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GPON – The Next Big Thing in Optical Access Networks

A Comparison Between EPON, APON and the Emerging GPON Technology

Abstract

This paper contains a comprehensive review of the various Passive Optical Network (PON) technologies in the marketplace today, namely APON, EPON and GPON, and draws an in-depth comparison between them.

Following a review of the history of the various PON flavors, as well as the service requirements set forth by service providers, the emerging ITU-T G.984 series Gigabit PON (GPON) technology is examined in detail. System performance between the various protocols is compared using efficiency and scalability factors, and conclusions are drawn as to the overall throughput efficiency of and cost influence on the solution.

GPON carries a two-fold promise of both higher bit rates and higher efficiency when carrying multiple services over the PON. It offers a scalable framing structure from 622Mbps to 2.5Gbps, as well as support for asymmetric bit rates, exceptionally high bandwidth utilization for any type of service and GPON Encapsulation Method (GEM) encapsulation of any type of service (both TDM and packet) onto a synchronous transport protocol. It is shown that in the worst-case scenario, based upon the most conservative assumptions regarding traffic distribution, **GPON is substantially more efficient, with an overall efficiency of 93% compared to 71% with APON and 49% with EPON**. Using a more detailed analysis based upon a traffic model provided by the service providers within the full service access networks (FSAN) consortium, it is shown in quantitative terms that GPON offers exceptionally higher bandwidth for the entire range of applications when compared to both APON and, especially, EPON, resulting in substantially lower cost per bit and a much faster payback period.

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The History of PON

Hot Topics

- *GPON is the focus of work in the FSAN/ITU-T committees*
- *GPON offers unprecedented bandwidth as well as support for both data and TDM*

In order to fully understand the various PON flavors and the merits of GPON as the next leading technology, it is important to first cover the history of PON development over the past few years.

The basic principle of a PON network is to share the Central Office (CO) equipment (Optical Line Terminal or OLT) and the feeder fiber among as many end units (Optical Network Termination or ONT) as possible within the physical and bandwidth constraints. Since this solution requires less fiber layout in order to cover a specific area, as well as less costly optical interfaces at the CO (one optical interface serves the entire network), the solution offered enables high speed optical connections for businesses or residential units in scenarios that could not be served in an economical manner using traditional point-to-point or ring architectures.

The first PON activity was initiated in the mid-1990s when a group of major network operators established the full service access networks (FSAN) consortium. The group's goal was to define a common standard for PON equipment so that vendors and operators could come together in a competitive market for PON equipment. The result of this first effort was the 155 Mbps PON system specified in the ITU-T G.983 series of standards. This system has become known as the B-PON system and it uses ATM as its bearer protocol (known as the APON protocol). The name B-PON was introduced since the name APON led people to assume that only ATM services could be provided to end users. Changing the name to BPON reflected the fact that BPON systems offer broadband services including Ethernet access, video distribution, and high-speed leased line services. Still, the most common and renowned name for the first generation of FSAN systems is APON.

The APON Standards were later enhanced to support 622 Mbps bit rates as well as additional features in the form of protection, Dynamic Bandwidth Allocation (DBA) and others.

On a parallel track, in early 2001, the IEEE established the Ethernet in the First Mile (EFM) group, realizing the enormous prospect that lies ahead in the optical access market. The group works under the auspices of the IEEE 802.3 group, which also developed the Ethernet standards, and as such is restricted in architecture and compliance to the existing 802.3

Media Access Control (MAC) layer. The EFM's work is concentrated on standardizing a 1.25 Gbps symmetrical system for Ethernet transport only.

In 2001 the FSAN group initiated a new effort for standardizing PON networks operating at bit rates above 1 Gbps. Apart from the need to support higher bit rates, the overall protocol has been opened for reconsideration and the sought solution should be the most optimal and efficient in terms of support for multiple services, and operation, administration, maintenance and provisioning (OAM&P) functionality and scalability.

As a result of this latest FSAN effort, a new solution has emerged in the optical access market place – Gigabit PON (GPON), offering unprecedented high bit rate support while enabling the transport of multiple services, specifically data and TDM, in native formats and with extremely high efficiency.

The following figure depicts the general architecture and topology of PON networks in general and specific features related to GPON, and will serve as a reference for the discussed network application. FlexLight's GPON architecture is used here as an illustration.

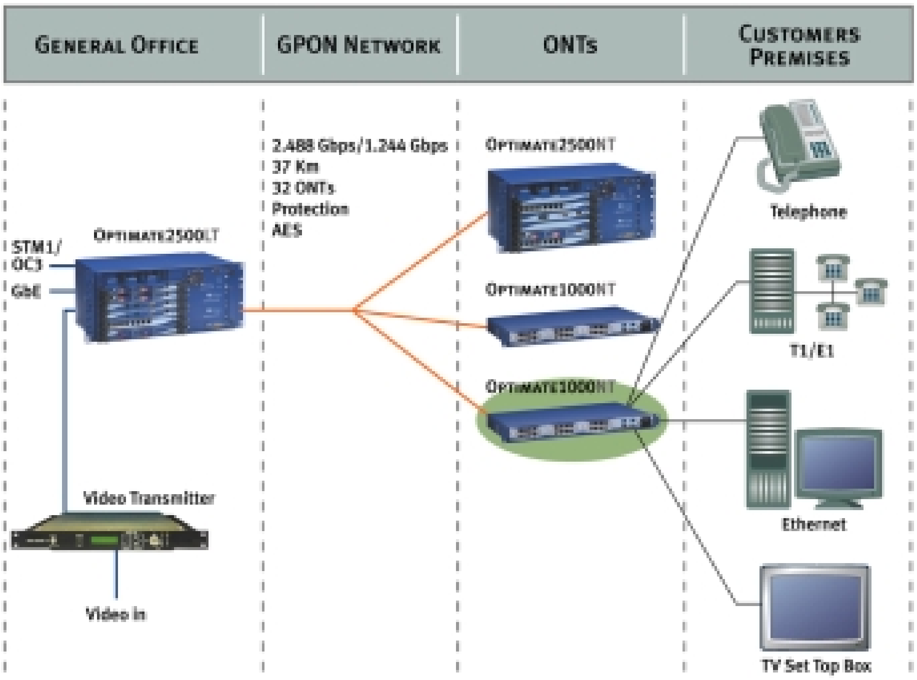

Figure 1 – PON/GPON Network Topology

Gigabit Service Requirements (GSR)

Hot Topics

- *GPON is a service provider driven solution*
- *Service providers from around the world have laid down Gigabit Service Requirements as the basis for GPON development*

An important attribute of FSAN is that it is a customer-driven group in which the telecommunications service providers set forth the service requirements and these in turn lay the basic foundations for the proposed solution. This is in strong contrast to the EFM effort, which is more vendor-driven towards a simple and Ethernet-compliant solution, rather than offering remedies to existing service and network demands.

As part of the GPON effort, a Gigabit Service Requirement (GSR) document has been implemented based upon the collective requirements of all member service providers, representing the leading RBOCs and ILECs of the world. The document was also recently submitted as an official recommendation to the ITU-T (recommendation G.984.1).

The main requirements resulting from the GSR document can be summarized as follows:

- Full Service Support – including voice (TDM, SONET and SDH), Ethernet (10/100 BaseT – 10 or 100 Mbps running on a twisted pair), ATM, leased lines and others.
- Physical reach of at least 20 km with a logical reach support within the protocol of 60 km.
- Support for various bit rate options using the same protocol, including symmetrical 622 Mbps, symmetrical 1.25 Gbps, 2.5 Gbps downstream and 1.25 Gbps upstream and others.
- Strong OAM&P capabilities offering end-to-end service management.
- Security at the protocol level for downstream traffic due to the multicast nature of PON.

Consequently, GPON systems that are standardized and developed these days are based on the entire set of requirements laid out by the GSR document, and thus represent a pervasive solution for the needs of service providers.

Various Flavors of PON

Apart from GPON, two alternative technologies exist for PON networks – APON (representing the incumbency of lower bit rate systems) and EPON (representing the emerging standards within the IEEE EFM group).

APON – ATM Based PONs

APON systems are based upon ATM as the bearer protocol. Downstream transmission is a continuous ATM stream at a bit rate of 155.52 Mbps or 622.08 Mbps with dedicated Physical Layer operation, administration and maintenance (PLOAM) cells inserted into the data stream. Upstream transmission is in the form of bursts of ATM cells, with a 3 byte physical overhead appended to each 53 byte cell in order to allow for burst transmission and reception.

Hot Topics

- *APON networks require every service to be mapped onto ATM before transmission on the PON network*
- *APON has developed a rich set of OAM functions to be used for other standards*

The transmission protocol is based upon a downstream frame of 56 ATM cells (53 bytes each) for the basic rate of 155 Mbps, scaling up with bit rate to 224 cells for 622 Mbps. The upstream frame format is 53 cells of 56 bytes each (53 bytes of ATM cell + 3 bytes overhead) for the basic 155 Mbps rate.

The downstream frame is constructed from two PLOAM cells, with one at the beginning of the frame and one in the middle, and 54 data ATM cells. Each PLOAM cell contains grants for upstream transmission relating to specific cells within the upstream frame (53 grants for the 53 upstream frame cells are mapped into the PLOAM cells) as well as OAM&P messages.

Upstream transmission consists of either a data cell, containing ATM data in the form of Virtual Paths and Virtual Circuits (VPs/VCs), or a PLOAM cell when granted a PLOAM opportunity from the central OLT.

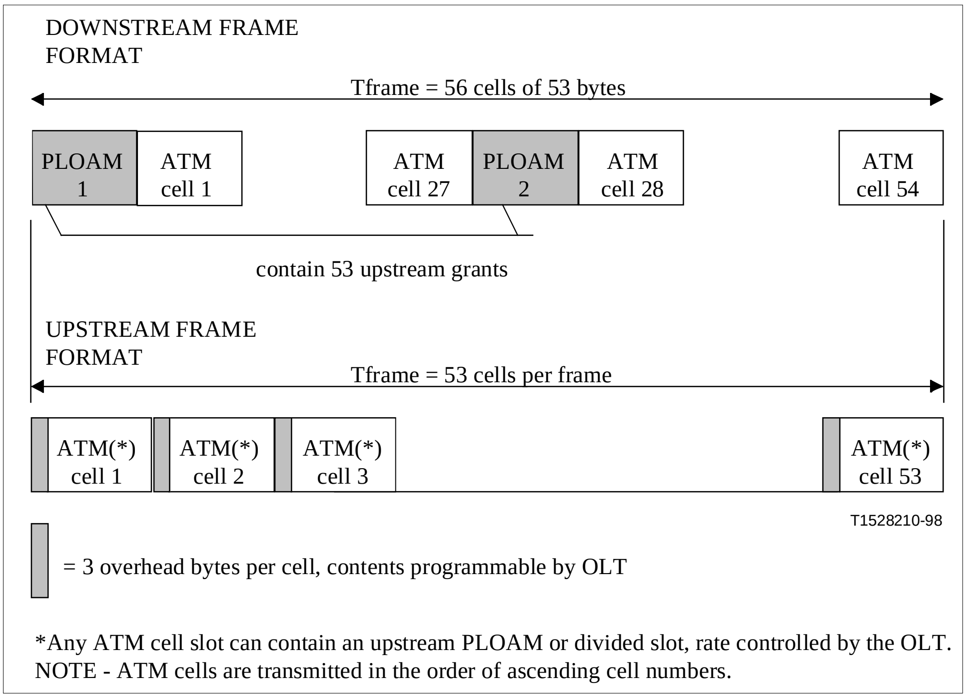

Figure 2 - Frame format for 155.52/155.52 Mbps PON

APON provides a very rich and exhaustive set of operation, administration and maintenance (OAM) features, including bit error rate (BER) monitoring, alarms and defects, auto-discovery and automatic ranging, churning as a security mechanism for downstream traffic encryption, etc. However, APON systems suffer from two substantial drawbacks in the form of low overall efficiency for data transport and the complexity of adapting and provisioning services over an ATM layer.

EPON – Ethernet Based PONs

Ethernet for subscriber access networks, also referred to as “Ethernet in the First Mile”, or EFM, combines a minimal set of extensions to the IEEE 802.3 MAC and MAC Control sub layers with a family of Physical (PHY) Layers. These Physical Layers include optical fiber and unshielded twisted pair (UTP) copper cable Physical Medium Dependent sub layers (PMDs) for point-to-point connections in subscriber access networks. EFM also introduces the concept of EPONs, in which a point to multipoint (P2MP) network topology is implemented with passive optical splitters, along with optical fiber PMDs that support this topology. In addition, a mechanism for network OAM is included to facilitate network operation and troubleshooting.

Hot Topics

- *EPON networks can only support Ethernet services and thus raise QoS issues when dealing with TDM*
- *EPON is more vendor-driven than customer-driven and lacks many required OAM capabilities*

EPON is based upon a mechanism named Multi-Point Control Protocol (MPCP), defined as a function within the MAC control sub layer. MPCP uses messages, state machines, and timers, to control access to a P2MP topology. Each Optical Network Unit (ONU) in the P2MP topology contains an instance of the MPCP protocol, which communicates with an instance of MPCP in the OLT.

The basis of the EPON/MPCP protocol lies in the point-to-point (P2P) emulation sub layer, which makes an underlying P2MP network appear as a collection of P2P links to the higher protocol layers (at and above the MAC Client). It achieves this by prepending a Logical Link Identification (LLID) to the beginning of each packet, replacing two octets of the preamble.

EPON as a protocol is still under work within the IEEE EFM group, with many issues, including those relating to the protocol itself, OAM functionality, and physical layer specifications still lacking a detailed definition. EPON suffers from two substantial drawbacks, namely extremely low efficiency and the lack of ability to support any service but Ethernet over the PON, thus introducing QoS issues when dealing with voice/TDM services. While the efficiency issue will be discussed in more detail later on, it is important to mention here the fact that EPON uses 8b/10b encoding as the line code (the line code ensures sufficient balance between 0s and 1s in the bit stream, which is crucial for the proper operation of any communication link).

The line code itself introduces a 20 per cent bandwidth penalty, resulting in a starting point of 1 Gbps out of the line rate of 1.25 Gbps, before dealing with the protocol itself. APON and GPON systems, however, use scrambling as the line code, which is the same mechanism used for line coding in any SONET or SDH network, with the benefit of no bandwidth penalty as bits are only changed and not added.

GPON – The Native Mode PON

GPON carries a two-fold promise of both higher bit rates and higher efficiency when carrying multiple services over the PON. When initiated, the GPON was intended as a complete bottom-up reconsideration of PON applications and requirements and, as such, laid the foundation for new solutions that are not based upon the previous APON standard.

<u>Hot Topics</u>

- *GPON offers native mode support for all service types, including both TDM (SONET/SDH) and data*
- *GPON is based upon ITU-T standard GFP mapping*

While much of the functionality that is not directly related to the PON is preserved, such as OAM messages, DBA, etc., GPON is based upon a completely new Transmission Convergence (TC) layer. The FSAN has recently selected the proposal put forward by FlexLight and numerous additional vendors, for a frame based protocol using GEM for service mapping, as the next GPON protocol. The standard was finalized as G.984.3 on February 2004.

Starting with the GPON work, the following objectives were put forward:

- Scalable framing structure for 622Mbps to 2.5Gbps, as well as asymmetric bit rates support.
- Exceptionally high bandwidth utilization/efficiency for any type of service
- GPON Encapsulation Method (GEM) encapsulation of any type of service (both TDM and packet) into 125 μsec periodic frames.
- High efficiency with no overhead transport of native TDM traffic required.
- Dynamic Allocation of upstream bandwidth via bandwidth maps (pointers) for each ONT.

At this point, a few words on GPON Encapsulation Method (GEM) are required. GEM is based on the ITU GFP standard (ITU-T G.7041), with some minor modifications to make it optimized for PON topologies. GEM provides a generic mechanism to adapt traffic from higher layer client signals over a transport network.

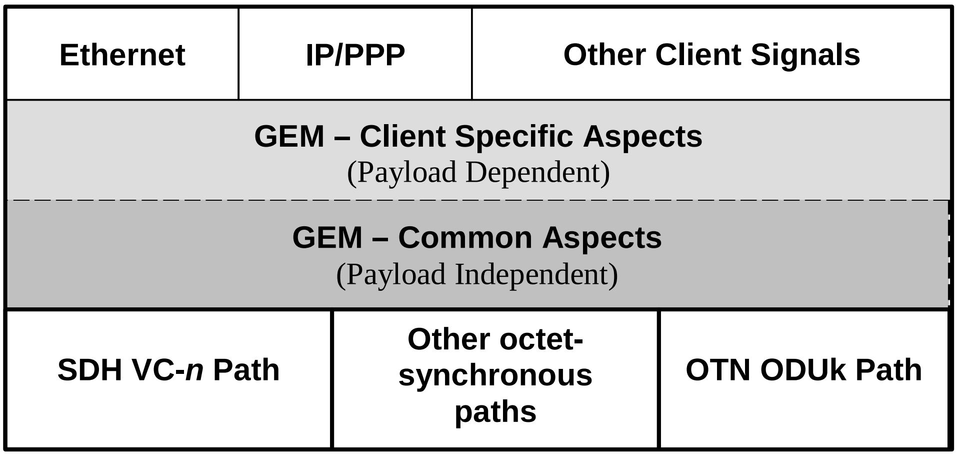

Figure 3 - GEM Relationship to Client Signals and Transport Paths

Since GEM provides a generic mechanism to transport different services in an efficient and simple manner over a synchronous transport network, it is ideally suited as the basis for the GPON TC layer. In addition, the fact that in using GEM, the GPON TC layer is synchronous in nature and uses the standard SONET 8 kHz (125 μsec) frame enables straightforward support for TDM services.

Summarizing the design choices for the GPON protocol, the following items can be mentioned:

- Frame-based, multi service (ATM, TDM, Data) transport over PON.
- Upstream bandwidth allocation mechanism via slot assignments through pointers.
- Support for asymmetric line rate operation. 2.488 Gbit/s downstream and 1.244 Gbit/s upstream rates.
- Line coding will be non-return-to-zero (NRZ) with scrambling.
- Out-of-band control channel at PHY layer for OAM functions using G983 PLOAMs.
- Fragmentation and concatenation of data frames for bandwidth efficiency.
- Upstream burst mode preamble, including clock and data recovery (CDR), will not be long.
- DBA reports, security, and survivability overhead are integrated into the PHY layer.

- Cyclic Redundancy Codes (CRCs) for framing header protection and bit-interleaved-parity (BIP) to support BER estimation.
- QoS supported at the PHY Layer.

The following two figures depict the frame structure of the GPON protocol for both upstream and downstream directions.

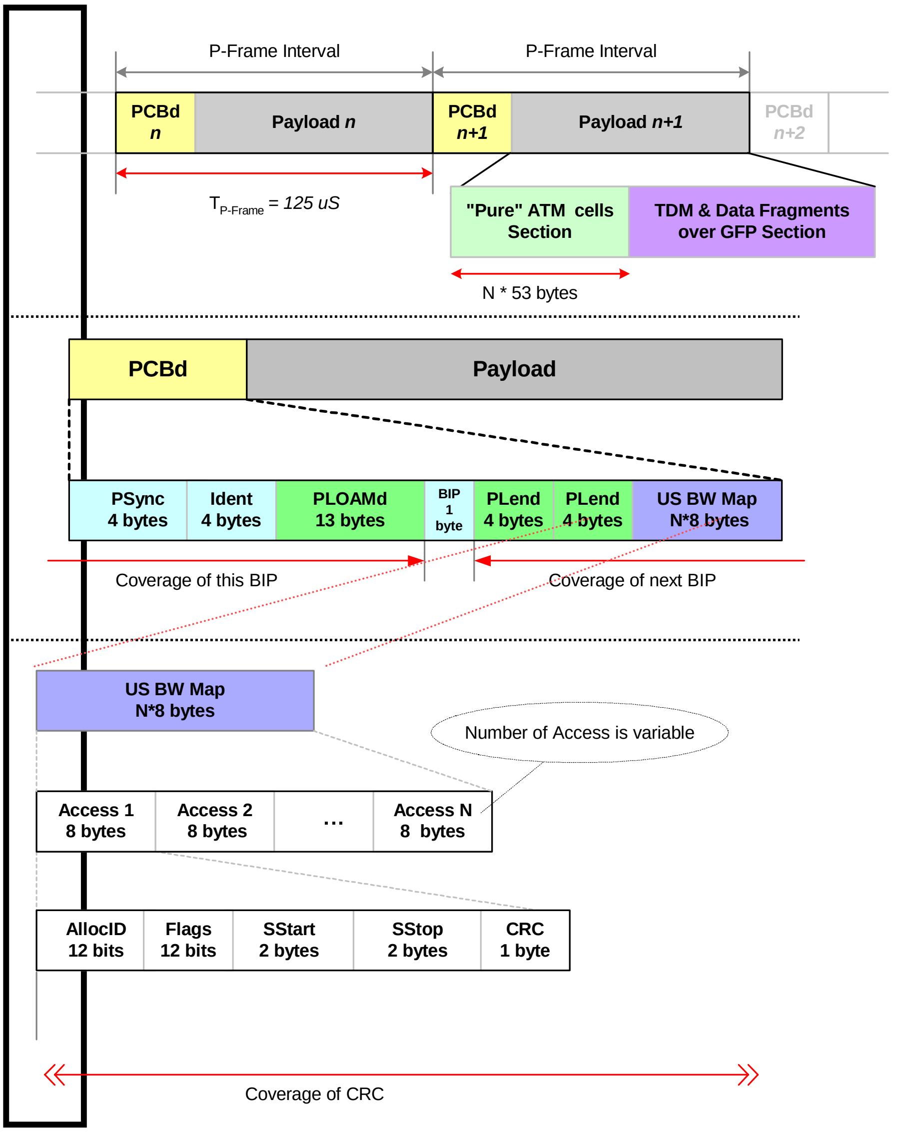

Figure 4 – GPON Downstream Frame Format

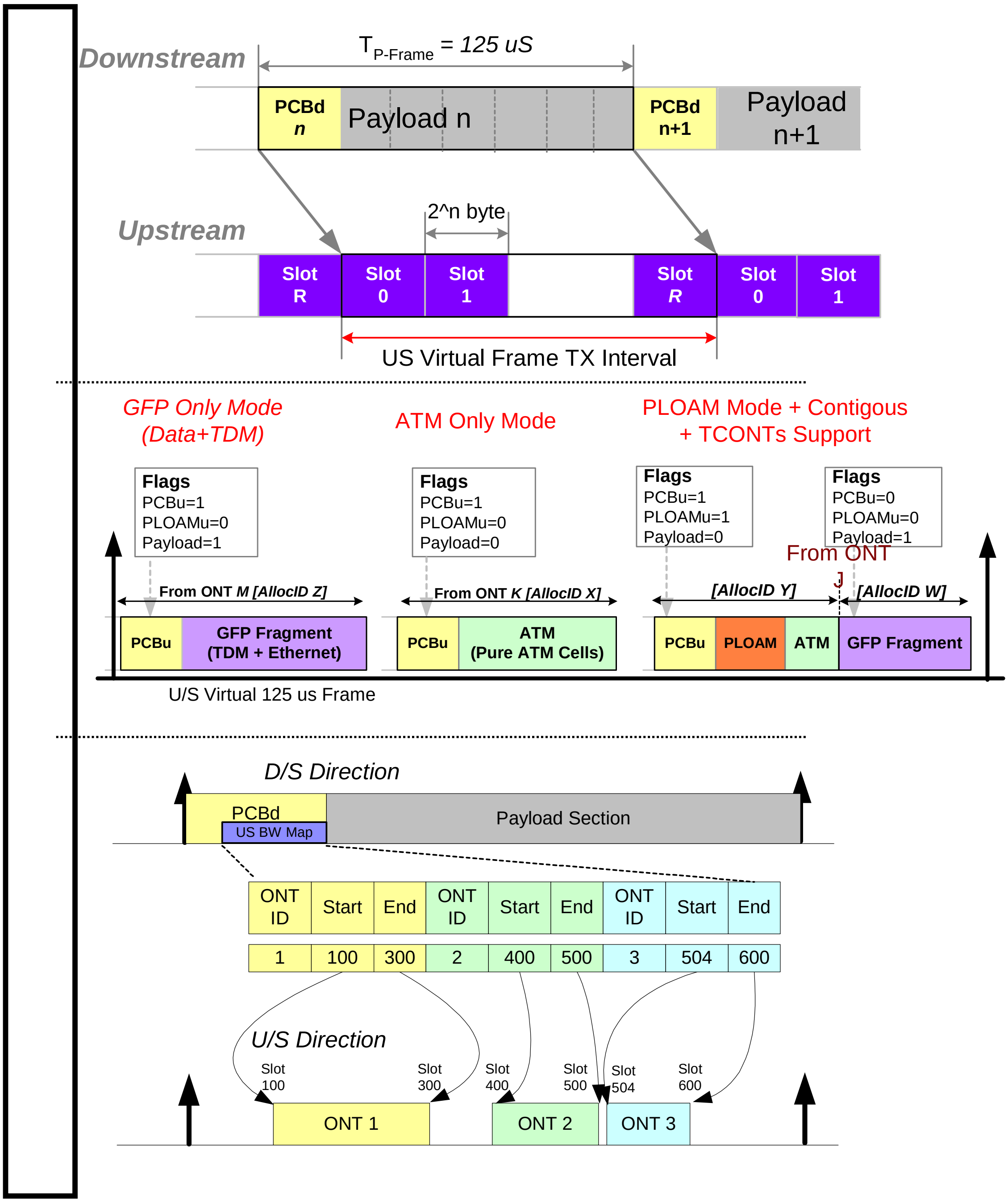

Figure 5 - GPON Upstream Frame Format

Efficiency and System Performance

The most important factor in analyzing a solution's overall cost is the efficiency factor, providing the overall bandwidth that can be sold as services over the system.

When comparing various PON systems such as APON, EPON or GPON, and assuming a similar bit rate of 1.25 Gbps, it can be safely assumed that the system cost itself will be very similar. A substantial portion of the system cost originates from the optical interface, which is independent of the PON protocol, while the rest of the system components are expected to be of similar prices based upon application-specific integrated circuits (ASICs) and other standard components. This is not to say that the overall solution will be of the same cost as, for example, when using an EPON system in which additional VoIP equipment is required, which would add an additional cost factor.

Hot Topics

- *Efficiency is the primary factor in determining the overall system cost*
- *System costs are assumed to be similar (same optics) and thus a more efficient system renders a lower cost per bit*

Assuming similar cost figures for the system itself, efficiency is the single most dominant factor when determining the cost per bit or the amount of "revenue bits" that can be extracted from the network. A 100% efficient network will provide 1.25 Gbps of available throughput, while a 50% efficient network would provide only 622 Mbps of throughput and thus two systems would be required for the same network configuration or twice the cost of a system.

Efficiency Comparison

When comparing efficiencies of different PON protocols, four factors should be taken into consideration – line coding, PON TC or MAC layer efficiency, bearer protocol (ATM, Ethernet or GFP) efficiency and service adaptation efficiency. It should be noted here that, when analyzing APON efficiency, the protocol assumptions for APON at 622 Mbps have been taken and extended for 1.25 Gbps, as the standard only reaches a 622 Mbps bit rate.

Table 1 summarizes the various factors in PON protocol efficiency analysis.

	Line Coding	PON TC Layer Efficiency	Bearer Protocol Efficiency	Service Adaptation	
				T1	FE
APON	100%	96%	90%	98%	80%
EPON	80%	98%	97%	72%	63%
GPON	100%	99%	100%	96%	94%

Table 1 – PON Protocols Efficiency Factors

Hot Topics

- *GPON provides exceptionally higher efficiency*
- *This higher efficiency is provided at no extra cost, while EPON systems require additional adaptation equipment for TDM (VoIP)*

The Ethernet efficiency factor has been calculated assuming Ethernet packet size distribution according to collected data (56.3% 64 byte packets, 28.1% 512 byte packets, 15.6% 1518 byte packets). Amazingly, EPON is the least efficient protocol even when dealing solely with Ethernet services, due to the high tax as a result of the lack of fragmentation between consecutive frames.

Table 2 summarizes the overall PON efficiency for the different protocols, including all four factors for two different scenarios of TDM/data distribution.

	Overall Efficiency 10% TDM, 90% Data	Overall Efficiency 20% TDM, 80% Data
APON	71%	72%
EPON	49%	49%
GPON	93%	94%

Table 2 – Overall PON Efficiency

It should be stressed that the above results are absolute worst case scenarios in terms of GPON, as the assumptions taken and the set of services including traffic distribution are all at their most conservative values.

System Performance

In order to analyze the overall effect of the PON protocol efficiency on system performance, operators within the FSAN group have issued a traffic model depicting several scenarios for PON deployment.

Hot Topics

- *Using traffic models defined by service providers GPON can be compared to other protocols.*
- *In all scenarios GPON offers much more available bandwidth, translated in turn to more revenues from the system.*

The traffic models cover all relevant parameters, including service distribution, latency requirements, number of ONTs over a PON, etc., and relates to different applications such as Fiber to the home (FTTH), Fiber to the business (FTTB) and others.

Figure 6 presents the additional bandwidth provided by GPON, compared to APON and EPON, for the different applications according to the FSAN traffic model. As can clearly be seen from the figure, GPON offers exceptionally higher bandwidth for the entire range of applications when compared to both APON and, especially, EPON.

Coupled with the fact that an EPON system has no mechanism for supporting TDM traffic and thus requires external adaptation equipment, an EPON solution is expected to be substantially higher in both absolute cost per system and even more in price per bit of data.

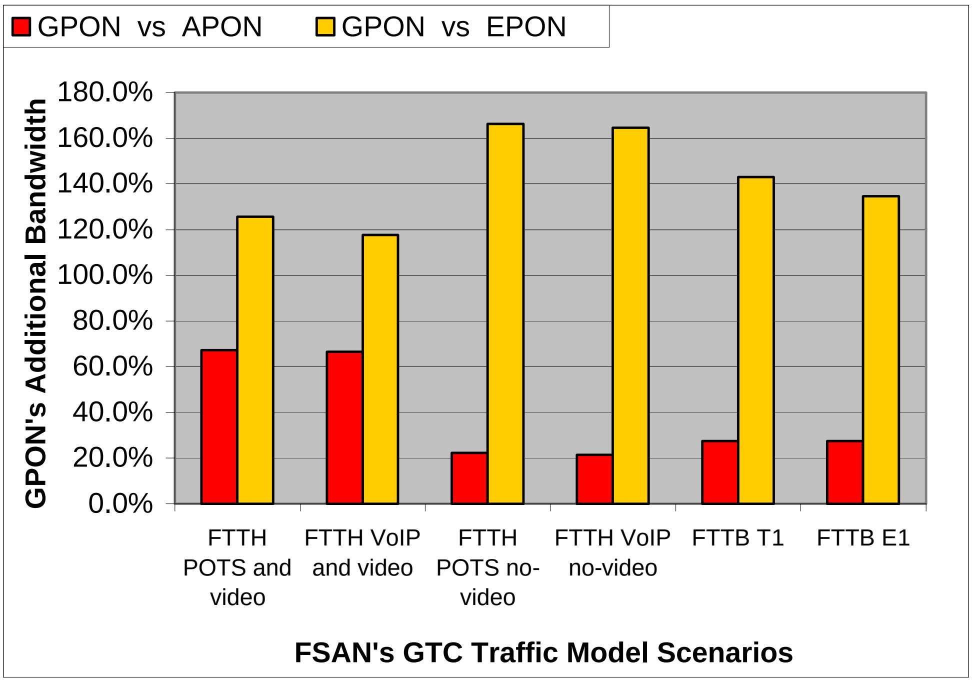

Figure 6 – Additional Bandwidth provided by GPON

Scalability in a Multi-Service Environment

Hot Topics

- *GPON offers not only higher efficiency but simplicity and scalability*
- *A clear migration path is offered for emerging services with no disruption to existing GPON equipment*

GPON not only provides substantially higher efficiency as a transport network, but also delivers simplicity and superb scalability for future expansion in supporting additional services.

As the access network is the closest layer within the network hierarchy to the end user, it is characterized by an abundance of protocols and services, starting with numerous TDM and data services today and expanding in the future to additional applications, such as Storage Area Networks (SANs), digital video etc.

GPON, through the GEM adaptation method, offers a clear migration path for adding these services onto the PON without disrupting existing equipment or altering the transport layer in any way. In contrast to both APON and EPON, which require a specific adaptation method for each service and, furthermore, require development of new methods for emerging services, the core foundation of GPON is GEM, which already covers adaptation schemes for any possible service.

Summary

- GPON is the most advanced PON protocol in the marketplace today, offering multiple-service support with the richest possible set of OAM&P features.
- GPON offers far higher efficiency when compared to both APON and, especially, EPON. Additional bandwidth offered over the same system ranges from 40% up to 160%, depending upon the specific application and supported services.
- GPON offers the lowest cost system for all modes of operation. Not only is the system cost itself expected to be lower as no external adaptation is required, but the exceptionally higher efficiency also leads to much more “revenue bits” from the same system, i.e. a much shorter payback period.
- GPON ensures simplicity and scalability when it comes to dealing with new and emerging services. A clear migration path is offered for emerging services without any disruption to existing GPON equipment or alterations to the transport layer.