224 Gbit/s Coherent PON Downstream Using a Wavelength-Uncalibrated LO and Blind Locking During ONU Startup

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Abstract: We experimentally demonstrate a novel blind LO-locking technique for 224 Gbit/s coherent PON downstream that is applied during ONU startup and allows using wavelength uncalibrated LO lasers in the ONU module. © 2024 The Author(s)

1. Introduction

The startup for optical network units (ONUs) in coherent passive optical networks (PON) desires a new mechanism to allow for wavelength-uncalibrated laser as a local oscillator (LO). Such an LO approach is beneficially applied especially at the very cost-sensitive ONU side. One drawback of that approach is that due to fabrication tolerances, the exact emission wavelength of the LO intrinsically cannot be guaranteed, resulting in a wavelength ambiguity that needs to be overcome by adding a scheme with very limited additional complexity.

ITU-T SG15/Q2 is analyzing various technologies as part of the very-high-speed passive optical network (VHSP) supplementary project, G.sup.VHSP, targeting PON line rates between 100 Gbit/s and 200 Gbit/s, with a fiber reach of 20 km to 40 km [1]. Among the many technology candidates, in-phase and quadrature modulation (IQM) and coherent receivers (Rx) are considered potential solutions for VHSP (e.g., for ≥40 km and ≥35dB loss-budget). However, due to tight cost constraints the adoption of coherent technology in PON depends on the evolution of high-volume markets (e.g., data center (DC)). As an example: the adoption of coherent technology for both inter- and intra-data center applications [2] will allow PONs to leverage existing, mature component technologies, and will reduce the non-recurring engineering costs [3]. Nevertheless, tailoring of coherent systems to PON-specific requirements and complexity reductions without sacrificing a substantial system performance are still required.

Thus, in this paper, we propose to modify the coherent receiver schematics, e.g. from DC-transceiver, by adding a wavelength uncalibrated LO and a method to locate the downstream signal. In the literature some proposals to overcome the LO wavelength ambiguity are available, e.g. injection locking based on a Fabry-Perot laser diode [5]; a semiconductor optical amplifier (SOA) with a narrow optical filter [6]; a frequency-comb laser-based optical line terminal (OLT) transmitter (Tx) [7]; and a digital frequency offset (FO) estimation (FOE)-based LO alignment [8]. All these approaches increase the complexity of either the OLT transmitter or the ONU receiver, or they require an LO laser that is already closely matched to the transmit laser (e.g., up to a few GHz). Contrary, in our work, we propose and experimentally validate a blind LO-locking technique for an uncalibrated LO laser at the ONU side, enabling cost-effective 224 Gbit/s coherent PON downstream (DS) operation and ONU activation. The relationship between temperature and emission wavelength of the LO is unknown and the emission wavelength can be centered anywhere within a 4 nm-wide band.

2. Blind LO-Locking Technique

The ONU startup mechanism in our method requires blindly identifying the DS wavelength of the OLT transmitter so that the LO laser can be locked to this wavelength. A coherent PON architecture using an uncalibrated LO laser

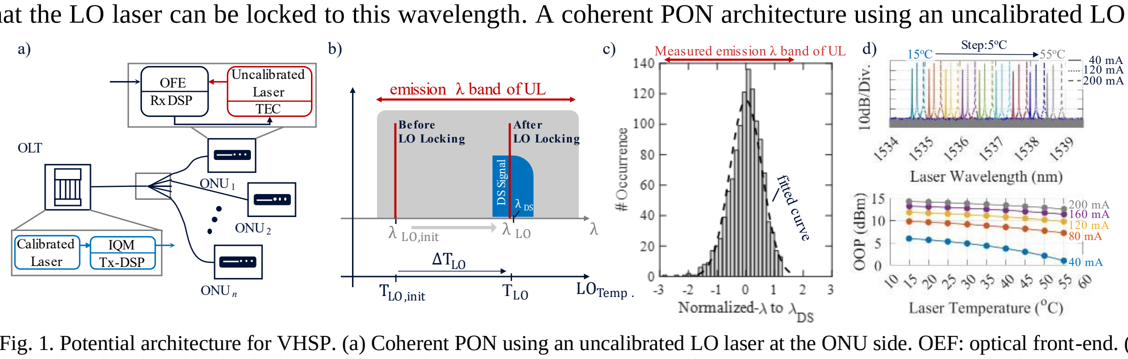

Fig. 1. Potential architecture for VHSP. (a) Coherent PON using an uncalibrated LO laser at the ONU side. OEF: optical front-end. (b) Illustration of the λ ambiguity for the uncalibrated laser (UL). (c) The histogram of the measured emission wavelength of over 1000 DFB lasers. (d) Characteristics of the DFB laser used in the experiment for different operating temperature and bias current.

at the ONU side and a dedicated wavelength-based transmit laser in the optical line terminal (OLT) is shown in Fig. 1 a). The wavelength alignment challenge for an uncalibrated LO laser is illustrated in Fig. 1 b). As an example case, the uncalibrated LO initially emits at an arbitrary wavelength $\lambda_{LO,init}$ (at temperature $T_{LO,init}$) within a wide emission band (gray shaded region) because of fabrication tolerances. The emission wavelength band is on the order of several nm, as illustrated by the measurement data in Fig. 1 c), which shows the emission wavelengths of over 1000 DFB lasers. As a result, the LO tone needs to be aligned with the DS signal centered at λ_{DS}. To avoid any significant increase in system complexity by LO-locking, we are limited to the information and control mechanisms available at the ONU transceiver (such as: electrical signal power / strength indicators, laser temperature, and bias current). Figure 1 d) shows the power characteristics of our LO laser with respect to laser temperature and bias current, both influencing the emission wavelengths. Here we observe that for a 200 mA laser bias current, the emission wavelength can be tuned over 4 nm by temperature with a 2 dB output optical power (OOP) penalty compared to maximum output power. The OOP penalty is significantly higher for lower bias currents.

We propose that each ONU performs three steps to acquire LO alignment with the DS signal during startup. In the first step, the ONU will perform a temperature sweep of the LO laser and simultaneously monitor the received electrical power at the analog-to-digital converter (ADC). The received electrical power will be maximized when λ_{LO} is coarsely aligned to the λ_{DS} at temperature T_{LO}. Next, the ONU performs a finer LO alignment using feedback from the digital signal processor (DSP). Note that the DSP-based FOE can resolve only few GHz offset (e.g., ±10 GHz « emission λ band of uncalibrated laser) [9]. Therefore, the blind coarse LO alignment using the temperature sweep is required for PON to ensure the LO is sufficiently close to λ_{DS}. Finally, the ONU will start the ONU activation mechanism, track slow changes, and perform fine LO adjustment using feedback from the DSP during operation.

3. Experimental Setup for Blind LO-Locking

We setup a proof-of-concept experimental setup to demonstrate and study the proposed blind LO-locking in a 224 Gbit/s coherent PON DS, see Fig. 2 a). At the OLT side, the transmitter consists of a fully calibrated micro-integrated tunable laser source (µITLS) with a laser linewidth of 100 kHz and a dual-polarization IQM that is fed by drive signals from a four-channel 88 GSa/s digital-to-analog converter (DAC) with 8-bit resolution. The test patterns generated as part of the transmitter DSP consist of two uncorrelated random sequences of quaternary phase shift keying (QPSK) symbols (644×512) at a symbol rate of 56 GBd having a root raised cosine spectral shape with a roll-off factor of 0.25. We emulate the optical distribution network (ODN) losses using a variable optical attenuator. To measure the received optical power, we use a 3 dB power splitter and an optical power meter before the integrated coherent receiver (Coh. Rx). We employ an uncalibrated DFB laser with a linewidth of 1 MHz as an LO laser. To adjust the laser temperature, we use a computer-controlled thermo-electric cooler (TEC) with a temperature stability of 0.01°C and a control frequency of 10 Hz. As an ADC, we employ a 4-channel 256 GSa/s real-time oscilloscope with an analog bandwidth of 42 GHz and 10-bit resolution. Finally, we apply the coarse and fine LO alignment technique to evaluate the FO and the bit error ratio (BER) performance of the DS signal.

4. Results of Blind LO-Locking

We performed various experiments to demonstrate blind LO-locking and validate the usability of the uncalibrated LO laser at the ONU side. In the first experiment, we measure the root mean square (RMS) of the signal captured with ADC for two different receiver bandwidths (BW), see Fig. 2 b). We observe a plateau and a single peak for a high-bandwidth receiver (e.g., Rx BW = 40 GHz » DS signal BW) and a low-BW receiver (e.g., Rx BW = 28 GHz ≤ DS signal BW), respectively, when the LO laser wavelength is in close proximity of the DS signal. The plateau leads to an ambiguous situation for the peak search algorithm. Therefore, we conclude that a high-bandwidth receiver requires digital filtering to reduce uncertainty. In the next experiment, we emulate the λ alignment ambiguity of an uncalibrated LO by changing the Tx laser frequency and investigate blind locking by changing the LO temperature.

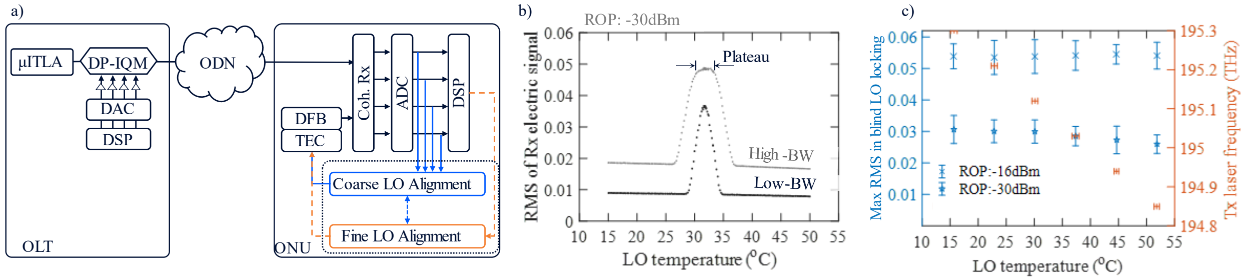

Fig. 2: (a) The experimental setup to analyze the blind LO-locking. (b) RMS of received electric signal as function of LO temperature. (c) Maximum RMS is found using the blind LO-locking in different Tx laser frequencies.

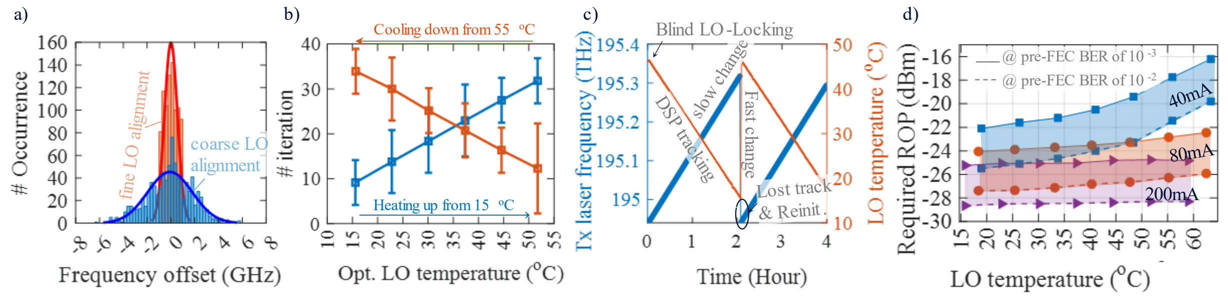

Fig. 3. Experimental results. (a) The histogram of the frequency offset after coarse alignment blind LO-locking and fine optimization using DSP feedback. (b) Required iteration to find the LO-locking using our blind LO-locking. (c) The emulated laser drift and the corresponding LO temperature. (d) The required received optical power at different pre-FEC BER levels for various LO bias currents and temperatures.

Figure 2 c) shows the maximum RMS value acquired in the coarse LO alignment step as a function of the LO temperature for various downstream OLT-Tx laser frequencies (see right y-axis) and for two different received ONU optical power (ROP) levels (indicated by markers). The bars indicate the variation across 50 different measurements for each Tx laser frequency. We find a linear relation with a slope of 0.094 nm/°C between the LO temperature required for LO-locking and the DS Tx laser frequency. The blue histogram in Fig. 3 a) shows the alignment accuracy after blind coarse LO-locking, with a residual FO of ±5 GHz. That accuracy is sufficient to activate the fine LO tuning mechanism applying the DSP-feedback. The red histogram in Fig. 3 a) shows an FO of ±1 GHz after DSP-aided fine LO alignment.

Figure 3 b) shows the required iterations to find the peak RMS of Rx signal as a function of LO temperature for two different scenarios: heating up the laser (blue) and cooling down the laser (red). The bars represent the variation observed in 50 measurements for each LO temperature, and the square symbol represents the mean value. As we can see, the number of required iterations depends on the chosen temperature tuning method and the optimum LO temperature. To simplify the possible reoccurring ONU startup, the optimum LO temperature can be stored in the firmware at every ONU startup and operation, reducing the temperature scanning window as well as the required number of iterations.

Next, we study the capability of DSP-based fine control to track slow changes, which we emulate by changing the Tx laser frequency after an initial blind locking phase, see Fig. 3 c). The Tx laser frequency is increased by 3 GHz per step corresponding to the blue curve labeled with "slow change". The experiment confirms that the ONU can track slow changes using DSP feedback. However, it cannot follow extremely fast frequency changes, which requires a reinitialization with the proposed blind LO alignment technique. In Fig. 3 d) we analyze the receiver sensitivity for different LO laser temperatures and bias currents with respect to two different pre-FEC BER thresholds. Since the proposed LO-locking is achieved by temperature tuning, a weak temperature dependence of the LO's OOP is crucial to keep receiver sensitivity penalties low. In our setup, we find a small receiver sensitivity penalty of 0.5 dB when comparing the most extreme temperature levels (15°C and 60°C) at a bias current of 200 mA because the coherent receiver sensitivity already saturates at such LO power levels (~13 dBm). As predicted, we observe a higher penalty towards lower bias currents because of stronger LO power variations with temperature.

5. Summary

We introduced and experimentally demonstrated that the wavelength-alignment challenge caused by using a cost-effective wavelength-uncalibrated LO laser can be overcome by our proposed novel locking technique. We demonstrate that the uncalibrated LO can be blindly locked to the DS signal with a remaining FO of ±5 GHz. This remaining FO can be further reduced to ±1 GHz by using a DSP-assisted fine alignment. We observe a small 0.5 dB sensitivity penalty under high LO bias currents associated with the power dependence of the DFB thermal tuning process.

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