2

SYSTEM REQUIREMENTS

In this chapter:

- *Overview of power-splitting PONs*
- *Optical network considerations*
  - *Split ratio*
  - *Maximum reach, differential reach*
  - *PON protection*
- *Reach extenders*
- *Coexistence with future generations*
- *Types of ONU*
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Before diving into the details of how a G-PON works, we need to understand something about the business case. We return repeatedly to business case questions over the course of this book because, ultimately, everything we do must add value to someone for something.

Gigabit-capable Passive Optical Networks, First Edition. ~~David~~ Hood and Elmar Trojer.

As with most companies, telecommunications operators are driven forward by market opportunity, cost reduction, and competitive pressure, and they are held back by existing investment and existing practices. New technology is comparatively easy to justify in a greenfield development—we have to do *something*, so let us go for the latest and greatest!—but most of the potential market is already served in one way or another, even if it's no more than ADSL (asymmetric digital subscriber line) from a central office. The difficulty arises in making a business case for the deployment of a new technology that may be of immediate interest to only a small number of existing subscribers, in what is called, for contrast, a brownfield.

Civil works—right of way acquisition, permits, trenching for underground cable, poles for aerial cable—are a very large part of the up-front cost of a change in technology, for example, from copper to fiber. Estimates range from 65 to as much as 80% of the total cost. No matter how economical the equipment may be, this cost must be paid. Once the business case has been made to install new fiber in the outside plant infrastructure, it makes sense to place large fiber-count cables, or at least a lot of empty ducts, through which fiber can easily be blown at a later date. The cost of additional ~~ducts or~~ fibers is comparatively small, even vanishingly small, in fiber trunks. With the optical infrastructure in place and spare fibers available, it becomes much easier to take subsequent evolutionary steps.

It is easier to develop a business case if all telecommunications services can be provided by a single network. This is the idea behind the oft-heard term *convergence*, a concerted ~~movement~~ to eliminate parallel networks, each of which serves only a subset of the service mix. Software-defined features, Ethernet, and IP are major steps along the road to convergence. The contribution of standards and of the network equipment is to ensure that the investment, once made, can be used for a complete range of services for decades to come. In keeping with the full-service focus of its FSAN parent, G-PON is designed to deliver any telecommunications service that may be needed.

2.1 G-PON OPERATION

2.1.1 Physical Layer

To recapitulate the brief overview in Chapter 1, a PON in general, and a G-PON in particular, is built on a single-fiber optical network whose topology is a tree, as shown in Figure 2.1. The OLT is at the root, and some number of ONUs connect at the leaves. Downstream optical power from the OLT is split at the branching points of the tree. Each split allocates an equal fraction of the power to each branch. The achievable reach of a PON is a tradeoff of fiber loss against the division of power at the splitter. Chapter 3 describes splitters and fiber loss in detail.

A power splitter is symmetric: Its loss upstream is the same as down, 3 dB for each power of 2 ~~dB~~ in the split ratio.

The OLT transmits a continuous downstream signal that conveys timing, control, management, and payload to the ONUs. The OLT is master of the PON. Based on

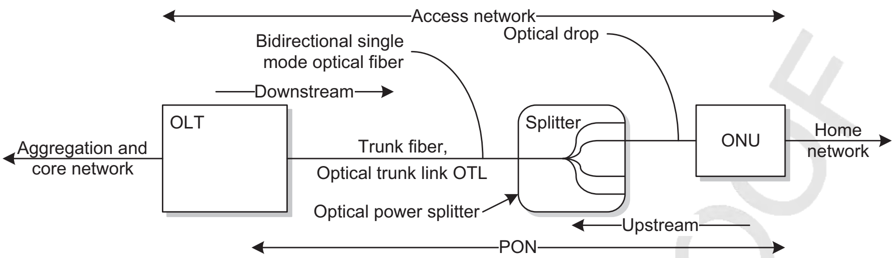


Figure 2.1 Tree structure of a PON.

service-level commitments and traffic offered by the ONUs, the OLT continuously develops an upstream capacity allocation plan for the near future—typically 1 or 2 ms—and transmits this so-called bandwidth map to the ONUs. The ONU is permitted to transmit only when explicitly given permission by a grant contained in a bandwidth map. During its allocated time, the ONU sends a burst of data upstream, data that includes control, management, and payload.

For the bursts to arrive at the OLT at precisely the proper interleaved times, each ONU must offset its notion of a zero reference transmission time by a value determined by its round-trip delay,* the time it takes for the signal from the OLT to reach the ONU, plus ONU processing delay and the time it takes for the signal from the ONU to reach the OLT. The OLT measures the round-trip delay of each ONU during ~~initialization~~ and programs the ONU with the compensating equalization delay value.

Another low-level requirement on a PON is the discovery of new ONUs, be they either newly installed devices or existing devices that have been offline for reasons such as fiber failure or absence of power, whether intentional or not. The OLT periodically broadcasts a discovery grant, which authorizes any ONU that is not yet ~~registered~~ on the PON to transmit its identity. Since the round-trip time of a new ONU is unknown, the OLT opens a quiet window, a discovery window, also called a ranging window, a time interval during which only ~~unregistered~~ ONUs are permitted to transmit.

It is possible that more than one ~~unregistered~~ ONU could attempt to ~~register~~ at the same time; if their transmissions overlapped in time, neither would succeed. Worse, they could deadlock, repeatedly colliding on every discovery grant forever. The ranging ~~protocol, therefore, specifies~~ that the ONU introduce a random delay in its response to the OLT's invitation. Even though the transmissions from two ONUs may collide during a given discovery cycle, they will sooner or later appear as distinct ~~registration~~ requests in some subsequent interval.

The size of the discovery window depends on the expected fiber distance between the farthest possible ONU and the nearest possible ONU. This is called maximum

* True, the correction could instead be applied locally by the OLT as an offset in the bandwidth map, but it is not.

differential reach, standardized with 10-, 20-, and 40-km options in G.984 G-PON. In G.987 XG-PON, the maximum differential reach options are 20 and 40 km.

Chapter 4 goes into detail on all of these aspects of G-PON operation.

2.1.2 Layer 2

In terms of the OSI seven-layer communications model,[*] the access network largely exists at layer 2. Perhaps the single most important concept underlying an Ethernet-based access network—which G-PON is—is that of the virtual local area network (VLAN), ~~described~~ in IEEE 802.1Q. A very substantial part of the hardware, software, and management of a G-PON is dedicated to classifying traffic into VLANs, then forwarding the traffic according to VLAN to the right place with the right quality of service (QoS). Although an ONU is modeled as an IEEE 802 MAC bridge, MAC addresses are usually less important at the ONU than are VLAN tags.

The access network operates at layer 2, but it judiciously includes some layer 3 functions as well, ~~especially~~ multicast management. For practical purposes, multicast means Internet protocol television ~~(IPTV~~) service; it is expected to represent a large fraction of the traffic and to yield a large part of the revenue derived from a G-PON. The PON architecture is ideally suited for multicast applications because a single copy of a multicast signal on the fiber can be intercepted by as many ONUs as need it. Each ONU extracts only the multicast groups (video channels) that are requested by its subscribers.

To determine which groups are requested at any given time, the ONU includes at least an ~~Internet group management protocol/multicast listener discovery (~~IGMP/MLD~~)~~[†] snoop function, about which we shall learn more in Chapter 6. Snooping involves monitoring transmissions from the subscriber's set-top box (STB), based on which the ONU compares the requested channels with a local access control list (ACL). If the requested content is authorized and is already available on the PON, the ONU delivers it immediately without further ado. Also acting as an IGMP/MLD snoop, or more likely as a proxy, the OLT likewise determines whether a given multicast group is already available, or whether it needs to be requested from yet a higher authority. As seen by a multicast router further up the hierarchy, a proxy aggregates a number of STBs into a single virtual STB, thereby avoiding unnecessary messages to the router and improving network scalability.

It is an open question what statistical capacity gain should be expected from multicast, now and in the future. Even if 80% of subscribers are watching the same 10 channels, a long statistical tail would require substantial capacity to carry content of interest only to the remaining few. Will a PON with 50 subscribers, each with 2 or more television sets and a recording device, need 50 multicast groups? Thirty? Twenty?

[*] See ITU-T X.200.

[†] Internet group management protocol (IPv4), multicast listener discovery (IPv6). We usually spell out acronyms the first time they appear; acronyms are also listed in a separate section at the end of the book.

There is a general expectation that video will move toward unicast, but no one is prepared to say how soon. At the end of the day, it may not matter. The considerations described above suggest that we should expect a busy hour load of two or three multicast groups per subscriber. At bit rates on the order of 5 Mb/s per multicast group, G-PON has enough downstream capacity for that level of loading. If it were to materialize, mass market demand for ultrahigh unicast video, up to 65 Mb/s per channel, could motivate further access network upgrade.

2.2 ONU TYPES

A variety of product configurations seeks to fit the range of operators' needs completely and optimally. Here we outline a few of the possibilities.

2.2.1 Single-Family ONU

At least in some markets, the single-family unit (SFU) is the most common form of ONU. Predictably, there are many variations on the SFU theme. The SFU may be located indoors or out. Power is always supplied by the subscriber, but the SFU may or may not include battery backup. The SFU may be regarded as a part of the telecommunications network, owned and managed by the operator, or it may be considered to be customer premises equipment, owned by the subscriber.

The simplest SFU, such as the one illustrated in Figure 2.2 with its cover off, delivers one Ethernet drop; it is essentially a G-PON-to-Ethernet conversion device. This one is intended to be mounted on a wall, at the demarcation point between the drop fiber and the subscriber's home network. The single Ethernet feed would then

Figure 2.2 Single-family ONU with power brick.

Figure 2.3 SFU with enhanced functionality.

be connected to a residential gateway (RG) at some location convenient to the subscriber's device layout.

Many SFUs, such as the one in Figure 2.3, add value by including several bridged Ethernet drops, suitable for direct connection to several subscriber devices, for example, two or three PCs and a set-top box. Some may also include built-in terminations for one or two POTS lines. Other applications for home use might include low-rate telemetry, for example, to read utility meters or to monitor intrusion detectors. M2M (machine to machine) communications are expected to mushroom over the next few years, and the SFU will surely play a part in backhauling information to centralized servers.

The SFU may also include a full residential gateway, with firewall, network address ~~translator (NAT~~) router, dynamic host configuration protocol ~~(DHCP~~) server, 802.11 wireless access, USB ports, storage or print server, and more. This form of SFU is typically managed jointly ~~directly~~ by the subscriber, by the ONU management and control interface (OMCI, G.988) model of G-PON, and by an access control server (ACS) as defined in various Broadband Forum technical reports and frequently short-handed as TR-69.*

2.2.2 Multi-Dwelling Unit ONU

The multiple dwelling unit (MDU) is an ONU that serves a number of residential subscribers. It may be deployed in an apartment building, a condominium complex, or at the curbside. The MDU is always considered to be part of the telecommunications network; that is, its power, management, and maintenance are the responsibility of the operator. Depending on their target markets, MDUs typically serve from 8 to 24 subscribers. Very similar to the MDU, a G-PON-fed digital subscriber line ~~(DSL)~~ access multiplexer (DSLAM) may serve as many as 48 or even 96 subscribers.

Subscriber drops from an MDU may be Ethernet, but the IEEE 802.3 physical layer is not specified to tolerate the stress of a full outdoor environment, specifically lightning transients. Even if the MDU is housed in the same building as the

* BBF designates it TR-069. It is always pronounced without the zero, and we like to write it in the same way we say it.

subscriber residences, it may be uneconomical to rewire the building with the cat-5 cable needed for Ethernet.

The alternative subscriber drop technology is DSL. When drops are short, the preferred form of DSL is ITU-T G.993.2 VDSL2; such an MDU may or may not also offer POTS. Existing telephone-grade twisted pair runs from the MDU to the subscriber premises, where there is a DSL modem and a splitter for POTS, if POTS is included in the service. With the short drops implied by fiber to the curb, it is feasible to deliver several tens of megabits per second—even 100 Mb/s and more—effectively overcoming the speed limitations of copper wiring. The rate-reach maximum can be extended through bonding of services across two or more pairs, while G.993.5 vectoring potentially increases attainable speed through crosstalk cancellation.

2.2.3 Small-Business-Unit ONU

As well as the ubiquitous Ethernet service, a small business unit (SBU) is likely to offer several POTS lines to a small-office customer. It may also support ~~one or two~~ TDM services such as DS1 or E1 via pseudowire emulation (Chapter 6 explains this). The SBU of Figure 2.4 has eight POTS lines, four Ethernet drops, and four 2.048-Mb/s E1 TDM services.

The cellular backhaul unit (CBU) is a variation of the SBU—perhaps a new category in its own right. In the cellular backhaul application, the ONU carries traffic between the core network and a radio base station. Legacy mobile backhaul requires interfaces such as DS1 or E1. As the cell network migrates from third to fourth generation, Ethernet backhaul is displacing DS1 and E1. As well as the tightly controlled frequency stability required of all TDM services, some wireless protocols require a precise time of day reference.

Another variation of the SBU is the multitenant unit (MTU), intended to be shared by several small businesses. The target market is the small islands of commercial activity common along major streets. The important distinction of the MTU from the SBU is its need to isolate services one from another, both in terms of traffic—no bridging between Ethernet ports—and in terms of service-level agreements (SLAs).

Figure 2.4 An SBU.

Figure 2.5 Outdoor ONU, outer access cover open.

2.3 NETWORK CONSIDERATIONS

While some operators favor the ~~customer premises equipment (~~CPE~~)~~ model, in which the ONU is indoors, located on the subscriber's desktop or perhaps mounted on an indoor wall, other operators wish to deploy ONUs outdoors. To a considerable extent, this reflects a difference in the operator's perspective: ONU as part of the telecommunications network or ONU as subscriber device~~, as CPE~~. Figure 2.5 illustrates such an outdoor ONU, which differs from the device of Figure 2.2 in that it provides two POTS lines, as well as an Ethernet drop, and is accessible to operator personnel without the need to enter the subscriber's home.

ONUs such as MDUs may go into equipment rooms or telecommunications closets in buildings. ONUs may also be designed for curbside pedestals (Fig. 2.6) or other outdoor housings, in which case they need to be fully hardened for outside plant conditions. ONU components must generally be rated for the full industrial temperature range, and ONU enclosures may be required to tolerate extremes of temperature and water exposure, including immersion (Fig. 2.7) and salt fog. Other considerations for outdoor ONUs include lightning protection for all metallic wiring, and insect and fungus resistance. All ONUs must satisfy regulatory requirements for electromagnetic interference (EMI) generation and operator requirements for EMI tolerance.

2.3.1 Power

ONU powering is indisputably a network consideration, but it warrants a separate discussion in its own right. We defer this topic to Section 2.5.

Figure 2.6 Chassis ONU.

2.3.2 Energy Conservation

Reducing the demand for power is an important topic. Power, especially remote power, is difficult and expensive to provide, and heat dissipation is a problem, especially in outdoor deployments subject to high ambient temperatures or direct sunlight.

The natural progress of technology is toward less power consumption for a given function. This is true not only in the silicon of the G-PON ONU itself, but perhaps more importantly, in the efficiency of the alternating current ~~(AC~~) power converter and the backup battery and its charger.

Not least because it is politically correct, the operator community is interested in saving additional power by shutting down functions when they are not in use. This follows the fine tradition of POTS telephony, in which an on-hook line consumes no power.

Inactive user network interfaces (UNIs) are comparatively easy to power down, but the PON interface presents difficulties: ~~If~~ its PON receiver is powered down, how does the ONU know when a terminating call arrives? And if the ONU's transmitter is shut down, how does the OLT know that the ONU has not failed? The answer is to take only very brief naps, a few tens or perhaps a few hundreds of milliseconds at a time.

Figure 2.7 Underground ONUs.

ITU-T supplement 45 to the G-PON recommendations outlines the energy-saving options, but the topic came to full maturity only in XG-PON. XG-PON defines two energy conservation modes, dozing and sleeping. In doze mode, the ONU keeps its receiver alive at all times. This is especially appropriate for one particular use case, IPTV, in which almost all of the traffic flows downstream. In contrast, sleep mode allows the ONU to shut down both transmitter and receiver. Both modes require the ONU to respond periodically, so that the OLT can confirm that the ONU is still alive and healthy, and to serve whatever traffic that may arrive.

Section 4.5 explores the energy conservation feature in detail.

2.3.3 Plug and Play

MDU ONUs are installed on engineering work orders and are maintained as telecoms equipment. While it is, of course, important that installation and provisioning be no more complex than necessary, it would never be expected that an arbitrary hitherto unknown and unexpected MDU might suddenly appear on the PON, with features and capacities only to be discovered after the fact.

At the other extreme is the desktop ONU. Some operators would like such an ONU to be purchased by the subscriber at the local electronics store and installed by simply plugging it in. The business aspects of installation can be dealt with: ~~The~~ subscriber calls the provider or browses to an introductory web page, signs up for service, provides billing details, receives some kind of license or login credentials, ~~possibly~~ implicit, whereupon everything just comes up and works.

More of an issue for the do-it-yourself subscriber is the physical installation. Although PON optics are rated to be eye safe, it is not really a good idea to leave optical fiber terminations exposed, launching even their small amount of invisible light in whatever random direction they lie. Not only that, but a single speck of dust in an optical connector can render the ONU nonfunctional; cleaning connectors requires tools and training beyond the level of the average subscriber. Because of the optical concerns, it may be that, even when the ONU becomes a commodity item, the operator will roll a truck to install it.

That said, we mention that the ONU of Figure 2.2 is intended to be installed just above floor level, with the optical connector facing down, minimizing concern about dust in the connector. The wall-mount unit and the optoelectronics module, suitably equipped with dust caps, can be uncovered and plugged together within a matter of seconds. So there may indeed be cases in which an ONU can effectively be installed or replaced directly by the subscriber.

2.3.4 How Far?

G-PON parameters specify a maximum reach of 60 km of fiber, with a maximum differential reach that defaults to 20 km~~—that is, the difference in fiber length between the nearest and the farthest ONU on a given PON~~.

Figure 2.8 illustrates what we mean by reach and differential reach. The reach is the total fiber distance from the OLT to the farthest ONU, in this case 30 km. Differential reach is the difference in fiber distance between the farthest and the

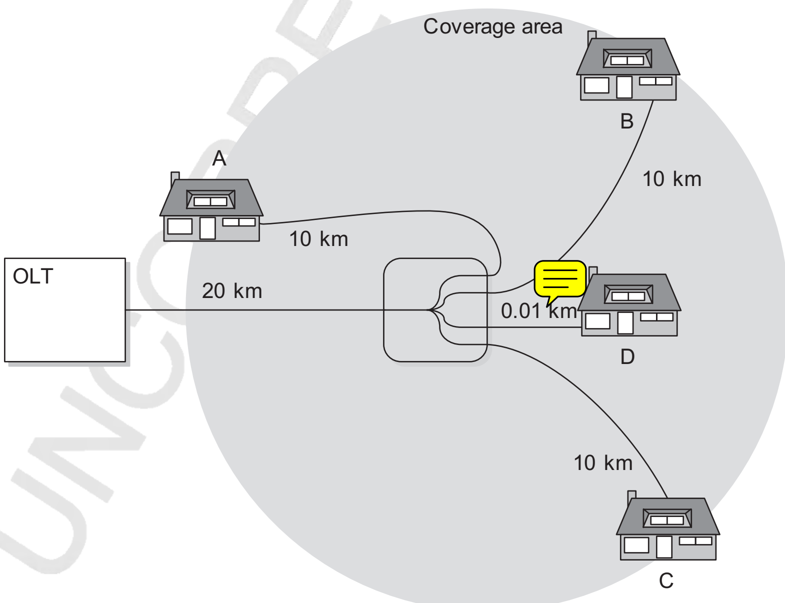


Figure 2.8 Reach and differential reach.

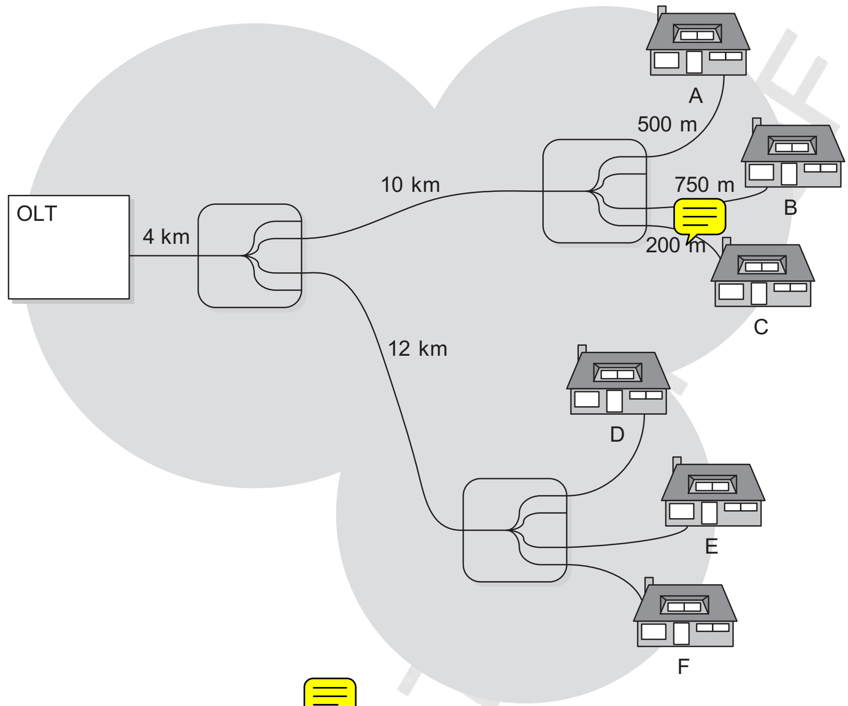


Figure 2.9 Multistage split.

nearest ONU. If our PON included only subscribers A, B, and C, the differential reach would be zero because each is 30 km from the OLT, measured along the fiber run. Add subscriber D to the PON, and the differential reach becomes 10 km.

It would be perverse to run the trunk fiber 20 km to a splitter, and then run a drop fiber back 10 km to subscriber A. In geographically spread-out locations such as imagined here, it often makes sense to deploy a cascade of splitters, as illustrated in Figure 2.9.

The first splitter usually has a lower split ratio, typically ~~1 : 4~~. The shape of the serving area can be tailored by the locations of the splitters.

Reach and differential reach are primarily issues of upstream burst timing, which can be addressed by varying the OLT's delays and quiet intervals. But greater reach, or a larger split ratio, also imply greater optical loss.

The need to go further with more splits made it natural to define G-PON reach extenders (REs). In its simplest form, an RE is simply an optical amplifier or an electrical regenerator in each direction. More sophisticated REs may extend a number of PONs, with the OLT (trunk) side either using a separate fiber for each PON or separate wavelengths on a single fiber. A multi-PON RE is also a likely candidate for trunk-side protection. Sections 2.4, 3.12, and 5.3 discuss reach extenders in more detail.

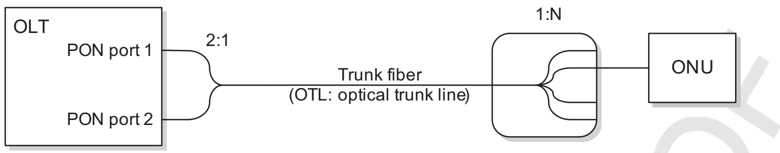


Figure 2.10 OLT port protection.

2.3.5 PON Protection

G-PON protocols do not directly support protection of the nature defined in classical transmission protocols such as SDH—linear or ring protection, for example, with or without bidirectional signaling—but several forms of PON protection are possible. ~~G.984.2 and G.987.2 describe G-PON protection, but as yet, details such as the message exchanges to coordinate protection switching have not fallen within the scope of standardization.~~

Figure 2.10 illustrates the simplest port protection.

~~In Figure 2.10, the~~ trunk fiber is connected to the OLT with a colocated ~~2 :~~ 1 splitter, at the cost of an additional 3 dB of loss. Both OLT ports receive the upstream signal, but only one port transmits at any given time. The OLT triggers protection switching if one of its ports fails or is unplugged, or if it declares loss of signal from all ONUs. The ONUs themselves do not know about PON protection. Depending on the OLT's architecture, fast switching is possible, less than the classical target of 50 ms. Depending on the OLT's architecture, it may be necessary to reinitialize or rerange the ONUs after a switch.

OLT port protection covers failures at the OLT itself but does not address issues such as cable cuts in the outside plant. Lack of protection against cable cuts is not necessarily a show stopper because cables in the access network are usually not routed diversely anyway. If a backhoe cuts one cable, it probably also cuts whatever redundant fiber might have been present in an adjacent cable. This is one reason why some operators are considering stationary wireless links for PON protection.

As shown in Figure 2.11, we can readily protect against cable cuts of the trunk fiber by using a ~~2 : N~~ splitter at the remote site. This layout also recovers 3 dB of optical budget that was lost in Figure 2.10. The ONUs cannot tell the difference between the feeders of Figures 2.10 and 2.11. As to the OLT, because the trunk cables are presumably routed diversely (else why protect them?), this protection design requires redetermination of the ONUs' equalization delays after a protection switch,

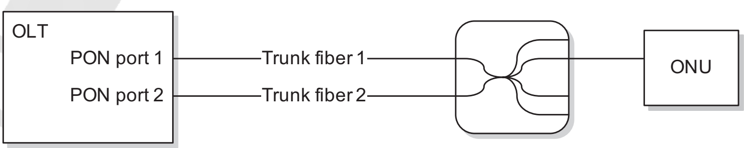


Figure 2.11 Trunk fiber protection.

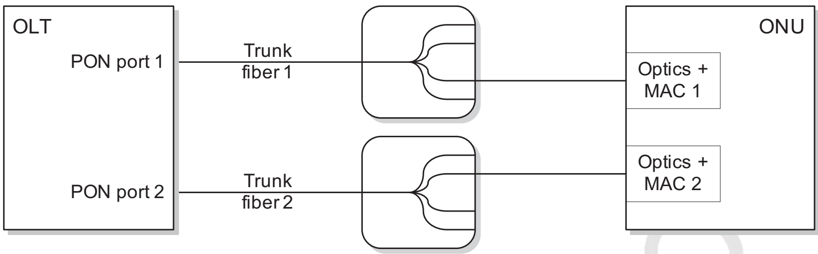


Figure 2.12 Complete redundancy.

although only the trunk delay differs. ~~G.987~~ XG-PON include~~s~~ the ability for the OLT to minimize recovery time by retiming a single ONU, deriving a correction factor, and broadcasting it to all ONUs.

PON protection may be generalized to use ports on separate OLTs, thereby protecting against complete OLT failure. Further, the separate OLTs may be located in separate central offices, providing at least some degree of protection from large-scale disasters. Dual homing, as this is called, raises additional issues in coordinating ~~both the provisioning~~ and the real-time switch-over between working and protect PONs.

In Figures 2.10 and 2.11, the ONUs need not know anything about PON protection. Figure 2.12 illustrates an ONU designed for protection, with two optical interfaces. It is possible for such an ONU to have only a single PON MAC (medium access control) device, but if we are going to pay for two optics modules, it could make sense to include two MAC interfaces, with the ability to carry traffic on both PONs at the same time, either duplicate traffic or extra traffic of low priority that could be dropped in the event of a switch.

Another possible merit of Figure 2.12 is that only some, but not all, ONUs need be protected, for example, those serving business customers, large MDUs, DSLAMs, or mobile base stations. Figure 2.12 follows the classical precedent of SDH, a core network technology that generally justifies higher costs. Because of high development cost for a low-volume product, the market for dual MAC ONUs has not yet developed.

There are other ways to do protection, specifically Ethernet link aggregation (originally in IEEE 802.3ad, now in 802.1AX). Figure 2.13 illustrates how individual ONUs may be protected on an end-to-end basis, end-to-end from the layer 2 viewpoint, at least. In this configuration, the ONUs, PONs, and OLTs need know nothing about protection. Standards and equipment already exist, avoiding the need for the PON subnetwork to reinvent the wheel.

2.3.6 How Many?

If we wish to dedicate a 50-Mb/s average downstream data rate to each subscriber, a 2.5-Gb/s G-PON can serve about 50 subscribers; a 10-Gb/s XG-PON about 200.

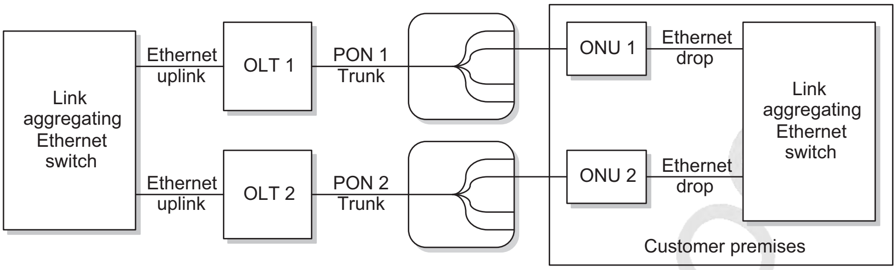


Figure 2.13 Link aggregation protection.

Some operators would like to serve 500 subscribers per PON; others would like to be able to deliver 100 Mb/s to each subscriber. Of course, multicast and bursty traffic patterns mean that these numbers are fairly arbitrary, but they do provide some indication of the capacity available.

When a PON is equipped with MDUs, it may be cost-effective to connect only 16 ONUs, or even fewer. For single-family ONUs, common planning numbers are 32–64 ONUs per PON. Although there is clearly a point of diminishing returns, operators find it economical to pay for higher split ratios, rather than installing additional fibers and OLT blades. Some operators talk about 128-way splits and even more. In the discussions leading up to XG-PON, a PON with 256 ONUs was the largest number anyone could imagine—but understanding how imagination works, the community allocated 10 bits to the ONU-ID, so that in theory, 1023* ONUs could be connected to an XG-PON.

The optical loss budget ranges from 28 dB (G-PON class B+) or 29 dB (XG-PON1 class N1), right up to 35 dB (XG-PON1 extended class E2). The standards put the options into the OLT as much as possible. Limiting the number of ONU types recognizes the fact that the ONU is the point at which high-volume components matter, and where the operator's inventory and logistics costs make a big difference. The OLT is also likely to support plug-in optics, while for cost reasons, the ONU is more likely to have integral optics.

Keep in mind that each ~~1 : 2~~ split costs something over 3 dB, so a 10-deep splitter ($2^{10} = 1024$ ONUs) would pretty well use up the most aggressive optical budget, all by itself. Having said that, nothing prevents the development of a reach extender that could indeed support, say eight 128-way splitters from a single PON. Nothing, that is, but the operators' understandable reluctance to deploy powered and managed equipment deep in the field.

2.3.7 Coexistence

Although G-PON will have a long service life, the nature of progress is such that someday, G-PON will be superseded by technologies that better satisfy evolution in demand, in services, in technology, and in revenue. How will we someday replace

* The 1024th address is used for ONU discovery, described in Chapter 4.

G-PON with the next generation? It is safe to assume that the next generation, whatever it may be, will be based on single-mode optical fiber, to or near the subscribers' premises.

The easiest answer would be to install a new optical distribution network in parallel with the existing one, and when all is said and done, this may well be the least-bad solution at some point. But particularly in residential areas—beyond the first of several possible splitters in tandem—this may be difficult. There is no guarantee that there will be spare fibers or ducts in existing distribution cable, and laying new cable is very expensive. Nor is it feasible to visit 32 or 64 or 128 subscriber premises simultaneously to replace their ONUs.

Indeed, the most complicated factor in the evolution story is that only a few subscribers will need to be upgraded anyway—G-PON ONUs are expected to satisfy the needs of most users for many years to come—and it is ~~very difficult~~ to justify a large new investment for only that first pioneering upgrade subscriber, especially when the take rate may be quite modest for many years to come.

It ~~is, therefore, required~~ that G.984 G-PON and next-generation G.987 XG-PON coexist on the same ODN indefinitely, and further, that upgrade not disrupt existing services more than momentarily—zero disruption is the target. Coexistence is achieved through compatible wavelength plans and optical budgets, as discussed further in Chapter 3.

Beyond G.987 XG-PON, the technology options are open. Further migration is sure to be required on existing ODNs, coexisting with at least one of G.984 G-PON or G.987 XG-PON, and possibly both. ~~Wavelength division multiplexing (WDM)~~ PON is regarded as a prime candidate, but its parameters remain under discussion. Chapter 7 outlines some of the issues and options of WDM PON.

2.3.8 Unbundling

For business benefit or regulatory compliance, more than one company may be involved in delivering telecommunications services to the subscribers of a PON.

In the context of a G-PON, suppose that company A owns the local network of optical cables or fiber ducts. Physical layer unbundling occurs when company A leases duct space or dark fibers to company B. Generally, this means that the fiber terminates at a fiber distribution frame and is patched to some separate network element that is owned or controlled by company B. Repairs to ducts and cables are ~~typically~~ the responsibility of company A.

Wavelength unbundling occurs when company A or B[*] leases one or more of the wavelengths on the fiber to company C. Generally, this means that company A is responsible to provide a filter and to break out the contracted wavelengths to a fiber distribution frame for patching to separate network elements. The contract also binds all parties not to cause harmful mutual interference, for example, by transmitting excessive power levels. Physical repairs are the responsibility of company A.

[*] Henceforth we omit the subleasing possibilities and just assume that company A is the principal.

In physical and wavelength unbundling, the lessor is free to modulate the fiber with its choice of signal format, subject to contracted channel characteristics and interference constraints.

In layer 2 unbundling, company A lights up the fiber with its own protocol—G-PON, for example—and company D leases capacity within that protocol. Typical lease parameters would include VLAN IDs and service-level commitments. The fiber terminates in an OLT owned by company A, and the unbundled stream is switched at layer 2 into network elements owned by company D. Diagnosis and repair is largely the responsibility of company A.

All of these options are important in terms of the companies' operations and business practices, but duct and fiber unbundling do not affect G-PON. Wavelength unbundling only affects G-PON in the sense of assigning wavelengths. In terms of G-PON requirements, layer 2 unbundling may include requirements to groom traffic into separate bundles, even when the committed QoS of one bundle is identical to that of another, differing only by contractual relationship.

One particular higher layer unbundling feature is wholesale multicast service, in which company A may offer IPTV bundles from companies E, F, G, and so on. This option has implications in the complexity of multicast provisioning, inasmuch as a subscriber may mix and match from a menu of offerings, some of which may overlap. Multicast, and in particular multiprovider multicast, is discussed in Chapter 6.

2.3.9 Synchronization

It is rather taken for granted that a G-PON OLT is timed from a stratum-traceable source, with at least stratum 4[*] and usually stratum 3 or 3E holdover, and a frequency accuracy within four parts per billion. The G-PON itself is synchronous, so a PON-derived frequency reference at the ONU is also stratum traceable. A stratum-traceable frequency reference is important for services such as DS1/E1 circuit emulation. A ~~G-PON~~ OLT may derive its ~~primary~~ reference ~~input~~ from a building integrated timing supply (BITS), but if it is located in a controlled environment vault or a remote cabinet, the OLT may be timed via IEEE 1588.

As well as precise frequency, some radio protocols also require a precise time of day, preferably to be supplied by the mobile backhaul ONU. The underlying reason is that these technologies share spectrum on a time-divided basis among several devices. If separately located transmitters are to know when they are allowed to use the spectrum, they need an accurate time reference. One-microsecond accuracy was provisionally specified for G-PON, in the absence of a better value. As the community works through the standardization issues of next-generation radio systems, it appears that a G-PON system will be asked to reduce its allocation quite considerably, perhaps to as little as 100 ns. This accuracy is a question of hardware design, not a standards issue.

[*] See Alliance for Telecommunications Industry Solutions ~~(ATIS)~~ 0900101 [formerly American National Standards Institute ~~(ANSI)~~ T1.101] for definitions of timing strata.

Time of day is not available from a frequency reference. Time of day can be conveyed via Internet Engineering Task Force ~~(IETF~~) network time protocol [NTP, request for comment ~~(RFC~~) 5905] or simple NTP (SNTP, RFC 2030). Time of day is also available from global positioning system ~~(GPS~~) receivers, which are regarded as too expensive to be desirable in every endpoint—nor can every endpoint rely on having a clear view of the sky. The favored candidate for ~~both frequency and~~ time distribution is ~~now~~ IEEE 1588.

The baseline assumption for packet timing is that delay through the network is (a) short, (b) symmetric, and (c) stable. None of these is necessarily true in a G-PON, where the upstream direction is delayed and subject to bandwidth allocation irregularities. Chapter 4 explains how the G-PON protocols include a way to transport time of day over the PON, using the PON ranging parameters for each given ONU. Transparent timing is also possible, in which the equipment merely records and forwards the transit delay of each given timing packet, a delay that can subsequently be used as a correction factor.

2.4 OLT VARIATIONS AND REACH EXTENDERS

The OLT is the interface between the PON and the telecommunications aggregation or core network. Conceptually, it is located in a central office, but in practice it may be located in a controlled environment vault (CEV) or an outdoor cabinet, as a way to extend the reach of the PON. Another way to extend reach is the so-called reach extender (RE; Fig. 2.14). Conceptually, a reach extender is just a repeater, either based on optical amplification or on electrical regeneration. The reach extender is usually located at the same site as the splitter; indeed the splitter may be integrated into the RE equipment itself.

Because a reach extender requires power, management, and possibly facility protection, it makes economic sense to extend several PONs with a single equipment unit. In this case, the reach extender may have one trunk fiber per PON, or may multiplex several PONs onto a single trunk fiber through WDM, either coarse (CWDM) or dense (DWDM).

2.4.1 Why Reach Extenders? The Business Case

In Payne, et al. (2006) British Telecom (BT) observes that the demand for bandwidth increases faster than can be supported by the combination of revenue growth—subscribers want more bandwidth but are not willing to pay very much for it—and the

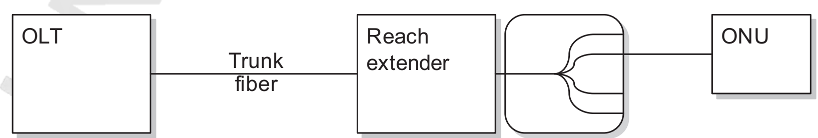


Figure 2.14 Reach extender.

normal year-over-year erosion of equipment cost. This makes it difficult to develop a business case that justifies investment for broadband access, be it G-PON or anything else. Some other economic factor must be folded into the analysis.

In the absence of a clearly visible killer app that will completely redefine the economics of telecommunications, operators look to cost reduction. The BT chapter in Payne et al. (2006) summarizes a study in which a number of best-case assumptions were made as a way to understand the best possible cost savings.

The study concluded that, ignoring the real-world issues, a dual-homed access network with a reach of 100 km could allow as few as ~~one~~ 100 well-chosen local exchanges (central offices) to cover the United Kingdom, replacing the 5000 that exist today. Exchange consolidation could represent a major cost savings.

In view of the real world, in particular the capabilities of G-PON:

- Substantial exchange consolidation is possible, even with only 20 km of reach. Twenty kilometers far exceeds the range achievable with the current exchange-fed copper infrastructure.
- G-PON's reach could be extended with C+ optics (explained in Chapter 3). Under this assumption, a very high percentage of the United Kingdom's population could be served with dual-homed G-PON.

It will not come as a surprise to learn that BT is very interested in extending the reach of G-PON in any way possible, or that BT continues to push for dual-homed redundancy.

If the optical network cannot be completely passive, BT would like to see the simplest possible reach extenders, ideally nothing more than optical amplifiers in footway enclosures. BT views this as a better choice than remote OLTs. As much as anything, this preference is a consequence of the increased power demanded by a remote OLT, deployed in an environment where every watt is precious.

In Edmon et al. (2006), SBC (now part of AT&T) considers somewhat the same problem in light of U.S. geography. They conclude that fiber to the home (G-PON) is the right solution for greenfield deployment. There is no question that new cable must be installed to serve new subdivisions, and it might as well be optical fiber. Greenfield developments are likely to be well away from the central city, so reach is an issue. Like most operators, AT&T has consistently pushed for increased optical budgets, just a few decibels more. Each decibel ~~widens~~ the circle that a central-office-based OLT can serve, and like BT, AT&T is keenly aware of the disproportionately higher cost of remote siting. These discussions have led to higher loss budget classes in both G-PON (32 dB C+) and XG-PON (extended classes up to 35 dB).

Edmon et al. (2006) also conclude that the right way to serve brownfield markets is through small remote DSLAMs. These DSLAMs would be sited close enough to the subscriber base that the necessary broadband services could be delivered over DSL copper. Although it could be done with G-PON, the fiber to the DSLAM is proposed to be point-to-point gigabit Ethernet (GbE).

Other operators found that, even without additional loss budget, a differential reach of 40 km, rather than the 20-km default, would assist in picking up isolated

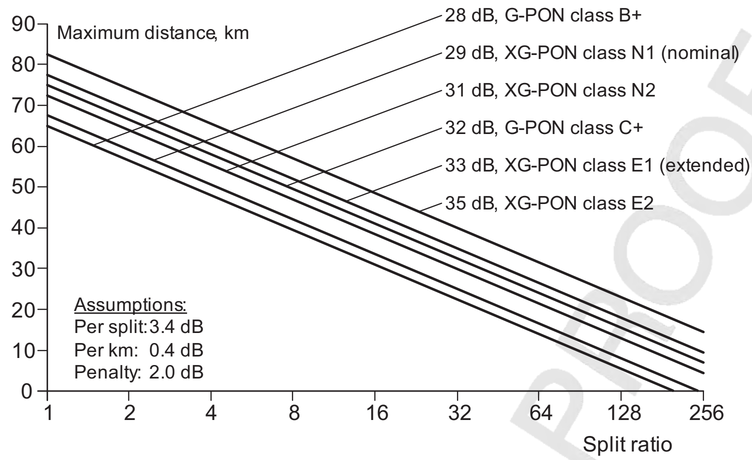


Figure 2.15 Reach–split ratio.

subscribers that would otherwise fall outside the footprint of any of the planned PONs in their territory.

Economic feasibility is a joint effort between subscribers' willingness to pay, between vendors' ability to reduce equipment costs, and between operators' ability to reduce operations costs. Longer reach and central office consolidation are a key aspect of the latter.

2.4.2 Demographics: Population Density

We have seen why operators want high split ratios and long reach, often both at the same time. Figure 2.15 illustrates the tradeoff between reach and split ratio for different ODN loss and power budgets. Chapter 3 goes into further detail.

Figure 2.15 is based on the assumptions shown.

- Per Split 3.4 dB. Each time we split* the flow of light, we send half the power down each side, a loss of 3 dB. That's in the theoretically ideal case. In practice, splitters lose a bit more than 3 dB in each split, nor is the division of power perfectly uniform. Splitter uniformity—specifically the branch that happens to have the greatest attenuation—affects the network design loss.
- Per kilometer 0.4 dB. Optical fiber absorbs energy, differing amounts of energy at differing wavelengths, as shown in Figure 2.16. The highest loss is at the 1270-nm upstream wavelength of XG-PON. Newer fiber technology may absorb even less energy than shown, although not by much. Some operators also budget a pro-rated allowance for splices by distance.

* The device is symmetric, so we also lose 3 dB each time we combine flows from two ONUs into a single upstream output.

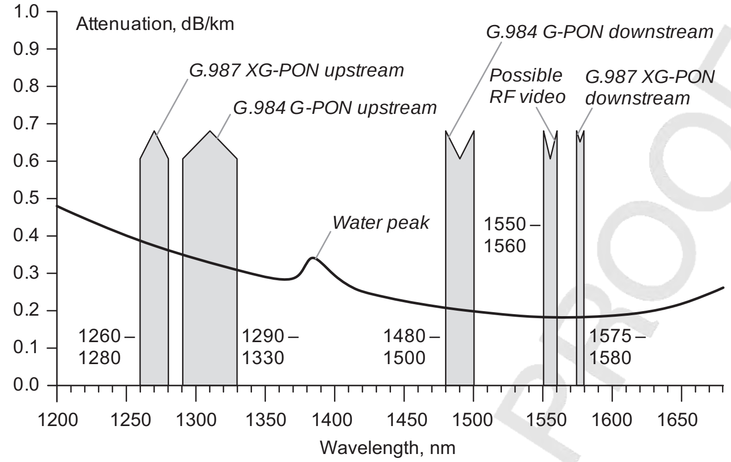


Figure 2.16 Loss vs. wavelength.

If the assumptions change, the results change. In particular, if the installed network is based on original G.652A fiber, the loss may be worse than shown. If an operator has reliable knowledge about the makeup of existing and new fiber plant yet to be installed, the planning margins necessary to determine the reach or split ratio of a proposed deployment can be reduced. Simply reducing the uncertainty could make the difference in determining whether a proposed project is feasible or not.

- Penalty 2 dB. Two factors contribute to this value: ~~The~~ recommendations specify an optical path penalty of 1 dB, which is essentially a catch-all for the multitude of little effects that prevent the link from operating at the level we would expect from just adding up the known impairments. A bit of extra margin is also good for unforeseeable contingencies. For example, if a wavelength splitter needs to be added into the PON to support future coexistence, it can use up an extra decibel all by itself.

As we see, the community has responded to the operators' need for decibels by standardizing budgets of as much as 7 dB more in XG-PON than the typical 28-dB budget of G.984 G-PON. Although it will be a challenge, and will certainly carry a price tag, component vendors believe that a 35-dB budget will be possible in XG-PON.

But Figure 2.15 demonstrates that, even with the best optics technology, an operator who wants a 128-way split at 60 km has a problem. Incremental gain from better fiber, increased optical launch power, and improved sensitivity of optical receivers are certainly worth having, but there are limits to this approach. Optical fiber is already very good. High launch power raises issues of eye safety and optical nonlinearity, while receiver sensitivity is ultimately limited by noise. So we need reach extenders.

Without a reach extender, the assumptions of Figure 2.15 tell us that a 32-dB class C+ G-PON loss budget is good for about 24 km with a 64-way split. If we can start

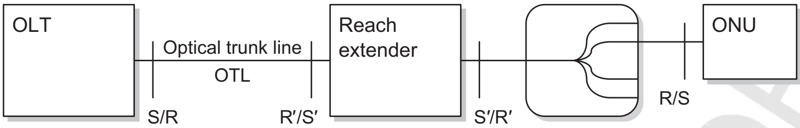


Figure 2.17 Reach extender notation.

the budget from a zero reference at a reach extender that cancels out the loss of the trunk fiber, that 24-km circle could be centered, for example, 36 km away from the OLT (to remain within the 60-km maximum logical reach).

A word about notation. For reasons clearly unrelated to human factors, the optical interface at the OLT is designated S/R, and its counterpart optical interface at the ONU as R/S. The proxy interfaces at the RE are designated S′/R′ and R′/S′, respectively (Fig. 2.17). And yes, we have to refer to the figures too because we can never remember which interface is where.

Q1

A reach extender may be based on electrical regeneration, with conversion between optical and electrical domains at its interfaces, the so-called optical–electrical–optical (OEO) architecture. It may also be based on optical amplifiers (OA architecture), or it may be a hybrid of both. Chapter 3 describes these options in detail.

Internal Split Multiplier As always, there are variations. In Figure 2.18, we see an RE with an internal split, either electrical or optical, into two separate regenerators or amplifiers. Each serves its own physical splitter, thereby doubling the number of subscribers that can be connected to the PON. Clearly, this approach can be extended to more than two splitters.

In the downstream direction, split multiplication is straightforward. In the upstream direction—at most one splitter can contribute upstream signal at any given time—care must be taken to prevent noise from the silent regenerator from corrupting the merged signal upstream. If the upstream process is optical amplification, this could be done with a squelch circuit, a circuit that enables its upstream output only when it detects the presence of light at its input. An equivalent function would be needed in an electrical regenerator to ensure that upstream receiver noise did not generate random bits toward the OLT.

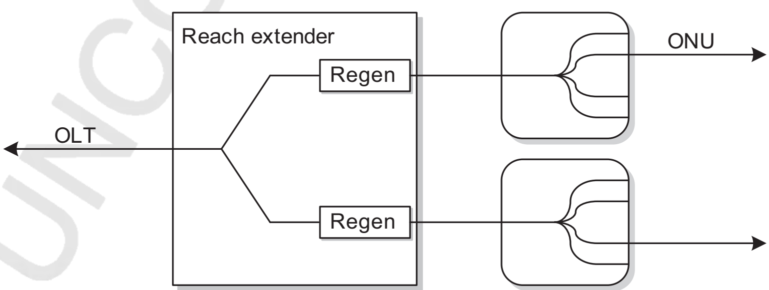


Figure 2.18 Split multiplication.

The split multiplier approach also enables one form of PON capacity upgrade. One or more of the splitters could in theory be relocated onto a new PON, effectively reducing the number of subscribers per PON and thereby increasing the capacity available for each. With or without a reach extender, this is known as PON stacking.

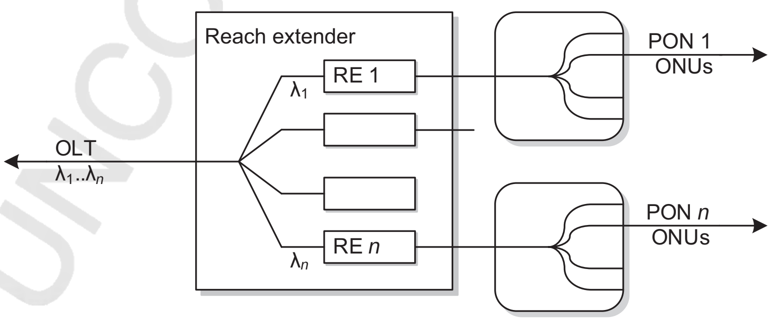
It remains to be seen whether PON stacking matches the economic realities of an upgrade, however. In practice, most subscribers will be adequately served by the existing PON, with a few randomly distributed subscribers who ~~demand~~ more capacity. Simply halving the split ratio for everyone on the PON may not be the best approach, especially if ONU drops are attached to the splitter through splices rather than connectors, so that they are not easily rearranged.

Extending Multiple PONs What other variations make sense? At the reach extender site, we have already paid for power, a protected environment, and management access. It is easier to amortize that cost if we can extend several PONs from the same RE equipment. This works especially well if we are serving a village or a small town that might need several PONs to provide complete coverage. So we expect to see composite REs containing 4–12 simple REs in parallel. Another economy, at least in terms of operational complexity, is that ~~all of the colocated extended PONs can be managed through~~ a single management agent.

WDM Trunking But 4–12 parallel REs imply 4–12 trunk fibers, and we are, after all, in the WDM business. Why not a single trunk fiber, with 4–12 wavelengths? Such modest numbers of wavelengths can be inexpensively served with CWDM.

Wavelength conversion is not impossible in the optical domain, but a wavelength-converting reach extender is probably better designed as an OEO equipment. Wavelength conversion is, of course, also necessary at the OLT. We save fibers, but at added equipment cost and complexity.

Protection Single PONs, especially those serving residential areas, may or may not justify protection–the threshold that justifies protection typically lies in the range of 24–64 subscribers. Aside from the individual ONU, the most likely failures are OLT blade or port failures, power outages, and fiber cuts due to construction,



Q2

Figure 2.19 Wavelength-converting composite RE.

accidents, or severe weather. In many of these cases, the cost of protection would exceed the marginal benefit.

But by the time we have half a dozen PONs served by the same equipment, there is enough traffic, generating enough revenue, that protection may be justified. This would be protection between the OLT and the reach extender, which could utilize most of the same concepts described above in Section 2.3.5.

OLT Considerations The G-PON recommendations allow for ~~15~~ dB of dynamic range between adjacent bursts. That is, if we take a given burst as a reference, the next burst could have a power level as much as ~~15~~ dB higher—or lower—subject, of course, to the maximum and minimum levels allowed for received power.

When an RE is based on OEO technology, the upstream signal on the OTL has zero dynamic range. An OA reach extender may also compress or eliminate the OTL upstream dynamic range.

Similar considerations apply to timing. Although an optical amplifier preserves the timing of the upstream signal, an OEO regenerator naturally locks onto the downstream clock—G-PON is synchronous, after all—and retimes upstream signals so that they all have the same bit phase.

Retiming does indeed introduce uncertainty in the ONUs' apparent round trip delay, but this turns out not to be a problem. The retiming uncertainty in an RE is bounded by one bit time, and as described in Chapter 4, delay need only be measured or monitored within eight bit times.[*]

What does this change in dynamic range and signal phase mean to the OLT? The presence of an RE could allow the OLT upstream receiver to be substantially less sophisticated and, therefore, less costly. But unless REs took over a large fraction of the market, developing custom RE optics would simply not be worthwhile.

This is not to say that an RE implies no consequences at the OLT. An important difference between a simple PON and a reach-extended PON is that of optical maintenance. For example:

- ONU and OLT optics are often capable of measuring their received power levels; when the ODN includes a reach extender, these measurements represent RE performance, not that of the termination equipment. OLT and ONU ~~performance~~ are measurements made by the RE itself. The OLT or element management system (EMS) software must know where to go to find performance information, and how to interpret it.
- The signature of a rogue ONU differs (Section 2.6.3), depending on whether it is behind an RE or connected directly to the OLT.
- Optical time domain reflectometry (OTDR) is a tool to measure faults in optical networks. But an OTDR at the central office cannot see the ODN beyond a reach extender.

[*] The RE must not perform byte alignment!

Transport Protocol on Trunk Fiber Our OEO reach extender is now generating a continuous signal upstream on the PON, possibly phase aligned, with interburst gaps possibly filled with padding bits, and with zero dynamic range. We always had a continuous signal downstream on the PON. Why not map the PON signal into the client layer of some suitable transport protocol for backhaul? If we are prepared to do the ranging in the reach extender instead of the ONU, we could use OTN (optical transport network) for backhaul, or even plain old GbE or 10GE. These options could bring carrier-grade protection and operations, administration, and maintenance (OAM) to the optical trunk fiber.

If the subscriber side of an RE is the G-PON part and the network side is a client mapping into a transport protocol, what PON-specific functions remain for the OLT? We could just locate a small OLT at the RE site and be done with it. And, in fact, that is where we started. Do REs make sense? Maybe, but a healthy RE market had not developed at the time of writing. Low demand discourages vendors, and remote powering discourages operators.

2.5 ONU POWERING

In the legacy copper network, the twisted pair delivers power for POTS, and in most venues, it is very reliable. Even when commercial power fails, the telephone works. Indeed, the ability to make emergency calls is likely to be especially important at such times.

With the move toward mobile telephony, backup power is becoming an option, rather than a necessity. But still today, when POTS is provided from a central office, or even from a field site such as a CEV (Fig. 2.20), reliable power is part of the service offering.

There is no twisted copper pair in an SFU deployment, so power for an SFU becomes the subscriber's responsibility. The ONU is furnished with an AC power converter unit, at least a brick (Fig. 2.2), but often including a so-called uninterruptable power supply (UPS; Fig. 2.21), which not only converts AC power to direct current ~~(DC)~~ but also contains a backup battery to keep the ONU alive during power outages. ~~Four-to-eight~~ hours of battery reserve for lifeline POTS is a typical requirement.

Those who have to start their cars in cold climates know that batteries lose capacity in cold environments. By the same principle, UPS units for ONUs are rated for installation at least in a garage or carport in moderate climates, fully indoors where winters are severe.

How long can the power cable be, from the UPS to the ONU itself? Most residential UPS units are rated at 12 V, and cable length is limited by the wire size. The well-equipped telephone installer will have indoor drop wire and possibly Ethernet cat-5 or cat-6 cable, but will not stock heavy-gauge power wire.

The ordinary twisted pair used for telephone sets—probably what the operator will use for in-house ONU power wiring as well—is typically 24 American wire

Figure 2.20 Above-ground part of a controlled environment vault.

gauge ~~(AWG~~)* (maybe 26 gauge), with a resistance of about 25.7 Ω per thousand feet at room temperature, 20°C. That is the resistance in one direction; in a twisted pair, the total resistance is twice that.

If the power supply delivers 12 V and the ONU consumes 6 W —just to use easy numbers that also happen to be in the right range—the current is 570 mA, and 50 ft of AWG 26 wire drops about 1.5 V.

Now suppose the ONU has an undervoltage shutdown at 10.5 V. If we start at 12.6 V, a typical storage battery output level, and lose 1.5 V in the wiring, we are left with 0.6 V of margin. When commercial power fails, the battery voltage gradually decreases. The lifetime of the ONU ~~on battery~~ is the time it takes for the battery voltage to sag by 0.6 V.

The minimum operating voltage of the ONU depends on its design, but we can see that power wiring should be kept as short as possible. If the wiring were to drop only 1 V, for example, instead of 1.5 V, we would have 1.1 V of discharge lifetime, almost twice as much.

The other question about a backup battery in the subscriber's home is that of battery maintenance. Backup batteries have a lifetime of only 2 years or so, 3 at most.

* The reader outside North America may find the following wire gauge conversion chart convenient:

AWG	mm^2
26	0.13
24	0.20
22	0.33

Figure 2.21 Uninterruptable power supply.

The general public has indisputably become more technologically savvy in recent years, but it is unduly optimistic to expect all subscribers to monitor and replace their own backup batteries. If the operator undertakes the task, it represents a continuing operational expense, not to mention periodically annoying subscribers by having to arrange a premises visit to replace the backup battery. This is all workable, but it is not without its problems. Q3

When the ONU serves multiple subscribers, as in an MDU, the operator must see to the powering arrangements.

- It may be possible for the operator to negotiate reverse powering, back down the subscribers' copper drops. This option is receiving increasing attention, as the simplest technical solution and perhaps not impossibly burdensome from a contractual point of view.
- In an apartment building, the MDU may reside in a utility equipment room, with AC power directly available. Space may even be available for backup batteries.
- AC power is rarely available at a curbside MDU. Even if AC power were available, backup battery technology is not currently economical for small loads—the MDU is limited by the feasible deployment environments to a maximum of perhaps 16 subscribers—in a full outside plant environment.

Therefore, power for curbside ONUs is often delivered over twisted copper pairs from a rectifier plant, which resides in a central office or in a CEV. Even if they are in cabinets (Fig. 2.22), these installations include environmental conditioning, backup battery plant, and often a ~~diesel~~ emergency generator.

In the real world, it is often the case that MDU power feeds must use existing cables, which may have very few spare pairs. The ultimate irony is having to install new copper cables to deliver power to an optical network unit!

Figure 2.22 Centralized power plant.

Power

Most telecommunications equipment is powered from −48-V battery plant. The reason for the negative voltage is to avoid electrolytic corrosion of outside plant conductors whose insulation may have pinhole leaks into damp environments. The reason it is called a battery plant is that there are lead-acid storage batteries in most installations, providing nonstop continuous power. When commercial power is available, the rectifiers normally float the nominal −48 V battery supply at around −53 to −56 V. The display at the far left of Figure 2.23 reads (−)53.4 V.

In some places around the world, −60 V battery plant is used. This is becoming less common as time goes on.

International safety standards (60950: the number is the same whether it is UL, IEC, EN, CSA, AS/NZS, . . .) define several classes of electrical circuit. Within the constraints of practical telecommunications wiring, the limit of voltage to ground is 200 V DC, and no conductor pair is permitted to deliver more than 100 VA (watts). Unbalanced current in the loop, which indicates a ground fault, is also strictly limited.

For the same reason as illustrated in our 12-V example above, it is desirable to use higher voltages, and therefore lower currents, with lower resistive voltage drops, when equipment is powered remotely. A common voltage for remote power is −130 V. In recent years, −190 V power sources have come into use, as a way to push the voltage as high as permitted, given manufacturing and lifetime tolerances. By going positive with respect to ground, +190-V circuits can also be used, creating the potential for ~~380-V~~ at the source end.

Figure 2.23 Rectifier units.

Figure 2.24 illustrates a simple circuit in which we have a remote power source delivering voltage V_S, connected to a resistive load R_L. The power feed is a twisted pair, each of whose legs has resistance $R_f/2$ (so the total feeder resistance is R_f).

Figure 2.25 illustrates the well-known fact of impedance matching that maximum power is delivered to the load if $R_L = R_f$. At the maximum power point, half the power is dissipated in R_f, and half of the original source voltage V_S is dropped across R_f. It is only 50% efficient, but it is nevertheless the maximum power transfer point. Higher efficiency is possible if we ask for less power.

In a purely resistive circuit such as that of Figure 2.24, we can operate anywhere on the graph of Figure 2.25, extending to 0 and 100%. On either side of center, we get less power to the load, but there are no surprises. So what is this caption in the picture about a Not OK Region?

Electronic circuits such as ONUs do not consume power as resistive loads. They are best thought of as constant power devices. If the voltage across their input

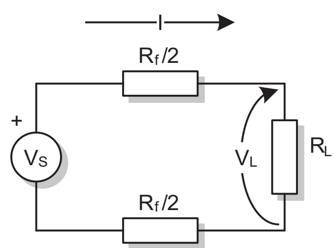


Figure 2.24 Simple Ohm's law circuit.

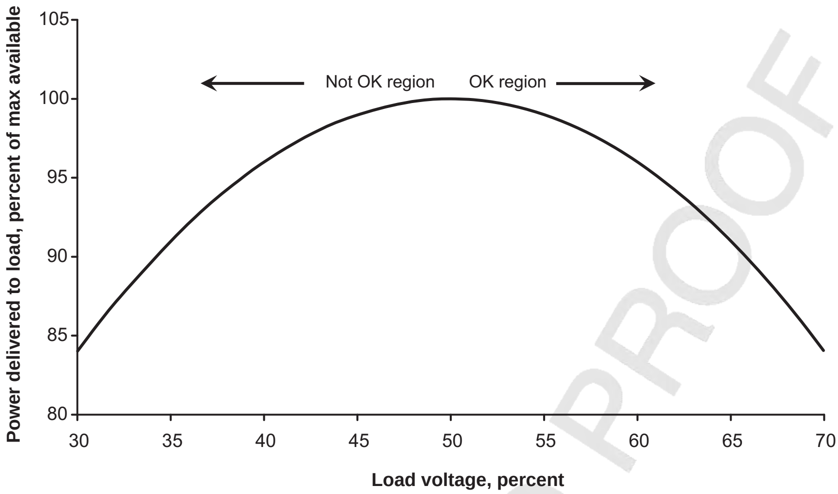


Figure 2.25 Power available at load, as a function of V_L.

terminals decreases, they demand additional current. For practical purposes, the ONU's power demand, $P_L = V_L I$, is constant.

That is fine if the ONU does not ask for too much power, say dropping 60% of the voltage across itself. But if the ONU were to try for 101% of the available power, it would not get it. Not only would it not get the power, but it would crash. That is the Not OK ~~Region.~~

We beg your indulgence for a whimsical analogy (Fig. 2.26). Suppose it is a pleasant winter's day in the Sierra Nevada, and we are hiking to the top of one of its

Figure 2.26 Sierra Nevada, California.

innumerable domes. On the south side, where we are, the sun has evaporated the ice and dried the surface; on the north side, we stipulate that the rock is covered with sheet ice.

Life is good as long as we stay on the south side of the peak. But, well, let us just say it is a bad idea to take even one small step across the crest to the north side. (The first ~~one who~~ correctly ~~identifies~~ this formation, wins a prize!)

Getting back to serious business: ~~If~~ the ONU ever steps onto the north side of the dome, its voltage will be a bit less than it wants. Being a constant power device, the ONU asks for more current to compensate for its voltage being too low. The drop across the feeder resistance increases, the voltage available to the ONU falls even further, the ONU tries for even more current, and gets even less voltage. Unless the ONU is designed to back off in a hurry, it crashes.

If the ONU's power demand is not a function of its software state, the ONU may just go down and stay down. It may also be that a crashed ONU consumes very little power, in which case the voltage recovers. As the ONU attempts to return to service, its power demand increases and it crashes again.

This is one of two bad things that can happen to a remotely powered ONU. We refer to this as the voltage-limited case because instability occurs when the drop across the feeder equals 50% of the source voltage. It can be shown that, for a given power demand P_L, the maximum survivable feeder resistance is

$$R_{f_{\max}} = \frac{V_s^2}{4P_L} \tag{2.1}$$

The other bad thing that can happen is referred to as power-limited instability. Safety requirements specify that no single source can deliver more than 100 VA (watts) into a load. Because of tolerances, a real-world supply may be limited by the manufacturer to an output of, for example, 95 W, as shown in Figure 2.27.

Suppose we lose 5 W in each leg of the feeder circuit. Then as long as the ONU requires power $P_L < 85$ W, we are okay. Suppose the feeder resistance increases a bit, for example, because it is carried in an aerial cable that gets hot in the summer sun. Suppose the feeder now wants to dissipate 6 W in each leg, while the ONU still demands 85 W. The ONU again tries to increase its feed current to get its full 85 W, which reduces voltage V_L, and the ONU crashes. This even though the ONU starts off well above the $0.5V_S$ point of the voltage limited case.

In the power-limited case:

$$R_{f_{\max}} = \frac{V_S^2}{P_s^1}(P_S - P_L) \tag{2.2}$$

where P_S is the maximum power available from the source.

As mentioned, the safety standards specify a maximum of 100 VA from any single source, typically margined down to about 95 W. The standards also specify 200 V as the maximum, also typically margined down to 190 V.

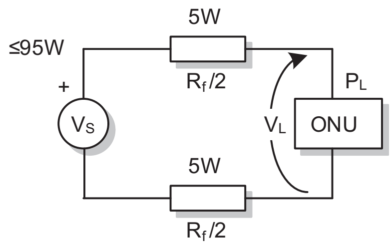


Figure 2.27 Power-limited circuit.

In practice, the manufacturer may only guarantee a voltage or a power level that is somewhat lower than our numbers. Because of the exponents in Eq. (2.2), this is expensive in terms of budget. A 1% decrease in the worst-case guaranteed output voltage costs about 2% in maximum resistance and therefore reach. The cost of a 1% reduction in the worst-case guaranteed output power depends on the ONU load P_L and may be either more or less onerous.

Plugging the nominal values ($V_S = 190$ V, $P_S = 95$ W, $P_L = 47.5$ W) into Eq. (2.1), we see that the total feeder resistance in the voltage-limited case must not exceed 190 Ω, or 95 Ω per leg.

For residential wiring, we previously hypothesized 26 AWG wire above, but for remote feeding of a curbside ONU, let us assume we have access to 22 AWG pairs. Their resistance at 20°C is 16.14 Ω/kft. The temperature coefficient of copper is about 0.393% per degree celsius, so at 60°C, our wire increases to 18.7 Ω/kft. If we can tolerate 95 Ω, we can feed an ONU at a distance of 5 kft, as long as it consumes no more than 47.5 W.

That would be 47.5 W absolute max, and with no margin. If a subscriber goes off-hook and increases the ONU's power demand to 47.6 W—well, it is like taking one tiny tiptoe step out onto that icy summit.

Peak and transient demand can be hard to predict. POTS is the worst because ringing a telephone consumes a substantial amount of power. The amount depends on the subscriber's equipage, and subscribers are pretty much free to connect as many devices as they like, each device different from the others. If the subscriber picks up the phone at a peak of ringing voltage, the resulting approximate short circuit causes a spike in power demand until the ring trip circuit operates. Further, a curbside ONU must be able to ring several phones at once, each of them an unpredictable load, with some number[*] of additional lines off-hook.

It is usually not feasible to provide a power circuit that can survive the absolute worst-case transient load conceivable. Short spikes, such as ring trip transients, can be absorbed by a capacitor in the ONU. But capacitors consume space, add cost, and have finite lifetimes.

[*] Telcordia GR-909 is a good requirements reference. It contains tables that specify *n* lines ringing with *m* lines simultaneously off-hook for ONUs of aggregate traffic capacity *t*.

On the proactive side, the ONU may be designed to deny power to loads that it cannot support, for example, by reducing the ringing voltage or staggering or abbreviating the ringing phase.

That is the bad news on the ONU side. On the feeder side, transients may be introduced by coupling from parallel power lines or from thunderstorms; if a transient causes the common-mode voltage of a feeder to exceed 200 V for more than a very brief period, the power source shuts down—safety requires it. The power source will restart, but in the meantime, the ONU has crashed. Transients can also generate unbalanced current in the loop, simulating ground faults. The power source shuts down, the ONU crashes.

Well, this is a pretty bleak picture, particularly if our ONU wants more than 47 W. What can we do?

Figure 2.28 shows two approaches, approaches that may be applied jointly or independently.

- If we provide two or more twisted pairs in parallel—such as pairs a and b—we reduce the feeder resistance proportionately. We can either deliver more power to the ONU or place the ONU farther from the power source. It goes without saying that in the real world, these pairs will be in the same cable, so that their resistance is very nearly the same. Downsides: ~~Existing~~ cables may not have spare pairs, so it is not necessarily possible to overwhelm the problem by adding pairs. And if one of the pairs were to fail, it could be difficult to diagnose the fault.
- To deliver more than 100 W (in reality 95 W less wiring loss) to an ONU, it is permissible to provide two or more sources—sources 1 and 2 in Figure 2.28—subject to the strict safety requirement that they be fully isolated from each other. The weak link controls the behavior, so it is important that each circuit deliver 50% of the total power. The downside of this approach is the cost of an additional power source, including its housing, cooling, and such.
- If we provide two pairs (a and b) for source 1, we clearly need to provide two pairs (c and d) for source 2; else we would be creating a weak link as the load attempted to share the power equally. To equalize feeder resistance, it also makes sense that the sources be colocated and that all feeder pairs be in the same cable.

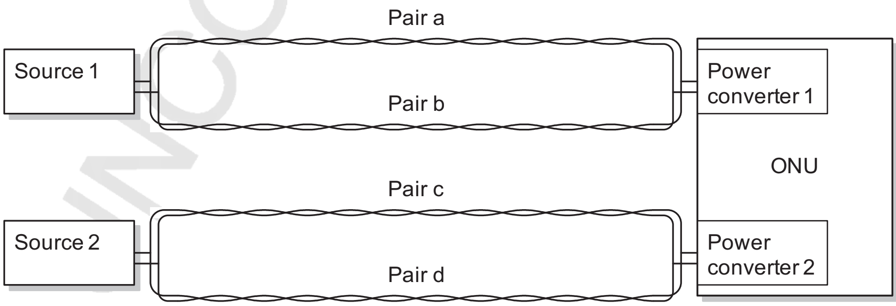


Figure 2.28 Multiple sources, multiple feeders.

In terms of transient immunity, buried cable is better than aerial—the 60°C thermal derating could also be relaxed—and power at 130 V has more margin against the 200 V overvoltage safety limit than does 190 V power. Because of the circumstances of a deployment, neither of these options may be feasible.

If it is at all possible, it is far easier to locate an MDU in the equipment room of a building, an apartment building, for example, a site with limited environmental extremes, with nearby AC and with space for backup batteries. The service drops are then indoor wiring rather than outside plant, so the requirements for lightning protection are also relaxed, saving even more in the total cost.

Even better, of course, is an SFU, located right there next to its power source in the subscriber's home.

Having said all this, it must be stated that powering difficulties are a major operational impediment to the expeditious roll-out of G-PON.

2.6 TECHNOLOGY REQUIREMENTS

2.6.1 VLANs

All Ethernet traffic—all traffic!—through a G-PON access network is carried in VLANs, either a dedicated VLAN per service per subscriber (~~1 : 1~~ model) or a dedicated VLAN per service per group of subscribers, the ~~*N* : 1~~ model. Layer 2 business customers may be served through so-called transparent LAN service (TLS), in which the operator tunnels the subscriber traffic through a service provider VLAN, with or without recognition of subscriber flow priority.

In terms of traffic flow, the primary function of a G-PON ONU is to classify traffic and forward it to the correct queue for output scheduling. This is true in both directions, although the downstream direction, and the queues serving the downstream subscriber interface, receive less attention in the recommendations.

Somewhere in the access network, Ethernet frame priorities and VLAN tags, and possibly IP differentiated service code point (DSCP) bits need to be added, stripped, translated, or interpreted. The ONU needs to be able to classify traffic based on these fields, as well as others: other fields such as ONU subscriber port or Ethertype.

Chapter 6 goes into considerable detail on the G-PON management model for VLAN classification and tag management.

2.6.2 Quality-of-Service Control

Depending on application, the upstream capacity of a PON is expected to be more than adequate for a few years, until the demand of applications such as peer-to-peer communications overtakes it. Nevertheless, upstream capacity is a finite resource, to be conserved and used wisely. Especially with business services, the day may come when the upstream PON becomes a congestion point.

An ONU is commonly required to offer at least four classes of service, and desired to offer six, with the ability to internally schedule and prioritize traffic among classes. Service priority may be based on VLAN tags, DSCP ~~code points,~~ or other criteria.

Among the several ONUs on a PON, the OLT assigns bandwidth in real time according to the load offered by each class of traffic on each ONU. This is referred to as dynamic bandwidth assignment (DBA). The OLT's assessment of offered traffic may be based on observation of idle upstream frames (called traffic monitoring DBA), upon explicit queue backlog reports provided upon request by each ONU (status reporting DBA), or a combination of both.

We discuss the model and management ~~for~~ quality of service (QoS) in detail in Section 6.3.

2.6.3 Security

There are essentially three areas of concern in G-PON: denial of service attacks, violation of privacy, and theft of service. The latter two are different aspects of the same technical issues.

2.6.3.1 Denial of Service

One of the disadvantages of the PON architecture is that anyone with access to the fiber can transmit an optical signal upstream, a signal that interferes with the legitimate signals and effectively brings down the PON. When this occurs due to an ONU defect, it is known as a rogue ONU. Although fanciful scenarios can be constructed involving malicious reprogramming of otherwise functional ONUs, it is hard to understand why an attacker would go beyond the cost and complexity of a simple laser and optical connector.

That is at the optical level. Various other attacks are also possible, for example, injecting traffic that descrambles to long sequences of zeros or ones, hoping to desynchronize the far end receiver. Higher layer threats such as flooding the network with illegitimate traffic are also recognized. They can be dealt with through management capabilities defined in OMCI, for example, to filter or limit the rate of various kinds of traffic.

2.6.3.2 Privacy and Theft of Service

Downstream traffic on a PON is accessible to anyone with an optical detector, even non-ONU devices of suitable sophistication. With this perspective, the original PON protocol specifications called for encryption of unicast downstream traffic. The characteristics of optical splitters and couplers are such that the upstream direction of a PON was deemed to be intrinsically secure. Splitters with redundant upstream ports would be located in safe places, and the upstream signal available at other subscriber drop fibers would be too weak to detect in practical terms. Upstream encryption ~~was, therefore, considered~~ unnecessary.

G.983 B-PON specified a weak form of downstream encryption called churning; G.984 G-PON specifies 128-bit AES (advanced encryption standard) encryption. The encryption key is generated by the ONU and communicated in the clear—if the upstream direction is physically secure, then we treat it as such—to the OLT.

Multicast traffic is not required to be encrypted at the PON level, but is expected to be secured at a higher layer, with keys distributed by a middleware server directly to set-top boxes. In this use case, the PON need not add security because the traffic is deemed to be secure already.

When G.987 XG-PON was developed, some operators regarded this security model as inadequate. They feared that physical access to the upstream fiber flow might indeed be possible. There were also concerns about counterfeit ONUs and even counterfeit OLTs (!). Accordingly, the G.987 XG-PON recommendations add upstream encryption to the options, as well as encryption of downstream multicast traffic. Following the principle of layered security, keys themselves are encrypted during key exchange. G.987 also allows for the possibility of mutual authentication of ONU and OLT, using capabilities across a range from a simple password (registration identifier) to IEEE 802.1X, with its open-ended ability to support virtually any authentication protocol.

We discuss G-PON security further in Section 4.6.

2.7 MANAGEMENT REQUIREMENTS

A G-PON ONU can be viewed in two ways, each of which is fully appropriate within its own scope.

ONU as CPE The ONU may be regarded as customer premises equipment, possibly to be purchased by the subscriber at the local electronics store. Such an ONU is owned, installed, activated, and maintained by the subscriber, who selects service packages from potentially many competing providers. The ONU is integrated with typical RG capabilities: NAT, local DHCP and ~~domain name servers (DNSs)~~, bridged LAN-side ports, and it may also include any number of additional features such as analog telephony adaptors (ATAs) for VoIP, 802.11 wireless connectivity, USB ports, print and storage servers, . . . the list goes on.

ONU as Network Equipment The ONU may be regarded as telephone network equipment, to be fully managed and controlled as an extension of the OLT, all the way to the UNI. This model is the same as that used for service delivery of POTS and ADSL from the central office. Such a model is also natural for MDUs, especially MDUs that provide POTS service along with DSL. The model also fits ONUs delivering business services such as DS1/E1, and ONUs providing mobile backhaul. For uniformity in management, provisioning, and maintenance, some operators choose to consider all ONUs in this way. This model anticipates that the subscriber will have a separate RG.

Even when the ONU is regarded as CPE, some functions must be controlled and managed from the telephone network equipment perspective, functions such as initialization, at least part of the software upgrade process, PON maintenance and diagnostics, and coordination of traffic mapping between the ONU function and the OLT, especially QoS and VLAN tags.

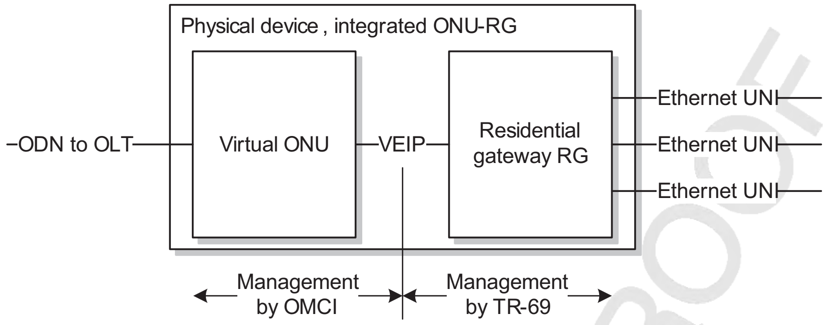


Figure 2.29 Separation of functions per TR-142.

To facilitate this partition, ITU-T and Broadband Forum have cooperatively developed a model that separates the RG (CPE) function from the ONU function, through what is designated a virtual Ethernet interface point (VEIP). Observe that this model best fits an SFU with an integrated RG (Section ~~2.1.1~~). The architecture (Fig. 2.29) appears in BBF TR-142, while the details are defined in ITU-T G.988.

This model separates the RG function from the ONU function, with a logical, rather than physical, Ethernet interface between the functions. Its merit is that operators can use much of the same provisioning and management infrastructure for an RG, be it integrated into an ONU or provided as a separate stand-alone device. Separating PON management from CPE management also facilitates service unbundling, in which the subscriber's services may not be delivered by the network operator.

A second application of the VEIP is the case where a G-PON ONU termination may be used as the integrated feeder of a remote DSLAM. Existing DSLAMs are often managed as stand-alone network elements via simple network management protocol ~~(SNMP)~~[*]; the VEIP allows this management model to be retained, while keeping the PON-specific uplink details within the realm of PON management.

In both cases, a further advantage of the VEIP model is that it helps isolate CPE management or DSLAM management from ONU and PON management. Operators lose a bit of efficiency through coordination that, strictly speaking, would not be necessary, but they gain by having uniform provisioning processes across a range of platforms.

This conclusion is based on the ONU regarded as CPE, deployed in parallel with conventional DSL in the operator's network, and intentionally choosing to minimize the management of the ONU through OMCI. In MDUs, CBUs, SBUs—ONUs that are necessarily network equipment—it is not straightforward to apply the TR-142 model. The operator may yet need different provisioning models.

Q4 G-PON is managed via the OMCI. OMCI is defined in the sunsetted ITU-T recommendation G.984.4, and the current recommendation G.988. Chapter 5 of

[*] IETF RFCs 2578, 3584.

this book discusses OMCI in some detail. This book has to draw a boundary somewhere, so we choose not to go into the details of TR-69 or SNMP management, which are, in any event, not ~~particularly~~ specific to G-PON.

2.8 MAINTENANCE

2.8.1 Connectivity Fault Management

Although at the time of ~~this~~ writing, it was more a wish than a fact, G-PON ONUs are supposed to support Ethernet connectivity fault management (CFM), as specified in IEEE 802.1ag. CFM has three basic aspects:

- Periodic connectivity check messages (CCMs) confirm connectivity of a VLAN (circuit) to the correct provisioned endpoint. Alternatively, if an unexpected ~~connectivity check message~~ appears at a given endpoint, the endpoint can declare a misconfiguration.
- On-demand loopback allows the two-way integrity of a path to be confirmed. Loopback does not disrupt normal traffic, unlike conventional TDM loopback, or for that matter, Ethernet loopback as defined in IEEE 802.3.
- On-demand path trace allows an endpoint to discover its route through the layer 2 network.

Extensions in ITU-T Y.1731 define additional functions such as AIS (alarm incoming signal), a signal that prevents unnecessary alarm propagation. A fault detected at a given network element (NE) causes an alarm at that network element. The NE then generates AIS to the affected downstream clients so they know that the problem has already been detected and reported, and they need not declare their own alarms.

Ethernet CFM is structured in nested layers, where a layer encompasses a pair of endpoints that typically corresponds to a domain of responsibility. Thus, one domain could extend from the service provider's interface (the ONU UNI) into the subscriber's home network. Other domains could extend back into the service provider's network, possibly at several levels in the case of a carrier's carrier. Section 6.1 goes further into Ethernet CFM in G-PON.

2.8.2 Troubleshooting

If an ONU knows that it is about to drop off the PON because of some local action, for example, power failure or simply because the subscriber has switched it off, it can signal dying gasp, DG. This advises the OLT that there is no fault in the fiber plant and assists in fault isolation, should there be a subsequent trouble report. An ONU without a backup battery has limited ability to signal dying gasp after a power failure, so it may not be able to do so. It is also true that power could recover after the ONU signals DG, so the OLT must be prepared for the ONU to stop signaling DG and remain active.

Faults in a direct fiber run are commonly diagnosed by OTDR equipment, which may be used in-service as long as it occupies a separate wavelength, with filters at the necessary points to separate the wavelengths. Wavelengths around 1625 nm are commonly used for this purpose. From the OLT side, it is difficult to see or interpret an OTDR reflection from a fault on the far side of a splitter. Cost-effective in-service centralized and preferably automated fault diagnosis is of considerable interest and remains an opportunity for vendor differentiation.

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