Real-Time Bidirectional Coherent Point-to-Multipoint Passive Optical Network

Tobias A. Eriksson(1), Telmo Almeida(1), Henrik Åhlfeldt(1), M. Sezer Erkılınç(1), Xi Chen(1), Johan Hellman(1), Ales Kumpera(2), Amir Rashidinejad(2), Antonio Napoli(3), Chris R. S. Fludger(3), Per Lembre(1), Johan Bäck(1), Magnus Olson(1), Dave Welch(4)

(1)Infinera Sweden, teriksson@infinera.com (2)Infinera Canada (3)Infinera Germany (4)Infinera USA

Abstract *The first real-time demonstration, including FEC and client traffic, of point-to-multipoint transmission over a single fiber passive optical network with two pluggable 100G Leaf modules communicating with a single 200G Hub module is presented. ©2023 The Author(s)*

Introduction

Passive optical networking (PON) has enabled operators to roll out commercial and residential broadband services at attractive prices. Current PON applications use intensity-modulated direct detection (IM-DD) with time-division-multiplexing-access (TDMA) solutions to allow a single receiver in a central office to aggregate traffic from multiple endpoints. Solutions using 25G and 50G PONs are feasible without the use of advanced DSP[1]–[3], leveraging 100 and 400Gb/s Ethernet data center intra-connect ecosystem, adopted by IEEE 802.3 and 802.3bs[4]. A higher capacity allows new use cases to be addressed, such as multi-access edge computing and mobile transport for radio access networks[5]. However, at some point, the IM-DD technology will no longer be able to scale to higher capacities.

Coherent PON has been demonstrated, focusing on 100G PONs[6], employing 4×25 Time-FDM sub-channels. Additionally, bi-directional (BiDi) transmission provides significant cost savings by halving the required number of fibers deployed and easing fiber management[7]. We investigate a coherent PON solution based on digital subcarrier multiplexing (DSCM). DSCM has been used in a wide range of applications, such as flexible spectrum allocation[8], waterfilling[9], ROADM filter penalty mitigation[10],[11], nonlinear mitigation[12],[13], and point-to-multipoint communication[14]–[16]. Using subcarriers (SCs) to enable BiDi transmission at the same frequency channel on single fiber systems has been proposed in[17] and experimentally verified in[18].

In this paper, we demonstrate, to the best of our knowledge, the first real-time, coherent bidirectional transmission system based on DSCM with two 100G pluggable Leaf modules communicating with a single 200G pluggable Hub module. This solution solves many of the issues with IM-DD PON: scalable up to metro core networks, no limit due to chromatic dispersion, avoids issues with back-reflection in single-fiber links. Further, our approach does not require separate Tx and Rx lasers as in other coherent single-fiber/bidirectional solutions[7],[19]. This also brings potentially low asymmetry in propagation time in up- and downlink, important for e.g. precision time protocol applications[20]. The modules operate at the same WDM channel using different SCs in the up- and downlink, mitigating impairments arising from reflections and Rayleigh scattering. The system is operating on a PON testbed and includes legacy 10G channels. Error-free end-to-end client traffic was observed over 3 days. The unique benefits of digital subcarrier-enabled pluggables are further featured, such as SC gain vs. Q optimization and re-configurable network traffic.

Experimental Setup

The transceivers used in this study are 400G XR CFP2 pluggable modules[14],[16], capable of using up to 16 SCs at ∼4 GBaud which amounts

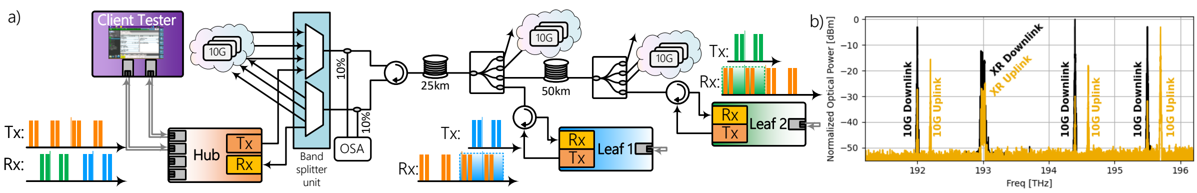

Fig. 1: (a) Experimental setup for the passive optical network. The test-bed consists of first 25 km of fiber followed by a 1-by-4 splitter unit. The branch used for the experiment then continues over 50 km of fiber followed by a second 1-by-4 splitter unit. (b) The optical spectrum (with arbitrary power scaling) in the down- and uplink.

to 400Gb/s if 16QAM modulation is configured. Each module contains real-time DSP/FEC ASIC and integrated transmitter-receiver optical sub-assembly, housing and control circuits. The DSP is divided into 16 parallel lanes, one per SC[21].

For single fiber operation, different SCs are used in the up- and down directions to avoid back-reflection issues. The Hub module is configured at 200G using alternating SCs in groups of two as indicated in Fig. 1. The FEC frames are interleaved over the groups of two SCs which aids to even out any performance difference between SCs. The Hub Tx signal is broadcast to both Leaf modules. The Leaf modules are assigned to use 8 SCs each, 4 for Rx and 4 for Tx. They tune their laser frequency to be centered around their assigned SCs. Only after the Leaf modules confirm successful wave-locking and acquisition on the Rx side do they turn their Tx signals on. Each module uses a shared Tx/Rx laser to save cost, real estate, power dissipation, and simplify frequency locking in P2MP operation. The Leaf modules are actively locked to the Hub laser, enabling extremely dense packing of SCs. As a result, as demonstrated later, bringing up new Hub⇔Leaf traffic is done without disturbing the traffic on any currently commissioned SCs.

In the uplink direction, the Leaf signals are aggregated using passive couplers. The full optical signal consisting of both Leaf signals is jointly detected by the Hub module (i.e., using the same optical front-end and DSP). To test end-to-end traffic, two 100G Ethernet client tester ports are used together with 100G pluggable modules. The client pluggables are connected to the Hub host board, while traffic is looped-back on the Leaf sides such that the each tester port corresponds to round-trip traffic for Hub ⇔ Leaf 1 and Hub ⇔ Leaf 2, respectively.

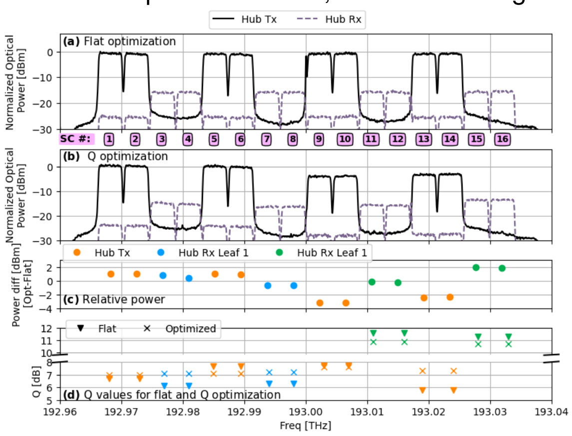

Fig. 2: Spectra for Hub Tx (solid line) and Hub Rx (dashed line) after (a) optimization for flat spectra and (b) optimization based on Q values. (c) Relative power comparison between flat and Q-based optimization. (d) The respective pre-FEC Q values per SC after the two optimization schemes. Note that for (a) and (b) the relative power scale between Tx and Rx spectra is arbitrary.

The passive optical network testbed is shown in Fig. 1(a). At the OLT site, the Hub module is multiplexed together with legacy 10G channels using a passive band splitter unit. The multiplexed signal is then routed through a circulator to 25km of single mode fiber (SMF) followed by a 1×4 splitter. Connected to one arm of the splitter is another circulator routing the signals to the Leaf, designated as "Leaf 1". Another arm of the first splitter is connected to the 10G traffic setup, while another continues to route the signals through 50 km of SMF and another 1×4 splitter. Two arms of this second splitter are also used for the legacy 10G signals while another arm is connected to a circulator and a second Leaf, denominated as "Leaf 2". The use of circulators allows for uplink and downlink signals to be multiplexed and travel in the same fiber. To monitor the Hub Tx and Rx signals, the 10% coupler taps are connected to a high-resolution OSA. The Hub Tx and Rx spectra are shown in Fig. 1(b) (with arbitrary power scaling for illustration purposes).

Results

The first step was to optimize the launch power per SC from each transceiver by adjusting the Tx output power and DSP equalization. Two different optimization targets were compared: flat spectrum and flat Q values. The Hub Tx and Rx spectra (with arbitrary scaling) are shown in Fig. 2(a) for flat spectrum and (b) for Q optimization. Note that in the Hub Rx spectra, the reflections from the SCs traveling in the opposite direction can also be observed. Fig. 2(c) shows the relative power dif-

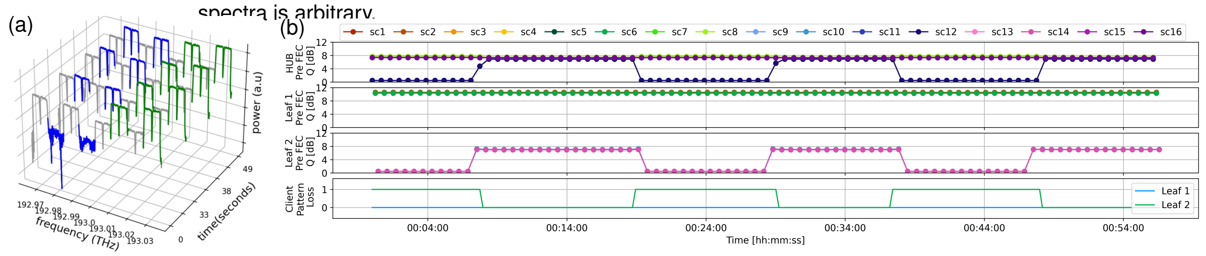

Fig. 3: (a) Time evolved spectrum showing Leaf 2 (blue) being brought up while Leaf 1 (green) has commissioned traffic running. (b) Pre-FEC Q values for all used SCs for Hub, Leaf 1 and Leaf 2 as well as client pattern loss for the traffic between Hub and both Leafs. Data are shown for three cycles of Leaf 2 being brought up and down with a few minutes soak in-between each event.

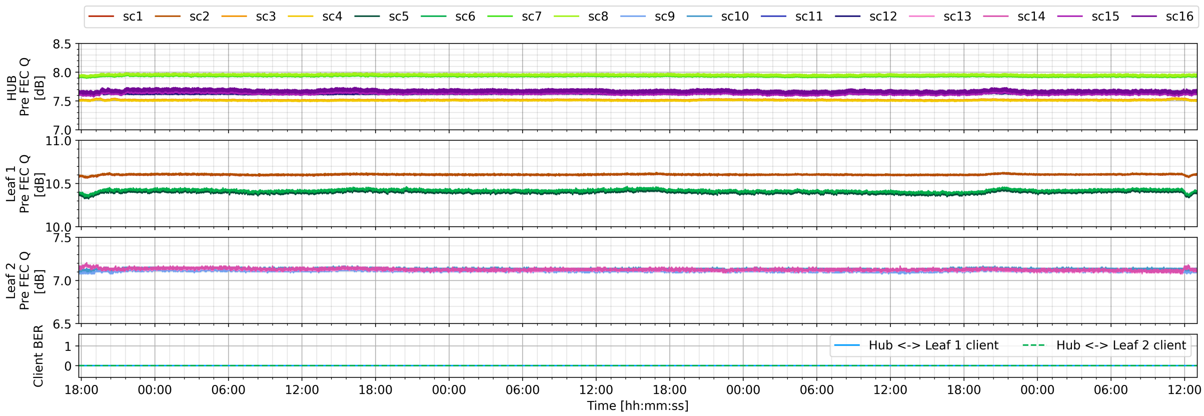

Fig. 4: Logged data over more than 3 days of both Leafs and Hub pre-FEC Q values, as well as client BER data logged from the traffic instrument.

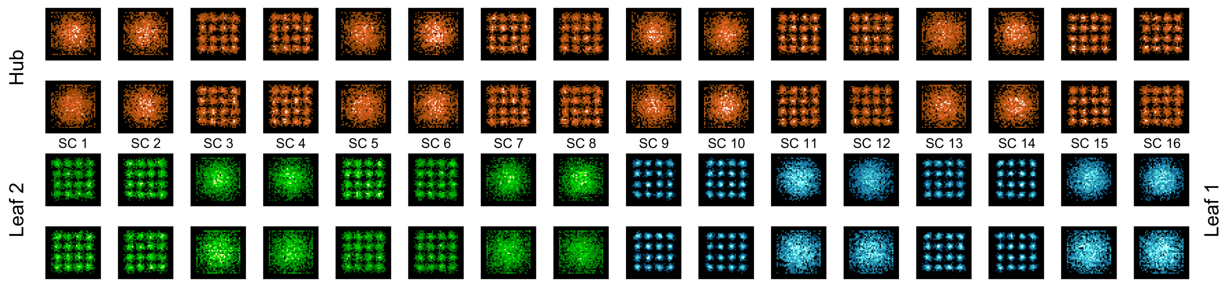

Fig. 5: On the top two rows, the orange-colored constellations for all 16 SCs (both x and y polarizations) are taken at the Rx of the Hub. The two bottom rows show the received constellations at Leaf2 (green, left side) and Leaf1 (blue, right side). Leaf 2 receives SCs 1,2,5,6 from the Hub and Leaf 1 SCs 9,10,13,14.

ference of the two schemes and Fig. 2(d) the corresponding Q values. The Q optimization yields the best performance across all SCs in both directions, improving Q values by more than 1 dB for the most performance hit SCs. In the following experiments, the Q optimization scheme was utilized exclusively.

The next test was to demonstrate that Leaf traffic can be commissioned and decommissioned without interfering with the traffic on another Leaf. In Fig. 3(a), a time resolved spectrum of Leaf 2 being brought up is being shown together with the SCs from Leaf 1. The optical spectra were taken at the Hub Rx side. In Fig. 3(b), the pre-FEC Q values for Hub, Leaf 1 and Leaf 2, are shown together with the loss of client patterns for client traffic between Hub ⇔ Leaf 1 and Hub ⇔ Leaf 2. Leaf 1 is continuously running, while Leaf 2 is periodically turned on and off over the course of one hour. Naturally, the Q values for Leaf 2 drop to zero when the service is brought down. The same applies to the SCs received from Leaf 2 on the Hub side. The Q values for the Hub and Leaf 1 remain the same when Leaf 2 is being turned on or off, and client traffic errors or loss of patterns are not observed. This demonstrates that the commissioning of new Leaf links is non-service impacting for the existing traffic in our P2MP system. We also tested the system with and without legacy 10G channels present and did not see any impact on performance.

Long-term testing of the full system was also performed. In Fig. 4 the pre-FEC Q values for Hub, Leaf1 and Leaf2 are shown together with the bit-error-rate of the two 100G clients. All pre-FEC Q values are well above the FEC threshold. The corresponding constellation plots are shown in Fig. 5. The test was carried out leaving the traffic running for over 3 days. The total optical power received (excluding the 10G channels) were -22.4 dBm for the Hub, -11.3 dBm for Leaf1 and -27.1 dBm for Leaf2. Note that the power includes the power of all 8 SCs on the leaf-side and that these measurements intrinsically include the reflected power in the SCs traversing the opposite direction. There were no disruptions on either the line nor the client side during the long-term test.

Conclusions

We demonstrate pluggable modules (based on prototype 400G XR CFP2s) with DSCM as a way to introduce coherent optics into PONs with bi-directional traffic over single-fiber. Real-time point-to-multipoint traffic over 3 days, including FEC and end-to-end client traffic, was demonstrated using a single 200G Hub module communication with two 100G Leaf modules, located at different branches of the network.

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