

# PANDA: Asymmetric Passive Optical Network for xDSL and FTTH Access

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## ABSTRACT

In this paper, we present an "Asymmetric Passive Optical Network for xDSL and FTTH Access" (PANDA) architecture that is suitable for providing end-users with broadband connections in a cost-effective and non-disruptive fashion. We first describe the need for expanding the current ADSL access to VDSL (and ultimately FTTH), as well as the network upgrades that will be required to perform this expansion. We then introduce the PANDA architecture, a multiwavelength passive optical network (PON) that implements a fiber-to-the cabinet (FTTC) access

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scheme and provides multi-ten Mb/s access to VDSL2 end-users. We also derive the PANDA capacity in terms of number of users and spatial coverage and show that PANDA is well capable of meeting the broadband needs in the Greece for the short and medium term. We conclude this work with a scalability study of PANDA in view of the goals set in the EU Digital Agenda.

## Categories and Subject Descriptors

C.2.1 [COMPUTER-COMMUNICATION NETWORKS]:  
Network Architecture and Design

## General Terms

Algorithms, Performance, Design, Standardization.

## Keywords

Broadband Access, Digital Subscriber Loop, Passive Optical Networks, Medium Access Control, Network Scalability.

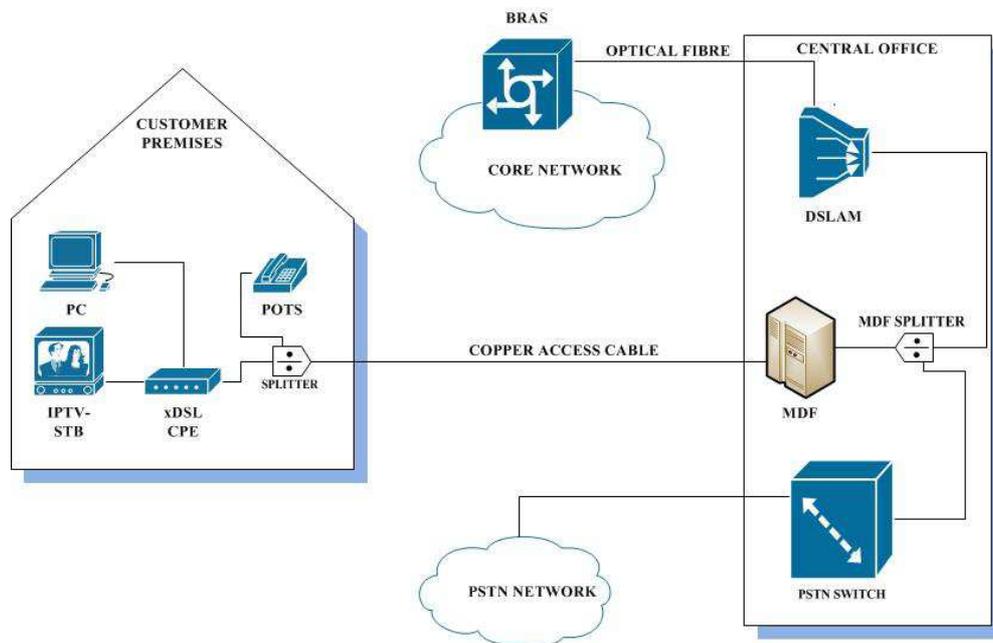


Figure 1. Broadband access via copper cables.

## 1. INTRODUCTION

Next generation access (NGA) networks envisage the deployment of an ultra-high capacity network infrastructure that will gradually extend end-user line rates and will ultimately provide Gb/s access via fiber-to-the-home (FTTH) or fiber-to-the-building (FTTB) schemes. To this end, the two key communication standardization bodies, ITU and IEEE, have provided a range of technical documents to define the operation of passive optical networks (PONs) that are generally considered a well-suited low-cost solution for the implementation of NGA networks [1]. Moreover, an update on ITU standards is expected in the short term, and the forthcoming standard will utilize multiple wavelengths so as to extend the PON capacity in terms of attainable user line rates [2].

Within this context, the consortium of the "Asymmetric Passive Optical Network for xDSL and FTTH Access" (PANDA) project designed a multiwavelength access architecture that is fully compatible with standardized ITU PONs (XG-PONs) and VDSL networks, and has a key objective of providing short and mid-term broadband access to thousands of users in the Greek state. The current paper discusses the proposed architecture, its key technological features and its capacity in terms of population and spatial coverage. The rest of the paper is organized as follows: section 2 summarizes the current status of broadband access in Greece and possible roadmaps that can be followed towards the deployment of future high-capacity access networks. In section 3, we present the PANDA architecture, and discuss its most important technical aspects with respect to the PON and VDSL segments. Section 4 illustrates the capacity of PANDA in terms of line rate and number of users, and also provides possible solutions for upgrading PANDA to meet the ever-growing end-user capacity needs. The paper concludes with the scalability study of section 5, where we demonstrate that the capability of PANDA to provide access lies well beyond the EU Digital Agenda goals.

## 2. CURRENT ACCESS STATUS AND UPGRADE ROADMAPS

### 2.1 Access Status in the Greek State

The current status of broadband access in Greece is mainly based on the installed plain old telephone service (POTS) infrastructure in a fashion that is summarized in Fig. 1. The end-user is served over a copper twisted pair that terminates on the main distribution frame of a local exchange (LE). The twisted pair provides both public switched telephone network (PSTN) and digital subscriber loop (xDSL) services, while splitters are employed at the user premises and the LE to multiplex and demultiplex PSTN and xDSL signals, respectively. The xDSL signal is then fed to the digital subscriber line access multiplexer (DSLAM), which multiplexes a number of end users and provides connection with the broadband remote access server (BRAS). The DSLAM-BRAS connection is implemented with optical technologies, under a scheme commonly known as fiber to the exchange (FTTEx).

The attainable line rate in the access architecture presented in Fig. 1 is mainly determined by the quality of the connection between the end-user and the DSLAM. Copper aging and physical impairments, as well as losses and crosstalk, may well reduce the available bandwidth and thus the end-user line rate. Moreover, the user-DSLAM distance also plays an important role in the available bandwidth, and remote users typically receive only a portion of the nominal bandwidth. For example, the nominal peak rate of ADSL2+ users is typically set to 24 Mb/s, however these rates may only be enjoyed by end-users that are within a few hundred meters of the LE. Statistics show that only ~35% of the end-users in Greece are closely located to the LE (access loop length <800m) and attain line rates up to 21 Mb/s, still most of the users attain distance dependent line rates ranging from 12 to 18 Mb/s.

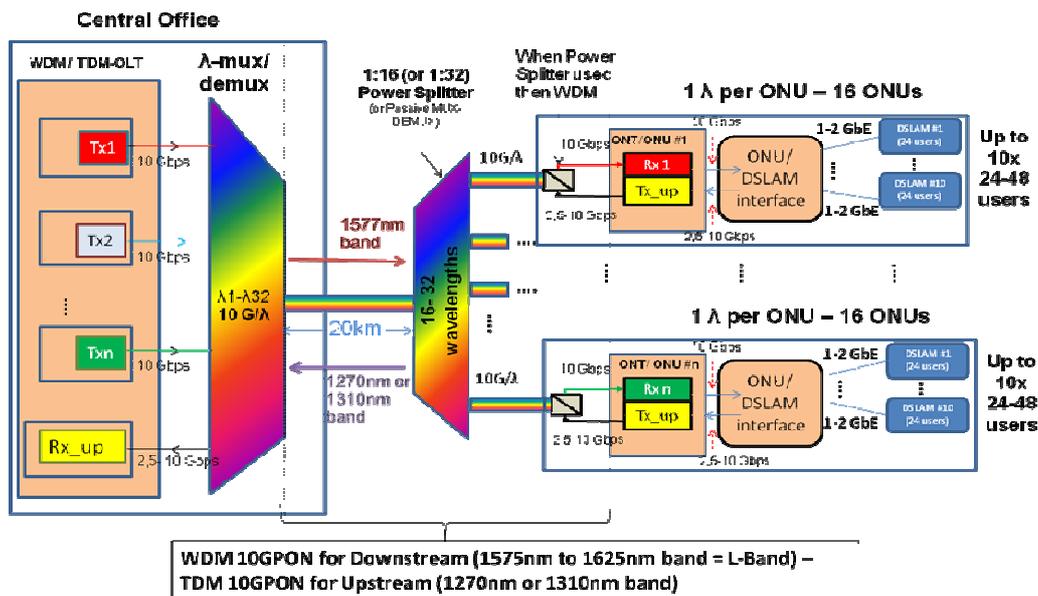


Figure 2. The PANDA architecture.

## 2.2 Upgrade Roadmaps

Following the above discussion, the provision of higher rates, a requirement mainly driven by new services and applications like IPTV, requires the modification of the current access architecture. Since the key limiting factor is the installed copper infrastructure, alternative access scenarios are being studied with respect to copper replacement or its utilization in a more efficient manner. One option is to fully replace copper local access loops with optical fibers and implement fiber to the home (FTTH) or to the building (FTTB) architectures that are capable of providing end-users with multi-Gb/s connections. While FTTH/FTTB schemes are particularly appealing in terms of providing users with almost unlimited network capacity, they are financially non-viable at the present time in Greece due to their high installation cost. A more viable alternative, which is actually implemented at the time of writing this paper, is the re-utilization of the copper loops with VDSL technologies. VDSL and its variants nominally provide over 100 Mb/s to users within a very short reach of the DSLAM, typically less than 200-300 m.

Given the reach limitation of VDSL, DSLAMs may no longer reside within the LE but need to be re-located very close to the end-users. In next generation access networks based on VDSL, the DSLAMs are placed in cabinets near the end users, and a group of local VDSL users have their copper connections terminated to the cabinet. The cabinet itself connects with the LE (or the BRAS) via optical fiber, and this results in a scheme denoted as fiber to the cabinet (FTTC). FTTC is preferable over FTTH/FTTB in terms of initial deployment cost, while in the same time end-users enjoy very high line rates regardless of their distance from the LE, since the operation of optical fibers is not affected significantly by the cabinet-LE distance that typically equals a couple of kms in access networks.

A final consideration in the FTTC access architecture relates to the implementation of the optical network that connects cabinets with LEs, and the two most common network architectures are active and passive optical networks (AONs and PONs, respectively). AONs typically incorporate active (i.e. Ethernet)

switches that feed the cabinets (downstream direction) or aggregates (upstream direction) their traffic. The active switch is, however, the main drawback in AONs due to its cost and its need for a power supply, and in practice active switches may only be placed in a limited number of network locations. If for example the active switch is collocated with the LE, then the optical network becomes a point-to-point network that requires an extensive number of fibers, typically two per cabinet-LE connection. The fiber count can be reduced in a tree-like AON architecture where multiple switches are deployed in active remote nodes (RNs) that feed/aggregate traffic from groups of cabinets; still each active RN needs to be powered, while the network deployment cost grows with the number of active RNs. PONs, on the other hand, utilize passive splitters to feed the optical signal from the LE to cabinets. The passive splitters can be freely placed almost anywhere in the fiber network, while their cost is only a fraction of active switches. As a result, PONs are a well-suited candidate for low-cost and implementation-flexible FTTC access architectures.

## 3. THE PANDA ARCHITECTURE

The PANDA architecture is summarized in Fig. 2. It can be categorized as a FTTC access architecture that provides end-user to cabinet connections over VDSL2 and cabinet to LE connections over a 10 Gigabit PON. The VDSL and PON segments of the network are further described in the following paragraphs.

### 3.1 VDSL2 End-User Access

The connection to the customer premises is realized in PANDA through VDSL2 [3]. VDSL2 exploits copper loops that are already available at the user premises and uses frequencies up to 30 MHz for conveying information over it. Under ideal conditions, bidirectional data throughput over a VDSL2 link may reach 200 Mb/s. The standard defines eight profiles tailored for specific deployment scenarios, namely 8a/b/c/d, 12a/b, 17a and 30a. Deployments literally next to the customer, such as FTTB, are expected to use profile 30a. For CO deployments, which

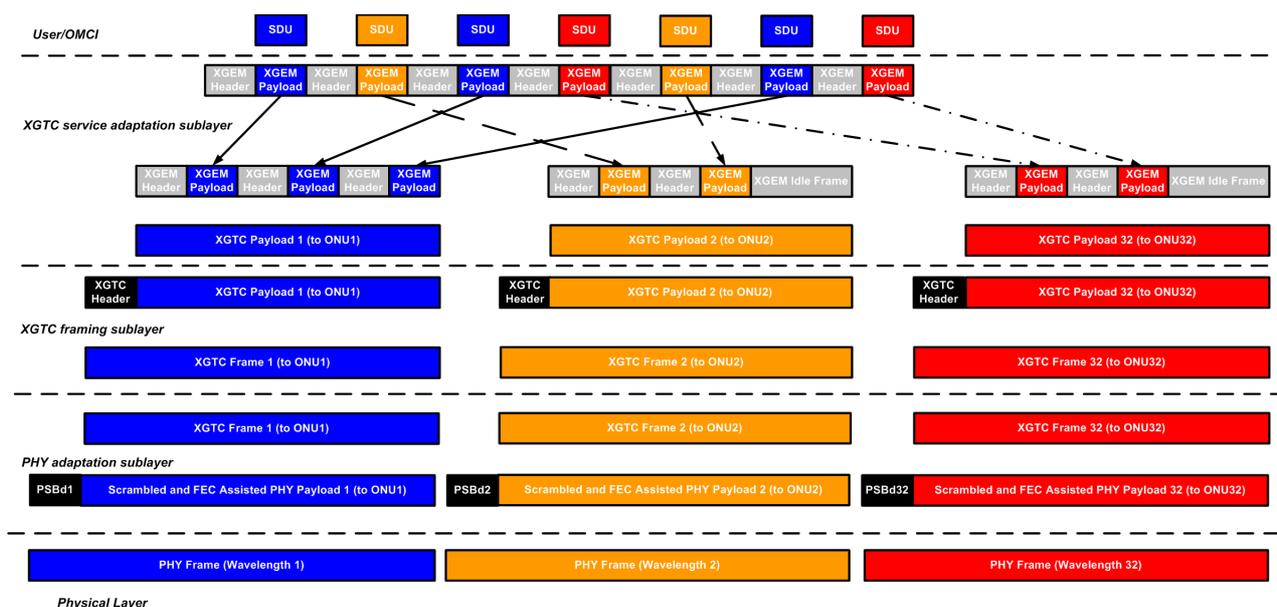


Figure 3. The PANDA PON MAC layer (downstream).

usually serve long copper loops, profiles 8a/b/c/d constitute better choices. Remote nodes in between, e.g. in FTTC scenarios, tend to use 12a/b and 17a, depending on the loop length.

The end-users are connected in PANDA architecture to 48-port VDSL2 DSLAMs. Each DSLAM supports profiles up to 17a, since the target deployment is FTTC. Ideally, the throughput on the VDSL2 link may reach 100 Mb/s in the downstream direction and 50 Mb/s in the upstream. Each DSLAM also offers 1 or 2 Gigabit Ethernet (GbE) uplink(s) and traffic from VDSL2 DSLAMs is concentrated at the Ethernet Aggregator (ONU/DSLAM interface in Fig. 2). The purpose of the Ethernet Aggregator is to act as a broadband access switch inside the cabinet, which multiplexes traffic from up to 16 DSLAMs through single or double GbE links. The Aggregator offers a 10GbE multiplexed uplink to the optical MAC unit (ONT/ONU in Fig. 2), which interfaces the cabinet with the PON.

Regarding the networking functionality, VDSL2 DSLAMs and the Ethernet Aggregator follow Broadband Forum's TR-167 recommendations [4], hence also TR-101 [5]. TR-167 Issue 2 provides architectural and network element requirements to allow the use of XG-PON to feed an access node as defined in TR-101, which provides triple play application support in an architecture that migrates from ATM to Ethernet access technology. Both DSLAM and Aggregator implement key networking features, which include:

1. VLAN bridging (IEEE 802.1Q VLAN tagging) and Stack VLAN tagging (IEEE 802.1ad Provider Bridges).
2. 1:1 and N:1 VLAN architectures.
3. Quality of Service through multiple queues per port.
4. IGMP v1/2 snooping and proxy reporting for multicast traffic.
5. User isolation.
6. DHCP Relay Agent (with option 82).
7. PPPoE Intermediate Agent (with VSA tagging).
8. Directed ARP.

9. Flooding and spoofing protection.
10. SNMP based management.
11. Ethernet OAM (IEEE 802.1ag and ITU-T Y.1731).

### 3.2 Multiwavelength Passive Optical Network

#### 3.2.1 The PON physical layer

The connection of cabinets to the LE is performed over a multi-wavelength 10 Gigabit PON (XG-PON). Under this scheme, a central office (CO) with 16-32 wavelengths (1575-1625 nm) is installed on the LE and each wavelength is utilized to transport 10 Gb/s data to a single cabinet in the downstream direction. The optical network terminates on the cabinet Optical Network Unit (ONU), an optical subsystem that interfaces the PON with the Ethernet Aggregator of the VDSL segment of the architecture. Wavelengths are passively routed over the optical infrastructure and two possible deployment scenarios are envisaged, depending on the distance between the CO and the ONUs:

1. If the distance is limited (urban deployment), then a power splitter is placed at RN(s). ONUs receive all wavelengths and each ONU is required to filter out its own wavelength. This scenario allows zero-touch upgrade from legacy PON infrastructures (no modification to the ODN is required), but induces extensive power losses due to splitting on the RN(s), thus small propagation losses (limited fiber lengths) are allowed.
2. If the distance is extended (rural deployment), then the power splitter is replaced by a wavelength demultiplexer (WDM). The WDM presents significantly lower losses than the power splitter, thus larger propagation losses can be tolerated over the optical network and an extended reach (up to 20 km) is achieved. In this scenario, each ONU receives a single wavelength and additional filtering is not required to isolate ONU traffic.

The upstream direction is, on the other hand, single wavelength and all ONUs share a common 2.5-10 Gb/s upstream (within

**Table 1. Attainable end-user line rates and total number of users in PANDA**

D/S per ONU (Gb/s)	Wavelengths	Users per DSLAM	U/S per ONU (Gb/s)	DSLAM Uplink (Gb/s)	DSLAMS per ONU	Users	D/S per user (Mb/s)	U/S per user (Mb/s)
10	16	24	10	1	10	<b>3840</b>	<b>42</b>	<b>2,60</b>
10	16	48	10	1	10	<b>7680</b>	<b>21</b>	<b>1,30</b>
10	16	24	10	2	5	<b>1920</b>	<b>83</b>	<b>5,21</b>
10	16	48	10	2	5	<b>3840</b>	<b>42</b>	<b>2,60</b>
10	32	24	10	1	10	<b>7680</b>	<b>42</b>	<b>1,30</b>
10	32	48	10	1	10	<b>15360</b>	<b>21</b>	<b>0,65</b>
10	32	24	10	2	5	<b>3840</b>	<b>83</b>	<b>2,60</b>
10	32	48	10	2	5	<b>7680</b>	<b>42</b>	<b>1,30</b>

1260-1280 nm). The main reason for the wavelength asymmetry in PANDA owes to the asymmetry of the xDSL access network itself. For example, the upload rate of an end-user is limited to 1 Mb/s in ADSL2+ deployments, while a less dramatic asymmetry is expected in VDSL2. Moreover, if multiple wavelengths are allowed in the upstream direction then tunable or multiwavelength optical sources are required on a per ONU basis, increasing the network cost and ONU complexity. Finally, the utilization of several upstream wavelengths is a very challenging task due to the shared upstream access in PONs. Typically, the CO in PONs implements an arbitration mechanism (dynamic bandwidth assignment - DBA) that resolves "collisions" between ONU transmissions over the shared segment of the optical network (between CO and RN(s)). Well-known DBA algorithms perform efficiently over a single upstream wavelength, still it is a non-trivial task to design and implement multiwavelength DBA algorithms in a commercial system.

### 3.2.2 The PON MAC layer

The MAC layer of the PON in PANDA bears close resemblance to XG-PONs, which utilize a single wavelength to transport traffic to and from ONUs [6]. XG-PON downstream traffic is transported over timeslots that endure 125  $\mu$ sec and each timeslot carries a number of frames to the PON ONUs. Due to the passive nature of the optical infrastructure, the downstream frames are broadcast to all ONUs in the XG-PON and frames need to be logically assigned to ONUs by means of special fields on frame headers known as "XGEM identifiers." In practice, each ONU inspects the XGEM identifiers on broadcast frames and disregards any frame that does not carry an XGEM identifier that corresponds to a local connection.

For compatibility and implementation purposes, the PANDA PON MAC follows the morphological conventions of XG-PON downstream (125  $\mu$ sec timeslots and XGEM frames); still a subtle differentiation exists with respect to XGEM identifiers, since PANDA downstream is not truly broadcast. Both implementation options in the physical layer (passive splitter or WDM) result in a point-to-point downstream connection between CO and ONUs and it can be argued that XGEM identifiers are not required in PANDA, provided that the CO includes an additional subsystem that assigns frames to ONUs based on their wavelength, as shown in Fig. 3. From a practical perspective, however, frame to wavelength mapping can be readily extracted from the (XGEM

identifier, ONU, wavelength) triplet at the CO. Moreover, if the XGEM frame structure is maintained, then XG-PON ONUs are fully compliant with PANDA in the downstream direction. PANDA ONUs, however, will never disregard XGEM frames, since the frame to wavelength assignment at the CO ensures that all arriving frames exhibit a valid XGEM identifier.

The upstream MAC operation in PANDA is also compatible with XG-PONs, since both PON architectures employ a single upstream wavelength. As a result, PANDA ONUs frame their data in the form of "bursts" and it is the responsibility of the CO to schedule the bursts so that incoming transmissions do not overlap in the shared segment of the optical network. To this end, the CO determines the bandwidth requirements of each ONU either by traffic monitoring or by explicitly requiring bandwidth reports from ONUs (the reports are carried on the upstream bursts). In both cases, the CO runs a DBA algorithm to establish the bandwidth grants to ONUs and then communicates these grants by sending a frame pre-amble in the downstream direction (denoted as PSBd in Fig. 3). The only additional requirement in PANDA is that the PSBd is communicated over all wavelengths, but this can be easily implemented by replication at the CO MAC layer.

## 4. ATTAINABLE LINE RATES AND POPULATION COVERAGE

### 4.1 Original PANDA Coverage Capabilities

The PANDA architecture has been a priori designed as a broadband FTTC solution, it is therefore of interest to study the actual end-user line rates it achieves, as well as the total number of end-users that can be served. The end-user downstream line rate is calculated from the number of users that connect to a single DSLAM and the DSLAM uplink rate. As it has been discussed in section 3, the number of users per DSLAM can be up to 48, while the DSLAM uplink rate is set to 1 or 2 Gb/s. The resulting end-user line rate is summarized in Table 1 and equals 21, 42 or 83 Mb/s depending on the DSAM configuration. It should be noted that it is a minimum guaranteed rate since the PON segment of the PANDA does not impose additional bottleneck (each ONU receives a full 10 Gb/s wavelength). The peak downstream rate in PANDA is determined by the VDSL2 connection maximum rate (100 Mb/s), since a user may enjoy full VDSL2 rate if other users in the same DSLAM remain idle. From an operator point of view,

**Table 2. Line rate and population coverage limits of the PANDA architecture**

Wavelengths	Users per ONU	Users	D/S per user (Mb/s)	U/S per user (Mb/s)
16	50	800	200	12,5
16	25	400	400	25,0
16	17	267	600	37,5
16	13	200	800	50,0
16	10	160	1000	62,5
32	50	1600	200	6,3
32	25	800	400	12,5
32	17	533	600	18,8
32	13	400	800	25,0
32	10	320	1000	31,3

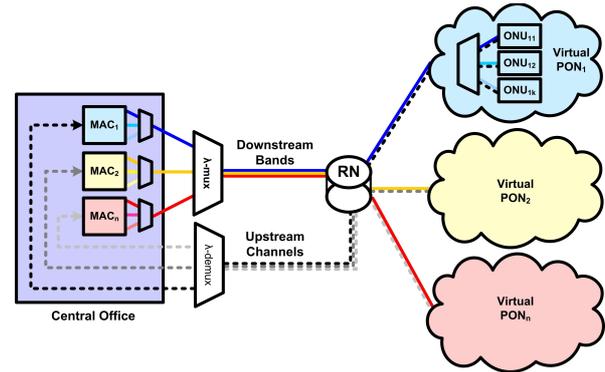
the PANDA architecture provides a content ratio of better than "1:5."

The upstream end-user rate, on the other hand, is calculated from the upstream line rate, the total number of ONUs (wavelengths) and the number of users per ONU. Following section 3, the number of wavelengths in PANDA equals 16 or 32, while the number of ONU users can be 120, 240 or 480, depending on the DSLAM configuration. This arrangement results in end-user upstream rates that range between 0.65 and 5.12 Mb/s, as it is illustrated in Table 1. It should be noted that, similar to the downstream rates, upstream rates are also minimum guaranteed ones; the peak upstream rate of an individual user may reach the VDSL2 limit (50 Mb/s), however this depends on the activity of all PANDA end-users rather than the ones that share the same DSLAM.

Finally, the total number of users that can be serviced by PANDA is determined by the number of ONUs (16 or 32) and the number of users per ONU (120, 240 or 480). Table I summarizes the total number of users for any possible arrangement of the PON and VDSL segments; results show that anywhere between 1920 and 15360 users can be connected to a single CO, depending on their line rate. Since no more than 10,000 users are expected on average at a LE even at urban areas, a single PANDA CO is adequate for connecting VDSL2 users with a content ratio of better than "1:5". Alternatively, a provider may wish to install more than one COs per LE so as to further increase user coverage or provide almost "1:1" line rates to end users.

## 4.2 Extensions of the PANDA Architecture

The results of the previous paragraph demonstrate that the PANDA architecture is well capable of serving several thousands of VDSL2 users and can provide guaranteed rates of at least 21 Mb/s and peak rates equal to 100 Mb/s. Given the low penetration of VDSL access in Greece, PANDA presents a viable alternative for the deployment of short- and middle-term broadband access. Still, it is also of interest to identify the long-term capacity of the architecture in terms of line rates and population coverage and seek possible extensions that will upgrade its lifetime.



**Figure 4. Fully multiwavelength PANDA architecture.**

For the rest of this paragraph we assume that end-user access is extended beyond VDSL2 (100 Mb/s), taking advantage of emerging end-user access technologies like VDSL bonding-vectoring that extends access to several hundred Mb/s or point-to-point optical Ethernet that may reach 1 Gb/s. We also assume that the access network does not exhibit any form of bottleneck and that users may enjoy the nominal rates. Under these assumptions, we present the limits of the PANDA architecture, in terms of attainable line rates and population coverage, in Table 2. The results show that up to 1600 200 Mb/s users can be connected in PANDA, but their number gradually declines to 320 users as their line rate increases to 1 Gb/s.

The table presents a clear trade-off between the minimum guaranteed rates and the number of users in PANDA, which is expected due to the limited capacity per wavelength (10 Gb/s). Extending the number of end-users requires an equal extension to the number of wavelengths that are fed to the cabinet, and possibly utilizing more than one ONU per cabinet. This eventually results in the requirement for a linear growth of the number of wavelengths as the end-users increase in PANDA and up to 128 wavelengths may be finally required to serve 1280 users at 1 Gb/s<sup>1</sup>. This can prove challenging unless a bandwidth efficient (non XG-PON compliant) modulation format is used at the physical layer, while at the same time a serious decrease in the upstream rate is to be expected due to the fact that the wavelength extension does not apply to the upstream direction and a single wavelength serves all upstream traffic.

A second option is to deploy more than one COs per LE, allowing for multiple PANDA instances to operate over the same optical fiber infrastructure. PANDA instances operate on separate wavelength bands, forming a dual-layer WDM PON that is illustrated in Fig. 4. This approach attains the same number of end users as the simple wavelength extension discussed earlier, provides better upstream rates and makes extensive re-use of existing optical fibers. On the other hand, it requires extensive a priori wavelength planning and a combination of wave-band demultiplexers, WDMs and passive power splitters at each RN.

Finally, a novel WDM/F(T)DM PON architecture has been proposed as a migration scenario of the PANDA architecture in order to accommodate larger number of users at a sustained line rate per user of at least 200 Mb/s based on the same ODN infrastructure. The principal idea is to share each wavelength

<sup>1</sup> Exact values can be derived from Table 2 after multiplying the number of users by the wavelength increase factor.

among a multitude of users using TDMA in the downstream direction and FDMA in the upstream, to enable sustainable per-user rate for a high user count [7]. In this approach, utilizing only 5 subcarrier components per wavelength accommodates in total 3840 users assuming 16 wavelengths and 2 DSLAMs per ONU with 24 served users each, yielding more than four-fold increase of the total number of users with respect to the case described in Table 2 with the same number of wavelengths required for 200 Mb/s D/S rate per user. Moreover, doubling the number of available wavelengths will result in subsequent doubling of the number of users. Symmetric DS/US operation at 10 Gb/s can be supported making it compatible with XG-PON1 implementations, yet without requiring expensive burst-mode TDM equipment at the ONU. Finally, the use of TDM multiplexing combined with FDM in the upstream direction can further increase population coverage, however at the expense of reduced line rate per user.

## 5. SCALABILITY STUDY

The next paragraphs summarize the main conclusions from the PANDA architecture scalability studies with respect to three main cases for data rate connectivity to the end users. These cases include:

1. Provision of at least 30 Mb/s to 50% of the connected end users and at least 10 Mb/s to the rest. This case assumes the penetration of the 52 Mb/s VDSL technology to half of the active connections.
2. Provision of at least 30 Mb/s to all users, assuming full VDSL penetration in the access network.
3. Provision of 100 Mb/s to 50% of the users and 30 Mb/s to the rest. This final case dictates the introduction of the advanced VDSL2 profile 17a connections with cross talk cancelation (e.g. via vectoring).

The study was based on a representative set of actual data provided by OTE that show the distribution of the end users and the remote nodes in dense urban, urban, sub-urban and rural areas.

### 5.1 Scalability of PANDA architecture with respect to coverage

The first scalability scenario is a short term solution that considers a penetration of 50.5% for the PANDA solution matching the current (i.e. first half of 2013) penetration rate for broadband connectivity in Greece. In this short term scenario, the aggregated rate at the ONU site is less than 5 Gb/s for all data rate connectivity scenarios, denoting that at least 2 ONUs can be grouped together per wavelength channel. More specifically, for the case of 30 Mb/s connectivity to 50% of the users (and 10 Mb/s to the rest) a grouping of 8 ONUs is possible per wavelength. This decreases to 4 ONUs for the case of 30 Mb/s connectivity to all and to 2 ONUs for 100 Mb/s connectivity to 50% of the users (with 30 Mb/s to the rest). These grouping numbers are observed for all urban deployment scenarios, which represent more than 90% of the total users.

A medium term scalability scenario assumes a penetration rate at 75% which matches the predicted average in the whole EU. Evidently, as the penetration rate increases, a larger number of end users per ONU require connectivity and as a result the aggregated traffic rate per ONU increases. In this medium term scalability scenario, the grouping factor of ONUs per wavelength is half than what observed in the short term scenario; 4, 2 and 1

ONUs per wavelength are required respectively for the cases of 30 Mb/s to 50% of the users, 30 Mb/s to all users and 100 Mb/s to half of the users. It is noted that the later connectivity scenario of 100 Mb/s to 50% of the users is actually achieved by considering one wavelength channel per ONU. However, the observed aggregated rate is 6.8 Gb/s to 7.6 Gb/s in urban and sub-urban areas and does not fully utilize the 10 Gb/s channel, allowing further expansion in terms of aggregated users per ONU.

The long term scalability scenario is in line with the demands of the EU digital agenda for complete broadband coverage by 2020 and assumes a 100% penetration rate [8]. In this case the grouping factor of ONUs per wavelength is the same as in the medium term solution, but the provided rate of 10 Gb/s per ONU (or pairs of ONUs) is almost fully utilized. The aggregated traffic rate for the connectivity scenario of 100 Mb/s to 50% of the users is 8.9 Gb/s to 10.1 Gb/s in urban and sub-urban areas.

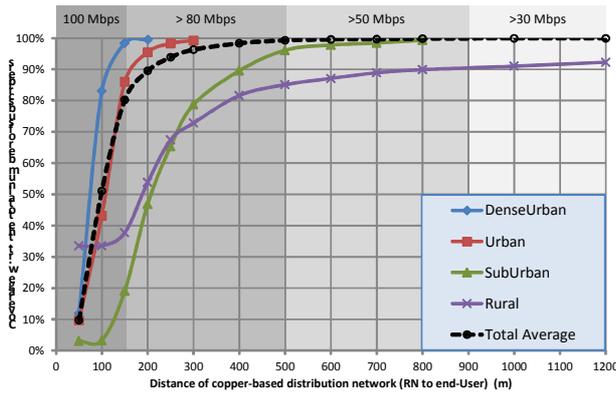
From a practical point of view, the key finding of this study is that the existing infrastructure and the location of the cabinets, especially in dense urban, urban and sub-urban areas, can meet the expectations in terms of connectivity demands for all scalability scenarios. This is important in order to maintain the required investment cost at minimum and concentrate on the optical distribution network. The increasing traffic demand (across the different scalability scenarios) is then handled by the scalable properties of the PANDA architecture which is able to provide direct wavelength connectivity to the ONU/cabinets according to current NG-PON standards at 10 Gb/s per wavelength.

### 5.2 Geographical coverage according to the user distribution

As it is presented above the PANDA architecture provides a scalable solution that meets all the future targets in terms of high speed connectivity to the end-users. The study that follows focuses on the extraction of the actual geographical coverage that is achieved with the PANDA architecture, considering the distribution of the users in the four different areas (dense-urban, urban, sub-urban and rural) according to the characteristics of the copper-based distribution network (i.e. the distance between RN and end-user).

This study focuses mainly on the use of VDSL2 technology using profile 17a in order to achieve maximum downstream rates at 100 Mb/s and 50 Mb/s upstream rates. The purpose is to evaluate the percentage of the coverage that is achieved over the total number of end users (i.e. assuming a 100% penetration) and with respect to different connectivity data rates.

The subscribers' distribution distances from the RNs, for the four different types of coverage areas are presented in Fig. 5 (see solid lines). The dashed line shows the average distribution for all cases. These distributions have been extracted from a large set of representative areas. The shaded areas in the same graph depict the guaranteed achievable data rate with the use of VDSL2 (profile 17a/AnnexB/ADE17). Note that all rates presented here in this graph refer to single-line performance only. Real customer rates after mass service deployment will be reduced due to the effects of crosstalk, quality and number of connections, and physical impairments of the lines. This graph shows that the all the subscribers in dense urban and urban areas are capable to achieve nominal connectivity rates of 80 Mb/s, while the vast majority of them (98.4% in dense urban and 86% in urban areas)



**Figure 5. Subscribers' coverage versus distribution network distance for different areas, and achievable data rates per distance for VDSL2 technology.**

can reach even the maximum targeted rate of 100 Mb/s. In sub-urban and rural areas, the percentage of the subscribers with connectivity at a nominal 100 Mb/s drops significantly to 19.1% and 37.7% of the total respectively. This is attributed to the fact that the subscribers' concentration around the RNs is scarcer with respect to urban areas and therefore a significant number of users are spread over large distances from the RNs. The percentage in rural areas is larger due to the fact that large villages are served directly by one RN that is usually located in the center of these areas. However, even the case of sub-urban and rural areas the vast majority of the subscribers are capable to achieve nominal rates in excess of 80 Mb/s (96.1% in sub-urban and 85.1% in rural areas). Moreover, it is derived that almost all the subscribers in sub-urban areas can have a nominal rate beyond 50 Mb/s, while there is a small percentage of 11.1% in rural areas that is not possible to be connected at a rate 30 Mb/s. However, this percentage corresponds to the 0.11% of the total number of subscribers in a national scale.

The geographical coverage results are summarized in Table 3. By observing the percentages of the geographical coverage with respect to the total number of subscribers (right column), it is concluded that almost all the users (> 99%) can achieve a nominal connectivity rate of 80 Mb/s and the total number of users with nominal rates at 100 Mb/s correspond to the 80.2% of the total number of subscribers. According to this study, it is evident that the PANDA architecture in combination with the advanced VDSL2 technology is fully scalable solution that goes beyond the targets set by the EU Digital Agenda 2020 for data rate coverage of 100 Mb/s to 50% of the network subscribers and at least 30 Mb/s to the rest.

## 6. CONCLUSION

We have presented the PON-VDSL compliant PANDA architecture for the implementation of NGA networks. The proposed architecture relies on the utilization of multiple wavelengths over a single PON, with each wavelength being mapped to a single cabinet (ONU-VDSL endpoint) so as to ensure

**Table 3. Geographical coverage for different guaranteed data rates per area and over the total number of subscribers for the combination of PANDA architecture with VDSL2**

Nominal Rate (Mb/s)	Coverage Distance	Coverage for Different Areas				Total Coverage
		Dense-Urban	Urban	Sub-Urban	Rural	
100	150m	98,4%	86,0%	19,1%	37,7%	80,20%
>80	500m	100%	100%	96,1%	85,1%	99,30%
>50	900m	100%	100%	100%	87,9%	99,88%
>30	1200m	100%	100%	100%	88,9%	99,89%

ten Gb/s access per cabinet and, as a result, multi-ten Mb/s access to end users. We have also derived the capacity of the proposed architecture in terms of users and line rates, and have showed that PANDA goes beyond the goals of EU Digital Agenda 2020; therefore is a well-suited solution for short and mid-term NGA implementations.

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## 8. REFERENCES

- [1] Chanclou, P.; Cui, A.; Geilhardt, F.; Nakamura, H.; Nettet, D., "Network operator requirements for the next generation of optical access networks," *IEEE Network*, vol.26, no.2, pp.8-14, March-April 2012
- [2] <http://www.fsan.org/task-groups/ngpon/>
- [3] ITU-T G.993.2, "Very high speed digital subscriber line transceivers 2 (VDSL2)," February 2006.
- [4] TR-167, "GPON-fed TR-101 Ethernet Access Node," Issue 2, Broadband Forum, September 2010.
- [5] TR-101, "Migration to Ethernet-Based Broadband Aggregation," Issue 2, Broadband Forum, July 2011.
- [6] ITU-T G.987.3, "10-Gigabit-capable passive optical networks (XG-PON): Transmission convergence (TC) layer specification."
- [7] Schrenk, B. et al., "Flexible WDM/FTDM Passive Optical Network with RZ-Seeded All-Optical Sub-Wavelength Grid Engine," in *Optical Fiber Communication Conference-National Fiber Optic Engineers Conference 2013*, OSA Technical Digest (online) (Optical Society of America, 2013), paper JTh2A.71.
- [8] <http://ec.europa.eu/digital-agenda/>