was found by optimizing the sampling time and decision threshold level to minimize the error count.

The smooth roll-off of the RSOA's frequency response (approximately -10 dB/decade from 0 to 5 GHz) coupled with its linear modulation response make it ideal for use with a combination of feed-forward (FFE) and decision-feedback equalizers (DFE) at the OLT receiver [6,30]. The taps were first trained using a 10^4 bit TS before the frames were equalized in parallel, where their values were dynamically adjusted for each frame using the least-mean squared (LMS) adaptive algorithm [30]. The BER was again calculated before and after FEC decoding by comparing the transmitted data frames with the hard decision output of the DFE.

3. 5 Gb/s Symmetric Transmission over 20 km

3.1. *Downlink*

A real-time oscilloscope (Agilent Infiniium DSCX93204A) facilitated the offline processing of the data, capturing the bit sequences at 20 GSa/s (4 Sa/bit) to a memory depth of 20.5 MSa. The oscilloscope's acquisition bandwidth was set to 4 GHz, acting as a sharp low pass filter and reducing the effects of out-of-band noise and clock leakage from the RF mixers.

A full characterization of the O-SCM WDM PON architecture was completed at a 5 Gb/s symmetric data rate and the results are summarized in Fig. 3. All BER calculations were completed using the analysis techniques described in the previous section. Beginning with the downlink in Fig. 3(a), we demonstrate the system's BER performance as a function of power transmitted from the OLT.

The BER calculated prior to decoding ($\circ$) drops below the FEC threshold $\left(1.8\times10^{-4}\right)$ at $P_{Tx} = 3$ dBm and continues to decrease until it reaches below 10^{-6} at 7 dBm. After decoding ($\bullet$), the BER quickly reaches the waterfall region where the last error was calculated at $P_{Tx} =$ 1 dBm.

An analytical model of the FEC performance is also presented to validate this behaviour and extrapolate to lower BERs. RS(255,239) is a block coding technique where the data is grouped into $m = 8$ bit symbols, and a single block is composed of 239 uncoded symbols followed by 16 symbols of parity information. Assuming a memoryless channel, up to $t = 8$ symbol errors can be corrected per block and the symbol error rate after FEC, P_{S_FEC}, is then [31]

$$P_{S\_FEC} \approx \frac{1}{2^m-1}\sum_{j=t+1}^{2^m-1} j\binom{2^m-1}{j} P_S^j\left(1-P_S\right)^{2^m-1-j}, \tag{1}$$

where the bit error rate, P_B, is related to the symbol error rate, P_S, by

$$P_B = 1-\left(1-P_S\right)^{\frac{1}{m}}. \tag{2}$$

This model agrees reasonably well with the analyzed data and extrapolates the waterfall region below the BER calculation threshold of 10^{-6}, estimating that $P_{Tx} > 3$ dBm would result in downlink transmission with BER $\sim 10^{-10}$. Although the model does not account for bursty errors, it should provide an acceptable estimate of the system's operating boundaries.

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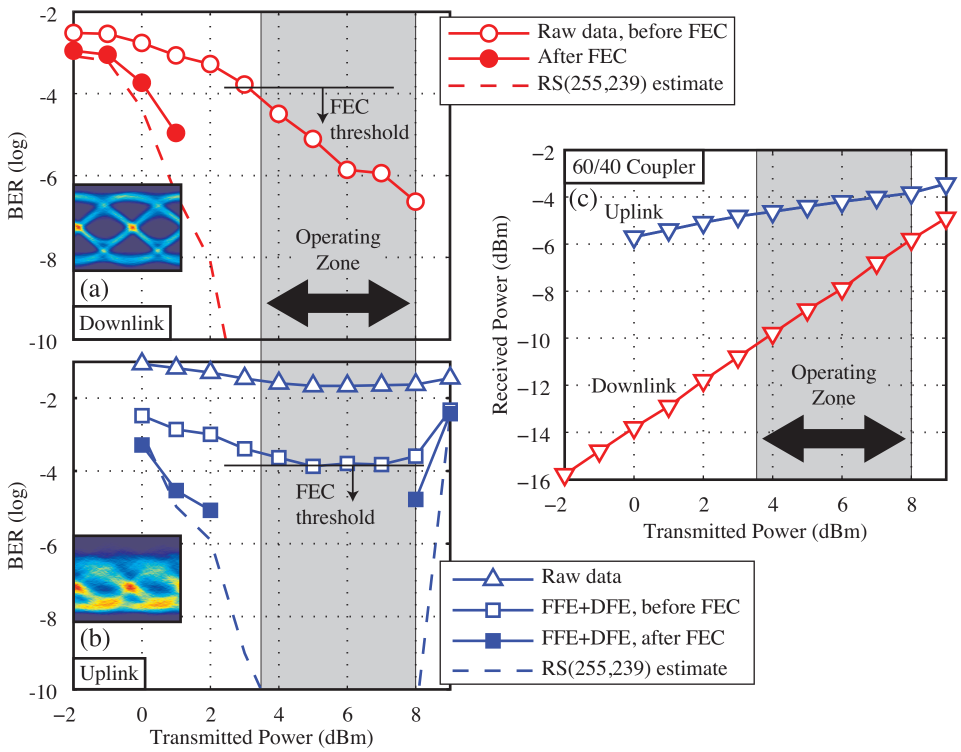

Fig. 3. BER performance as a function of OLT transmitted power in (a) downlink and (b) uplink directions for 5 Gb/s symmetric transmission over 20 km. The inset eye diagrams are of the raw data captured at $P_{Tx} = 5$ dBm. (c) The corresponding received uplink and downlink power versus transmitted power for the optimum 60/40 coupler.

3.2. Uplink

Similar measurements were repeated in the uplink direction, shown in Fig. 3(b). The BER of the raw captured data ($\triangle$) never falls below 10^{-2} due to the severe inter symbol interference (ISI) caused by the RSOA's narrow modulation bandwidth.

The 4 Sa/bit data was initially downsampled to 2 Sa/bit using a polyphase filter method with an additional 10 point finite impulse response (FIR) filter to reduce aliasing effects. It was then equalized using a 6 tap 1/2-symbol spaced FFE and a 1 tap DFE. The number of taps was optimized to minimize the number of detected errors while maintaining a reasonably low computational complexity. The uplink BER after equalization ($\square$) reaches a floor near the FEC threshold over a range from 4 to 8 dBm. Following FEC decoding($\blacksquare$), the BER drops sharply below the calculation limit at $P_{Tx} > 2$ dBm. The analytical model from Eq. (1) again estimates the system's performance down to BER $\sim 10^{-10}$ at $P_{Tx} > 3.5$ dBm, consistent with the downlink boundary due to the optimized 60/40 coupler.

Figure 3(c) compares the received power incident on the uplink and downlink photoreceivers and P_{Tx} for the system using the 60/40 coupler, which was selected to balance the system's power budget and minimize the launch power required for full-duplex transmission. The received uplink power measured at the OLT remains approximately -5 dBm over the transmission power sweep due to the RSOA operating in gain saturation.

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3.3. *Operating zone & reflection tolerance*

Comparing the BER waterfall curves for both transmission directions, we define an *operating zone* as the range of OLT transmission powers over which the analytical FEC curves from Eq. (1) cross below the BER threshold of 10^{-10} and no errors were calculated.

The lower zone boundary is fixed by the minimum launch power required for full-duplex transmission. This operating point was dictated by the typical design tradeoffs between ER_{down}, RSOA gain, and ONU coupling ratio common to bidirectional WDM PONs using re-modulation. At high launch powers (≥ 8 dBm) the system's upstream performance degrades as impairments, such as RB, become more dominant and cannot be tolerated by the O-SCM technique. Selecting suboptimal values results in an imbalance between the uplink and downlink power budgets, creating an offset between their respective operating ranges and reducing the system's overall operating zone.

Figure 4 examines this behaviour for two cases. The 5 Gb/s symmetric O-SCM system in Fig. 4(a) provides some separation between the uplink and residual downlink noise spectra to reduce the effects by electrically filtering $\sim 50\%$ of the spectral power. As the transmission power increases more reflected power is contained within the filter passband, further impairing the uplink performance. The design tradeoffs become more evident when considering that the conventional asymmetric SCM system in Fig. 4(b) has a guard band separating the 1.25 Gb/s uplink from the residual 2.5 Gb/s downlink [21]. The out-of-band crosstalk is more easily filtered, giving the greatest resistance to RB but at the high cost of bandwidth efficiency.

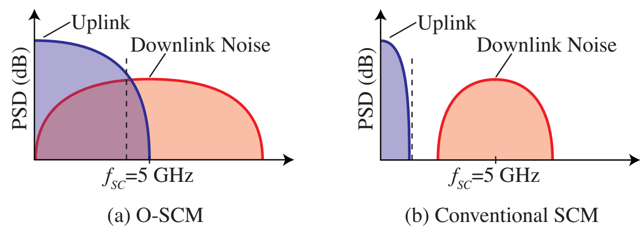

Fig. 4. Illustration of the downlink noise tolerance for (a) this O-SCM WDM PON and (b) a conventional asymmetric SCM PON. The dashed vertical line represents the cutoff frequency for the receiver's electrical low pass filter.

It is well known that increasing the transmission power in WDM PONs using re-moduation does not necessarily provide better performance [16]. This O-SCM architecture relaxes this launch power design constraint to a 4.5 dB range by providing enhanced resilience to RB and reflections while maintaining efficient use of modulation bandwidth and enabling higher transmission rates. Thus operators are supplied with additional flexibility to help manage network variations in real-world deployments.

4. Conclusion

We have presented an improved O-SCM architecture for next generation WDM PONs. Experimentally we demonstrated full-duplex transmission at 5 Gb/s over a 20 km PON using low cost IM/DD transceivers and data re-modulation. A colourless ONU was enabled by a directly modulated RSOA whose ~ 2 GHz bandwidth was compensated for with electronic equalization at the OLT receiver. Standards compatible RS(255,239) FEC codes were used at the receivers to provide additional performance gains. Full-duplex operation commences at a low $P_{Tx} = 3.5$ dBm launch power and spans up to 8 dBm, thus confirming the system's resiliency to upstream impairments.

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The experimental results demonstrate greater bandwidth efficiency than other SCM techniques and a twofold increase in symmetric data rates from previous O-SCM implementations. The low launch power requirements and tolerance to uplink impairments eases some well known design constraints for bidirectional WDM PONs and provides additional flexibility for very little additional cost, making the design an attractive solution for network operators.

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