02

NG-PON2

This paper presents an overview of the NG-PON2 Technology.

The requirements, the deployment and coexistence scenarios and the NG-PON2 optics innovations are presented, namely in tunable optics and photonic integrated circuits.

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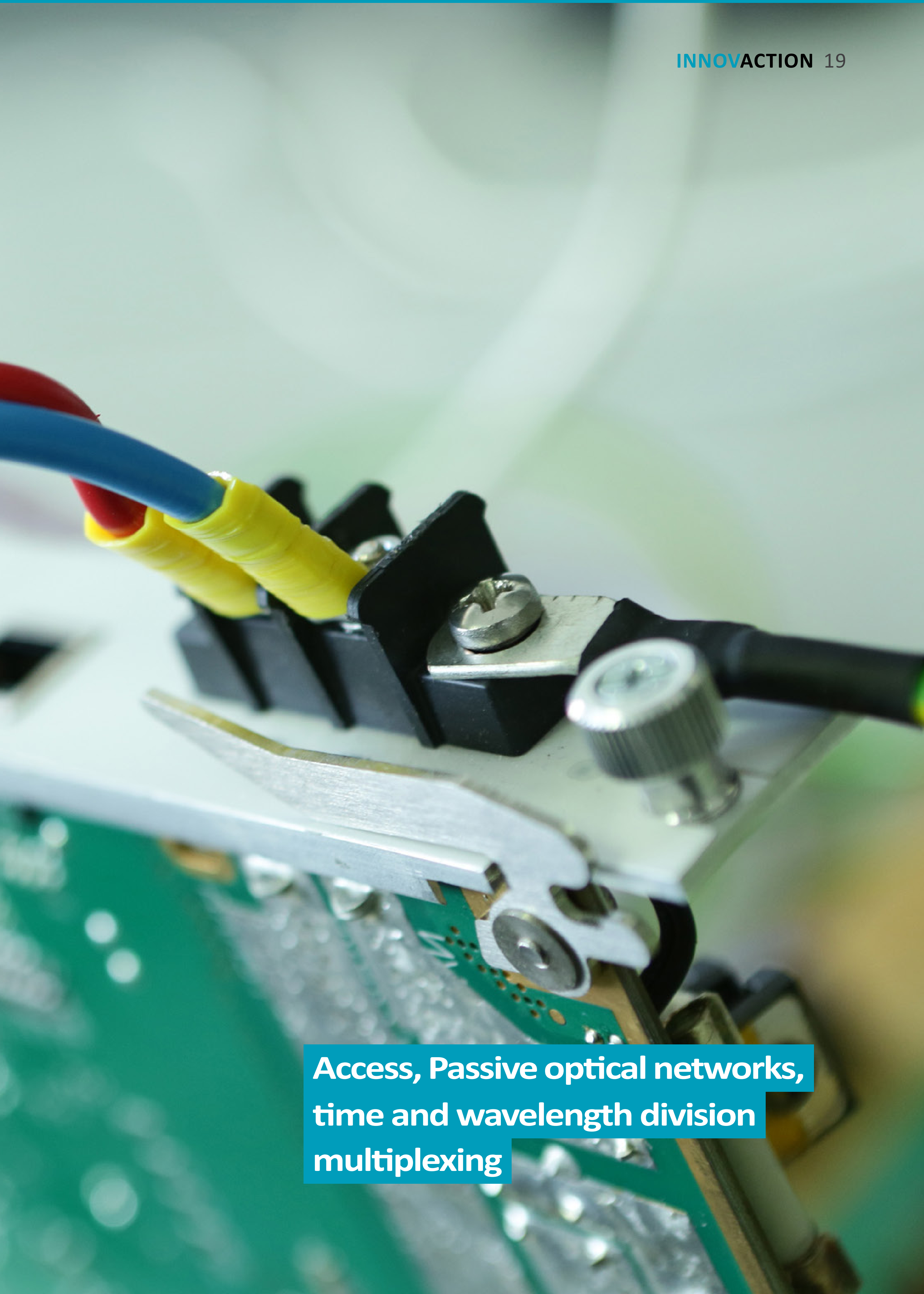

Access, Passive optical networks, time and wavelength division multiplexing

Introduction

Driven by the proliferation of heterogeneous bandwidth-consuming services, passive optical network (PON) architectures have been evolving in the last decade, providing enhanced availability, data rates and services. An evidence of this fast evolution is that both IEEE 802.3 and ITU-T together with the full services access network (FSAN) group are currently working towards the standardization of next-generation PON2 (NG-PON2) [1][2].

Several PON access technologies are currently deployed in the field, namely, EPON, 10G-EPON, BPON, GPON, XG-PON and the choices have been to evolve from the legacy systems without discontinuity of the previous technology, in other words maintaining coexistence over the same fibre span to further exploit the investment [3]. Additionally, as shown in Figure 1, spectral scarcity is now becoming a reality, since most of the low loss bands of the fibre are fully exploited. Gigabit PON technology, driven by the ITU-T, has conquered several markets and achieved high uptake rate. XG-PON was developed to try and improve the data rate, and due to the lack of component maturity together with tighter filtering and laser requirements, some risks were already taken. Starting from there, a new standard is now under finalization, the time and wavelength division multiplexing PON (TWDM PON) or NG-PON2 [2][4], representing a major change in the paradigm of previous technologies.

NG-PON2 is based on ITU-T G.989 series:

- ITU-T G.989.1 - 40-Gigabit-capable passive optical networks that contains the general requirements for the NG-PON2;
- ITU-T G.989.2 - 40-Gigabit-capable passive optical networks (NG-PON2): Physical media dependent (PMD) layer specification, that specifies parameters for the physical layer as wavelength plans, optical loss budgets, line rates, modulation format, wavelength channel parameters and ONU tuning time classes;
- ITU-T G.989.3 - 40-Gigabit-capable passive optical networks (NG-PON2): Transmission Convergence Layer Specification;

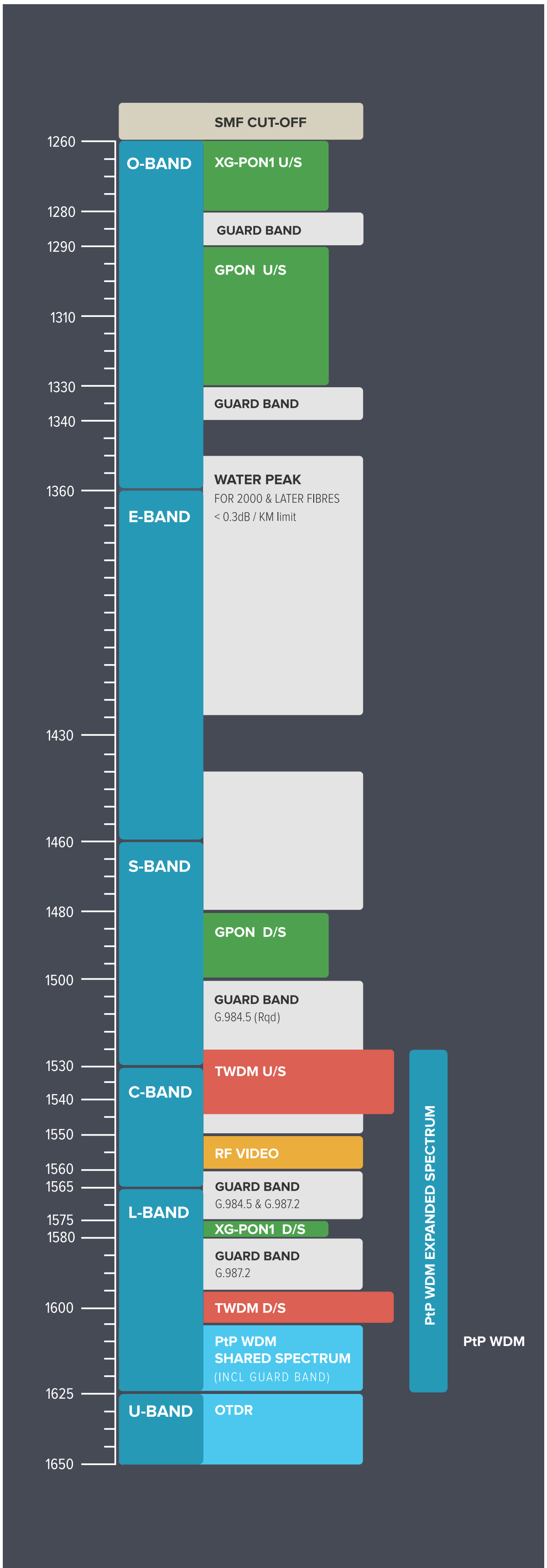

FIGURE 1 PON spectrum

- ITU-T G.989- contains the common definitions, acronyms, abbreviations and conventions of the G.989 series of Recommendations.

This paper is organized as follows: Section 2 presents the main requirements and drivers for NG-PON2. Section 3 explains the basic functionalities of NG-PON2 and continues into section 4, with TWDM PON main advantages. In Section 5 the TWDM PON development scenarios are discussed. In Section 6 and 7 the NG-PON2 optics are discussed. Section 8 concludes the paper.

Requirements and Drivers for NG-PON2

NG-PON2 main target requirements are the increase of aggregate capacity per Optical Line Terminal (OLT) PON port, a sustainable bandwidth on any Optical Network Unit (ONU) at downstream of 1Gbit/s and upstream of 0.5 to 1 Gbits, support of 64 or more ONUs per port, be compatible with legacy PON infrastructure, a 40 km differential reach and a smooth migration, i.e., legacy PON coexistence (GPON and/or XG-PON1), support for multiple applications on the same Optical Distribution Network (ODN) (residential, business, backhaul), embedded test and diagnostics capabilities and PON resilience, including dual parenting [18].

TWDM PON was selected as the primary technology solution for NG-PON2 (in April 2012). This decision was based on considerations of system cost, technology maturity, loss budget, complexity and power consumption.

There are several applications driving the demand for next generation PONs, namely:

- FTTB for multi-dwelling units;
- Enterprises;
- Mobile Backhaul;
- Fronthaul;
- Cloud-RAN.

Nowadays, content presents itself as the main driver for the high access bitrate requirements and it is more than the usual streaming to which we are used to, such as linear TV and video on demand.

Video content is also found in examples such as video surveillance, remote health care, video file transfer / data burst, etc.

Residential was the primary focus but mobile, business and M2M are demanding more and more content capacity.

As a consequence, CSPs need to prepare the access network for the future, which includes serving several segments and different backhaul features. It can thus be concluded that future access networks will be a truly multi-service solution.

The “cloud opportunity” is also a very important driver to evolve to NG-PON2 because:

- Software packages must be downloaded from data centres;
- Personal data is nowadays stored in data centres;
- Very high upload and download speeds are required as well as symmetry and low latencies.

Next Generation PONs will be a significant asset to promote successful cloud delivery.

What is NG-PON2

NG-PON2 is a 40 Gbit/s Capable Multi-Wavelength PON system that can grow up to 80 Gbit/s. It has 3 types of channel rates: basic rate 10/2.5 Gbit/s or optionally 10/10 Gbit/s and 2.5/2.5 Gbit/s. ONUs are colourless and can tune to any assigned channel [18 to 21].

In Figure 2 it is possible to find the basic NG-PON2 system.

The downstream TWDM channels, in L band, 1596-1603 nm, fit between XG-PON1 downstream and OTDR monitoring band. This enables simultaneous coexistence with legacy PON and 1550 nm RF video.

In upstream, the TWDM channels work in C band, 1524-1544 nm (wide band), 1528-1540 nm (reduced band), 1532-1540 nm (narrow band), above the WDM1r coexistence filter edge and below the 1550

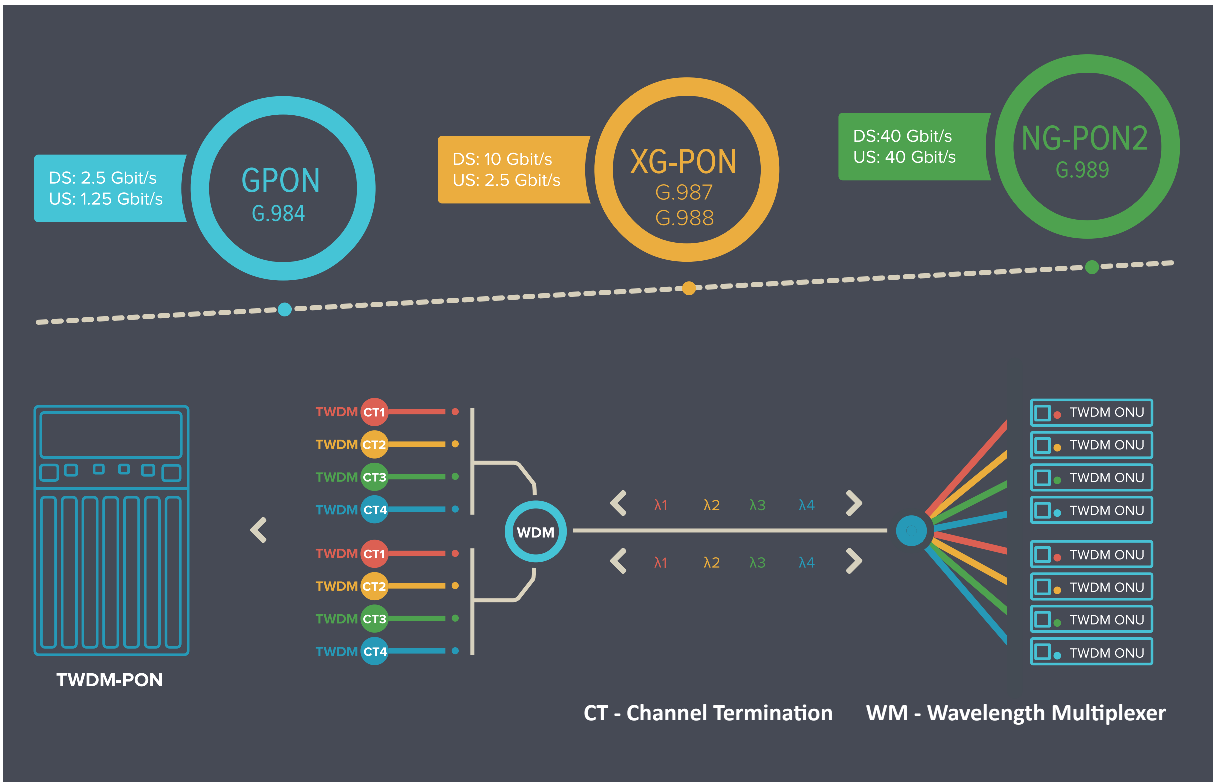

FIGURE 2 TWDM PON basic scenario

nm RF video band. The use of C-band allows lower cost ONUs [18 to 21].

Upstream wavelength options are driven by differing capabilities of the ONU transmitter to control its wavelength, i.e., wide band option is usable by wavelength set approach to channel control where a DFB laser may drift over a wide range, narrow band option may be most appropriate for temperature controlled lasers than can lock onto the assigned DWDM wavelength [18 to 21].

In Figure 3 is possible to see the wavelength tuning capabilities of the ONUs in the NG-PON2 system.

NG-PON2 is compatible with legacy loss budget classes, i.e., B+ and C+ of GPON and N1, N2, E1, E2 of XG-PON1.

It requires a minimum optical path loss of 14 dB and allows a differential reach of 40 km.

The optical path loss and fibre distance classes are presented in next tables [18 to 21].

class	N1	N2	E1	E2
Min loss (dB)	14 dB	16 dB	18 dB	20 dB
Max loss (dB)	29 dB	31 dB	33 dB	35 dB
Max. differential optical path loss	15 dB			

Fibre Distance Class	Minimum (km)	Maximum (km)
DD20	0	16 dB
DD40	0	31 dB

NG-PON2 has defined 3 classes of Tx/Rx wavelength channel tuning time and these classes were broadly defined based on known wavelength tunable technologies [18 to 21]:

- Class 1 components may include switched laser on arrays;
- Class 2 components could be based on electronically tuned lasers (DBR);
- Class 3 components could be thermally tuned DFBs.

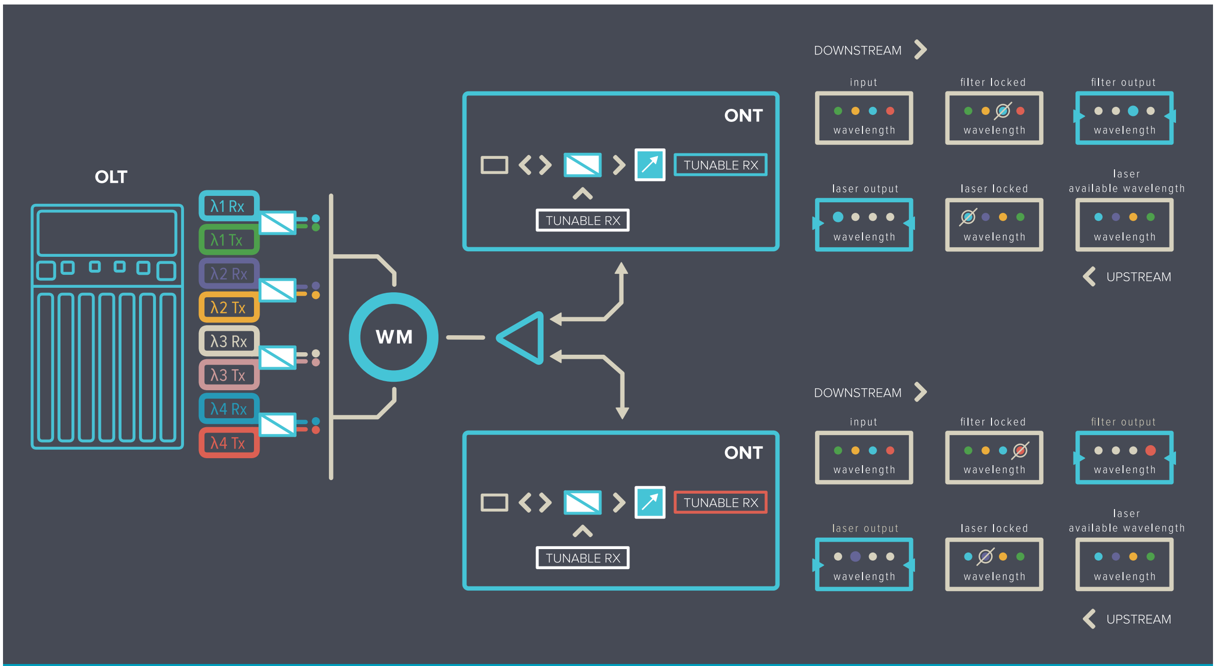

FIGURE 3 TWDM PON Wavelength tuning

Class 1	< 10 us
Class 2	10 us to 25 ms
Class 3	25 ms to 1 s

Through wavelength agility TWDM PON allows enhanced network functionalities unavailable in previous generations of pure TDM PONs, namely [18 to 21]:

- Incremental bandwidth upgrade (pay-as-you-grow);
- Selective OLT port sleep for power saving during low traffic periods, i.e., during times of low traffic load all ONUs can retune to a common wavelength and allow OLT ports to be powered down;
- Resilience against OLT transceiver failures through ONU retuning, i.e., all ONUs can retune to a common standby or working wavelength under a fault condition to maintain a basic service until the fault is cleared;
- Fast, dynamic wavelength and timeslot assignment using DWBA (extra degree of freedom c.f. DBA today) to improve bandwidth utilization efficiency.

NG-PON2 transmission convergence layer has new capabilities supported by the protocol, as multiple wavelengths, TWDM and point-to-point channels. Communication starts with a single channel adding more channels later and distributed OLT Channel Terminations (CTs) which can drive a single fibre [18 to 21].

These new protocol functions allow [18 to 21]:

- Multiple wavelengths so protocol supports tuning;
- New identities to distinguish system and wavelength channel;
- New management protocol for PtP WDM and TWDM activation;
- Dealing with ONUs with uncalibrated lasers that must not be allowed to transmit in the wrong wavelength channel;
- Inter-channel messaging for some procedures over distributed OLT channel terminations;
- New rogue scenarios that can be detected and mitigated.

Regarding the tuning support, the ONU state machine covers activation and channel management. PLOAM messages control tuning and new ONU parameters were added for tuning time.

Identities for multiple wavelengths and distributed OLT CTs are taking into account [18 to 21] that:

- Each downstream channel wavelength advertises channel information including channel number and an identity of the PON system that owns the channel;
- OLT CT can feed back upstream channel identity to ONU;
- ONU can feed back the downstream channel and system identity it is receiving to OLT CT;
- Distributed OLT controls ONU ID uniqueness across all channels, PtP WDM and TWDM;
- To not limit a potential future extension, the protocol has code space for 16 wavelengths even though the physical layer specifies up to 8.

NG-PON2 has an inter-channel termination protocol. The OLT CTs are distributed so that some procedures require messages to be passed between OLT CTs [18 to 21]:

- Synchronizing OLT CT Quiet Windows;
- ONU tuning;
- ONU activation;
- Parking orphaned ONUs;
- ONUs connected to the wrong ODN;
- Guided hand-off of ONUs between OLT CTs;
- Rogue ONU Isolation.

NG-PON2 covers different protection scenarios and rogue behaviours of the ONU [18 to 21]:

- ONU transmitter hops to wrong upstream channel;
- ONU transmitter starts transmitting at wrong upstream wavelength;
- OLT CT transmits in the wrong downstream wavelength channel;
- Interference from coexisting devices, either faulty ones or due to spectral flexibility;
- Distributed OLT channel terminations can be used for protection, requiring inter-channel termination coordination.

TWDM PON major advantages

FTTH for everything

A major advantage of TWDM PON is its ability to support different types of subscribers and applications by using different wavelengths and different bitrates on those wavelengths. It can assign a single wavelength to a particular customer, such as a business, or to a particular application, such as mobile backhaul.

Legacy investment preservation

TWDM PON coexists with legacy PON systems. No changes are required to the ODN, i.e., fibres, splitters and cabinets, as so, GPON network investments are preserved. TWDM PON can be added over an existing GPON or XG-PON network: an existing GPON network can be upgraded gradually over time (pay-as-you-grow). An operator could deploy TWDM PON where it has identified new market opportunities, such as enterprise subscribers. It could use TWDM PON for internal support of fronthaul and backhaul needs. The service provider could also take the option to upgrade existing high-end residential customers to TWDM PON where it faces significant competition from other service providers promoting 1Gbit/s and beyond.

Pay-as-you-grow

Wavelengths can be added one by one, as needed, to support customer growth and high-bandwidth applications.

TWDM PON deployment scenarios

In NG-PON2, different wavelengths are used.

The downstream wavelengths are multiplexed at the OLT using a WM1 device. This device multiplexes the downstream L band wavelengths into a single port and *demultiplexes* the C band upstream signals from the ONUs forwarding them to each OLT CTs.

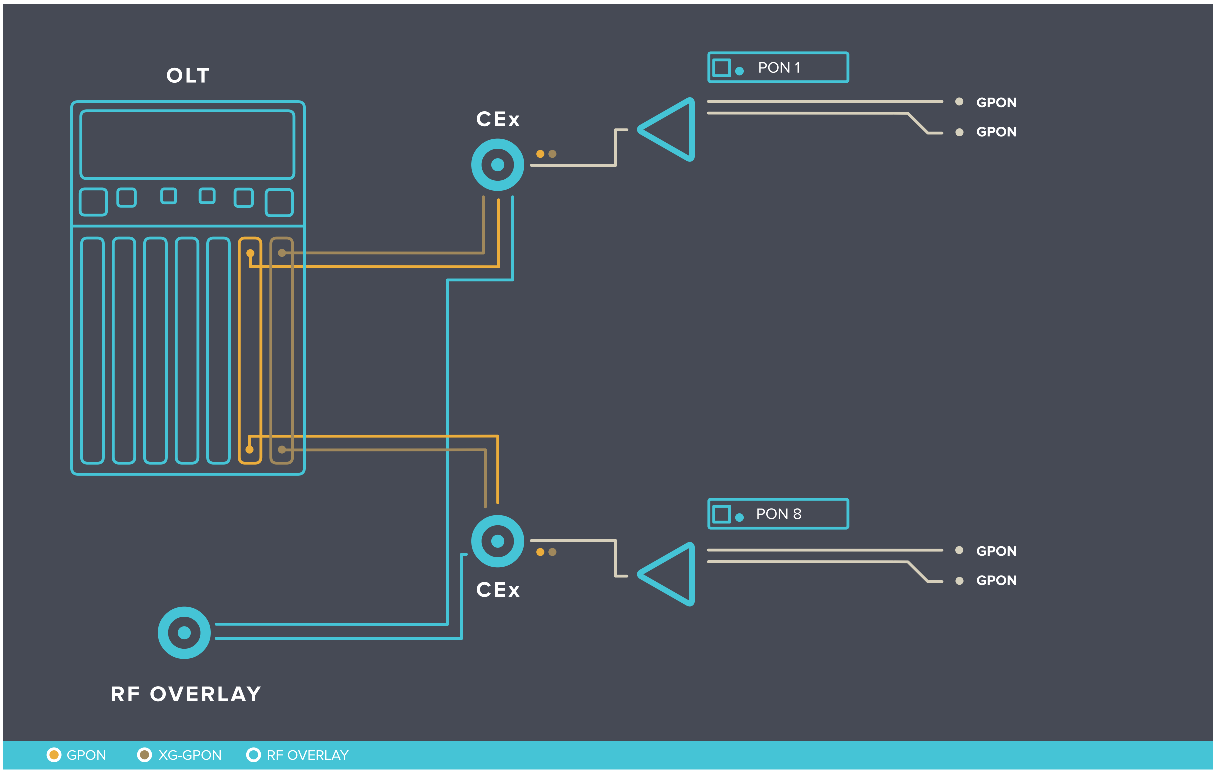

FIGURE 4 Coexistence scenario

In order to coexist with legacy PON networks a coexistence element is needed. This coexistence element can have different configurations depending on the technology that the service provider wants to deliver (Figure 4).

In the case of an existing GPON network, the most likely upgrade approach is to insert a TWDM card into the OLT platform. The TWDM PON line card can have the same wavelength on each port or different wavelengths on the various ports of the line card depending on subscriber, application and bandwidth projections. Several implementations of WM1 devices are possible, and they can be external to the TWDM card or integrated on it.

Three different arrangement options are possible:

- Option 1, one TWDM card per fibre with 4 wavelengths per PON card with WM1 integrated in a single output PON port;
- Option 2, one TWDM card per fibre with 4 wavelengths with external WM1 module;
- Option 3, based on the pay-as-you-grow approach, where the wavelengths are across TWDM cards with external WM1.

Next table provides a comparison from a service availability perspective of the different scenarios.

Scenario	Lambdas on a Single Card	Lambdas across cards
Wavelength Failure	Affected ONUs moved to other wavelength ports of the same card; All ONUs are down while the card is rebooting.	Affected ONUs moved to other linecards; Other ONUs on the card are tuned to other wavelength prior to card reboot.
Complete Line card Failure	Affected ONUs are down while card is not replaced.	Affected ONUs are moved to other linecards.
Software Upgrade	Affected ONUs are down during reboot and reactivation.	Affected ONUs are tuned in advance of upgrade.

The non-integrated modular approach provides several operational and economic advantages, such as:

- Straightforward support for pay-as-you-grow by addition of wavelengths;
- Easy bitrate configuration for each wavelength;
- Simple facilitation of wavelength unbundling per operator, which supports governmental requirements for fibre sharing or co-investment partnership business models.

From an operational perspective, to upgrade a network from the legacy GPON to NG-PON2, existing GPON subscribers that will remain on GPON must be briefly out of service during installation of the coexisting element (CEx), after which, the service is restored. Residential subscribers that will be remaining on GPON and not upgraded to TWDM PON will experience a brief service outage (which can be planned during low-usage hours), but only when the CEx is introduced. Wavelength additions or changes will not impact existing subscribers except those being upgraded to new wavelengths.

It should be noted that the same scenario described here would also apply in the case of XG-PON upgrades, since a CEx would also have to be introduced to enable the combination of GPON and XG-PON.

Figure 5 to Figure 8 present coexistence and pay-as-you-grow scenario.

NG-PON2 OLT and ONU optics

The current NG-PON2 OLT optics are based on Bi-directional Optical Subassemblies (BOSAs) integrated on XFP form factor. They are suitable for TWDM PON, 10Gbit/s downstream, 2.5 Gbit/s or 10 Gbit/s upstream. The XFP integrates an electro-absorption integrated laser diode with semiconductor optical amplifier (SOA) in order

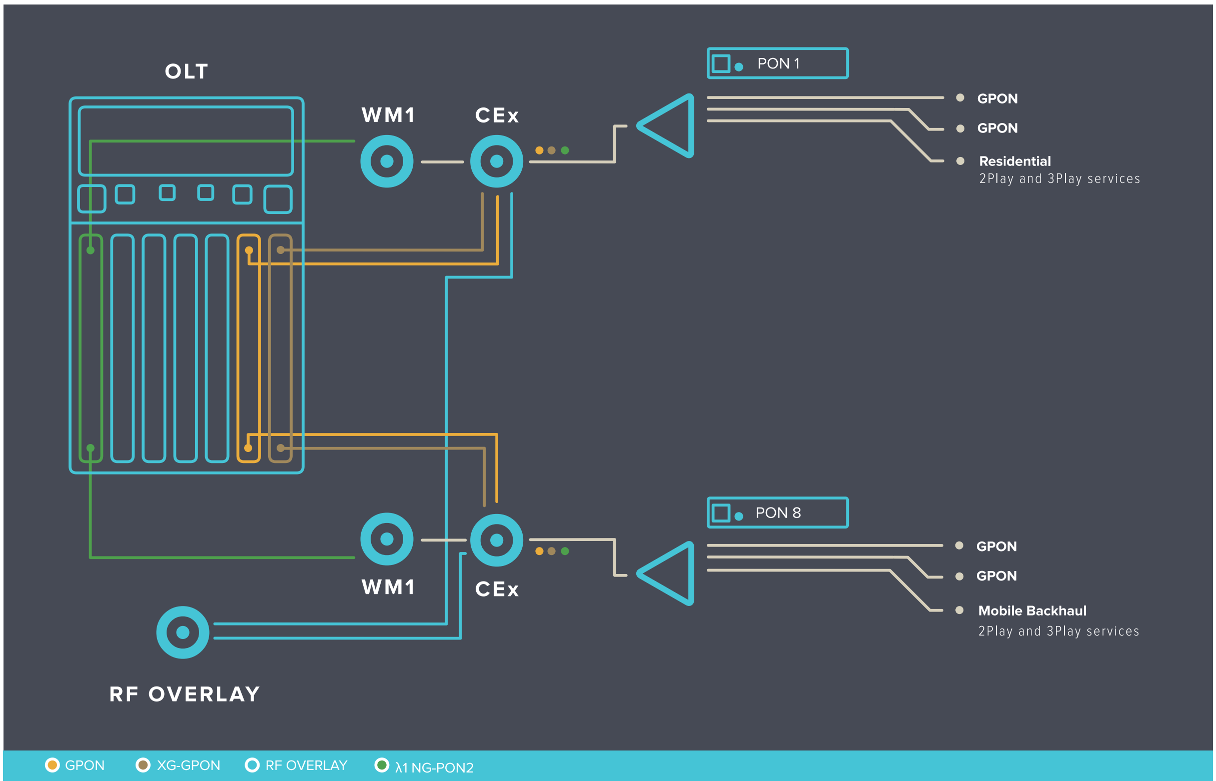

FIGURE 5 Pay-as-you-grow. 1st phase

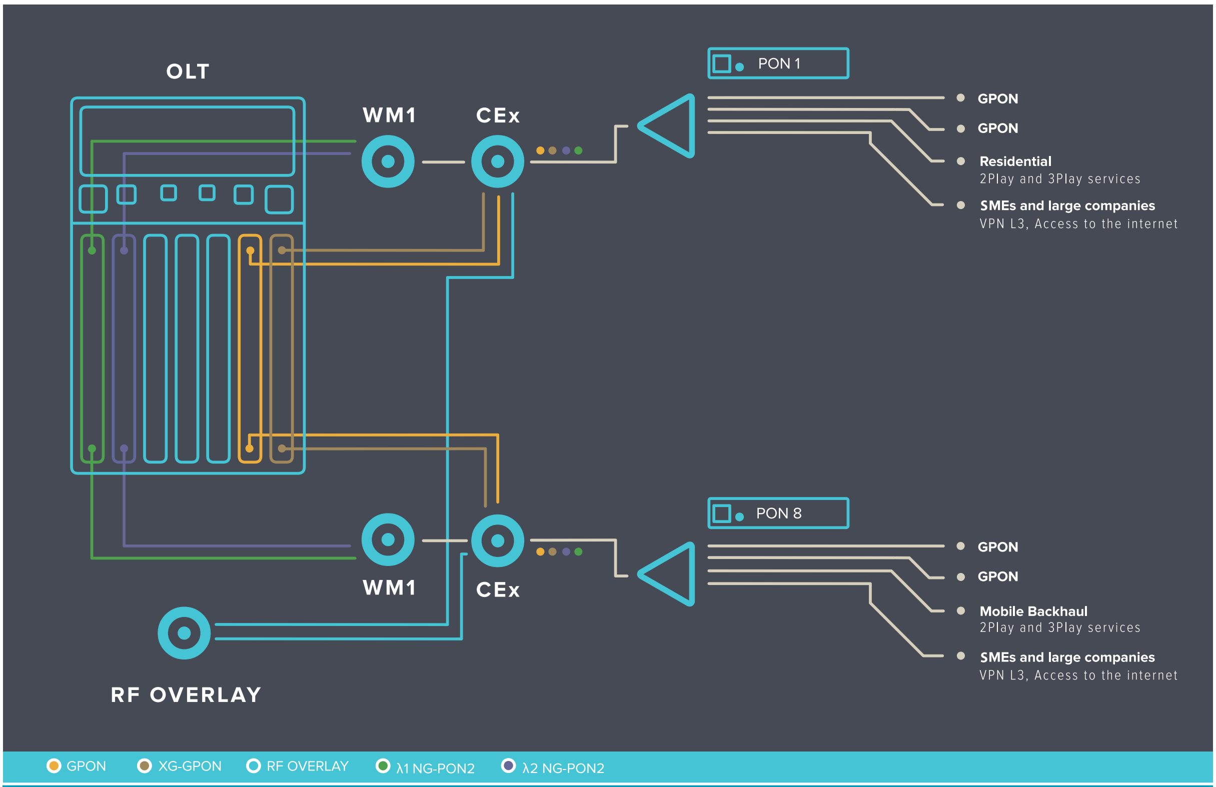

FIGURE 6 Pay-as-you-grow. 2nd phase

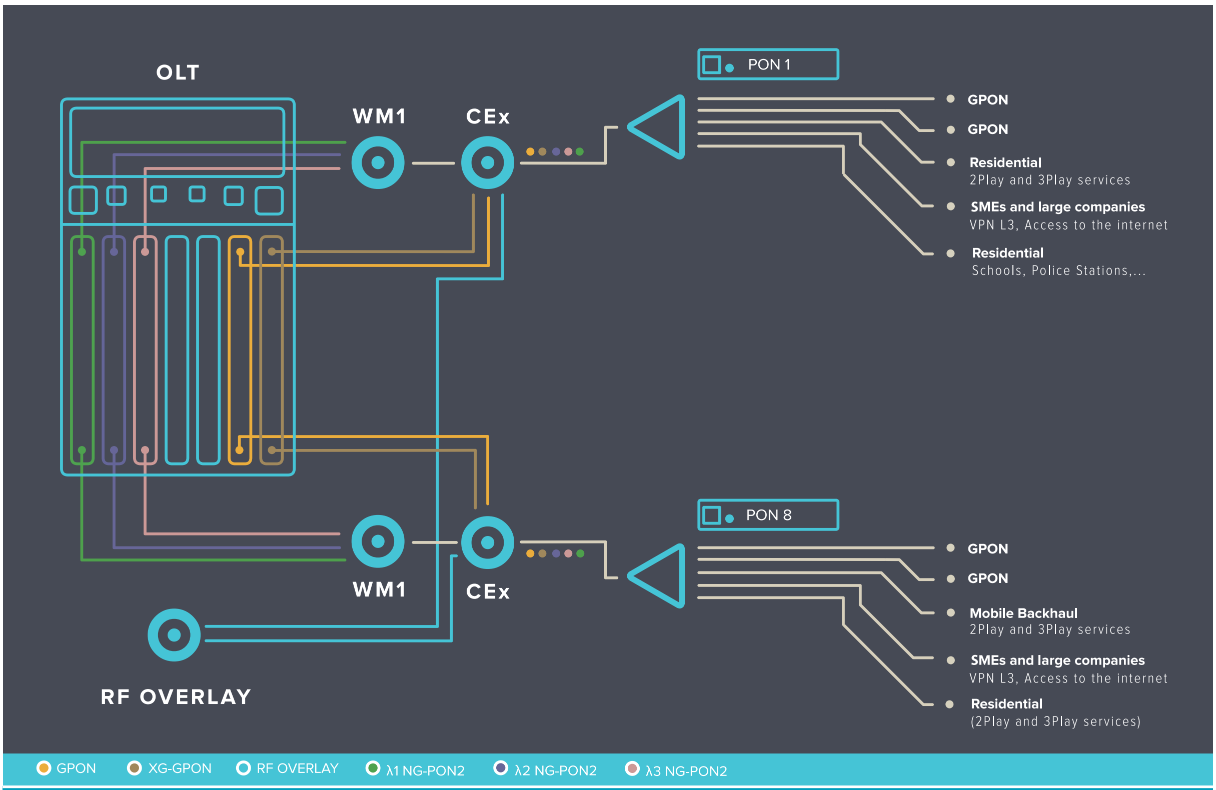

FIGURE 7 Pay-as-you-grow. 3rd phase

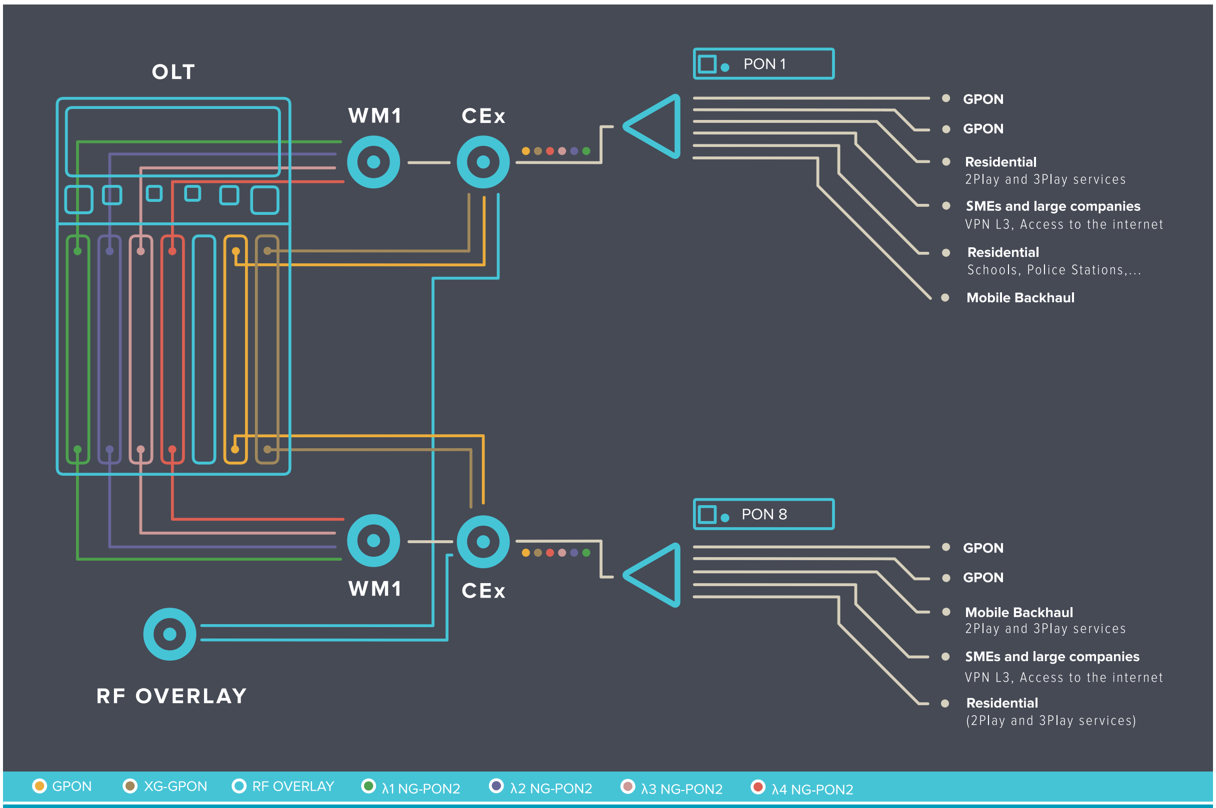

FIGURE 8 Pay-as-you-grow. 4th phase

to reach the type A N1 class NG-PON2 optical requirements (+5~+9 dBm at the output of the XFP). A high sensitivity burst mode avalanche photodiode (APD), a pre-Amplifier and a limiting amplifier as receiver components are mounted into a package integrated in single mode fibre-stub with a sensitivity equal to-28.5 dBm at 10 Gbit/s; and-32 dBm at 2.5 Gbit/s).

The NG-PON2 ONU optics are based on BOSA on board. The BOSA integrates a burst mode tunable distributed feedback lasers (DFB) at 10 Gbit/s or 2.5 Gbit/s emitting high optical power in a N1 type A link, +4~9 dBm capable of doing 4 upstream channels.

On the receiver side, a high sensitivity 4 channels tunable APD a pre-Amplifier and a limiting amplifier are able to operate at a sensitivity of-28 dBm at 10 Gbit/s.

Closing the gap between Photonic Integrated circuits and PONs

The road to commercial Photonic Integrated Circuits

It was back in 1965 that Gordon E. Moore predicted the number of transistors inside an electronic integrated circuit would double every year. Today, 50 years later, we face a technological revolution where electronic devices surround us and we cannot imagine our lives without them. Integration was the key to success and allowed mankind to develop computers, specific application hardware for numerous applications and small devices (yet very powerful) like our smartphones. Integration brought compactness, ease of fabrication and cost accessible technologies meaning success in the electronic industry. Affordable, efficient integration is now starting to occur in photonics. Photonic Integrated Circuits (PICs) are the dual of electronic integrated circuits in the optical domain, as they perform integrated computing and signal processing functions that are based on light. Their main application is in fibre-optic communications but they can also be used in biomedicine, photonic computing and sensing devices.

Photonic integration emerged at the end of the 1960s [5]. By that time, it was expected and believed that photonic integration would take a similar development path as electronic integration. However it took almost four decades until the first complex PIC (more than just a few components) entered the market [6]. This was due mainly to two reasons. In one hand in the 1990s a shift on technology focus from 'technology push' to 'market pull' delayed the funding for photonic integration. On the other hand there was a failure on the coordination of technology development which led to high costs and several different technologies developed [7]. An early example of a PIC circuit was reported in the Applied Physics Letter on WDM light sources [8] which integrated three lasers, a power combiner and a booster amplifier. In 1991, Duthie [9] reported a 4x4 cross-bar switch and in 1994 Kaiser [10] produced a polarization diversity heterodyne receiver. The era of high-complexity PICs started in 1988 when Smit published the invention of the Arrayed Waveguide Grating [11]. Almost 20 years after, Infinera launched the first truly complex PIC in a commercial telecommunications system [12].

Research context, objectives and work plan

PICs, as stated above, can be used in countless applications however their fast development was due to the systems based on fibre optics communications. In the telecommunications industry the goal is to reach as many clients as possible with the lowest cost while providing the best service. The demand for bandwidth and number of users has been increasing constantly and the only technology that can keep up with these demands is the fibre optic communication because it is the only technology that can supply high data rates and reach large distances. PONs are networks that do not need amplification or regeneration of the signal from the central office to the users, which due to fibre properties can extend up to 40 km. Although it was a success, the bitrates that are provided do not take full advantage of the fibre capabilities and thus new standards such as NG-PON2 are now ready to be deployed. It can quadruple the bandwidth and uses the spectrum more efficiently. With these improvements, the complexity of the networks and the components also increases, which translates in more difficulties controlling the components, more room needed and more power consumption. In order to tackle the problems that arise with this evolution, PICs are an inevitable evolution. With the integrated version of the discrete implementations, the control complexity, the floor space and power consumption will decrease. Integration also means the decrease of costs which will make these networks more affordable. However research still needs to take place to turn PICs competitive.

To increase competitiveness of PICs, several projects were developed so that generic foundry models were created and different users can contribute to the design of a single wafer in the same process, those are the so-called Multi Project Wafer (MPW) run [6] [7]. The cost of a MPW run when compared with a normal commercial run can be one to two orders of magnitude cheaper leveraging the increase of research in the field. To promote and streamline these processes, consortiums like Jeppix [13] were created. Jeppix offers contact with foundries and design houses of the different technologies as well as organizes the schedules of the different MPWs. The idea of generic integration is that the user is agnostic to the way the foundry implements the technology and sees the components as building blocks which means that if different foundries have the same building block (e.g. amplifier) it is very easy to translate from one foundry to another. Currently, there are three main platforms to develop PICs: Silicon (Si), Indium Phosphide (InP) and TriPleX (combination of Silicon Nitride – Si_3N_4 and Silicon Dioxide – SiO_2). Each platform has different characteristics and main applications; the major difference is that with Indium Phosphide it is possible to have active elements (e.g. lasers) that are needed for the telecommunications applications.

Altice Labs and Instituto de Telecomunicações team started to work in the field of PICs two years ago within the scope of the NG-PON2 project. A complex PIC, able to transmit and receive NG-PON2 signals, with more than 40 components inside was designed, produced and tested [14] (see Figure 9 and Figure 10).

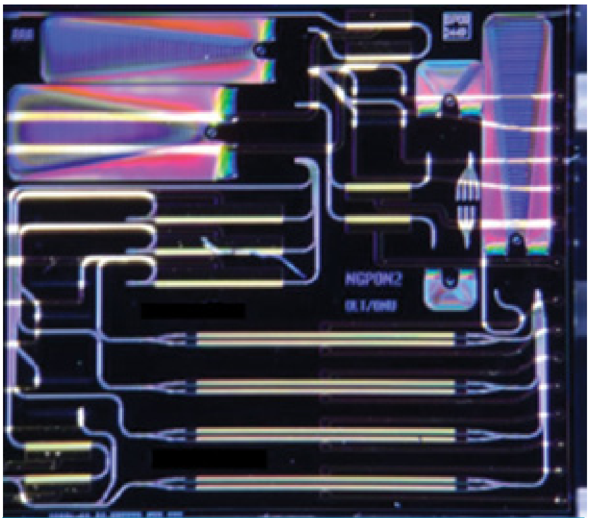

FIGURE 9 PIC for NG-PON2. Chip received from the foundry

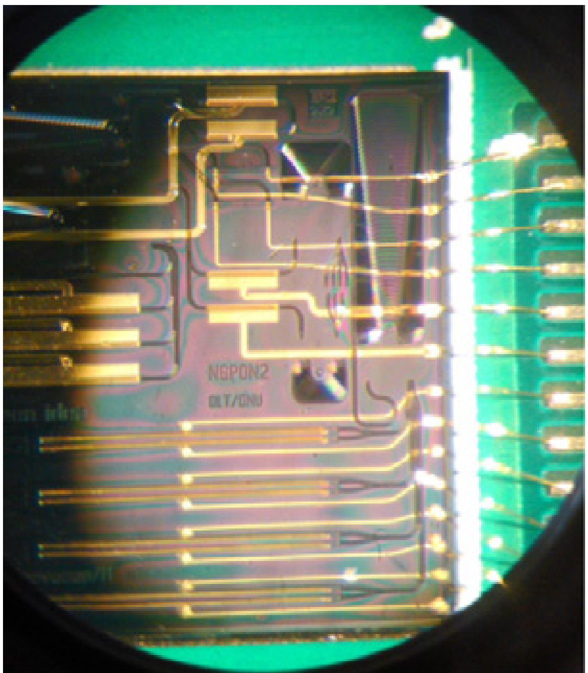

FIGURE 10 PIC for NG-PON2. Detail of packaging with wire bonding for the electronic circuit

For non-standardized networks that used advanced modulation formats and coherent detection an integrated circuit was also designed [15]. This last case was designed to operate in 100 Gigabit/s networks. Outside the scope of telecommunications, a PIC for optical signal processing was also designed and produced at Instituto de Telecomunicações and produced [16]. All this background gave the team experience with most of the foundries as well as an insight in the processes.

Despite the achievements that were obtained so far in the design and testing of PICs, there are still major difficulties in the process which are mainly due to the novelty of the technology. At this point in time, all the members of the consortiums like Jeppix are putting their effort to improve the platforms and links among them; this is also part of the research phase: providing feedback from the tests in order to help improving the results. One of the problems that the researchers currently face when designing for an MPW is the lack of information about the building blocks that the foundry provides. Despite the fact that there are design manuals with information about the process and building blocks, the information is not enough to perform the most accurate simulations before the design and production, which can lead to errors that only in a later stage will be found. To solve this, optical simulations software are starting to integrate the models from the foundries and the foundries encourage the users to develop their own blocks of simulations' [17].

With the first steps already taken towards a mature process on design and production of PICs this is an essential area to keep up with the evolutions that occur on the field and properly contribute to this topic. In 2016, the first commercial solutions of NG-PON2 are planned to be deployed and they will be based on discrete components. Their scalability depends on the appearance of integrated solutions and thus it is important that PIC research focus on this trend. As the demand for PIC production increases, foundries are also providing more options for MPW runs which will ease the whole process.

Optical communications and PIC are fields of science and technology under constant and fast development. New standards are created every year and the PIC technologies are still in development. In order to follow the trends, focus and investment must be conjugated in this field. This is the only way to guarantee growing and novelty in the fast changing world of innovation.

The first NG-PON2 photonic integrated circuit prototype totally compliant with ITU-T G.989 is expected in the 2nd quarter of 2016 and its mass production is foreseen for the 4th quarter of 2016.

Conclusions

TWDM PON will certainly become the network access technology that supports the widest range of subscribers and applications, leading to faster network monetization. The table below provides a summary of the advantages and disadvantages of TWDM PON versus GPON.

	GPON	TWDM PON
Flexible growth – pay-as-you-grow	+	+++
Ability to support MBH	+	+++
Ability to support mobile fronthaul	-	+++
Ability to support enterprise services	-	+++
Overall fixed–mobile convergence support	-	+++
Ecosystem status	+++	++
Commodity priced equipment	+++	++

TWDM PON's architecture enables the assignment of wavelengths to specific customers or applications. The wavelength design also enables a pay-as-you-grow development. While GPON can also support MBH, TWDM PON can provide more bandwidth, thereby supporting more MBH traffic. The assignment of wavelengths enables an easier support of enterprise services. In addition TWDM PON was designed to allow point-to-point overlays for the support of fronthaul.

In order to reach the full potential of the NG-PON2 in terms of density and capacity, technologic and industrial advances and innovations are undergoing, namely in the field of high integration PICs.

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