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INTRODUCTION

Fiber optic access networks have been a dream for at least 30 years. As speeds increase, as the disparate networks of the past converge on Ethernet and IP (Internet protocol), as the technology and business case improve, that dream is becoming reality.

The access network is that part of the telecommunications network that connects directly to subscriber endpoints. This book details one of the technologies for fiber in the loop (FITL), namely gigabit-capable passive optical network (G-PON) technology, along with its 10-Gb sibling XG-PON. Figure 1.1 shows how G-PON and XG-PON fit into the telecommunications network hierarchy. This book is about the G-PON family.

For quick reference, Table 1.1 summarizes the common PON technologies, including both the G-PON and EPON families. The G-PON family is standardized by the International Telecommunications Union—Telecommunication Standardization Sector (ITU-T), while EPON comes from the Institute of Electrical and Electronic Engineers (IEEE). Chapter 7 includes a comparison of G-PON and EPON.

Because they share many properties, this book uses the term G-PON generically to refer to either ITU-T G.984 or G.987 systems unless otherwise stated. Where a distinction needs to be made, we make it explicit: G.984 G-PON or G.987 XG-PON.

Figure 1.2 illustrates the fundamental components of a PON. The head end is called the optical line terminal (OLT). It usually resides in a central office and usually

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

TABLE 1.1 PON Family Values

Technology	Standard		Speed
G-PON	ITU-T	G.984	2.5 Gb/s downstream, 1.25 Gb/s upstream
XG-PON	ITU-T	G.987	10 Gb/s downstream, 2.5 Gb/s upstream
EPON	IEEE	802.3	1 Gb/s symmetric
10G-EPON	IEEE	802.3	10 Gb/s downstream, 1 or 10 Gb/s upstream

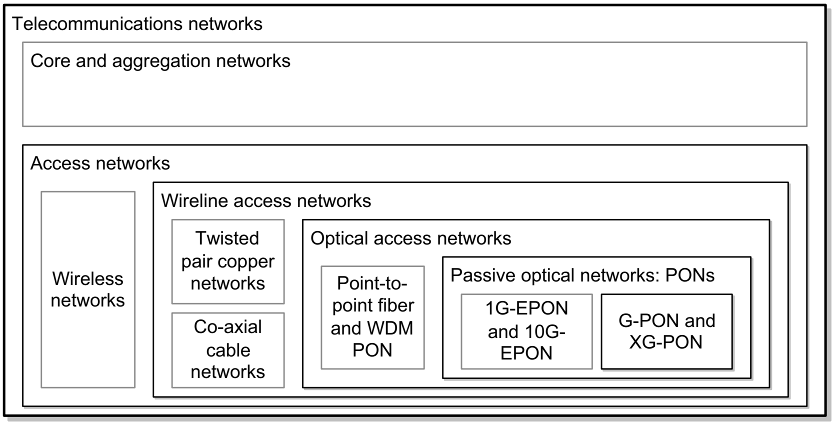

Figure 1.1 G-PON taxonomy.

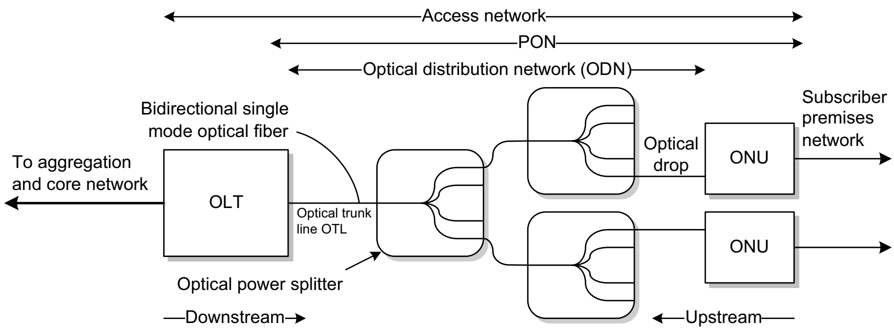

Figure 1.2 G-PON terminology.

serves more than one PON.* The PON contains a trunk fiber feeding an optical power splitter, or often a tree of splitters. From the splitter, a separate drop fiber goes to each subscriber, where it terminates on an optical network unit (ONU). ONUs of various kinds offer a full panoply of telecommunications services to the subscriber.

* The term OLT is therefore ambiguous: it may refer only to the terminating optoelectronics and MAC functionality of a single PON or it may mean the entire access node, terminating a number of PONs and forwarding traffic to and from an aggregation network.

A single-fiber connection is used for both directions, through specification of separate wavelengths for each direction. As we shall see, wavelength separation also allows for coexistence of other technologies on the same optical distribution network (ODN).

After a brief overview and history in this chapter, Chapter 2 outlines the requirements and constraints of a G-PON access network. Chapter 3 explains the optical layer of the network. Moving up the stack, Chapter 4 covers the transmission convergence layer, the home of most of the features that uniquely distinguish G-PON from other access technologies. Chapter 5 introduces the management model in the context of equipment and software management, while Chapter 6 shows how the management model is used to construct telecommunications services. Finally, Chapter 7 describes current and future alternatives, competitors, and partners of G-PON.

Two appendices, a list of references, a guide to acronyms and abbreviations, and an index appear at the end of the book.

1.1 TARGET AUDIENCE

This book is written for the experienced telecommunications or data communications professional whose knowledge base does not yet extend into the domain of PON or, in particular, G-PON and XG-PON. We also address this book to the advanced student, who cannot be expected to have a grounding in the ancient and forgotten lore of telecoms. Hoping to strike a balance against excessive redundancy, we nevertheless include a certain amount of background material, for example, on DS1 and E1 TDM services, and we always try to indicate where to find additional information.

We argue that a simple restatement of the standards adds no value. Accordingly, we structure this book with a view toward explaining and comparing the standards, rather than simply paraphrasing them. This is most evident in the frequent side-by-side comparisons of G-PON and XG-PON. This book also addresses many important aspects of real-world access networks that lie beyond the scope of the standards.

Disclaimers The complete and authoritative specifications are in the standards themselves. While we make every attempt to be accurate, we have necessarily elided any number of secondary details, especially in the peripheral standards. We trust that the reader who ventures into the formal standards will find few surprises. Although both authors are employed by Ericsson, we should also state that this book is not sponsored by Ericsson, and the views expressed do not necessarily represent Ericsson positions.

1.2 EVOLUTION OF G-PON TECHNOLOGY AND STANDARDS

PON technology began in the 1980s with the idea of a fiber ring dropping service to each subscriber. Ring topology was abandoned early for reasons that will be apparent upon reflection, and subsequent PONs have been based on optical trees. In the early days, several companies* developed products around the integrated services digital network (ISDN) standards. The systems delivered plain old telephone service (POTS), but offered few advantages over copper-fed POTS. Although there were some deployments, the technology (cost) and the market need (revenue) were too far apart to justify a realistic business case.

By the 1990s, optical communications were starting to mature in the long-haul network, speeds were increasing, and the industry was starting down the cost curve on the technology side. At the same time, a market for Internet access was developing, and subscribers were increasingly frustrated with modems running at 9.6 or even at the once-impressive speed of 56 kb/s. The PON industry tried again.

The first generation of what might be termed modern PON was based on asynchronous transfer mode (ATM), originally designated A-PON. Significant commercial deployments of ATM PON occurred under the moniker B-PON (broadband PON). B-PON was standardized and rolled out in the last years of the twentieth century.

Like G-PON, B-PON is defined by the ITU-T, in the G.983 series of recommendations. Several data rates are standardized. Early deployments delivered data services only, at aggregate bit rates of 155 Mb/s, both upstream and down. This is one of the bit rates used by the synchronous digital hierarchy (SDH), an optical transport technology developed during the 1980s and 1990s and widely deployed today, albeit having evolved over the years to the higher rates of 2.5 and 10 Gb/s and beyond. B-PON specified the same bit rates as SDH, with the intention to reuse component technology and also parts of the SDH standards for specifications such as jitter.

In the early years of the millennium, B-PON matured in several ways:

- Service definitions expanded beyond best-efforts data, most notably to include POTS and voice over Internet protocol (VoIP).
- The original downstream wavelength spectrum was redefined into two bands, a basic band for use by the B-PON protocols and an enhancement band intended for radio frequency (RF) content such as broadcast video. Spectrum was also identified for use by independent dense wavelength division multiplex (DWDM) access, coexisting on the same fiber plant.
- To improve the utilization of upstream capacity, dynamic bandwidth allocation (DBA) was defined and standardized.
- Although the common upstream rate remained at 155 Mb/s, the technology, cost, and market requirements had evolved to the point that 622 Mb/s—another SDH speed—became the expected downstream rate.

* One of the original companies—DSC-Optilink—can be tied to today's Alcatel-Lucent; another—Raynet—can be linked to Ericsson.

Reasonable B-PON deployment volume was achieved at these levels. At the time of writing, in 2011, B-PON was still being installed to fill out empty slots in existing chassis.

Although the B-PON standards are ITU-T recommendations, a group called FSAN (Full Service Access Network) guided the requirements and recommendations and continues to guide its successors to this day. FSAN is an informal organization of telecommunications operators founded in 1995. Unlike formal standards development organizations (SDOs) such as ITU-T and IEEE, and non-SDOs such as Broadband Forum (BBF), FSAN has no membership fees and no staff. Equipment and component vendors are members by invitation only. While FSAN emphasizes that it is not an SDO, the same companies and the same people carry their discussions from FSAN into ITU-T for the formal standardization work, often on successive days of the same meeting. In the early days, the text of the recommendations was actually developed under the FSAN umbrella, then passed to ITU-T for formal review and consent.

Around the turn of the millennium, digital video began to come out of the lab. The bandwidth limitations of B-PON became a concern—622 Mb/s distributed across 32 subscribers is only (!) 20 Mb/s average rate per subscriber, much of which would be consumed by a single contemporary high-definition digital video stream—while the cost of technology had continued to improve. Standardization discussions began on a new generation of PON, this one known as gigabit-capable PON, or G-PON. The first G-PON standards, the ITU-T G.984 series, were published in 2003. As with B-PON, the G-PON standards recognize several data rates, but the only rate of practical interest runs at 2.488 Gb/s downstream, with 1.244 Gb/s in the upstream direction, capacity shared among the ONUs. These are also SDH bit rates.

The initial versions of the G.984 series recognized the ATM of B-PON, but ATM was subsequently deprecated as a fading legacy technology. Another capability that was initially standardized and later deprecated was provision for G-PON to directly carry TDM (time division multiplex) traffic. This might have been useful for services such as DS1 (digital signal level 1) or SDH, but detailed mappings were never defined, and it was overtaken by the development of standards for pseudowires, about which we shall learn in Chapter 6.

The only form of payload transport that remains in G.984 today is the G-PON encapsulation method (GEM), usually encapsulating Ethernet frames.* It is perfectly accurate to think of G-PON as an Ethernet transport network, notwithstanding marketing claims from the EPON competition that G-PON is not real Ethernet.

Another important evolutionary step from B-PON to G-PON is accommodation of the operators' requirement for incremental upgrade of already deployed installations. The B-PON wavelength plan did not provide for the coexistence of B-PON and G-PON on the same optical network. The eventual need to upgrade access network technology thus presented a dilemma:

* Other mappings are also defined in G.984 G-PON; some were recognized to be of no market interest and were not carried forward into G.987 XG-PON. The only additional mapping in G.987 XG-PON is multiprotocal label switching (MPLS) over GEM. Time will tell whether it is useful.

- It was usually not economical to install a new optical distribution network, particularly the distribution and drop segments, in parallel with an existing one.
- It was not feasible to replace all ONUs on a PON at the same instant. Imagine an army of 32 service technicians calling on 32 subscribers at precisely 10 AM next Tuesday morning—or at any other time for that matter!
- It was unacceptable to shut down telecommunications service to a group of subscribers for several hours or days to allow for a realistic number of service technicians to schedule realistic service appointments with subscribers.
- And maybe only 1 of those 32 subscribers was willing to pay for upgraded service anyway.

The upshot of this consideration was a requirement for G-PON networks to reserve wavelengths to allow incremental upgrade to the next generation of PON technology, whatever that might be, and to include the necessary wavelength blocking filters in ONUs. Chapters 2 and 3 discuss this in further detail.

G-PON began to be deployed in substantial volume in 2008 and 2009.

Once a standard is implemented and deployed, it is natural to want to confirm that everyone has the same interpretation and that the various implementations will interwork. This led to a series of interoperability test events, beginning with the basic ability of an OLT to discover and activate an ONU on the PON. The first G-PON plugfest occurred in January 2006, and there have been two to four events per year since then. Today's G-PON equipment is largely interoperable, although the final proof remains to be seen: there have not yet been widespread live deployments of multivendor access networks.

As testing moved further up the stack, it became apparent that the flexibility of the ONU management and control interface (OMCI) was not an unmixed blessing. Different vendors supported given features in different ways. If the OLT tried to provision the feature in one way and the ONU supported only some different way, the pair would not interoperate.

Interoperability was a primary motivation for standardization. FSAN therefore created the OMCI implementation study group (OISG) with the charter to develop best practices, recommendations for the preferred ways to implement various features. OISG was and is a vendors-only association, theoretically free to discuss implementation considerations under mutual nondisclosure agreements.

In 2009, OISG released an implementers' guide of OMCI best practices, originally published as a supplement to the OMCI specification ITU-T G.984.4. As G.984.4 was migrated into G.988, the implementers' guide material was incorporated into G.988, where it resides today.

OMCI best practices continue to evolve as minor questions arise, but the issues that spawned OISG have largely been resolved. OISG's charter also evolved and it became an early preview forum for OMCI maintenance, an opportunity for sanity checks and consensus building before new OMCI proposals were formally submitted to the ITU-T process.

Although OISG has not been formally disbanded, it is now dormant, both because of its success at resolving interoperability issues and because of the shift of responsibility from FSAN to BBF. Test plans are published as BBF technical reports, specifically TR-247 and TR-255. Responsibility for plugfests also shifted from FSAN to.

Broadband Forum entered the G-PON scene only recently, but in a major way. Previously known as DSL Forum, BBF changed its name and expanded its scope to include, among other things, the entire access network and everything attached to it. In 2006, BBF published TR-101, which defined requirements for migration of the access network from ATM to Ethernet, but still with a DSL mind-set. The ink had scarcely dried on TR-101 when BBF began a project to define its applicability to the special aspects of G-PON, resulting in TR-156 (2008).

Although there are some rough edges at the organizational boundaries, the scope addressed by BBF is theoretically disjoint from the scope of the ITU-T recommendations. ITU-T specifies an interface between OLT and ONU and the fundamentals of its operation. ITU-T includes tools for maintenance and tools from which applications can be constructed and extends the tool set as necessary when new applications arise.

In contrast, BBF views the overall network architecture as its scope. BBF takes the ITU-T tools as a given, identifies preferred configuration options, and writes network- and service-level requirements to serve these options. Vendors and operators are, of course, free to develop other applications on the same base, but if BBF does its job well, its model architectures prove to be satisfactory for most real-world needs and are suitable as reference models even for applications that lie beyond the strict bounds of the BBF architecture.

If BBF does its job well? In fact, TR-156 has largely been accepted by operators worldwide as a satisfactory model for simple ONUs that deliver Ethernet service to end users. Additional BBF technical reports (TR-142, TR-167) define how the G-PON toolkit can be used to control only the ONU's PON interface, with the remainder of the ONU managed through other means. Chapter 2 expands this topic.

Once the G-PON standards began to mature and vendors busied themselves bringing product to market, FSAN turned its attention to the question of the next logical step after G-PON. Starting in about 2007, as the outline became clearer, the operators launched a white paper project to define the requirements for the next generation. FSAN completed the next-gen white paper in mid-2009. Parallel work had begun in late 2008 to develop the details of the necessary recommendations.

FSAN structured its view of the future into two domains: Next-gen 1 (NG-1) was the set of PON architectures that was required to coexist on the same fiber distribution network with G-PON, while next-gen 2 designated the realm of possibilities freed from that constraint, an invitation to take a long view of technology to see what might make sense at some unspecified time in the future.

As it turned out, NG-1 PON bifurcated further, into versions known as XG-PON1 and XG-PON2, or often just XG-1 and XG-2, where X is the Roman numeral 10, designating the nominal 10 Gb/s downstream rate. Both versions run downstream data at 9.953 Gb/s, another SDH bit rate. The upstream capacity of XG-PON1 is

2.488 Gb/s, while XG-PON2 runs at 9.953 Gb/s upstream. The reason for the distinction was the substantial difference in technological challenge, coupled with the perception that market need was insufficient to justify the significantly higher cost of high-speed upstream links.

XG-PON1 is standardized in the ITU-T G.987 series of recommendations. At the time of writing, XG-PON2 is being held in abeyance, pending the convergence of market demand and technological feasibility. Because IEEE has already standardized a symmetric 10G form of EPON (10G-EPON, Chapter 7), it is possible that XG-PON2 will not be pursued further. If that comes to pass, operators who need symmetric 10G will deploy 10G-EPON, and the G-PON community will work toward next-next-generation access, probably WDM PON.