Optical Transmission Technology

Passive Optical Networks – Roads of Glass

Overview of the structure, functional principle and further developments of the PON standards

by Dr. Alexander C. Adams

The primary driver in the development of broadband communications technologies is the ever-growing hunger for bandwidth and bitrate. Bandwidth requirements are increasing steadily – they double about every two years – and nowadays encompass all aspects of human life. An infrastructure is needed that can provide the capacity for future demands on data throughput. DOCSIS 3.1 and Remote-PHY-technologies have pushed fiber closer to the customer in recent years. In Germany, the next step will increasingly take fiber all the way to the customer's home.

A Roman citizen would presumably have expressed it as "fibra vitrea ad portas – fiber-optic cable at the gates". Ancient Romans should have appreciated today's need for extending optical footprints – they were connectivity-experts, interconnecting all corners of their empire with an outstanding infrastructure of roads. These so-called "Roman-roads" posed the world-wide web of their time, providing for an exchange of goods and information at rapid rates for the era. In present times, information travels on roads of glass.

Bringing fiber optics closer to the customer

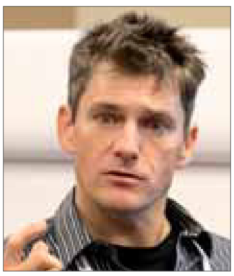
In the years to come the focus of the broadband industry will lie upon replacing the remaining coaxial portions of the networks with optical fiber. A technology employed for this purpose is abbreviated "PON", standing for "Passive Optical Network". PON is a collective term, roughly to be differentiated into EPON (Ethernet Passive Optical Network) and GPON (Gigabit Passive Optical Network), each class breaking up into several different variants. The main differences between EPON and GPON lie within the protocols used for up- and downstream transmissions.

What is a passive optical network?

Passive optical networks are fiber-optic short-range networks used for data transport, Voice-over-IP-traffic (VoIP) and digital-TV signaling, mainly in metropolitan areas. Further fields of application include mobile backhaul-links, the connection of WiFi-hotspots and distributed antenna systems. A PON is an optical network consisting only of fiber-optic cable (glass) and passive components such as splitters and combiners. Hence, a passive optical network does not contain active elements – such as amplifiers or repeaters – requiring a power supply. Of course, even passive optical networks require active components in transmitters and receivers at either end of the line. Generally, passive equipment is a lot less pricy than active components. On the other hand, a significant disadvantage of PON-networks is their relatively short range, which is being limited by signal power and attenuation. Active optical networks (AON) exhibit a range of about a hundred kilometers, while PON-networks usually range between twenty and forty kilometers.

The structure of passive optical networks

The typical structure of a passive optical network is a point-to-multipoint-system (P2MP) with an optical line terminal (OLT) in a network operator's central hub location, distributing data signals to between 16 and 128 customers per fiber. The OLT serves as the interface between the access-network toward the customer and the backbone, similiar to the function of a CCAP in an HFC-network. The OLT converts signals coming from higher network levels into framing structures used on the PON and transmits them onto the optical line. Further, it coordinates the multiplexing of upstream signals coming from the customers' modems. The optical fibers are fed into passive optical splitters, located in a cabinet or an underground coupling along the transmission path. An optical splitter divides an incoming signal into several equally powered signals. Power seen as partial power at one of the exits of the splitter is dependent on the total number of exits of that splitter (e.g., 1:32, 1:64) – the more of them, the less power is available on each of the exits. The signals are then routed across drop-terminals to the individual users. Note that a splitter in the downstream direction acts as a combiner in the upstream direction. A so-called optical network unit (ONU) terminates the passive optical network on the customer's side. This principle



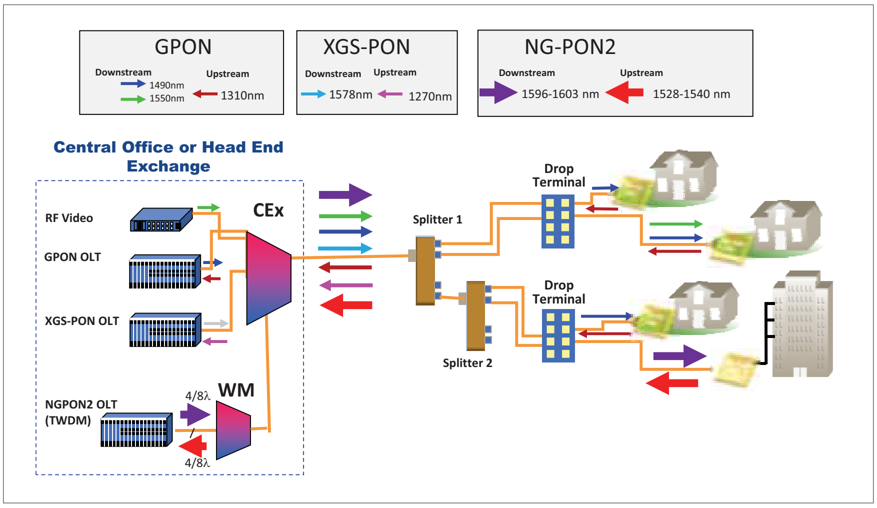
Curriculum Vitae

Dr.-Ing. Alexander C. Adams is managing director of Adams Network Engineering, a company of the Adams Group. Alex looks back upon 20 years of experience in the German, European and international cable industry. He is the European representative of SCTE – Society of Cable Telecommunications Engineers (US), as such part of the CableLabs Proactive Network Maintenance Research Group, and Instructor at the Jade University of Applied Science in Wilhelmshaven/Oldenburg, Germany. Further, he is auditor with dibkom – German Institute for Broadband Communications. Alex holds a Bachelor- as well as a Master-of-Science degree in Electrical Engineering from the University of Hawai'i, USA, and a Doctorate degree (Dr.-Ing) from the Technical University of Darmstadt, Germany.

is depicted in Figure 1. In context with passive optical networks, an optical network unit (ONU) is also called an optical network terminal (ONT). GPON is an ITU-standard – "ITU" standing for "International Telecommunications Union" – using the term "ONT", while EPON is a standard of the Institute-of-Electrical-and-Electronics-Engineers (IEEE), denominating the same equipment an "ONU".

How a PON works

The fundamental principles behind a passive optical network are not unsimilar to those of an HFC-network. Downstream signals on a single wavelength between OLT and ONT/ONU are distribution signals. They are received by all ONUs/ONTs, which can identify and differentiate those signals designated for them. The upstream situation is a tad more complicated. Upstream transmissions are time-division multiplexed (TDM), meaning that every ONT/ONU is allocated designated time slots for the transmission on an upstream wavelength. The transmission of an entire user message usually requires several of these transmission opportunities called burst-mode operations, and therefore the allocation of several non-correlated time slots is needed. Essentially, the message is "chopped up" und sent in pieces. Downstream data rates generally exceed those of the upstream direction in PON-systems, since time-division multiplexing allows for a multitude of simultaneous upstream users at any given point in time, sharing the upstream bandwidth. Our first experiences with the principle of time-division multiplexing date back to elementary school. When the teacher speaks to the entire class, all students can absorb the information simultaneously and identify the parts relevant to them. When the teacher asks a question, the students raise their hand and hold their contribution to the discussion until they are called upon. This way each student gets his or her turn in an efficient fashion, such avoiding any kind of jumble. Hence, a time-multiplexing approach proves advantageous whenever a lot of parties simultaneously want to talk to one party.



Source: Anedis/BTV Multimedia Group

Figure 1: Structure of a PON

PON-standards

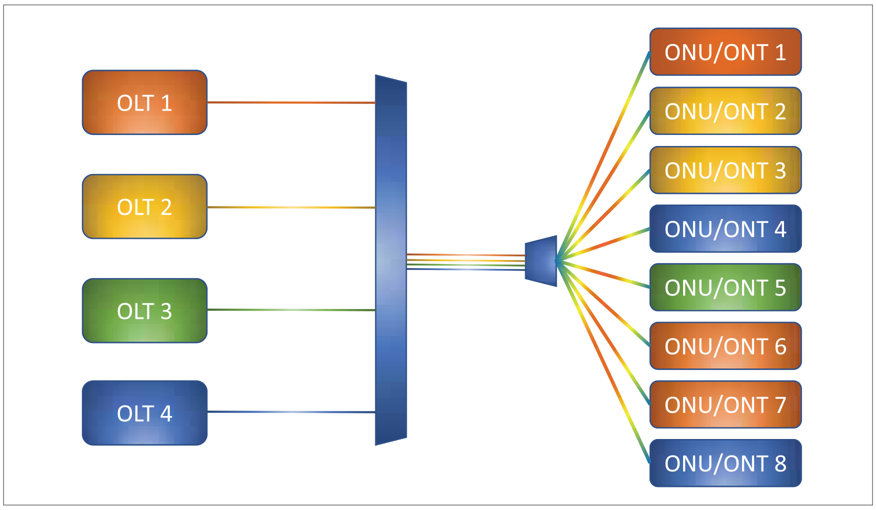
A plethora of PON-standards have been described over the years. The late Nineties saw the release of the ITU's APON-standard, utilizing the already available Asynchronous Transfer Mode (ATM) for the transferal of data-packets. BPON – short for "Broadband-PON" – constitutes a refined version of the APON-standard. BPON's official "name" is ITU-T G.983, it boasts data rates of 622 Mbit/s in the downstream and 155 Mbits/s in the upstream. Nowadays, most passive optical networks are based upon the GPON-standard, GPON standing for "Gigabit PON". Especially in the United States GPON finds plentiful application. ITU's official denomination for GPON is ITU-T G.984. This "classic" GPON delivers 2.5 Gbit/s data rates for the downstream, and 1.25 Gbit/s for the upstream directions. GPON is based upon Asynchronous Transfer Mode (ATM) for the transmission of voice signals and the Ethernet-protocol for the transmission of data. Further, GPON contains generic encapsulation methods for the transfer of other protocols across the GPON-network. In this fashion, Ethernet, IP, TCP, UDP, T1/E1, Video, VoIP and other protocol data can be transported, by encapsulating for example an Ethernet packet as the payload of a GPON-packet. An analogy would be an automobile that is driven into a transport aircraft, then jetted to its destination and consequently unloaded there.

GPON advancements

Additionally, GPON systems appropriate optical wavelength division multiplexing (WDM), meaning that different wavelengths are used on the same fiber, analogous to the concept of using modulation frequencies. This way the same fiber can be used for up- as well as downstream transmissions. Downstream communication is transmitted on a wavelength λ=1490 nm, upstream traffic on λ=1310 nm. Further, λ=1550 nm may be utilized for TV-video signals (RF-overlay). While every ONT/ONU receives the full downstream data rate of 2.5 Gbit/s, the upstream implements a time-division multiple access approach (TDMA), which was essentially described in principle in the time-division multiplexing method above. Upstream capacity is segmented into time slots that are being allocated as transmission-burst opportunities to ONTs/ONUs requesting them. Consequently, the total available upstream bandwidth is being divided amongst several users. A fiber can connect 32, 64 or 128 customers. It is entirely possible that up to 128 users are simultaneously accessing the upstream at a given point in time. In these cases, the "Autobahn-principle" holds – it takes a little longer when it is full.

XG(S)-PON and NG-PON2 constitute the latest versions of the GPON-family. They pose as ITU's answer to increased demands for bandwidth, especially for over-the-top (OTT) services and HD-video. XG-PON (ITU-T G.987) is the 10G-version of the GPON-standard. It delivers 10 Gbit/s in the downstream direction and 2.5 Gbit/s in the upstream. XG-PON is based upon the GPON-structure, albeit it appropriates different wavelengths for transmission than classic GPON. A wavelength of λ=1577 nm is introduced for downstream transmission and λ=1270 nm for the upstream direction, hence enabling XG-PON and classic PON systems to be operated on the same network in parallel. The optical distribution in XG-PON systems is 1:128. The even higher-performance version of XG-PON is XGS-PON (ITU-T G.9807), empowering GPON with symmetric 10 Gbit/s capabilities in up- and downstream.

The answer to future appetite for bandwidth is NG-PON2, the "Next-Generation PON" (ITU-T G.989). It is technically more complex than its older siblings and is also denominated TWDM-PON. "TWDM" abbreviates "time- and wavelength division multiplexing". As in the upstream, a time-division multiplexing approach is now being applied to the downstream direction as well. Additionally, wavelength division multiplexing is introduced into up- and downstream, combining the signals from up to four OLTs, each modulating on a different wavelength, into one signal by means of a wavelength multiplexer. Figure 2 illustrates this principle. At the ONU/ONT, the signals are filtered optically, the filter tuned to the wavelength that the information for a respective device is being transmitted upon. ONU/ONT-devices also contain dynamic lasers, that may be tuned to a desired upstream wavelength for transmission. The upstream signals coming from the ONTs/ONUs are equally sent through a wavelength multiplexer. NG-PON2 uses wavelengths between λ=1596 nm and λ=1602 nm for downstream transmission and wavelengths between λ=1524 nm and λ=1544 nm for upstream transmission. Again, NG-PON2 occupies different wavelengths than previous versions of the GPON-standard, facilitating the parallel operation of NG-PON2 and legacy versions of GPON on the same network. The combination of several 10G-wavelengths results in a symmetric system throughput of 40 Gbit/s, which should provide each customer on the line with symmetric 10 Gbit/s in up- and downstream. Figure 3 gives an overview of the wavelengths used in different GPON-systems.



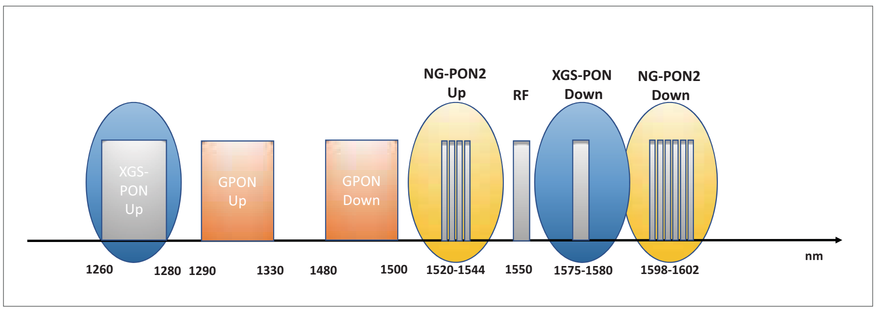
Source: Wikipedia

Figure 2: Principal of a NG-PON2-Systems

Family of Ethernet-PONs

Next to the ITU's family of Gigabit-PONs, there is the IEEE's family of Ethernet-PONs, which is more widely distributed in Europe and Asia than it is in North America. Based upon the Ethernet-standard 802.3, EPON 802.3ah defines a similar passive optical network concept with a range of twenty to forty kilometers. It uses wavelength-division-multiplexing on the same wavelengths as GPON does, as well as a time-division-multiplexing approach in the upstream. Data rates achievable are 1.25 Gbit/s in up- and downstream, which is why it is also called "Gigabit-EPON" (GEPON). EPON is compatible with other Ethernet-based standards, therefore no encapsulation processes need to be employed when transmitting data between Ethernet-based systems. This might prove advantageous in certain situations, since Ethernet poses the primary technology utilized in Local Area Networks (LAN) and Metropolitan Area Networks (MAN) and therefore no protocol conversions need to be considered. The EPON-family's 10G-representative is 10G-EPON – its official denomination is 802.3av – enabling symmetric 10 Gbit/s capacities in both directions. Wavelengths between λ=1575 nm und λ=1580 nm are used for downstream signals, while wavelengths between λ=1260 nm und λ=1280 nm carry upstream data. Figure 4 serves as an overview of different passive optical networks.

Advantages of passive optical networks are manifold. They contain only few components requiring a power supply, therefore reducing failure probabilities along the transmission path and easing network service measures. Further, only few distribution cabinets are needed in PON networks, and future upgrades will be focused on the OLTs and ONUs/ONTs rather than on the optical infrastructure itself. Passive optical networks pose a flexible tool in the hands of network opera-



Source: Anedis/BTV Multimedia Group

Figure 3: Wavelengths used in GPON-Systems

tors, for whom it is imperative to be able to implement future technology upgrades on an existing network footprint. Different standards of PON-architecture can coexist on the same network in parallel, allowing network operators to offer a multitude of services to their customers. PON-networks may be combined with applications such as RF-over-glass (RFoG)/RF-Overlay approaches, modulating RF-signals like analog or digital TV upon a single wavelength (typically λ=1550 nm) and broadcasting them on the optical line. Finally, PON-networks are easy to maintain and service, since their glassy character results in significantly less ingress and impulse noise effects than exhibited with their coaxial cousins.

PON-Type	Characteristics
PON	Optical access-network, Time Division Multiplexing
APON	ATM-Protocol, Downstream 622 Mbit/s, Upstream 155 Mbit/s
BPON	ATM-Cells like APON, separate wavelengths for video-services
EPON	Standardized as IEEE 802.3ah, symmetric data rates 1,25 Gbit/s
GPON	ATM, TDM, Ethernet, Up- und Downstream up to 2,5 Gbit/s
10GEPON	IEEE 802.3av, symmetric and asymmetric transmission 10 Gbit/s
NG-PON	Symmetric data rates 10 Gbit/s, Wavelength Divison Multiplexing

Source: dibkom

Figure 4: Different PON-Systems

Conclusion and outlook

However, research and development efforts are not at their terminal end yet. Future PON-design will focus on handling the increasing demands for bandwidth as well as improving the range of the networks and improving splitting ratios. PON-designs will continue to be solid solutions, not only for environments such as universities, hospital complexes and large office-structures. PON-networks also pose an opportunity for HFC-network operators to replace the remaining coaxial infrastructure close to the customer with optical lines. The path to the future leads along roads of glass – fibra vitrea ad portas. ■