A COMPARISON OF PON ARCHITECTURES

James O. "Jim" Farmer
Wave7 Optics, Inc.

Abstract

Several Passive Optical Network (PON) standards have been proposed as new architectures for delivering video, voice, and data to homes. PONs are being built in large numbers in Asia, and in increasing numbers in the Americas and Europe. Several cable operators are starting to deploy PONs in selected greenfield applications, typically in situations where required by the developer.

This paper shows the most popular forms of PONs in use today. We compare the performance of the PONs, and talk about how and when one may want to consider PON architectures.

WHAT IS A PON?

PONs, or *passive optical networks*, are just that: fiber optics all the way to the home, with only passive (non power-consuming) devices in the field. With no powered devices in the field, you save on power costs, and maintenance is much lower than with hybrid fiber-coax (HFC). Since the network is all glass (usually called "all dielectric"), you eliminate problems such as sheath current. Lightning issues are generally limited to anything that comes into the home over the power line and, through subscriber equipment, jumps to your equipment.

Figure 1 illustrates the basic PON. A single fiber optic strand extends from the headend to an optical splitter located near a group of homes. Outputs of the splitter supply optical signals to a group of homes. Signals are terminated on each home in a device called an *Optical Network Terminal* (ONT). In many cases the ONT is located on the outside of the home at the utility entrance. Alternate locations include inside the home and in a purpose-built niche in the outside wall.

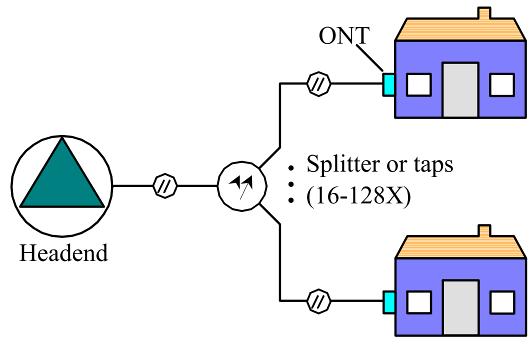

Figure 1. Basic PON

Frequently the splitting is done in a central location as shown. In other cases the splitting may be replaced by a tapped architecture more like that used in HFC architectures. The number of homes served by one PON is limited by the loss budget. While PONs are built with more or fewer subscribers, 32 subscribers is considered the "sweet spot" in PON sizing today. We show up to 128-way splitting, but the optics available today don't support this high a split ratio.

Done correctly, the advantages of PONs include much lower operational expenses, higher quality, elimination of leakage and the resultant measurement requirements, and incredible bandwidth. Data bandwidth of at least 1 Gb/s in each direction, shared over just 32 subscribers is the norm today. This bandwidth is delivered over separate wavelengths from that used for broadcast video, so the entire 54-1,000 MHz RF band is available for video.

TYPES OF PONS

We shall describe several types of PONs in this paper, including BPON (*Broadband Passive Optical Network*, approaching end-of-life), GPON (Gigabit Passive Optical Network), and GE-PON (*Gigabit Ethernet Passive Optical Network*). We shall mention a variant used in some places, called an *active optical network*. We'll also describe an emerging adaptation of an HFC network to extend fiber deeper. It is called RFoG (*Radio Frequency over Glass*), and is an option to consider when a developer requires fiber-to-the-home (FTTH).

GPON and GE-PON systems (and BPON) share a common physical layer architecture, with some differences in optical levels and speeds, so we will cover them together while discussing the physical layer. We'll compare them with the likely RFoG architecture. We say "likely" architecture because work on the RFoG standard has just started this year, and while there are some pre-standard systems entering the market, the standard system has not been defined. Thus, what is described herein is the author's conjecture of what the system may be.

PHYSICAL LEVEL ARCHITECTURE

Figure 2 illustrates the physical layer architecture of PONs. Figure 2a illustrates the BPON/GPON/GE-PON architecture, and Figure 2b illustrates a possible RFoG architecture. In each case, the headend comprises what headends usually comprise in the way of video, voice, and data equipment, except that in the standard PONs of Figure 2a, there is no CMTS – this will be explained later. Downstream RF signals are supplied to a downstream optical

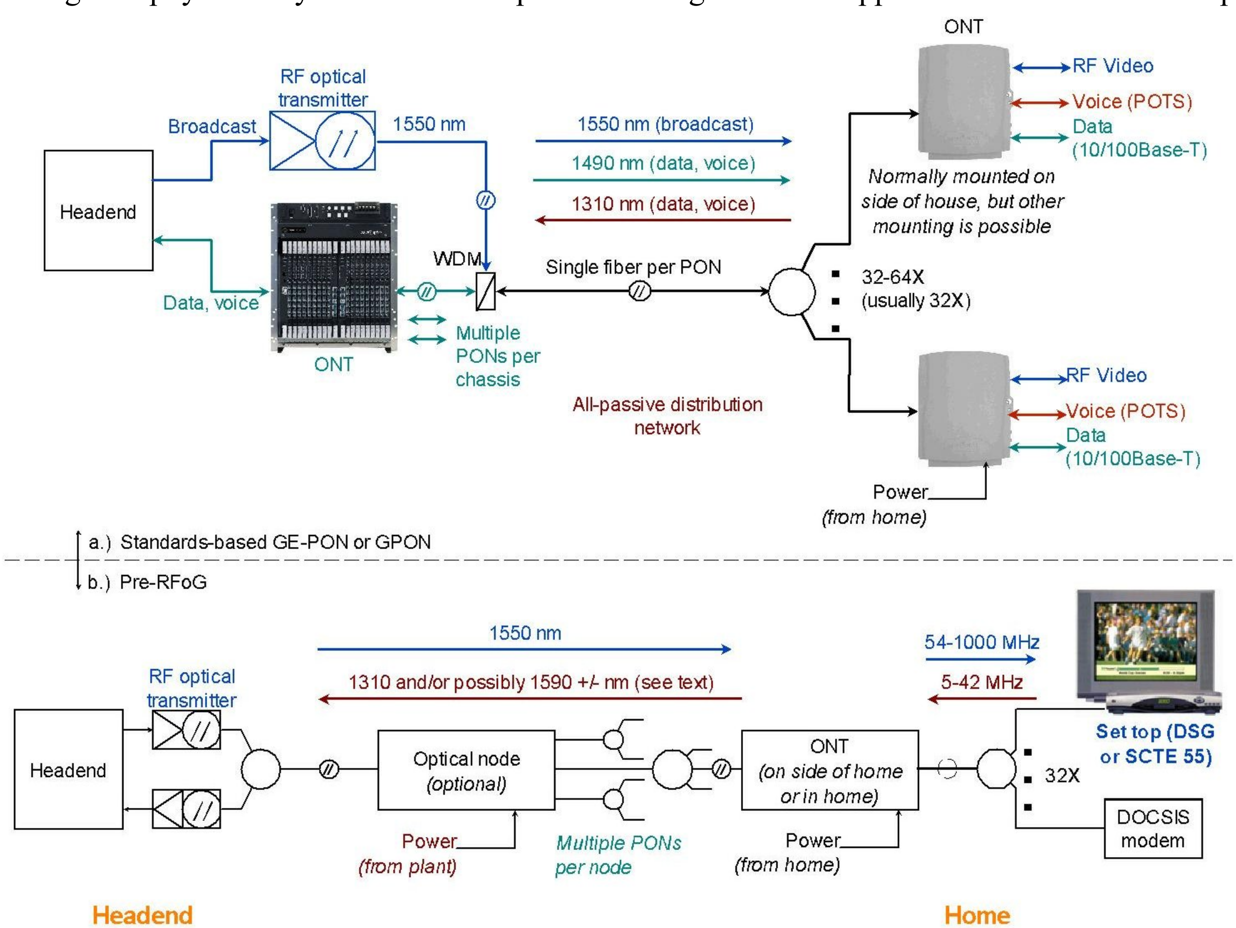

Figure 2. Physical Layer Architectures

transmitter, usually an externally-modulated transmitter and always at 1550 nm because amplification of the optical signal is needed. While you can amplify other wavelengths, amplification at 1550 nm is the most mature and economical process today. All of the standards use 1550 nm for downstream RF broadcast.

GPON/GE-PON

Unlike HFC networks, the network interface for data is not a CMTS – none is used – but rather is an analogous device called an *Optical Line Terminal*, or OLT. It serves the same function as the CMTS in that it converts data (usually delivered as gigabit Ethernet) into the format needed for PON transmission. That conversion includes conversion to the particular PON protocol being used, and conversion to light. The downstream signals are carried at 1490 nm and the upstream at 1310 nm. These are combined with the 1550 nm broadcast signal in a *wave division multiplexer*, or WDM. The WDM operates analogously to a diplex filter in the HFC world.

Typically, the OLT includes many PONs in one chassis, density being very important. There are some cases in which you may need a less-dense solution for outlying pockets of subscribers, and some manufacturers have accommodated this. While we show only one PON, typically many PONs feed into an area and all splitters may be located at a common point called a local convergence cabinet. We can show that this architecture, particularly in greenfields, results in a very economical deployment of equipment.

After splitting, individual fibers supply optical signals to the ONTs at individual homes. An ONT may have one RF output that looks just like the downstream signals from an HFC network, and it may have one or more data connections, usually 10/100Base-T and sometimes 1000Base-T. Also, several analog telephone lines (POTS – plain old telephone service) will be supplied. Other options are shown below.

RFoG

A possible RFoG system is shown in Figure 2b. The headend is identical to that of an HFC system, because RFoG is really an HFC node serving one subscriber. The downstream is again a 1550 nm transmitter, because you will need to amplify the optical signal. The upstream receiver is similar to that used in upstream paths today. The upstream may be analog or it may be digital; this has not been decided in the standardization effort as of this writing.

An optical node in the field is shown as optional. Of course, if used, the network is no longer completely passive. If used, the optical node will likely contain optical amplification in the downstream direction, and combining (in the optical and/or RF domains) in the upstream. Some proposals convert the upstream to digital.

Again, for RFoG we show a 32-way split, though in practice, some may elect to go with different split ratios. Optical budgets will lead to these answers, and as of this writing, optical budgets for RFoG have not been decided.

The RFoG upstream wavelength issue is interesting. One naturally gravitates to 1310 nm as an upstream wavelength, based on widespread availability of low-cost lasers and the zero-dispersion wavelength of standard cable. Since this is the nominal zero-dispersion wavelength of the fiber, it may be possible to use Fabry-Perot lasers, at least for shorter distances. On the other hand, there are applications in which you may want to have some GPON or GE-PON and some RFoG ONTs on the same network. For instance, you may want to serve some businesses with GPON and some nearby residences with RFoG. Or, you may someday want to upgrade from RFoG to GPON or GE-PON. Since GPON and GE-PON use 1310 nm for upstream data transmission, you cannot put RFoG with a 1310 nm upstream on the same PON.

These considerations would lead to a different wavelength choice for RFoG upstream signaling. 1590 nm is a candidate, but the next generation of GE-PON (and perhaps GPON) has already staked out this wavelength for faster upstream. Any other wavelength that can be passed through the fiber with low attenuation could be used, so the RFoG working group may choose some other wavelength. While the lasers might be more expensive at first, presumably with volume and competition the cost will drop. Of course, it is more likely that DFB lasers will have to be used since we are well away from the zero dispersion wavelength of the fiber.

THE ONT

Figure 3 illustrates the Optical Network Terminal (ONT) at the home. In Figure 3a we illustrate a fully-featured GE-PON or GPON ONT, and in Figure 3b we illustrate a possible RFoG ONT. In Figure 3a we show the optical input to the ONT coming from a 32-way splitter, common practice today. In Figure 3b we are showing a tapped architecture. While people deploying FTTH today tend to favor the splitter architecture, some in the cable TV community are leaning toward a tapped architecture.

Experience has shown that centralizing splitters from a common point within the network and dedicating fiber to each home in a star configuration provides the most cost effective deployment option. An additional benefit centralized splitters provides is the ability to scale OLT ports and splitters in accordance with sub-

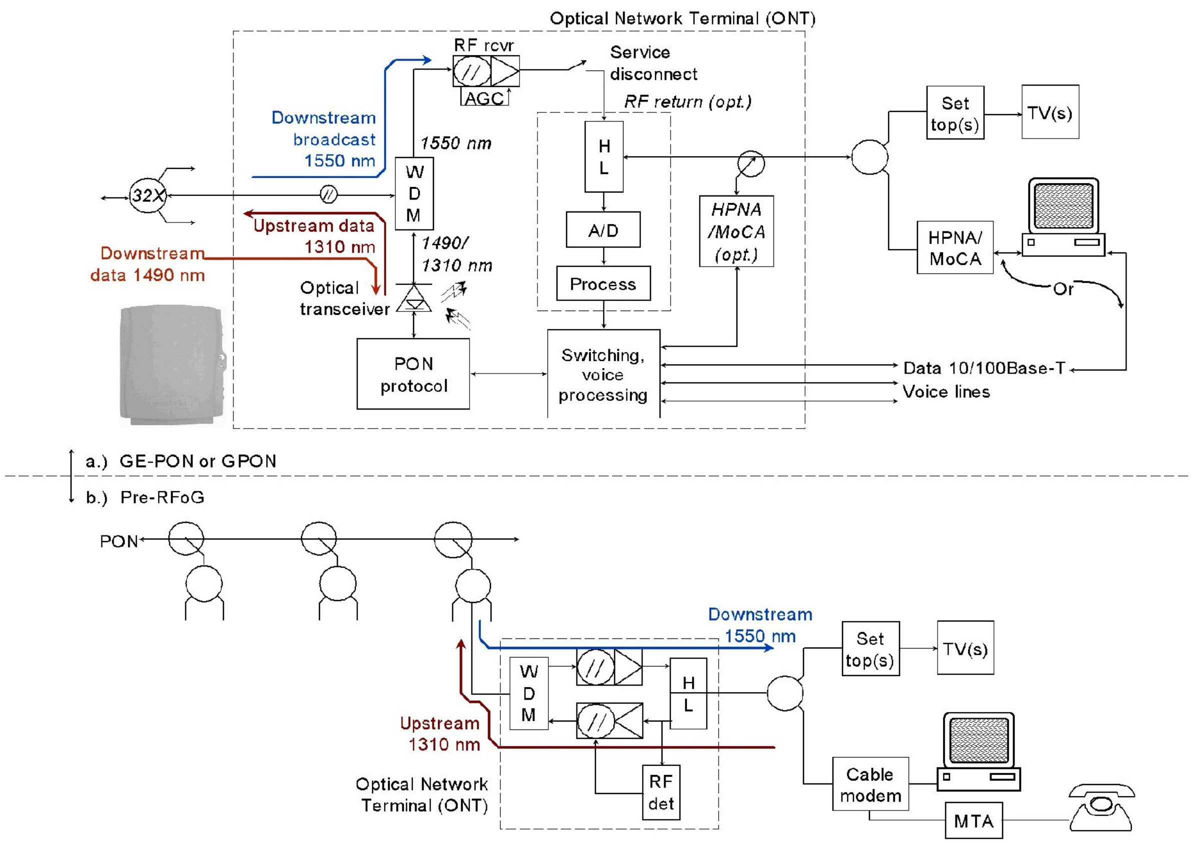

Figure 3. Optical Network Terminations

scriber penetration. In comparison a tapped topology necessitates provisioning the network for 100% of homes passed. A typical serving area for centralized splitters is 250 homes. Either topology will work.

GPON/GE-PON ONT

Figure 3a illustrates a fully-featured GPON or GE-PON ONT. These are three-wavelength systems. The broadcast downstream, 54 – 1,002 MHz, comes in on a 1550 nm carrier. A WDM in the front end of the ONT routes the wavelength to an RF receiver not unlike those in HFC nodes, except that it has been optimized for low cost. Since there are fewer sources of noise and distortion in FTTH plant compared with HFC plant, more contribution can be allocated to the ONT than to an HFC node.

This ONT was described in a paper by this author presented at the 2007 NCTA Convention,[i] so the detailed description will not be repeated here. We shall review enough detail to compare with the RFOG ONT of Figure 3b. The Figure 3a ONT includes a data transceiver interfacing with a PON protocol chip. This is an ASIC (*application-specific integrated circuit*) built by merchant silicon vendors for the appropriate PON standard. It can be thought of as roughly analogous to a DOCSIS modem. Processing on the output of the PON protocol chip converts the data into voice lines and data lines, as well as providing control to the ONT.

Typically, two or more voice lines are provided, with the internal processing supporting any of the common VoIP protocols in use today. Data is usually presented on 10/100Base-T ports, or sometimes on a 1000Base-T port. Many manufactures have a way to put data on coax in order to reduce the amount of wiring that must be done at a home. Two technologies dominate today: HPNA and MoCA. Some manufacturers use an external gateway to provide the data over coax solution, while others use an internal bridge as illustrated. This can be used for delivery of data to a computer or home network, or it can be used for delivery of IPTV (Internet Protocol Television). It can be used for both.

In greenfield applications, it is common practice today to include cat5 data wiring, so for greenfield applications, it may not be necessary to use data over coax at all.

The ONT includes an RF receiver for the 1550 nm broadcast wavelength. As shown, it includes circuitry to convert the upstream RF transmission from set tops to digital for transmission back to the headend. Other systems may use a separate analog transmitter for this function, or it may not be available.

RFoG ONT

Compare Figure 3a, a fully-featured GPON or GE-PON ONT, with Figure 3b, a stripped-down RFoG ONT. Again, we don't know yet what standard RFoG ONTs will have in them, so we start with the simplest possible solution and we'll discuss possible upgrades.

As with the GPON/GE-PON OLT, the fiber is connected to a WDM, which separates the downstream RF on a 1550 nm carrier, from the upstream RF (not data) signal on whatever wavelength is chosen. The downstream receiver could be identical to that in Figure 3a.

A diplexer separates the downstream from the upstream RF signals. Inside the home, RF wiring is exactly as it is for HFC, including the use of a cable modem and, for voice, an MTA, either embedded in the cable modem or separate as shown here.

The RFoG upstream transmitter presents an interesting situation. Analogous to the way upstream RF signals are combined, the upstream optical signals from many transmitters will be combined before being detected in a common receiver. If we allowed the upstream transmitters to be on all the time, we would have unacceptable interference at the upstream receiver. Thus, each transmitter must be turned on only when something in the house, be it a set top or a cable modem, is transmitting. The RF detector of Figure 3b detects RF signals coming from the house and turns on the upstream transmitter, turning it off when the RF transmission ceases.

A concern is based on the fact that there could be two or more independent systems using the upstream path. The most common situation being a set top upstream transmitter and a DOCSIS upstream transmitter. There is no way to coordinate when the two disparate systems come on, so it is possible to have a set top in one home transmitting at the same time that a DOCSIS modem in another home is transmitting. If the two optical transmitters are close enough in wavelength, it is possible that they will interfere, resulting in neither transmission getting through. Retransmitting routines may mitigate this to an extent, but if a voice packet is affected, there will be a noticeable customer event.

Some people assume that the probability of the above situation is sufficiently small that the industry can live with it if the upstream wavelength utilized is 1310 nm and FP lasers are utilized. Others are not so sure. The assumption is that FP lasers utilize a wide wavelength spectrum with a variance between devices, and with 32 devices being combined statistically this would be ok. The center wavelengths of these devices tend to drift with temperature so determining the statistical frequency in which two or more wavelengths will overlap is rather unscientific. As set tops are used for more applications, it is likely that the percentage of time they transmit will go up, and we know that DOCSIS modems are transmitting a lot. A solution would be to use set tops using DOCSIS set top gateway (DSG), an internal modem, for their upstream. This would work, but restricts you on the set tops you can use. Due to cost, it is not likely that low-end set tops will use DSG.

Of course, the RFoG upstream optical transmitters will need to work with DOCSIS 3.0, which can have multiple upstream data channels in use at the same time. This adds to the performance required of the upstream optical transmitter. DOCSIS 3.0 is likely to work better with RFoG than with HFC because there are fewer sources of distortion, and the RF detector in the ONT will prevent noise funneling.

Since RFoG utilizes optical combining in the upstream direction the architecture will only support one upstream DOCSIS domain per serving group. The upstream bandwidth capacity is now limited by the capacity of a single DOCSIS domain rather than being frequency limited.

It is logical that the RFoG specification, when complete, will have a specification for the RF level threshold at which the transmitter is turned on. This threshold would logically be set as high as possible in order to improve immunity against noise generated in the house. It is desirable to force the highest possible upstream levels, because this puts operation as far above the noise level as possible.

<u>Possible Enhancements to the RFoG ONT</u>

We have shown a basic RFoG ONT in Figure 3b. Some have suggested putting a DOCSIS modem in the ONT. This is possible, but deviates from current cable TV practices. If the market likes the idea of outside ONTs, as are commonly used with GPON and GE-PON now, this would require a wider operating temperature range of the modem, again driving up cost.

An advantage of having some sort of communications in the ONT is that it would allow management of the ONT, something that is not possible with the simple configuration shown in Figure 3b. A DOCSIS modem in the ONT would allow two-way communication, permitting the ONT to report on it's health and environment, something that is standard with GPON and GE-PON. Lacking two-way communications, a one-way communications path would permit remote disconnect, a standard function of GPON and GE-PON ONTs. Of course, there would be no confirmation, but that may not be seen as too great a price to pay for reducing the cost of the ONT.

ACTIVE ETHERNET

Before we change the subject, we'll mention one non-PON FTTH architecture that is popular in certain places. This is variously called Active Ethernet or Point-to-Point (P2P) FTTH.

In an active Ethernet system, a switch is placed in the field close to a cluster of subscribers. An individual fiber is run from the switch to each home, as shown in Figure 4. The IEEE Ethernet standard has a section that standardizes this configuration. The speed on the fiber to the home can be either 100 Mb/s or 1 Gb/s. However, there is typically no speed advantage with active Ethernet, because the common fiber to the left of the remote Ethernet switch has limited bandwidth, depending on what the operator wants to provide.

Active Ethernet systems are difficult to provision with RF video, because the video would have to be WDM'ed into each individual subscriber's fiber. A few such systems have been built with a second fiber system for video, but for the most part, active Ethernet systems

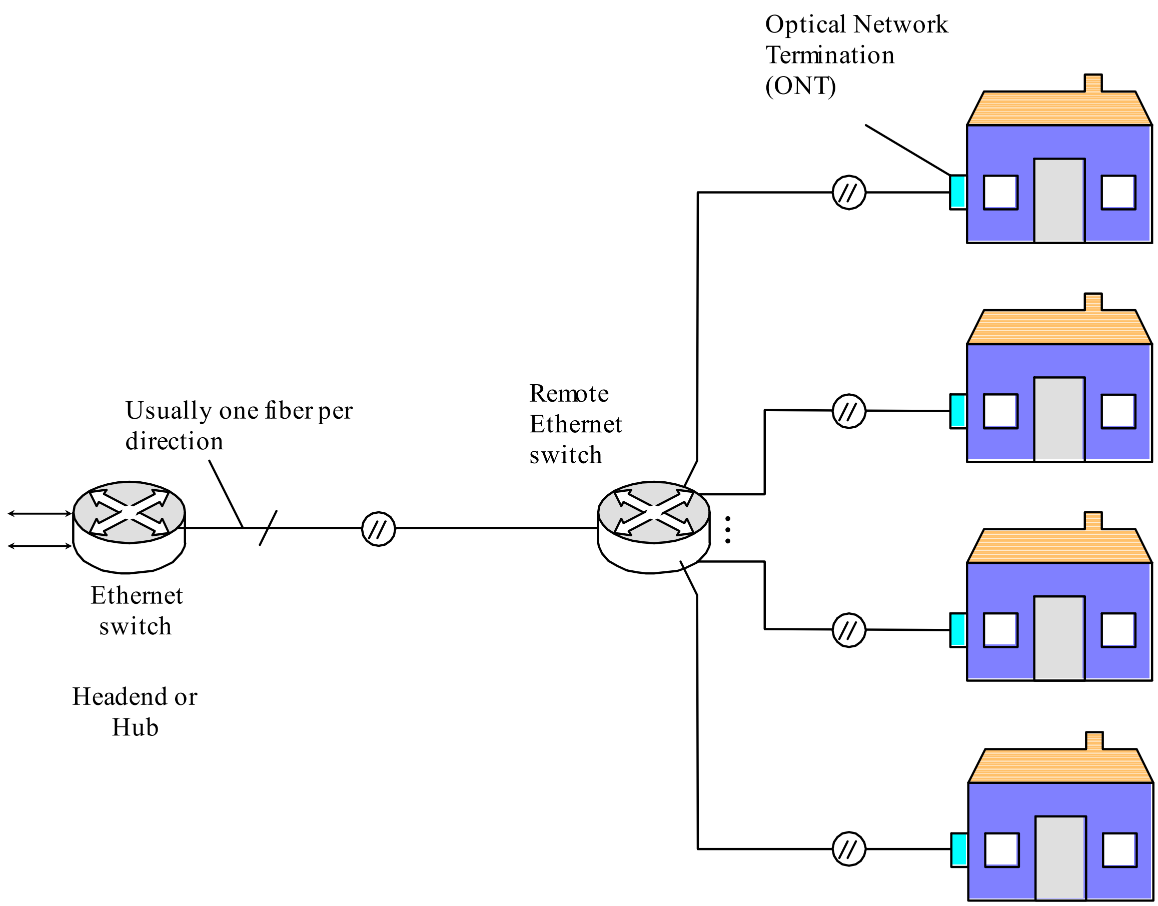

Figure 4. Active Ethernet FTTH System

carry only IPTV or no video at all.

ORGANIZING THE OPTIONS

We've talked a lot about the physical architectures of PONs. Now we need to try to make some sense of the various types of PONs, organizing them so we can understand what each does and where they fit with each other. Figure 5 diagrams the options under discussion. Starting on the right, we have the ongoing development of RFoG. This standardization effort is ongoing within the SCTE, in the fiber optics working group of the Interface Practices Subcommittee. It will be an option for cable operators to consider when required to install FTTH.

In the center of the figure is the IEEE effort, which has been incorporated into the Ethernet specification, managed by the IEEE 802.3 committee. The standard is referred to in this paper as GE-PON, but it is also known as EPON (*Ethernet Passive Optical Network*), 802.3ah (after the IEEE designation of the working group that developed it), or EFM (*Ethernet in the first mile* – someone wanted to emphasize that this applied close to the subscriber, so it was considered to be the first, rather than the last, mile). The active Ethernet architecture of Figure 4 is also a part of this standard, as is a version operating on twisted pair, at much lower data rates.

The specification was approved in 2004, and volume quantities of ASICs became available about 2006. GE-PON is very popular in Asia, which is currently leading the world in FTTH deployment, so most of the PONs in the world are GE-PON. It is also being used in North America and in Europe.

Currently GE-PON operates at 1 Gb/s in both directions. The wire speed, or speed on the fiber, is actually 1.25 Gb/s, but 8b/10b coding[ii]

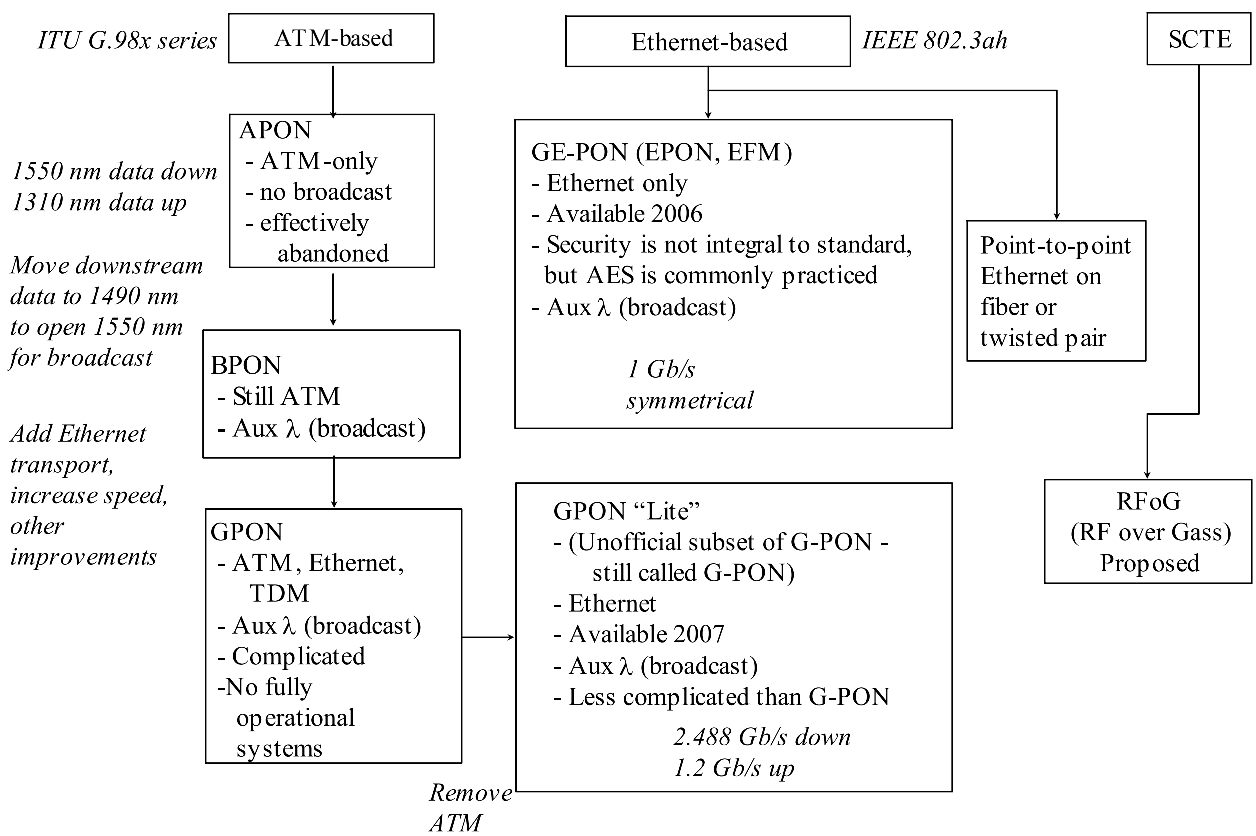

Figure 5. Comparison of PON Types

is used in order to ensure frequent transitions for clock recovery and other purposes, so the net speed is 1 Gb/s. The IEEE is currently working on a new version of the standard that will operate at 10 Gb/s downstream and either 1 Gb/s or 10 Gb/s upstream.

To the left in Figure 5 are the ITU standards. The first ITU standard, ca. 1995, was called APON for *ATM Passive Optical Network*. It used 1550 nm for downstream data and 1310 nm for upstream. It was replaced shortly by BPON (*Broadband PON*), which moved the downstream data to 1490 nm to make room for a broadcast overlay at 1550 nm. This is the version of PON that Verizon is currently deploying, though they have announced an eventual switch to the next standard in the ITU series, GPON (*Gigabit PON*).

GPON, ITU's G.984 series, was approved in parts, in 2003 and 2004. It started as a combined standard that would encompass ATM, Ethernet, and TDM (*time division multiplex*, in this context referring to DS-1 or E-1 transmissions). The standard is written to encompass all three layer 2 technologies. The problem was that implementing the complete standard was exceedingly complex. By the time people started considering implementing G.984, it had become clear that Ethernet was the choice technology for the last mile (or first mile if you use IEEE-speak).

Thus, the real implementation of GPON is based on the Ethernet portion of the standard, with the ATM portion not implemented. The author has called this "GPON Lite," but this is not an official designation – it is still known as GPON. The currently-favored version of GPON has a downstream wire speed of 2.488 Gb/s and an upstream speed of 1.2 Gb/s. It is specified to work with splits to 128 ways, but current optics don't support this many splits over any meaningful distance. The ITU's announced plan for future enhancement has been to use wave division multiplexing, where either each subscriber or a group of subscribers gets a different wavelength. However, this tends to be expensive, and there is some talk in the industry about revisiting the strategy.

Table 1. Comparison of PON Capabilities

Standard:	RFoG	GE-PON	GPON
Year standard available:	Not yet	2004	2004
Year of product general availability	Not yet (pre-standard now)	2006	2008
Field actives?	Optional	Exceptional cases	
Downstream wavelength	1550 nm	1550 nm (broadcast, optional), 1490 nm data	
Upstream wavelength	Probably 1310 nm and one longer wavelength	1310 nm (possibly going to 1590 nm in next generation)	
RF Bandwidth	54 – 1,002 MHz, depending on manufacturer		
Downstream data	DOCSIS	1 Gb/s (after removing 8b/10b)	2.488 Gb/s
Upstream bandwidth	DOCSIS	1 Gb/s (after removing 8b/10b)	1.2 Gb/s
Headend data interface	CMTS	OLT	
IPTV ready?	DOCSIS	Yes	
Service disconnect?	Not decided	Yes (depends on manufacturer)	
ONT management?	Not decided	Yes	
Upstream interference potential?	Maybe	No	

COMPARING THE PONS

Table 1 list comparative features of the PON technologies being discussed. We've listed the year that product started to be generally available to the marketplace, though there could have been limited deployments earlier. Usually, GE-PON and GPON are built strictly as passive networks, with all active equipment being restricted to the headend or hub. However, some manufacturers have made provisions for a smaller field-mounted OLT for several scenarios in which this configuration is optimum.

Everyone carries downstream broadcast on 1550 nm in order to provide for economical optical amplification, and because good optical transmitters are available for that wavelength. This is the only downstream wavelength in RFoG, but the other two standards carry all data (including voice) on a 1490 nm optical carrier. Thus, they don't loose any of the downstream RF band for data – you have up to 158 RF channels exclusively for analog and digital video. If you used them all with 256 QAM, you would have on the order of 6 Gb/s broadcast to all homes.

The upstream wavelength for GE-PON and GPON is currently 1310 nm for economy. There is talk in the industry of using 1590 nm for the next generation of GE-PON (and maybe for GPON, though this is conjecture). RFoG may provide an option of 1310 nm and something else, but this is not decided yet. The trick is to allow interoperability between RFoG and the other standards, while keeping cost low. Interoperability will allow you to deploy RFoG now, and migrate to something else later if you wish. Alternatively, you might deploy RFoG to residences, but need to serve a few businesses from the same PON, using either GE-PON or GPON. Obviously you cannot do this if you are using 1310 nm for the RFoG upstream and the other standard is using it for digital upstream.

Data is where we see the major differentiation between RFoG and the other standards. RFoG data uses DOCSIS for transport and is limited to DOCSIS speeds. At four channel DOCSIS 3.0 bonding, you have the potential for roughly 160 Mb/s of downstream data spread over, using common practice, 32 subscribers. This is an average data rate per subscriber of 5 Mb/s per subscriber, assuming one DOCSIS channel per node. Absent IPTV, this is a lot of data, because of the statistics of data sharing, a subject in which the cable TV industry has developed a lot of expertise. Yet it pales when comparing with the other two standards, which offer, respectively, average data rates per subscriber of 31.25 Mb/s and 77.5 Mb/s.

DOCSIS 3.0 upstream bonding should work better in RFoG than in HFC because of the lack of noise funneling, but the difference in upstream bandwidth is more dramatic than in the downstream direction. Developers demanding FTTH often employ telecommunications consultants who are familiar with GE-PON and GPON, and how they will react to a solution offering less bandwidth is not known yet. We are certainly talking about a lot of bandwidth with any of these PON solutions. Yet the history of data communications is that there has never been enough data bandwidth for long. With all the over-the-top video and peer-to-peer traffic today, it is not clear how long the old bandwidth sharing statistical models will hold true.

IPTV is certainly on everyone's mind today. Both GE-PON and GPON come ready to implement IPTV, and a fair number of users are doing so, some in North America, more overseas. While there are IPTV solutions designed for DOCSIS on the market, the case for putting IPTV over DOCSIS is not as clear as it is with other PON technologies – with DOCSIS/RFoG you still have the broadcast infrastructure, and switched digital video seems to have the potential for doing the same thing as IPTV, using more mature set top technology and likely minimizing overhead.

More and more subscribers are streaming IPTV from internet web sites as the amount of content available from major networks continues to increase. In essence your subscribers have already launched you into over-the-top IPTV distribution.

SO WHEN DO YOU CONSIDER FIBER?

We have not addressed the question of when a cable operator should build a PON. As we look at the competitive landscape, HFC is in much better shape than is DSL, so the urgency is not what it is for someone with twisted pair plant.

While cable is in better shape than it's competition, bandwidth demands always go up. Your competition is starting to build FTTH. A wise decision today is to build greenfield areas with your choice of fiber technologies, while continuing to operate HFC plant where it exists. Some developers are demanding FTTH because they have learned that it improves the salability of homes.

Conversion of HFC to fiber may make sense when contemplating upgrading old plant to higher bandwidths. This is particularly true when contemplating use of bandwidth above 1 GHz, where massive plant modifications are frequently required. But this conversion can be done only on an as-needed basis, in areas of high demand (and presumably high revenue).

If you start with RFoG and later convert to either GE-PON or GPON, you would need to convert an entire PON (normally 32 or fewer subscribers) at one time. Alternately, if you elected to use a non-interfering upstream wavelength in RFoG, with suitable headend modification and taking loss budgets into account, you could convert one customer at a time. You could also operate in mixed mode for an indefinite time. You will have DOCSIS on the downstream that is not used in the GE-PON or GPON area, but having the signal there will not hurt except for the four RF channels you loose for video (DOCSIS 3.0, four channel bonding).

CONCLUSION

FTTH systems are ready to be deployed now and may make sense for greenfield deployment. The widely-recognized standards are GE-PON and GPON, which are similar in capability from a user perspective, except for speed. If you are not ready to make that leap, you can derive some of the benefits of FTTH by deploying RFoG, though the standard is not complete yet.

Author contact: jim.farmer@w7optics.com

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