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Chapter 14

FTTx Access Networks: Technical Developments and Standardization

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Abstract

This chapter provides a review of factors driving technical development of broadband access networks, mostly toward higher bit rates and symmetrical services, together with a review of "fiber to the x" (FTTx) technologies for fixed access networks, including development and performance limitations of digital subscriber line (DSL) systems using twisted-pair copper cables, as well as fiber to the home systems. Characteristics and standardization of these systems are presented, together with a review of the two main competing broadband technologies: Data over cable service interface specification (DOCSIS) in coaxial cable TV networks and the 4G and 5G wireless networks. Additionally, a short list of recent developments in passive technologies (fibers, cables, and connectors) is included. Finally, the issues related to dismantling of the traditional copper telephone network and ensuring continuity of voice services in emergency situations are analyzed.

Keywords: broadband access network, FTTx, FTTH, PON, DOCSIS, standardization, backup power

1. Introduction

Developments of fixed (wired) access networks are driven by services and related demands on network infrastructure, including:

a. Bandwidth adequate for all services, stable performance, and reliability

b. Low cost

c. Continuity of "lifeline" services in emergency situations

Requirement (a) is most important, with bit rate being the differentiator and marketing tool, complemented by consistent performance, including bit rate, error rate, and latency. As the importance

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of digital services grows, customers and regulators no longer accept “best effort” and “up to” services, but the cost sensitivity of access market (b) forces operators to make compromises between quality and expenditures and reuse existing facilities wherever possible. Currently, available access technologies are capable of providing gigabit services, while streaming of 8 K video needs less than 100 Mb/s. However, with the shift of data storage and processing to “cloud” services, customer requirements will evolve toward even faster and symmetrical access.

Access to basic “lifeline” services in emergency situations (c) is overlooked by operators and customers alike; it comes to light only in times of major disaster like the Sandy hurricane [1].

Finally, there is a possibility of 5G wireless networks largely replacing the wired ones after 5G standards are finalized and equipment becomes available after 2020.

2. Bandwidth demands

The majority of traffic today is generated by video services, characterized by steady increase of resolution, which during the last 15 years rose from 320 × 240 clips and 640 × 480 standard definition (SD) broadcasts to 4 K (3840 × 2160) now and 8 K (7680 × 4320) in the near future. 8 K broadcasts with H.265 coding require a 75–100 Mb/s bit rate, exceeding the requirement of voice service (64 kb/s) by a factor of 1500. Video is predicted to constitute 81% of all consumer Internet traffic in 2021, with the latter growing at an annual rate of 26% [2].

2.1. Nielsen’s law and residential Internet access

According to a Nielsen’s Law of Internet Bandwidth, the fastest speeds offered to residential customers rise 40–50% each year and even faster recently (**Figure 1**).

Available bandwidth, in fact, rises faster than demands imposed by streaming services. While SD video in 2005 required 2–6 Mb/s, which digital subscriber line (DSL) network barely delivered, full HD needs 10–15 Mb/s today, while 40–100 Mb/s access is available in FTTH, FTTC, and data over cable service interface specification (DOCSIS) 3.0 networks (4, 5, 6). Even the 100 Mb/s required for an 8 K video after 2020 is well below top rates (200 Mb/s–10 Gb/s) in current FTTH and DOCSIS 3.1 networks.

Proliferation of cloud services and social networks after 2010 has also changed the directions of traffic. While watching TV or web browsing required mostly downloading of data, residential users now upload a lot of content they created (photos, videos, scans, etc.); the same applies to professionals and business. Consequently, customers want symmetrical access with equal bit rates in both directions. In this respect, the differences between specific broadband access technologies like XG-PON and XGS-PON (5.2.2) are substantial.

2.2. Is there a limit?

Is there a fundamental limit to demand for faster Internet access?

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In principle, there should be, because the performance of the human brain and senses (primarily vision) is limited. In particular, the resolution of 4 K and 8 K video already matches or exceeds the capacity of human vision, while adding a 3D and surround capacity will probably increase the streaming data rate by a factor of 2–4x, to some 300 Mb/s. The best audio (192 kHz sampling, 24-bit coding, six channels, uncompressed) needs only approx. 30 Mb/s. Still, there is the need for rapid transfer of massive files with movies, games, or photos. Or, a complete backup of data stored on a PC to a cloud storage. Transfer of 20 TB from a machine with the two largest hard disk drives available now (10 TB) in 5 hours requires 10 Gb/s, exactly the fastest fiber access available in 2017 (see **Figure 1**).

Will subscribers need even more? Probably not, if cloud services replace local storage and streaming replaces file downloading, the mainstream demand can then saturate at 1 Gbit/s.

A significant increase of bit rate above 10 Gb/s will be difficult even in FTTH networks due to high chromatic dispersion of standard single-mode fiber at 1550 nm [4], and the need to use low-cost transceivers with non-return-to-zero (NRZ) modulation and direct detection. With this technology, transmission distance is inversely proportional to the square of bit rate: approx. 80 km at 10 Gb/s, 20 km at 20 Gb/s, and only 5 km at 40 Gb/s. This is a "hard" limit, costly to break (by employing coherent detection and digital dispersion compensation), resembling the situation in commercial aviation, where cost and noise issues associated with breaking the sound barrier keep speeds below 950 km/h [5].

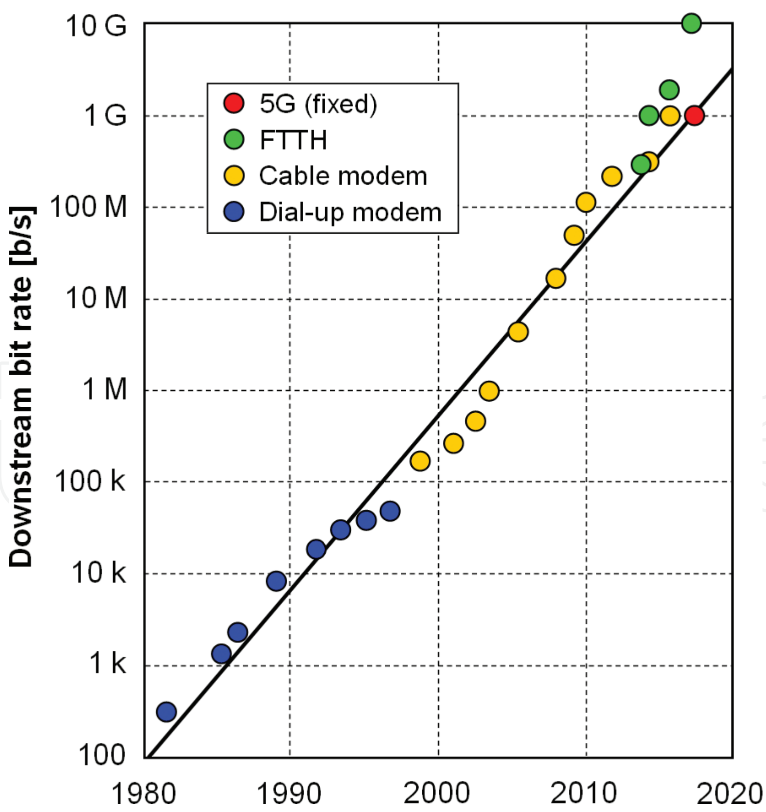


Figure 1. Top download rates offered to residential customers in the USA. (Pre-2012 data from [3]).

3. FTTx access networks

3.1. Reference architecture

The reference architecture of fiber access networks defined by ITU-T Recommendation G.984.1 allows to use both fiber and copper cables as transmission medium, with a possible transition between them in the middle of access loop, as shown in **Figure 2**. Because optical fiber can reach various locations with respect to customer premises, marked as "x," this architecture is called fiber to the x (FTTx).

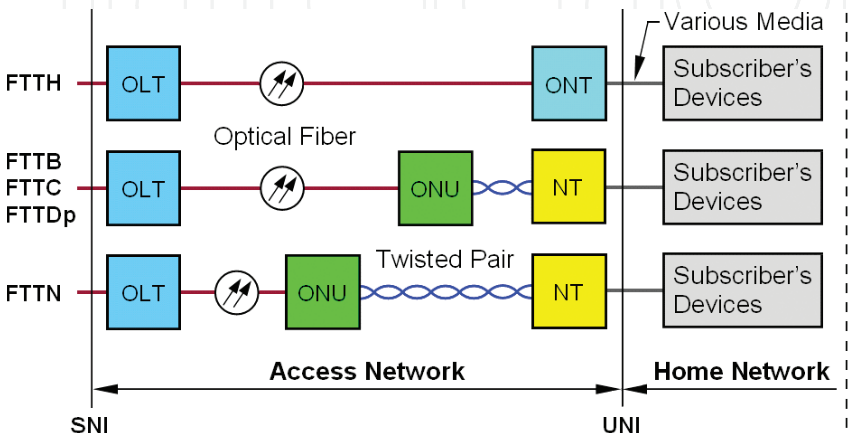
The termination on customer's side is called either NT/ONT or ONU, e.g., by IEEE [7]. ONU performs termination of optical fiber link to transmit data further, using a medium other than fiber, extending toward the customer; its functionality may include multiplexing of several data streams to and from multiple customers. ONT is located at customer's premises and has interfaces to his devices like PC, TV set, telephone set, etc. In practice, this distinction is blurred, and ONT can have fiber interfaces to a home PC or router or include the router, performing multiplexing of data to/from all devices at home.

3.2. Distances to subscribers

OLT equipment is preferably located in existing central offices (CO), having space, backup power, cable ducts, etc., and is expected to serve all subscribers in associated area. **Figure 3** shows lengths of telephone loops in selected countries before introduction of remote units.

3.3. Transmission media

Optical fibers in access networks are exclusively of non-dispersion-shifted single-mode type, standardized in ITU-T Recommendations G.652 and G.657 [4, 8]. To reduce cabling costs, FTTH networks transmit signals in both directions over a single fiber. LAN cables in FTTB networks have four twisted pairs of 0.5 mm or 0.6 mm copper wires, of which either two or four are utilized for data transmission. Telephone cables have twisted pairs with wire sizes ranging from 0.4 to 0.8 mm, with 0.5 mm most common; a standard telephone loop consists of a single pair.



ONU	Optical Network Unit
ONT	Optical Network Termination
OLT	Optical Line Termination
NT	Network Termination
SNI	Service – Network Interface
UNI	User – Network Interface

Figure 2. The reference architecture of fiber access network defined by ITU-T [6].

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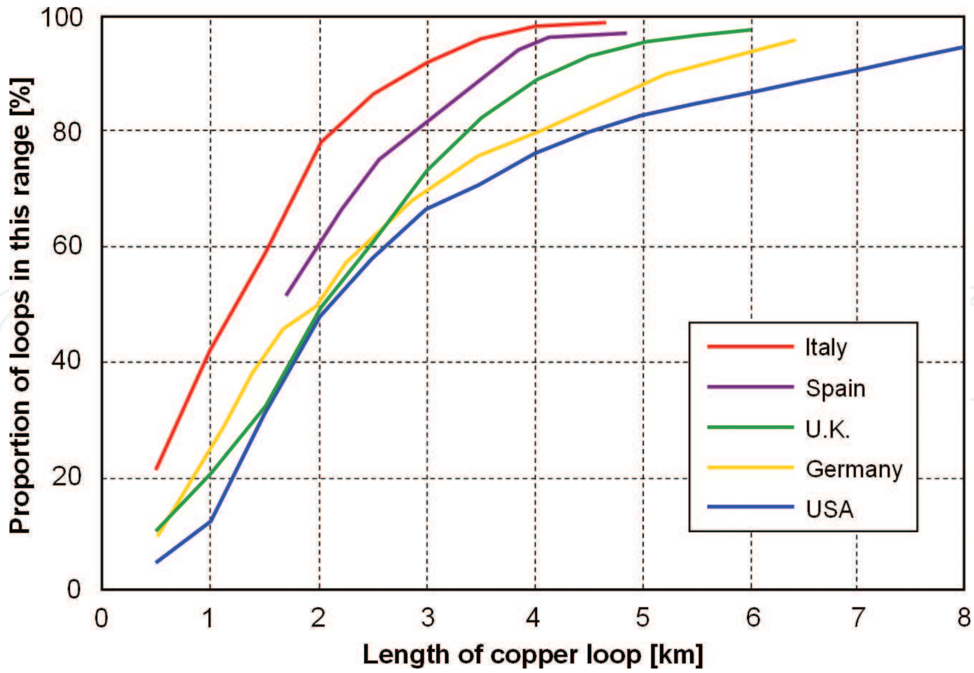

Figure 3. Lengths of subscriber loops in selected countries. Note: There are large differences between data published, probably due to variations of network characteristics with time.

3.4. Classification of FTTx networks

The most common implementations of FTTx networks, listed below and shown in **Figure 4**, differ by the length of remaining copper loop (if any) and splitting of optical fibers (PON) or use of point-to-point fibers (P2P), while the ONU performing media conversion from fiber to

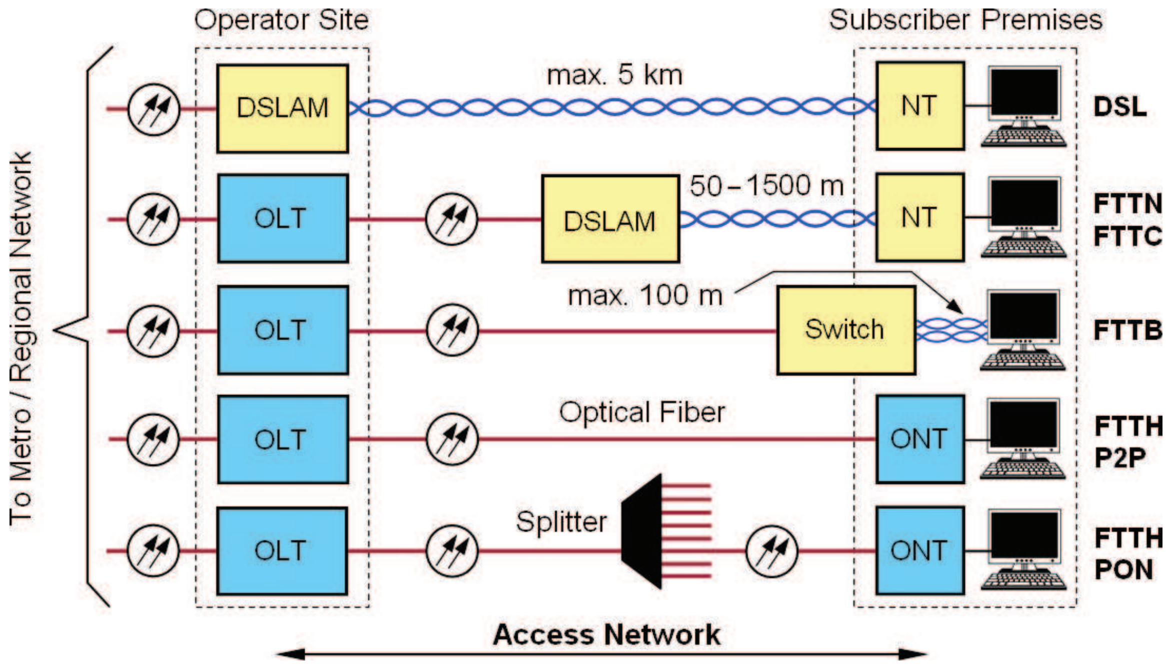

Figure 4. Basic variants of FTTx broadband access networks.

twisted pair is called a digital subscriber line access multiplexer (DSLAM) or Ethernet switch in case of LAN in apartment block.

– FTTB (fiber to the building)

The apartment block is wired with unshielded twisted-pair (UTP) data cables (newly installed), forming a LAN serving all inhabitants, with its Ethernet switch performing termination of fiber link. Data rates up to 1 Gb/s, most often 100 Mb/s.

– Fiber to the curb/cabinet (FTTC)

Optical fibers extend to a remote unit with a DSLAM. From there, short (50–400 m) twisted-pair loops extend to NTs at customer's premises. Data rates up to 100 Mb/s.

– Fiber to the distribution point (FTTDp)

Access network based on G.fast technology, with very short (10–250 m) twisted-pair or coax loops terminated at distribution point unit (DPU) located close to subscriber's premises: at the corridor, on pole, in manhole, etc. Data rates up to 1 Gb/s.

– Fiber to the home (FTTH)

Network with optical fibers extending all the way to ONT at customer's premises, also known as **fiber to the premises (FTTP)**. No active devices in the middle.

– FTTH-PON

FTTH network where a feeder fiber extending from OLT is split into 8–128 distribution fibers reaching customer's premises, forming a passive optical network (PON). OLT bandwidth is shared among all users in a PON with time division multiplexing (TDM).

– FTTH-P2P (point to point)

FTTH network with a separate optical fiber to each customer, no fiber splitting. Each customer is connected to a separate port at OLT. No sharing, data rates up to 1 Gb/s.

– Fiber to the node (FTTN)

Network similar to FTTC, but with longer copper loops, up to approx. 1500 m; fever remote units; and lower data rates up to 20–40 Mb/s.

4. Hybrid networks: FTTN, FTTC, FTTDp, and FTTB

4.1. DSL technology and its limits

Digital subscriber line (DSL) technology was developed to reuse existing copper telephone cables for broadband services, with the minimum use of optical fibers. This approach reduced costs, but limitations imposed by the use of twisted pairs as transmission medium are severe:

a. Attenuation and cross talk rise with frequency, reducing bit rate and reach (**Figure 5**).

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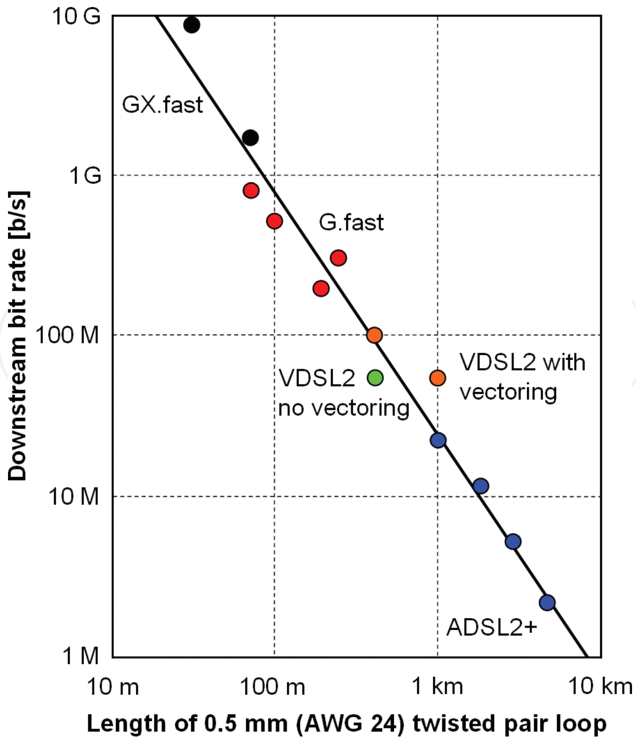

Figure 5. Typical reach vs. bit rate in DSL systems using twisted pairs in telephone cables.

b. Cross talk between adjacent pairs prevents NTs from simultaneously operating at the same frequencies, making the cable a medium with shared bandwidth.

c. Old telephone cables are frequently in poor condition (deteriorated insulation, entry of moisture, deformations), and failures are frequent.

d. Copper cables are often stolen for metal scrap, increasing maintenance costs.

Problem (b) can be eliminated with digital cancelation of cross talk, known as vectoring [9].

Twisted pairs exhibit rise of attenuation and cross talk with frequency, resulting in interdependence between bit rate B and reach L of DSL link, in accordance with a formula:

$$\mathbf{B} = \mathbf{k}\mathbf{L}^{-1.5} \tag{1}$$

where k is a factor dependent on wire diameter, design, and condition of cable, as well as signal processing employed in active equipment. This dependence is presented in **Figure 5**. Higher bit rate requires shorter copper loops and larger number of remote units, which in turn need construction permits and electric power. The acute need for remote units becomes clear after comparing reach values presented in **Figure 5** and distances from the CO to 90 or 95% of customers shown in **Figure 3**.

Development of DSL systems is focused on increasing bit rates, combined with attempts to deliver a good fraction of full capacity at longer distances. Equipment must dynamically adopt to a frequency-dependent, variable transmission characteristics of copper loops, including attenuation, cross talk, and external interference. This is achieved by employing a discrete multitone (DMT) modulation and division of occupied bandwidth into a large number of equally spaced narrow sub-bands, e.g., 2048 in the 2.2–106.0 MHz band with 51.75 kHz spacing in the G.fast system [10]. Only the sub-bands with sufficient signal-to-noise ratio are used, resulting in variable bit rate and "up to" service specifications.

Bandwidth and bit rate data in **Table 1** are maximum values set in standards. Reach achieved in service depends on cable design and its technical condition; data in **Figure 5** and **Table 1** are only indicative.

Performance of DSL link can be improved by pair bonding: the use of two or more copper pairs for parallel transmission, most effective when combined with vectoring.

Comparison of **Figures 1** and **5** suggests that further upgrades of legacy copper networks are not feasible, as system reach becomes too short for most purposes, barring exceptional situations like historical buildings in Europe, where installation of new cables is strongly opposed. This has been already experienced with gigabit version of G.fast system. Despite issuance of standards in 2014 [10, 11], large-scale deployments began only in 2017, and operators prefer 250 Mb/s products with reach of approx. 200 m. However, development continues—a prototype XG-FAST system transmitting 10 Gb/s at a distance of 30 m over one or two pairs, using 500 MHz bandwidth, was demonstrated in 2014 [12, 13].

4.2. FTTB networks

The main advantage of FTTB network (**Figure 4**) over DSL one (4.1) is that the transmission medium between the Ethernet switch and subscriber's premises (a flat in apartment block) is a new Category 5, 6, or 7 unshielded twisted-pair (UTP) data cable, installed in accordance with local area network (LAN) standards. The use of dedicated LAN cables with lengths restricted to 100 m and rated performance up to 100 MHz (Cat. 5), or even 600 MHz (Cat. 7), removes limitations of DSL systems presented in Section 3.2, therefore 100 Mb/s and 1 Gb/s symmetrical services are possible. There is also no need for separate NT devices, as this functionality, at least at 100 Mb/s bit rate, is included in all PCs, laptops, routers, TV sets, etc.

System	Standard	Max. bandwidth occupied (MHz)	Max. bit rate [Mb/s]	Typical reach with a single 0.5 mm pair	Vectoring
ADSL2+	ITU-T G.992.5 (2009)	2.208	24	1600 m @ 20 Mb/s 3000 m @ 10 Mb/s	No
VDSL	ITU-T G.993.1 (2001)	12	52	1200 m @ 40 Mb/s	No
VDSL2	ITU-T G. 993.2 (2006)	30	200	250 m @ 200 Mb/s 800 m @ 50 Mb/s 3500 m @ 4 Mb/s	Optional
VDSL2+	ITU-T G. 993.2 Amd. 1 (2015)	35	300	200 m @ 300 Mb/s	Optional
G.fast	ITU-T G.9700 (2014) ITU-T G.9701 (2014)	106 212 (in the future)	1000	25–70 m @ 1000 Mb/s 100 m @ 500 Mb/s 250 m @ 250 Mb/s	Yes

Table 1. Comparison of DSL systems in use or being introduced. (dates of standards refer to publication of the first edition).

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How big is the improvement provided by LAN cables? Cat. 7A cable has useful bandwidth of 1200 MHz at distances up to 100 m, supporting a 10 Gb/s bit rate, while the newest Cat. 8 provides 2 GHz bandwidth and is expected to support 40 Gb/s applications, but with cable length reduced to 30 m. The G.fast system with a similar reach (**Table 1**) uses 106 MHz of bandwidth and reaches 1 Gb/s, so the difference in terms of achievable bit rate is 40:1.

Assuming a 100 m reach, allowing to wire all apartments in a 15-floor block to one technical room, FTTB technology can provide 10 Gb/s services at low cost. This is competitive with all FTTH technologies and shall satisfy customer demands for another decade, if the demand trend shown in **Figure 1** has to continue.

5. Fiber networks

5.1. FTTH point-to-point (P2P) networks

Architecture of FTTH-P2P network is simple: the whole path between OLT and ONT (**Figure 1**) is made of one, continuous single-mode fiber, without splitting or intermediate active equipment, resembling the traditional telephone network. There is also no sharing of OLT capacity between multiple ONT units belonging to different subscribers. Full-duplex, symmetrical transmission, with equal bit rates in both directions, is possible due to wavelength division multiplexing (WDM), using the following wavelengths:

– Downstream (to subscriber): 1480–1500 nm (nominal 1490 nm)

– Upstream (from subscriber): 1260–1360 nm (nominal 1310 nm)

The necessary WDM coupler (duplexer) is part of a "single-fiber" optical transceiver module, usually of SFP type. Choice of the 1490 nm wavelength (**Figure 6**) resulted from allocation of 1550 nm in all FTTH networks to analog distribution of TV programs. This was initially necessary because the copyright law in several jurisdictions like Japan and the USA made digital distribution of video content subject to new, burdensome licensing, while a retransmission in original analog format (PAL or NTSC) was covered by existing licenses.

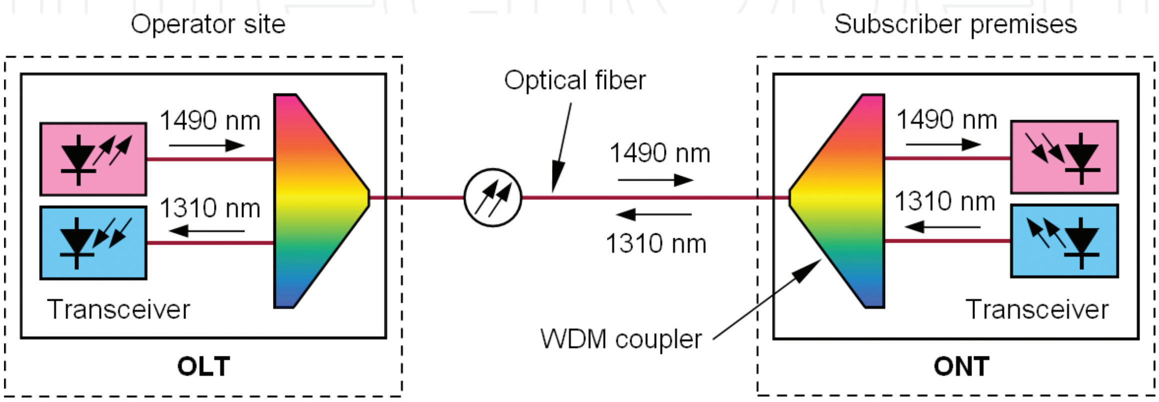

Figure 6. Optical connections and wavelengths in FTTH-P2P network. Optical transceivers are manufactured in separate versions for use in OLT and ONU.

Active equipment for FTTH-P2P networks is based on Ethernet standards [7], and this type of network is known as "active Ethernet." The dominant physical interface is 1 Gb/s 1000BASE-BX10, with a power budget of 5.5/6.0 dB at 1310/1490 nm and 10 km maximum fiber length. This reach corresponds to maximum length of subscriber loops in Europe (**Figure 3**), and conversion of access network from copper to fiber is possible without installing remote units.

More expensive 1 Gb/s transceivers with extended reach of 20, 40, or 80 km are available for use in sparsely populated areas. The 1 Gb/s FTTH-P2P networks are covered also by ITU-T Recommendation G.986 [14], where the power budget of OLT-ONT path in the lowest category S is extended to 15 dB but still combined with a 10 km reach.

10 Gb/s SFP Ethernet transceivers are available but still too costly for use in ONTs. However, prices began to fall after the start of mass production of 10G PON equipment in 2016.

5.2. FTTH-PON networks

5.2.1. Technology

The idea of passive optical network (PON) was first proposed at British Telecom in 1987 [15] to reduce demand for fibers and splicing, both expensive items at the time. As the cost of passive infrastructure of typical FTTH network makes 35–45% of the total [16, 17], this rationale remains valid despite falling prices of optical fiber cables. In a PON there are no active devices between site housing OLT equipment and subscriber premises, as can be seen in **Figure 7**, hence the term "passive." The single feeder fiber extending from OLT optical port is passively split into multiple (8–64) drop fibers extending to each ONT, using a passive, spectrally nonselective, and compact fiber splitter. The whole passive fiber network between OLT and group of ONTs is called an optical distribution network (ODN).

The benefit of splitting is a great reduction in the number of feeder fibers, splicing costs, and duct space for feeder cables. In most cities, duct space is scarce, while construction of new cable ducts

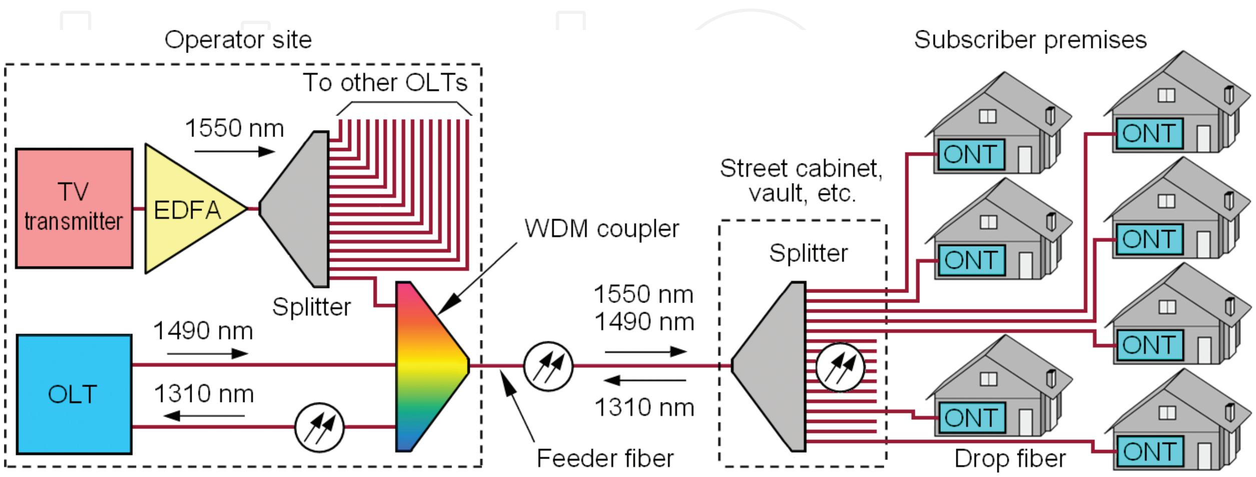

Figure 7. Connections and wavelengths in FTTH-PON access network (GPON). Wavelengths depend on a specific PON system (**Table 4**). Analog distribution of TV signals is optional.

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is slow and expensive. Savings grow with distance between CO and served residential area, so the FTTH-PON technology is of particular interest to large operators who want to consolidate their access infrastructure into a smaller number of facilities.

Splitting may be executed in two or more stages. For example, the first 1:4 splitter may feed four apartment blocks, while the final splitting into subscriber drops is done by a second splitter in each building, as presented in **Figure 8**. Such arrangement is flexible, and savings on cables are made, but the combined loss of two splitters is larger than of equivalent single device (see representative splitter specifications in **Table 2**).

In general, passive optical networks have three issues absent in P2P networks:

a. High insertion loss of splitter, rising with the split ratio, as shown in **Table 2**.

b. Sharing of OLT bandwidth between all ONTs in a PON.

c. Different transmission delays to each ONT.

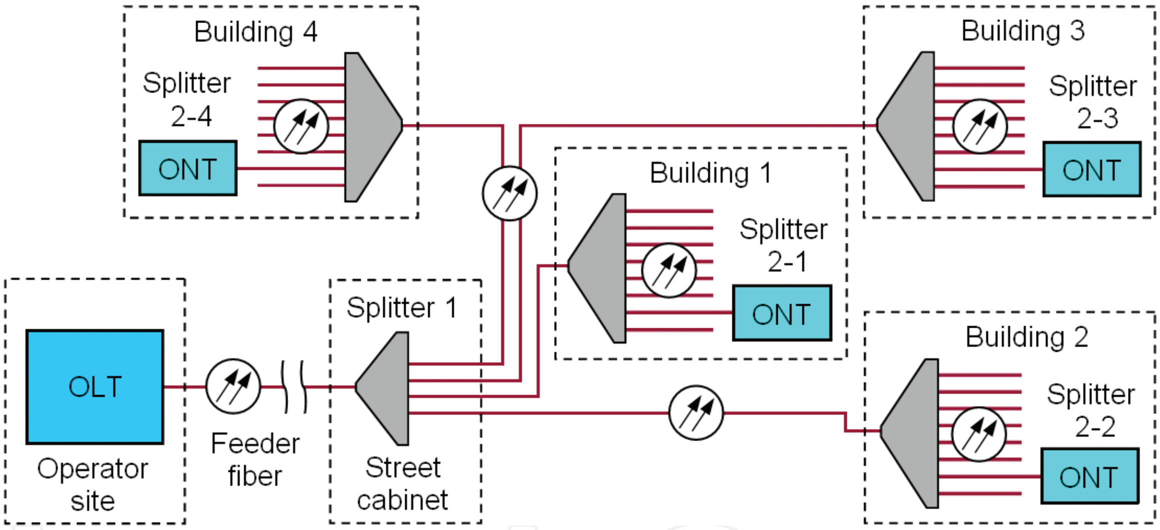

Figure 8. PON covering four apartment blocks with fiber splitting arranged in two stages.

Split ratio	Power division loss (dB)	Actual insertion loss (dB)
1:2	3.01	≤ 4.0
1:4	6.02	≤ 7.3
1:8	9.03	≤ 10.7
1:16	12.04	≤ 13.8
1:32	15.05	≤ 17.0
1:64	18.06	≤ 20.5

Table 2. Insertion loss of fiber splitters: (a) theoretical value calculated for equal division of power between ports and (b) actual data of commercial splitters for the 1260–1650 nm band [18].

Splitter loss rises by approx. 3.5 dB with doubling of the split ratio and is the largest part of loss of the OLT-ONT path. In a typical PON with a 1:32 split, the combined loss of splitter and drop fiber with connectors is approx. 19 dB, while 10 km of feeder fiber with 0.35 dB/km attenuation at 1260 nm, plus a 0.1 dB splice every 2 km, contributes only 4 dB. In a network built in a dense urban environment, splitter loss consumes up to 75% of OLT-ONT loss budget, which, depending on the version of transceivers, is between 20 and 33 dB, of which 2–3 dB shall constitute a margin allocated for equipment aging, repair splices, etc.

Loss calculations are made for the shortest operating wavelength in a given PON (**Table 4**), at which currently manufactured single-mode fibers exhibit the highest attenuation.

As a consequence, upgrade of existing PON to a higher split ratio is hard because there is usually no adequate loss margin, and replacement of transceiver modules with another type having higher loss budget is very costly and requires visits to all subscribers.

Sharing of OLT bandwidth between multiple ONTs is arranged by time division multiplexing (TDM) of data packets sent in both directions. Duration of frame is 125 μs in GPON, XG-PON, and XGS-PON systems and 2 ms in EPON.

Typical PON exhibits large differences in distances from OLT to each ONT and corresponding transmission delays. An exception to this rule is a PON covering one apartment block, with a single splitter and all connections to apartments made with patch cords of equal length. Standards require FTTH-PON equipment to tolerate (compensate) differential fiber distance up to 20 km, corresponding to 200 μs of round-trip differential delay. Transmission delay between OLT and ONT is measured when ONT is activated for the first time; this procedure is known as “ranging.”

5.2.2. Development and standards

Standardization of FTTH-PON systems is carried out by IEEE—as part of Ethernet technology and the Technical Standardization Section of International Telecommunication Union (ITU-T). ITU-T traditionally caters for needs of large operators, with considerable attention given to network monitoring and management. ITU-T Recommendations G.988 [19] and G.997.1 [20] cover management of FTTH-P2P, FTTH-PON, G.fast, VDSL2, and ADSL systems in a uniform way, which is important for incumbent operators using both copper and fiber infrastructures. In contrast, the voluminous IEEE 802.3 Ethernet standard [7] is aimed at fast, low-cost implementation in diverse environments, including core and metro networks, data centers, LANs, etc. Management and maintenance of EPON and 10G EPON networks are covered by a separate, relatively new 1904.1 standard [21].

In agreement with demand evolution presented in Section 2, the main direction of development is the increase of system capacity by periodic introduction of new active equipment (**Figure 9**), while the passive fiber infrastructure is retained. A summary is shown in **Table 3**. While high split ratios up to 1:256 are included in several standards, both the need to reuse existing passive infrastructure and rising demand for 1 Gb/s services while OLT operates at 10 Gb/s or 2.5 Gb/s keep them between 1:16 and 1:64.

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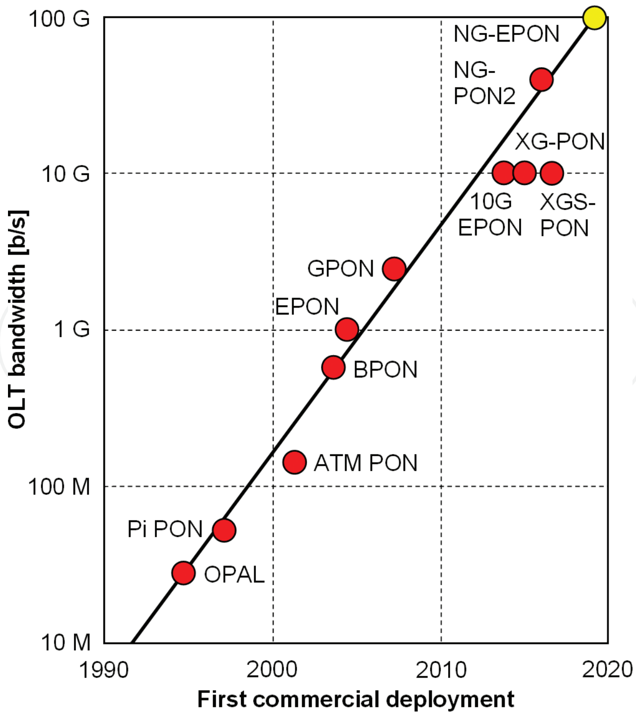

Figure 9. Evolution of OLT bandwidth with time. Date of NG-EPON introduction is estimated.

System	EPON	GPON	10G EPON	XG-PON	XGS-PON	NG-PON2
Standard(s)	IEEE 802.3 [7]	ITU-T G.984 [6, 24, 25]	IEEE 802.3 [7]	ITU-T G.987 [26, 27]	ITU-T G.9807.1 [28]	ITU-T G.989 [29, 30]
Standardized	2004	2003	2009	2010	2016	2010
First deployed	2004	2007	2014	2015	2017	2016
Multiplexing	TDM	TDM	TDM	TDM	TDM	TWDM
OLT downstream bit rate (Mb/s)	1000	2488	10,312	9953	9953	≥4 * 9953
OLT upstream bit rate (Mb/s)	1000	1244	1000 / 10,312	2488	9953	≥4 * 2488
Rate asymmetry	1:1	2:1	10:1/1:1	4:1	1:1	4:1
Reach (km)	20	20	20	40	40	40

Notes: (a) XG-PON is also known as NG-PON1; (b) ITU-T Recommendations are issued as series, e.g., G.987., G.987.1, etc.; (c) all IEEE standards, first separate, are now part of 802.3; (d) date of standardization applies to issue of the first document; (e) GPON capacity data refer to dominant "best practice" variant.

Table 3. Comparison of FTTH-PON systems in use or planned for deployment.

XG-PON, XGS-PON, and NG-PON2 systems are based on a common set of technologies, including management, TDM multiplexing, and ranging; differences are in OLT capacity and optical interfaces. XG-PON was standardized in 2010, when subscribers downloaded a lot of data, watching movies, downloading video clips and music, or browsing, but uploaded much less (except for users of peer-to-peer networks, but ISPs did not like it). At the same time, the XGS-PON project was halted due to lack of interest among major telecom operators.

Development work at ITU-T shifted to further increase of OLT capacity. However, increase of bit rate at a single-carrier wavelength to 40 or 100 Gb/s for transmission over a standard single-mode fiber 20–40 km long requires multilevel coherent modulation and detection, complemented by digital compensation of fiber dispersion [22]. This technology has been successfully implemented in core and metro networks after 2006 but is too complicated and costly for access networks. The dense wavelength division multiplexing (DWDM) technology was adopted instead, with a low number of wavelengths: 4 or 8. The combination WDM and TDM multiplexing is abbreviated as TWDM. To save energy, NG-PON2 includes the option of deactivating some wavelengths during periods of low traffic. However, while WDM transmission in a PON with spectrally non-selective splitter enables “stacking” of multiple physical PONs into a single logical PON of larger capacity, the full use of this feature requires expensive and not yet technically mature transceivers with tunable transmitters and receivers. As in case of WDM-PON (5.2.3), network operators became wary of high costs, not supported by profits achievable in the price-sensitive access market.

By 2015, big operators like Verizon (the first large customer for GPON) requested XGS-PON back, as the demand for symmetrical Internet access grew large and symmetry was important to compete against cable TV operators, whose DOCSIS 3.0 networks could not support it (5.1).

In 10G EPON, the option of having two upstream bit rates mitigated the symmetry issue, but relatively high cost of 10 Gb/s transceivers in comparison to 2.5 Gb/s devices for GPON equipment delayed its deployments, and GPON dominates since 2010. The commercial use of 10G EPON was limited to linking switches in FTTB networks in China until 2016 [23].

IEEE began to work on NG-EPON standard including TWDM multiplexing and Nx25 Gb/s bit rate in 2015. This requires replacing the simple two-level (on/off and NRZ) modulation with more complex solutions to achieve a 20 km reach. A prototype 4x25 Gb/s symmetric PON system developed at Huawei Technologies was tested together with BT Openreach in 2017.

5.2.3. Overlay operation

Upgrade of FTTH-PON running out of capacity or not supporting gigabit services may include gradual conversion to a new standard with “overlay” operation of OLTs and ONTs belonging to two generations in the same ODN. Purchases of new equipment are spread over time, initially to fulfill orders from new customers or for new services, without replacing working equipment at customers unwilling to upgrade.

Overlay operation is ensured by allocation of separate wavelength bands, shown in **Table 4**, for each of the three system generations: (1) GPON, (2) 10G EPON, XG–PON, and XGS–PON, (3) NG–PON2 (see **Table 3**), except for old GPON devices. The 1550–1560 nm band is reserved for analog TV distribution. WDM multiplexers and wavelength blocking filters must be installed at OLT and ONT locations [30], adding combined loss up to 2 dB.

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System	EPON	GPON	10G EPON, XG-PON, XGS-PON	NG-PON2 (TWDM-PON)
Downstream (OLT to ONT)	1480–1500	1480–1500	1575–1580	1596–1603
Upstream (ONT to OLT)	1260–1360	1290–1330[1]	1260–1280	1524–1544[2]
Distribution of TV programs	1550–1560	1550–1560	1550–1560	1550–1560
Monitoring of fiber network	1625–1675	1625–1675	1625–1675	1625–1675

(1) Initially 1260–1360 nm. (2) ITU-T G.989.2 [30] sets also narrower bands: 1528–1540 nm and 1532–1540 nm.

Table 4. Wavelength bands allocated to FTTH-PON systems (values in [nm]).

This arrangement does not cover 1 Gb/s EPON systems, still having a very wide band allocated for upstream transmission. To avoid collisions, 1G and 10G EPON upstream data must be separated in time domain, but implementation of this feature by equipment manufacturers is not universal.

5.2.4. WDM–PON

In this type of PON, each ONT uses a unique wavelength or a pair of them, and splitter is replaced with a WDM multiplexer. WDM-PON is logically a set of P2P connections between OLT and each ONT at different wavelengths. This eliminates issues [(a)–(c)] in PON networks (Section 5.2.1), and each subscriber can use full bandwidth of OLT port.

Despite trials in South Korea [31], Malaysia, and the Netherlands, WDM-PON was neither standardized nor commercially adopted. The main reason is the cost of transceiver modules, because DWDM technology with 100 GHz channel spacing is required to ensure similar split ratio (1:16 or more) as in FTTH-PON networks and reuse passive infrastructure. The fiber split ratio is doubled with reuse of the same wavelength for transmission to and from ONT and is made possible by adding a high-power broadband light source at the OLT site and remodulation of spectral slice of this radiation filtered by the WDM multiplexer with upstream data at ONT. However, cost and stability of such system during tests were not acceptable [32].

5.2.5. Comparison of P2P and PON networks

Despite the dominance of FTTH-PON technology in literature, which can be explained by its relative complication and many standards shown in **Table 3**, worldwide deployments are, in fact, split almost 50–50% between P2P and PON networks. Each of them has its merits, and investor must carefully choose the best option in local conditions. Properly installed passive fiber infrastructure, while expensive, has a very long lifetime estimated at 40 years, so the selection of network technology has lasting consequences.

Relative advantages of FTTH-P2P technology include:

– Flexibility: subscriber loops are physically separate; may work with different equipments, wavelengths, bit rates, etc.; and be selectively upgraded as needed.

– Security: data are sent from OLT to one ONT only and are not accessible to others.

– Unbundling: individual fiber loops can be leased to any operator and for use with any type of transmission equipment without restrictions.

– Fibers can be diverted to other uses by the operator, like backhaul and fronthaul links to wireless base stations, Ethernet links to business customers, etc.

– Low loss of subscriber loops, because there is no splitting.

– Distances to customers limited only by power and dispersion budget.

– Simple diagnostics of subscriber loops.

The FTTH-PON option is superior in the following respects:

– Construction costs are lower due to smaller mileage of optical fibers, cable installation costs (pulling, splicing, etc.), and fewer OLT ports; the cost of P2P network can be up to 30% higher in comparison to PON [16], but estimates depend considerably on characteristics of deployment area and local labor costs.

– Lower demand for space in ducts to lay optical fiber cables; additionally, a P2P network in a large city may require cables with very high fiber counts, up to 1000.

– Less space required for OLT equipment and optical distribution frame at the CO.

– Considerably lower power consumption of OLT equipment.

P2P network is not necessarily more reliable in service. The dominant type of network fault in urban or suburban area is a cable cut affecting all fibers in the cable and all customers in the area fed by it, regardless of fiber splitting. However, the repair of large fiber count cable typical in the feeder segment of P2P network takes more time and money. The advantage of P2P network is that a defective, continuously transmitting "rogue" ONT does not jam any other, so only one subscriber loses a service, while in a PON, all customers are affected.

In terms of access speeds, both types of networks (with up-to-date active equipment) can support 1 Gb/s services; upgrade to 2–10 Gb/is possible, although expensive.

Market regulators in Western Europe often display preferences for P2P networks due to possibility of fiber unbundling, support for multiple service providers, and compatibility with the idea of separating wholesale infrastructure operators from retail service providers. However, cost comparisons and shortage of duct space favor the FTTH-PON option, as far as large incumbent operators like Orange, Telefonica, NTT, or Verizon are concerned.

5.2.6. Passive optical LAN (POL)

This is an optical fiber LAN based on GPON, XG-PON, or EPON technology (Section 5.2.1 and 5.2.2). Advantages of POL over LAN with twisted-pair cabling include:

– Elimination of the 100 m distance limit.

– Total immunity to electromagnetic interference.

– Better security (fiber tapping is relatively difficult).

– Light, compact cables (fiber cable, 2–3 mm; UTP cable, 6–7.5 mm).

While the NT in LAN is built into a PC, printer, etc., the ONT in fiber network is usually a mains-powered stand-alone device, typically having four twisted-pair RJ45 data ports (10/100/1000 Mb/s) and a telephone socket.

5.2.7. Cost issues

Provision of consumer Internet access and video services in fixed access networks in most countries is a highly regulated and competitive business, with exceptional price sensitivity and lower profit margins in comparison to mobile or business services.

As shown in **Table 5**, the relative cost of building an FTTx network in area already having a copper network rises with the degree to which the copper loops are replaced with fibers.

The FTTH option involves full replacement of existing copper plant with fiber optics. While the conversion greatly reduces demand for space in cable ducts and buildings, construction is costly and disruptive. A temporary overlay of old and new infrastructure is inevitable, especially when rapid switchover is hampered by regulations protecting customers and alternative operators making use of local loop unbundling. Most money is spent on passive network, with design, cables, accessories, and installation costs constituting 60–75% of the total [33], similarly as was the case with copper telephone network 50 or 100 years ago. The proportion rises with labor costs and restrictions on digging and building access (6.1), putting Western European countries at considerable disadvantage.

Total cost per home passed strongly depends on characteristics of deployment area: population density, terrain, availability of existing ducts or poles, type of buildings, CO locations, rights of way, etc. [34, 35]; published estimates range from 200 up to 6000 EUR. This dependence is much stronger than in wireless networks (7.2), precluding commercial deployment of FTTH networks in sparsely populated areas, despite their excellent performance with loop lengths up to 40 km and even more (5.1, 5.2).

Cost component	New cabling	Remote units	OLT, ONT	Remarks
FTTN	—	**	*	Reuse of existing copper drops, few remote units
FTTC	*	***	*	Many remote units—power and permit issues
FTTDp (G.fast)	*	****	**	Many small remote units, nonstandard locations
FTTB	**	**	*	Switches and new cables in buildings (≤ 100 m)
FTTH-P2P	****	—	****	Full replacement of copper with fiber, very disruptive
FTTH-PON	***	—	****	As above, but less fibers and equipment at the CO

Table 5. Relative cost components of different FTTx access networks (see **Figure 4**). Remote units include Ethernet switches of FTTB networks (4.2) located in apartment blocks.

The FTTH-P2P option, most flexible, supporting multiple operators and easy to upgrade (5.2.5) is also the costliest because no fibers are shared between multiple subscribers. Therefore, market regulators shall support joint investments and cost sharing between operators, taking into account long life (approx. 40 years) of and low operating costs of passive fiber plant. On the contrary, heavy-handed unbundling requirements applied to incumbents in several European countries have stopped FTTH investments and created conditions for proliferation of HFC networks with inferior technical performance (7.1) and hard-to-break monopoly on provision of broadband services.

Cost of passive infrastructure can be significantly (20–30%) reduced with optimized design of cable routes, splitting ratios and points, etc. after analysis of service area [34]. Investors must also analyze demand for services and assume realistic take-up rates to avoid overinvestment, especially in areas with competing service providers. Average take-up rates in Europe range from 10 to 35% and differ widely.

Contrary to big upfront investment in passive infrastructure, most expenditures on active equipment in FTTH networks result from installation of OLT and ONT devices after orders from subscribers are received and are roughly proportional to service take-up rate. Here, the typical cost is between 100 and 400 EUR per subscriber, depending on the system chosen.

Equipment costs tend to dictate selection of FTTH-PON technology. While trials of new systems are reported within months of its standardization, mass introduction often waits before prices drop and demands of customers overwhelm capabilities of older systems. An example is delayed, and selective adoption of 10 Gb/s FTTH-PON systems, standardized in 2009–2010 (**Table 3**), but waiting for large deployments till 2016–2017, when subscribers finally wanted 1 Gb/s services the EPON and GPON networks could not deliver.

Now, this mechanism works in favor of XGS-PON, and against the more advanced and earlier standardized, but some 30% costlier NG-PON2. In the future, it will significantly delay rise of bit rate on a single wavelength above 10 Gb/s (2.2, 5.2.2).

6. Passive fiber technologies for access networks

Here, we focus on changes and progress in this field during the last decade.

6.1. Fibers and cables

FTTx access networks, particularly of FTTH-P2P type (5.1), require large volume of optical fiber cabling, frequently installed in challenging conditions:

a. In crowded underground ducts.

b. In old buildings, where laying cables is considered invasive and restricted.

c. In apartments, where cables are subject to rough handling: sharp bends, stapling, etc.

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The primary solution to problem (a) is reduction of fiber and cable diameter. Because single-mode fibers must retain standardized 125 μm cladding diameter [4, 8] for compatibility with existing tools, fusion-splicing machines, connectors, etc. and adequate handling strength, savings are made on protective coatings and cable elements, by:

– Cutting coating diameter from 250 to 200 μm (56% more fibers in the same space).

– Using microcables with thin sheath (approx. 0.5 mm), tight-fitting tubes, marginal strength member, and outer diameter reduced to 1.5–9.6 mm.

– Subdivision of secondary cable ducts (32–40 mm) into 3–12 "microducts," intended exclusively for blowing of fiber microcables.

– Replacement of cable pulling with blowing, using special machines for microcables.

– Using thin (1.2–2 mm) indoor cables where conditions allow.

In 2013, a 9.6 mm microcable with 288 fibers appeared, while an equivalent "traditional" cable with stranded loose tubes 20 years ago had a diameter of 18–20 mm. As a result, four such microcables can be installed in a secondary duct instead of one conventional cable.

Most of these changes are made possible by development and mass adoption of "bending-tolerant" and "bending-insensitive" single-mode fibers. They retain stable attenuation while subjected to macrobending at radius reduced (depending on fiber category and loss limits) to 3–15 mm [8] rather than 30 mm in telecom fibers intended for other applications [4]. This enabled also significant, approx. 50%, size reduction of splice cassettes, joint closures, termination boxes, or distribution frames with LC connectors (4.2).

Problem (b) is partly alleviated by making cables thin or alternatively flat, and in color matching the one of wall, usually white or cream. Installation in "sensitive" areas requires the use of suitable attachment methods to follow the shape of wall corners, door frames, etc. and, if necessary, masking accessories. Still, some 30% of managers of historic properties in Western Europe say "no" to any drilling. But how were the much bulkier telephone and power cables installed there 80 or 100 years ago? Or the water and sewer pipes?

Problem (c) appears when fiber cables entering houses and apartments are hastily installed by poorly trained personnel, stapled to wall corners, or passed through working surfaces of doors or windows (no drilling, please!!!). Because of multiple sharp bends, crushing by staples or pulling, the use of "bending-insensitive" (ITU-T G.657.A2 or B3 [8]) fiber is a must, together with a special 4.5 mm cable of design allowing the fiber to smoothly bend *inside* the cable when its jacket is firmly pressed against a 90° corner or squeezed by a staple.

6.2. Connectors, splitters, and filters

In this area changes are less disruptive, but ones worthy of note include:

– Proliferation of LC connectors with 1.25 mm ferrule (**Figure 10**), smaller, more durable, and less sensitive to the use of lower-grade plastics than SC connectors.

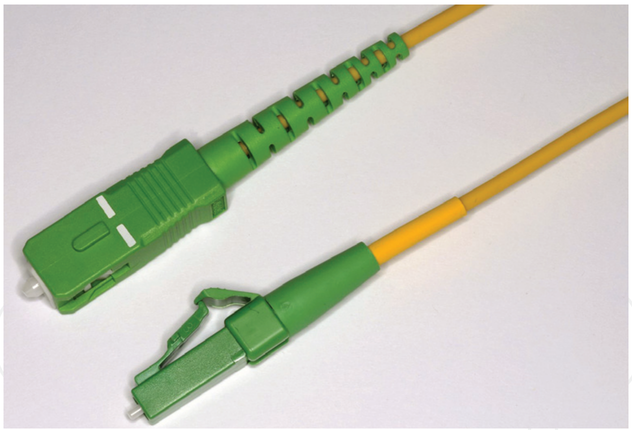

Figure 10. Comparison of fiber connectors: SC (top) and LC (bottom) (couplers not shown).

– Mandatory inspection of connector endfaces before making a connection, with availability of portable multifunction test instruments including ferrule inspection cameras and adoption of IEC 61300–3-35 standard for endface quality [36].

– Steadily rising demand for WDM multiplexers and bandpass blocking or reflecting filters for FTTH-PON networks and monitoring of fibers with a 1650 nm OTDR.

– Abortion of plans to introduce very high-fiber split ratios like 1:256 or more; commercial splitters are available with up to 64 or (rarely) 128 ports (5.2.2).

7. Alternative broadband access technologies

7.1. Coaxial cable TV networks

These originally served for one-way distribution of analog TV programs (since 1948), but were later upgraded, in particular by introduction of return channel for telephone services (1980s) and data services (1990s). Coaxial cable has two main advantages over twisted pairs:

– Wide bandwidth: the frequency range is up to 550–862 MHz in most networks, and 1218 MHz in early implementations of DOCSIS 3.1, being limited rather by available amplifiers than characteristics of the cable.

– Effective shielding against cross talk and external interference.

The attenuation of coaxial feeder cable is high: 40–130 dB/km at 800 MHz vs. 0.25–0.50 dB/km for a single-mode fiber with splices, and periodic amplification is required. Therefore, cable network includes more and more optical fibers in the trunk segment, being known as hybrid fiber-coaxial (HFC) networks.

Typical network in Europe uses the 85–862 MHz (777 MHz wide) band downstream (most of it for distribution of TV and radio programs) and 20–65 MHz (45 MHz wide) upstream.

Standards for data segment of cable TV networks, known as data over cable service interface specification (DOCSIS), are developed by Cable Television Laboratories (CableLabs). Current implementations conform to DOCSIS 3.0 standard, first issued in 2006 [37], while the latest is DOCSIS 3.1 [38] published in 2013.

In DOCSIS 3.0, data are modulated on carriers replacing selected video channels in both directions. The resulting downstream data rate per channel is 38 Mb/s and 50 Mb/s in the USA (6 MHz channels) and Europe (8 MHz channels), respectively, and 27 Mb/s upstream; channel bonding is possible. Maximum capacity is 1216 or 1600 Mb/s downstream and 216 Mb/s upstream. It is shared between all subscribers using the same feeder cable, as in FTTH-PON network.

In DOCSIS 3.1, widening of the upstream band to 204 MHz and downstream band to 1218 or 1794 MHz and spectrally effective QAM-1024 modulation increased the capacity to 10 Gb/s (downstream) and 1 Gb/s (upstream), as in the asymmetric variant of 10G EPON (**Table 3**).

Internet access in cable TV networks is impaired by low upstream capacity; the ratio of upstream and downstream bit rates offered by operators of DOCSIS 3.0 networks is 1:20 or more compared to between 1:10 and 1:1 in FTTH and FTTB networks (5.1, 5.2).

The fastest Internet access provided in DOCSIS 3.1 networks in 2017 was no exception: 35 and 1000 Mb/s or 1:28.6.

This problem is to be eliminated in Symmetrical DOCSIS 3.1 system announced by Intel in 2016, where echo cancelation in a fully passive coaxial node without amplifiers shall allow the use of full frequency range to transmit in both directions at 10 Gb/s [39]. Corresponding CableLabs standard, known as Full Duplex DOCSIS 3.1 (FDX), was issued on October 2017.

Despite upgrades made to DOCSIS, optical fibers and EPON, 10G EPON, GPON, or XG-PON equipment are introduced in many cable TV networks. However, the provisioning of FTTH equipment is performed using DOCSIS-based systems and policies, enabling uniform management of fiber-based and coax-based network elements and services. In such case, the DOCSIS service layer interfaces to media access control (MAC) and physical (PHY) layers of FTTH-PON network. This architecture was developed and standardized since 2013 by CableLabs and known as DOCSIS Provisioning of EPON (DPoE) or GPON (DPoG).

7.2. Broadband wireless access

7.2.1. 4G: LTE and LTE-A

This is the first generation of cellular networks providing a (moderately) reliable Internet access at rates up to 120 Mb/s (LTE, 2 x 20 MHz spectrum) or approx. 300 Mb/s (LTE-A), but such performance is available only for a single user in area served by one sector of base station. With more users, capacity is shared between them, with up to 60% of it being lost.

Despite modest (by the standards of fiber networks) performance, LTE made large impact when introduced around 2012. An interesting case is Japan, a country where FTTH networks exist since 2001 and pass majority of population. However, as can be seen in **Figure 11**, LTE networks eclipsed all fixed networks within 3 years, with a slowdown of demand for new FTTH connections, particularly from young, single, and mobile persons [40, 41]. Growth in new FTTH subscriptions resumed only after the incumbent carriers NTT East and NTT West

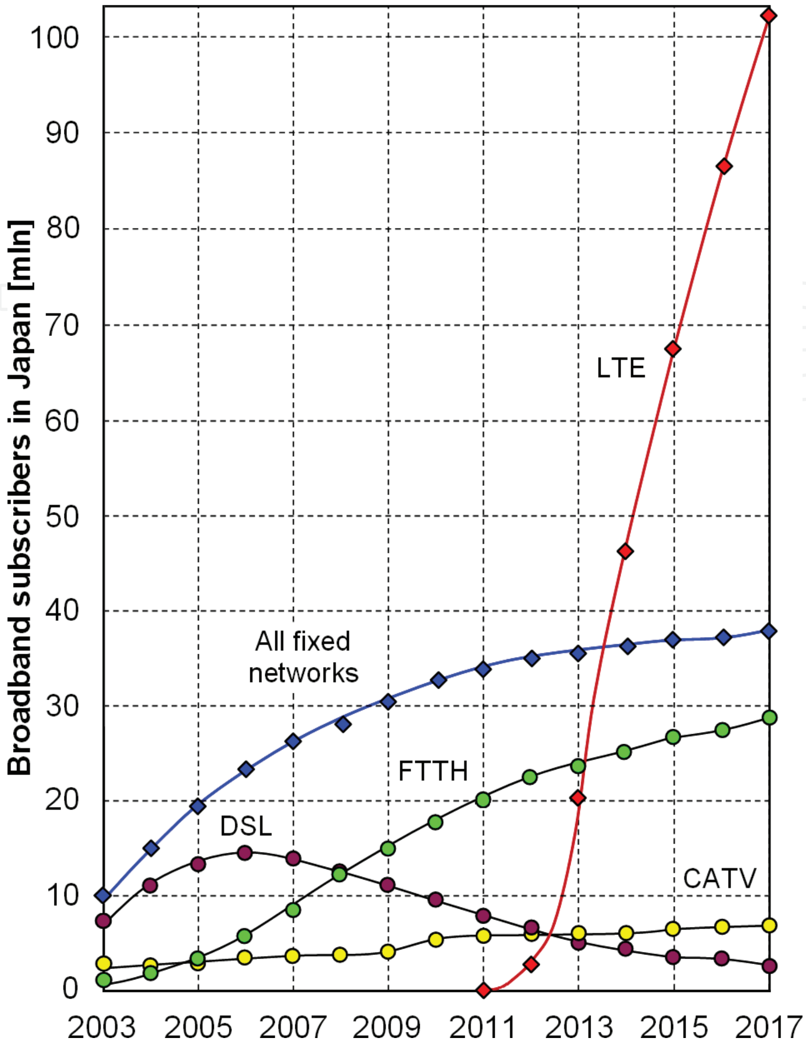

Figure 11. Broadband subscribers in Japan by access technology [41] (data for march of each year).

took the unprecedented step of expressly *inviting* other companies to use their fiber networks within the "Hikari Collaboration Model," and offering dedicated application programming interfaces, technical support, service test environment, etc. in 2014. In 2016, the same companies were the first to introduce software-defined networks (SDN) technology to FTTH networks in a drastic attempt to reduce costs.

7.2.2. 5G: The network of the future?

The set of technologies constituting the fifth generation (5G) of mobile systems, to be standardized in 2020, is not fully defined yet, but performance goals include 1 Gb/s access for a mobile user (with multiple users served by a single base station) and 10 Gb/s for a fixed one [42]. Interestingly, the first use of 5G technology announced by the US operator Verizon for 2018 will be in fixed networks in areas where laying fibers to subscribers is not economical; data rates up to 3.6 Gb/s were reported after trials in 2017.

In the full version, 5G networks will offer mobility and support for unlimited number of user devices without setting up a home network. Lessons from LTE deployments (7.2.1)

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suggest that after 2025, 5G wireless and its successors can permanently dominate access market, providing universal broadband service after demise of copper networks. The main difficulties in commercial deployments will be high cost and construction of backhaul and fronthaul links; the necessary capital will likely be reassigned from FTTx projects. FTTH and FTTB networks built before will remain in service due to superior quality of service and excellent handling of large volumes of data (8 K video, business applications, etc.), but their expansion is likely to be curtailed.

8. Transition from copper to fiber

8.1. Service continuity in emergency situations

Access to voice services in emergency situations (fire, hurricane, blackout, etc.) is of critical importance for public safety. In a traditional telephone network, central office has backup batteries and generators, while telephone sets are remotely powered over the copper loop.

In FTTx network, the termination installed at subscriber's premises (NT or ONT) is locally powered from the mains. The same applies to cable modem (CM) in a cable TV network.

Several major disasters, in particular hurricanes, recorded in the twenty-first century included loss of mains power for up to 15 days [1], so the communications infrastructure providing basic voice services shall be able to operate without mains power as long as possible.

Remote units in FTTN/FTTC networks (usually located in street cabinets) have batteries providing backup power for 2–8 hours, and traditional telephone sets still work being powered over the twisted pair. However, this duration is not enough in many emergencies.

The most acute problem is powering of equipment at customer's premises: NT, ONT, or CM.

These devices usually consume 5–25 W and are typically powered by 12 V DC from a mains adapter. Backup power can be provided by a rechargeable (sealed lead-acid) or non-rechargeable (alkaline) battery; ONT provides battery charging and monitoring. A typical 5 Ah lead-acid battery can provide power for approx. 8 h. A bank of eight D (LR20) alkaline batteries may power the ONT for 24 hours and can be stored for approx. 10 years.

To prolong operation on backup power, ITU-T G.988 standard for management of GPON, XG-PON, XGS-PON, and NG-PON2 networks [19] includes several options for selective deactivation of nonessential functions to reduce energy consumption after loss of mains power. Alas, most network operators treat backup power as a cost item rather than a safety feature. In the USA, the country frequently affected by hurricanes, twisters, and earthquakes, the telecom regulator (Federal Communications Commission) imposed a requirement for an 8-h backup power at ONTs since 2015, and 24 h beginning from 2018 [43], but installation is not mandatory. It is made at the request of a customer, and charges apply.

Replacement of rechargeable battery is required after approx. 5 years. It usually has to be done by the subscriber, after the operator remotely detects signs of battery aging and mails a replacement unit; the old battery is sent back for recycling.

All this provides continuity of voice service, if the subscriber still has a traditional, wired phone attached to the ONT. The portable, wireless phone does not work during mains failure, as the docking station has no backup.

8.2. Remote powering

DSLAMs and other active equipments located in remote units, usually street cabinets, can be powered from the central office or other large operator's sites via a bundle of free copper pairs in existing telephone cable, working at DC voltages up to 800 V with automatic current limiting to 60 mA for safety (RFT-C system). System working on a bundle of ten pairs with 0.5 mm wires can deliver 250 W of power at distances up to 5 km [44].

Another option is laying a special hybrid cable, comprising both copper power conductors of larger size and optical fibers, with a metallic screen over the core. In this case, a dedicated DC power system is used, with power conductors insulated from the ground, known at Isole Terre (IT) or remote feed for telecommunications with limited voltage (RFT-V) and operating voltage up to ±200 V. For electrical safety, the system can detect a leakage between power conductors and ground, e.g., when the cable is damaged [45]. The RFT-V system normally uses twisted pairs from a telephone cable and has power output limited to 100 W per circuit.

Remote powering has attracted considerable interest of network operators in Europe after 2010, as it allows to avoid costly and cumbersome local powering from commercial AC power network and greatly improves network resilience to power failures. However, there is no consensus on the best technology yet.

Remote powering is implemented in G.fast systems (4.1), where the DPU is jointly reverse powered by all active NTs. However, this arrangement is aimed at simplifying DPU installation and does not protect against mains failure.

Power over Ethernet (PoE) is standardized for LANs [7], where a DC power (up to 57 V and 960 mA) and data share the same copper pairs, with each power circuit utilizing the difference between common mode voltages in two pairs ("phantom circuit"). PoE technology can, in principle, be used to provide interruptible power to NTs in FTTB networks (3.4, 4.2), ensuring continuity of voice service.

8.3. Dismantling of legacy copper plant and regulatory issues

The fate of copper cable plant and conventional telephone switching systems is sealed:

- Telephone cable networks in developed countries are old (40–80 years) and deteriorated, with frequent failures and rising maintenance costs.

- Most existing copper loops do not support true broadband services (4.1).

- The number of subscribers to traditional telephone services has been falling since 2000 due to migration to mobile networks or VoIP services; in the USA, the proportion of households with wired phone fell from 93% in 2003 to 25% in 2013 [46].

- Servicing and spare parts for TDM telephone switching systems are often no longer available, the equipment is fully deprecated, and technical specialists are retiring.

- Wired networks are saddled with extensive regulatory obligations, primarily universal service and local loop unbundling the incumbent operators want to get rid of [47].

Retaining copper network is rejected due to added maintenance costs and the need to vacate cable ducts for optical fiber cables. From the operational point of view of incumbent operator, the migration toward FTTH or LTE/5G wireless is inevitable. The only issues are:

- Deadline, estimated as approx. 2025.

- Type of new infrastructure: fiber or wireless (or both, chosen depending on area).

- Response of market regulators and consumers.

Large-scale dismantling of copper network has already begun in Spain, Portugal, and the USA. In the last country, the largest wireline operators AT&T and Verizon have reportedly stopped maintenance of copper networks around 2005, including open refusals to perform any repairs [48]. As a result, deteriorating quality of service and frequent outages force customers to migrate to a fiber or wireless network.

9. Summary

There are several competing fixed broadband access technologies, and the case for FTTH networks is not made simpler by existence of two standard bodies, ITU-T and IEEE. The winner may ultimately be the 5G wireless, offering the mobility most customers want.

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