OFDM/WDM PON With Laserless, Colorless 1 Gb/s ONUs Based on Si-PIC and Slow IC

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***Abstract*—We introduce a next-generation long-reach access optical network (35 dB loss budget +2 dB margin) delivering up to 40G/40G per passive 1:256 optical distribution network, supporting symmetrical 1 Gb/s rates per home user or up to 40 Gb/s for business users (e.g., enterprises, antenna sites). The proposed system is based on a novel spectrally efficient orthogonal frequency division multiplexing/wavelength division multiplexing OFDM/WDM architecture symmetrically using 16-QAM OFDM polarization diversity in both the downstream and upstream in order to serve low-cost energy-efficient symmetric 1 Gb/s optical network units (ONUs), which are self-coherent, laserless, colorless, and tunable-filter-free. Each ONU comprises a standard semiconductor optical amplifier (SOA), a silicon-based photonic integrated circuit (PIC), and mixed-signal electronic integrated circuits (ICs) performing the signal processing at a relatively slow rate as compared with the overall passive optical network (PON) throughput: digital to analog converters (DACs) and analog to digital converters (ADCs) at 417 MS/s for the home user ONUs.**

***Index Terms*—Access network; DFT-spread OFDM; OFDM PON; Optical communication; Orthogonal frequency division multiplexing (OFDM); Passive optical network (PON); WDM PON.**

I. Introduction

Multiple alternatives have been considered for the next-generation passive optical network (NG-PON2) [1], among them time division multiplexing (TDM), wavelength division multiplexing (WDM), time wavelength division multiplexing (TWDM), coherent WDM, and coherent and direct-detection orthogonal frequency division multiplexing (OFDM) [2–15]. TWDM has been recently selected by the Full Service Access Network (FSAN) forum as the preferred approach toward NG-PON2; however, the other systems are still "in play" for future phases. Our interest here is in coherent OFDM PON, as pioneered by the NEC group of Cvijetik *et al.* [7,10,12,14], which demonstrated 40–108 Gb/s PON transmission, recently further developed in the FP7 Accordance project [6,13].

Upstream (US) OFDM transmissions onto a pilot launched from the optical line terminal (OLT) were introduced in [16], spectrally separated from the downstream (DS) transmissions that were carried on a different wavelength.

Here we aim to show that a *self*-coherent OFDM(A) PON may be realized based on tightly spectrally interspersing US and DS 16-QAM transmissions, without lasers in the optical network units (ONUs). This is to be contrasted with the recent *fully* coherent PON [17], necessitating a local oscillator (LO) in each ONU.

A recent PON tutorial [1] acknowledged the unique OFDM PON operational advantages but has referred to it as an "*expensive and complex approach*." Here we aim to reverse this common perception by constructing a new OFDM next-generation PON system with compact low-cost Gb/s ONUs and simplified OLTs. We show that OFDM-based PONs may be re-engineered based on a fresh top-down system architectural concept redefining the spectral structure, coupled with opto-electronic integration at the subsystem and component levels; mixed-signal electronic low-complexity techniques enable slow digital signal processing (DSP) with sampling rates of just 417 MS/s for the analog to digital converters (ADCs) and digital to analog converters (DACs) in ONUs. This compelling OFDM PON technology may approach low cost and low power consumption by major reduction of clock rates in the ONU and OLT, taking advantage of efficient analog front-ends and 16-QAM OFDM spectrally efficient frequency division multiple access (FDMA). The proposed PON system

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consists of a novel combination of OFDM(A) and ultra-dense WDM.

The OFDM(A)-WDM-based PON system (subsequently abbreviated as OTONES as per the EU project under which it is being investigated) supports three classes of networks: class I, 1:64 10G/10G; class II, 1:128 20G/20G; class III, 1:256 40G/40G (this class exceeds the NG-PON2 FSAN requirements). The OLT bandwidth and cost proportionally increase across classes, whereas ONU costs only marginally increase. All three classes support 1 Gb/s per ONU burst, subject to statistical multiplexing, but they trade off average throughput, passive fan-out, and costs.

A compressed preview of the proposed OTONES architecture has been presented in [18]. This paper elaborates the novel system concept, focusing on the top level description of the topological and spectral architectures of the proposed OTONES PON system, as well as its key subsystems and components: OLT, remote hub (RH), ONU, and its novel photonic integrated circuit (PIC) and mixed-signal application specific integrated circuit (ASIC).

The paper is structured as follows. Section II overviews the key OTONES attributes. The system and spectral architecture and subsystems structure and functionality for class I 10G/10G are described in Section III. It is this version that is currently in the process of being experimentally demonstrated. The OTONES rate evolution ($10G/10G \rightarrow 20G/20 \rightarrow 40G/40G$) over the three service classes will be elaborated in Section IV.

II. Key OTONES PON Attributes

Capacity: OTONES supports up to 40G/40G (G = Gb/s) US/DS aggregate rates serving up to 256 users (subs) per 50 GHz, sustaining bursts of 1G per sub. The bandwidth allocation is flexible and dynamic, enabling multiservice as well as multioperator residential/enterprise/backhaul networks.

Traffic symmetry: The OTONES 40G/40G class III for 256 subs capability conforms with FSAN's NG-PON2 in the DS, yet in the US it quadruples the rate (provides 40G rather than 10G), yielding *fully symmetrical* ($US{:}DS = 1{:}1$) transmission.

Single wavelength (λ) *full duplex*: OTONES is the first OFDM PON to duplex both the DS and US transmissions of each OLT over a single-λ with 50 GHz spacing [free of *Rayleigh backscatter* (RBS) noise penalty]; other PON systems typically deliver the DS/US over dual-λ, which are far separated (1.3/1.5 μm). OTONES then eliminates the dual-color optical DS/US filters from the ONU and OLT.

Spectral efficiency (SE): Bidirectional SE is defined here as

$$\mathrm{SE_{bidir}} \equiv \frac{\mathrm{DS[b/s]} + \mathrm{US[b/s]}}{\{\mathrm{DS} \cup \mathrm{US}\}[\mathrm{Hz}]} = \frac{40[\mathrm{Gb/s}] + 40[\mathrm{Gb/s}]}{50\ \mathrm{GHz}} = 1.6[\mathrm{b/s/Hz}]. \tag{1}$$

The OTONES SE of 1.6 b/s/Hz is distinctly higher relative to other PONs. This is achieved by packing up both US and DS into a single-λ spectral design with 16-QAM OFDM. In addition, single-λ duplexing saves the spectral guardbands conventionally required for the dichroic filters separating the 1.3 and 1.5 μm US and DS bands. In comparison, the recent TWDM proposal [1] viewed as the primary solution for NG-PON2 carries 40G/10G over four bands of 100 GHz around 1.3 μm for DS plus four bands of 100 GHz around 1.5 μm for US. Not accounting for various filtering guardbands, this yields

$$\mathrm{SE_{bidir}}\{\mathrm{TWDM}\} = \frac{40[\mathrm{Gb/s}] + 10[\mathrm{Gb/s}]}{(4 \cdot 100 + 4 \cdot 100)[\mathrm{GHz}]} = 0.065[\mathrm{b/s/Hz}]. \tag{2}$$

Colorless, laserless self-coherent ONU: OTONES effectively uses self-coherent detection, eliminating the expensive tunable laser from the ONU. By using only a 10 nm wide optical filter (OF) after the semiconductor optical amplifier (SOA), the ONU is practically rendered colorless.

Long reach: Total loss budgets of 40, 38.5, and 35 dB were analytically calculated and verified by simulation for classes I, II, and III (10G, 20G, and 40G), respectively [yielding a 2 dB margin above the target signal-to-noise ratio (SNR) for $\mathrm{BER} = 10^{-3}$]. The overall extended loss budget of 35 dB comprises the 29 dB ODNs and the 6 dB metro feeder.

Impairments tolerance: By design, immune to Rayleigh and Brioullin backscattering, dispersion, and DS phase noise.

Remodulation without reflective semiconductor optical amplifier (RSOA): The laserless ONU reuses the received DS light by means of a novel patented remodulation scheme, replacing the RSOA with a conventional SOA copackaged with a silicon-PIC-based *in-phase and quadrature* (IQ) modulator, enabling advanced modulation formats US.

Novel OFDMA supports coherent 16-QAM OFDM US: Prior OFDM PONs were based on intensity modulation US, wasting SE and sensitivity. Here we propose and simulate a single-sided *coherent* 16-QAM OFDMA multiple access system in the US, modulating phase in the US as well as amplitude, based on interweaving in frequency disjoint sets of subcarriers launched from different ONUs and time-frequency synchronizing the distinct US transmissions from the individual ONUs. To the best of our knowledge, this is the first reflective system proposal managing to utilize the phase degree of freedom (DOF) in the US in addition to the intensity DOF, while operating on reflected light.

In this paper we focus on the physical layer underlying the US (DS) transmission from (to) any particular ONU to (from) the OLT. The OFDMA multiple access will not be elaborated here, but it was briefly previewed in [18] based on the OLT aggregating and detecting a composite US OFDM signal that is cooperatively generated by multiple ONUs launching individual OFDM subcarriers.

Simplified ONU/OLT optics: The OTONES ONU and OLT optics are photonically integrated as PICs, and the ONUs operate at much lower electrical bandwidths (BWs) than other PON systems.

Low cost/power by electronic BW reduction: At the ONU, the electronic sampling for ADC (DAC) data conversion is remarkably low (relative to the 10G, …, 40G aggregate throughput): just 417 MS/s invariably in all three classes. This relatively low ONU sampling rate provides major cost- and power-consumption reductions in the ONU DSP, dispelling the notion that 40G/40G OFDM PON must necessarily incur high ONU costs. Notice, however, that migrating from a class I 10G/10G system to the 20G/20G and 40G/40G higher classes II and III requires proportionally faster OLT electronics (OLT ADC/DAC rates are 3.33, 6.66, and 13.3 GS/s for classes I, II, and III, respectively). The ONU optical modulation and detection rates must also increase across classes (see Section IV for details). Nevertheless, the ONU ADC and DAC rates remain invariant at 417 MS/s, enabling slow signal processing and reduced ONU power consumption across all three classes.

Coexistence: OTONES is backward compatible with existing passively split outside plant and interoperable with legacy NG-PON1 (XGPON) and earlier PONs, allowing reuse of the FSAN class B+ passive access plant on the output ports of the RH.

III. OTONES Operating Principle and Subsystems

We present the novel network topology and subbanded spectral architecture (Fig. 1). The network layout [Fig. 1(A)] comprises the OLT, a metro feeder (trunk) fiber, RH feeding multiple passive split optical distribution networks (ODNs), and the ONUs associated with each ODN. The physical topology and spectral structure are closely coupled; thus they will be described together. The description in this section pertains to the lowest 10G/10G

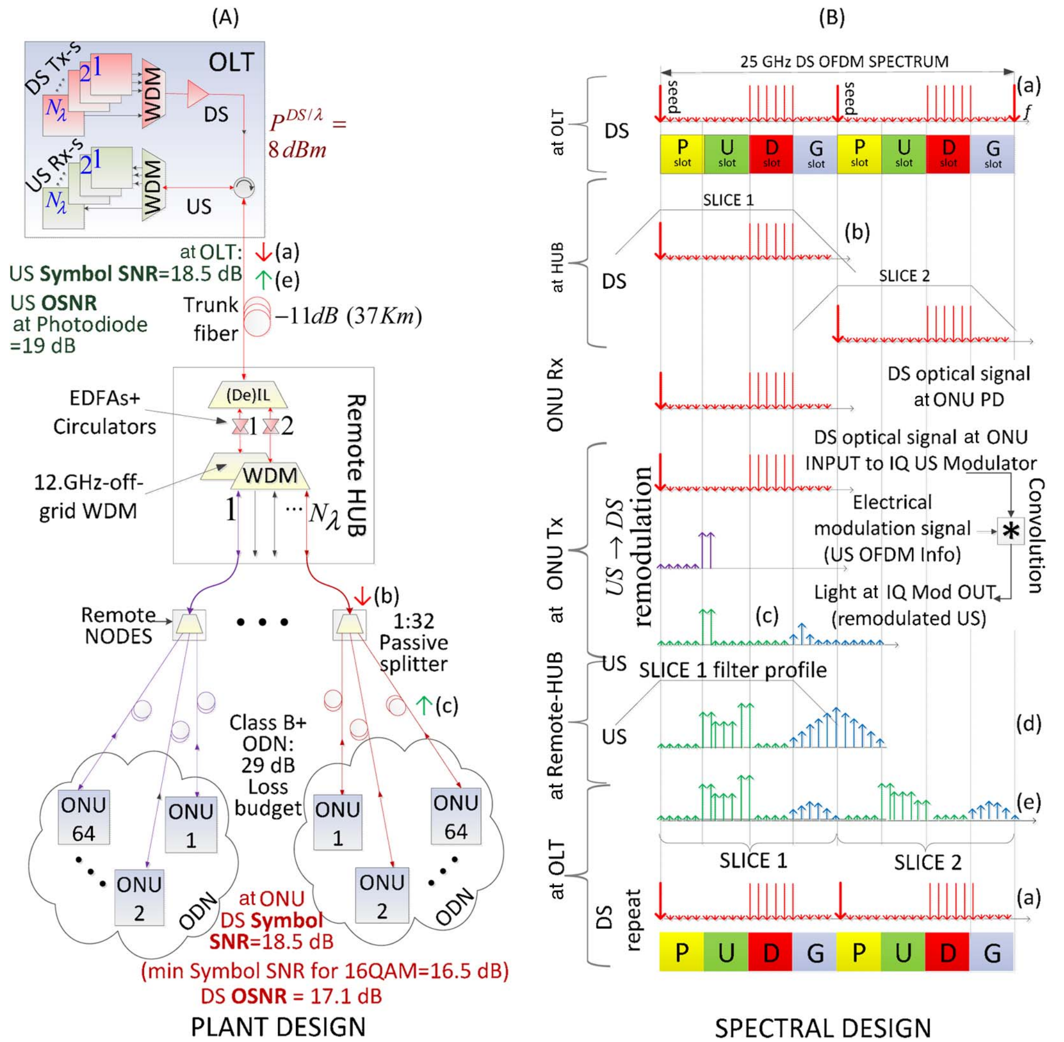

Fig. 1. Class I OTONES network and spectral design. (A) Plant: a single subnetwork (served by one wavelength out of many) comprising OLT, RH, and two passive ODNs (each ODN containing up to 64 ONUs). (B) Spectral design associated with two ODNs: (a) DS at OLT output. Downward arrows mark OFDM tones with sparse spectra containing two pilot (seed) tones and two D slots with nonzero tones. (b) Fractional wavelength demux at RH. (c) Remodulation at ONU Tx and single ONU US output. Marked by upward arrows for US signal. (d) 3.125 GHz US signal aggregating (up to) 64 ONUs per ODN. (e) US signal aggregating 2 ODNs per 25 GHz wavelength. A 13 dB loss budget is dedicated (extra to the total 35–40 dB end-to-end loss budget) to RH components; RH OAs have gains of 34 (24) dB in DS (US).

OTONES service class supplying symmetrical 10 Gb/s per ODN.

A. Spectral Hierarchy and Data Rates

The available spectrum is structured over the ITU-T G.694.1 dense wavelength division multiplexing (DWDM) flexi-grid as follows (Fig. 2): 12.5 GHz *slices*, viewed as fractional or fine subwavelengths; *slots* of BW $W_{\text{slot}} = 3.125$ [GHz]; and *streams* of $(1/10)W_{\text{slot}} = 312.5$ [MHz] BW. Throughout the paper the BW of a spectral interval refers to its full spectral support.

Each slice comprises four spectral slots marked P (pilot or seed), U (US), D (DS), and G (guardband). The D and U slots, carrying active data DS and US, respectively, are digitally partitioned into 10 spectral streams each. The throughput per stream is up to 1 Gb/s US and DS; thus each slot carries 10 Gb/s bidirectionally. The targeted OTONES SE is very high compared to other PON systems: 40G/40G over 50 GHz (four slices of 10G/10G each over 12.5 GHz). Within the D and U slots a "local" SE of (10 Gb/s)/(3.125 GHz) = 3.2 b/s/Hz is achieved by bidirectionally transmitting 16-QAM. Starting with the ideal SE of 4 b/s/Hz for 16-QAM, our implementation incurs a 20% transmission *overhead* (OH), allocated to FEC, cyclic prefix (CP), and pilot tones, reducing the ideal 4 b/s/Hz to 3.2 b/s/Hz. Considering the bidirectional SE averaged per slice [Eq. (1)], the presence of P and G guardbands dilutes it down by a factor of 2, to 1.6 b/s/Hz. Notice that this net bidirectional SE is more than an order of magnitude higher than the low SE [Eq. (2)] of the NG-PON2 TWDM variant.

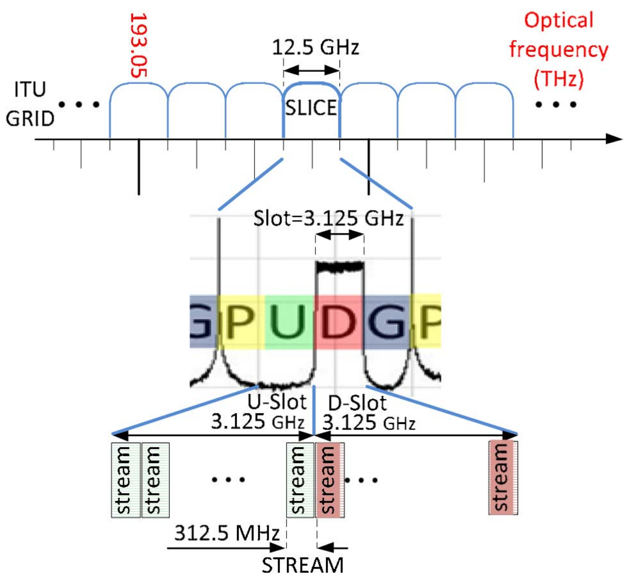

Fig. 2. Class I OTONES DS signal on the ITU-T G.694.1 flexible WDM grid, consisting of multiple 12.5 (GHz) bands (referred to here as *slices*) at center frequencies $193.1 + n * 0.00625$ THz (for index, $m = 1$, indicating one ITU BW granularity unit of 12.5 GHz). Each slice further consists of P, U, D, G slots and streams as indicated. The finest subdivision of the "stream" carries 1 Gb/s bidirectionally, using symmetric US/DS 16-QAM OFDM.

B. OLT

In the DS direction, the OLT essentially generates an ultra-dense WDM signal composed of contiguous 12.5 GHz slices on the ITU-T G.694.1 flexi-grid, with each slice carrying a sparse *discrete Fourier transform spread* (DFT-S) OFDM signal in its D slot. In addition an optical pilot tone (seed) is inserted at the left end of the P slot, while the rest of the slice spectrum is left empty. The G slot is a guardband, and the P slot is also largely empty except for the aforementioned seed tone. The U slot is also empty, to be filled up by the ONUs' US transmissions.

In the US direction, each ONU transmits data over a fraction (up to 1/10th) of the U slot. The OLT demultiplexes the received ultra-dense WDM multiplex, routing the slices to distinct physical receivers. The received U slot of each slice is filled up with multiple US signals generated by all ONUs associated with the ODN, whereby the ONU substreams are juxtaposed in frequency to fill up the U slot. The composite OFDM signal is demodulated by the OLT.

1) OLT Opto-Electronic Design: From an implementation perspective, various OLT opto-electronic designs are possible. In this paper we shall assume that the OLT processing handles one slice (12.5 GHz) at a time, e.g., by means of slice transceiver cards, each comprising a D-slot Tx and a U-slot Rx.

The ASICs of the slot Tx and Rx are baseband ones, over the two-sided spectral range $\{-W_{\text{slot}}/2, W_{\text{slot}}/2\}$. The slot Tx and Rx then have a two-sided baseband BW W_{slot} (i.e., a one-sided BW $W_{\text{slot}}/2$ corresponding to an OLT ADC/DAC Nyquist rate of $W_{\text{slot}} = 3.125$ [GHz]).

In contrast, the D slot and U slot carry bandpass single side band (SSB) signals, when referenced to the P-slot seed (optical carrier) position, which is viewed as DC of the complex envelopes: the U-slot signal resides in the bandpass $\{W_{\text{slot}}, 2W_{\text{slot}}\}$ with center frequency $1.5W_{\text{slot}}$, whereas the D slot resides in $\{2W_{\text{slot}}, 3W_{\text{slot}}\}$ with center frequency $2.5W_{\text{slot}}$.

The OLT [Fig. 3(a)] comprises two mutually locked 12.5 GHz combs (the generation of which from a narrow linewidth laser is not illustrated in the figure). The "P-comb" provides the P-seed frequencies of adjacent slices, whereas the "U-comb" provides spectral lines in the centers of the U slots of adjacent slices. These combs are deinterleaved into "P-lines" and "D-lines." In each slice transceiver, a P-line (a single spectral line of the P-comb) is used as a CW source for the P and D slots, whereas a U-line is used as an LO in homodyne detection of the U slot. The slot Tx modulates the data onto the D-line to fill up the D slot, driving the optical IQ modulator by an electronic SSB-modulated signal. This electrical signal is generated by an RF SSB IQ modulator leading from the OLT D-slot Tx DAC outputs to the two electrical ports of the photonic IQ modulator.

The P-line is used to inject the P-seed pilot as well as E-O modulate the D-slot electrical data onto it, electrically SSB upshifted by $2.5W_{\text{slot}}$ to the right of the P-seed spectral line. To enable the OLT E-O modulator to pass through the

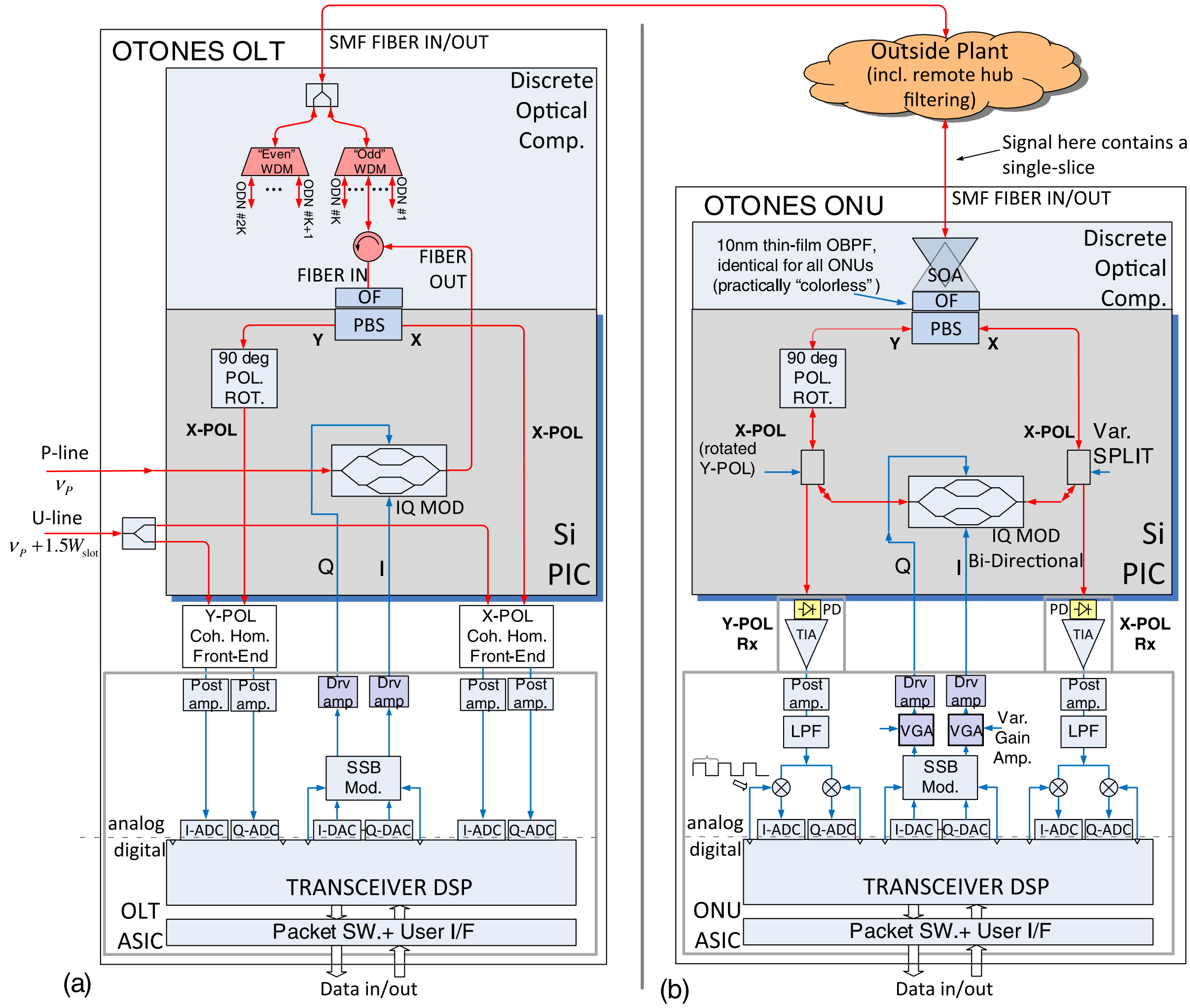

Fig. 3. OTONES integrated transceivers: (a) OLT and (b) ONU.

P-seed spectral line (while also modulating the D-slot data onto it), the modulator is intentionally detuned off the operating point of full carrier suppression.

The D-slot signal generated by the slot Tx along with the injected P-seed (which is passed through by the E-O modulator) propagate DS and are self-coherently detected in the ONU without requiring an LO laser, but rather using self-heterodyne detection with the P-seed as remotely supplied LO from the OLT.

The slot Rx in the OLT detects the received U slot of the slice by dual polarization coherent homodyne, using the "U-comb" as an LO. The mixing products generated in the photodiode pairs are low-pass filtered around the baseband (rejecting mixing products due to spurious signals outside the U slot), where they are digitized and processed by the U-slot Rx mixed-signal electronic integrated circuit (IC) at a Nyquist rate of W_{slot} (sampling rate of 3.33 GS/s including oversampling).

2) Energy Efficiency of our OLT Design: Our RF upconversion + homodyne detection with U-line technique enables processing the U-slot and D-slot signals around the baseband. Alternative more straightforward but far less efficient approaches have been initially considered in the course of our investigation.

A far less efficient "brute-force design I" would be a straightforward extension of long-haul OFDM techniques, generating and detecting the PUDG slice OFDM spectrum digitally with IQ signals occupying the full 12.5 GHz BW (at sampling rates exceeding 25 GS/s), which would have considerably increased the OLT transceiver cost and significantly reduced the resolution of the high-speed ADC/DAC and therefore degraded signal quality.

A somewhat improved "brute-force design II" attempts to take advantage of the sparseness of the PUDG spectral structure, generating an optical line at the P-seed frequency filtering and digitizing the transmitted and received spectra just from DC (corresponding to the P-seed) to the highest frequency of $2W_{slot}$ for the U slot and $3W_{slot}$ for the D slot. Brute-force digital–analog interfaces for these signals would have required Nyquist rates of $3W_{slot}$ for the DAC and $2W_{slot}$ for the ADC. These are still excessive rates to be compared with our efficient Nyquist rate of W_{slot} for the slot Tx and Rx DACs and ADCs, which operate around baseband, with a one-sided BW of just $(1/2)W_{slot} = 1.56$ GHz enabling affordable sampling rates as low as 3.33 GS/s for ADC and DAC data/conversion, as well as using clock rates at a fraction thereof for the DSP within the transceivers. Notice that the incremental cost and power consumption of the proposed RF upconversion enabling our scheme are relatively low and may be incorporated in mixed-signal designs in the analog portion of the mixed-signal ASIC of the baseband transceiver, digitizing the 3.125 GHz spectra of the U and D slots at bare minimum sampling rates of 3.33 GS/s. This "slow-down" of electronic speeds bodes well for the energy and cost efficiencies of the OLT. Similar "reduced RF" policies have been considered in [3,6], but here we provide a comprehensive US/DS solution.

3) OFDM Structure: The OFDM (inverse) fast Fourier transform [(I)FFT] size is 1024 (Fig. 4); however, the 32 subcarriers at both ends of the slot are nulled out (leaving 960 active subcarriers). The nulled-out subcarriers provide for ADC/DAC oversampling (without costing SE, but requiring a 1024/960 faster processing clock), while the inner 960 data subcarriers fill up the D slot of 3.125 GHz BW in the DS and the U slot of 3.125 GHz BW. Both the US and DS have the same OFDM structure, symmetrically conveying the aggregate 10 Gb/s data rate per slot in each direction. The DAC in the D-slot Tx of the OLT then has the same sampling rate as the ADC of the U-slot Rx, namely, 3.33 GS/s inclusive of oversampling.

4) DFT-S OFDM: Although the system may be realized by means of plain OFDM, it is advantageous to adopt the DFT-S [19] variant of OFDM (DFT-S OFDM) for DS transmission (Fig. 4), effectively partitioning the respective D-slot spectra into 10 spectral streams, each coinciding with a DFT-S spectral subband. The main advantage of this approach over conventional OFDM consists of improved peak to average power ratio (PAPR) tolerance for DFT-S OFDM. Each stream effectively behaves as a narrowband single carrier, synthesized over the OFDM infrastructure by incorporating into the OLT slot Tx the 10 "spreading" FFTs of 96 points each, generated ahead of the 1024-point IFFT.

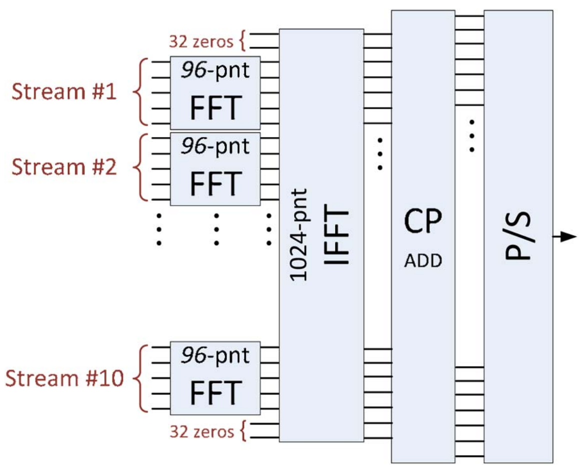

Fig. 4. DFT-S OFDM OLT transmitter over the D-slot 3.125 GHz spectral band.

C. Remote Hub

The RH is a critical photonic element of the novel OTONES architecture, enabling colorless ONUs by concentrating the entire optical spectral (de)multiplexing functionality (with slice granularity) in one network location. No optical filtering is further required in the individual ONUs, which become colorless.

The main function of the RH is to act as an interleaver with 12.5 GHz spacing and flat passbands. The RH is located in the field between the OLT and the ODNs and is connected on one side to the metro feeder fiber carrying the DWDM signal from the OLT, while on its other side it provides multiple ports each leading to a passively split ODN, carrying a 12.5 GHz slice. The multiple 12.5 GHz slices are fine-wavelength multiplexed by the OLT and transported DS over the single metro feeder fiber, reaching the RH, whereas the composite WDM signal is spatially separated to distinct optical ports in the DS direction, directed to the various ODNs. In the US direction, multiple US-propagating slice signals, as aggregated from all ODNs, are collected by the RH and are frequency multiplexed, generating a composite DWDM signal sent US from the RH to the OLT over the feeder fiber.

1) RH Fine Optical Spectral Filtering: A key attribute of the RH is its capability to mux/demux between the aggregate signal and the narrowband slices of optical spectrum with minimal spectral loss at passband transitions. On the demux side (DS), each three-slot PUD active band out of each slice, with spectral extent of $3 * 3.125$ GHz, is spectrally filtered with the transition from pass- to block-band occurring over the G-slot bandwidth acting as a guardband. Each active PUD band of each slice is distributed to all ONUs in the corresponding ODN, while neighboring slices are spectrally blocked from reaching that particular ODN. The RH narrowband demux functionality is one of the factors enabling cost-effective colorless ONUs with relatively slow electronics.

The fine spectral resolution of the flat-top demux architecture in the RH is enabled by a cascaded optical filtering design, as outlined in Fig. 5. The separation of 25 GHz spaced DWDM channels to slices spaced at 12.5 GHz is a spectral function that may be typically carried out by a deinterleaver. However, the highly efficient OTONES spectral structure requires relatively flat PUD three-slot passbands of 9.375 GHz, with sharp transitions to block-band over the 3.125 GHz G slot. The RH spectral specification might be achieved by a multistage interferometer design; however, the rapid pass-to-block transition implies a large and complex design prone to alignment errors between the multiple stages. Instead we opt for a novel design based on high-resolution dispersive optics, spatially directing one half of the spectrum to one output port and the other half to a second output port with a spatial light modulator (SLM), akin to an SLM-based

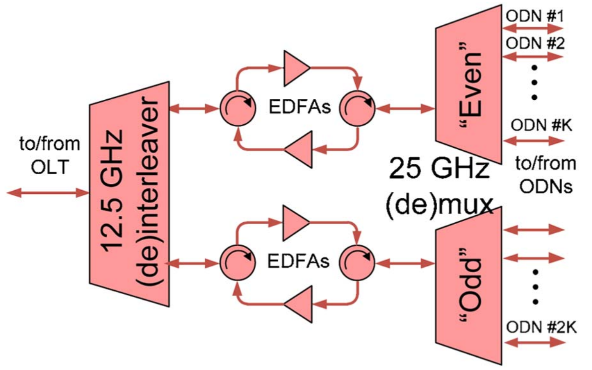

Fig. 5. OTONES RH block diagram.

wavelength-selective switch (WSS), in effect yielding a high-precision flat-top deinterleaver functionality. However, in our case the light spectrum has to be dispersed with very high resolution and in a cyclical fashion with a 25 GHz period, ensuring that our spatial and spectral manipulation will be identical over all channels. We achieve both requirements by dispersing the light with a custom arrayed waveguide grating that is designed to operate with a 25 GHz free spectral range and 1 GHz spectral resolution, configured to disperse the spectrum outside of the lightwave circuit (in free space). This hybrid guided-wave/free-space optics deinterleaver design is realized with a silica-on-silicon lightwave circuit and a liquid-crystal on silicon (LCoS) SLM used to separate the two spectral slices of the DWDM bandwidth. The design of the high-precision deinterleaver will be detailed in a future publication, but here we note that the innovative RH optical design makes the end-to-end RH effectively act as a fine-WDM (de)mux with 12.5 GHz spacing, albeit with unusually flat passband spectral response over the PUD slots; the transition bands are very steep, rolling off down to the stop-band over just 3.125 GHz. The two outputs of the 25/12.5 GHz interleaver are then conventionally demultiplexed by two 25 GHz demuxes (one on-grid and the second with its grid shifted by 12.5 GHz). In this respect, the interconnected modules of Fig. 5 provide a solution to the stringent spectral requirements.

2) RH Optical Amplification: As OTONES aims for *laserless* ONUs, based on recirculating remodulation and for long-reach access networks, the prohibitive round-trip loss cannot be possibly bridged by an entirely passive design, especially accounting for the RH passive loss, which is currently about 10 dB (further improvements in this specification will directly contribute to improving the current 40 dB net loss budget of the class I 10G/10G system). Thus, the need arises to introduce signal amplification in the RH, bridging between the remoted OLT and the high-split ODNs, enabling central office (CO) consolidation by incorporating a range extender into the RH. The bidirectional optical amplification is provided by a pair of erbium-doped fiber amplifiers (EDFAs) connected between a pair of circulators as shown in Fig. 5. The attainable end-to-end link budget for the OTONES network is 40 dB for class I (10G/10G), e.g., 73 km and 1:64 passive split assuming an average loss of 0.3 dB/km or 35 dB for class III (40G/40G) attaining 36 km and 1:256 split.

D. ODN

Each RH fiber port, bidirectionally carrying a 12.5 GHz spectral slice, is connected to a passively split ODN of the FSAN class B+ type (passive legacy "black-box" PON subnet with 29 dB max loss) with all its 64 (or 32) users sharing FDMA multiple access over the same 3.125 GHz OFDM D slot for the DS and 3.125 GHz U slot for the US.

1) Backward Compatibility and Coexistence: Remarkably, although optical amplification is incorporated in the RH, to enable long reach, compatibility with existing PON plants such as class B+ ODNs is fully preserved. Already deployed passively split ODNs need not be altered, but may be fed from the ports of the RH. Moreover, the OTONES system requires so little bandwidth that it may be overlaid in any free small spectral band atop any legacy PON system, such as (X)GPON or even upcoming TWDM NG-PON2.

E. DS Spectral Flow

Heretofore we described the individual OLT, RH, and ODN subsystems. We now proceed to an intertwined description of the spectral structure and DS signal flow via all interconnected elements forming the PON network.

Each 12.5 GHz transceiver in the OLT handles a slice, carrying the PUDG spectral tiling pattern of four slots (Fig. 2), each 3.125 GHz BW. Figure 1(B) illustrates two adjacent slices. While seemingly wasteful, the spectral sparseness of the PUDG scheme turns out to be essential for mitigating RBS and remodulation impairments, enabling isolation between the US and DS transmissions and laserless remodulation of the US information in the ONU. Despite the spectral sparseness, the OTONES SE is very high relative to other PON systems; see Eqs. (1) and (2) for SE comparison. In addition, confining both DS and US signal within the same ultra-dense WDM slice circumvents the need to allocate two well-separated spectral bands for DS and US, each containing its own guardbands.

Examining the OLT transmitted signal in the DS direction [Fig. 1(B), signal (a)], its P slot contains just an optical pilot tone or "seed" at the left end of the slot. The D slot is filled up with 960 OFDM subcarriers composed of 10 spectral streams each with 96 DFT-S subcarriers, conveying the DS data. The U slots are DS transmitted spectrally empty, ready to accommodate US modulation in the ONU, while avoiding RBS from adjacent D slots. The G slots are also transmitted empty to provide guardbands for the optical filtering transitions in the RH and also to absorb spurious products generated in the ONU US modulation, as further detailed below.

The WDM-muxed OLT signal arrives at the RH over the metro feeder fiber. Figure 1(B) tracks the opto-electronic processing of a pair of neighboring slices at the RH. The frequency responses of the RH optical bandpass filters corresponding to these two slices are depicted as trapezoidal spectral shapes, with flat-top responses over the PUD slots and with roll-off transitions over the G slots. The RH acts as fine-WDM demux for the multiple slices, which are routed to distinct optical ports, directed to multiple ODNs.

The ODN passive split implies that the same slice spectrum is replicated at all 64 ONUs of the ODN that receive the same D slot 3.125 GHz signal and remote-transmitted pilot tone acting as an LO at ONU Rx. As there is a multiplicity of ODNs, the DS system may be characterized as DFT-S OFDM multicasting to groups of 64 users, each group associated with an ODN. The multicast spectral vehicle is the slice, which is broadcast DS within each ODN multicast group and is collectively assembled in the US, jointly generating a composite OFDM signal by frequency division multiplexing the US streams from all ONUs.

F. ONU

1) ONU Overview: Referring to Fig. 3(b), the compact ONU comprises just an SOA (bidirectionally used), a silicon PIC, two 10 GHz PIN PDs with trans-impedance amplifiers (TIAs), and a mixed-signal ASIC.

The unique 1 Gb/s ONU design with a slow electronic rate (relative to other 1G per ONU PON proposals that run their ONU at 10G or 40G) enables a highly efficient ONU ASIC [Fig. 3(b)], reducing ONU cost and power consumption, further aided by the use of silicon photonics for the PIC. The ONU opto-electronics (the full modem PHY except the mixed-signal ASIC) may be compactly packaged, as will be treated in a follow-up publication.

The SOA used in the ONU is a simpler, less demanding device than a modulated RSOA (as used in other laserless PON systems). The bidirectional optical signal levels through the OTONES SOA are sufficiently weak to prevent SOA nonlinear interactions. The SOA gain may also be adjusted to contribute to near–far power management.

2) ONU PIC: The PIC constituent units are a POL splitter/combiner, two power splitters, and an electro-optic bidirectional IQ modulator. Our novel Si photonic integrated ONU structure [Fig. 3(b)], first introduced in [20], resembles that reported in [9,14], yet it differs from it in system-level purpose. Unlike [9,14], the objective is *not* to use a single-POL receiver in the OLT, while capitalizing on the Faraday-mirror-like capability of the ONU structure. Instead we use POL diversity in the OLT, ignoring the orthogonal Faraday-mirror-like POL rotation, which may not be precisely 90° due to POL-dependent loss (PDL). In addition, the RBS is depolarized to a degree; thus one may not reliably obtain RBS rejection just relying on POL rotation as in [9,14]. OTONES robustly addresses RBS rejection (as well as tolerance to other spurious optical reflections) by frequency diversity over the D and U spectral slots.

The DS/US signal flows and various integrated components along the ONU PIC path are detailed next.

3) DS Optical Signal Flow in the ONU: Following the optical path through the ONU [from the top down, looping around in a (counter)clockwise ((C)CW) sense in Fig. 3(b)], the DS light gets amplified in the bidirectional SOA, then passes through a fixed 10 nm wide bandpass OF deposited onto the SOA facet, limiting the ASE × ASE noise mixing term generated at the photodiode. Notice that the same wideband OF is used in all ONUs, which are made identical; thus our scheme fully qualifies as “colorless,” and it does not even require a tunable filter in the ONU (which would also qualify to be referred to as “colorless” but would be more expensive).

4) DS Polarizations in the ONU: The polarizing beam splitter (PBS) is the next element in line and the first element on the PIC. The integrated PBS spatially separates out the orthogonal X and Y POL components, aligned with its axes, and also rotates the Y-POL by 90°, such that both X and Y polarization of the fiber are transformed into the fundamental TE mode of the on-chip waveguides (though we shall continue to refer to the X-oriented POL component on the PIC originating from Y as “Y-POL”). The DS X and Y signals (respectively circulating in the CW and CCW senses around the loop) are tapped by two variable power splitters feeding two optical receiver analog front-ends (each consisting of a PD + TIA) with the $P \times D$ beat terms for the two POLs. The electrical outputs of the two optical receiver front-ends are connected to a POL-diverse coherent heterodyne receiver residing on the ASIC, using electrical downconversions to extract the I and Q analog components that are input to the two baseband ADCs.

5) US Polarizations in the ONU: Just a fraction of the light circulating in each sense around the loop (corresponding to the X and Y received POLs) is tapped to the DS heterodyne self-coherent receiver, while the rest of the light traverses the US modulator bidirectionally; thus both the X and Y POL components of the P-slot optical seed tone experience identical US modulations. These remodulated signals circulate through the loop CW and CCW with matched lengths. Since low bandwidth modulation (<1.6 GHz) is applied, the modulator may be treated as a lumped component. The X and Y components are then coherently mapped onto the two orthogonal polarizations of the fiber by the same PBS and propagate back up, boosted by the SOA through the ODN to the RH, finally reaching the OLT, where it is detected as described earlier. Thus, the two identically remodulated signals appear as X and Y components of the US signal emerging from the PBS and may be coherently combined by the OLT POL-diversity coherent Rx into a single US signal.

6) Relatively Slow ONU Electronic Processing: Coherent OFDM requires data-conversion interfaces (ADC/DAC); however, a distinctive feature of OTONES is that the Gb/s user modems are realized with relatively slow ADCs, DACs, and especially DSP, reducing ONU cost and power consumption dramatically. In principle, using an optical receiver at the full one-sided BW of $3W_{\text{slot}} = 9.375$ GHz would allow detecting the full spectral extent of the P + U + D slots. This would be wasteful since 2/3 of this BW is vacant; the preferred alternative is to reduce the electronic speed as much as possible by limiting the reception of each ONU to a single spectral substream out of the D slot. The ONU downconverts this spectral substream to baseband, detects it, and extracts a subset of the data-packets carried by the particular spectral substream, which are marked as addressed to the particular ONU. In the "peak mode" (1 Gb/s per ONU) all data-packets in the spectral stream are accessed by a single ONU, drawing the maximal 1 Gb/s rate. This method yields substantial electronic rate reduction to only $(1/10)W_{\text{slot}}$, relative to the simplistic options of having each ONU detect the full PUD BW, or downconvert the full D slot (which would still require a W_{slot} ADC Nyquist rate). Likewise, in the US direction, rather than using a transmitter with one-sided electrical BW of $2W_{\text{slot}}$, i.e., the spectral extent of the P + U slots, we use electrical SSB upconversion, yielding electrical Tx BW reduction by a factor of 40 (two-sided bandwidths down from $4W_{\text{slot}}$ to $(1/10)W_{\text{slot}}$). Notice, however, that the opto-electronic interfaces (ONU modulator and optical receiver) require the full electro-optic bandwidths from DC to the highest frequency in the U or D slot, respectively, though the quality of the frequency response from DC to the lowest frequency in the U or D slot is of no concern, which may alleviate the opto-electronic designs.

The ONU mixed-signal ASIC is equipped with a low-complexity analog front-end [21] performing the down/up spectral translations of the passband D and U slots to/from baseband, extracting just 1/10th of the D- or U-slot full BW. The slow-electronic processing speed, substantially reducing ONU cost and power consumption, is based on an analog implementation of cost-effective (de)modulation structures employing recent analog RF ASIC techniques [21] for robust up/downconversion. For example, for downconversion, the signal at the TIA output is high-pass filtered to reject PD + TIA baseband noise terms; then—as depicted in the analog section of the mixed-signal ONU ASIC in Fig. 3(b)—we use simple on–off switches as mixers, driven by quasi-square clock signals. The spurious images generated in the IQ demodulation process are rejected by the antialiasing filter of the baseband ADCs following the IQ mixers. Corresponding upconversion techniques are used in the analog design of the electrical SSB modulator used for one-sided upshifting of the complex baseband spectrum of the drive signal of the optical IQ modulator.

By appropriate selection of the up/downconversion frequency it is possible to selectively down/upconvert to/from baseband any of the 10 spectral groups within the 3.125 GHz U or D slot. In the DS direction, the particular selected spectral group is then digitized by the two ADCs and processed by the ONU transceiver. This enables realizing the ONU with slow ADC/DAC (417 MS/s) and DSP with a clock rate equal to $(1/p) * 417$ MS/s, where the ASIC processing parallelization factor p may be 1, 2, or 4. The ADC/DAC sampling rate of 417 MS/s (with baseband one-sided BW 312.5 MHz and 33% oversampling) is required to data-convert a single spectral group [with 1/10th of the slot BW, or 312.5 MHz, supporting over this BW a rate of up to 1 Gb/s (1/10th of the 10 Gb/s carried by the D-slot DS and by the U-slot US)].

To take advantage of this stream-oriented FDMA approach, the data intended for any particular ONU should be packaged by the OLT slice within one of the 10 spectral streams. In particular, one spectral stream may be temporarily dedicated to single ONU, providing a 1 Gb/s rate burst for that user. This burst mode will be further elaborated.

7) ONU DS Self-Coherent Detection: We now explain the principle of DS self-coherent, or *self-heterodyne*, detection.

The ONU photodiode detects a single slice comprising the P + D optical field. Quadratic detection generates a photocurrent of the form $|p(t) + d(t)|^2$, containing a $P \times D$ mixing product: the P-seed is seen to provide a remotely transmitted LO for heterodyne coherent detection, enabling us to eliminate the LO tunable laser from the ONU—laserless ONUs are highly beneficial for network economics. Elaborating, the $P \times D$ mixing product in the detected photocurrent linearly conveys the DS signal. The electrical mixing product is then a bandpass signal in $\{2W_{\text{slot}}, 3W_{\text{slot}}\}$, which is converted to baseband and then digitized in the front-end of the DSP-based coherent receiver. Additional spurious mixing products also appear in the $|p(t) + d(t)|^2$ photocurrent, in particular $D \times D$, namely, $|d(t)|^2$, occupying the $\{-W_{\text{slot}}, W_{\text{slot}}\}$ baseband and $P \times P$, namely, $|p(t)|^2$, which is very narrowband around DC. By virtue of the spectral design, these mixing products are generated spectrally distinct, not overlapping with the desired $P \times D$ mixing product.

For bidirectional transmission, there is a new mixing product to contend with, namely, $P \times U$, due to RBS of the US signal that also gets filtered by the high-pass. All these unwanted signals are also spectrally separated from the desired DS $P \times D$ mixing product and are thus not converted to baseband and therefore do not impair the signal. We will employ a high-pass filter to avoid possible saturation of electrical amplifiers and nonlinear interactions in the mixers.

8) Laserless US Remodulation: The laserless ONU US operation is more challenging, requiring mitigation of remodulation impairments. A notable advantage of the OTONES ONU is its *laserless* attribute: besides self-coherent detection in the ONU, which was already discussed, OTONES also achieves US transmission from the ONU without requiring a tunable optical source in the ONU. Instead, both self-coherent DS detection and US transmission reuse the P-slot optical tone of the DS spectrum. Unlike conventional reflective ONUs, for which it is typically just the optical power rather than the phase that is US remodulated, here we propose an US remodulation system supporting a coherent 16-QAM advanced modulation format in the US (as opposed to intensity modulation of 16-QAM, which is less efficient in both power and bandwidth utilization). It is nontrivial to impart both amplitude and phase US data onto the reflected DS signal, which is already modulated in both amplitude and phase, while avoiding cross-talk between the DS and US distinct data. The remodulation impairment mitigation is supported by the proposed OTONES PUDG spectral design and the ONU PIC layout and functionality.

The OTONES ONU reuses the P-seed light for US remodulation, avoiding remodulation cross-talk despite the concurrent reception of the modulated D slot, which also gets US-modulated. The U slot arrives from the OLT spectrally vacant, ready to accommodate US remodulation in the ONU, unaffected by RBS from the adjacent D slot. The U slot is filled up in the ONU US transmission by optically modulating the received P-seed optical tone by means of a 16-QAM bandpass electrical US data signal. The E-O modulation process may be described as $U \times (P + D) = U \times P + U \times D$, where $U \times P$ is the desired US signal illustrated by green OFDM tones in Fig. 1(B) [signals (d) and (e)] that represents signals from various ONUs. The second term is $U \times D$, which is the remodulation spurious mixing product falling outside the U and D slots, thus causing no interference. Performing the spectral convolution for the $U \times D$ remodulation term, the resulting mixing product is seen to fall in the range indicated by the blue triangle in Fig. 1(B) [in signals (d) and (e)]; thus this spurious signal indeed partially overlaps with the G slot of the current slice, which absorbs this spurious product (further to the role of the G slot to provide a guardband for the roll-off of the RH OF). Note that a portion of this spurious signal also overlaps with the P slot of the next slice; however, that portion will be strongly attenuated in the RH, due to roll-off of the OF associated with the current slice, and thus backscattering is negligible. Therefore, the unique OTONES spectral design precludes interference between this spurious mixing product and any of the desired signals.

The piece of spectrum allocated US to a particular ONU is referred to as a *substream*, extending to a full stream for a 1 Gb/s US peak user. This variable BW signal emitted US by the ONU then occupies up to 1/10th of the U slot.

This analysis indicates that the proposed spectral scheme effectively decouples between the US and DS transmissions, eliminating US/DS cross-talk both due to the fiber plant (RBS) and in the ONU PIC (parasitic US remodulation of information bearing a DS signal) enabling robust bidirectional transmission.

The digital baseband Tx in the ONU generates a band-limited "mini-OFDM" subband I and Q signal (a full spectral stream in the peak 1 Gb/s mode) with spectrum contained within the frequency range $\{-(1/20)W_{\mathrm{slot}}, (1/20)W_{\mathrm{slot}}\}$. Several ONUs typically share a common spectral stream in the US, and each such ONU is assigned a fraction of the 96 OFDM subcarriers of the spectral stream. The electrical SSB mixer in the ONU shifts the baseband subband spectrum up to a passband SSB range given by $\{(1 + (96s + r_1/960))W_{\mathrm{slot}}, (1 + (96s + r_2/960))W_{\mathrm{slot}}\}$, where $s = 0, 1, 2, \ldots, 9$ is an index designating the spectral group and $r_1, r_2 \in \{0, 1, \ldots, 95\}$. The SSB upshifted range stated above is then a subset of the $\{W_{\mathrm{slot}}, 2W_{\mathrm{slot}}\}$ "electrical" U-slot range, occupying $r_2 - r_1 + 1$ out of the 96 OFDM subcarriers.

The US-modulated substream from the ONU gets juxtaposed to similar substreams from other ONUs, forming a contiguous composite OFDM signal at the output of the ODN combiner. This composite signal traverses the RH in reverse, passing through the FWDM mux (where other slices get juxtaposed to it in frequency), and then proceeds upward through the metro trunk fiber, finally reaching the OLT [Fig. 3(a)], where a DWDM demultiplexer separates the US channels to individual OLT line-cards, each handling a 12.5 GHz slice. Each US slice is optically mixed with the corresponding U-line for homodyne detection.

9) POL Impairment: POL-Diversity Receivers in ONU and OLT: To our knowledge, this is the first ONU to support bidirectional POL diversity, using the 16-QAM DFT-S OFDM modulation format in both DS and US. The POL-diversity operation is tolerant to random time-varying rotation of the *state of POL* (SOP) in both the DS and US directions. The DS POL-diverse Rx in the ONU is fed by a single-POL Tx in the OLT; evidently although the DS data stream is modulated onto a single POL in the OLT, the SOP evolves along the DS path and is received at the ONU as an unknown random SOP (but both the X and Y POL components are modulated by the same DS data). As the X and Y received POLs are separately available by virtue of the PIC design, DS POL diversity at the ONU mitigates the polarization rotation of both the remote heterodyne carrier (the P-slot seed pilot) and the signal (D slot).

Note that even if the P-seed carrier (used as self-coherent LO) faded away on one POL axis, it would still be available on the orthogonal POL axis. Generally, the signal and LO powers are divided in some arbitrary ratios between the two POL axes. Taking advantage of having as the same DS data modulated onto both POLs, the best reception strategy in the ONU is *coherent combining* of the two orthogonal POLs, sorting out the random splitting between the two orthogonal X and Y POLs in the digital domain, by adaptive LMS or blind 2×1 MISO linear processing, effectively superposing two received POLs with optimal complex weights such that they are aligned in phase, adding up to a resultant signal with maximal SNR. This technique, known in wireless MIMO theory as maximal ratio combining (MRC), ideally yields an SNR diversity gain of 3 dB, beneficially contributing to the loss budget.

The MRC POL-diversity combining is made possible by the OTONES compact spectral structure featuring the P and D spectra being at most 9.375 GHz apart. Thus, the SOPs of P and D are nearly identical.

Similarly, in the US direction we have seen that the novel ONU remodulation scheme also modulates the same data signal onto both POLs of the received seed signal (the received P-slot optical pilot, which is redirected upward around the PIC loop), generating an US-modulated signal with random SOP. No matter the power ratio of the X/Y POL of the received P-seed propagating CW and CCW around the loop in the ONU PIC, both are modulated in the IQ E-O modulator by the same US data. Propagating back up, the US-modulated signal is randomly POL-transformed and arrives at the OLT with random SOP. The OLT uses homodyne coherent detection for the US signal also

TABLE I
RATES AND BW OF VARIOUS CLASSES

Class (#ONUs)	Total loss budget	DS (& US) Net Rates Gbps			BW GHz			OLT			ONU				
		Total	Peak per ONU	Avg. per ONU	Slice	Slot	Spectral group	DAC/ADC rate GS/s	E-O mod. BW GHz[a]	PD BW GHz	DAC/ADC rate GS/s	E-O mod. BW GHz	PD BW GHz	Tx mod. carrier GHz	Rx demod. carrier GHz
I (1:64)	40	10	1	0.156	12.5	3.125	0.312	3.33	9.75	1.7	0.41	6.25	9.4	6.25	9.38
II (1:128)	38.5	20	1	0.156	25	6.25	0.312	6.67	19.5	3.4	0.41	12.5	18.8	12.5	18.8
III (1:256)	35	40	1	0.156	50	12.5	0.312	13.33	39	6.7	0.41	25.0	37.5	25.0	37.5

[a]The OLT E-O mod. and PD bandwidths are specified for the OLT transceiver of Fig. 3, based on homodyne Rx and passband Tx. An alternative design also generating an optical "D-comb" would enable us to reduce the OLT E-O mod. BW to equal the PD BW.

featuring POL diversity as used in the ONU. The OLT applies POL-diverse adaptive in-phase combining of the two received POLs (also 2×1 MISO as in the ONU), also attaining ~3 dB POL-diversity gain. Robust POL-diverse US operation is then achieved despite random POL rotation of the P pilot in the DS and the random US SOP-transformation of the U slot.

IV. HIGHER-GRADE OTONES SERVICE CLASSES

Heretofore we have elaborated on class I (10G/10G) of the novel PON system. The OTONES network and spectral architecture supports graceful service class upscaling: $10G/10G \rightarrow 20G/20G \rightarrow 40G/40G$. The 20G/20G and 40G/40G classes II and III are derived from class I by scaling up the spectral structure and OLT digital rates by factors of 2 and 4, respectively. Table I summarizes the parameters pertinent to the three service classes, corresponding to upgrading class I by doubling/quadrupling the split ratio per ODN, while maintaining fixed data throughputs of 156.25 Mb/s average symmetrically US/DS for each of the users. Alternatively, the operators may opt to constrain a fixed split ratio, say 1:64, yielding successive increases in average throughputs per ONU: $156.25 \rightarrow 312.5 \rightarrow 625$ Mb/s. Other flexible trade-offs between rate, number of ONUs per ODN, and OLT system costs are possible.

Beneficially, home subscriber ONU ADC and DAC is kept invariant, providing peak 1 Gb/s for all three classes based on 417 MS/s ADC and DAC and the same DSP in the mixed-signal ASIC, invariably retaining a 312.5 MHz spectral group structure. To support the upscaling transition, it is required that the ONU double/quadruple its E-O modulator BW ($6.25\text{ GHz} \rightarrow 12.5\text{ GHz} \rightarrow 25\text{ GHz}$), as well as the optical photodetection BW ($9.4\text{ GHz} \rightarrow 18.8\text{ GHz} \rightarrow 37.5\text{ GHz}$) and the RF carrier frequencies used for up/downconversion. The upscaling transition is just borne by the analog opto-electronics, whereas no change is required in the rest of the PIC (excluding the E-O modulator and PD) and the signal processing ASIC. Fortunately, photonic modulation and detection in the ONU remain narrowband; e.g., the opto-electronic design of the 25 GHz modulator required for class III (40G/40G) ONU is relieved since this is not a DC to 28 GHz modulator but rather a passband design, whereby the modulating signal riding on the 12.5–25 GHz RF carrier features a narrowband 312.5 MHz BW. However, while ONU costs are just marginally increased in return for the doubled/quadrupled throughput, the "bill is footed" at the OLT, the cost and optical power of which linearly increase with the provided aggregate rates. As SE is kept constant, the data-bearing BW per slot must be scaled up, $3.125\text{ GHz} \rightarrow 6.25\text{ GHz} \rightarrow 12\text{ GHz}$; the slice BW evolves as $12\text{ GHz} \rightarrow 25\text{ GHz} \rightarrow 50\text{ GHz}$. The OLT cost per Gb/s of provisioned throughput is expected to be approximately constant over the three-class successive upscaling, $10G/10G \rightarrow 20G/20G \rightarrow 40G/40G$.

It is also possible to have the three classes spectrally coexist within the same network for both home and business users. OTONES various classes may also coexist with legacy or future PONs. Multiple ONU types may all be flexibly combined in the frequency domain. In particular, high-throughput users—e.g., enterprises and antenna sites—may coexist with 1 Gb/s peak home users on the same OTONES system. OTONES may be used as spectral overlay, as its long-reach capability makes it compatible with existing plants. An OTONES overlay requires relatively very small BW occupancy, fitting in small available regions of the optical spectrum. The flexible coexistence of the OTONES classes and user types among themselves as well as with legacy and future PONs capitalizes on the ease of multiplexing in the frequency domain and the very high SE of OTONES. The coexistence at all levels is further facilitated by OTONES eliminating dual wavelengths far apart as in conventional PON. In contrast, in order to symmetrically provide 40G/40G, OTONES just needs a single patch of 50 GHz in any region of the spectrum, whereas in order to provide 10G/10G per ODN, OTONES would require just a 12.5 GHz spectral patch.

V. Conclusions

In this paper we presented an overview of a novel end-to-end next-generation access network architecture at all levels: topological, spectral, subsystems, opto-electronic devices, and signal processing. The cost-effective “slow” ONUs support bidirectional symmetric transmission up to the sustainable peak of 1 Gb/s (subject to statistical multiplexing of all 64 ONUs), while the ADC and DAC sampling rates are kept low at 417 MS/s. The proposed ONU is optically and electronically integrated, containing just an SOA, a PIC, and a relatively narrowband ASIC with analog up/downconverter interfaces. The multiple access method is FDMA in both DS and US, and the SE is extremely high.

A key design objective has been low cost and energy efficiency, attained by adopting the most suitable spectral, photonic, and signal processing venues. Coherent 16-QAM symmetric US/DS modulation is adopted, random polarization rotation is mitigated by a diversity technique, US/DS transmission is tightly colocated within a few tens of GHz range, and OFDM is used to enable US FDMA combining of multiple ONU transmissions. To reduce ONU cost, extensive use is made of analog up/downconversion, being significantly cheaper than digital broader-band alternatives, enabling low-speed mixed-signal ASIC. The Si-PIC-based photonic integration and the use of an SOA is another major ingredient in simplifying the ONU, which is laserless, colorless, and tunable-filterless.

We have shown that OTONES attains more than an order of magnitude improvement in bidirectional SE. The jury is out on whether SE is a useful figure of merit for access networks. We observe that today’s wastefulness of the spectral resource in access networks resembles a similar situation in long-haul transmission several years ago. We conjecture that our proposed efficient use of the spectral resource is likely to become increasingly important, as the access networks spectrum becomes increasingly crowded. High SE enables using OTONES as flexible wavelength overlay over narrowband patches of available spectrum in an existing PON system. The proposed scheme enables efficient integration of metro and access systems; however, investigation of this aspect is outside the scope of this paper.

The ONU photonic integrated devices and real-time FPGAs for the ONU and OLT are currently under design toward a future experimental system demonstration. Follow-up work will also detail the US and DS multiple access scheme based on a time ranging protocol similar to that used in DOCSIS (for cable modems) and in WiMax (for wireless) and elaborate on analytic models of performance (which were previewed in [18]), predicting long reach (35–40 dB loss budget), enabling CO consolidation. We shall also treat power ranging algorithms for equalizing the signal levels received at the OLT and ONU at various distances.

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