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Frank J. Effenberger ; Hiroaki Mukai ; Soojin Park ; Thomas Pfeiffer All Authors

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Next-Generation PON—Part II: Candidate Systems for Next-Generation PON

Frank J. Effenberger, Huawei Technologies

Hiroaki Mukai, Mitsubishi Electric Corporation

Soojin Park, Korea Telecom

Thomas Pfeiffer, Alcatel-Lucent Bell Labs

ABSTRACT

Given the requirements for a next-generation PON, the architecture of the system solution must be considered. There are many different systems that can provide the services and system-level features desired for a next generation PON; however, each has its own challenges and advantages. This article presents the set of possible solutions, and puts them into perspective of likely standardization. It also considers how the key requirement of coexistence could be accommodated.

INTRODUCTION

As introduced in the previous companion article, there is a strong interest in defining the next generation of passive optical network (PON) systems that are compatible with the current G-PON [1–6] and E-PON [7] systems. This article reviews the next-generation (NG)-PON1 family of systems, reviewing all the potential solutions in that space and their coexistence properties. The next companion article more fully develops the technical specifications of the 10 Gb/s G-PON systems that appear most favorable for standardization and deployment.

The content of this article is organized as follows. In the next section we present a review of all the possible architectures that could meet the NG-PON1 requirements. The main stream set of possible systems include 10 Gb/s downstream/2.5 Gb/s upstream PON (termed XG-PON1), 10 Gb/s symmetric PON (termed XG-PON2), extended wavelength and reach versions of the XG-PONs, and hybrid dense wavelength-division multiplexing (DWDM)/XG-PON systems. We also briefly review several systems that were considered, but then discarded as essentially ineligible for further study. This section concludes with a summary of the architectures, and the intended focused direction for standardization. We then review the situation surrounding coexistence, and reviews the possible methods that can

be used to achieve backward compatibility with G-PON systems. This includes the use of WDM in both directions, WDM in the downstream and time-division multiple access (TDMA) in the upstream, and time-division multiplexing (TDM) in both directions.

ARCHITECTURE COMPARISON

This section reviews the major system architectures that appear at this moment to be candidates to fulfill NG-PON1 requirements. This section reviews candidate system architectures that were considered by FSAN and discusses the ones that were selected (or not) and rationale for having done so.

XG-PON1 WITH 10 GB/s DOWNSTREAM, Nx2.5 GB/s UPSTREAM

The Full-Services Access Network (FSAN) community considers 10 Gb/s transmission over fiber to be the logical next step in access systems. This is viewed as being analogous to WDM transport systems, where most new capacity being deployed today is 10 Gb/s per wavelength. The 10G PON system is referred to as XG-PON, where the Roman numeral X signifies 10 Gb/s transmission speed.

Among the many challenges in 10 Gb/s transmission in PON systems, the most significant is its requirement to maintain compatibility with burst-mode TDMA. Optical burst-mode transmission has always been the defining issue for PON systems, and the higher the data rate, the more difficult it becomes. It is believed that significant technological barriers emerge to practical burst mode OLT receivers at or above approximately 5 Gb/s. Key issues include timely and accurate adjustment of the decision threshold across upstream bursts, and timing recovery. Recent research in high-speed burst receivers suggests that these limitations can ultimately be overcome. However, the timeframe for commercialization of such devices is not clear.

Therefore, the first candidate architecture attempts to avoid this potential problem by using 10 Gb/s only in the downstream direction, and one or more parallel 2.5 Gb/s channels in the upstream direction (Fig. 1). Note that the next generation system is multiplexed with the existing G-PON system using a WDM device, denoted WDM1. The number of upstream channels is design dependent. If full symmetrical capacity is desired, four upstream channels can be used. However, this presents issues in terms of spectrum compatibility with the existing G-PON systems. There are techniques that could share spectrum between two channels with different data rates in a TDMA fashion; however, this would add another level of complexity. Another alternative would be to follow the asymmetry of the current G-PON system (2:1), and provision only two upstream channels. This would result in a system with 10 Gb/s in downstream and 5 Gb/s in upstream channels, which seems quite adequate for most applications; and it avoids the spectrum conflict with the existing G-PON systems. In a third variant, one could only deploy a single 2.5 Gb/s channel, reserving spectrum for future systems. Yet another possibility would be a single channel at approximately 5 Gb/s. However, upstream transmitters for such a system are not presently commercialized.

In the variations with multiple upstream channels, the same issues of wavelength assignment that are described in the following article would apply (i.e., managing multiple colors of optical network units [ONUs]). Of course, in a two-channel system the statistics work in our favor, and the chances of a very lopsided distribution of ONUs is small. However, the FSAN operators have expressed concern with the operational implications of such an approach. Furthermore, gaining optical access to multiple channels on a working PON is difficult, because more channels generally require more filter elements, and hence induce more loss. Therefore, the FSAN community has a consensus to develop a single channel, 2.5 Gb/s upstream. It is understood that 4:1 asymmetry is an acceptable cost/performance trade-off, at least in the intermediate term. Note that historically the traffic patterns observed by most carriers is that most subscribers has been asymmetric, especially when the PON is used to deliver video services such as broadcast television and video-on-demand. Systems with additional channels and/or higher rates may be the subject of future study.

The downstream link in this system will be serial at 10 Gb/s. Dispersion becomes an issue for transmission at 10 Gb/s and above. Dispersion causes inter-symbol interference (ISI), especially when there is chirp. Dispersion coefficient in optical fiber varies with wavelength, and in G.652 fibers the zero dispersion point is approximately 1310 nm. ISI due to dispersion can be reduced by operating in the low dispersion region of the fiber, by reducing chirp at the transmitter (e.g., with externally modulated lasers or chirp managed lasers), by use of appropriate lengths of dispersion compensating fiber or by electronic dispersion compensation.

There is also concern that ONU hardware for processing a 10 Gb/s signal will require signifi-

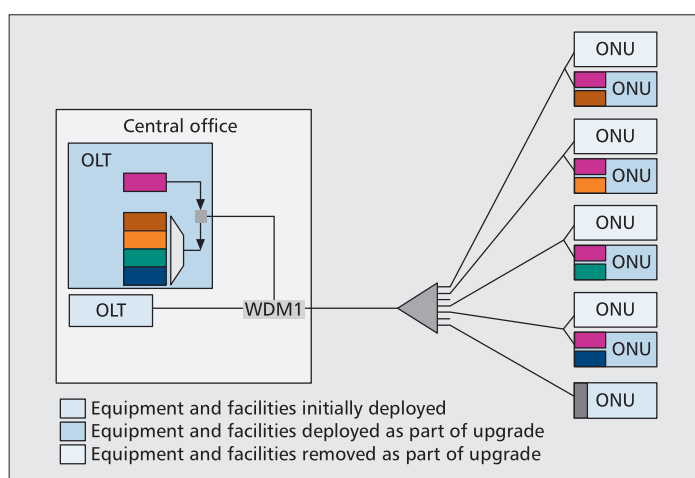


Figure 1. XG-PON1: 10 Gb/s downstream, Nx2.5 Gb/s upstream.

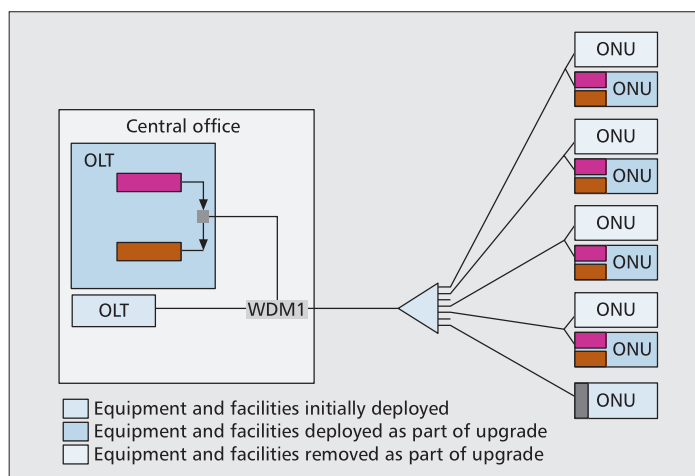


Figure 2. XG-PON2: 10 Gb/s symmetrical.

cant incremental processing capability, and thus consume more energy than a comparable G-PON ONU. Emerging regional and national regulations attempt to restrict energy consumption by network equipment to alleviate environmental concerns. For this reason, consideration has been given to dividing the 10 Gb/s downstream into 4 channels of 2.5 Gb/s so that each ONU only terminates 2.5 Gb/s of signal. This variation does come with some difficulties of configuration, and also of reducing the apparent peak bandwidth of the PON system. For these reasons, most interest is in a single 10 Gb/s channel system. Alternative approaches to energy conservation in XG-PON are being studied.

XG-PON2 WITH 10 Gb/s SYMMETRICAL TRANSMISSION

Figure 2 illustrates the symmetrical XG-PON2 system. As noted above, the FSAN community understands that 10 Gb/s upstream burst transmission is more challenging than 2.5 Gb/s, and

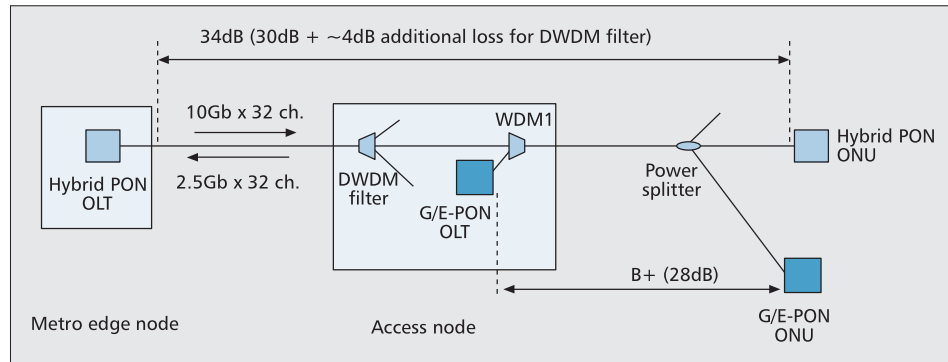


Figure 3. Architecture of a hybrid DWDM/XG-PON.

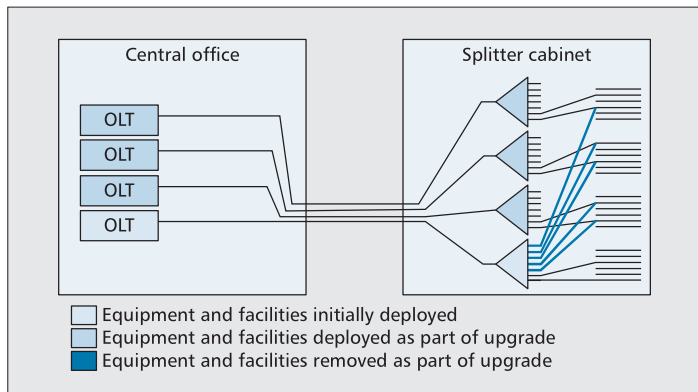


Figure 4. PON split reduction in the case of a centralized splitting scenario.

expects it to be practical in a longer time frame. It will also be more expensive, although cost is expected to decline with volume.

The 10 Gb/s data rate does present challenges in terms of optical budget. Typical receiver sensitivities are approximately 8 dB worse at this rate than at 1~2.5 Gb/s, and the jitter budget is more challenging. For this reason, most designs assume that FEC will be mandatory. In addition, a stronger FEC, capable of handling a raw BER of 10^{-3} , may need to be specified. Even so, to meet the required higher link budgets, APDs and amplified transmitters may be needed.

As noted above, dispersion is a concern at 10 Gb/s. The FSAN community has selected a wavelength band for the 10 Gb/s upstream which is in the low dispersion region of the fiber. This choice is expected to allow directly modulated DFB lasers to be used in XG-PON2 ONUs without dispersion compensation.

It should be noted that mid-span reach extenders are an objective of the XG-PON systems. These reach extenders can use a range of technologies, such as optical amplifiers or optoelectronic regeneration. In addition, the reach extenders may provide wavelength translation capabilities (e.g., with wavelength selected regenerators or all optical wavelength converters), thereby enabling multiplexing of several PONs on a single feeder fiber.

EXTENDED REACH AND WAVELENGTH CONTROLLED VERSIONS OF XG-PON

It is a requirement of the XG-PON systems described above that they operate over PON ODN, which to a large extent is the same as G-PON ODN today. The link loss for XG-PON1 will be approximately 28.5 to 31dB at BER of 10^{-12} (depending on wavelength), yielding a reach of 20 km with a split ratio up to 1:32, or a reach of 10 km with a ratio up to 1:64. It is difficult to go beyond this single-span link loss without use of advanced receiver and transmitter technology such as optical pre- and post-amplification in conjunction with more tightly controlled system wavelengths.

While there are many applications for the increased link budget and split ratio, the basic feature at play here is a more controlled ONU wavelength. The performance of optical amplifiers as detection pre-amplifiers is largely determined by the width of the signal wavelength band. This width determines the ASE filter bandwidth, and the excess ASE-induced noise within the passband of the ASE filter is the primary limiting factor of receiver sensitivity. Conventional systems specify bandwidths on the order of 20 nm, which is very wide for amplification purposes. If we use a wavelength-controlled ONU (e.g., cooled laser source), then the bandwidth can be reduced to about 0.5 nm. This allows sensitivity to be improved by many dB. A wavelength-controlled ONU also opens the possibility for WDM-based multiplexing upgrades in future. However the cost of wavelength controlled transmitters is a significant concern.

HYBRID DWDM/XG-PON

The hybrid DWDM/XG-PON combines multiple XG-PONs using a DWDM MUX/DEMUX and colorless technology for the ONUs. The primary motivation for this system is focused on potential for significant CAPEX and OPEX savings in the case where there is limited feeder fiber. In some scenarios, a hybrid DWDM/XG-PON may reduce cost by increasing the number of subscribers served by a feeder fiber (e.g., by reusing deployed fibers or duct).

The architecture of a hybrid DWDM/XG-PON is shown in Fig. 3.

The primary difference between the hybrid DWDM/XG-PON and other candidate architec-

ture is the use of colorless subscriber ONU. The bit rates for the downstream and upstream channels are up-to 10 Gb/s and 2.5 Gb/s, respectively. The total split-ratio can reach more than 1000 depending on the available wavelength bands, but it comes at the expense of having to support a higher optical link budget.

The key components for the system are a colorless transmitter and WDM filter. The available candidate devices for the colorless transmitters include the seed light injected R-SOA and tunable LD. The seed light injected R-SOA can be used for the direct modulation at 2.5 Gb/s. It has problems with reflection noise, which limits the ODN loss budget. However, it was shown that the reflection noise can be eliminated by employing a coherent detection technology. Even though a coherent receiver increases the total system cost, it is shared by 32 or 64 ONUs. Tunable LDs have advantages over the seed type colorless ONU since they do not need seed light. However, cost reduction is challenging.

The hybrid DWDM/XG-PON system is for further study.

NEAR-TERM UPGRADES THAT ARE NOT CANDIDATES FOR NG-PON1

The following three systems are not presently in the scope of the NG-PON standardization process. They are mentioned here to record that they were considered, but were not selected.

G-PON with Symmetrical Physical PON Split Reduction — The simplest method of increasing customer bandwidth is to physically reduce the PON split-ratio. A typical G-PON supports a 1:32 physical split. If such a PON is divided into N (typically four) smaller PONs, the effective capacity per user is increased by roughly a factor of N (Fig. 4). The key benefits of this upgrade method include complete reuse of all ONU and OLT equipment. However, it does require provisioning, and possibly installation of more feeder fiber and OLT interfaces. The large number of new OLT interfaces would more likely require the installation of a new OLT platform that has higher port density and larger backplane capacity. This method also potentially requires re-configuration of PON splitters, so that many smaller PONs are created. Obviously, this requirement of PON re-arrangement makes this option out of scope of standardized NG-PON1 systems. However, an operator is not precluded from pursuing such an approach using the existing G-PON standards.

G-PON with Downstream Wavelength PON Split Reduction — The split-reduction scheme described above has the major disadvantage that additional feeder fiber must be provisioned. This scheme addresses this issue by using WDM to multiplex multiple downstream channels into a single physical PON. A typical system (Fig. 5) requires upgrade of OLT interfaces with new type devices, which have four downstream transmitters but only one upstream receiver. This renders a PON with a downstream capacity of 10 Gb/s, but an upstream capacity of 1.2 Gb/s. The PON power splitter (potentially only the first

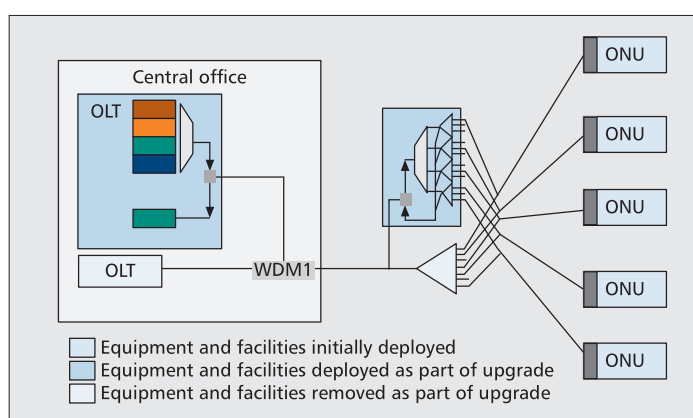


Figure 5. PON split reduction using WDM in the downstream only.

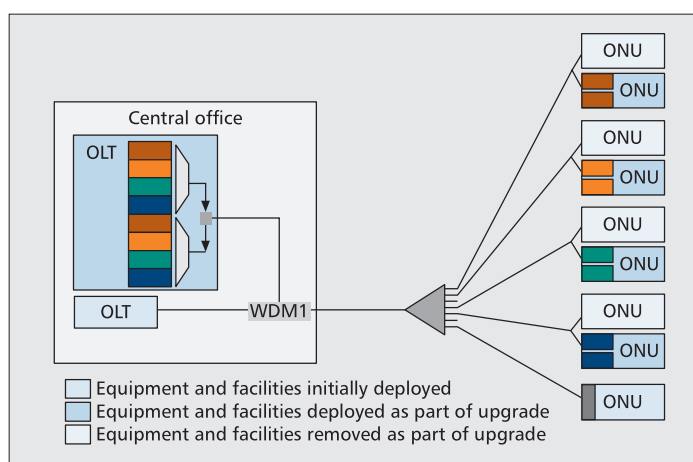


Figure 6. PON split reduction using symmetrical WDM.

stage in a multistage arrangement) is replaced with a WDM-aware device that acts as a simple splitter in the upstream, but as a WDM mux/demux combination in the downstream. This requirement of PON rearrangement and the lack of incremental upstream bandwidth upgrade make this system out of scope for NG-PON1 standardization process.

Overlay G-PON System — This system focuses on the use of WDM to transport multiple (typically 4) independent PON streams over a common PON ODN. This kind of system is sometimes called a hybrid PON, since it combines WDM and TDMA technology. A typical system is shown in Fig. 6.

The major challenge with this system is finding suitable wavelength allocations that balance the need for more channels (dictating a tight wavelength plan) against the desire for cheaper optical components (requiring a looser wavelength plan).

In the upstream direction, it is likely that CWDM plan would be used, because ONU transmitter is more cost sensitive and often must withstand outdoor temperature ranges. Such specification combination makes a cooled

The largest requirement for NG-PON1 is its coexistence with an operational G-PON, and in some cases a video overlay system, on the same ODN. This presents a challenge due to multiplexing the new system with the old one.

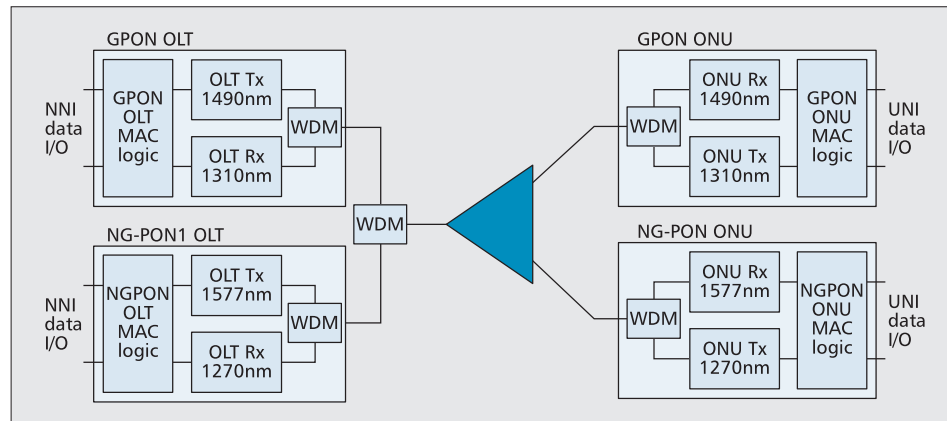


Figure 7. G-PON and NG-PON1 coexistence using WDM for both directions.

DWDM transmitter at the ONU difficult to achieve. The opposite is true for the downstream direction, where cost is not as much a concern and temperature ranges are smaller. Additionally, the spectrum in the traditionally downstream 1480 to 1600 nm band is relatively scarce, and so DWDM technology is needed to conserve it.

One of the issues with any WDM scheme is provisioning of equipment wavelength. For the OLT side, most systems envision a new OLT interface that supports all the channels in a single module; therefore, there is no issue. However, each ONU only supports a single wavelength in either direction. Given the CWDM direction for the transmitter, it is unlikely that the upstream transmitter would be tunable (due to the large wavelength range to cover); however, wavelength selectable sources, such as a laser array, might be a possibility. The downstream receiver filter might be tunable without too much of a cost penalty (but would add optical loss). In addition, use of a 2.5 Gb/s receiver reduces energy consumption and cost.

Alternatively, the ONU interfaces may be *colored*, and so there would be four types of equipment in the field. Colored ONUs may present operational problems; however, the magnitude of the issue is a question. In fact, if the operator chooses to deploy four different ONU types completely at random on 1:32 PONs, the probability of all the customers receiving the same color is very small. In over 95 percent of the randomly assigned channels, the loading of the channel will be less than 12 subscribers. On top of this, simple heuristic provisioning schemes could work to lower the changes of extreme imbalance even further. So, it may be a manageable problem. Of course, a wavelength selectable ONU would obviate this operational issue, albeit at the cost of a more complex ONU.

In addition, this scheme forces a division of the bandwidth into four pools of 2.5 Gb/s each. Doing so somewhat reduces the performance gains from the NG-PON, relative to a single pool of 10 Gb/s.

There is presently a consensus of the FSAN operators that the overlay G-PON approach is out of the target for NG-PON1.

ARCHITECTURE SUMMARY

This section reviewed many of the architectures that have been considered for use in the next generation PON systems. At this time, it would seem that asymmetric XG-PON1 system fits best the requirements in a cost-effective manner. For this reason, the XG-PON1 system is the primary focus.

With that primary objective defined, there are several additional lines of consideration. One is the interest in considering the symmetric XG-PON2 system, and how that system might be designed so as to share design elements with other PON systems, and potentially have compatibility with XG-PON1 systems. Another side-interest is the support for extended wavelength / reach versions of XG-PON system.

COEXISTENCE CONSIDERATIONS

The largest requirement for NG-PON1 is its coexistence with an operational G-PON, and in some cases a video overlay system, on the same ODN. This presents a challenge due to multiplexing the new system with the old one. For this purpose, we can use WDM techniques, or TDM techniques. Each of these methods will have different requirements for the wavelength plan, and that in turn will result in different coexistence behaviors. The next few sections present various methods that have been considered for coexistence.

PRACTICAL SITUATION REGARDING COEXISTENCE

The choice of coexistence methodology depends a great deal on the practical situation of the deployed systems. At the physical layer, there seem to be three basic groups of deployment in the world today.

1G-EPON [7] or 622/155 Mb/s BPON using the entire O-band (1260–1360 nm) for the upstream, with the video overlay, and ODN limited to 1580nm maximum wavelength. In terms of spectrum, the only band that is available is above 1560nm, and some allowance for guard-band is necessary. This is enough for a down-

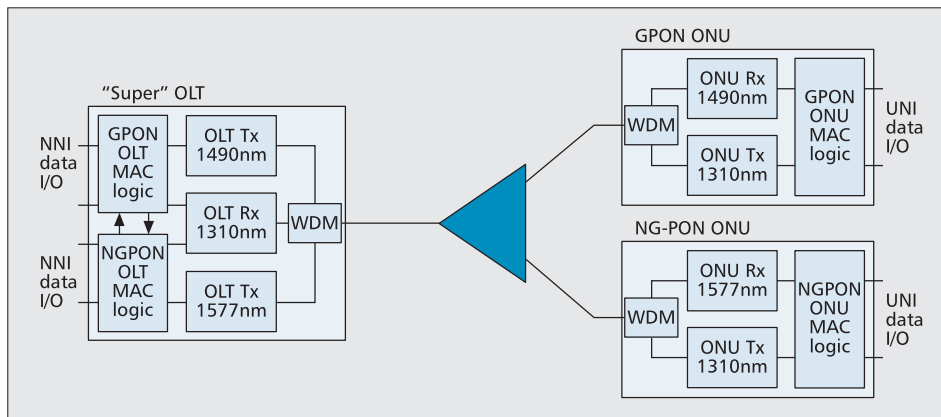


Figure 8. G-PON and NG-PON1 coexistence using WDM downstream and TDMA upstream.

stream wavelength, but not for the upstream. If coexistence were to be required, the upstream must share O-band spectrum using TDMA.

2.5 Gb/s G-PON using the center of the O-band, with video overlay, and an ODN that is limited to perhaps 1600 nm; however some operators might have deployed splitters that are specified only to 1580 nm. This scheme has more spectrum available in either O-band or C/L bands. Also note that, the video overlay is combined with the G-PON in the central office using a WDM filter. When NG-PON1 is added, this filter will likely need to be replaced with one that combines NG-PON1, G-PON, and the overlay.

2.5 Gb/s G-PON using the center of the O-band, without overlay, and an ODN limited to 1600 nm (or possibly 1580 nm). This scheme has significant long wavelength spectrum allocation, since the C-band is available.

Once a system moves into large-scale deployment, it is very difficult to change it, or to place additional requirements upon it. This presents a dilemma. It would be impractical to accommodate all the coexistence methods, because this would result in multiple, non-interoperable wavelength assignments for a given channel, and that is not interoperable. A single wavelength plan that would suit all the above deployment situations would be highly desirable, because then the optical device manufacturers would have a clear single target in order to achieve economies of scale as well as interoperability.

WDM IN BOTH DIRECTIONS

The simplest scheme considered is the use of WDM to separate NG-PON1 signals from G-PON signals, as shown in Fig. 7. This system requires G-PON ONUs to be equipped with a wavelength blocking filter, so that additional NG-PON1 wavelengths are ignored [5]. Many G-PON ONUs possess such filters already; however, some may not, in which case separate blocking filters must be installed in the field.

If the existing OLT equipment is to be retained for a smooth migration, a WDM branching filter must be placed between the ODN and the G-PON OLT. This filter not only

provides interface port for the NG-PON1 OLT, but also protects the G-PON OLT from NG-PON1 signals. Pre-placement of the WDM1 filter can prevent a brief G-PON service outage when NG-PON1 is deployed.

WDM DOWNSTREAM, TDMA UPSTREAM

While WDM is simple, there is an important case where the upstream channel spectrum may need to be shared with the previous system. This is the case where the previous PON system uses the widest upstream spectrum band (1260–1360 nm), which is where the NG-PON1 is planned to transmit. For G-PON, this is only a concern where the G.984.5 *regular* wavelength band option is used by at least one ONU on the PON. Dispersion becomes a major impairment at 10 Gb/s, and the use of economical transmitters at ONUs strongly motivates the use of the 1310 nm window for the XG-PON2 upstream. If the G-PON system already reserved the whole 1310 nm band, then there is no other option but to use TDMA channel sharing between the two systems. Note that the NG-PON1 system may use only a portion of the whole 1310 nm band, but this does not avoid the difficulty.

In this scheme, the existing G-PON OLT would be replaced with an OLT that supports both the G-PON and NG-PON1 systems, as presented in Fig. 8. This tight integration of two systems allows for synchronization of two upstream bandwidth allocations.

If the G-PON OLT is to be retained for a smoother migration, then it is possible to use a special optically amplified NG-PON1 OLT system, described in detail in [8]. As shown in Fig. 9, the NG-PON1 OLT would be installed between the ODN and the existing G-PON OLT. The NG-PON1 OLT would perform two additional functions in order to coexist with the G-PON OLT. First, it would amplify the upstream signal, so that it can take its share of the upstream light to perform 10 Gb/s reception while still providing the G-PON OLT with its normal signal level. Second, the NG-PON1 OLT would mimic a G-PON ONU to the G-PON OLT, and thereby request and obtain upstream timeslots, which it would then use to

While WDM is simple, there is an important case where the upstream channel spectrum may need to be shared with the previous system. This is the case where the previous PON system uses the widest upstream spectrum band, which is where the NG-PON1 is planned to transmit.

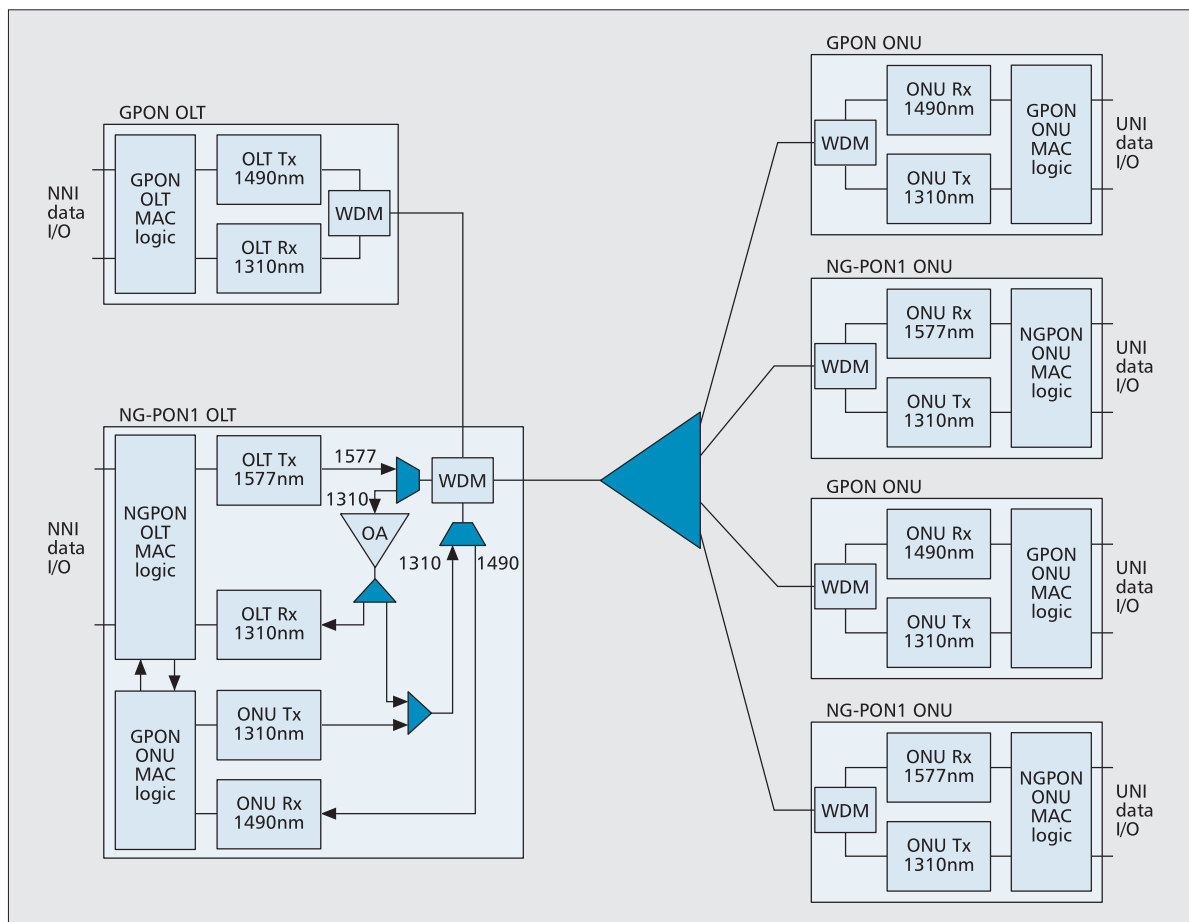


Figure 9. WDM/TDMA coexistence with special backward compatibility to G-PON OLTs.

allocate slots to NG-PON1 ONUs connected to it. This mimicked G-PON ONU signal would overwrite the 10 Gb/s upstream signals from the NGPON ONUs, thereby protecting the G-PON equipment from being disturbed. Because the mimicked G-PON ONU is very close to the G-PON OLT, if no extra care is taken, the 20km differential range limitation on the system will limit the reach of the PON. However, it is possible for the mimicked ONU to apply an internal delay to its transmissions, making it appear to be at an arbitrary distance, thereby resolving this difficulty.

TDM DOWNSTREAM, TDMA UPSTREAM

There may be cases where the existing G-PON ONUs do not have blocking filters, and where reworking the deployment with add-on blocking filters is not attractive. The objective therefore would be to devise the downstream signal such that existing G-PON receivers will only see the typical G-PON signal, but that new NG-PON1 receivers will see only the 10 Gb/s signal. Indeed, it is possible to construct signals that are sufficiently orthogonal, where the very same wavelength can be used to transmit both signals. This approach is further generically referred to as bit-stacking.

The concept of applying a reduced amplitude for 10 Gb/s data to ease continued operation of the G-PON ONUs in presence of 10 Gb/s data can be beneficially applied to a dual wavelength operation in downstream [9]. In this approach the bit-stacked signal is generated by two different optical sources at the OLT (Fig. 10). One source generates conventional binary 2.5 Gb/s downstream signal at the legacy wavelength range 1480–1500 nm, the other source generates a binary 10 Gb/s signal at the new wavelength, e.g., at 1577 nm. The relative optical modulation depths (optical powers) of 10 Gb/s and 2.5 Gb/s signals are adjusted in the ratio of about 30 percent (see inset of Fig. 10 for definition of relative amplitudes). The legacy ONU receivers only detect 2.5 Gb/s tributary signals due to its electrical bandwidth constraints. The new 10 Gb/s ONU is equipped with an additional WBF passing only the 10 Gb/s channel. In this way, the 10 Gb/s channel is not disturbed by the legacy G-PON signals. Legacy ONUs benefit from the special adjustment of modulation amplitudes, and their limited electrical bandwidth allows them to extract only the 2.5 Gb/s data from the multiplexed signal.

With this dual wavelength operation the bits of the two tributaries do not need to be edge

aligned and the data rate of the new channel does not need to be an integral multiple of the G-PON bit rate. This offers very simple upgrade opportunities for legacy G-PONs by simply adding a second optical source for transmitting 10 Gb/s data, operating at suitable wavelength and power. The upgrade can be accomplished by either replacing the G-PON OLT by a new hybrid G-PON/NG-PON OLT or by combining the optical data streams of the existing G-PON-OLT and the new NG-PON OLT by employing an additional separate *combiner box*. This box accepts both optical data streams as input and adjusts their relative power levels to a suitable level at the output. It can be removed afterwards, when all ONUs are migrated to the new data rate.

Bit stacking may be a subject of future study.

SUMMARY

This article has reviewed the architectures that have been considered for use in the next generation PON systems. Systems that are potential candidates for NG-PON1 include the asymmetric 10 Gb/s PON, the symmetric 10 Gb/s PON, extended wavelength/reach versions of those systems, and hybrid DWDM versions. The asymmetric XG-PON1 system fits best the requirements in a cost-effective manner. For this reason, the XG-PON1 system is the primary focus of further development work.

With that primary objective defined, there are several additional lines of consideration. One is the interest in considering the symmetric XG-PON2 system, and how that system might be designed so as to share design elements with other PON systems, and potentially have compatibility with XG-PON1 systems. Another side-interest is the support for extended wavelength/reach versions of XG-PON system.

With this basic choice of focus being made, we then consider the methods to achieve coexistence with existing G-PON systems. The situation regarding the deployed system characteristics are presented at a high level. Then, the three combinations of WDM and TDM multiplexing techniques are reviewed. Given that the majority of G-PON systems implement spectral features defined in G.984.5, it seems that using WDM in both directions is the best coexistence solution. In the next article in the series, these basic conclusions will guide the development of more detailed system specifications.

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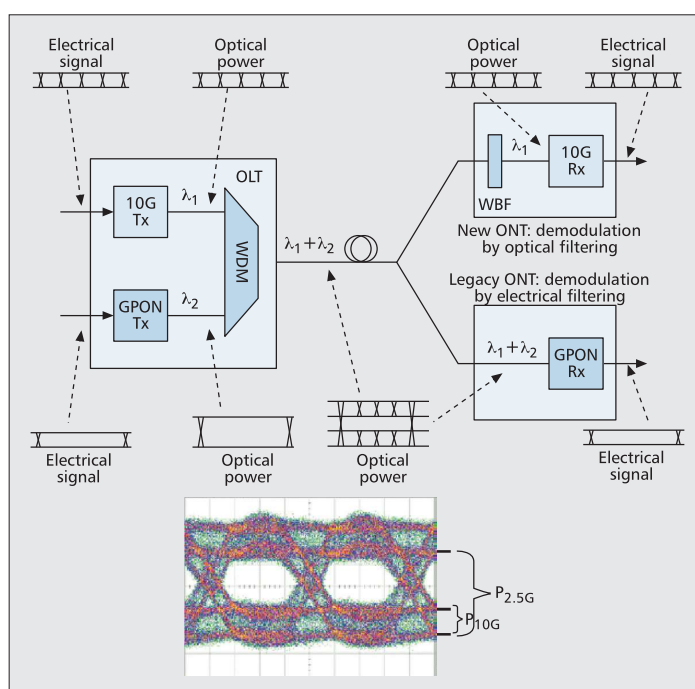


Figure 10. Principal setup for dual wavelength bit stacking.

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BIOGRAPHIES

FRANK J. EFFENBERGER [M'94, SM'01] (feffenberger@huawei.com) received his Ph.D. degree from the University of Central Florida in 1995. He was a staff scientist at Bellcore where he analyzed all types of access network technologies. In 2000, he moved to Quantum Bridge, where he led the development and standardization of advanced optical access systems based on B-PON and G-PON technologies. In 2006, he became Director of FTx in the advanced technology department of Huawei Technologies. In 2008, he became the chairman of ITU-T Q2/15.

HIROAKI MUKAI received his B.E. and M.S. degrees in electrical and electronic technology from Chiba University, Japan, in 1988 and 1990, respectively. He joined Mitsubishi Electric Corporation, Japan in 1990. Since 1990 to 2008 he was engaged in research and development of optical communication system. Particularly, since 1998, he has been engaged in development of PON (Passive Optical Network) systems.

SOO JIN PARK has been working on optical devices, systems and optical access network in KT R&D group after he received his Ph.D. degree in material sciences from the University of Texas at Austin in 1995. Currently, he is interested in the re-optimization of access and metro networks for the effective deployment of optical access technologies.

THOMAS PFEIFFER is leading the Optical Access research department in Alcatel-Lucent Bell Labs Stuttgart. After finishing his Ph.D. in solid state physics he joined Alcatel in 1986, investigating optical transmission phenomena and developing fiber amplifiers and lasers, before turning to metro and access networks research. He has been involved in many national and international research projects dealing with various optical systems technologies like HFC and HFR, OCDMA, GPON/10G-PON, and WDM-PON. He also contributes to standardization efforts at FSAN/ITU-T and CENELEC.