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Evaluating Strategies for Evolution of Passive Optical Networks

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ABSTRACT

Rapidly-increasing traffic demands will require the upgrade of optical access networks, namely deployed Passive Optical Networks (PONs), which may soon face capacity exhaustion. Such upgrade options must consider several technical and cost factors for evolution toward a shared multiple-channel PON using Wavelength-Division Multiplexing (WDM). WDM can facilitate the seamless upgrade of PONs, since capacity can be increased by adding new wavelength channels. We study the requirements for optimal migration toward higher bandwidth per user, and examine scenarios and cost-effective solutions for PON evolution.

INTRODUCTION

Network evolution is a natural way to handle increasing traffic. Access networks are experiencing demands to offer higher bandwidths to subscribers. Several architectures have been proposed for next-generation Passive Optical Networks (PON) [1]. We investigate the evolution path for future generations of PONs. We study strategies for increasing the PON's capacity regardless of its technology: EPON (Ethernet-based PON) or GPON (Gigabit-capable PON).

In PON, a fiber is extended from an OLT (Optical Line Terminal) at the Central Office (CO) to a remote node (RN) (usually an optical power splitter) located in the service area (10–20 km from CO). From the RN, fiber drops are extended to each subscriber or ONU (Optical Network Unit) [2].

Legacy PONs (EPON, GPON) generally use two wavelengths as transmission channels. The downstream channel (1490 nm) is broadcast in nature, and any ONU can filter the data intended for it. The upstream channel (1310 nm) is shared in time among all ONUs. Thus, legacy PONs are referred to as TDM (Time-Division Multiplexing) PON. OLT authorizes timeslots when an ONU can transmit. Timeslot sizing is part of a dynamic bandwidth allocation algorithm, which provides fairness and differentiated services to users by exchanging control information between OLT and ONUs [3].

Bandwidth supported by legacy PONs is limited: 1 Gb/s upstream and downstream for EPON, and up to 2.5 Gb/s downstream/1.25 Gb/s upstream for GPON today. Sustained growth of Internet traffic is being observed with new applications such as multi-player gaming, e-health, e-learning, 3D full-HD (High-Definition) video, etc. which increase bandwidth demands to unprecedented levels. Current GPON and EPON need to be upgraded to cope with these demands.

Recent publications [4, 5] overview candidates and architectures for next-generation GPON. Our article focuses on long-term evolution of currently-deployed PONs (EPON or GPON), and considers basic requirements for future PON generations. We anticipate three principal evolutionary phases, where WDM is the main technology that allows coexistence among PON generations. To the best of our knowledge, we are the first to evaluate the combined generations of PON according to the defined migration requirements, optical power budget, CAPEX, and capacity usage. Moreover, we introduce the immediate WDM-based migration phase as a suitable option to allow transparent coexistence among a number of generations. We also evaluate gradual capacity upgrades, which are cost-efficient and accomplish the migration requirements.

REQUIREMENTS FOR FUTURE PON GENERATIONS

Future PON generations may take diverse evolution paths, for which we define constraints to identify key enabling technologies and architectures for PONs. We present five requirements for the evolutionary path (Fig. 1), as discussed below.

Minimize Equipment-related Investments:

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For PON migration, a new technology (including components) may need to be deployed, besides existing ones or as a replacement at end points (e.g., at OLT and ONUs). Capital expenditures must be evaluated with current and future benefits for a cost-effective evolution path.

Support Coexistence: PONs must support legacy devices. Coexistence means that next-generation devices must operate on the same infrastructure without interfering with existing operation whenever possible. Backward-compatible devices need to be considered for coexistence.

In PON evolution, even within one category of users, traffic demands may be different. Some users will be satisfied with minimal service and will not upgrade to newer devices or will upgrade much later, when prices become comparable. Therefore, network upgrades must allow coexistence among new-generation and legacy devices.

Maximize Profit from Existing Resources: Usage maximization of current and extended capacities can be achieved by dynamically allocating bandwidth among users. Efficient capacity utilization brings revenue to the service provider and facilitates recovery of initial and subsequent investments.

Keep and Reuse Fiber Infrastructure: For cost-effective upgrade, neither the Remote Node (RN) should be changed, nor should more fiber be added to the existing PON. Most of the fiber is lying underground, so civil engineering/deployment increases capital expenditure (CAPEX). Although changes to outside plant could help further upgrades, they can cause service disruptions.

Avoid Disruptions: Some service disruptions are expected during network migration, but we need to reduce their number and effects depending on which devices/fibers are being replaced. A disruption at an ONU only affects its users, and not the rest of the network, unlike changing the OLT or the RN, where the entire PON is affected. However, making a change at the OLT is performable under a more-protected environment than replacing the RN, which is a field operation.

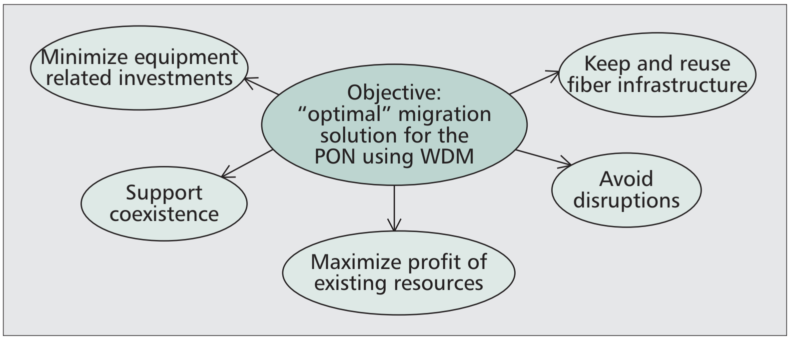

Figure 1. *Constraints for PON evolution.*

Main Evolution Phases and Scenarios

PON evolution depends on many factors, including technology advances and their implementation cost. Based on current standardization efforts, to introduce 10 Gb/s rate on PONs, we anticipate three principal evolutionary phases:

- Line-rate upgrade
- Multi-wavelength channel migration
- Other future PON technologies

Line-Rate Upgrade

A natural PON evolution is to increase existing PON capacity to a higher line rate, namely 10 Gb/s. Work has been conducted by IEEE and ITU-T to standardize next-generation 10 Gb/s-PONs. The standards are influenced by the ability to coexist with legacy PONs, price, and implementation feasibility. IEEE ratified a new standard for 10 Gb/s-EPON (IEEE-802.3av) in September 2009. Also, ITU-T (Question 2, Study Group 15) released a series of recommendations for 10 Gb/s-GPON (XG-PON), namely G-987.1, G-987.2 (both approved in January 2010) and G-987.3 (approved in October 2010). Both IEEE-802.3av and ITU-T-proposed architectures (in NGA1, Next-Generation Access 1) [5] are good examples of line-rate upgrades that allow coexistence with current PONs.

Longer-term PON evolution may consider higher line rates: 40 Gb/s or 100 Gb/s. However, for higher line rates, it is difficult to reach the typical PON distances without signal amplification.

This migration can occur in an "as-needed" fashion, and two sub-phases of evolution are expected: asymmetric and symmetric line-rate upgrades [5, 6].

Asymmetric Line-Rate Upgrade — Downstream traffic from OLT to ONUs is traditionally higher than upstream traffic. PONs are attractive due to their broadcast capability on the downstream channel. With growth of broadcast services (e.g., Internet Protocol High-Definition TV), we have the first part of line-rate upgrade. Another reason for asymmetric migration is the fact that adding 10 Gb/s upstream capability (symmetric approach) would require more expensive ONU devices.

Figure 2 shows a new downstream channel added to the PON using WDM. To not interfere with the existing legacy PON (light-colored ONUs in Fig. 2), the new wavelength channel can be taken from the L-band. A new OLT card or module can manage legacy and 10 Gb/s downstream services. We call this module Enhanced-OLT (E-OLT). New ONUs (dark-colored ONUs in Fig. 2) are added to the PON to support 10 Gb/s service.

However, some precautions are needed to support this coexistence. New wavelength-blocking filters (boxes next to each ONU in Fig. 2) should be attached to ONUs to avoid interferences between downstream channels. Reference [7] shows that adding these filters during legacy PON deployment can significantly reduce the migration cost. These filters can ease coexistence with future-generation PONs, as discussed later.

An external or embedded amplifier may be needed at the OLT due to the low sensitivity of the ONUs' receivers and the low optical power level needed to reach the receiver of high-line-rate signals (at 10 Gb/s). OLT may operate at dual rate in the downstream channel, with two MAC (Medium Access Control) layer stacks; consequently, a new class of PON chipsets is needed [6].

Symmetric Line-Rate Upgrade — Symmetric line-rate upgrade is achieved when both downstream and upstream directions operate at the same rate, say 10 Gb/s. This depends on the symmetry of traffic demands, e.g., due to new peer-to-peer communications, multimedia real-time applications, and 3D Internet services. Two approaches can be considered: TDM and WDM coexistence [8].

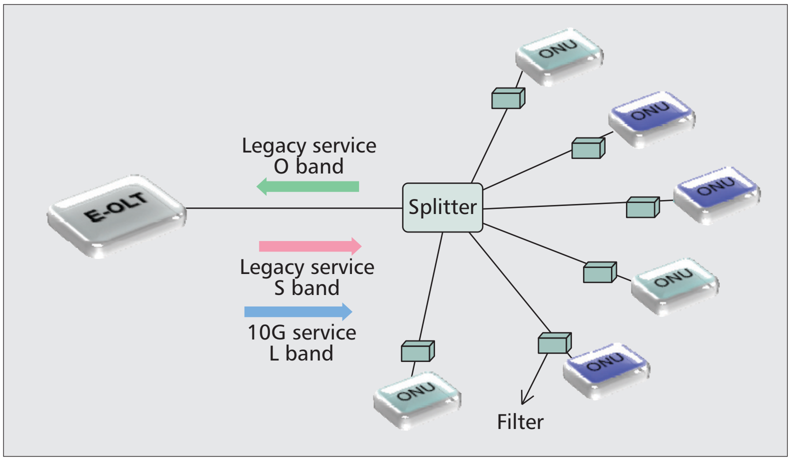

Figure 2. *Asymmetric line-rate upgrade to 10 Gb/s.*

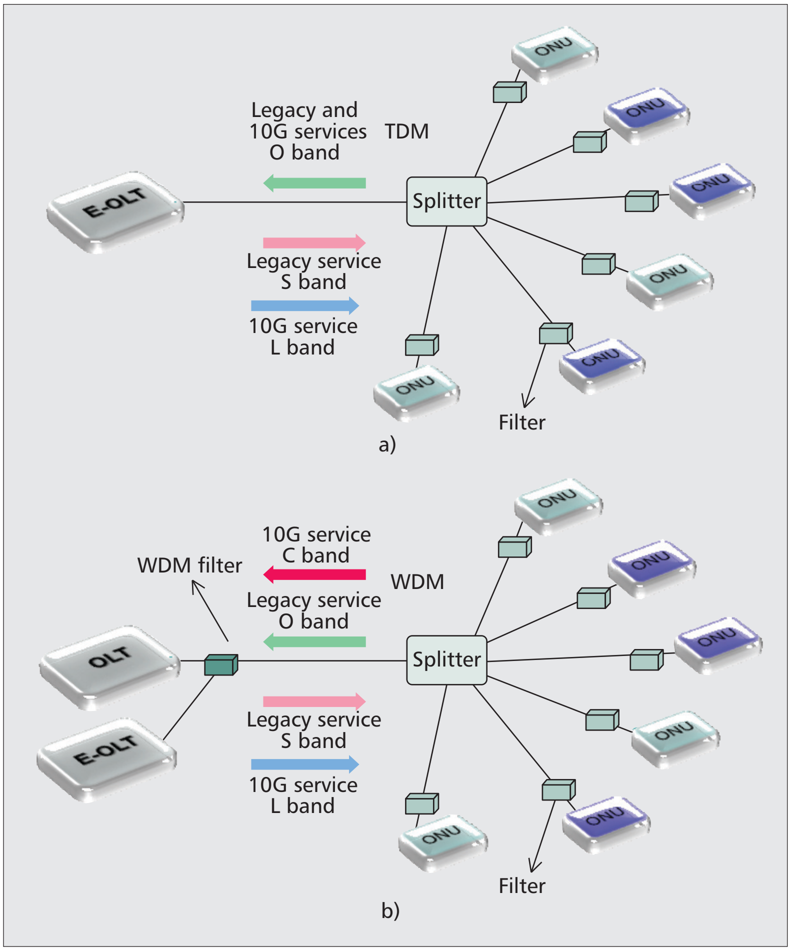

Figure 3. *Symmetric line-rate upgrade example to 10 Gb/s: a) TDM coexistence and b) WDM coexistence.*

Symmetric Line-Rate Upgrade with TDM Coexistence — The upstream channel can be upgraded to 10 Gb/s by sharing a wavelength in time and using two different line rates (Fig. 3a). This approach is approved in IEEE for 10 Gb/s-EPON, where the 10G-service upstream channel (1260–1280 nm) overlaps with the legacy-service channel (1260–1360 nm). It can reduce deployment cost, because the legacy upstream channel is on the lower-dispersion fiber band. New ONUs can operate with commercially-available distributed feedback (DFB) lasers, and the optical transmission system can be reused to reduce cost. However, network implementation becomes complex since an extra control mechanism is needed to manage the upstream channel with different rates, and it must also deal with time alignments.

An important challenge is imposed on the OLT's burst-mode receiver, which now has to adapt its sensitivity to the incoming optical burst signal, to detect different-line-rate traffic on the same channel. This problem affects the PON at the discovery stage, when the OLT incorporates ONUs with unexpected rates. IEEE 10 Gb/s-EPON standard addresses this problem by allowing separate discovery windows for 1G- and 10G-services.

Symmetric Line-Rate Upgrade with WDM Coexistence — The alternative to a shared upstream channel upgrade is to add another upstream channel at 10 Gb/s (Fig. 3b). Now, independent OLTs can manage legacy (OLT) and 10 Gb/s (E-OLT) services. The new optical transmission for ONUs can be slightly-more expensive because the transmission system cannot be reused as before. Now, the laser at the enhanced-ONU has to transmit at a different wavelength in C or L bands, e.g., at 1550 nm [8]. However, this wavelength is currently reserved for analog video broadcasting.

Other wavelength bands may be explored to support coexistence. For example, in [4], two symmetric non-overlapping upstream channels are located in the O band (1270 nm and 1310 nm). Now, the legacy ONUs (often covering the whole O band, centered at 1310 nm) would need narrower transmitters (e.g., coarse-WDM or dense-WDM transmitters) to not overlap with the new channel at 1270 nm in the same band.

Network disruption can occur due to installation of a WDM filter (box near OLT and E-OLT in Fig. 3b). The WDM filter separates wavelengths directed to the legacy OLT from the ones to the E-OLT. For guaranteed services, the OLT can be installed in a redundant way such that changes to any module do not generate disruptions since the spare OLT will be working. Many current deployments do not use protection schemes, but protection will become important in the future.

Multiple Wavelength Channel Migration

The natural second step for PON evolution is based on WDM technology. However, other technologies (part of the third migration phase) may change this expectation, due to a reduction of their cost and better implementation feasibility. The advantage of WDM is that it allows coexistence between two or more PON generations over the same infrastructure. Provisioning multiple channels on the PON allows deployment of different migration technologies or capacity extensions transparently, where devices of a generation are unaware of the coexistence with other generations.

Today, there are concerns regarding challenges to implement WDM in PONs, especially regarding: type of transceivers at the OLT and ONU, sharp filtering, and type of RN. Details of enabling technologies and challenges can be found in [1, 9]. Another consideration is wavelength planning. Initially, when there are few wavelengths, they could be spaced far apart, e.g., using the 100G grid. If more wavelengths are needed, unused wavelengths from the 50G grid can be invoked. Care must be taken to ensure that closely-spaced wavelengths are operating at lower rates to reduce interference. Practical aspects such as these must be handled by the Service Provider in its actual deployment and upgrade situations.

Diverse architectures for this migration stage can be considered [1, 9]. Some WDM-based PON architectures involve changes at the RN, including addition of active components [10]. In this article, we consider changes that allow the network to remain passive (RN is fully passive), and we study two main architectures: WDM-PON and Overlaid-PONs.

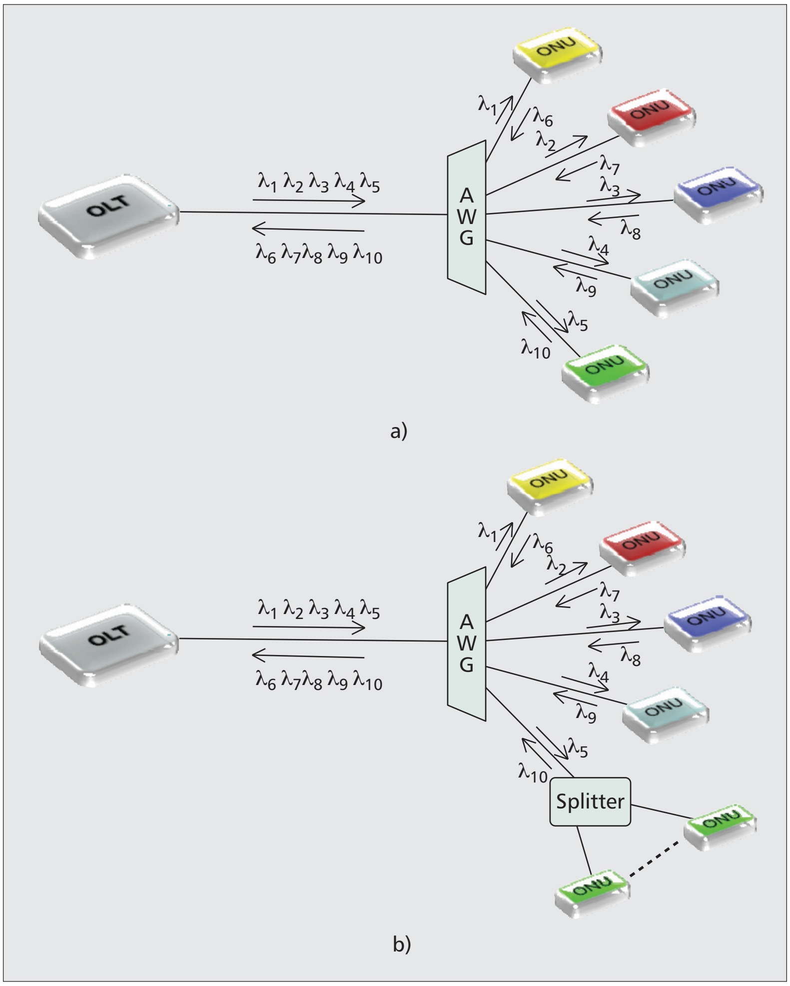

Figure 4. *WDM-PON with five ONUs: a) two different wavelengths assigned to each ONU by using an AWG and b) WDM-PON with cascaded TDM-PON.*

WDM-PON — WDM-PON is known as wavelength-routed or wavelength-locked WDM-PON. It requires the replacement of the optical power splitter by an Arrayed Waveguide Grating (AWG) (Fig. 1a). In the upstream direction, the AWG acts as a multiplexer of different wavelengths into a single fiber; and in the downstream direction, the AWG is used as a de-multiplexer by directing a different wavelength to each fiber drop. Therefore, AWG allows a fixed assignment of two wavelengths (upstream and downstream channels) to each ONU.

Devoting an optical channel to each ONU implies a substantial increase in the offered capacity per user. However, fixed-channel assignment is inflexible and does not allow dynamic reuse of wavelengths by different ONUs for efficient capacity utilization, especially when traffic demands are bursty.

ONUs in WDM-PON will require new transmitters working on different wavelengths. A good option is to use colorless ONUs either with tunable lasers or RSOAs (Reflective Semiconductor Optical Amplifier). However, today the price of RSOAs is one order of magnitude higher than an entire (EPON-based) ONU, whereas tunable lasers are significantly more expensive than RSOAs.

A WDM-PON with cascaded TDM-PON can dynamically allocate unused bandwidth from one ONU to other ONUs (Fig. 4b). Addition of a splitter in one (or more) fiber drops allows time-sharing the dedicated wavelengths among some ONUs in that PON branch. This architecture can improve the maximum number of ONUs supported by a single PON, but it does not facilitate capacity upgrades in an "as-needed" fashion by adding wavelengths.

WDM-PON is a highly-disruptive migration option since the RN has to be replaced by another device (AWG). This procedure will provoke a major PON disruption unless the RN is installed in a protected configuration. More importantly, all existing devices on the network must migrate at the same time, and this does not meet the coexistence requirement. A complete migration of all user devices will lead to prohibitive costs, especially when some users may not want a capacity upgrade. Although WDM-PON is considered to be a next-generation PON after 10 Gb/s, the above arguments suggest that it is not suitable for a smooth PON evolution.

Overlaid-PONs Using WDM — Overlaid-PONs form a valuable option for the second migration phase. They exploit WDM technology, but now the RN remains an optical splitter, and it does not need to be replaced by an AWG as in WDM-

When using Overlaid-PONs, some disruptions observed in WDM-PON are minimized since there is no need to replace the RN; only end-devices will require a change. Moreover, some users may need capacity extension while other ONUs may remain the same, so "as-needed" growth is accomplished.

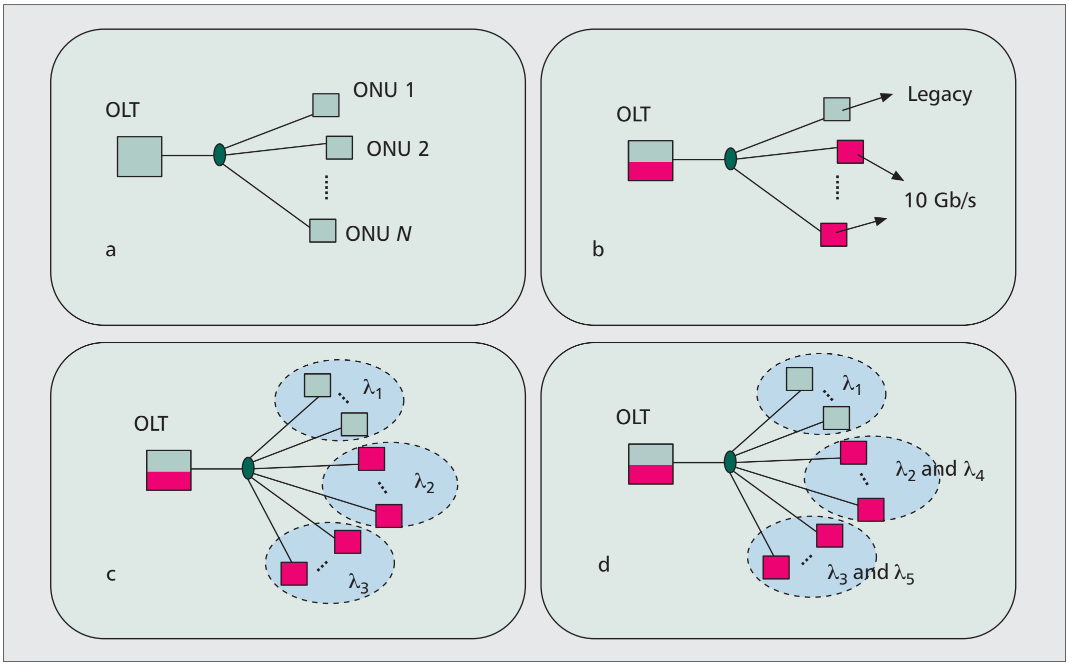

Figure 5. *Evolution using Overlaid-PONs: a) legacy PON, (b) partial upgrade to 10G-PON, c) extending capacity by adding downstream (and/or upstream) channel to a set of ONUs; and d) extending capacity by adding more channels to sets of ONUs as needed.*

PON. In Overlaid-PONs, PON capacity is incremented by adding more wavelength channels based on traffic demands. If existing channels are time-shared among users, a new channel will also be time-shared by the ONUs on the new wavelength. OLT will control an ONU's usage of a wavelength at a specific timeslot. Thus, ONUs working on a new wavelength form the set of devices pertaining to the new overlaid-PON (over the legacy PON or previous-generation service). Some devices may belong to two or more different overlaid-PONs according to their hardware capabilities which can lead to a flexible distribution of bandwidth. Overlaid-PONs form a next-generation architecture for GPON in the NGA1 proposal (ITU-T, Study Group 15).

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Overlaid-PONs require that new ONUs and OLT operate at different wavelengths than existing ones in legacy PON and 10G-PON. Existing legacy standards, for cost reasons, allocated wide bands for upstream and downstream channels which may interfere with the new optical channels. Thus, we need blocking filters at the first migration phase for all ONUs. These filters can be costly because they should have a very steep response characteristic in order to fit into the narrow guard band left between the channels. The suggested evolution path allows migrating first toward an intermediate line-rate upgrade phase which may give time to fully migrate existing legacy ONUs, before moving to the second migration phase. New wavelengths can be targeted at the legacy bands. By that time, the filters' prices may become affordable.

To transmit over more than one wavelength, an ONU may use:
- Tunable lasers
- Fixed-wavelength laser arrays

Tunable lasers increase network flexibility, but their price is high. Fixed-wavelength laser array is cheaper but less flexible compared to tunable lasers. The choice of lasers for ONUs will depend on their price.

Using L-band could be an immediate solution for a capacity upgrade using WDM. Future increments in the number of wavelengths can be obtained through the spectral space left empty by a total migration of previous generations working at lower bands.

Overlaid-PONs allow the coexistence of multiple generations on the same fiber infrastructure (Fig. 5). Starting from a legacy PON (Fig. 5a), the first evolution is a line-rate upgrade for some ONUs (Fig. 5b), which requires the addition of wavelengths for coexistence with the legacy PON. Later, some users may need more capacity, which can be resolved by adding a new wavelength to any or both traffic-flow directions (Fig. 5c). Some ONUs can share two or more wavelengths as required. Finally, some ONUs may need to increase the number of wavelengths to be shared among them (Fig. 5d). Thus, Overlaid-PONs using WDM not only can increase a PON's capacity by adding wavelengths, but also keep PON generations coexisting by stacking them with different wavelengths.

Consider traffic growth in a PON. Figure 6a shows the number of ONUs per service during each period (which approximates a year) and PON traffic is assumed to grow by a factor of

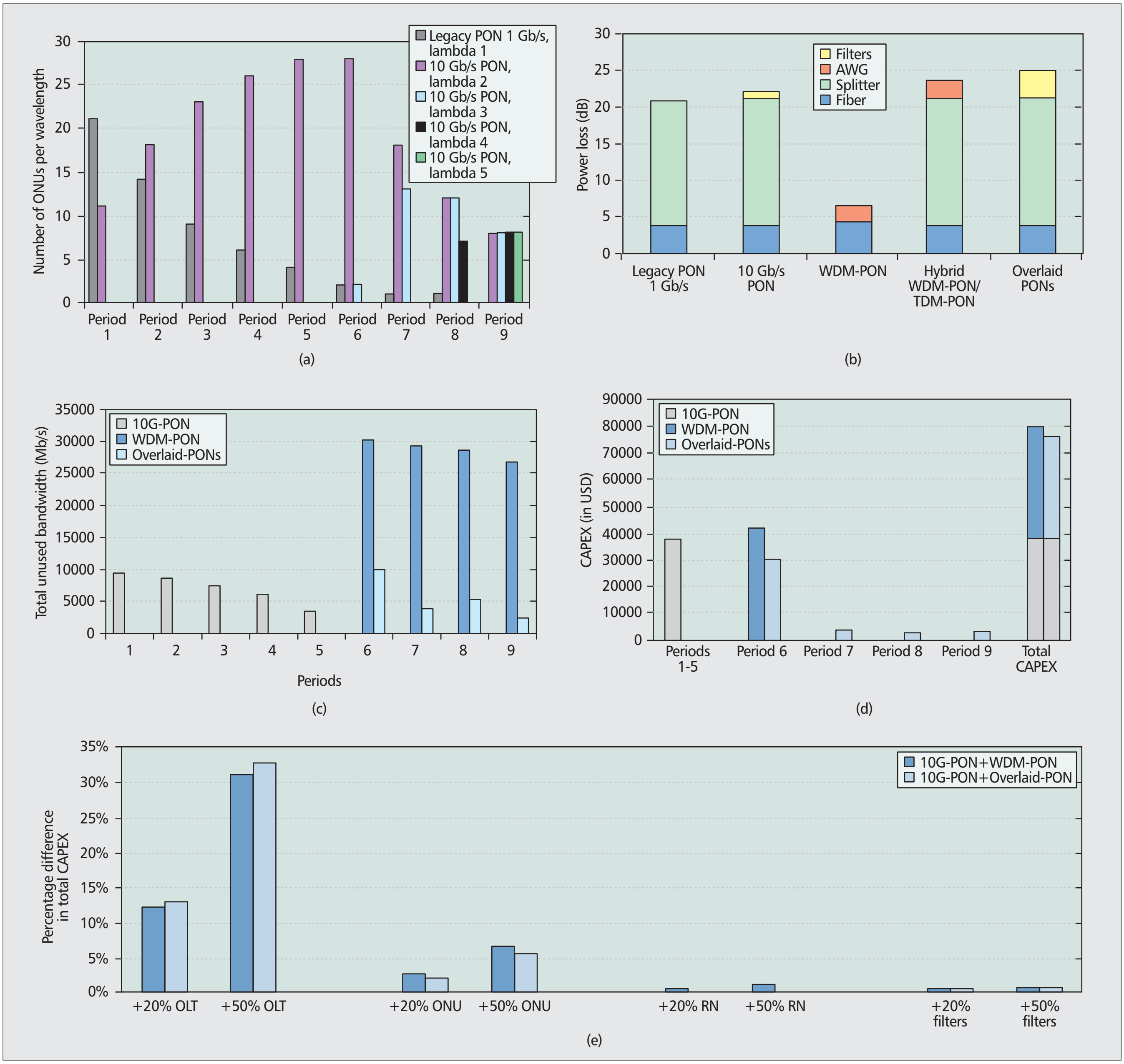

Figure 6. *Quantitative results: a) number of ONUs migrating to 10 Gb/s line rate and to extra optical channels per period using the Overlaid-PONs approach (when each period approximates a year); b) optical power loss for different upgrading approaches; c) total unused bandwidth per period for 10 G-line rate upgrade combined with WDM-PON or Overlaid-PONs; d) CAPEX for 10 G-line rate upgrade combined with WDM-PON or Overlaid-PONs; and e) percentage difference of total CAPEX between respective total CAPEX in (d) and total CAPEX adding 20 percent and 50 percent to the cost of WDM-based PON elements.*

1.5 per period. The number of ONUs during these periods is constant (32) and traffic at each ONU will grow on average in the same proportion. Initially, just before period 1, the legacy-PON's capacity is totally consumed (total traffic volume is 1Gb/s on average). In this PON, existing ONUs will be upgraded gradually (a line-rate upgrade first, then wavelengths at 10 Gb/s are added as needed) trying to utilize the available capacity in previous services as much as possible.

Figure 6a shows that coexistence among 1G and 10G services can last for eight periods. From period 6, additional wavelengths are needed to support the growing traffic demand. In the last period shown, there are four channels serving eight ONUs each. Note that the capacity of the four channels can be shared among a subset of ONUs, according to their needs. That would require colorless ONUs and a wavelength-assignment algorithm. Determining the time instants to run the provisioning and its bandwidth granularity is a challenge for the network operator. Note that this is an illustrative example assuming a constant traffic growth factor, which leads to a nine-year interval to operate with four channels (considering only one flow direction). Actual upgrade decision periods will be affected by many other factors, namely economy and traffic-growth evolution.

OCDM-PON (Optical-CDM PON) technology addresses capacity upgrade in PONs by adding a code-based dimension to the system. However, the design of orthogonal codes to reduce interference and noise when the number of users grows is an open issue.

Quantitative Comparisons: WDM-PON vs. Overlaid-PONs — To compare the upgrading alternatives WDM-PON and Overlaid-PONs, we address optical power loss, unused capacity, and capital expenses (CAPEX).

PONs require a higher optical power budget to compensate for increased insertion loss along the paths between OLT and ONUs. We calculate the lower bound of the total power loss (without adding the optical penalty to cope with physical impairments) for different upgrade approaches. As shown in Fig. 6b, WDM-PON offers the minimum total power loss, which means that it can support longer distance or more ONUs. WDM-PON with cascaded TDM-PON increases considerably the power loss if we assume the insertion of a 1:32 splitter. Furthermore, Overlaid-PONs experience the highest total optical power loss due to the insertion of filters at ONUs (1dB) and at OLT (3 dB) [7]. However, the maximum optical power budget, usually 29 dB (e.g., IEEE 802.3av, for 1:32 splitting ratio), is not reached. This is an important consideration for adding more devices to the system.

Using the example presented earlier, we evaluate the amount of unused capacity for WDM-PON and Overlaid-PONs. In periods 1 to 5, we upgrade the network using 10G-PON, and after that, we upgrade with WDM-PON or Overlaid-PONs, as presented in Fig. 6c. In this case, we have set the maximum channel capacity of WDM-PON and Overlaid-PONs to 1 Gb/s; however, if we set 10 Gb/s as the maximum per channel, then the unused capacity would be proportionally larger. The amount of unused capacity in the case of WDM-PON is very high compared to the case of Overlaid-PONs in Fig. 6c. However, the extra capacity in WDM-PON cannot be shared among ONUs, unless the service provider implements a WDM-PON with cascaded TDM-PON.

Now we analyze the CAPEX impact that a new technology will have on the upgrade process. At the moment, WDM-PON is not a widely deployed technology, hence the exact cost of this technology is difficult to estimate or forecast. However, some current technical challenges (type of transceivers, wavelength plan) suggest the high cost of components required to implement WDM-PON. To illustrate the CAPEX required for the example mentioned earlier, we use the cost per device in [11]. We assume a cost reduction of seven percent per period (which approximates a year). We also assume that the cost of 10 Gb/s equipment is in the middle between the cost of WDM-PON equipment and the cost of Legacy PON (TDM-PON in [11]). Overlaid-PON ONU and WDM-PON ONU have the same cost in this calculation ($525).

In Fig. 6d, we present the CAPEX needed in our example. We have two stages: period 1-5 when we upgrade to 10 Gb/s, and period 6-9 when we upgrade using WDM technology (i.e., adding wavelength channels). We calculate the required CAPEX for each period, and the total CAPEX for both WDM-PON and Overlaid-PONs (i.e., 10G-PON and WDM-PON, or 10G-PON and Overlaid-PONs). The CAPEX for Overlaid-PONs is lower that for WDM-PON due to the gradual investments needed (split over several periods) in Overlaid-PONs, which is attractive. However, it is reasonable that in this example they have comparable CAPEX totals since both are WDM-based and face similar technical challenges. Note that in this example, ONUs' traffic grows uniformly and at a fast rate. However, in a practical scenario (e.g., using different growth patterns per user), the investment for Overlaid-PONs would be distributed over several periods, leading to more cost reductions per period.

Finally, we evaluate the sensitivity of total CAPEX to variations in cost of some elements. For every network element, we increase its cost by 20 percent and 50 percent. Figure 6e shows the percentage difference between the total CAPEX in Fig. 6d and the new recalculated CAPEX. We observe that, compared to the base cost (total CAPEX in Fig. 6d), the CAPEX is more sensitive to cost variations for OLT, especially when its price increases by 50 percent. Otherwise, the effect on CAPEX is not large (<15 percent). Although in Fig. 6e it may seem that the combined evolution of 10G-PON and Overlaid-PONs is more expensive than the combined 10G-PON and WDM-PON, note that percentage differences are calculated using their respective base total CAPEX (in Fig. 6d) as a reference.

Other Future PON Technologies

The third PON-migration phase can be based on different possibilities. It can carry different hybrids between WDM and other multiplexing technologies such as CDM (Code-Division Multiplexing) and SCM (Sub-Carrier Multiplexing) [12], or it can be an upgrade of WDM-based PONs by using Coherent PONs. By using separate wavelengths for different PON generations, any subsequent generation can be deployed over specific wavelength channels, forming a hybrid. Below, we briefly discuss future hybrids.

CDM Hybrids — OCDM-PON (Optical-CDM PON) technology addresses capacity upgrade in PONs by adding a code-based dimension to the system. However, the design of orthogonal codes to reduce interference and noise when the number of users grows is an open issue. Coders/ decoders and corresponding transceivers are still in the early stages of development. Few orthogonal codes can be implemented to create more Overlaid-PONs (WDM/CDM) [13]. The combination of some codes on different channels (as needed) can provide more flexibility to the network.

SCM Hybrids — With SCM, signals are separated (electronically or optically), and shifted to different subcarrier channels using modulation techniques. This option may require a different wavelength to support it in a hybrid fashion to avoid interference with existing and operating services on other channels. A good example of PONs using this technology is OFDM (Orthogonal Frequency-Division Multiplexing) PON [14].

Coherent PONs — An attractive trend for PONs is where transmitters are based on coherent lasers (using ultra-dense-WDM band, U-DWDM), and optical heterodyne or homodyne reception [15]. This may be a good candidate for future U-DWDM-based PONs. To upgrade an existing WDM-PON, only end-devices (ONU and OLT) need to be replaced. Coherent PON allows longer reach (100 km) and a splitting factor of 1:1000, and can provide one different wavelength channel per user.

CONCLUSION

We introduced and evaluated different options for the evolution of PONs toward higher bandwidth per user. The evolution is divided into three migration phases: line-rate upgrade, multi-channel migration, and future PON technologies. The first migration phase is in the process of standardization and can follow two sub-phases: asymmetric and symmetric upgrades. Asymmetric sub-phase aims at adding a new channel at 10 Gb/s in the downstream direction. Symmetric sub-phase delivers 10 Gb/s in the upstream direction also by either time-sharing with legacy services or adding a new upstream channel. The second phase is based on multiple channels (wavelengths) in both downstream and upstream directions, and the technology used is WDM. In the second phase, it is necessary to have filters at existing and new ONUs to select the appropriate optical signals. The quality of these filters plays an important role in future migration procedures over the same network, especially if they are installed at an early stage. Finally, a third migration phase includes new hybrids with previous technologies: TDM and WDM. Possibilities are OFDM and OCDM, coexisting with previous generations. Another future technology may consider an extension of WDM technologies by deploying Coherent PONs.

Any evolution path can lead to bifurcations at different phases. The second migration phase can be chosen by using WDM-PON or Overlaid-PONs. The benefits of Overlaid-PONs over WDM-PON are disruption minimization and coexistence. WDM-PON does not allow the flexibility to build different channels that could be shared among a number of ONUs. Overlaid-PONs ease the implementation of future generations by preserving coexistence with the previous one through the addition of new wavelengths per service and not per ONU.

The third migration phase (other future PON technologies) can be considered with many options, each of which can be implemented independently over the PON by using different channels, guaranteeing coexistence. The evolution path enabled by Overlaid-PONs is more convenient when the aim is to permit coexistence between different evolution generations and technologies.

Important open issues need to be addressed. First, an insightful cost analysis of future network evolution and investment is needed, for which research on colorless ONUs is important. Second, a smart allocation and coexistence of new and existing users is needed, together with a graceful combination of different types of users such as residential and business subscribers. Consequently, higher network revenue can be obtained by designing the best user-coexistence combination. Third, increasing the optical power budget is essential to follow Overlaid-PON's solution. Fourth, an analysis of future PON technologies is needed if it can be related to cost and ease of implementation. Finally, amplified PON for longer reach is important to take into account in PON evolution. Therefore, long-distance effects over different technological candidates to Next- and Future-Generation PONs should be evaluated.

Important open issues need to be addressed. First, an insightful cost analysis of future network evolution and investment is needed, for which research on colorless ONUs is important. Second, a smart allocation and coexistence of new and existing users is needed, together with a graceful combination of different types of users.

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