Rayleigh Backscattering Rejection in Single-Laser Homodyne Transceiver for ud-WDM using λ -shifting

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Abstract— With the aim of using a single laser in single fiber splitter-based Passive Optical Networks (PON) with coherent homodyne transceivers, we apply wavelength shifting in an ultra-dense Wavelength Division Multiplexing (ud-WDM) scheme. The studied architecture is based on IQ modulator operating in Carrier-Suppressed Single-Sideband (CS-SSB). In this configuration, a single laser feeds both the coherent homodyne receiver, and the transmitter, simplifying the wavelength management in the PON. The modulator carries out both data modulation and wavelength shifting. In this study, a bit rate of 4 Gbit/s in QPSK is used to test several roll-off factors and channel spacing configurations. The results show that power budget gains of 18 dB are achievable with a channel spacing equal to only the symbol rate.

Index Terms— Passive optical networks, access networks, wavelength shifting, coherent detection, homodyne detection.

I. INTRODUCTION

The growing use of multimedia streaming and the network requirements for 5G technologies call for higher capacity and spectral efficiency in optical networks. Current access networks rely on time division multiplexing (TDM) and use free-running lasers at the transmitters (Tx) and direct detection (DD) at the receivers (Rx), but this technology may soon not be able to keep up with the new capacity and efficiency demands.

As a response, the concept of λ -to-the-user appeared as an application of ultra-dense Wavelength Division Multiplexing (ud-WDM). UD-WDM enables a much higher spectral efficiency and user allocation. By dedicating a single wavelength to a user, or by having several users sharing it in burst mode (ud-TWDM), the high sampling requirements, energy consumption and guard time between bursts of current TDM are avoided [1].

Bidirectional propagation over a single fiber in access links leads to reflective impairments that affect both TDM and ud-WDM. While angular fiber connectors and fiber input control have been successfully used to reduce extrinsic reflection and inelastic scattering, respectively, Rayleigh Backscattering (RBS) requires alternative strategies such as the spectral separation of up and downlink wavelengths. With coherent technologies now becoming cost-effectively more accessible, RBS mitigation remains as the main limiting factor preventing extended power budgets, inherent to coherent detection schemes, from being fully exploited in access networks.

Coherent detection requires a laser to act as a local oscillator (LO) at the Rx, in either a heterodyne or homodyne fashion. The heterodyne format allows for spectral separation of up and

downlink with a single laser per transceiver. However, compared to the homodyne format, it comes with several drawbacks, including a 3 dB sensitivity loss and a 50% channel spacing penalty due to image frequency interference. The use of two lasers in a homodyne transceiver adds to the cost and to the complexity with the requirement of wavelength control.

The separation between the upstream and downstream channels can be obtained using a dual-parallel Mach Zehnder Modulator (DP-MZM) in CS-SSB configuration, in which the data modulation and the wavelength shifting are done simultaneously. In [2] a DP-MZM was used in CS-SSB along with wavelength demultiplexers, resulting in neither a colorless PON nor an ultra-dense scheme. Moreover, ASK over FM remodulation was proposed in [3], which resulted in increased sensitivity loss.

Half duplex links have been proposed in [4], and heterodyne schemes were presented in [5,6], with the aforementioned penalties as compared to homodyne demodulation. λ conversion was studied in [7,8], but either multiple spurious were generated, leading to low spectral efficiency, or the methods were not λ agnostic.

A scheme combining coherent detection and a DP-MZM modulator in CS-SSB configuration is proposed in [9], but does not provide RBS rejection measures and operates in a heterodyne fashion.

To the best of our knowledge, in this work we propose and test for the first time a homodyne transceiver consisting of a single laser acting as LO, and also feeding the DP-MZM in CS-SSB configuration for both modulation and wavelength-shifting (λ -shifting) at the Tx. Several channel spacing and roll-off factors are tested to optimize the spectral efficiency. Sensitivity improvements higher than 18 dB have been obtained for channel spacing as low as the baud rate R_b . The experiment was done using QPSK at 4 Gbit/s.

II. PON ARCHITECTURE

The proposed scenario is the transparent, splitter-based, ud-WDM PON depicted in Fig. 1. The ONU/OLT consists of a coherent receiver (Rx) with a LO laser that also feeds the transmitter (Tx) module. The Tx uses a standard IQ modulator in CS-SSB configuration that performs both the λ -shifting and the complex data modulation as seen in Fig. 2, equation 1 and done in [9]. This configuration needs extra RF mixers, but avoids a second modulator and its power losses. Moreover, integration of the DP-MZM with DFB in SFP transceivers further increases the cost-effectiveness of the proposal.

Fig. 1: Proposed splitter-based PON architecture

Fig. 2: CS-SSB modulation using a DP-MZM.

Fig. 3: Optical spectral distribution of users for homodyne and heterodyne cases

The required amount of frequency shifting is dependent on the tolerable bidirectional crosstalk among the detected signal, the RBS, and the adjacent users. The electrical filtering at the Rx is responsible for canceling the out-band crosstalk components. As seen in Fig 3, the most critical point is at the front feeder for upstream detection and in the end drop for downstream detection. For homodyne detection, the minimum shifting for Nyquist filtering is $\Delta f_{RF} > \frac{R_D + R_U}{2} (1 + \beta)$, where R_D and R_U stand for the downlink and uplink baud rates respectively with β being the roll-off factor. For symmetric link where $R_D = R_U = R_B$, channel spacing between up and downstream channels is $\Delta f_{RF} > R_B (1 + \beta) = B$, with B defined as the total optical width of the data channel, and between two consecutive downstream channels $\Delta f_{RF} > 2B$.

Our proposed system's main competitor is heterodyne detection using the same architecture; in its natural scheme, by modulating the LO laser, up and downstream spectra do not overlap in the fiber. However, heterodyne detection requires an extended RX bandwidth, has 3dB sensitivity penalty and, most importantly in ultra-dense-WDM, it suffers 50% increase in the channel spacing. The minimum channel spacing between up and down channels in both detections is $\Delta f_{RF} > B$, but between consecutive channels in the same direction it becomes $\Delta f_{RF} > 3B$ for heterodyne detection, while using homodyne detection allows for a separation as low as $\Delta f_{RF} > 2B$ as seen in Fig. 3. Heterodyne Rx also allows for demodulation with phase diversity using only a 2x2 front-end, but as demonstrated in [10], phase diversity can be obtained for homodyne detection using a 3x3 front-end.

In the next section the minimum required shifting between the upstream and downstream channel to avoid the RBS penalty in sensitivity is studied. To do so, the roll-off factor β using a square-root raised cosine filter at both the Tx and Rx is varied with cases $\beta = \{0.2, 0.5, 1\}$, the channel spacing tests where done for $\Delta f_{RF} = \{0.5, 1, 1.25\} \cdot R_b$, and a downstream adjacent channel was located at $2\Delta f_{RF}$ and maintained at the same power level as the detected signal. Results of Bit Error Ratio (BER) as a function to the received Signal to Rayleigh Ratio (SRR) are presented. When the target BER was not reached in very narrow channel spacings, results are presented without the presence of the adjacent channel to study the effect of the RBS independently.

III. EXPERIMENTAL SET-UP

The setup configuration (Fig. 4a) is designed to validate the proposal using two homodyne ONUs. To this end, three signals are used: the one to be detected (ONU 1 Tx), the neighbor user (ONU 2 Tx) and the RBS source (OLT Tx). The ONU 2 Tx and OLT Tx implement standard MZM with BPSK modulation in baseband. Laser 2 is tuned so another downstream channel is present at a channel spacing of $2\Delta f_{RF}$ with respect to the detected signal.

In our proposal, the OLT should either use another laser tuned to the same wavelength of laser 1 for the upstream transmission, or to also perform frequency shifting to that wavelength using its local laser (laser 3). In order to simplify the setup, we only employ the frequency shift at ONU1, and we use laser 1 to feed both downstream frequency-shifted TX of ONU1 and the OLT upstream TX. This eliminates the λ -drifts between the OLT and the ONUs lasers, thus the RBS interference is maximum. The effect of such λ -drifts will be studied in future research, but rather importantly here, frequency drifts are successfully kept under ± 50 MHz by automatic wavelength control (AWC) using commercial DFB lasers in [11].

In our setup, Laser 1 and 3 are narrow linewidth tunable lasers with 300 & 100 kHz linewidth respectively, and Laser 2 is a thermally tunable DFB with 4 MHz linewidth emitting at the same power as ONU1. To avoid coherent interferometric effects between ONU 1 Tx and OLT Tx, 25 km of standard SMF fiber is used for the feeder so the optical signals are no longer coherent.

Fig. 5: Detected constellations for 4 Gb/s QPSK with $\beta = 1$, error free and $BER=10^{-3}$ respectively.

Before coherent homodyne detection by a 3x3 optical frontend^[10] at the OLT Rx, the signal is split to perform both power and spectral monitoring in real time. Fig. 4 b) shows the photodetected spectra, centered at 5 GHz for visualization, of the bidirectional transmission in an experiment case, and Fig. 4 c) provides a higher separation between channels for further clarity.

Data is generated using arbitrary wave generators (AWGs), and amplified before optical modulation. Finally, a 50 GSa/s digital oscilloscope is employed for data gathering and in-line signal processing using Matlab. The QPSK information is synchronously detected with the feedforward Viterbi carrier recovery algorithm, and the BER is computed by counting errors over $3 \cdot 10^6$ bits. Fig. 5 plots the detected constellations for error free and $BER=10^{-3}$ cases.

The total bandwidth at -3 dB of the DP-MZM modulator is 6.3 GHz. The maximum input frequency to the modulator is $\frac{R_B}{2}(1 + \beta) + \Delta f_{RF}$, so in order to carry all channel spacing and roll-off tests in the same conditions, the baud rate selected for the experiments is $R_B = 2$ GHz. This ensures that all studied cases are modulated in the frequency range where the response of the modulator is flat.

In our experiment the maximum SRR reached is -2 dB, as the power output of the OLT Tx is of -7 dB, leading to a RBS power of -44 dBm after the link losses.

The state of polarization is manually adjusted at the input of all modulators, as well as at the coherent Rx, thus ensuring the maximum BER penalty due to RBS and adjacent channel crosstalk. Power fluctuations of 1.5 dB are observed, as well as ± 1 dB fluctuation in Rx sensitivity due to polarization misalignment.

IV. RESULTS

Wavelength shifts of $\Delta f_{RF} = \{0.5, 1, 1.25\} R_B$ are evaluated for $\beta = \{0.2, 0.5, 1\}$ and the results are shown in Fig. 6. The absolute sensitivity for a $BER = 1 \cdot 10^{-4}$ is -46 dBm for $\beta = \{1, 0.5\}$ and -45 dBm for a $\beta = 0.2$. This power level determines the BER floor in Fig. 6, and is set and maintained constant using Attenuator 1. Attenuator 3 is used to set the adjacent channel and the detected channel at the same power.

The RBS power is set using Attenuator 2 to compute the BER versus the SRR. Even low SRR levels down to -2 dB, which is the experiment range limit, does not impair the detected signal enough to measure a $BER = 10^{-3}$, as summarized in Table 1, so a lower bound of the SRR rejection is provided in these cases. In Fig. 6 (a)-(c), the reference BER curve is measured without adjacent channel, and without λ -shifting; i.e., full spectral overlap between detected signal and RBS. The RBS rejection gain is defined as the difference in the required SRR between curves for a given BER. In this study, the received power is adjusted to provide $BER = 10^{-4}$ without any interference. Then the RBS and adjacent channel were carefully added, by using Attenuator 3, making sure ONU 1 and ONU 2 power outputs were equal while the SRR swept. For clarity, the critical case of $\Delta f_{RF} = 0.5$ is studied with and without adjacent channel.

It is observed how, for all the roll-off values considered and in the presence of an adjacent channel, λ -shifts equal to the data rate provide significant BER improvements over the reference case with no shift and no adjacent channel. Only for the critical case of 0.5 SRS, the presence of the adjacent channel results in a penalty over the reference for $\beta=0.5$ and 1.

Fig. 6: Measured BER against different Signal-to-Rayleigh ratio (SRR), for different λ -shifts and roll-off factors.

Table 1 summarizes the RBS rejection gain for $\text{BER} = 10^{-3}$. Rejection of the RBS becomes a BER sensitivity improvement when the Rayleigh interference dominates over the Rx noise. For significant cases of $\beta = 1$ with $\Delta f_{RF} = 1.25 R_B$ and $\beta = 0.2$ with $\Delta f_{RF} = 1 R_B$ the system reaches rejections higher than 15 dB, which allows recovery of remarkable sensitivities of coherent detection without interference.

Notably, even some spectral overlap between users caused by a shift of $\Delta f_{RF} = 0.5 R_B$ is tolerable for a low $\beta = 0.2$. The neighbor downstream channel did not have an effect for channel spacing between up and downstream greater than R_B .

From Fig. 6 it can be seen how, without increasing the signal power level, shifting and lower roll-off factors enable to recover a BER performance of 10^{-3} , even with an RBS power as high or higher than the detected signal itself. This enables the PON to support the same power budget it had without the RBS presence.

Δf_{RF}	Sensitivity improvements		
	$\beta = 1$	$\beta = 0.5$	$\beta = 0.2$
0.5 R_B	—	—	4.16
0.5 R_B (without adjacent channel)	1.2	4.8	5.21
1 R_B	10.4	10.14	> 18
1.25 R_B	15.2	> 15.6	>> 18

Table 1: Summary of the sensitivity improvements by RBS rejection in dB with respect to the no λ -shifting case in Fig.5(a)-(c), for $\text{BER} = 10^{-3}$

V. CONCLUSIONS

Wavelength shifting for coherent homodyne detection in ud-WDM PON has been proposed and successfully demonstrated, enabling the use of a single laser per transceiver even in presence of low Signal-to-Rayleigh-Ratios down to -2 dB.

Large λ -shifts, along with low Nyquist roll-off factors, translate into high RBS rejection as the spectral overlap decreases. Significant rejections, higher than 18 dB, were measured for channel separation as low as the data baud rate.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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