Technologies for Cost Effective udWDM-PONs

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***Abstract*— New technologies for ultra-dense WDM-PON (udWDM-PON), enabled by coherent techniques and low cost devices, are developed for an efficient utilization of the optical spectrum, revealing that the "Wavelength-to-the-User" concept can be feasible. In this work, an udWDM-PON with only 6.25 GHz channel spacing is implemented with conventional DFB lasers, for a splitter-based PON infrastructure with 256 ONUs. The results of the analysis of udWDM access network architecture with respect to their associated complexity, cost and migration scenarios, exhibit the potential for higher aggregate throughput, higher split ratios and node consolidation, when compared to competing technologies.**

***Index Terms*—Fiber optical communications, fiber-to-the-home, access networks, PON, WDM.**

I. INTRODUCTION

A number of converging factors are contributing to the strong growth in fixed broadband subscriptions and mobile traffic. The increasing number of video-capable devices in consumers' hands and the growing availability of multimedia content that can be streamed to fixed and mobile devices are accelerating this trend. This growth will not be possible without faster network speeds that come with wireless development towards 5G, higher capacity in optical networks and better spectral efficiency [1-3]. Currently deployed FTTH passive optical networks (PONs), based on TDM (time division multiplexing) equipment, use only one or two wavelengths and may not cope with these expected bandwidth demands; more advanced techniques, based on wavelength division multiplexed (WDM-PONs), are being intensively developed in research, standard bodies and industrial prototypes with network demonstrations [4-7].

The envisioned access network evolves from the almost-commercial WDM-PON architecture to the realization of the Ultra-Dense WDM (udWDM) solution, opening the way to the "wavelength-to-the-user" (WTTU) concept. The key enabling technology can be a new cost-effective coherent detection scheme with flexible wavelength allocation. The udWDM approach can be useful in supporting, over the same fiber infrastructure of current PONs, different applications as depicted in Fig. 1: mobile back-haul, both as micro- and macro-cells, as well as fixed-line users (either residential or business). In principle, the wavelengths channels can be dedicated (ptp) or shared in time among users (sWTTU) with burst mode transceivers.

It has been proposed that optical coherent technologies, as recently done in core networks, can be used to enhance the power budget and capacity of PONs also, although with different requirements and architectures [8-15]. The main challenge is that expensive optical and electronic components do not simply scale down in cost to be affordable for access networks. Although conceptually complex, coherent terminals for access networks must be commercially compatible with low-cost consumer electronics.

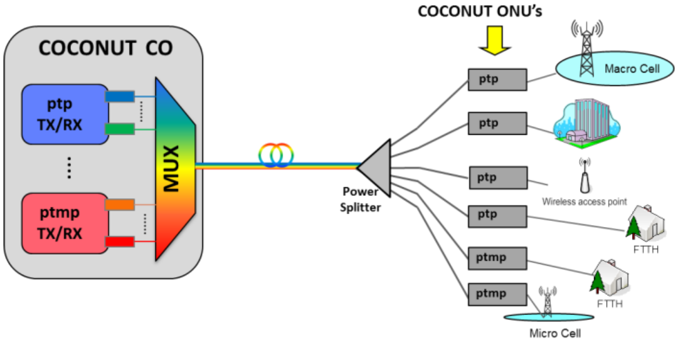

Fig. 1: udWDM-PON application scenario (ptp: point to point, ptmp: point to multipoint, CO: central office, TX/RX: transceivers).

With this purpose, an optical access network based on simplified coherent technology supporting ultra-dense Wavelength Division Multiplexing is developed in the EU FP7 COCONUT project (COst-effective COherent ultra-dense-WDM-PON for λ-to-the-user access networks) [16, 17]. It addresses research and realization of coherent transmitter / receivers exploiting low-cost components and simple electronics, so that typical line terminals would be affordable to the end-users. It aims for a seamless evolution from present

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PON architectures and support of the new emerging applications. With respect to [17] we here detail the specific transceiver designs and transmission results, as well as a PON dimensioning and cost analysis. These coherent techniques enable serving a higher number of users (e.g. 256 users over 60 km reach), each with a wavelength at 1.25 or 10 Gbit/s, over the existing splitter-based PON. This is possible thanks to both the udWDM spacing (of 6.25, 12.5 or 25 GHz), and the higher power budget (>45 dB), which is a direct result of the enhanced receiver sensitivity (down to -50 dBm).

This paper presents an overview of the proposed architecture (sect. II), of the optical spectrum allocation (sect. III), the enabling transmission techniques and experimental results (sect. IV), as well as discussing migration paths, costs and challenges (sect. V, VI and VII).

II. ARCHITECTURE

The reference architecture is based on the standard passive optical network tree, with one or several stages of power splitting, avoiding optical filters or multiplexers at the optical distribution network (ODN) that could limit the bandwidth extension or require changes in the external infrastructure. The scenarios of interest are: remote front-haul, small cell backhauling and residential, business and macro cell backhauling [18]. The main difference among these scenarios is the functionality of the ONU: i) the ONU feeds a 3GPP cell, ii) it feeds a Wi-Fi spot or iii) wired devices such as a PC or TV. According to traffic demand forecasts, a connection of 1.25 Gbit/s per user (1 GEthernet to the user) fulfills scenarios ii) and iii), while 10 Gbit/s can be required for macrocell in i). In addition, the wavelengths can be dedicated to each ONU or shared between several by applying a TDMA protocol at the MAC layer [18, 19].

As target features to cope with the future demands in these scenarios, the COCONUT optical line terminals of the central office (CO OLT) should be able to support 256 ONUs, by using between 64 to 256 wavelengths at 6.25 GHz spacing (for 1.25 Gbit/s data rates) or 12.5 / 25 GHz spacing (for 10 Gbit/s), providing proper wavelength selectivity over the udWDM flexible grid. The terminals are required to be, for mass production and provisioning, low cost and all identical a priori, without preselected wavelengths.

In Fig. 2 we depict the basic hardware architecture of the ONU and the OLT at the CO, which are constituted by: udWDM coherent transmitters (TX) and receivers (RX), downstream and upstream combiners, TX and RX local oscillator (LO) laser automatic wavelength controllers (AWC), a CO digital switch to map external data channels to OLT coherent transceivers and a CO wavelength control module, which includes a high resolution spectrum monitor and manager and the OLT-ONU control communications signaling system.

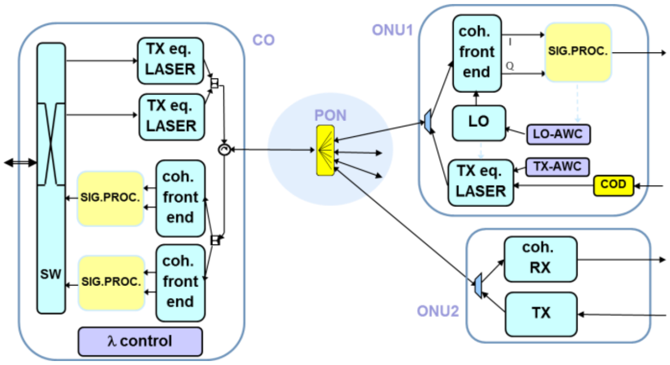


Fig. 2: System architecture (SW: Switch; coh: coherent; TX eq: Equalized Transmitter; LOL: Local Oscillator; L-AWC: Local Oscillator Automatic Wavelength Controller; T-AWC: Transmitter Automatic Wavelength Controller; COD: Coder).

III. SPECTRUM MANAGEMENT

The most critical elements to manage in the udWDM PON are the TX and LO lasers, in the ONU and OLT transceivers. For cost and simplicity matters, here we do not consider the use of widely tunable lasers (e.g. external cavity or multi-electrode DBR), nor reflective ONUs, that present transmission limitation in terms of power budget and bandwidth. On the contrary, we resort on the use of common single-electrode single-mode lasers, such as Distributed FeedBack (DFBs). A main consequence to be addressed is the narrow tunability of the ONUs with respect to the defined PON spectral band. We have therefore adapted the optical spectrum organization and the transceiver operation as explained in the following. Given the ultra-dense channel spacing, the common temperature-based tuning (typically between 200 and 400 GHz) allows covering many, though not all, grid positions, here at 6.25 GHz spacing. The fact that users can employ any ONU at any initial non-preselected wavelength in the band has been defined as “statistical WDM multiplexing” [20, 21], where random wavelengths ingress in the network and contention could occur in the case that they overlap causing crosstalk. At the same time, the CO laser wavelengths have to adapt to those of the ONUs, reversing the common WDM-PON policy where the PON multiplexer and the OLT sets the lightwaves. The overall cost of the access network, dominated by the user equipment, can thus be minimized. This novel concept implies a radical new management procedure of the optical spectrum and terminals, as well as for the activation of additional ONUs in the spectrum in a hitless form [19, 22-24].

The statistical WDM multiplexing concept has been analyzed, in terms of number of feasible active ONUs, by means of Montecarlo simulations accounting up to 640 wavelength slots, which are available if the full C-band is considered (32 nm, between 192.1 and 196.1 THz), at a 6.25 GHz spacing. The minimum wavelength separation between two adjacent channels can be as low as 3 GHz [24], but it was found convenient to leave few GHz as guard band. In this study, the laser tunability is here assumed to be 0.1 nm/ºC as typical in DFBs, with a tuning range of 2 nm (250 GHz) by +/-10ºC, that can be easily achieved with a Peltier cell, or just by heating.

Three heuristic strategies for ONU wavelength assignment are analyzed: First Fit (FF), which selects the closer free channel, Maximum Scattering (MS) and Maximum Admittance (MA) for future requests [25]. The FF is the simplest assignment scheme and the one requiring less initial temperature tuning; it is used as a basis for comparison. As it can be derived from Fig. 3, MS exceeds the FF performance in the activation process, but MA provides the best results, with the lowest rejection probability of 10^{-4} (one ONU replacement every 10,000 installed ONUs) for 500 active ONUs allocated, hence a channel efficiency of 78% over the 640 slots. With the same acceptance ratio, when employing MS, 440 ONUs can be allocated; and while using FF, only 405 ONUs are assigned. Variable environmental conditions and demand evolution have been analyzed to guarantee efficient flexible setup of new and existing connections and minimizing the probability of possible conflicts. The sporadic ONU replacement can be best done at the installation time, for minor disturbance of the user and operator. Outdoor and indoor environmental conditions have been considered to design activation and reconfiguration algorithms in the TX and LO boards in [23], providing similar results when dynamic adaptation is implemented. Regarding the dimensioning of the OLT laser array, it would not require oversubscription generally because they can be preselected along the spectrum band and operated under controlled thermal conditions.

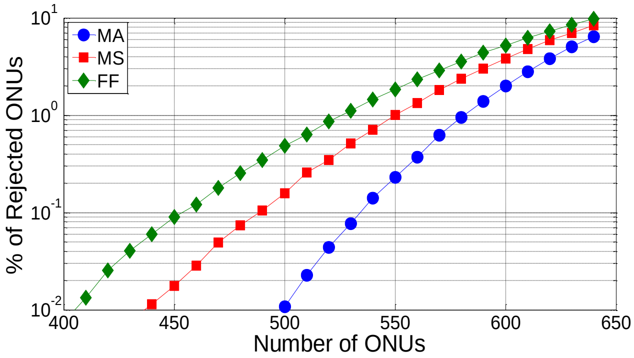


Fig. 3: Activation rejection probability % against active ONUs using FF, MS and MA heuristic assignment schemes, for 32 nm band (640 slots).

IV. TRANSCEIVER DEVELOPMENTS

Considering the previous principles, several novel transmission techniques have been proposed and tested, exhibiting advanced performances with reduced complexity compared with traditional coherent transceivers. Two main key points have been considered: the use of direct laser modulation and the investigation of new solutions to achieve polarization independent coherent detection in smarter and simplified ways.

A. *Direct phase modulation*

Direct modulation is a convenient solution to attain the low-cost target of access networks. The generation of a PSK signal with direct DFB laser modulation at 1.25 Gbit/s (1 GEthernet) and coherent detection has been developed in this project by taking advantage of the natural adiabatic frequency chirp of the laser. In Fig. 4, the measured phase response (PM) of a DFB laser (model LC25ET) with 4 MHz linewidth (Δν) is shown. It well approximates the expected 1/f characteristic of the adiabatic chirp. By means of a simple derivative pre-equalizer, the frequency chirp is converted into flat phase chirp, and adjusted to 180° phase shifts for PSK. The equalized PM response depicts an almost flat phase shift characteristic below the range of interest (<2.5 GHz approximately). The residual IM was about 1.5 dB [26], achieving a penalty with respect to external modulation of only 2 dB. An RX sensitivity of -52 dBm was obtained with intradyne detection based on a 3x3 coupler, at a BER=10^{-3} with off-line processing; it attained a channel spacing of only 3 GHz (24 pm) and negligible phase noise effect [24, 27]; by extending the technique to QPSK with 4 current levels, 5 Gbps was reached [28].

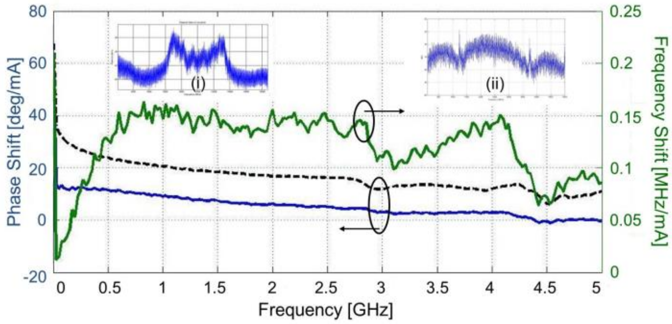


Fig. 4: Original (dotted) and equalized (down) PM and FM responses (solid lines). The insets correspond to the optical signal spectrum: (i) unequalized at 1.25 Gb/s, (ii) equalized at 1.25Gb/s, and (iii) equalized at 2.5Gb/s.

At the same time, ASK direct modulation and coherent detection have been also demonstrated, also using a coherent receiver based on a 3x3 symmetric coupler. Exploiting the intrinsic chirp of DML, the detection can be carried out similarly in a FSK signal, thus yielding a sensitivity of about -48 dBm at BER:10^{-3} in a 6.25 GHz udWDM experiment [29].

B. *Polarization independent 3x3 frontend*

A common solution to achieve polarization-independency is usually to exploit polarization-diversity, which however requires doubling the receiver structure (one receiver per orthogonal polarization). This clearly results into an excess of components and power consumption, especially when polarization multiplexing is not considered.

A novel architecture for low-cost polarization-independent detection of OOK signals has been proposed in [30] and experimentally demonstrated in [31], based on a modification of the phase-diversity receiver with a 3x3 symmetric coupler. When tested experimentally, it achieved polarization-independence with a very limited penalty compared to the polarization-sensitive solution, <1dB at the sensitivity level, as seen in Fig. 5, for 1.25 Gbit/s. It requires intradyne operations, which might become advantageous when considering bidirectional operations as will be discussed later in sec. IV-D.

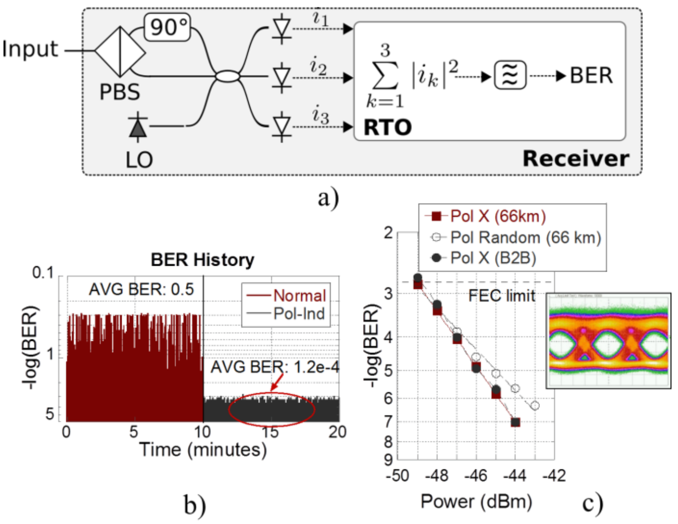
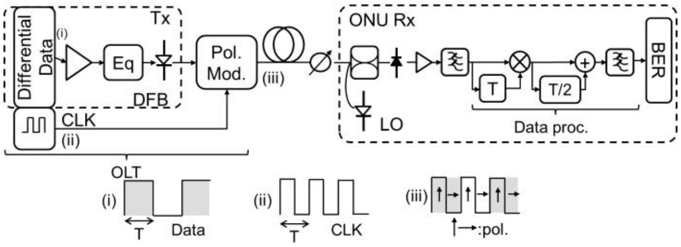


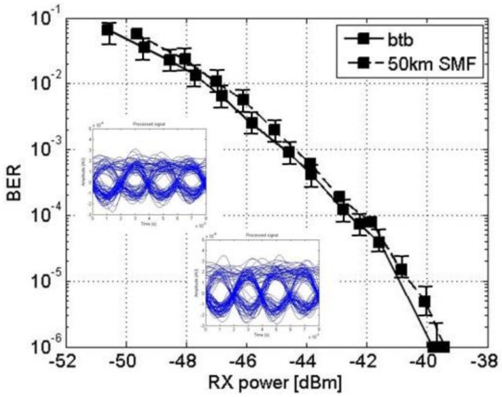
Fig. 5: a) Schematics of polarization-independent ASK receiver and b) eye diagram taken with real-time implementation; c) BER evolution in a polarization-scrambled signal for a conventional RX and this RX; d) BER curves for single-polarization and scrambled signals (RTO: real time oscilloscope, PBS: polarization beam splitter, FEC: forward error correction, CDR: clock and data recovery).

C. *Common polarization scrambling*

An alternative polarization-independent detection scheme with only one photodiode, for minimum complexity, has been also investigated for the downstream receiver; it is based on a centralized polarization scrambler placed at the OLT side, and synchronized with the data clock [32]. Fig. 6 depicts the experimental setup scheme; the polarization is switched to the orthogonal state at the second half of the bit, simultaneously for all downstream wavelengths. At the RX both halves are combined after the differential demodulation. The BER plot shows an Rx sensitivity of -45 dBm at BER=10^{-3}, and below 1 dB after a transmission over a 50 km SMF link, at 1.25 Gbit/s.



(a)



(b)

Fig. 6: a) Experimental setup schematics; the insets represent qualitatively the signal modulation; b) BER against Rx power; the eye-diagrams correspond to BER=10^{-4} for (i) btb, and (ii) 50km SMF (Eq.: electrical equalizer).

D. *Single laser ONU*

As shown in sec. III, careful laser wavelength control allows to operate a large number of preallocated lasers. In order to simplify the wavelength management and the overall power consumption, it would be desirable to reduce the number of lasers to control, especially at the ONU side. We therefore investigated two schemes based on the use of a single laser at the ONU, serving both as local oscillator and source for the upstream data external modulator.

In a first experiment, we achieved upstream phase modulation exploiting the chirp of a reflective semiconductor optical amplifier (RSOA) optimized to operate as phase modulator. This has been tested with a simplified heterodyne bidirectional transmission, where one DFB laser was shared as TX and as LO, as depicted in the scheme and spectrum in Fig. 7. With an intermediate frequency of 2.5 GHz, -46 dBm RX sensitivity was achieved [33]. In this case, the channel spacing was 12.5 GHz, but we note that this includes both down and upstream channel.

In a second set-up, a simple bidirectional system based on ASK signaling was also demonstrated to support up 35 dB ODN loss [34]. In that case, by using intradyne detection, we could achieve increased tolerance to the intrinsic crosstalk due to Rayleigh scattering with minimum frequency offset (1 GHz) of the down and upstream channels and proper emission power balance; again, this allows operation of the ONU with a single laser used, both as LO and signal source for upstream.

Other transmitters realized in photonic integrated chips have been developed ad-hoc and are also employed to implement a single laser ONU. These chips under test include: a Dual Externally Modulated Laser (DEML), a pure Frequency Modulated Lasers (FML) and a BPSK externally modulated laser (BPSK-EML).

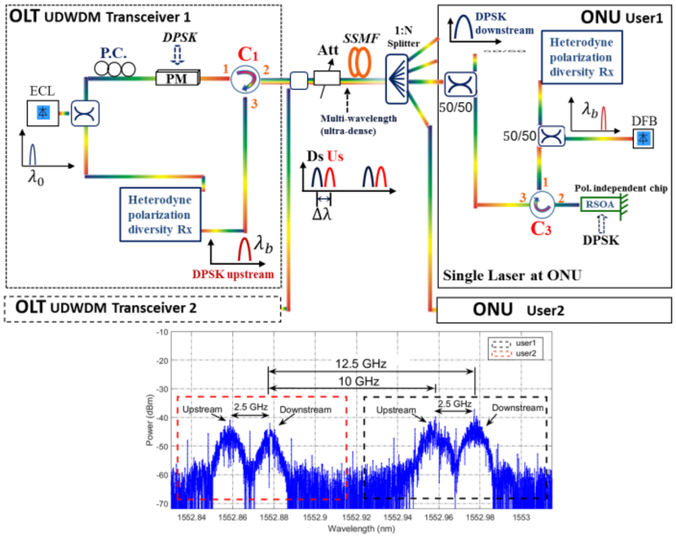
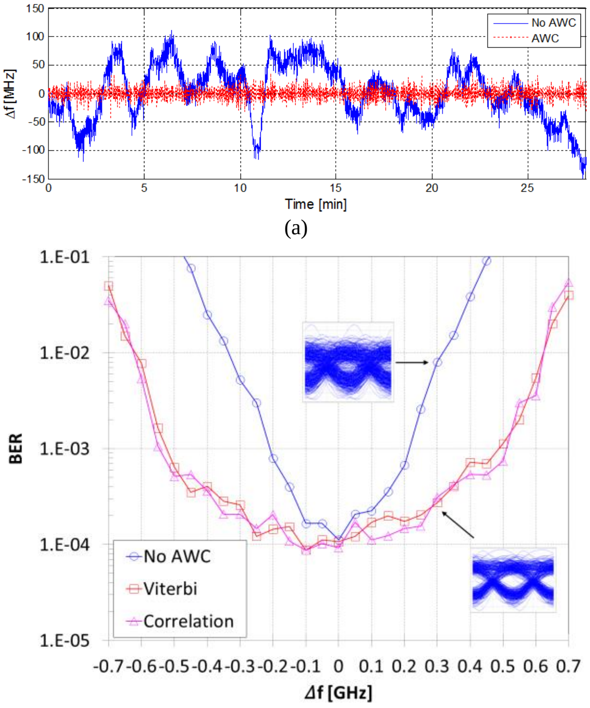


Fig. 7: Bidirectional subsystem using heterodyne detection sharing one laser at ONU for UDWDM-PON using RSOA chip, and spectrum for two DPSK-DPSK ONUs bidirectional transmission (ECL: external cavity laser, P.C.: polarization controller, C: circulator).

E. Wavelength control

Critical aspects of the proposed architecture to be handled are the frequency noise and the long-term frequency drift of the lasers, which must be addressed when the operation of closely spaced DFB lasers is considered. Fig. 8 a) depicts a measurement over 30 minutes of frequency offset for free-running lasers (one TX and one LO). The lasers were physically separated and kept with uncorrelated temperatures. It can be noticed that about 200 MHz drift can occur in about one minute time. Such a detuning might prevent correct detection and cause undesired crosstalk on adjacent channels.

While ASK scheme has strong immunity to frequency noise, and provides higher tolerance to the frequency drift between signal and LO (up to around 1 GHz at 1.25 Gbit/s), DPSK systems must be carefully optimized. To this aim, an automatic wavelength control (AWC) embedded in the coherent intradyne DPSK receiver with DFB LO has been developed by applying joint feed-back stabilization and feed-forward compensation. At stable operation, a real-time correction of ±500 MHz was achieved in 600 ms, at an Rx sensitivity point of -47 dBm, which provides a target BER of 10^{-4}. In the absence of feed-forward compensation, the drift tolerance was about ±100 MHz, resulting in 1 dB power penalty, whereas data detection with DSP offset compensation can tolerate up to ±300 MHz for 1 dB power penalty. In comparison with uncompensated detection, Viterbi and correlation DSP methods obtained 4 dB improvement as shown in Fig. 8 b) [35]. The second one was selected in the real time FPGA DSP implementation due to its higher simplicity.



(a)

(b)

Fig. 8: (a) Frequency offset measurement over 30 minutes, with and without AWC, and (b) BER dependence against frequency drift for intradyne receiver with/out data offset compensation, with eye diagram at 300MHz drift.

By combining thermal (slow) and laser current (fast) control, wavelength control circuits were implemented in the laser boards, for the ONU tracking, activation and reconfiguration processes, exhibiting a wide operative tuning range and fast channel jumps [19, 24]. Wavelength channel jumps below one microsecond were generated.

F. Further developments

Further investigations in other transmission formats are relevant for faster bit rate, channel spacing reduction and link budget increase, by means of duobinary phase modulation [36], IQ phase time scrambling [15] or half duplex transmission [37], along with its real-time implementation [38], both analog and DSP based. The several developed transceiver solutions mentioned will be tested in practical conditions in a field trial.

V. NGPON2 AND COCONUT COMPARISON

The Full Service Access Network (FSAN) group is currently working on the standardization of next generation – passive optical network 2 (NG-PON2) in ITU-T. It is not yet decided what will be the next step (NG-PON3), but previously reported results represent a promising competitive technology candidate for either enabling advanced features in NG-PON2 or for a future next generation PON system. NG-PON2 consists of stacking 4-8 10 Gigabit XG-PON1 pairs of wavelengths and making the optical network unit (ONU) tunable across all wavelengths channels, which is denoted as Time and Wavelength Division Multiplexing PON (TWDM)-PON [34]. NG-PON2 also defines an optional set of ONU-dedicated point-to-point wavelengths (i.e. a WDM-PON), which can be overlaid on top of the TWDM-PON channels. NG-PON2 uses three key elements: a) a wavelength multiplexer (WM) at optical line terminal (OLT), b) a coexistence element at OLT to enable co-existence and migration from legacy PON systems such as gigabit (G)PON, etc., and c) a tunable filter at ONU. Strict requirements are set with respect of: i) channel isolation, which dictates the use of either cascaded filters or more practically the increased channel separation in expense of reduced spectral efficiency and ii) filter tuning times, which limit significantly the technology choices, while increasing the overall implementation cost.

The two main differences of COCONUT at the physical layer are coherent detection and udWDM. These two parameters could give several benefits when benchmarked against NGPON2, as summarized in Table 1,

i) ONU receivers do not need optical filters or broad guard bands,
ii) more channel wavelengths can be used, spaced at 6.25GHz when transmitting at 1.25Gb/s,
iii) high receiver sensitivity, thus requiring a lower transmitted power, enabling to multiplex more channels without surpassing the eye-safety power-limit and the fiber non-linearity thresholds,
iv) crosstalk interaction between COCONUT and other PON systems is reduced, especially when using PSK or FSK modulation,
v) the thermal tunability and random selection of low cost lasers in COCONUT strategy can enable to evolve from 4/8 channels in NGPON2, to e.g., 256.

TABLE 1: KEY CHARACTERISTICS OF NG-PON2 AND COCONUT

	COCONUT	NG-PON2
Wavelength channels	64 - 128 - 256	4 - 8
Channel spacing	6.25 – 12.5 GHz 0.05 – 0.1 nm	50 - 100 GHz 0.4nm – 0.8 nm
Channel BitRates	1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s (down and upstream)	2.5 Gbit/s, 10 Gbit/s (down and upstream)
Max. Aggreg. Rate	256 Gbit/s (at 1.25 G), 2.5 Tbit/s (at 10 G)	40 Gbit/s (80 with dedicated λ).
Receiver sensitivity (dBm)	-48 @ 1.25G, BER 10^{-3} -38 @ 10G, BER 10^{-3}	-30 @ 2.5G, BER 10^{-4} -28 @ 10G, BER 10^{-3}

With this, for example an NG-PON2 channel slot can be divided into 16 sub-wavelengths with 6.25 GHz spacing, allowing a capacity of 20 Gbit/s (with a 1.25 Gbit/s per ONU) per 100 GHz channel.

Considering the discussed basic performances and limitations, a simple general dimensioning of the number of ONUs can be performed. Fig. 9 depicts the number of allocated ONUs as a function of the total bandwidth, in terms of number of optical slots. First, the power budget of the transceivers enable for up to 256 split ratio, plus fiber loss, emitting at a low power e.g. -3dBm per channel. Second, the eye-safety regulation establishes a maximum transmitted power, of 21.3 dBm in C-band. Third, the total optical bandwidth reserved for COCONUT is here a variable, at a channel spacing of e.g. 6.25 GHz; finally, the analyzed blocking probability when using laser thermal tuning (2 nm with +/-10ºC), instead of fully tunable lasers, with the Maximum Allowance algorithm at 0.1% blocking probability. This designates that 256 wavelengths can be allocated in 14.1 nm, hence losing less than 10% (12.8/14.1 = 90%) in spectral efficiency when using limited tunable DFB lasers instead of widely tunable lasers. Also, it implies that there is no need of sharing wavelengths and burst mode transceivers if this 10% extra bandwidth is reserved, since the network size would be then limited by the power budget and the eye safety limits at 256 ONUs.

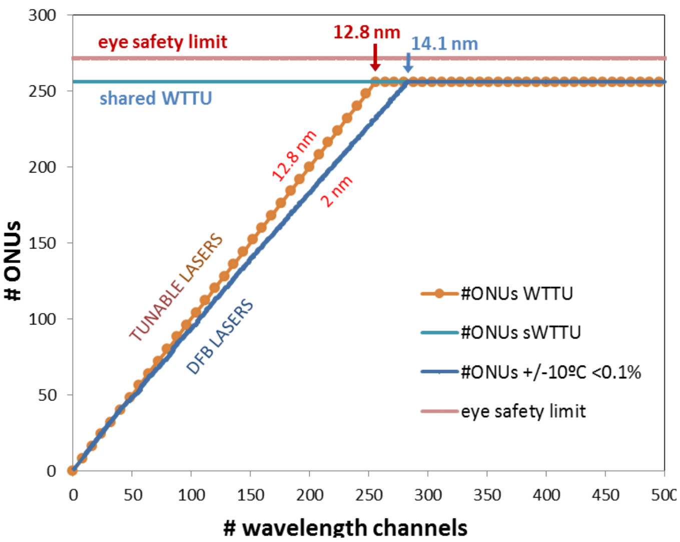


Fig. 9: Number of allocated ONUs as a function of the total bandwidth, in terms of number of optical slots, for the Maximum Allowance algorithm with 0.1% blocking probability and a maximum power budget for 256 split.

VI. MIGRATION PATHS

In order to make migration possible from currently deployed systems, some elements need to be in place to enable a smooth upgrade of individual customers from legacy PON systems to the proposed one. In our view, the two key optical elements are the Co-existence Element on the OLT side, and a blocking filter in front of the Receiver on the ONU side.

The coherent technology enables an increased loss budget which, in turn, allows for: a) reaching far away customers by just extending a distribution fiber of the first splitting stage, b) node consolidation, c) increase the number of homes passed. The udWDM grid allows COCONUT to co-exist in the same fiber with legacy optical solutions (L-PON), occupying a small portion of the overall spectrum.

Fig. 10 shows one example of a migration scenario. Increased splitting sizes also help saving costs in a low take-up situation, thus increasing the homes passed with a single PON port. It may be useful to reach far away customers by just extending a distribution fiber of the first stage of splitting. It is worth noting that this scenario can save costs to the operator. Other migration scenarios are depicted and explained in [2]. The compatibility of COCONUT is eased by the reduced crosstalk effects because it operates at lower powers, with very narrow spectral bandwidth and can use orthogonal constant envelope modulation formats, like PSK and FSK.

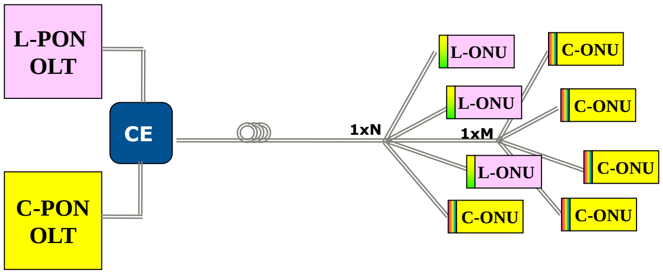


Fig. 10: Reach and rate extension scenario of Legacy PON with Coherent udWDM PON (L-PON: legacy PON, C-PON: coherent PON, CE: compatibility element).

VII. Cost Study

The different COCONUT system solutions have been compared against benchmarked technologies. The methodology of the cost study is described in [2]. In brief, the OLT and ONU have been broken down to components and parts, and a cost value has been assigned to each element. Here the dedicated wavelength-to-the-user (WTTU) scenario is illustrated; the analysis that discusses both dedicated and shared wavelength scenarios is detailed in [2]. The COCONUT transceiver solutions have been also compared with a conventional coherent receiver based on a 90º optical hybrid. As a reference, the cost of an InGaAs PIN for 1.25 Gbit/s operations was set to 1 a.u. and the rest of components scaled accordingly, as one of the central elements in the COCONUT coherent frontend receiver is the photodiode.

The results of the cost modelling of the COCONUT ONU options for the WTTU@10G connection configuration are shown in Fig. 11. The estimated savings in comparison to the conventional coherent receiver based on the 90° optical hybrid is a maximum of ~87%. Our ASK and DPSK solutions are shown to have very similar costs (differences are within the estimation error); further improvements may come by implementing fully analogue signal processing. On the other hand, the lowest cost COCONUT design shows a ~30% increase over the benchmarked solution of XG-PON1, although it must be noted that this technology cannot match the capacity of the COCONUT architectures and has been included only for the purpose of reference. At 1G, the relative results are analogous but around 25% lower than at 10G, due to the decreased bandwidth requirement.

Regarding energy consumption efficiency, the fact that the coherent transceivers operate at the user low bit rate, instead of the TDM aggregate rate, improves the power efficiency, as it is to be demonstrated in the practical prototypes. Analogue implementations of the signal processing have lower energy consumption [2].

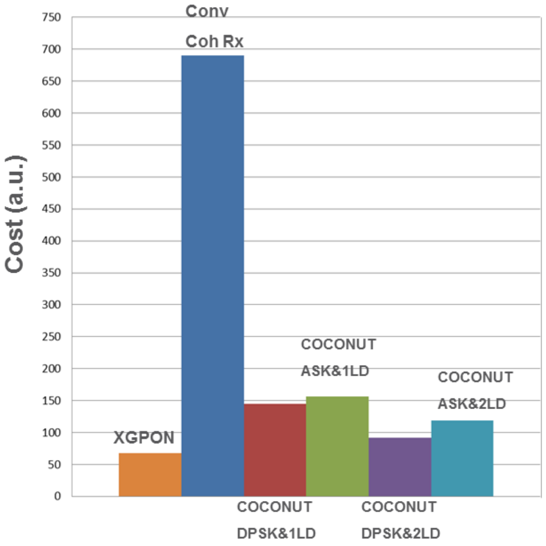


Fig. 11: WTTU@10G ONU relative costs of XGPON, conventional coherent transmission system and COCONUT versions.

VIII. Conclusions

Our analysis shows that ultra dense wavelength division multiplexing distributed among distant users can be a feasible alternative to high bit rate TDM-PONs for future access networks, with aggregate bandwidth of hundreds of Gbit/s with limited energy consumption of the ONU. The feasibility for 320 Gbit/s aggregate bandwidth, by 1.25 Gbit/s per 256 ONUs, in 14.1 nm only has been demonstrated.

We have shown that COCONUT approach solves inherent NG-PON2 issues, i.e., tunable filters and the cross-talk acceptance at the input ports of the wavelength multiplexing device. In addition, our proposed solution shows about 80% cost reduction when compared to a conventional coherent receiver as we have demonstrated that it is possible to eliminate the need for external modulators, external cavity and fully tunable lasers and 90º hybrids, among others, without sacrificing the performance.

The proposed udWDM PON offers, in the migration path, an increased loss budget allows for node consolidation, increased number of homes passed, longer reach and, by using narrow band in the same fiber, increased spectral efficiency. For this to become a deployable solution, further investigation has to be done on e.g. flexible fast sharing and tuning the wavelength channels, simplified real time processing, software defined transceivers, integrated optics, among others.

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