MASTERARBEIT

Power Efficiency of State-of-the-Art and Advanced Wired Access Networks

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“Hvala ti Majko, hvala ti Oče…” ;-)

Vienna, January 2010 *Ana Lovrić*

Abstract

According to the global trend of “green technology”, power consumption of electronic equipment is becoming a very important issue, which among other fields concerns also the information and communication technology (ICT). The entire communication and information network infrastructure contributes increasingly to the world’s electricity consumption. The most significant contributor among network subsystems is the access network. Taking into account the impact on the environment as well as the potential savings of operational costs by using highly power-efficient networks, it is of great interest to estimate and compare the power consumption of different access network technologies.

This master thesis gives an overview of different wired state-of-the-art and advanced technologies for implementing access networks as well as a comparison of those technologies with respect to power consumption. The state-of-the-art networks with copper-wired access, which are considered in this work, are digital subscriber line (DSL) and hybrid fiber-coaxial (HFC) technologies, both based on the fiber-to-the-node architecture. Fiber-to-the-home networks that are considered in this work are time-division multiplexed passive optical network (TDM PON) and point-to-point optical Ethernet network. Apart from the mentioned state-of-the-art wired access networks, this master thesis takes into account one wireless access technology, namely the worldwide interoperability for microwave access, i.e., WiMAX. The work focuses also on advanced and currently not widely deployed access options, which support higher bit rates and a larger number of users. Such access technologies are 10 Gbit/s Ethernet PON (10G-EPON), wavelength division multiplexed (WDM) PON, hybrid TDM/WDM PON and long-reach PON. Additionally, the main features of future Ethernet components and systems operating at 40 Gbit/s and 100 Gbit/s data rates, which are the scope of the new Ethernet standard IEEE 802.3ba that is expected to be completed mid-2010, are given. Finally, the description of the assumed network models is provided. The considered access technologies are compared with each other regarding their energy efficiency. The obtained results show a generally higher energy efficiency of optical access solutions in comparison to electric (i.e. copper-based) wired access. It is also shown that the hybrid TDM/WDM PON has the potential to provide the highest energy efficiency, in contrast to the WiMAX which has the highest power consumption.

Kurzfassung

Im Bezug auf den globalen Trend zu “grünen“ Technologien werden sowohl Leistungsfähigkeit als auch Energieverbrauch der Netzinfrastruktur zu sehr wichtigen Themen, die nicht nur im IKT (Informations- und Kommunikationstechnologie)-Bereich sondern auch in anderen Wirtschafts- und Sozialbereichen an Wichtigkeit gewinnen. Die gesamte Infrastruktur der Kommunikations- und Informationsnetze trägt zunehmend zum weltweiten Stromverbrauch bei. Den größten Beitrag unter allen Netzsubsystemen leistet das Zugangsnetz. Im Betracht der Einführung neuer energie-hocheffizienten Netzkonzepten und möglichen Auswirkungen auf die Umwelt so wie potenziellen Betriebskosteneinsparungen wird es immer wichtiger den Leistungsverbrauch unterschiedlicher Zugangsnetzlösungen zu bewerten und zu vergleichen.

Diese Masterarbeit gibt einen Überblick über verschiedene drahtgebundenen Netzzugangstechologien, die derzeit entweder bereits eine breite Anwendung finden oder sich im Entwicklungs- bzw. Forschungsstadium befinden. Diese Technologien wurden im Bezug auf den Leistungsverbrauch verglichen.

Die derzeit verfügbaren kupfer-basierte Zugangsnetze, die im Rahmen dieser Arbeit betrachtet wurden, sind Digital Subscriber Line (DSL) und Hybrid Fiber-Coax (HFC) Systeme. Die beiden Systeme basieren auf der Fiber-to-the-Node (FTTN) Netzarchitektur. Die im Rahmen dieser Arbeit aufgefassten Fiber-to-the-Home (FTTH) Netze sind so genannte Time-Division Multiplexed Passive Optical Networks (TDM PONs) und Punkt-zu-Punkt Ethernet-basierte optische Netze. Neben den angeführten drahtgebundenen Zugangsnetze schließt diese Arbeit auch eine drahtlose Zugangstechnologie ein, nämlich das WiMAX - Worldwide Interoperability for Microwave Access. Darüber hinaus werden die wichtigsten Eigenschaften fortgeschrittener und derzeit nicht breit verwendeter Zugangsoptionen vorgestellt, die höhere Datenraten und eine höhere Anzahl der Anschlüsse unterstützen können. Diese Technologien umfassen 10 Gbit/s Ethernet PON (10G-EPON), Wavelength-Division Multiplexed (WDM) PON, hybride TDM/WDM PONs und PONs mit großer Reichweite. Zusätzlich werden die Hauptmerkmale der künftigen Ethernet-Komponenten und -Systeme mit Datenraten von 40 Gbit/s und 100 Gbit/s beschrieben, die im neuen Ethernet-Standard IEEE 802.3ba, der voraussichtlich Mitte 2010 verabschiedet wird, spezifiziert werden. Letztendlich wird das zur Berechnung des Leistungsverbrauchs

verwendete Netzmodel beschrieben. Die betrachteten Zugangsnetztechnologien werden im Bezug auf Energieeffizienz bewertet. Die erhaltenen Resultate zeigen eine allgemein höhere Energieeffizienz der optischen Zugangslösungen im Vergleich zu elektrischem, d.h. kupfer-basiertem, Netzzugang. Es wurde auch gezeigt, dass hybride TDM/WDM PONs das Potenzial haben, die höchste Leistungseffizienz anzubieten. Im Gegensatz dazu weist WiMAX den höchsten Leistungsverbrauch auf.

Contents

Chapter 1

1 Introduction

1.1 Background and Motivation

In many countries, more than one third of population uses regularly Internet [1]. It has become a significant element of everyday life. Its presence expands into multiple social segments starting by information sharing and searching over communication and entertaining up to a row of e-applications such as e-learning, e-health, e-government and many others. In addition to the expanding residential Internet usage there is also a growing number of small- and medium size enterprises whose business is based upon Internet. The spreading out of Internet based services contributes remarkably to the World economy. Internet influences strongly the quality of life, which hence depends more and more on the availability of low-cost broadband access. The access to the network is provided by telecommunication network operators and Internet providers, popularly known as Telcos. The connection of users to the global interconnected network starts within the access networks that are connected to the metropolitan or regional network which provides further linkage to the backbone network. The global network comprises a huge number of interconnected network devices, i.e., switches and routers. It forms a complex geographically distributed communication system with a lot of equipment that needs power supply. Figure 1.1 shows a symbolic map of a potential network in a large regional area and it helps visualizing the complexity of network interconnections. The points in the network represent active network nodes that are in reality premises housing hundreds of network servers' racks, storage devices, fans and so on. These nodes require power supply for the equipment as well as for all facilities including the necessary air-conditioning. All network nodes must be equipped with cooling systems because of high heat dissipation of network devices. According to this background it is self-evident that the power consumption of information and communication technology (ICT) networks becomes an important issue.

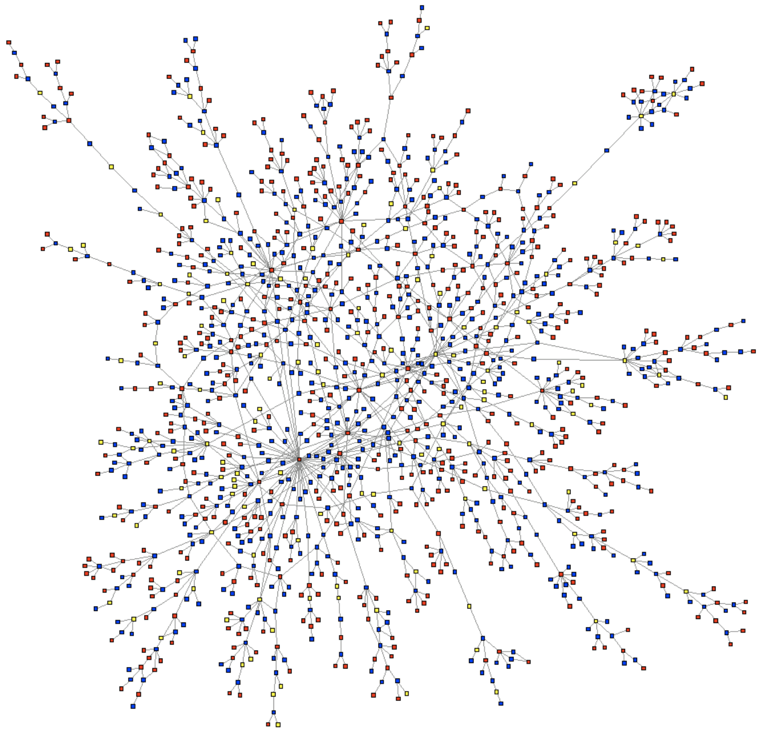


Figure 1.1 Visual representation of a network map in a large geographical area [2]

It has been estimated that ICT alone is responsible for 2% to 10% of the worldwide power consumption [3]. Researches and network operators, such as cable multiple system operators (MSO), Internet service providers (ISP) and content delivery network (CDN) operators, are forecasting tremendous growth of IP traffic. This growth is driven by many new data-intensive applications and by the number of broadband access subscribers, which is in constant increase too. Moreover, the subscribers are generating and consuming their own content (for example YouTube, Wikipedia and Facebook) and they use Internet more often and for longer periods. Several applications and high-speed services that contribute to the remarkable IP traffic growth are listed below:

- Downloading and streaming video files (Video on Demand - VoD), IPTV
- Voice-over-IP (VoIP)
- Peer-to-peer file sharing
- Teleworking, Telepresence, Teleconferencing, Telemedicine
- E-commerce, e-learning, e-government, e-health
- Entertainment content distribution, gaming
- Remote storage
- Virtual private network (VPN) services
- Mobile broadband services
- Triple-play services (convergence of VoIP, high-definition (HD) digital TV and data)

- Quadruple-play services (convergence of VoIP, HD digital TV, data and wireless access possibility)

The growing bandwidth requirements lead to a growing network infrastructure that comprises higher quantities and capacities of data transmission but this also induces a larger footprint[1]. Both increased network capacity and larger footprint induce a rise of power consumption which reflects on a larger carbon footprint[2]. According to [4] the energy consumption of Internet is growing exponentially. This is a matter of great importance since power efficiency is an economical and environmental issue. Network operators aim to lower their energy bill but also their carbon footprint since it has been estimated that ICT emissions will almost double reaching 1.43 $GtCO_2e$ by 2020. [3] Relating to the global warming, energy consumption becomes an environmental, political and social issue that refers also to telecommunication networks. Apart from the ecological aspect and the trend of “green technology”, by reducing power consumption network operators can directly influence their operational expenditures (OPEX) in a positive manner since today they deal with a high energy related OPEX.

In modeling energy consumption of Internet, three major subnetworks can be considered separately, i.e., core network, metro network and access network. Currently, the energy consumption is dominated by access networks. Due to the scaling property of access network and a great number of connected subscribers, its architecture impacts powerfully the operators’ energy consumption. Users’ networking equipment, i.e, modems, with their power inefficient operational mode, contributes significantly to the power consumption of access networks. Therefore efforts are done currently to estimate and determine the power efficiency of different access network types. Future higher-speed access networks should be more power efficient, and hence, it is a challenge to estimate which access technologies can fulfill this requirement and which should be deployed in the future.

1.2 Objectives

Today, the majority of broadband access subscribers have a wired access over telephone lines, in most cases a version of digital subscriber line (DSL). Certainly, they can have a local wireless access over a wireless local area network (WLAN) router. This is the so called fixed wireless access because the real access to the network is still wired. What is commonly understood under wireless access networks are mobile-access networks, such as WiMAX, WiFi, GSM, UMTS and others.

[1] In telecommunications the footprint means the physical space occupied by telecommunication equipment.

[2] Carbon footprint is a measure for total greenhouse gas emissions caused by a person, organization, event or product and has the unit tonnes of carbon dioxide equivalent (tCO_2e). [71]

Figure 1.2 shows the historical evolution of the wired access networks. The x-axis represents the time of the deployment that is based on historical data up to 2009 while the y-axis shows only an illustration of the deployment trend that serves as a comparison for different broadband access techniques. The first generation of broadband access, i.e., ISDN, had its peak deployment around 1995. Its successor was the ADSL with highest deployment around 2005. The ADSL curve shows also a high deployment volume in present, together with the next DSL version, i.e., VDSL, whose peak deployment is predicted to be in 2015. The generation 4 describes fiber-to-the-cabinet (FTTCab) or fiber-to-the-building (FTTB) networks, which can be described with the general name FTTx. These are broadband access solutions in which the optical fiber reaches a point of network that is very near the user and provides a high access bit rate per user. Currently, the most promising solution in terms of access capacity is the fiber-to-the-home (FTTH) access solution. Its deployment started around year 2000 and is progressing relatively slow because of the high investment costs needed for the new optical-fiber network infrastructure. That is why the generation 4 is a realistic transition step toward the FTTH and is expected to dominate in the near future. An overall comparison of different generation diagrams shows a constant growth of broadband access deployment, i.e., Internet users over time (see the dashed line).

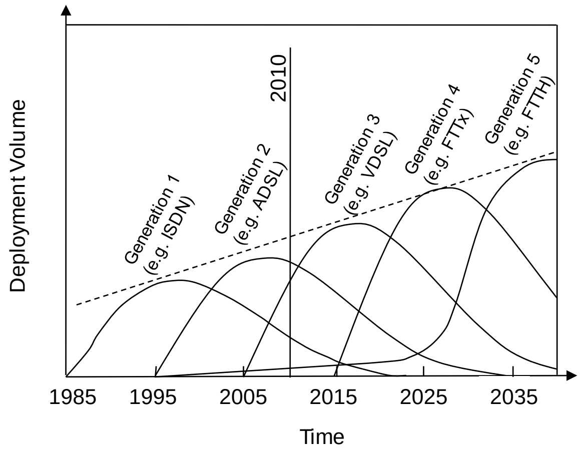


Figure 1.2 Evolution of access technologies and their deployment trends [1] ISDN: integrated services digital network, ADSL: asymmetric digital subscriber line, VDSL: very high-bit rate digital subscriber line, FTTx: fiber-to-the-x, FTTH: fiber-to-the-home

Figure 1.2 depicts several access network techniques from past, present and future. In practice, there are more wired and wireless access network options than those given as examples on Figure 1.2.

The objective of this master thesis is to describe current and future wired access network technologies and options and to estimate their power consumption. The analysis provides a comparison in terms of power efficiency. It considers the power consumption per user and per bit, as well as the total power consumption of a network model.

1.3 Structure of the Thesis

In this master thesis, access networks presented and analyzed in terms of power consumption are divided in two groups: state-of-the-art access networks and advanced access networks. Subsequent to this introductory chapter, Chapter 2 gives the overview of state-of-the-art access networks. It describes their technical features and practical importance. The considered copper-based access systems are digital subscriber line (DSL) systems and hybrid fiber-coaxial (HFC) network. Optical fiber-to-the-home networks that are considered in this chapter are time-division multiplexed passive optical netwok (TDM PON) and point-to-point optical Ethernet It includes also one wireless access network, i.e., WiMAX as a representative of wireless access methods that serves for comparison with wired access techniques.

Chapter 3 describes the technical properties and architectural highlights of advanced access networks which emerge from the need for higher transmission capacities and longer reach distances. Since standards are a crucial requirement for the wide acceptance and adoption of new technologies Chapter 3 includes the description of novel standards and access methods that are still not widely deployed but form a part of popular research area. These are 10 Gbit/s Ethernet PON (10G-EPON) and the emerging 40 Gbit/s and 100 Gbit/s Ethernet standard, which is expected to be completed mid-2010. Additionally, the advanced access networks that are described in Chapter 3 include wavelength division multiplexed (WDM) PON, hybrid TDM/WDM PON and long-reach PON.

Chapter 4 concerns the analysis of power consumption for both state-of-the-art and advanced access networks. It gives the considered network model description and the results about power consumption. Moreover, it points out the differences between access options in terms of power efficiency.

Finally, Chapter 5 represents a summary of the work. It includes the conclusions about power efficiency in access networks and gives an outlook for future access networks. Apart from the 5 chapters, the thesis contains Appendix A which includes the tables which list the commercial network component with their power consumptions for state-of-the-art access networks and Appendix B containing the corresponding data for advanced networks. The data contained in the Appendices are result of an intensive research about network elements and the study of products data sheets. The data is sorted by access technologies and by the function in the network. All calculations of power consumption are based upon these data.

Chapter 2

2 State-of-the-Art Access Networks

A modern telecommunication network can be divided into three main functional parts, namely into the core, regional or metro and access network, as shown in Figure 2.1. Access network is the *first mile* if observed from the subscriber side or the *last mile* if observed from the network core. Subscribers are connected to the distribution part of the network over appropriate *network terminals* (NT) also referred to as *customer premises equipment* (CPE). CPE is usually located in customers' homes or business offices. The access network usually ends in the *central office* (CO) of a network provider. Depending on the access technology and its practical transmission distances, there might be a *remote node* (RN) between the CPE and CO that contains necessary distribution equipment. This equipment can be either active (a switch, a multiplexing device or an amplifier) or passive (such as signal splitters for instance).

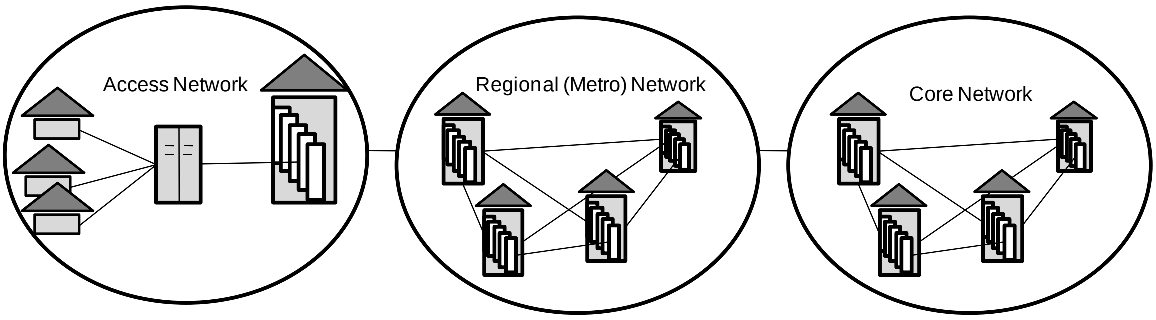


Figure 2.1 Generic structure of a communication network

Concerning the geographical area covered by a network, i.e., the transmission distances, one can distinguish between long haul network and metropolitan area (metro) network. Metro networks lie within an urban area or a region. They consist of a metro access network and a metro interoffice network. The access networks' reach is typically a few kilometers, but it can also be extended to 20 kilometers or more depending on the access technology. The metro interoffice network is a group of interconnected central offices within this metropolitan area and it usually spans several tens of kilometers. The transmission distances in long haul networks can vary from hundreds to thousands of kilometers. The topology of interoffice and long haul networks is typically either meshed or ring [6].

One can distinguish between two principal types of access to a network: wired and wireless access. Wired access includes different access technologies that need electric or optical cables in order to connect user's equipment to a network. In the wireless case, the user's equipment accesses the network via radio frequency (RF) signal. Three major access cable types in the wired access are copper twisted pair cables, coaxial cables and optical fiber cable, as shown on Figure 2.2. The oldest type of access medium is the twisted copper pair wire that has been deployed in the telephone network. The youngest access medium is the optical fiber, which nowadays gains great importance.

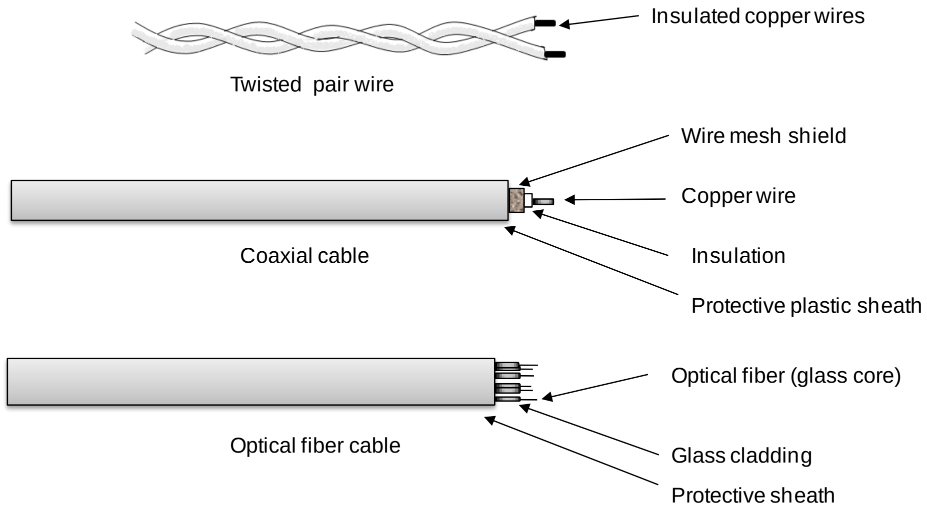


Figure 2.2 Cable types used for wired access

2.1 Copper-based and Hybrid Access Technologies

Through the time of access networks growth, the greatest investments have been in copper cabling providing the users across the world with *public switched telephone network* (PSTN) services, which are popularly known under the name POTS, plain old telephone system. The twisted wire pairs dominate the telephone network but except for the PSTN services, they are also used for broadband digital transmission of data in DSL (Digital Subscriber Line) access technology. Two copper wires are twisted together to ensure the cancellation of electromagnetic interference from external sources [7]. It is a simple trick for improving the signal transmission quality. Crosstalk between neighboring pairs is also avoided by twisting the wires. Twisted pairs are then grouped into larger cables. Coaxial copper cables are less noise sensitive then twisted pairs owing to their external shielding. They are also larger and more expensive than twisted pairs, but they are still very common access medium due to the wide popularity of CATV (Community

Antenna Television or popularly "Cable TV"). For example in the USA the majority of households is connected to network service providers through coaxial cables; firstly because of the high degree of the coaxial CATV plant coverage and secondly because of the too old and too long twisted pair cables what has made DSL less popular than cable modem access. The latter reason relies on the fact that the United States was the first country with ubiquitous telephone service deployments [5].

The greatest advantage of copper wires in comparison to other transmission media is its existence and availability. This infrastructure is already deployed and almost every home has copper connection. Hence, the expensive new cabling, which today would be optical fiber cabling, is avoided. On the other hand, the attenuation of electromagnetic waves on copper wires is approximately proportional to the square root of the signal frequency. Therefore, on twisted pairs, higher frequency signals attenuate faster then low frequency signals. This fact limits the transmission distance and data rate on copper wires [5].

Hybrid access technology represents a migration step from metallic access to the fiber access. It stands for a mixture of these two transmission media in the area of access networks. In hybrid systems, fiber usually runs from CO to the remote node where the signal is converted from optical into electrical. This is a common access scenario today offered by network providers. It is practical because it does not require running individual optical fibers to each subscriber, which would be expensive, but rather exploit the already existing copper cabling. Such an access scenario can also be referred to as *fiber-to-the-node* (FTTN), which is one of the many possible *fiber-to-the-x* (FTTx) options. FTTx is the common name for hybrid fiber network architectures and it will be nearly discussed in Subsection 2.2 of this chapter.

2.1.1 Digital Subscriber Line (DSL)

The first significant step in the history from the old telephone system toward the broadband digital transmission was the digital subscriber line (DSL). In the *plain old telephone system* (POTS) information, voice was transmitted in analog manner. The digitalization started with *integrated services digital network* (ISDN). It was the first broadband DSL standard developed in the 1980s by CCITT[3],. being the predecessor of DSL. It is also known under the name IDSL (ISDN Digital Subscriber Line).

[3] CCITT (**C**omité **C**onsultatif **I**nternational **T**éléphonique et **T**élégraphique) is the predecessor of the ITU-T (**I**nternational **T**elecommunication **U**nion - **T**elecommunication Standardization Sector). In 1993 CCITT was renamed in ITU-T. ITU is one of the specialized agencies of the United Nations founded to regulate and standardize international telecommunications. Its headquarter s are located in Geneva, Switzerland. The so called ITU-T recommendations contain specifications and instructions for international developers and providers of network components.

Integrated Services Digital Network (ISDN)

ISDN offers two service levels: BRI (Basic Rate Interface) for home and small enterprise and PRI (Primary Rate Interface) for large users. The services include a number of so called B-channels and D-channels. BRI provides two 64 kbit/s bearer channels (B-channels) for voice and data and one optional 16 kbit/s signaling digital channel (D-channel). That is why the BRI is also called 2B+1D scheme [5]. The PRI consists of 23 B-channels and one 64 kbit/s D-channel on a T1 line with respect to the US standard or 30 B-channels and one D-channel on the E1 line with respect to the European standard. The data rate of 64 kbit/s results from the predefined pulse code modulation scheme in which the analog signal is sampled every 125 µs and every sample point is represented with 8 bits. E1 line stands for a defined level of the Plesiochronous Digital Hierarchy (PDH). PDH is a multiplexing technology which defines different speed levels at which digital data can be transmitted over a transmission medium. (see Table 2.1)

Hierarchy level	Data rate [Mbit/s]	No. of Channels
E0	0.64 Mbit/s	1 E0
E1	2,084 Mbit/s	32 E0
E2	8,448 Mbit/s	128 E0
E3	34,368 Mbit/s	16 E1
E4	139,264 Mbit/s	64 E1

Table 2.1 PDH levels and capacities

With a total of 144 kbit/s in both directions (BRI case), ISDN technology stands for the first broadband digital data transmission on twisted copper pairs. The integrated services provided by ISDN are multiple simultaneous connections over a single twisted pair wire. That way a single telephone line is used for different services such as voice and data. However in comparison to existing xDSL connections and other access techniques that are available today, ISDN access capability is too poor and does not have the commercial popularity as a broadband type of access. More advanced transmission techniques used in DSL systems are more powerful and efficient in terms of exploitation of cable transmission capacity and therefore provide a greater access bandwidth.

xDSL – Overview

With booming of Internet usage and a row of bandwidth-hungry applications such as video streaming, xDSL access systems have become very popular. The development of DSL has led to several different DSL techniques. xDSL systems have been developed by different standardization bodies including International Telecommunication Union –

Telecommunication Standardization Sector (ITU-T), European Telecommunication Standards Institute (ETSI), American National Standards Institute (ANSI) and different forums. Their work flows in a coordinate manner because all the leader vendors and network operators are members of all these standardization bodies [8]. The different DSL flavors can be grouped in three main categories according to the transmission distance, symmetry and bit rate, as shown in Table 2.2.

DSL	Digital Subscriber Line	Transmission property	Further versions
HDSL	High bit rate DSL	symmetric	SDSL and SHDSL
ADSL	Asymmetric DSL	asymmetric	G.lite, ADSL2 and ADSL2+
VDSL	Very high bit rate DSL	symmetric or asymmetric	VDSL2

Table 2.2 DSL chategories

Asymmetry property of DSL systems has a practical advantage. Some services such as surfing the Internet exhibit an asymmetric bit rate distribution in up and down link. Usually the data rate in the direction from network provider to the customer is much higher then the data in the uplink i.e. from user to service provider. Providing a symmetric data rate distribution for DS and US would be waste of resources.

Another important feature of every access system is the reach distance. It is the maximum allowable or realizable distance between transmitter and receiver. Because of the already existing wire lines the system needs to be adapted on the given distances and be able to transmit the signal if possible without intermediate amplifier. All DSL systems are designed to work without the intermediate amplifier except the HDSL, where it is optional. The symmetry characteristic refers to the difference between the downstream and upstream speed. In a symmetric system the down and up speed are equal, while in an asymmetric system downstream and upstream data rates are different. A graphical comparison between different DSL families is given in Figure 2.3.

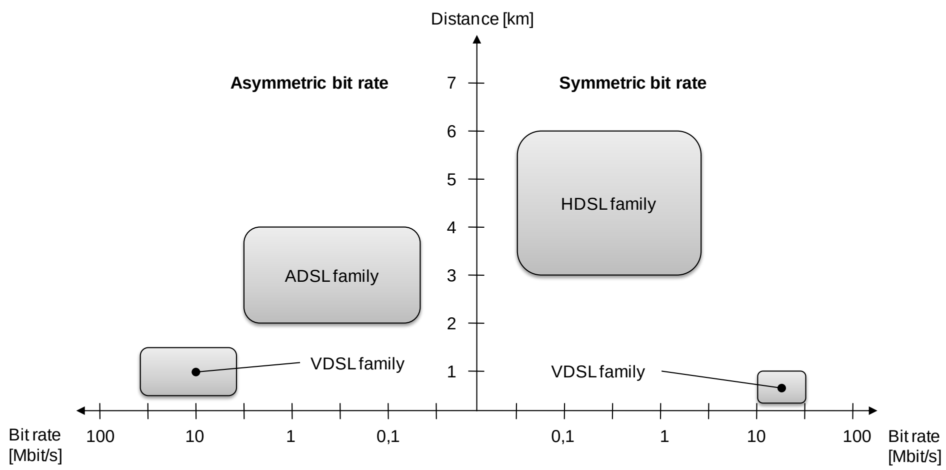


Figure 2.3 xDSL families (taken from [8])

The functional parts of every DSL system are a modem on the subscriber side and a *DSL Access Multiplexer* (DSLAM) in the CO. DSLAM does the multiplexing of individual DSL data streams onto one high speed link and performs the switching functionality. It is a chassis-formed device providing a number of line card slots. One line card (or module) supports usually several lines. Hence, DSLAM provides often a scalable modular multislot design or multiport-per-slot design. The modem is DSL CPE with minimum two interfaces, one for the DSL and the other for home networking equipment. Its name refers to its modulation/demodulation transceiver functionality.

High bit rate DSL (HDSL)

In Europe, HDSL transmits 2048 kbit/s or 1544 kbit/s in both directions. Hence, it is a bidirectional and symmetrical system. First HDSL standard was developed in the United States by ANSI. The European standard developed by ETSI is based on the ANSI standard. The ITU-T G.991.1 standard gives the HDSL specification. In order to maximally exploit the transmission capacity of copper wires, complex signal processing techniques have to be implemented in the system [8]. ITU-T G.991.1 standard recommends two options for line codes: pulse amplitude modulation 2B1Q and carrierless amplitude/pulse modulation (CAP) [9].

2B1Q coding scheme maps two redundancy free bits on one symbol. The symbol alphabet is a set of four amplitudes, which represent the quaternary symbols. The possible bit streams are 00, 01, 10, 11. The first bit (msb = most significant bit) carries the information about the amplitude sign and the second bit (lsb = least significant bit) about the amplitude level. An example of such mapping is: 00 → -3, 01 → -1, 10 → +1, 11 → +3. With such a coding technique the symbol rate is 1/2 the data rate because two bits are mapped on one pulse. In this case the signal spectrum is influenced in a positive manner comparing to a bit-by-bit transmission where each bit represents one pulse. Namely, the bandwidth of the spectrum is halved and larger transmission distances are possible [8].

Older access technologies such as Primary Rate Interface (PRI) in ISDN include simplex transmission. Simplex means that each transmission direction requires an own twisted pair, what automatically means that no separation is needed for signals travelling in opposite directions. HDSL comprises the duplex method which allows simultaneous transmission in both directions on a single twisted pair, just like on the common analog telephone line. It is achieved through the use of the mechanism called Echo Cancellation Hybrid (ECH). The echo canceller produces a replica of the signal echo, which is then subtracted of the total received signal. The echo is the result of impedance discontinuities, caused for example by splicing different kinds of cables. On this discontinuity position in the cable the wave is being reflected back in the wire. Separating the two transmission directions by the ECH technique becomes difficult for high data rate systems and is not used for them. HDSL system includes also the so called dual duplex technique. In this method, the total bit rate is divided on two twisted pairs, each of them providing a duplex transmission with half of the total bit rate. This results firstly in a faster processing in the transceivers and secondly in a half narrower spectrum, for which transmission conditions are better on a copper wire. Additionally, duplexing methods can be realized in frequency domain (Frequency Division Duplex, FDD) or in time domain (Time Division Duplex, TDD). In FDD, different frequency bands are used for up and down directions. In TDD the signal is alternately received and transmitted in time slots.

Functional blocks of HDSL system are depicted in Figure 2.4. Two main functional blocks are HDSL core and application interface. HDSL core includes a common circuitry and one, two or three transceivers, depending on data transmission rate. In common circuitry synchronization and management overhead is added to the core frame, which is then passed on transceivers. The mapping part adapts the interface to the HDSL core. The system part that is on the customer side is named *Network Termination Unit* (NTU) and the one on the network provider side is *Line Termination Unit* (LTU). Deployment of regenerators between NTU and LTU is optional. NTU and LTU include three types of frames: application frame, core frame and HDSL frame (see Figure 2.4). The application frame is transformed in the core frame by mapping. Multiple core frames build up a HDSL frame, which is then transmitted over the twisted pair.

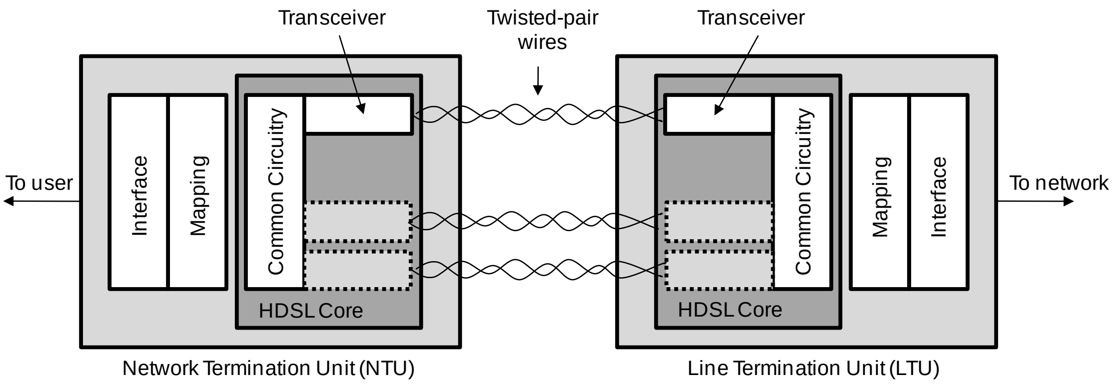


Figure 2.4 Block diagram of HDSL transmission units

The European version of further HDSL development realized by ETSI yields the *Single pair HDSL* (SDSL)[4] system. The equivalent standard named *Single-pair High-speed DSL* (SHDSL) is given by ITU-T G.991.2 recommendation. SHDSL supports data transmission only on a single twisted pair. It does not support conventional voice service on the same pair because it uses the frequency band reserved for POTS in order to provide symmetrical data rates. In the two-wire (one pair) operational mode, possible data rates lie between 192 kbit/s and 2.312 Mbit/s. The allowed data rate are given by $n \times$

[4] SDSL has different descriptions in literature; sometimes it stands for Symmetric high bit rate DSL or Symmetric single pair high bit rate DSL.

$64 + i \times 8$ kbit/s, where $3 \leq n \leq 36$ and $0 \leq i \leq 7$. But for $n = 36$, i can be only 0 or 1. The G.991.2 standard defines also an optional M-pair operational mode, for $1 \leq M \leq 4$. Data rates in this mode are in the range from $M \times 192$ kbit/s to $M \times 2.312$ Mbit/s. An optional extended mode allows data rates up to $M \times 5696$ kbit/s [10]. The payload may be either an unstructured channel, i.e., the so called clear channel, T1 or E1, ISDN BRI, Asynchronous Transfer Mode (ATM) cells or Ethernet packets.

Asymmetric DSL (ADSL)

Asymmetric digital subscriber line (ADSL) is a data transportation scheme on telephone copper wires, which has been developed by different standardization bodies such as ANSI, ETSI, ITU-T, ADSL Forum and ATM Forum.

The systems on the user's side and on the provider's side are not identically constructed. User's equipment is referred to as *ADSL Transmission Unit – Remote end* (ATU-R) and provider's equipment as *ADSL Transmission Unit – Central office* (ATU-C). ATU-R sends low rate data to the ATU-C, while ATU-C transmits the high rate downstream signal which was previously combined with the telephone signal in a splitter. The difference in upstream (US) and downstream (DS) data rates explains the asymmetry property of this DSL type. The functional block diagram of an ADSL system is shown in Figure 2.5. The system includes transceivers on both ATU-R and ATU-C sides, splitters and DSLAM. On the CO side ATU-Cs are connected to the DSLAM forming a module. The multiplexing capacity of an ADSL DSLAM can vary from 252 DSLs up to 576 DSLs per network interface [8].

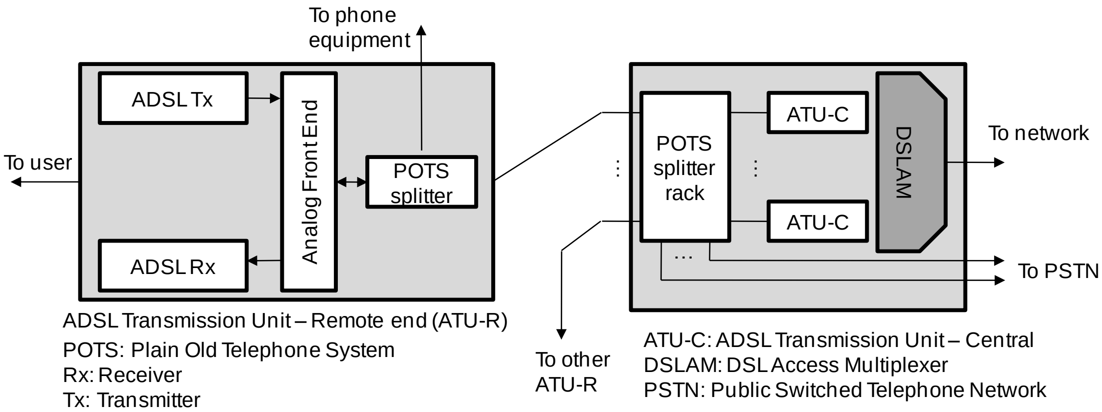


Figure 2.5 Block diagram of an ADSL system

ADSL is applicable together with POTS or ISDN on a single telephone line. The separation of different signals (POTS/ISDN signal, upstream and downstream data) can be achieved in two ways, either by FDD or by echo compensation. In the first case the US and DS signals are transmitted in different non-overlapping frequency bands and the DS occupies a relatively high frequency band in which cable loss is also higher. This can be a drawback when filtering the DS channel. In the second case, i.e., separation by echo cancellation, the whole ADSL frequency band is used as downstream channel. Thus, US and DS channels share the same frequency interval. ADSL system includes digital interfaces for reception and transmission of broadband data and an analog interface for POTS or ISDN baseband signal.

Because of the asymmetry property, i.e., because of a low US data rate, ADSL system benefits from a longer transmission distance without regenerators, which are in contrast to HDSL not allowed for in ADSL. Therefore 2 Mbit/s over 4 km, 4 Mbit/s over 3 km or 6 Mbit/s over 2 km are achievable in the downstream. ADSL can transmit either Synchronous Transfer Mode (STM) data or ATM data. It has seven bearer channels which are composed of at least one or at most four unidirectional (simplex) DS channels and of at least one or at most three bidirectional US channels, as specified in the ITU-T G.992.1 standard [11]. The unidirectional DS channels are referred to as AS (Asymmetric) and the narrow-band bidirectional channels as LS (Low Speed). In the STM mode, there is at least one bidirectional LS channel, while in ATM mode only one unidirectional LS channel is needed in the upstream direction. The bit rate can be chosen as an integer multiple of 32 kbit/s. The highest DS bit rate is 6144 kbit/s, corresponding to the multiplication factor 192. The highest US bit rate is 640 kbit/s, which corresponds to a multiplication by the factor 20. The modulation technique used in ADSL transmitters is referred to as *Discrete Multi Tone*[5] (DMT) is. In DMT, the available frequency band is divided in multiple narrow bands, each having a central frequency called carrier. Altogether there are 255 carriers (not counting the one at zero frequency). The number of bits per carrier will depend on the transmission quality of the given carrier. The method of dedicating a variable number of bits to a carrier according to its channel-property quality is called *bit allocation*. The channel quality varies generally with frequency because of the frequency-dependent attenuation and cross-talk. The measure for channel quality that is used for bit allocation is *Signal-to-Noise Ratio* (SNR). An ADSL transmitter performs also interleaving and Reed-Solomon error correction coding to increase signal’s robustness against errors.

Splitterless ADSL (G.lite)

In 1997 Universal ADSL Working Group (UAWG) has developed a new ADSL system named *Splitterless ADSL* or *Universal DSL* (UDSL) or *G.lite*. The splitterless ADSL is specified in the ITU-T G.992.2 recommendation [12]. It is supposed to work without the splitter filter, which serves for splitting the voice from the data, and function as a simple modem. The transport capacity is programmable in integer multiples of 32 kbit/s, from 64

[5] The ITU-T G.992.1 is also called G.DMT standard.

kbit/s to 1.536 Mbit/s for the downstream bearer channel AS0 and from 32 kbit/s to 512 kbit/s for the upstream bearer channel LS0 [12].

ADSL2 and ADSL2+

The next generation of the ADSL was ADSL2 specified in the ITU-T G.992.3 standard from 2002 [13]. The main improvements concern transmission speed and reach, as well as rate adaptation, modulation and encoding schemes. The maximum ADSL2 downstream data rate is 12 Mbit/s and upstream 1 Mbit/s. According to the ITU-T G.992.3 Annex J the upstream bit rate is increased up to 3.5 Mbit/s.

The new standard includes also some new features such as power management with the power efficient stand-by mode. One can distinguish between two low power modes: *L2 mode* and *L3 mode*. In the L2 mode, the transmitter unit in CO (ATU-C) saves energy by rapidly changing the operational mode from full power mode to low power mode, depending on the amount of Internet traffic on the ADSL connection. The L3 low-power mode enables a stand-by mode at both sides, ATU-C and ATU-R, when the connection is not used. There is also a splitterless version of ADSL2 specified in ITU-T G.992.4 standard in 2002 [14]. The transmission speeds however remain the same as in the splitterless ADSL (G.lite) standard, i.e., 1.536 Mbit/s downstream and 0.512 Mbit/s upstream.

ADSL2+ is standardized through ITU-T G.992.5 under the name *Extended bandwidth ADSL2* (ADSL2+) in 2003 [15]. One new ADSL2+ feature is the so called *seamless rate adaptation* (SRA), which enables data rate changes on an active line without service interruption or disturbance. ADSL2+ doubles the downstream frequency bandwidth in comparison to ADSL2. The upper bandwidth limit is moved from 1.1 MHz to 2.2 MHz. Therefore, ADSL2+ achieves the double maximum theoretical downstream rate of 24 Mbit/s. An optional mode provides doubling the upstream frequency band, and hence, the upstream speed too. The maximum uplink data rate is then 1.4 Mbit/s. Practically, the transmit rates will vary according to the distance between the DSLAM and customer premises equipment (CPE) [16].

Very high bit rate DSL (VDSL)

Very high bit rate digital subscriber line (VDSL) system has been developed by ETSI, ITU-T and Full Services Access Network (FSAN) forum [17]. The ITU-T G.993.1 recommendation from 2004 gives the specification of VDSL technology [18]. Duplexing method for VDSL recommended by ITU-T is FDD, which divides US and DS in four frequency bands, thereby occupying a range from 138 kHz to 12 MHz. The four frequency bands are denoted as DS1, US1, DS2, US2. It specifies two modulation formats for VDSL: *quadrature amplitude modulation* (QAM) and discrete multitone (DMT). VDSL implements also scrambling, *forward error correction* (FEC) with Reed-Solomon codes and interleaving as protection against different types of errors.

VDSL is mostly used in hybrid access architectures, i.e., in FTTN scenarios. In FTTN network, the DSLAM situated in the remote node is connected via an *optical network unit* (ONU) to an *optical line termination* (OLT) located in the CO. ONU and OLT are the two opposite ends of a *passive optical network* (PON), which will be more exactly described in Subsection 2.2.1. VSDL is then applicable on copper wires reaching from the remote node's DSLAM to the CPE. The remote node is a general description; it can actually be a curb near the user (*fiber-to-the-curb*, FTTC) or a cabinet (*fiber-to-the-cabinet*, FTTCab). VDSL connections are deployed in FTTN architectures because they provide high bit rates on relatively short distances. The major property of VDSL is the support of both, symmetrical and asymmetrical data rate modes. It is capable of delivering maximum 52 Mbit/s DS and 1.54 Mbit/s US in the asymmetrical mode and 10 Mbit/s DS and 10 Mbit/s US in the symmetrical mode. Different transmission speeds reflect on the transmission distance, therefore VDSL systems can be classified in three groups according to the reach:

- Long Range VDSL (1 – 1.5 km)
- Medium Range VDSL (0.3 – 1 km)
- Short Range VDSL (< 0.3 km)

VDSL is designed to transport ATM and Plesiochronous Transfer Mode (PTM) data. It supports also POTS and ISDN BRI signals. Short range VDSL provides the highest data rates.

VDSL2

The next generation of VDSL standard is VDSL2, defined in ITU-T G.993.2 recommendation in 2006 [19]. It is the newest ant the most powerful DSL flavor, which has been designed to support *triple-play* services. It provides an extension concerning transmission speed that enables 100 Mbit/s in the symmetrical and short range mode.

2.1.2 Hybrid Fiber Coax (HFC) Access Network

HFC access network is hybrid FTTN architecture with fiber running from the CO to the remote node and coaxial cable from the node to the subscriber. An adequate converter in the RN adapts the signal from one to the other transmission medium. HFC system is the common *Cable TV* (CATV) network structure. In the terminology of CATV service providers the remote fiber node in the network is called the *hub node* and the CO is called *headend*.

In HFC, coaxial cable is used not only for video signals but also for upstream and downstream data transmission providing broadband Internet access. In comparison to twisted pairs, coaxial cable enables a very good broadband transmission with the usable frequency range up to 1 GHz. CATV video signals are transmitted from the backbone to the hub nodes through optical fiber. In the hub nodes, the signals are converted back to the radio frequency (RF) and distributed to the end users through coaxial cables. The evolution of the CATV system started with the analog broadcast signals. An analog signal was distributed in only one direction, from the service provider to the end users. In the mid-1990s CATV systems were enriched with bidirectional amplifiers and return optical fibers in order to provide a bidirectional communication between the service provider and the end user. Such a transmission system offered data services and other services such as video-on-demand (VoD).

The headend contains a so called *cable modem termination system* (CMTS), which is connected to residential cable modems over the tree-and-branch fiber-coax plant (see Figure 2.6). *Cable modem* is the CPE in the HFC access system. The customer data are multiplexed on the shared medium using TDM. An individual cable modem recognizes its downstream broadcast data by the slot ID. The upstream slots are assigned to cable modems by CMTS, which acts as a master medium controller, i.e., control of bandwidth allocation to cable modems is performed by CMTS. This concept differs from the DSL system which provides a dedicated connection between DSL modem and DSLAM. Despite different transmission media, cable modem architecture is similar to the power-splitting PON architecture. In both cases there is a *point-to-multipoint* (P-t-MP) tree-and-branch transmission medium topology, distributed among the end users. Both technologies use TDM *medium access control* (MAC). Just like between OLT and ONU, in HFC systems, there is a master-slave relationship between CMTS and cable modem for medium control. Therefore, OLT is functionally equivalent to the CMTS and ONU to the cable modem. Both systems require *dynamic bandwidth allocation* (DBA) [5].

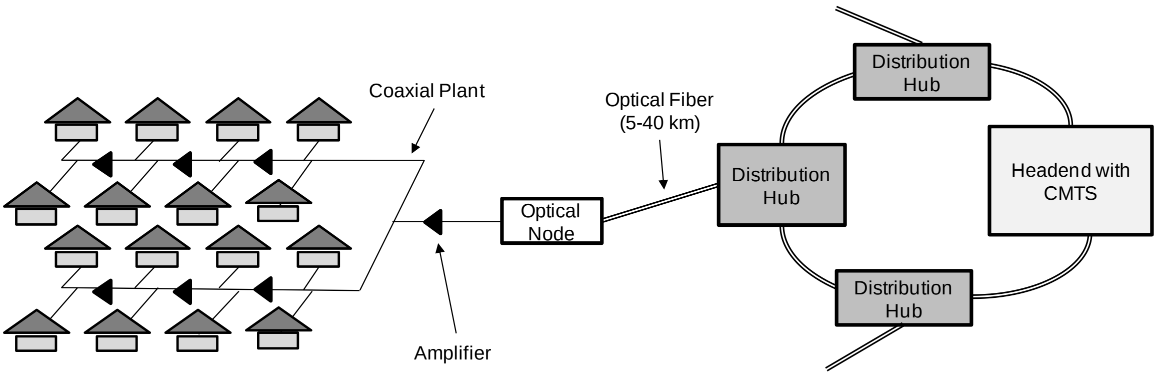


Figure 2.6 Architecture of a hybrid fiber-coaxial network, CMTS: Cable Modem Termination System

The standardized transmission protocol used in HFC systems is the *Data-Over-Cable-Interface Specification* (DOCSIS). It is standardized by CableLabs and the first version DOCSIS 1.0 was released in 1997. The latest version DOCSIS 3.0 was released in 2006. The specification known under the name EuroDOCSIS is a version of DOCSIS adapted to the European frequency bands for CATV and its bit rates are different from those specified in DOCSIS. Data rates of all DOCSIS versions are listed in Table 2.3.

DOCSIS Version	**Number of channels**		**Maximum data rates**	
	DS	**US**	**DS [Mbit/s]**	**US [Mbit/s]**
DOCSIS 1.1	1	1	38	9
EuroDOCSIS 1.1	1	1	50	9
DOCSIS 2.0	1	1	38	27
EuroDOCSIS 2.0	1	1	50	27
DOCSIS 3.0	m	n	m x 38	n x 27
	4	4	152	108
EuroDOCSIS 3.0	m	n	m x 50	n x 27
	4	4	200	108

Table 2.3 Data rates in different DOCSIS standards

DOCSIS 3.0 employs the new technique of logically combining multiple RF channels to provide one broadband channel that is suitable for triple-play services. This is known as *channel bonding*. This feature is applicable on both, US and DS channels. Maximum four channels can be bonded together, giving the data rates listed in Table 2.3 [20].

2.2 Optical Access Technologies

Since the amount of Internet traffic grows with new services, many improvements have been made to increase the bandwidth in core networks. On the other hand, access networks have remained the same. Accordingly, they have become a bottleneck in today’s network architecture. Optical access technology could be the solution to the existing bandwidth problem in access networks. It provides 10 to 100 times higher data rates then copper access technologies and enables longer transmission distances [21]. Optical fiber has several advantages over copper transmission medium. These are:

- low attenuation,
- low noise,
- no electromagnetic interference (EMI), and
- large bandwidth.

According to these properties optical fiber networks require fewer power amplifiers and are more suitable for long-haul data transmission than copper wires. Consequently, an optical fiber network is basically more efficient in terms of power consumption.

Any generic network architecture that uses optical fiber for broadband transmission of data is generally named fiber-to-the-x (FTTx). There are different flavors of FTTx depending on how near to the subscriber the fiber reaches. Correspondingly, the x represents a variable that can be replaced by the initial letter of any spot in the network reached by the optical fiber. A typical example is FTTH (fiber-to-the-home)[6], which means that optical signal reaches the end user's equipment situated in the subscriber home[7]. Other examples are FTTB (fiber-to-the-building), FTTC (fiber-to-the-curb), FTTN (fiber-to-the-node) and so on. In such a hybrid network infrastructure, the users are connected to the fiber-ending location via coaxial cables or twisted pairs wires. The term FTTx does not precise any network topology, transmission technology or speed. It points out only the use of optical fiber as data transportation medium.

FTTH systems can have either point-to-point (P-t-P) or point-to-multipoint (P-t-MP) topology. The remote distribution node can contain active equipment, such as an Ethernet switch, or a passive one, such as a passive splitter used in PONs. Passive remote nodes that do not require power supply are very attractive access solution because of its efficiency and simplicity.

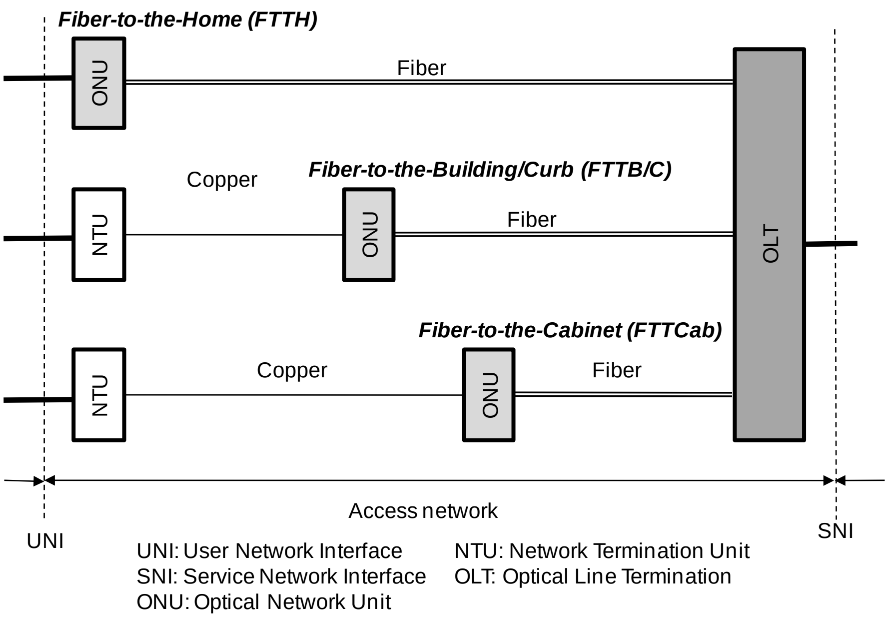


Figure 2.7 PON and FTTx architectures (taken from [22])

[6] Early fiber access systems were called FILT (fiber-in-the-loop). Today the term FTTH is more common.

[7] FTTH is commercially often used in a wider sense and can actually mean Fiber-to-the-Building or Fiber-to-the-Curb.

Therefore the number of FTTH connections is remarkably growing in recent years. For example in the United States, the annual grow rate was 112% between September 2006 and September 2007 [23]. In Japan, the number of FTTH connections exceeded that of ADSL in January 2007 [24].

2.2.1 Passive Optical Network (PON)

PON is an architecture that was proposed as a solution for sharing large fiber bandwidth among many users. PON standardization began in the 1990s with the growth of bandwidth demands. First steps toward standardized requirements and services in the passive optical access system were made by FSAN consortium[8]. The goal was promotion of common standards in order to lower the cost of fiber access systems. Later ITU-T adopted the FSAN recommendations and offered their PON standards.

Every PON has the same generic structure that includes an optical line terminal (OLT) in the CO and multiple optical network units (ONUs) at the customer side. Between them there is the remote node which houses a passive splitter. The fiber plant together with the splitters is called *optical distribution network* (ODN). PONs may generally be divided in two groups according to data transportation property:

- TDM-PON (usually simply termed PON)
- WDM-PON.

TDM-PON implements *time division multiplexing* (TDM) as method for sharing the transmission medium among users, while WDM-PON uses *wavelength division multiplexing* for the same purpose. In both cases, the whole fiber plant is a passive structure. However the splitters are two different devices. In a TDM-PON the same signal is broadcasted from the CO to different ONUs through a passive power splitter. Each ONU selects its own data according to the address labels attached to the signal.

In a WDM-PON, a wavelength is dedicated to each ONU so that the signals for different ONUs are multiplexed on different wavelengths. The routing of signals to the appropriate ONU is done by the WDM coupler. Hence, the ONU receives only its own data which makes a WDM-PON much better in terms of privacy and scalability. On the other hand WDM-PON has more expensive components and is therefore economically less attractive [5]. However, sharing the resources through a passive splitter improves the per user cost of FTTH system and reduces the fiber mileage.

Possible splitting architectures are shown in Figure 2.9. Usual splitting ratios in PON systems are 1:16 and 1:32. A higher splitting ratio means more efficient power sharing among ONUs but it also influences the power budget and transmission loss. It

[8] FSAN group was formed in 1995 by 7 global telecommunication operators.

requires higher-power transmitters, highly sensitive receivers and low-loss optical components. OLT bandwidth is also split onto multiple ONUs. Therefore a larger splitting ratio means less bandwidth per user.

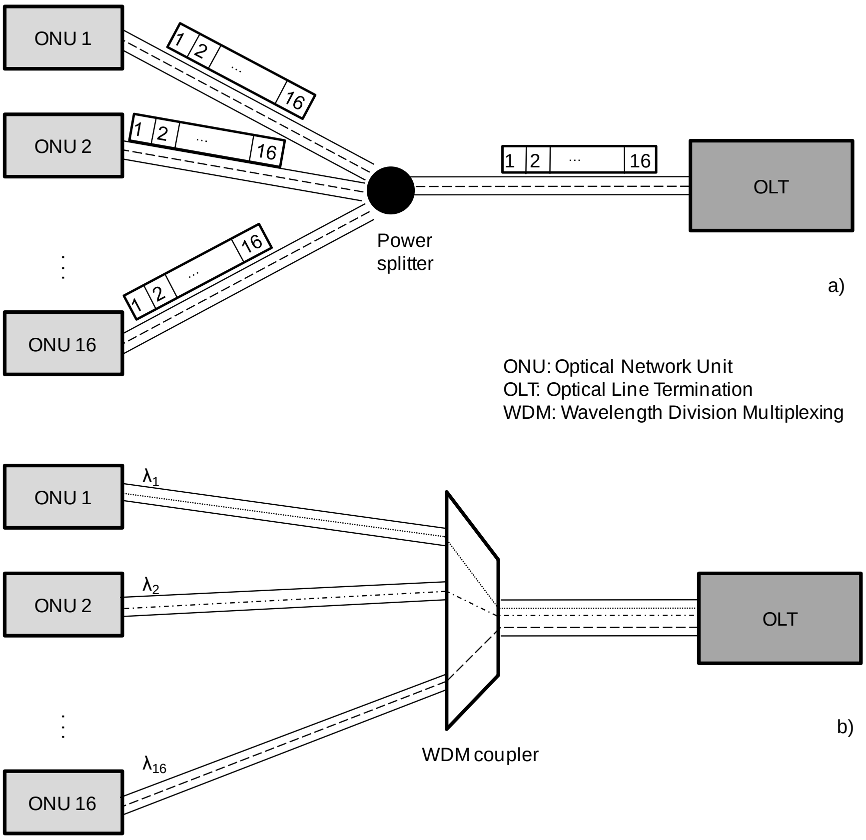


Figure 2.8 Difference between TDM and WDM PON transmission principle a) TDM PON b) WDM PON (taken from [5])

The system is characterized by minimum energy per bit required to achieve a given maximum allowable *bit error rate* (BER). BER is the measure of system performance. An increase of bit rate at the OLT results in increasing transmission power, which is constrained by available laser technology and required safety standards. Transmission power and splitting ratio also limit the achievable distance between OLT and ONUs. TDM-PON options and the corresponding standards are listed in Table 2.4.

PON	**Passive Optical Network**	**Standardization body**
APON or BPON	ATM PON or Broadband PON	ITU-T G.983
GPON	Gigabit capable PON	ITU-T G.984.1-4
EPON	Ethernet PON	IEEE 802.3ah EPON
10G-EPON	10 Gigabit Ethernet PON	IEEE 802.3av

Table 2.4 PON flavors and standards

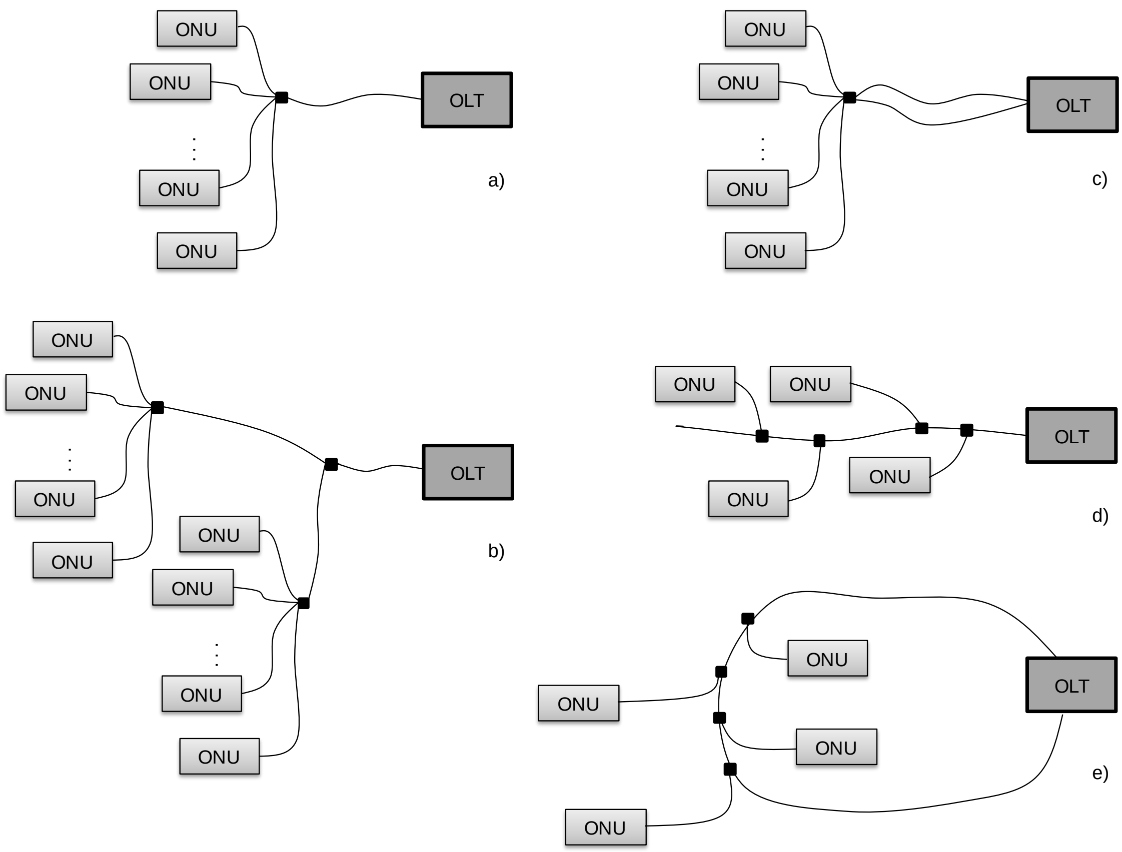


Figure 2.9 TDM PON topologies: a) tree topology (one-stage splitting), b) tree-and-branch topology (multistage splitting), c) tree topology with redundant trunk, d) bus topology and e) ring topologies (taken from [25])

In PON, data are transmitted on the 1.49 µm or 1.55 µm wavelength in the downlink and on the 1.3 µm wavelength in the uplink. The bidirectional transmission using a different wavelength for each direction over a single fiber is called *diplex*. In the case of duplex transmission, the same wavelength is used for both directions over a single fiber. The transmission mode with a third frequency used for video signals is termed *triplex*. ONU is usually equipped with a number of voice and data ports. If the ONU contains a triplexer receiver, it can then have an RF video port. Equivalently to DSLAM and CMTS, the OLT is composed of a chassis that hosts the backbone switch or cross-connect and insertable PON line cards. The chassis interconnects the line cards through a high-speed backplane. Such an OLT can provide many PON service interfaces.

The signals transmitted between OLT and ONUs, i.e., in the PON section, can be encoded and multiplexed in different manners, depending on the applied transmission scheme associated to the given PON standard. BPON transmits ATM cells, EPON uses Ethernet as transmission protocol and GPON uses the so called *GPON encapsulation method* (GEM). In each type of PON, downstream transmission is a broadcast connection. The OLT interleaves frames destined for different ONUs and each frame header carries the ONU ID for the unique ONU identification. The upstream is a many-to-one connection. The communication between individual ONUs must flow over the OLT, which performs the forwarding and routing function [5].

Each ONU has its own transmitter but there is only one OLT receiver. Thus, the interference at the receiver is avoided in such a way that each ONU needs to take its turn to send data. Additionally, when the ONU has no data to send it has to switch off its transmitter. According to the interference issue, PON system uses a *burst mode* transmission in the uplink. Before sending a burst, ONU sends a preamble to the OLT as a training sequence for synchronization and decision threshold adjustments. Bursts coming from different ONUs are separated by a guard time interval, which generally lower the bandwidth efficiency and should be designed as short as possible. The OLT MAC layer performs the scheduling that is necessary in a PON system in order to avoid collision between bursts. The control mechanism used in early Ethernet to avoid scheduling is the *carrier sense multiple access with collision detection* (CSMA/CD). It is not applicable in PON systems because of the non-compatibility of PON properties and CSMA/CD protocol. In PON, the so called *ranging process* enables the timing reference between OLT and ONUs. Since ONUs are located at different distances from the OLT, the round-trip delay between an ONU and OLT has to be measured in order to perform ranging. After receiving the ranging request that is broadcasted from the OLT, the ONU replies with a ranging response within a time window reserved for that purpose. The round-trip time is measured in the OLT and the ONU's delay has been updated. The round-trip time is stored in the OLT or ONU and it is used for adjustment of transmission time. After ranging, all ONUs are aligned to a timing reference so that collision can be completely avoided [5]. Achievable transmission distances specified in the PON standards are 10-20 km.

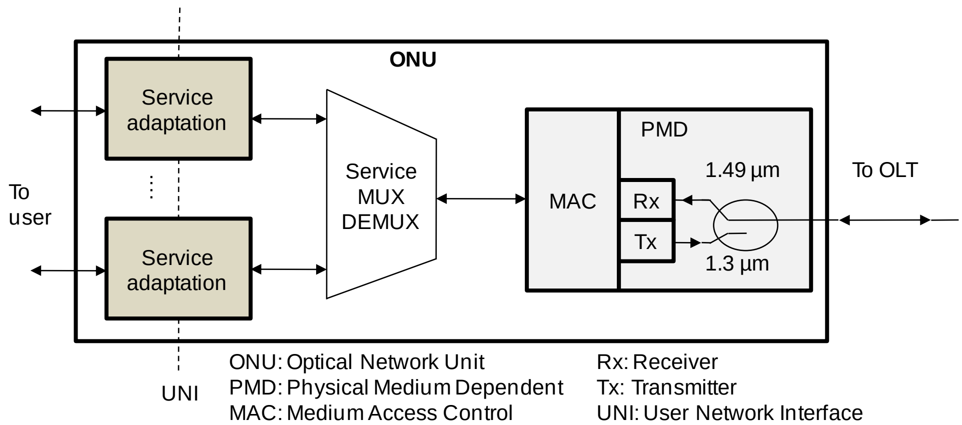


Figure.2.10 Generic structure of a TDM-PON ONU (taken from [5])

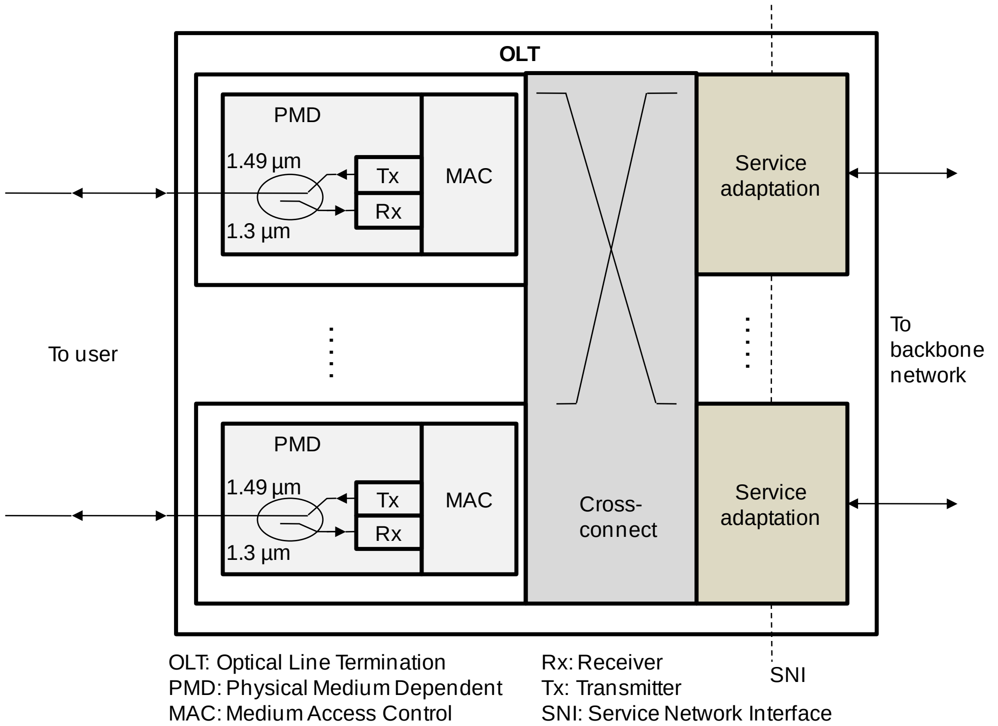


Figure 2.11 Generic structure of TDM-PON OLT with multiple line cards packed in a chassis with cross-connect and service adaptation unit (taken from [5])

Figure.2.10 and Figure 2.11 show generic structures of the PON elements An OLT contains a *physical medium dependent* (PMD) part and a *medium access control* (MAC) unit. The OLT transmitter works on 1.49 µm downlink wavelength. This is, consequently, the wavelength of the ONU receiver. The ONU transmitter transmits data to the OLT receiver on the 1.3 µm uplink wavelength. The service adaptation layer in the ONU provides the necessary signal conversion between user's equipment and PON section. Figure 2.11 shows a block diagram representing a chassis with multiple interconnected OLT line cards. Each OLT with its own MAC and PMD layer corresponds to a separate PON. The interface between the OLT and backbone network is called *service node interface* (SNI)[9]. The interface between the ONU and customer's network termination equipment is called *user network interface* (UNI). Usually there are different types of UNIs for different types of services. UNIs may support different signal formats. Different user interfaces are multiplexed in the Service MUX/DEMUX unit.

APON / BPON

The terms APON and BPON refer to the same technology given in the ITU-T G.983 series standard [22]. The APON standard was firstly developed by FSAN [17] and later

[9] In the literature SNI stands often for service network interface. However, in the ITU-T PON recommendations it is called service node interface.

the work was transferred to the ITU-T SG15 [26]. The name APON (ATM PON) is an older one and it points out better the transmission technology used in this PON system, namely the asynchronous transfer mode (ATM) frames. The name BPON (Broadband PON)[10] serves the marketing purpose pointing out high transmission speeds. Many basic technical properties of APON are also present in next PON generations, namely the GPON and EPON.

APON line rates are defined as multiples of 8 kHz, the basic SONET/SDH frame repetition rate. Possible downstream data rates are 155.52 Mbit/s, 622.08 Mbit/s and 1244.16 Mbit/s in combination with upstream data rates of 155.52 Mbit/s or 622.08 Mbit/s. Downstream data rate has to be greater then or equal to the upstream rate. APON include previously described diplex working mode with downstream wavelength range from 1480 to 1580 nm and upstream wavelength range from 1260 to 1360 nm. Unidirectional transmission over two fibers (one for each direction) of 1310 nm range wavelength is also possible [22].

The signals in APON are transmitted in time slots. A time slot is occupied either by an ATM cell or a physical layer OAM (PLOAM) cell, which is 53 byte long. PLOAM carries physical layer management information such as protocol messages. Protocol messages concern ranging, time slot requests by ONUs, assignments of upstream time slots by OLT, performance monitoring, etc. PLOAM cell is sent every 28 time slots. Downstream frame for 155.52 Mbit/s speed is divided in 56 time slots (54 ATM cells and 2 PLOAM cells) and the upstream frame is divided in 53 time slots each 56 byte long. The upstream time slot has 3 overhead bytes more than the downstream time slot and it can also be divided in multiple mini-slots. The three overhead bytes include guard time between consecutive cells, preamble and delimiter indicating the start of the ATM cell or minislot which can be used for byte synchronization. OLT controls the content of the upstream time slot using downstream PLOAM cell. For 622.08 Mbit/s and 1244.16 Mbit/s speed the number of time slots is multiplied by 4 and 8 respectively.

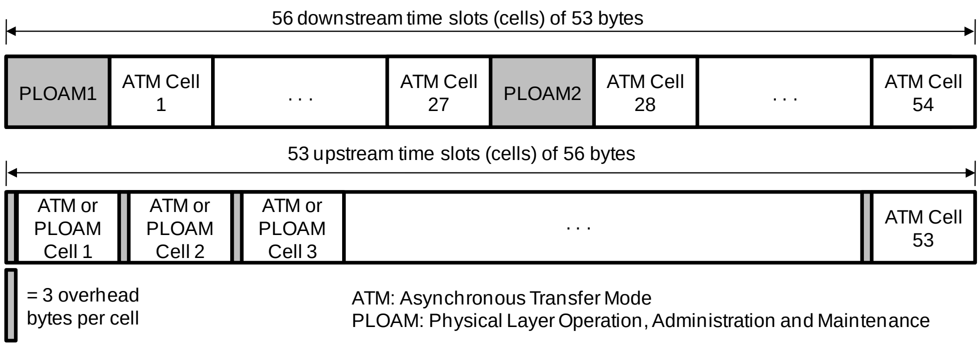


Figure 2.12 Frame formats for the 155.52/155.52-Mbit/s symmetric APON system (taken from [22])

[10] In the ITU-T G.983.1 recommendation the full name of the standard is Broadband optical access systems based on Passive Optical Networks. The shorter and in literature more common description is Broadband PON.

Both APON and GPON feature three transmission classes distinguished by predefined attenuations in the ODN. ITU-T G.982 [27] specifies the three following classes:

- Class A: 5-20 dB
- Class B: 10-25 dB
- Class C: 15-30 dB

For practical and cost reasons, Class B+ with 28 dB attenuation was commercially the most dominant [5].

Control and management functions are specified in the ITU-T G.983.2 recommendation [28]. OLT and ONUs are in a master-slave relationship. The OLT as master manages the ONUs through the so called *ONT management and control interface* (OMCI). The communication channel reserved for OMCI is the *ONT management and control channel* (OMCC). OLT and ONU are connected via ATM *virtual circuits* (VC). A *virtual path identifier* (VPI) and a *virtual channel identifier* (VCI) are assigned to each virtual circuit. This pair of identifiers identifies an ATM connection. In APON, various services are mapped to the ATM virtual circuits through the *ATM adaptation layer* (ALL). Three different ATM adaptations (AAL-1, AAL-2 and AAL-5) are specified in the ITU-T G.983.2 recommendation [28]. AAL-1 is used for time-sensitive, constant bit-rate and connection-oriented services such as T1/E1 circuits (transmission of voice). Variable bit-rate connection-oriented services such as video and audio streaming are provided in the AAL-2 while AAL-5 is used for connectionless services such as transmission of IP packets. Non-return-to-zero (NRZ) coding is used in both transmission directions.

GPON

Giga-bit capable PON (GPON) is the standard created by ITU-T in the G.984 recommendation [29]. Like in APON ITU-T G.984, it specifies the data rates as multiples of 8 kbit/s. Hence, the following data rates are achievable:

- Downstream: 1244.16 Mbit/s, 2488.32 Mbit/s
- Upstream: 155.52 Mbit/s, 622.08 Mbit/s, 1244.16 Mbit/s, 2488.32 Mbit/s

Downstream data rate has to be higher then or equal to the upstream rate. According to the gigabit-capability of GPON, the most important bit rate is 1.2 Gbit/s upstream and 2.5 Gbit/s downstream. The usual splitting ratios in GPON are 1:32 and 1:64, but 1:128 is also considered for future optical modules. The physical reach in GPON is also 10 or 20 km, but larger distances are also possible applying *reach extension* solutions. Because of the higher bit rates, GPON system requires higher-power transmitters then APON. Fabry-Perot laser diodes were proposed by ITU-T G.984.1 for data rates such as 1.25 Gbit/s and above. Consequently the GPON receivers need to handle higher powers and low cost PIN receiver have been substituted by *avalanche photo-diodes* (APDs), which are more sensitive and more suitable for the Class-B and Class-C loss budget requirements. The transmission can be bidirectional in the diplex mode using WDM techniques and same wavelengths or unidirectional over two separate fibers for each direction as described for APON [30].

The protocol layer in GPON providing transport multiplexing between OLT and ONUs is the *GPON transmission convergence* (GTC) layer. Data transportation scheme in the GTC layer that is specified in ITU-T G.984.3 [31] is *GPON encapsulation method* (GEM). It provides the transmission of connection-oriented variable-length data services. The transport is frame structured and independent of SNI type at the OLT and UNI type at the ONU. Besides the frames (GEM), GPON can transport ATM cells, but the specification of the ATM cell transport has been removed from the latest version of ITU-T G.984.3 because ATM transport was not needed for any service of interest [31]. GTC layer defines a traffic-bearing object in the ONU named *transmission container* (T-CONT). T-CONT is a logical link between the OLT and the ONU. It is the traffic-bearing entity that receives the upstream bandwidth allocations within the ONU and is identified by the *allocation ID* (Alloc-ID) that is assigned by the OLT [31]. More than one T-CONT can be assigned to an ONU. The individual logical connections of a GEM-based[11] T-CONT are identified by 12-bit GEM port identifier, which is assigned by the OLT [31].

GPON standard defines a power-leveling mechanism for the upstream OLT burst mode receiver. Received power is controlled dynamically by instructing the ONUs to increase or decrease the launched power in accordance with their distance to the OLT. The ONU which is closer to the OLT sees less loss and transmits less power. The transmit power is adjusted to improve the signal-to-noise ratio at the OLT.[12]

EPON

Ethernet PON (EPON) standard is given as a part of the IEEE 802.3ah *Ethernet in the First Mile* (EFM) specification [32]. It introduces the concept of a point-to-multipoint (P-t-MP) optical Ethernet network. The EPON standard was finished in June 2004 and has since then emerged as a highly successful technology serving in the last 5 years 30 millions of subscribers worldwide [33]. In order to make such a P-t-MP topology realizable, some extensions have been introduced to the MAC layer and the *reconciliation sublayer* (RS) as well as to the optical PMDs. EPON includes also some

[11] A T-CONT can be ATM- or GEM-based.

[12] This concept of power control is common in cellular network to combat the so called near-far cross talk effect.

additional methods for *operations, administration, and maintenance* (OAM) to facilitate network operation [32]. Ethernet covers the physical layer and data link layer of the open system interconnect (OSI) reference model, as shown in Figure 2.13, which gives a comparison of the point-to-point (P-t-P) and point-to-multipoint (P-t-MP) Ethernet layer architectures.

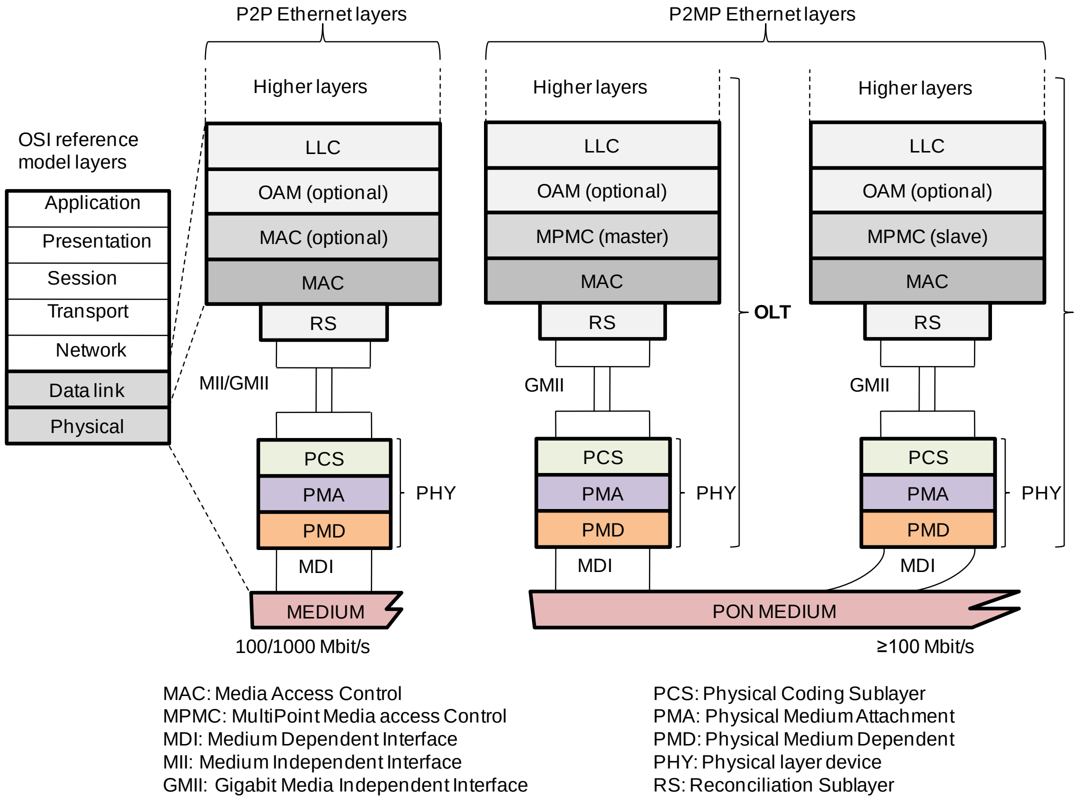


Figure 2.13 P-t-P Ethernet and P-t-MP EPON layering architecture [32]

Physical and data link layers are divided into multiple sublayers. There are a few major differences between P-t-P and P-t-MP layered structures. The connection between the PHY and the data link layer is *media independent interface* (MII) or *gigabit media dependent interface* (GMII). Instead of the optional MAC layer in P-t-P Ethernet, EPON uses mandatory *multipoint media access control* (MPMC) layer. ONUs' access to the shared EPON medium is controlled in by the *multipoint control protocol* (MPCP) running at the MPMC layer. OLT and ONU MPMC layers have a master-slave relationship. Optical transceivers, in Ethernet mainly low-cost mature devices, are specified in the PMD layer. The PMD characteristics and nomenclature are given in Table 2.5.

The *physical coding sublayer* (PCS) deals with line-coding in PHY devices, which use the 8B/10B code. The minimum splitting ratio is 1:16 in contrast to the 1:32 GPON splitting ratio. The defined transmission distances are 10 and 20 km. The transmitter properties at the ONU are almost identical for 10 and 20 km. This allows the user to keep the same ONU if the distance is increased. OLT transmitter characteristics such as the output power differ for 10 and 20 km. Data rates in EPON are symmetric; 1 Gbit/s in the upstream and the downstream direction[13]. In the PON section, data is transmitted in Ethernet frames, which can have variable size.

PMD	Transmission modes and speeds	Reach	Type
OLT (D-type)	Transmitting at 1.25 GBd continuous mode and receiving at 1.25 GBd burst mode (Symmetric data rates)	10 km	1000BASE-PX10-D
		20 km	1000BASE-PX20-D
ONU (U-type)	Transmitting at 1.25 GBd burst mode and receiving at 1.25 GBd continuous mode (Symmetric data rates)	10 km	1000BASE-PX10-U
		20 km	1000BASE-PX20-U

Table 2.5 Description of 1G-EPON PMDs

2.2.2 Point-to-Point (P-t-P) Optical Ethernet

P-t-P optical access network with Ethernet interfaces relies on the IEEE 802.3ah standard known as the Ethernet in the First Mile (EFM) Task Force [32]. The P-t-P Ethernet network is the subject of this subsection, while point-to-multipoint (P-t-MP) access Ethernet network is referred to as EPON. There are many different Ethernet physical layer implementations referring to various transmission speeds, medium and reaches, but the EFM defines the following:

- 100BASE-LX10 – providing point-to-point 100 Mbit/s Ethernet links over a pair of single-mode fibers up to at least 10 km.
- 100BASE-BX10 – providing point-to-point 100 Mbit/s Ethernet links over an individual single-mode fiber up to at least 10 km.
- 1000BASE-LX10 – providing point-to-point 1000 Mbit/s Ethernet links over a pair of single-mode fibers up to at least 10 km.
- 1000BASE-BX10 – providing point-to-point 1000 Mbit/s Ethernet links over an individual single-mode fiber up to at least 10 km.

EFM supports only full duplex links. The major advantage of P-t-P optical Ethernet comparing to other FTTH architectures is that it can provide a dedicated high capacity connection per user, unlike the PON in which the users share DS and US transmission capacity. Additionally, it can provide very large transmission distances. In this FTTH access option, the CO houses an Ethernet switch with multiple ports that can have

[13] EPON is sometimes designated by network operators and components vendors as GEPON to stress the gigabit capability of EPON for the purpose of marketing.

different transmission speeds according to its Ethernet interface. An Ethernet switch has usually a modular design and contains several multiport line cards.

P-t-P FTTH networks provide better data privacy and easier fault localization then P-t-MP network configurations. Additionally, service upgrades are performed without affecting other user since each user has its own fiber. On the other hand, the need for separate fibers can give rise to possible scalability, power consumption and footprint issues at the CO [23]. The composition of the data link layer and physical layer for the P-t-P Ethernet can be seen in Figure 2.13. The layer structure of 10 Gigabit Ethernet is the practically the same except of the interfaces which can support 10 Gbit/s data rate.

2.3 Wireless Access Technologies

In this section, a single example of technology for wireless access will be addressed. Although the whole thesis concentrates on wired access networks, this section will give a brief overview of the worldwide interoperability for microwave access (WiMAX), which is chosen to be a representative of wireless access for purpose of comparisons. Since WiMAX is recently developed and allows data rates and transmission distances that are comparable with wired state-of-the-art access networks, it can well serve as an example of advanced wireless access technology in power consumption studies.

2.3.1 Worldwide Interoperability for Microwave Access (WiMAX)

Worldwide Interoperability for Microwave Access (WiMAX) is the wireless access technology that competes the wireline access techniques described in previous sections. It is based on the IEEE standard 802.16, which defines the broadband wireless access. IEEE 802.16 is officially named the standard for wireless metropolitan area network (WirelessMAN™), but it is commercially more popular under the name WiMAX. The first version (IEEE 802.16d) was developed as a fixed wireless technology working only for *line-of-sight* (LOS) connections. The newest version (IEEE 802.16e) from 2005 offers mobility under *non-line-of-sight* (NLOS) conditions. Even fast mobility has been introduced, what makes WiMAX a competitive solution next to UMTS and WLAN [34]. The 802.16e-2005 version uses the *scalable orthogonal frequency division multiple access* (SOFDMA) in which subsets of orthogonal subcarriers are assigned to individual users. Another feature is the adaptive modulation and flexible bandwidth for each user according to the quality of the wireless channel. Performance improvements are also achieved by use of advanced antenna techniques such as smart antennas with beam forming and MIMO antennas [34].

The data rate in WiMAX depends on the modulation scheme, code rate and channel width. Table 2.6 depicts the dependence of these parameters for the mobile WiMAX. It shows a list of achievable bit rates in DS and US directions for different modulations and codes rates in the case of 5 MHz and 10 MHz channel width. The maximum achievable data rates are 31.68 Mbit/s in the DS and 23.52 Mbit/s in the US direction. The fixed WiMAX uses up to 20 MHz wide channels and achieves, in case of 64QAM and a code rate of ¾, a DS data rate of 74.81 Mbit/s. All WiMAX data rates are shared among users and not dedicated to a single user, and therefore, there is a trade-off between the number of users and the bit rate per user.

Modulation	**Code Rate**	**Bit Rate (5 MHz Channel)**		**Bit Rate (10 MHz Channel)**	
		DS [Mbit/s]	**US [Mbit/s]**	**DS [Mbit/s]**	**US [Mbit/s]**
QPSK	1/2	3.17	2.28	6.34	4.70
	3/4	4.75	3.43	9.50	7.06
16QAM	1/2	6.34	4.57	12.67	9.41
	3/4	9.50	6.85	19.01	14.11
64QAM	2/3	12.67	9.14	25.34	18.82
	3/4	14.26	10.28	28.51	21.17
	5/6	15.84	11.42	31.68	23.52

Table 2.6 Achievable data rates for different modulation schemes and code rates in mobile WiMAX (802.16e-2005) [35]

Features	**802.16-2001**	**802.16d-2004**	**802.16e-2005**
Spectrum	10 – 66 GHz	< 11 GHz	< 6 GHz
Channel Conditions	LOS only	NLOS	NLOS
Channel Bandwidth	20, 25, 28 MHz	Scalable 1.5-20 MHz	Scalable 1.5-20 MHz
Bit Rate	Up to 134 Mbit/s in 28 MHz channel	Up to 75 Mbit/s in 20 MHz channel	Up to 32 Mbit/s in 10 MHz channel
Mobility	Fixed	Fixed, portable	Nomadic portability Full mobility
Air Interface	TDMA with TDD and FDD	OFDM and OFDMA with TDD and FDD	SOFDMA with TDD and FDD
Typical Cell Radius	2-5 km	7-10 km	2-5 km

Table 2.7 Comparison of different WiMAX versions (taken from [36])

Table 2.7 shows the evolution of WiMAX giving the comparison of the three main WiMAX stages. It summarizes the most important features concerning spectrum, channel, data rate and mobility. Feature described as full mobility stands for the support of multiple mobile station locations and high vehicular speeds, as well as soft handovers between different base stations. A simple mobility, on the other hand, can support only hard handovers and low vehicular speeds. The difference between simple portable and nomadic portable lies in the fact that nomadic means stationary but possible on different locations while portable supports walking speed.

The WiMAX network architecture includes three parts: the *mobile subscriber station* (MSS), the *access service network* (ASN) and the *core service network* (CSN). The network can also be divided in two functional parts: the *network access provider* (NAP) and the *network service provider* (NSP). The NAP provides the ASN, enabling the wireless access to the CSN that is realized by the NSP. The CSN is further connected to the so called applications service provider (ASP) network. The WiMAX network architecture is depicted in Figure 2.14. The equipment contained in ASN includes base stations (BSs) and ASN gateway. The base station of a cell comprises basic BS equipment, radio equipment and BS link toward core network. The ASN gateway performs the connection and mobility management. It aggregates the traffic from BSs and manages the handovers between them [37]. All WiMAX products must be certified by the WiMAX Forum formed in 2001 as a not-for-profit industry-initiated organization [38].

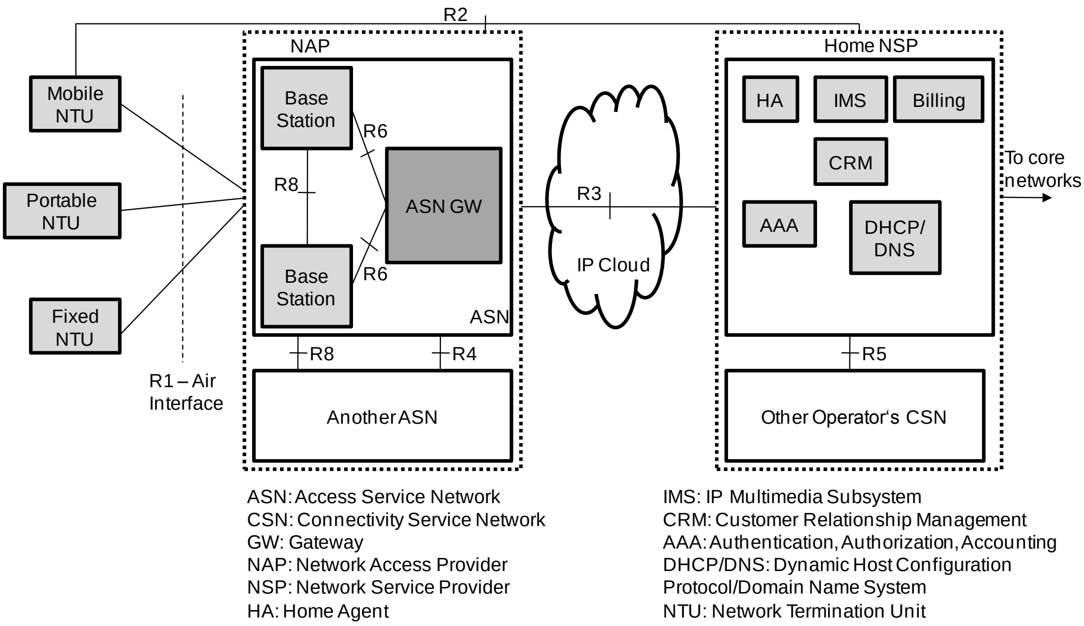
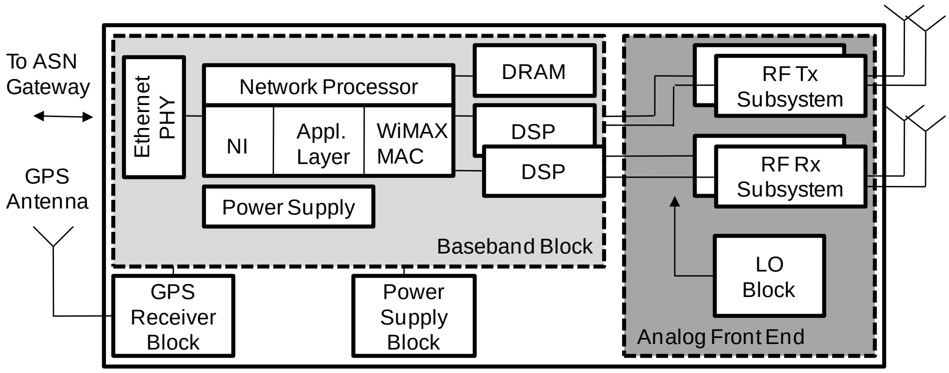


Figure 2.14 WiMAX network reference model [36]

2.3.2 WiMAX Implementation

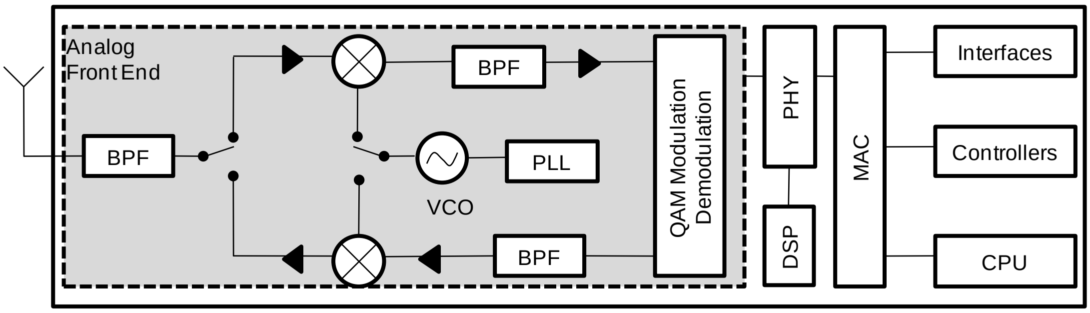
The structure of a WiMAX base station can be seen in Figure 2.15. Its block diagram comprises several subblocks. The analog front end includes a row of antennas functioning as a multiple-input-multiple-output (MIMO) system. Each antenna is attached to a RF subsystem that contains elements such as filters and amplifiers. Analog front end includes also a local oscillator for frequency conversion. Apart from that, there is a baseband block which makes the signal processing and includes the WiMAX medium access control. Moreover, it provides the Ethernet interface toward the ASN gateway. Every mobile WiMAX BS includes also a global positioning system (GPS) receiver.



GPS: Global Positioning System
PHY: Physical Layer
DSP: Digital Signal Processor
LO: Local Oscillator
RF: Radio Frequency
Tx: Transmitter
Rx: Receiver
DRAM: Dynamic Random Access Memory
NI: Network Interface
MAC: Medium Access Control
ASN: Access Service Network

Figure 2.15 Block diagram of a WiMAX base station

Figure 2.16 depicts the block diagram of the WiMAX CPE. Similar to the BS, there is an analog front end that transmits and receives the RF signal. The rest includes digital signal processing, MAC, interfaces toward user and other functional blocks shown in Figure 2.16.



BPF: Bandpass Filter
PLL: Phase Locked Loop
VCO: Voltage Controlled Oscillator
PHY: Physical Layer
DSP: Digital Signal Processor
MAC: Medium Access Control
CPU: Central Processing Unit
QAM: Quadrature Amplitude Modulation

Figure 2.16 Block diagram of WiMAX customer premises equipment

Chapter 3

3 Advanced Access Networks

The cost-effective PON has emerged as one of the leading optical access technologies. GPON and EPON have already been massively deployed worldwide. The growing need for more access bandwidth, for longer transmission distances and higher network capacities has led to the development of *next-generation* (NG) access networks, such as NG-PON. NG-PON comprises the novel 10G-EPON standard, WDM-PON and long-reach PON. High-speed Ethernet networks have also been a research field recently, giving rise to 40G and 100G Ethernet.

3.1 10Gbit/s Ethernet-based Passive Optical Network (10G-EPON)

The extension of the EPON system to 10 Gbit/s is specified by the IEEE 802.3av [39] standard accomplished by the 10G-EPON Task Force [40]. The standard defines both symmetric and asymmetric transmission modes:

- 10 Gbit/s DS and 10 Gbit/s US
- 10 Gbit/s DS and 1 Gbit/s US.

It specifies the RS sublayer, 10GBASE-PR and 10/1GBASE-PRX PCSs, PMAs and PMDs that support both symmetric and asymmetric data rates while remaining compatible with already deployed 1Gbit/s EPON equipment. The goal of 10G-EPON standard is to upgrade the channel capacity in both transmission directions, but still to remain compatible with existing 1 Gbit/s EPON. The logical layer has to preserve existing MPCP and DBA specifications.

The Ethernet layering structure for 10G-EPON includes the *10 Gbit/s medium independent interface* (XGMII) instead of the GMII defined for EPON between the RS and PCS. The PCS contains the forward error correction (FEC) function, which is mandatory for all links operating at 10 Gbit/s. Links operating at 1 Gbit/s use the optional 1G-EPON FEC. Coding scheme defined in 10G-EPON PCS is 64B/66B. It has greater coding efficiency than the 8B/10B code used in 1G-EPON [41]. The DS and US wavelength plan of both 10G-EPON and EPON is shown in Figure 3.1.

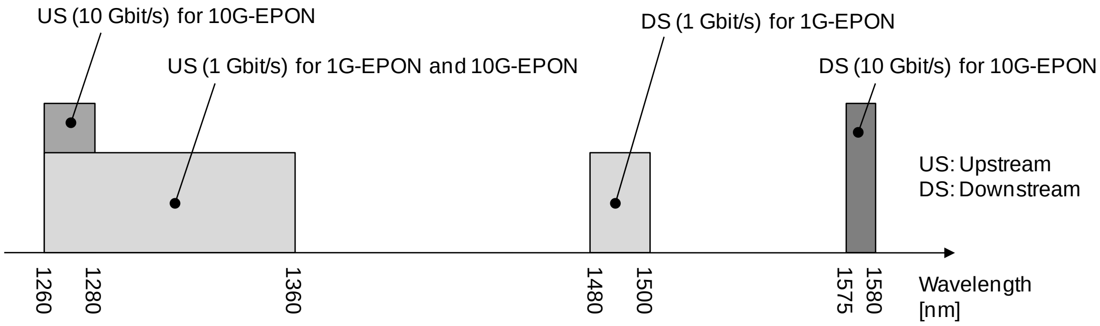
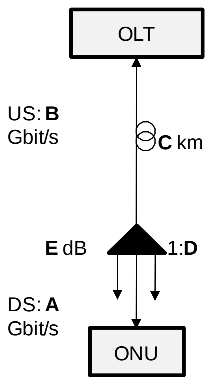


Figure 3.1 10G-EPON vs 1G-EPON wavelength plan (taken from [41])

Some new terms used in the IEEE 802.3av standard are ChIL and power budgets. *Channel insertion loss* (ChIL) is the total attenuation introduced by the optical channel (fibers, splitters, splices, etc.), excluding penalties. There are three power budget classes (low, medium and high) defined in 10G-EPON, which are represented by PR-type and PRX-type power budgets, as shown in Figure 3.2. Each class is identified by a numeric value; value 10 stands for low power budget class, value 20 for medium and value 30 for high power budget class.



Power budgets		Downstream data rate [Gbit/s] **A**	Upstream data rate [Gbit/s] **B**	Nominal maximum distance [km] **C**	Nominal split **D**	Maximum ChIL [dB] **E**
Symmetric data rate	PR10	10.3125	10.3125	10	16	20
	PR20	10.3125	10.3125	20	16	24
	PR30	10.3125	10.3125	20	32	29
Asymmetric data rate	PRX10	10.3125	1.25	10	16	20
	PRX20	10.3125	1.25	20	16	24
	PRX30	10.3125	1.25	20	32	29

Figure 3.2 10G-EPON power budgets (taken from [41])

Power budget types ending on 10 and 20 (PR10, PRX10, PR20 and PRX20) are options that are compatible with the EPON PMD PX10 and PX20, respectively.[14] EPON has no PMD that is compatible with the 10G-EPON PR30 or PRX30 standard. Table 3.1 gives the list of PMD interfaces with their features concerning transmission modes and speeds.

[14] For comparison, see Table 2.4.

PMD	Transmission modes and speeds	Data Rate	Type
OLT (D-type)	Transmitting at 10.3125 GBd continuous mode and receiving at 1.25 GBd burst mode	Asymmetric	10/1GBASE-PRX-D1
			10/1GBASE-PRX-D2
			10/1GBASE-PRX-D3
	Transmitting at 10.3125 GBd continuous mode and receiving at 10.3125 GBd burst mode	Symmetric	10GBASE-PR-D1
			10GBASE-PR-D2
			10GBASE-PR-D3
ONU (U-type)	Transmitting at 1.25 GBd burst mode and receiving at 10.3125 GBd continuous mode	Asymmetric	10/1GBASE-PRX-U1
			10/1GBASE-PRX-U2
			10/1GBASE-PRX-U3
	Transmitting at 10.3125 GBd burst mode and receiving at 10.3125 GBd continuous mode	Symmetric	10GBASE-PR-U1
			10GBASE-PR-U3

Table 3.1 Description of 10G-EPON PMDs [39]

Figure 3.3 depicts two operational modes of 10G-EPON, i.e., symmetrical 10G/10G mode and asymmetrical 10G/1G mode. It represents the OLT and ONU structures as well as the communication paths within the physical layer for both 10G/10G and 10G/1G cases.

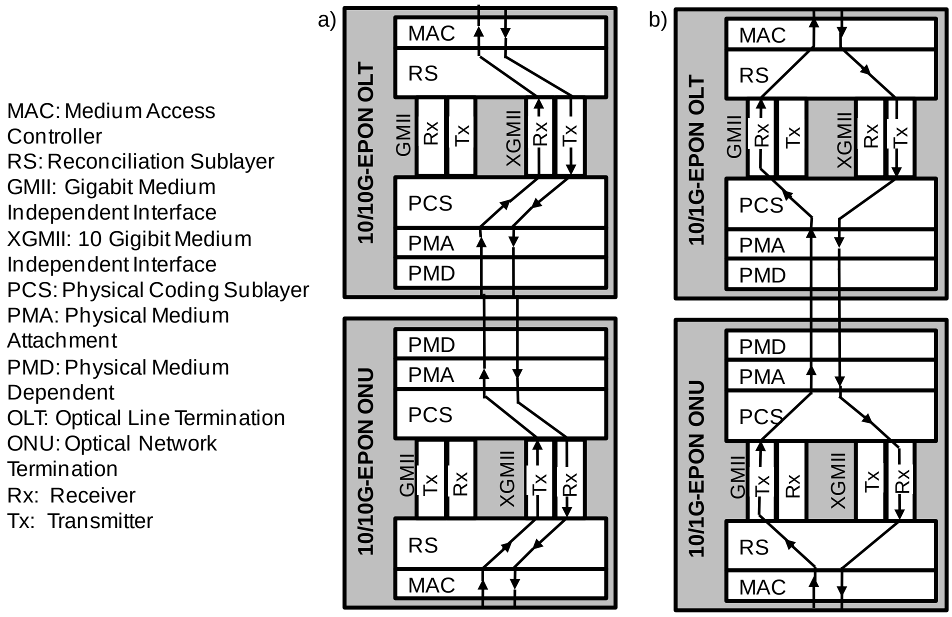


Figure 3.3 Operation of OLT and ONU a) for symmetrical 10/10G-EPON b) for asymmetrical 10/1G-EPON (taken from [39])

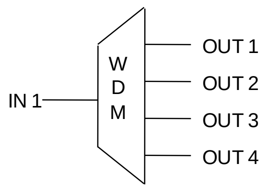
The coexistence with the strongly deployed 1G-EPON is an important factor in the 10G-EPON design. It will protect the 1G-EPON investments and offer upgrading of networks in the 10G direction. In order to support the coexistence with 1G-EPON but also the asymmetrical transmission option, 10G-EPON PHY includes both gigabit medium independent interface (GMII) and 10 gigabit medium independent interface (XGMII).

Figure 3.3 a) shows both OLT and ONU transmitting and receiving in both direction at 10 Gbit/s over the XGMII. In the asymmetrical mode the DS data rate is 10 Gbit/s and the US data rate is 1Gbit/s. Therefore the data from OLT to the ONU is transmitted over XGMII. In the US direction ONU's GMII transmitter sends the data to the OLT's GMII receiver, as shown in Figure 3.3 b).

3.2 Wavelength-Division Multiplexed (WDM) Passive Optical Network

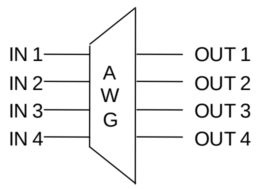
In a wavelength-division multiplexed passive optical network (WDM PON), a unique pair of wavelengths is assigned to each user. One is used for the transmission of US data and another one is reserved for the DS data. The device that performs the passive splitting in WDM-PONs is the WDM coupler. It is located in the remote node and acts like a wavelength demultiplexer in the DS direction and as a wavelength multiplexer in the US direction. The WDM coupler is one of the most important functional parts of a WDM-PON. It is practically an *arrayed waveguide grating* (AWG) coupler that does the combining and the separating of individual wavelengths. The input light carrying all wavelengths enters the AWG over an optical fiber. It is then passed on a bundle of waveguides[15] of unequal lengths. Each waveguide arm is related to the adjacent arm by a constant length difference. At the output coupling points the waves interfere in such a way that different wavelengths are routed on different fibers. The waveguides function as an optical grading separating the wavelengths. The structure of a 1×N and an N×N AWG coupler is shown in Figure 3.4. N is the number of input or output wavelengths.

a)



	OUT 1	OUT 2	OUT 3	OUT 4
IN 1	λ_0	λ_1	λ_2	λ_3

b)



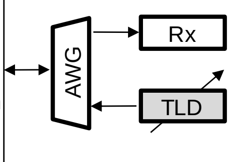
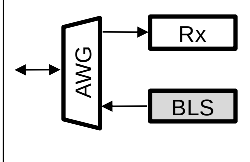
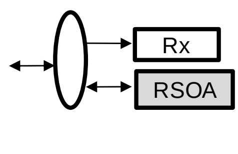
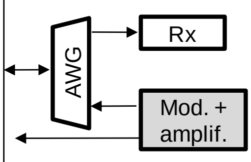
	OUT 1	OUT 2	OUT 3	OUT 4	OUT 1	OUT 2	OUT 3	OUT 4	OUT 1
IN 1	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8 ...
IN 2	λ_{-1}	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7 ...
IN 3	λ_{-2}	λ_{-1}	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6 ...
IN 4	λ_{-3}	λ_{-2}	λ_{-1}	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5 ...

Figure 3.4 WDM coupler versus arrayed waveguide grating (AWG) and their wavelength routing tables: a) conventional WDM coupler b) AWG

The main issue of WDM-PONs concerns currently the CPE. Since each ONU transmits on its own wavelength, it becomes highly wavelength dependent and requires

[15] Optical waveguides can also be replaced by optical fibers.

single-frequency laser diodes or *distributed feedback* (DFB) lasers. Moreover, different users require laser sources emitting at different frequencies. This option is too expensive for the subscriber loop. Therefore, alternative concepts have been researched in order to lower the cost of the CPE. The concept of the so called *colorless ONU* has been proposed. Colorless ONUs are wavelength independent and do not require any wavelength tuning or wavelength stability circuit. Thus, they all can have identical transmitters. This is possible due to a solution in which a portion of the incoming light is looped back though a modulator toward the CO. The other portion is detected by the receiver in the ONU. That way, the need for a light source inside the ONU is avoided [23]. Since this concept includes the reflection of the incoming light, colorless ONUs are often referred to as *reflective ONUs*. Many approaches and techniques have been introduced for colorless ONUs. Table 3.2 shows an overview of different colorless ONU approaches, which can be divided in two groups. Namely, the ONUs with local light emission and the ONUs that do not have their individual light sources for the upstream transmission but are rather characterized by a source placed at OLT. The transceiver inside the OLT can be either a tunable transceiver or an array of fixed-tuned transceivers, each one emitting at one operational wavelength. The tunable transceiver is suitable for transmission of not only downstream data but also of *continuous wave* (CW) bursts that are used for upstream transmission by means of remote modulation at the ONU. This results in a half-duplex communication between each ONU and OLT [23]. In the following, different realization possibilities of ONUs for WDM PONs are described.

	Local emission		**Wavelength supply (source at OLT)**	
Technique	Wavelength tuning	Spectrum slicing	Injection locking or Wavelength seeding	Loop-back
ONU configuration				
Modulation	Direct/External	Direct	Direct	External
Data Rate	10 Gbit/s	1.25 Gbit/s	1.25 Gbit/s	10 Gbit/s
Location of US light source	ONU	ONU	ONU	OLT

ONU: Optical Network Unit
OLT: Optical Line Termination
AWG: Arrayed Waveguide Grating
TLD: Tunable Laser Diode
BLS: Broadband Light Source
RSOA: Reflective Semiconductor Optical Amplifier

Table 3.2 Colorless ONU approaches and techniques for WDM PON [42]

1. Wavelength tuning

The most intuitive solution for realization of a non-wavelength-specific device is a *tunable laser diode* (TLD). Since each ONU needs one individual upstream wavelength, the TLD is simple solution because it can be tuned to any wavelength within the given wavelength range. It can also provide high bit rates. However, TLDs are expensive components to be employed in CPE, therefore a lot of research has been done to provide other more cost-efficient solutions.

2. Spectrum slicing

Instead of TLD, the OLT can include a broadband light source that can be a superluminescent *laser diode* (SLD), a *Fabry-Perot laser diode* (F-P LD) or a supercontinuum-based broadband light source. The broadband light is then spectrally sliced in the remote node. Thus, upstream wavelengths for data modulation are generated in the remote node and distributed among ONUs. The broadband light source can also be integrated inside the ONU where an optical filter performs spectrum slicing. The approach depicted in Table 3.2 represents the later option.

3. Injection locking

The optical transmitter with a F-P LD is an attractive solution for WDM-PONs because those transmitters are the most cost effective. On the other hand F-P LDs can not be used in high-performance WDM-PONs because they suffer from a high *mode partition noise* (MPN). By injecting spectrum-sliced broadband light into the F-P LD, the MPN can be reduced and the output upstream wavelength is locked on the wavelength of the injected light [43]. Apart from F-P LD, *reflective semiconductor optical amplifier* (RSOA) or *vertical-cavity surface-emitting laser* (VCSEL) can also be employed at each ONU. An *amplified spontaneous emission* (ASE) light is then injected into the devices in order to provide the light source for the upstream traffic.

4. Loop back

In the loop back method, no light source is required in the ONU. The incoming downstream light is split inside the ONU in two parts. One part is the downstream data that ends up in the receiver. The other part is a CW signal used as the upstream carrier. It is modulated and re-amplified and finally transmitted back in the upstream direction. To perform this upstream transmission, ONU may deploy a *semiconductor optical amplifier* (SOA) as both a modulator and a preamplifier. The ONU and the OLT communicate then in a half-duplex mode. The full-duplex mode is possible by using two different wavelengths for DS and US and by replacing the SOA with a stabilized laser. The ONU is then wavelength independent since it gets an assigned dedicated wavelength, which can be the same as the DS wavelength or different from it. If the same wavelength is used for both DS and US directions, then two different modulation formats have to be used. For example, a phase-shift keying may be used for the DS signal and intensity modulation for the US transmission. This concept of putting all necessary light sources in the OLT is also described as the option with *centralized light sources*. WDM-PON offers some advantages upon the power splitting PON:

- Each user receives only its own wavelength. This provides a better privacy and a virtual P-t-P connection. Unlike P-t-P FTTH network where each subscriber connects to the CO via its own fiber, WDM-PON offer fiber gain by providing a single shared feeder fiber between the CO and the RN.
- The MAC layer is simplified because of the missing P-t-MP media access control, which is not required due to the wavelength domain connections between OLT and ONU.
- In a power splitting PON, when the OLT speed is increased, then consequently, all ONUs need an adequate upgrade. In a WDM-PON on the other hand, all wavelength channels are transmitted independently, i.e., each wavelength channel can be modulated at a different speed and with a different protocol [5].
- Small insertion loss of WDM devices enables longer reaches and higher splitting ratios then those achievable in TDM-PONs. This represents an increase in network capacity and scalability by accommodating a higher number of users.

Some other properties of WDM-PON can be seen as challenges or even drawbacks when compared to power splitting PONs.

- The cost of WDM components are high.
- WDM components are temperature sensitive. They require power-consuming temperature control electronics.
- Each ONU transmits on its own upstream wavelength. Consequently each ONU requires a tunable laser to adjust the appropriate transmission wavelength. However, this wavelength dependent option is a functional and economical issue which should be avoided. Thus, recent research activities are in the area of wavelength independent ONUs, i.e., *colorless ONUs*. Since cost reduction is the key issue specifically in access networks, devices and components should be mass produced and widely applicable. The aim is also to lower installation costs by the do-it-yourself method.

Replacing existing PON architecture with the WDM-PON would require replacing the power splitter with an athermal, i.e., passive AWG. Such an upgrade is not desirable because it requires work on the outside fiber plant and disrupts running users' connections. Another upgrade solution can be to leave the power splitters and to replace the ONUs with such equipped with an additional bandpass filter [23]. However, this option, just like the conventional PON, includes broadcasting of all wavelengths to all ONUs and makes it less secure then the original WDM-PON concept. The most common and intuitive way of introducing WDM-PON is the smooth migration path from conventional TDM-PONs to future WDM-PONs, resulting in *hybrid TDM/WDM PON*. Such a network design is the objective of Stanford University access network project, i.e., SUCCESS [23]. SUCCESS's migration scenario includes several steps as depicted in Figure 3.5. The first step comprises replacing of the power splitter in the RN with a thin film add-drop *coarse WDM* (CWDM) filter. Additionally, feeder fibers in the tree topology are replaced by a single fiber collector ring that connects the CO with RNs. The ring can be functionally divided in a west side and an east side part. In the error-free case west side RNs communicate with the west side OLT in the CO and analogously the east side RNs with the east side OLT. If a fiber on the ring is cut, the affected nodes change their transmission direction. This allows for protection against failures on the ring. The second migration step includes adding of AWG-based RNs, which are used as DWDM (de)multiplexers of dedicated ONU wavelengths. The final migration step of SUCCESS network depicted in Figure 3.5 is one possible extension, in which one additional PON is attached to two RNs.

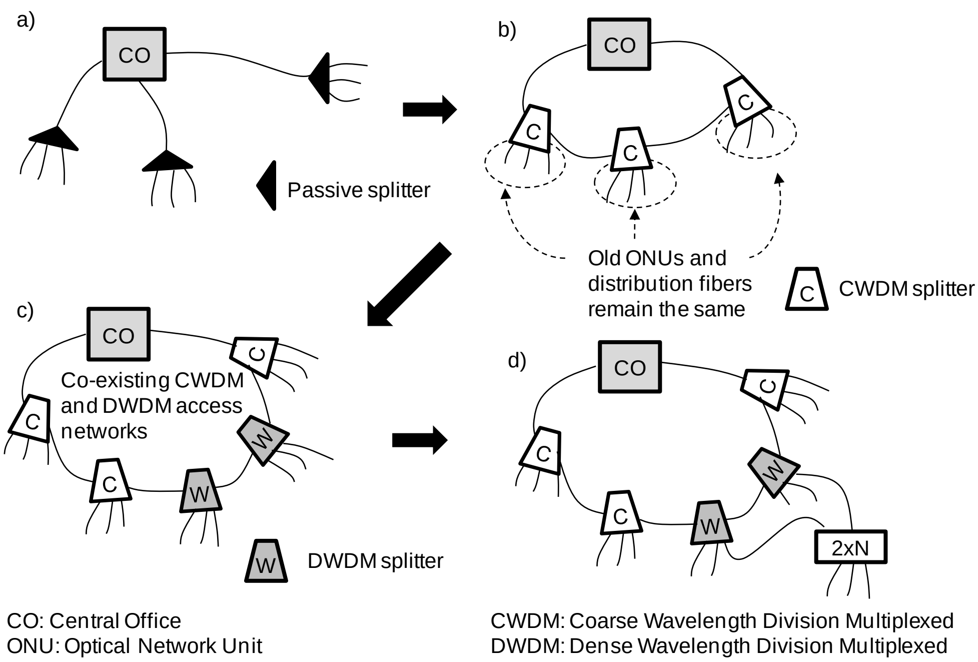


Figure 3.5 SUCCESS migration scenarios toward hybrid TDM/WDM PONs [23]

Connecting one PON to two RNs is one possibility for realization of redundancy and protection. Apart from the redundancy, attaching PONs to the collector ring, and thereby increasing the network capacity, depicts the good scalability of the SUCCESS network. There are also other projects such as MARIN and STARGATE that propose similar TDM/WDM PON concepts [23].

3.3 Long-Reach Passive Optical Network

Conventional PON architectures have predefined and limited reaches between OLT and ONUs. However, in some cases the need for longer transmission distances arises. The network concepts that are made to satisfy this requirement are called *long-reach PONs*. Optical integration of access and metro networks requires achieving long-reach network configurations. Consolidation of optical access and metro network through the use of an up to 100 km long optical fiber section provides an all-optical network with the advantage of reduced number of required optical-electrical-optical (OEO) conversions. Long-reach PON also improves the capacity of the network by enabling an increased splitting ratio compared to the conventional PONs. However, these improvements are realizable through deploying optical amplifiers needed for the compensation of splitting and propagation losses. The need for longer reach exists in the rural areas, which have, on the other hand, lower service demand. Unlike rural areas, urban areas require an increased splitting ratio because of the high subscriber density in a relatively small geographic area [23]. Depending on the location in the network where the optical amplifier is placed, the network can remain passive or become active. If the amplifier is inserted into the network at the RN between OLT and ONUs, the network architecture becomes active because the amplifier requires power supply. This option is generally not desirable because one of the PON's greatest advantages is its passiveness. One more requirement that a reach extender must comply in PON is the transparency to existing OLT and ONUs. It must work in the adequate frequency range and possibly not add additional noise in the transmission line.

Different long-reach PON concepts that have been investigated in the framework of different projects target different reaches and splitting ratios. ITU finalized the G.984.6 standard [44] in March 2008 that specifies the reach extension for GPON. This standard defines 60 km reach with regenerators and optical amplifiers installed in the RN. A GPON reach extender usually includes:

- wavelength filters to separate the US and DS transmission directions
- amplifiers for each direction
- optical bandpass filters, when possible in both directions, to cut off the noise.

Overview of GPON reach extenders' main characteristics and their performance is given in Table 3.3. The performance is classified in three levels (not suited, suited and very well suited) and is different for US and DS transmission bands.

Characteristic	**DFA**		**SOA**	
	US (O-band)	**DS (S-band)**	**US (O-band)**	**DS (S-band)**
Maturity	not suited	very well suited	suited	very well suited
Size	not suited	not suited	suited	very well suited
Cost	not suited	not suited	suited	suited
Power Consumption	not suited	not suited	very well suited	very well suited
Gain	not suited	very well suited	suited	very well suited
Optical Bandwidth	very well suited	very well suited	suited	suited
Noise	very well suited	very well suited	not suited	suited
Overall	not suited	suited	suited	very well suited

Table 3.3 Overview of main characteristics of doped-fiber amplifiers (DFA) and semiconductor optical amplifiers (SOA), as reach extenders for US and DS signal amplification in GPON [45]

Many studies focus on the long-reach TDM-based PON called *SuperPON*. SuperPON is the most well-known long-reach PON developed under the European project "PLANET" in the mid-1990s [46]. SuperPON's targets are 100 km reach and 2048 ONUs as well as data rate increase up to 10 Gbit/s in the DS direction. SuperPON includes amplifiers in the RN and hence is an active network.

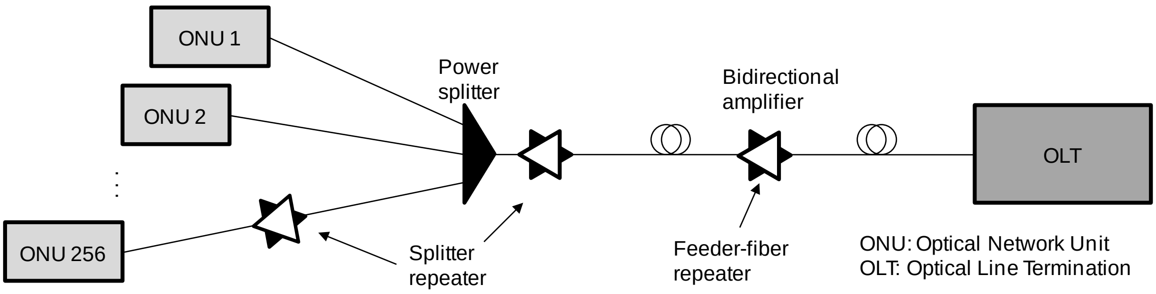


Figure 3.6 Generic structure of the SuperPON

In the case of active amplification, the equipment inserted to provide extra optical budget can generally be referred to as an *extender box* (EB). On the other hand, the technique to preserve the passiveness of the network is to use *remotely pumped optical amplifier* (ROPA) or Raman amplifier. In both cases, ROPA and Raman amplifier, the pump light is installed at the CO. For ROPA, the amplification medium is a doped fiber that is inserted in the transmission line and in the case of Raman amplification, the amplification occurs in the optical fiber itself. EB solutions, which are also used in GPON or SuperPON, can be also based on *optical-electrical-optical* (OEO) repeaters or on *semiconductor optical amplifiers* (SOA).

OEO repeaters can be divided in two groups according to their regeneration functions:

- 2R repeaters (reshaping and reamplification)
- 3R repeaters (reshaping, reamplification and retiming).

OEO repeaters are a low-cost and simple solution that provides complete regeneration of the signal, and consequently, there is no additional output optical noise. Nevertheless, the electrical processing of OEO repeaters is not yet available for 10 Gbit/s applications. Besides the 2R or 3R property, they also can have different configurations in terms of signal direction. They can be either bidirectional or unidirectional (DS or US).

SOAs are the most suitable components for optical amplification because of their low cost and good efficiency in terms of gain and noise factor. One SOA version that can be used for PON is the *double* SOA (DSOA), which includes two SOAs on one chip, one for the US and the other for DS amplification. Unlike OEO repeaters, SOA represents a significant source of optical noise [47].

Doped-fiber amplifiers (DFAs) can be based on different materials. For reach extension in PON, following DFAs have been used or proposed:

- erbium-doped fiber amplifier (EDFA)
- praseodymium-doped fiber amplifier (PDFA)
- thulium-doped fiber amplifier (TDFA).

EDFA is proposed for bidirectional PON reach extension in [48] and PDFA is proposed for amplification at GPON US wavelength of 1310 nm in [49], while TDFA is employed for DS amplification in GPON.

3R OEO repeaters and DSOA that have shown good performance in GPON systems are considered short-term solutions because they harm the passiveness of the network. Long term-solution is the remote amplification. For this type of reach extension, DFAs are well suited because they can be remotely pumped.

One long-reach PON approach that tries to keep the passive structure of the network by providing remote amplification of the optical signal is the SARDANA[16] network project. Since SARDANA project also focuses on WDM-based PON, its network architecture is a long-reach TDM/WDM PON, as depicted in Figure 3.7 [47]. This hybrid PON has a WDM ring with a number of RNs that feed TDM tress at different wavelengths. SARDANA's main objectives can be summarized ad follows [50]:

- Very high splitting ratio, up to 1:1024
- 10 Gbit/s data rate
- Remote passive amplification
- Wavelength-independent CPE (colorless ONU).

[16] SARDANA is the acronym for Single-fiber Advanced Ring Dense Access Network Architecture.

The experiments have been carried out to demonstrate the feasibility of reaching up to 512 ONUs in a 100 km ring or 1024 ONUs in a 50 km ring at 10 Gbit/s DS and US transmission. In these experiments, the remote nodes of the SARDANA network have been used as mid-span passive add/drop multiplexers and ROPAs [47].

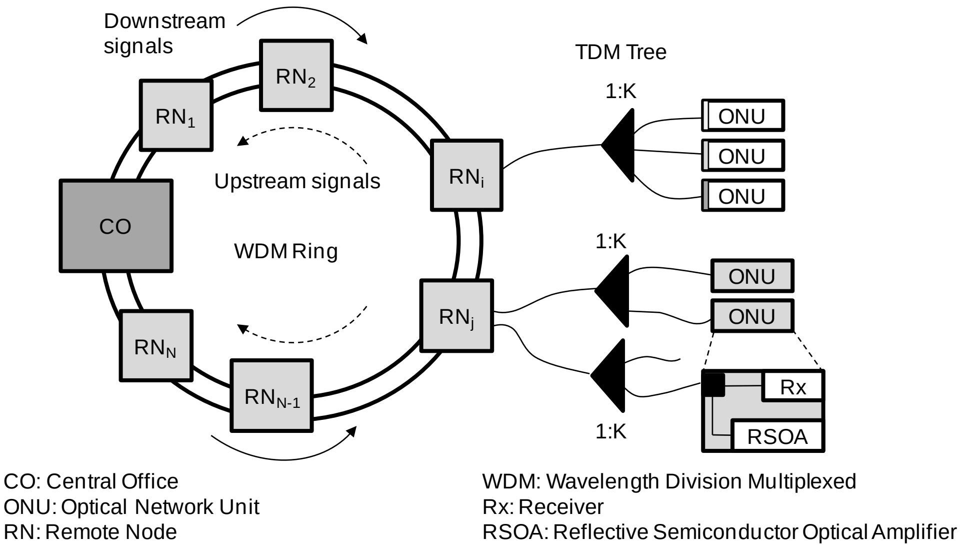


Figure 3.7 Architecture of the SARDANA long-reach PON [47]

3.4 40 Gbit/s and 100 Gbit/s Ethernet

Ethernet has become the preferred packet transport technology. Its deployment covers enterprise LANs, broadband access, data center networking and interconnections across metropolitan and wide area networks. Multiple services such as Internet Protocol TV (IPTV) or Video-on-Demand (VoD) are the main drivers for higher aggregate capacities in edge and aggregation networks. Network aggregation bandwidth is doubling every 12 to 18 months due to the growth of IP-based traffic in access networks, enterprise networks, provider networks and optical transport networks. The other bandwidth critical application area is computing. Computing I/O bandwidth doubles every two years driven by Moore's Law [51]. This historical development of network bandwidth is shown in Figure 3.8. Given the two different growth slopes, standardization bodies decided that the two primary application areas would be best served with two different data rates. Consequently, 40 Gbit/s and 100 Gbit/s Ethernet (40GbE and 100GbE) become the next step in Ethernet evolution.

Today, carrier networks include mainly 10 Gbit/s interfaces. Although scaling of networks can be done by parallelizing 10 Gbit/s connections, these can have poor performance and efficiency at packet level, as routers constantly perform rebalancing of different length packets onto different interfaces. This scaling problem can be avoided by 100GbE interfaces.

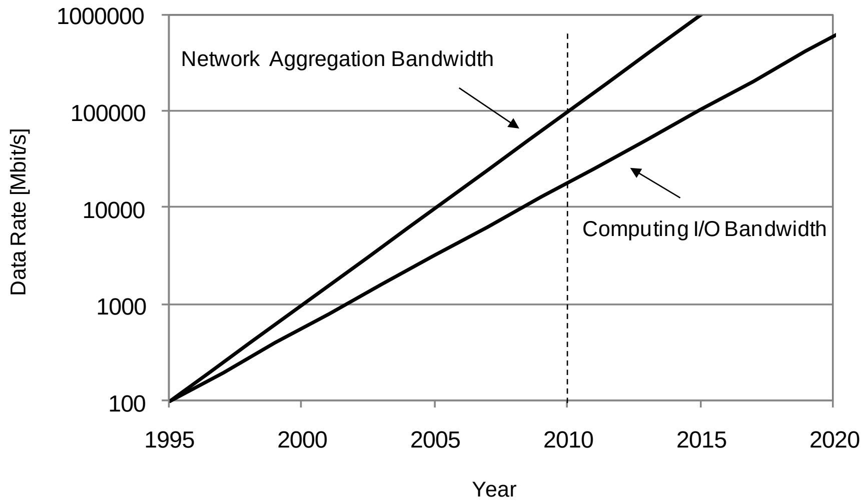


Figure 3.8 Historical development of Ethernet speeds for two most bandwidth demanding Ethernet application areas [51]

There are three major standardization bodies involved in the specification of 40 Gbit/s and 100 Gbit/s high-speed Ethernet: IEEE, ITU-T and OIF[17] [52]. To respond to the trend of growing bandwidth demand, IEEE 802.3 Working Group formed a Higher Speed Study Group (HSSG) in July 2006, which evolved into the IEEE P802.3ba 40Gbit/s and 100Gbit/s Ethernet Task Force in January 2008 [53]. The objectives of the IEEE P802.3ba project are to provide physical layer specifications supporting the two data rates over different media and diverse distances as listed in Table 3.4. Besides PHY specifications, the objective is to support MAC at both data rates. The standard should be finished in mid-2010.

Distance and Medium	40GbE	100GbE
1 m backplane	40GBASE-KR4	-
10 m copper cable	40GBASE-CR4	100GBASE-CR10
100 m MMF	40GBASE-SR4	100GBASE-SR10
10 km SMF	40GBASE-LR4	100GBASE-LR4
40 km SMF	-	100GBASE-ER4
> 40 km SMF	40GBASE-ER4	100GBASE-ER

Table 3.4 List of physical layer specifications for IEEE P802.3ba [54]

The naming of PHY specifications includes rich nomenclature. All names of PHY standards include a prefix and up to three suffixes to the word BASE as described in Table 3.5.

[17] OIF is the Optical Internetworking Forum and it provides the worldwide interoperability and implementability testing.

<table>
<tr><th colspan="3"></th><th>Nomenclature</th><th>Description</th></tr>
<tr><td>Prefix</td><td colspan="2">Speed</td><td>40G
100G</td><td>40 Gbit/s
100 Gbit/s</td></tr>
<tr><td rowspan="9">Suffix</td><td rowspan="5">Medium</td><td rowspan="2">Copper</td><td>K</td><td>Backplane</td></tr>
<tr><td>C</td><td>Cable Assembly</td></tr>
<tr><td rowspan="3">Optical</td><td>S</td><td>Short Reach (100 m)</td></tr>
<tr><td>L</td><td>Long Reach (10 km)</td></tr>
<tr><td>E</td><td>Extended Long Reach (40 km)</td></tr>
<tr><td colspan="2">Coding</td><td>R</td><td>64B/66B Block Coding</td></tr>
<tr><td rowspan="3">Lanes</td><td>Copper</td><td>n</td><td>4 or 10</td></tr>
<tr><td rowspan="2">Optical</td><td>n</td><td>Number of Lanes or Wavelengths*</td></tr>
<tr><td colspan="2">* if n = 1, i.e., serial transmission, no number is required</td></tr>
</table>

Table 3.5 IEEE P802.3ba PHY naming nomenclature [53]

There are three different options for realization of 100GbE PHY. They concern the number of *virtual lanes* that represents transmission parallelization in order to achieve 100 Gbit/s. Accordingly, 100GbE can be realized with ten lanes each transmitting 10 Gbit/s, or four lanes each running at 25 Gbit/s or one lane for serial 100 Gbit/s transmission. The second-generation implementation concept of 100GBASE-LR4 is presented in Figure 3.9.

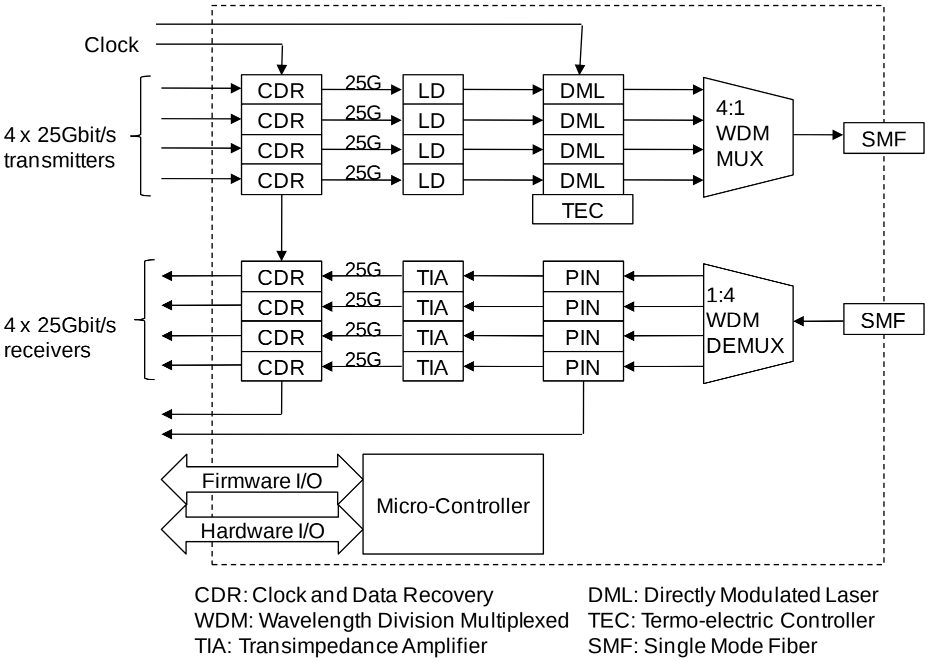


Figure 3.9 2nd generation 100GBASE-LR4 implementation concept [55]

The introduction of 40GbE and 100GbE instead of 10GbE reveals diverse challenges in terms of performance and efficiency [56]. 40 Gbit/s provides following characteristics compared to 10 Gbit/s:

- 6 dB lower OSNR
- 16 times lower tolerance to chromatic dispersion (CD)
- times lower tolerance to polarization mode dispersion (PMD)
- lower OADM tolerance
- higher impact of nonlinear effects
- higher power dissipation
- larger footprint
- 2-3 times higher price

The challenges of 100 Gbit/s compared to 10 Gbit/s are:

- 10 dB lower OSNR
- 100 times lower tolerance to CD
- 10 times lower tolerance to PMD
- higher impact of nonlinear effects
- higher power dissipation
- larger footprint
- 6-7 times higher price

Enabling higher dispersion tolerance in high-speed technologies can be done by introduction of advanced modulation formats and multiplexing. An overview of modulation and multiplexing formats that can be used is given in Figure 3.10.

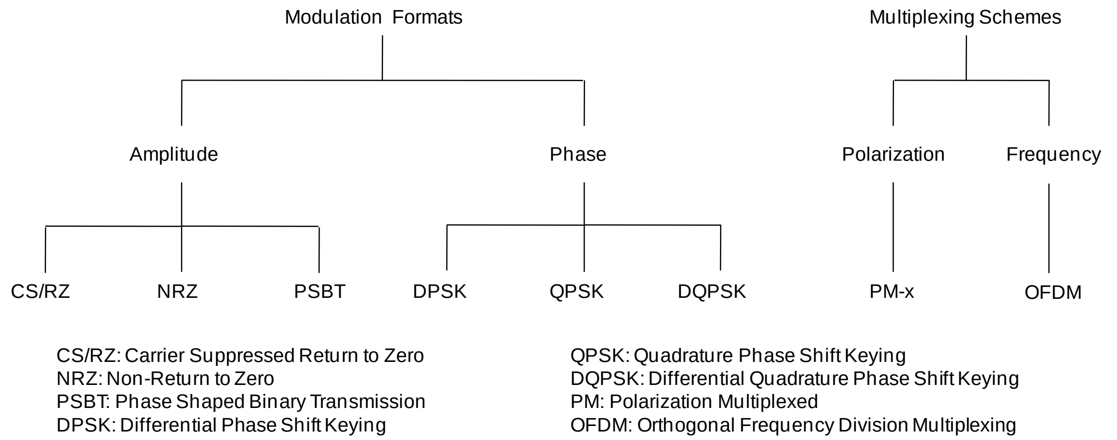


Figure 3.10 Modulation formats and multiplexing schemes options for 40GbE and 100GbE [56]

Recently, different modulation schemes that enable serial transmission speeds up to approximately 114 Gbit/s have been proposed in research papers. Besides their modulation attributes, they differ in characteristics such as achievable distance, complexity and dispersion tolerance. A summary of different modulations schemes that are proposed for 100GBASE-ER implementation and their performance comparison is shown in Table 3.6.

Modu-lation	Spectral efficiency [bit/s/Hz]	OSNR sensivity [dB/0.1 nm]	Tolerance		Complexity			Reach [km]
			CD [ps/nm]	PMD [ps]	Analog	Digital	Optical	
OOK	0.4	20	15	1	H	L	L	400
DPSK	0.8	17	12	1	H	L	M	800
DQPSK	1.6	18	35	2	M	L	M	700
QPSK	1.6	15.5	35	2	M	H	H	1000
PM-DPSK	3	18	140	2.5	L	M	M	700
PM-QPSK	3	15.5	140	2.5	L	H	H	1000

Table 3.6 Proposed modulation formats for serial 100GBASE-ER implementation and their performance. OOK: On-Off Keying, OSNR: Optical Signal-to-Noise Ratio, CD: Chromatic Dispersion, PMD: Polarization Mode Dispersion, H: High, M: Medium, L: Low [56]

The systems using the modulation techniques mentioned above can be inline dispersion compensated or noncompensated. The inline dispersion compensation is achieved by deploying so called *dispersion compensation fiber* (DCF). However, DCF adds loss into the system. It also introduces nonlinear degradation due to its large nonlinear coefficient. Besides already mentioned polarization multiplexing and advanced modulation techniques, one more promising multiplexing scheme that is being investigated for 100 Gbit/s optical systems is the *coherent optical orthogonal frequency division multiplexing* (CO-OFDM). CO-OFDM offers high spectral efficiency and high robustness to dispersion, thus no DCF is required [57].

Chapter 4

4 Analysis of Power Consumption

According to Chapters 2 and Chapter 3 the access networks are divided in two groups; the state-of-the-art access solutions, which included electrical as well as optical access technologies, and advanced access networks that comprise either novel standards or still researched methods for broadband access. This chapter includes the power consumption evaluation of technologies and structures belonging to the two access networks groups. It describes the network models and assumptions used in the study. Moreover, it gives the results and comparisons of power consumption for different access techniques.

4.1 Power Consumption of State-of-the-Art Access Networks

4.1.1 Limitations and Assumptions

In order to be able to compare different access networks, it is important to stress their limits. The limits concern the maximum access data rate and the achievable transmission distance. These two parameters are practically inversely proportional, i.e., the higher the data rate the shorter the transmission distance. This effect is depicted by measurements shown in Figure 4.1 for different high-speed DSL standards. Every access technology standard specifies the maximum possible data rate. The maximum theoretical access rate is in practice rarely achievable and the users are served with bit rates that are generally lower. Anyway this is the theoretical maximum bit rate (R_{MAX}) which will be considered as the upper rate limit in the calculation of power consumption.

The provided data rates can be symmetrical, i.e., DS and US data rates are equal, or asymmetrical, i.e., DS and US data rates are different. Asymmetrical data rates mean typically that the DS bit rate is higher then the US bit rate. This is a practical scenario for residential network subscribers whose applications invoke more traffic in the DS than in the US direction. Business users may require symmetric data rates because of the larger amount of US traffic like some business-oriented applications, e.g. teleconferencing. Access technologies with both symmetric and asymmetric data rates are included in the power consumption calculation.

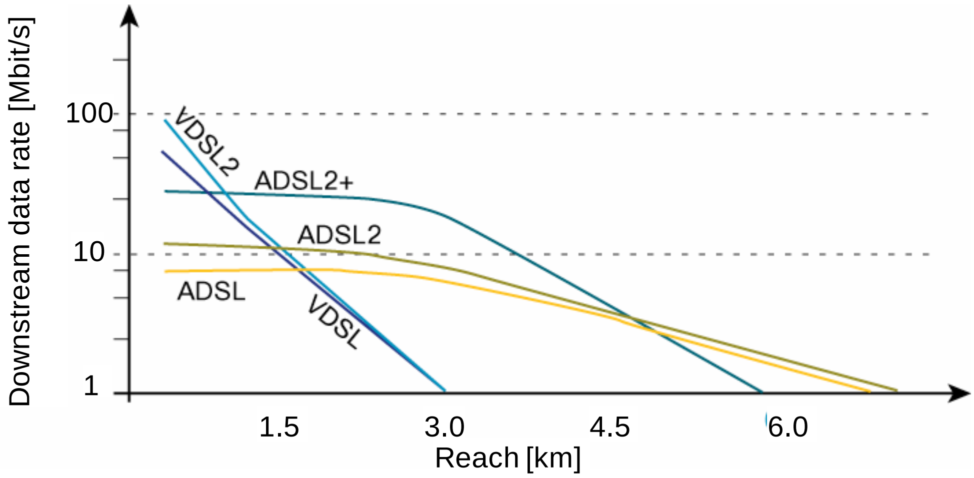


Figure 4.1 Dependence between achieved distance and DS bit rate for different high-speed DSL access techniques (taken from [58])

The following tables give the overview of maximum data rates in both transmission directions and theoretically achievable transmission distances for all state-of-the-art access technologies. The realistic distance corresponding to the maximum data rate will be much lower then the maximum achievable distance. For DSL techniques there is a rapid decrease of data rate with increasing distance from the source. Table 4.1 shows the values of all DSL standards.

Technology	**Maximum data rates**		**Max. reach [km]**
	DS [Mbit/s]	**US [Mbit/s]**	
HDSL	1.54	1.54	3.65
G.lite	1.54	0.512	5.7
SHDSL	5.696	5.696	6.7
ADSL	8.032	0.864	5.5
ADSL2	12	1.2	5.5
ADSL2+	24	1.4	5.5
VDSL asymmetric rates	52	1.54	2
VDSL symmetric rates	10	10	2
VDSL2 asymmetric rates	100	50	2
VDSL2 symmetric rates	100	100	2

Table 4.1 Overview of data rates and reaches for different DSL standards

Hybrid fiber-coax (HFC) network has a different architecture that can not be easily comparable with DSL. It provides very high subscriber densities and has a complex coaxial cable plant used primarily for video signals. DOCSIS standard does not specify any maximum transmission distances, like PON standard for example. Because of the high number of taps, i.e., coaxial splitters and cable attenuation, it requires a lot of amplifiers. Ranging the amplifiers along the coaxial plant the transmission distances are usually very large. 100 km reach is in HFC architecture a reasonable distance. The distance is also dependent on how deep into the field the fiber reaches. Therefore for the DOCSIS standard, a maximum reach is not a fixed well defines value (see Table 4.2).

DOCSIS Version	Number of channels		Maximum data rates		Max. reach [km]
	DS	US	DS [Mbit/s]	US [Mbit/s]	
DOCSIS 1.1	1	1	38	9	N/A
EuroDOCSIS 1.1	1	1	50	9	N/A
DOCSIS 2.0	1	1	38	27	N/A
EuroDOCSIS 2.0	1	1	50	27	N/A
DOCSIS 3.0	m	n	m x 38	n x 27	N/A
	4	4	152	108	N/A
EuroDOCSIS 3.0	m	n	m x 50	n x 27	N/A
	4	4	200	108	N/A

Table 4.2 Overview of data rates and reaches for different DOCSIS standards

In contrast to HFC network, each PON standard defines maximum transmission distances. The maximum reach in PON depends on the splitting ratio. Table 4.3 summarizes the main properties of different PONs and since it gives the maximum reach the lower split ratio of 1:32 was considered. To provide a better overview of all PON features, 10G-EPON solutions are also listed. However, they are part of advanced access network and their power consumption will be discussed in Subsection 4.2.1.

Technology	Split ratio	Maximum data rates		Max. reach [km]
		DS [Mbit/s]	US [Mbit/s]	
EPON	1:32	1000	1000	20
GPON	1:32	2500	2500	20
10G-EPON sym.	1:32	10000	10000	20
10G-EPON asym.	1:32	10000	1000	20

Table 4.3 Overview of data rates and reaches for different PON standards

Ethernet P-t-P network can provide the largest transmission distance, namely up to 40 km without signal amplification. The achievable distance will generally depend on the physical layer standard, i.e., on the transmitter and transmission medium. Here only optical Ethernet is considered since it is the most suitable for access network applications and as it is known optical interfaces consume less power then electrical interfaces. 1GbE

P-t-P network is compared to other state-of-the-art access networks, while 10GbE P-t-P network belongs to the group of advanced access techniques and like 10G-EPON will be considered in Subsection 4.2.1. The features of considered optical Ethernet P-t-P links are listed in Table 4.4.

Technology	Description	Maximum data rates		Max. reach [km]
		DS [Mbit/s]	US [Mbit/s]	
1GbE P-t-P	1000BASE-LX	1000	1000	10
10GbE P-t-P	1000BASE-ER	10000	10000	40

Table 4.4 Overview of data rates and reaches for different P-t-P Ethernet standards

Finally, the two WiMAX standards' features are shown in Table 4.5. Besides the maximum rates and reach, the corresponding channel width is given because these properties are related to each other. In order to remain consistent with the study on power consumption of other access technologies in this work only the ASN will be considered. Mobile stations are home networking equipment and are therefore not included in the power consumption calculation. However the consumption of the terminal equipment, i.e., WiMAX CPE, which has the function of a modem, is taken into account.

Technology	Max. Channel Width	Maximum data rates		Max. reach [km]
		DS [Mbit/s]	US [Mbit/s]	
802.16-2004	20 MHz	75	2	7
802.16e-2005	10 MHz	31	23	5

Table 4.5 Overview of data rates and reaches for WiMAX standards

4.1.2 Network Model

The model of the access network architecture used for estimation of power consumption consists of three parts as shown in Figure 4.2. Starting from the network edge at the user side, these are network termination (NT) located at user's homes or business offices, remote node (RN) and central office (CO). Network termination is CPE, i.e., different modems and ONTs that connect the customer's home equipment to the network. The subscriber's networking equipment like PCs is not included in the calculation. The remote node (RN) is usually a cabinet situated somewhere between the CO and the subscriber. It usually houses the cable splitter needed for the P-t-MP access architectures or amplifiers for reach extension. According to the access type the RN can be passive or active. If there is no reach extension with amplifiers, the CO is assumed to be maximum 20 km away from the subscriber. It houses an access termination unit that represents the edge of the access network and a link to the metro network.

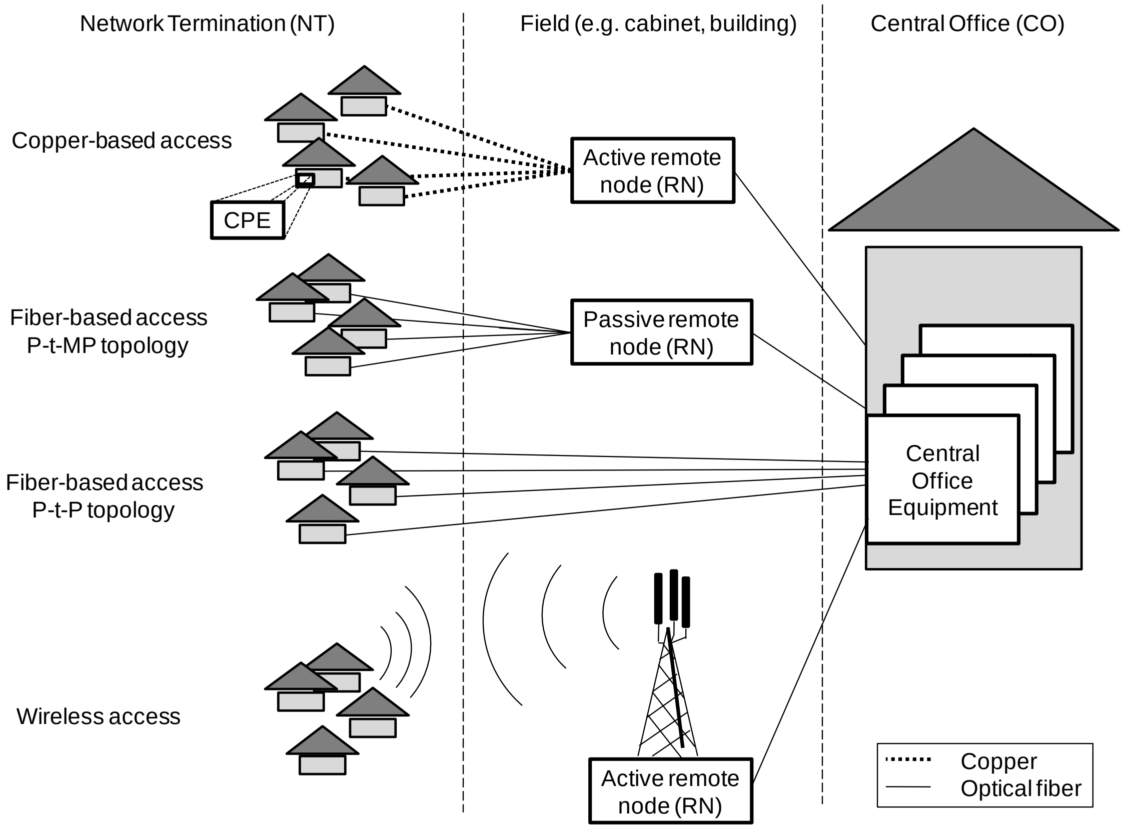


Figure 4.2 Generic model of access network, CPE: customer premises equipment

Data about power consumption of all network elements are taken either from product specifications and data sheets published by the manufacturers or from research papers. The products with their relevant features and power consumption are sorted in tables providing an overview and a comparison of commercially available equipment. The equipment is sorted by access technology and by its function in the network, i.e., CPE or CO equipment. All tables are contained in Appendix A. It is important to stress that not all manufacturers give the power consumption values in the data sheets. Accordingly, some devices even of major network equipment vendors are left out from the data base tables because the power consumption of those devices was not available in their technical specifications that are provided online by the vendor, i.e., manufacturer.

The question that arises when modeling any access network is: how many users can be connected to given CO network equipment? This question can equivalently be expressed as: how many users will share the cost of the CO equipment? The answer to this question will depend on the trade-off between the number of users and their access rate. The CO equipment has a limited uplink capacity I. The uplink capacity is related to the throughput from the CO equipment toward the core network. It is a measure of aggregate data rate toward core network and is thus expressed in bit/s. The given uplink capacity is shared between users and hence the more users the lower their access rate. Many commercially available edge switches have configurable ports, which can be used either as an uplink (toward the network core) or downlink (toward the user) port. Therefore, the throughput at the access edge as well as the number of connected CPEs can be variable. Figure 4.3 shows the dependence between the number of users and the access rate per user for different uplink configurations of the CO switch, when assuming an Ethernet based PON. The CO equipment used for this calculation is an Alloptic edge10™ OLT comprising a chassis with 12 slots for either a PON interface module (PIM) or a network interface module (NIM) [59]. Any card can be inserted in any slot. There are three types of PIM realizations with:

- 8 × 1G-EPON ports providing a total data rate of 16 Gbit/s,
- 2 × 10G/1G PON ports providing a total data rate of 22 Gbit/s,
- 2 × 10G/10G PON ports providing a total data rate of 40 Gbit/s.

The network interface module (NIM) can provide two following options:

- 8 × 1 Gbit/s ports providing an 8 Gbit/s uplink,
- 2 × 10 Gbit/s ports providing a 20 Gbit/s uplink.

The system controller card of the chassis contains a 160 Gbit switching fabric.

Two uplink capacity options are represented in Figure 4.3. The first configuration of the OLT includes 6 PIMs of 22 Gbit/s capacity and 6 NIMs with the 20 Gbit/s uplinks. This configuration provides a total uplink of 120 Gbit/s. The second option is a combination of 6 PIMs with the 16 Gbit/s capacity and 3 PIMs with the 22 Gbit/s data rate plus the 3 NIMs with the 20 Gbit/s uplink. The second OLT configuration provides a total uplink of 60 Gbit/s.

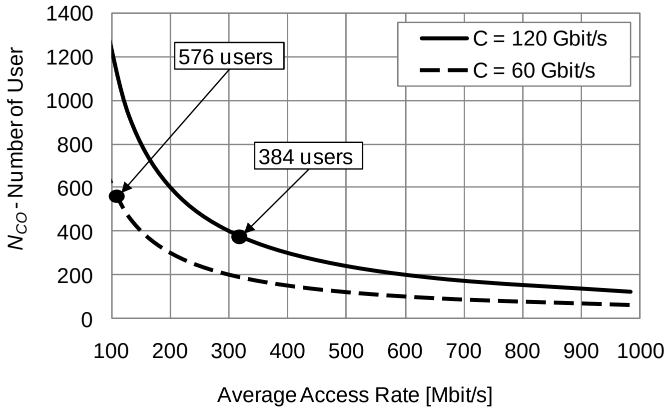


Figure 4.3 Number of users that share the CO equipment vs. average access rate per user for two values of uplink capacity C of the CO equipment. The dots represent the theoretical number of users for two different chassis configurations.

The Figure 4.3 shows the number of connected ONUs or users in dependance on the user’s average access rate for two uplink capacities. The theoretical number of users per chassis configuration is calculated for the PON splitting ratio 1:32. The first option provides 12 PONs with 1:32 splits, which gives 12 × 32 = 384 users per CO. In Figure

4.3, one can see that this number of subscribers could have an average access rate of about 300 Mbit/s. In a realistic scenario with residential applications, this would be a huge bit rate. Therefore it would make sense in this case to connect more users to this OLT. In the second option, the theoretical number of users is 18 × 32 = 576, because the second configuration provides 18 PONs. In this case, one user can have an average access rate of about 100 Mbit/s. The whole CO has usually a high aggregation capacity and serves a large number of subscribers located in its service area. Service area can have for example $N_A = 2^{14} = 16384$ users (dense urban area), $N_A = 2^{13} = 8192$ users (urban area) or $N_A = 2^{12} = 4096$ users (rural area) [60].

The calculated power consumption in this study is given in Watt (W), but also in Watt per user. The consumption in Watt gives the absolute power values of comparable access architectures. However it makes more sense to compare different access networks in terms of power per user. The mathematical model of consumption calculation includes the following variables and parameters:

- P_U – Power per user
- P_{CO} – Power consumed by terminal equipment located in the CO
- P_A – Power consumption of a service area
- P_{RN} – Power consumed by the equipment located in the RN
- P_{CPE} – Power consumed by the CPE located in or near to the customer's home
- R_A – Average access data rate per customer
- R_{MAX} – Maximum achievable access data rate of the given access technology
- N_A – Number of users in a service area
- N_{CO} – Number of users that share the CO equipment
- N_{RN} – Number of users that share the RN equipment
- C – Uplink capacity in bit/s of the CO equipment

The power consumption per user is given by:

$$P_U = P_{CPE} + 2 \cdot \frac{P_{RN}}{N_{RN}} + 2 \cdot \frac{P_{CO}}{N_{CO}} \tag{1}$$

Every facility that house network equipment requires the system for temperature regulation, i.e., air conditioning system, because of the high heat dissipation of network elements. Thus, the total power consumption of a complete access network infrastructure includes also the power consumed by room cooling equipment. Another important practical factor that contributes to overall energy consumption is the power supply for facilities. In order to take into account the cooling requirements and external power supply losses, the power consumed by the network equipment in RN and CO is multiplied by a factor of two [61]. The total power consumption of a service area is then proportional to the power consumption per user:

$$P_A = N_A \cdot P_U \tag{2}$$

4.1.3 Results

This subsection summarizes the results of power consumption estimation for state-of-the-art access networks. It points out the differences and similarities in terms of power consumption per user for different access network standards. It also gives the comparison of different versions of the same access standard. Finally, an overall comparison of all state-of-the-art networks is given.

Results for FTTN Access Networks

In order to be comparable with PON and P-t-P distances, the model of any DSL network contains the DSLAM inside the remote node that is sufficiently close to the subscribers This is a realistic scenario since the largest theoretical reach value of currently deployed DSL systems is only 6.7 km. The results of power consumption calculations for currently deployed DSL systems with highest data rates are shown in Figure 4.4. It shows the power consumption per user over average user access rate that increases up to the theoretical rate limit, as listed in Table 4.1. Figure 4.4 shows little difference between the VDSL2, ADSL2+ and SHDSL network. The consumption per user is approximately 10 W. Taking into account the highest bandwidth per user and the relatively small power differences, VDSL2 can be characterized as the most efficient solution in terms of the power-bandwidth ratio. It is also interesting to mention that for data rates near the maximum, the power per user does not increase significantly, it rather stays constant over the whole bit rate interval.

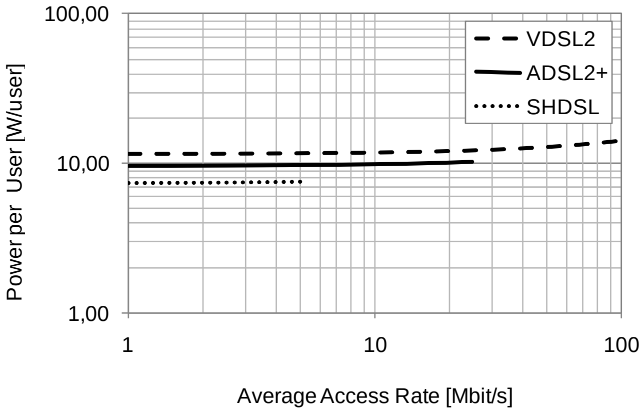


Figure 4.4 Power consumption of the most common DSL options

WiMAX is the wireless solution that is considered in this study. Although many operators offer services of the latest WiMAX version, the so called mobile WiMAX, the older version of fixed WiMAX is still deployed. There is a remarkable power consumption difference for the two WiMAX versions base stations. This can be seen on the example of Telsima's StarMAX™ 6400 base station [62], which exists in two versions, one for the fixed and the other one for the mobile WiMAX standard. Both base stations support the same number of sectors, provide the same network capacity, but still have very different power consumptions. The comparison of their power consumption per user can be seen in Figure 4.5. Although very few data sheets of devices that are designed only for fixed WiMAX can be found with power consumption values, it can be expected that Telsima's devices are a realistic example.

Product	**WiMAX version**	**No. of Sectors**	**Network Capacity [Mbit/s]**	**Power [W]**	**Power per sector [W]**
StarMAX 6400 16d	802.16d-2004	8	256	840	105
StarMAX 6400 16e	802.16e-2005	8	256	2280	285

Table 4.6 Power consumption values and main features of Telsima's StarMAX™ 6400 WiMAX base stations [62]

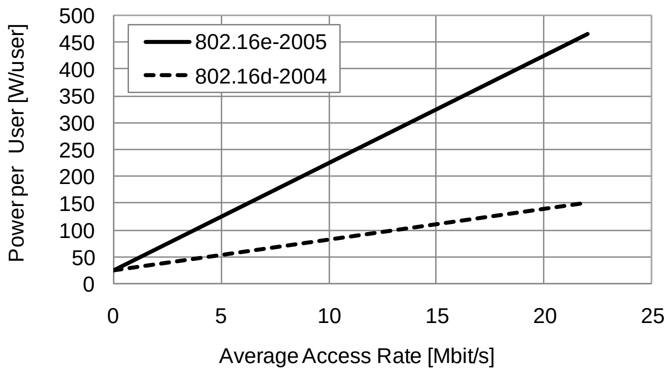


Figure 4.5 Power consumption of WiMAX equipment for two standard versions (Telsima's StarMAX™ 6400 base station)

WiMAX and DSL are the two good examples of today's deployed non-optical access techniques. Both with average access rate lower then 100 Mbit/s, WiMAX stands for wireless access and DSL for electric access. The comparison of their power consumption is given in Figure 4.6. One can see that the wireless solution consumes significantly more power then the DSL. The fixed WiMAX (802.16d-2004) has 9 times higher and mobile WiMAX (802.16e-2005) 11 times higher consumption per user then the VDSL2 for an average access rate of 10 Mbit/s.

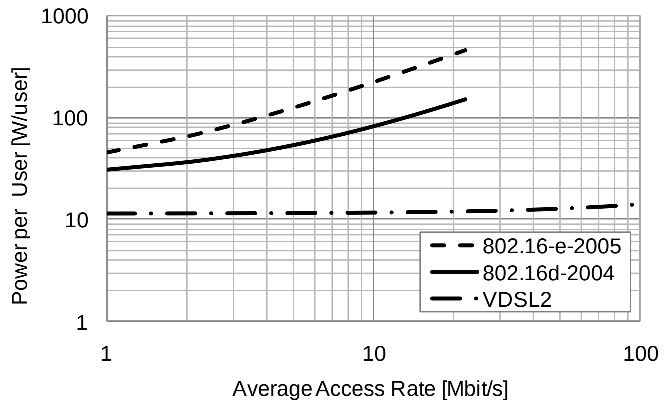


Figure 4.6 Power consumption of some copper-based wired and wireless access technologies with access rates up to 100 Mbit/s

Results for FTTH Access Networks

It might also be interesting to compare today's access technologies that have approximately the same limits in terms of access rate. These are GPON, EPON and 1GbE P-t-P network. The research on GPON and EPON products' power consumption that has been done within the scope of this work has shown relatively high variations of ONU power consumption. Figure 4.7 shows the variations in terms of minimum, mean and maximum appeared values for EPON and GPON. This comparison includes only the ONUs described as single-family unit (SFU) component. There is also a considerable difference between the given CPE for EPON and GPON. This result may rely on the fact that GPON supports a symmetric bit rate of 2.5 Gbit/s, while EPON transmits symmetrically 1 Gbit/s. For further calculations of power consumption in GPON and EPON, the minimum ONU consumption has been considered, because it is the most power efficient solution that is commercially available and moreover, it represents well the CPE needed for a single residential user in the considered network model.

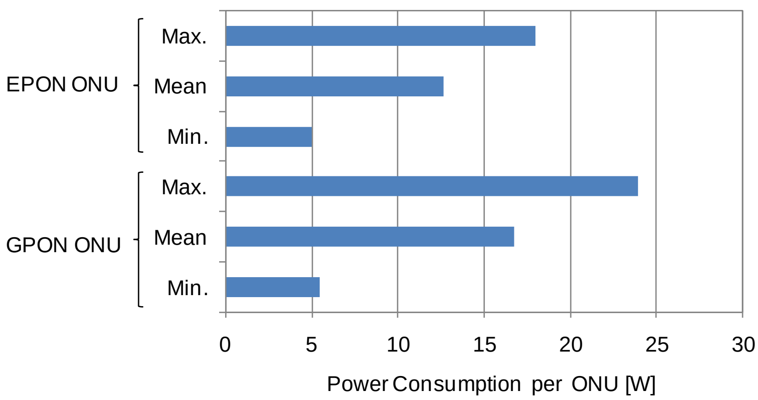


Figure 4.7 Minimum, mean and maximum power consumption of PON ONUs

Figure 4.8 gives the comparison of power consumption per user for the broadband FTTH solutions with average access bit rates of up to 1 Gbit/s. It shows almost no difference between the GPON and EPON line, but a considerable growth of consumption can be seen for higher bit rates. This is, however, different for P-t-P network. On the other hand, P-t-P network has a much higher consumption per user. For very high access bit rates, the PON power becomes even higher then the P-t-P consumption. This is due to the fact that only a small number of users share the resources and cost of the CO when they are served with very high bit rates. It can be concluded that the P-t-P network solution is well suited for customers that need very high bit rate, e.g. business customers, and that PON is a power efficient solution for a large number of residential users.

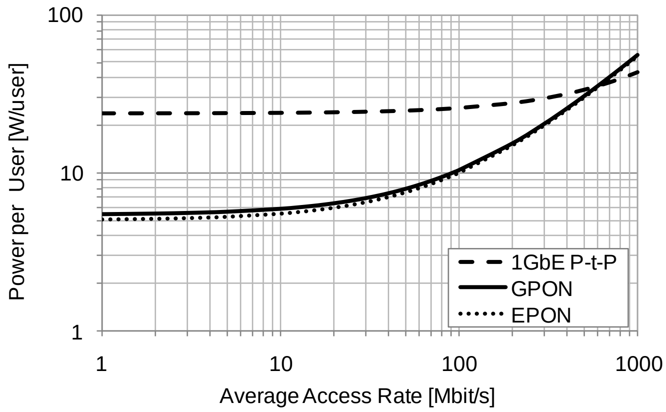


Figure 4.8 Power consumption of FTTH access technologies with access rates up to 1 Gbit/s

Overall Comparison of Power Consumption

This subsection provides the comparison of all considered state-of-the-art access network technologies. The used network model consists of three parts as already shown in Figure 4.2. The power consumption values of considered devices are taken from tables contained in Appendix A.

The considered DSL networks are FTTN architectures with currently most deployed DSL technologies, i.e., VDSL2 and ADSL2+. The other non-optical wired access network, which is taken into account, is the HFC network. It comprises a CMTS in the CO that is connected to the RN over optical fiber. From the RN coaxial cables run to individual users' cable modems. The wireless network that is included in the comparison is the mobile WiMAX network supporting the 802.16e-2005 standard. Since GPON and EPON have approximately the same power consumption, as shown in Figure 4.8, in the overall comparison only EPON is considered. Besides EPON, 1GbE P-t-P network is the other FTTH solution included in the evaluation. Figure 4.9 depicts the power consumption per user of the mentioned access networks. It is quite obvious that the WiMAX has a huge consumption in comparison to all other technologies. Among the considered wired access networks, HFC network is the one that consumes the most power and enables relatively low access rates. In this comparison, the technique of bonding multiple channels was not taken into account. The most energy efficient access technology is EPON. P-t-P network is characterized by a higher consumption, which can still be considered as efficient, since it provides high dedicated access rates. In conclusion, PON, i.e. EPON or GPON, is the most power efficient solution among all wired state-of-the-art access networks.

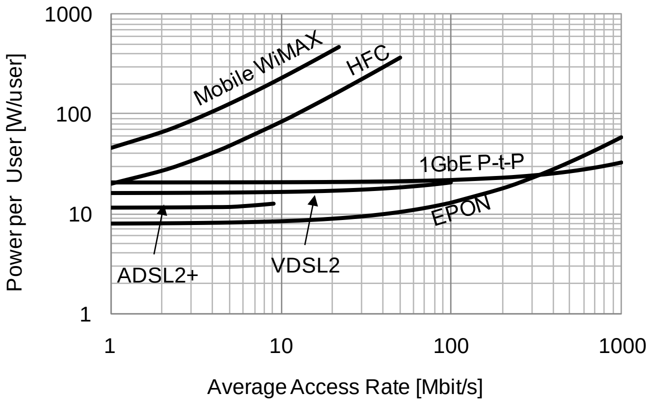


Figure 4.9 Power consumption of all considered access technologies. In the case of ADSL2+ and VDSL2, the FTTCab installation option has been considered.

4.2 Power Consumption of Advanced Access Networks

Data traffic in communication networks increases constantly. Both the number of Internet users and the required bandwidth per user is in permanent growth. According to this booming trend, new high-capacity access technologies are being developed. The overview of current advanced access techniques is given in Chapter 3. This Subsection is devoted to an estimation of power consumption of both newly developed and recently proposed high bit rate access technologies. Accordingly, not all components are commercially available since they are currently being researched. Data about consumption of such components is often found in research papers that deal with that specific topic. The considered network technologies support data rates of 1, 10, 40 and 100 Gbit/s.

4.2.1 Network Models of Advanced FTTH Solutions

The state-of-the-art PON solutions, i.e., GPON and EPON, have already been massively deployed worldwide. They provide high access bandwidth per user while offering low power consumption. The next step in their evolution leads to next-generation PONs (NG-PONs). Different kinds of latest PON systems like 10G-EPON, WDM-PON, hybrid WDM/TDM PON and long-reach PON are often described in the literature as NG-PONs.

Besides the various types of NG-PON, advanced FTTH solutions include P-t-P optical high-speed Ethernet links. The major difference between P-t-P access networks and PONs is the distribution of resources. In a P-t-P system, a separate optical fiber link delivers to each user a dedicated DS and US bandwidth. On the other hand in a PON, the total system bandwidth is shared among users that are connected to the same OLT.

The network architecture that is considered in the case of P-t-P Ethernet is shown on the left hand side of Figure 4.10. Additionally, the model we developed for the Ethernet line card of an aggregation switch, which is located in the CO, and the model we used for the CPE are shown on the right hand side of Figure 4.10. The models contain several stages of components, which are optical transmitter and receiver, PHY chips, MAC chip, switch and network processor. The CPE model includes also a number of PHY components for connection of home networking equipment. The values of power consumption for individual components are listed in Tables B1 and B2 in Appendix B. The optical Ethernet links are represented with two different lines. The full line depicts the DS fiber while the dashed line symbolizes the US fiber. The P-t-P Ethernet network provides to each subscriber dedicated 10 Gbit/s in full-duplex mode. From the today's point of view this access data rate might seam exaggerated, especially for residential users, but including 10GbE in the power consumption estimation of access networks gives an outlook for the power efficiency of future access networks.

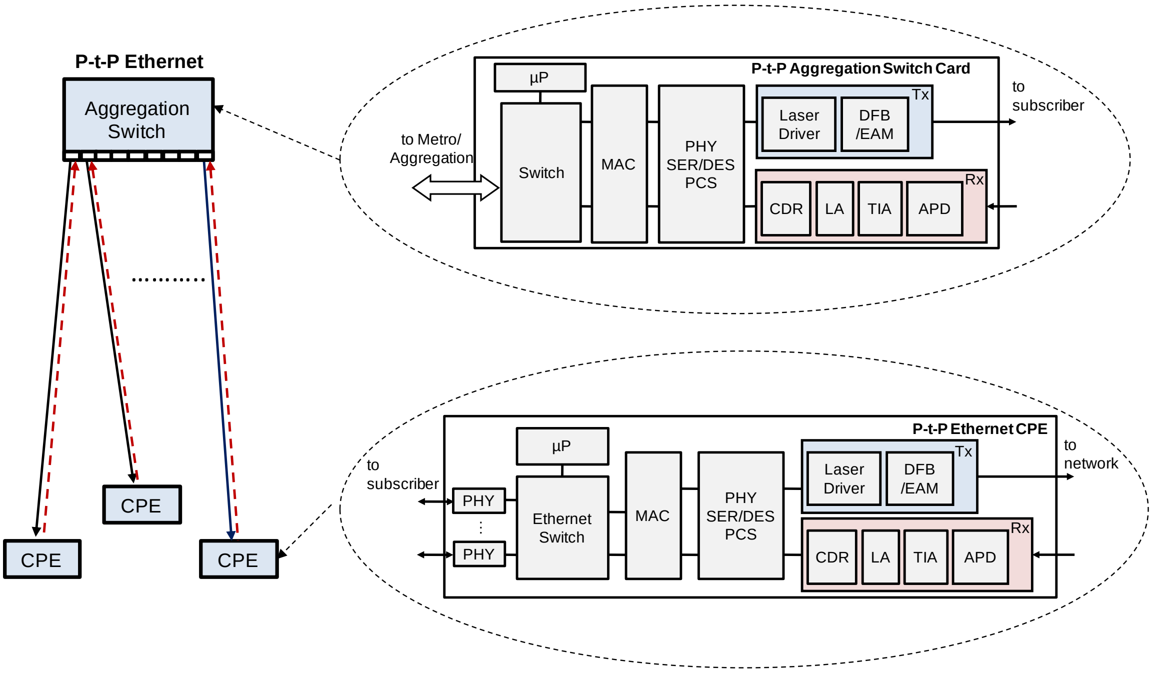


Figure 4.10 P-t-P Ethernet network architecture and model of network elements used for calculation of power consumption

The next advanced FTTH solution that is considered in this Chapter is 10G-EPON. The network topology of 10G-EPON does not differ of other TDM PONs. The DS traffic is broadcasted on the same wavelength through an optical splitter to every user, which recognizes its own data due to the ONU ID. Both 10 Gbit/s DS and US data rates are shared among users. The US total data rate that is aggregated from all users can normally be either 1 Gbit/s, in the asymmetric 10G-EPON version (10G/1G), or 10 Gbit/s in the symmetric 10G-EPON variant (10G/10G). Analogously to P-t-P model, on the right hand side of Figure 4.11 one can see the architecture of the considered OLT and ONU. In every PON, US data is transmitted in bursts, what requires firstly a burst mode transmitter in the ONU and secondly a burst mode receiver in the OLT. The burst mode transmitter and receiver running at 10 Gbit/s are technically the most challenging 10G-EPON components. They have been therefore an attractive research topic recently. The research paper by Yoshima et al. [63] presents a realization option of a burst mode transmitter for 10G-EPON. Nakagawa et al. presented in their study [64] a 10 Gbit/s burst mode receiver for PON application. The power consumption values of these components that are still not available commercially are taken from the two mentioned research papers. The lists of all components and their power consumption values, which are considered in this network model, are given in Tables B3 and B4 within Appendix B.

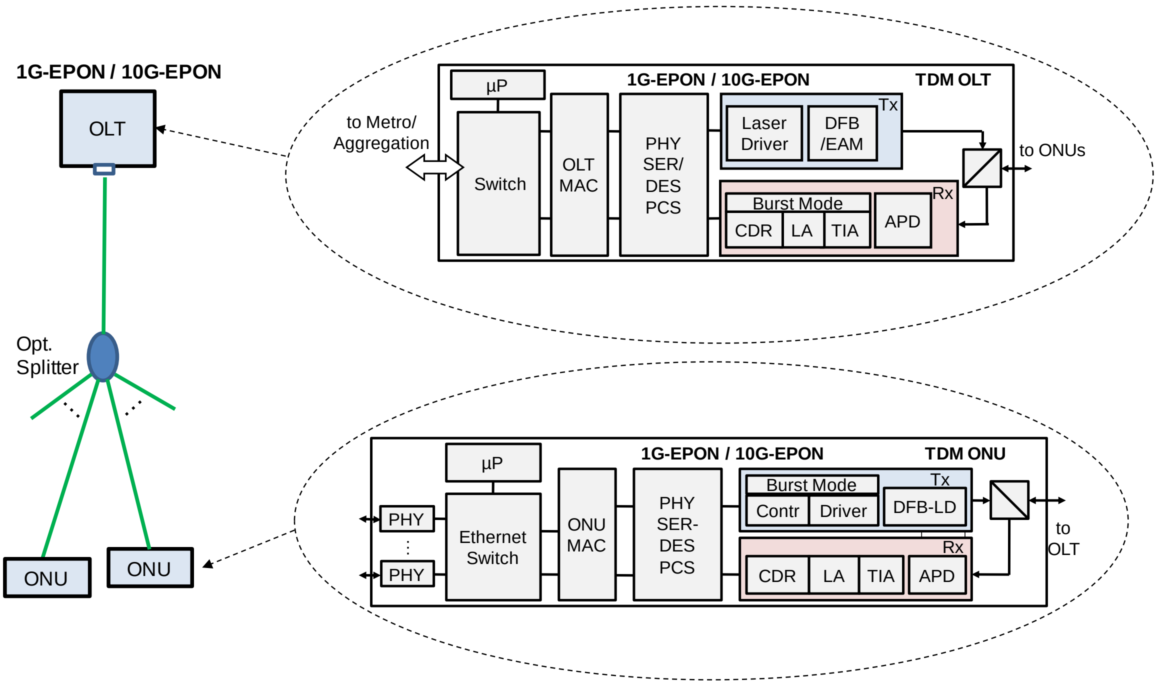


Figure 4.11 10G-EPON topology and model of network elements used for calculation of power consumption

As described in Subsection 3.2, WDM-PON can be realized in various manners, especially when it comes to the realization of the ONU. Several crucial WDM-PON drawbacks compared to TDM PON have made WDM-PON less successful in the access area. Thus they are still not widely used. However, currently there is a notable WDM-PON deployment in South Korea [23]. The ONU configuration option can be divided in two groups as shown in Table 3.2. The solution with local light emission is generally considered inefficient since it requires a wavelength specific light source in the ONU, which can be a tunable laser or a broadband source that has to be spectrally sliced. Tunable laser are generally being avoided because of their high price compared to other light sources, while WDM-PON products using spectrum slicing technique have only recently become commercially available, so no appropriate data could be found about them [23]. Therefore, the WDM ONU model considered in this Subsection is based on wavelength supply technique. As shown in Figure 4.12, the OLT includes a broadband light source, i.e., an SLED or a tunable laser diode (TLD), which supplies the source-free ONUs with an optical signal comprising a number of wavelength channels. SLED is used for 1 Gbit/s WDM PONs, however for higher bit rates TLD is more suitable [43]. The colorless ONU is equipped with a reflective SOA (RSOA) that receives the light from the OLT, then performs the modulation and amplification of the optical signal, and finally loops it back in the US direction. The DS data are sent by an array of OLT transmitters whose signals are then multiplexed in a WDM coupler, which is usually realized by an arrayed waveguide grating (AWG). The US signals are analogously demultiplexed by an AWG decoupler in the OLT and sent to an array of receivers. At the input of the OLT a circulator separates the DS and US signals. The block diagrams of TDM/WDM network elements can be seen in Figure 4.12.

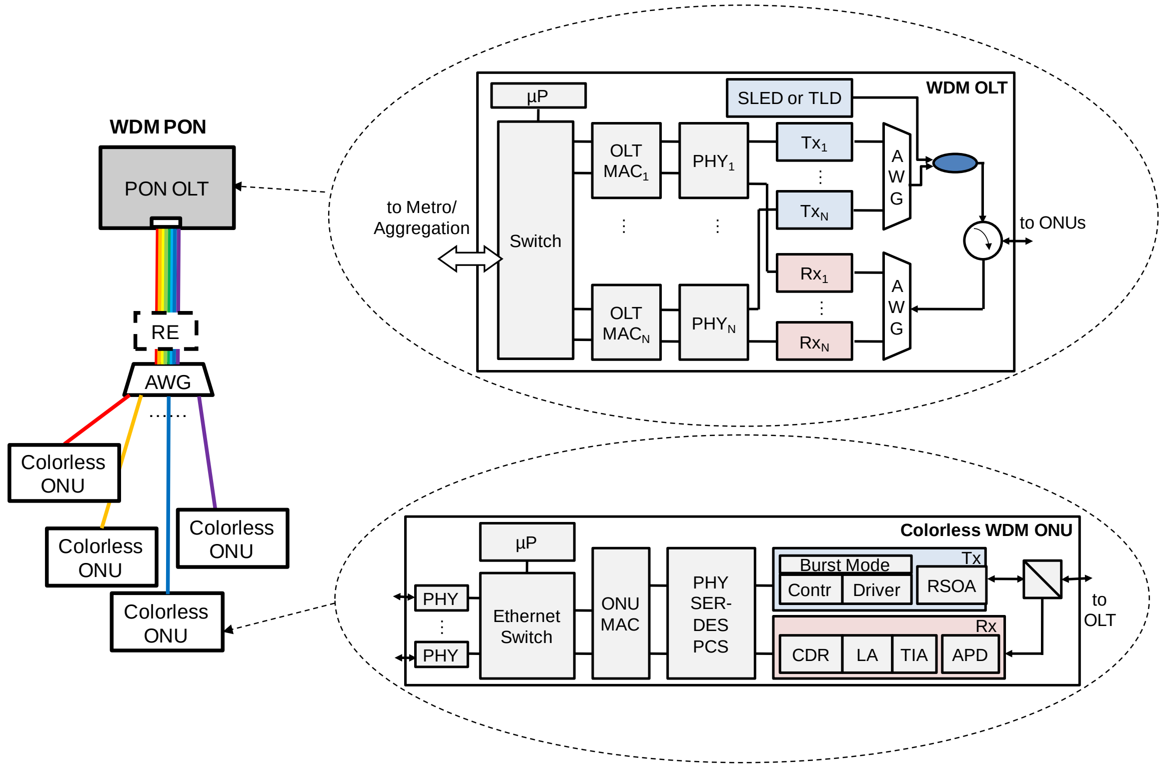


Figure 4.12 WDM PON topology and model of network elements used for calculation of power consumption

The topology of WDM PON that (de)multiplexes the signals in a remote node by means of an AWG is also shown in Figure 4.12. The 32 WDM channels with the channel spacing of 100 GHz provide 32 virtual P-t-P connections with dedicated US and DS bandwidth per user. The remote node remains passive since AWG is an athermal passive element. Each WDM channel transmitted over a feeder fiber that runs from the AWG to the point of a passive optical splitter that distributes the optical signal to a number of TDM ONUs. That branch of the WDM network acts like a TDM PON. Such a configuration is referred to as hybrid TDM/WDM PON and it seams to be more practical because it represents an extension of currently widely deployed TDM PONs. The coexisting of WDM and TDM PONs in order to obtain higher transmission capacities might be a more realistic scenario for the future optical access then the scenario including a hard switch from TDM to WDM PON. The lists of all components and their power consumption values considered in this network model are given in Tables B5 and B6 within Appendix B.

All described network models can be extended in terms of their reach distance. P-t-P Ethernet links can be up to 40 km long, 10G-EPON is specified for reaches up to 20 km and WDM PON that provides 1 Gbit/s symmetric and dedicated data rate per user can reach 50 km. With means of reach extenders (RE), i.e., amplifiers and regenerators, 10G-EPON can be extended up to 60 km and WDM-PON up to 100 km [65]. Figure 4.13 shows the three advanced FTTH architectures with reach extenders.

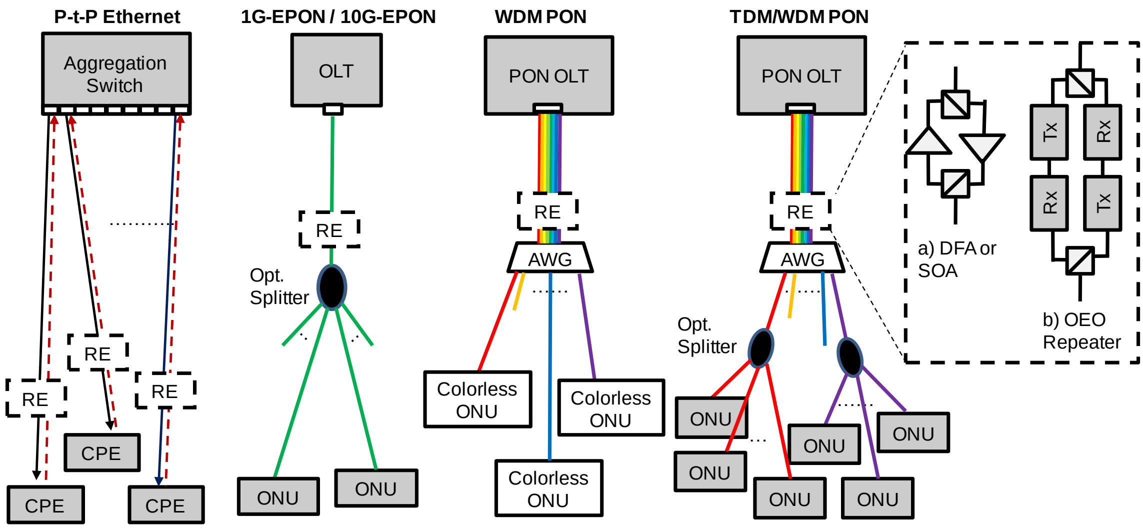


Figure 4.13 Reach extended options of advanced FTTH solutions with block diagrams of reach extenders (RE) a) optical amplifiers (DFA or SOA) and b) OEO repeater. CPE: Customer Premises Equipment

In this model, a RE is placed in the remote node in all three cases. Figure 4.13 depicts also the options used for REs. Depending on the transmission technique, two types of REs can be used: optical amplifiers, i.e., doped fiber amplifier (DFA) or semiconductor optical amplifier (SOA) and OEO repeaters. However by placing the REs in the remote node or somewhere in the field between the OLT and the ONUs, the PON loses its major property which is the passiveness. There have been proposals for remotely, i.e., from the CO, pumped DFAs in order to preserve the passiveness of the remote node. Table 3.3 gives the characteristics overview of optical amplifiers used for PONs. SOA is the most suitable and the most power efficient amplifier for PONs. All doped fiber amplifiers (DFA) are generally larger and consume more energy than the OEO repeaters but since OEO repeaters are essentially digital transceivers, they function only for a single wavelength channel and a predefined modulation format and data rate. Therefore, they are not suited for either WDM PONs or hybrid TDM/WDM PONs.

4.2.2 Results

All networks are modeled with 32 users because it is a standard splitting ratio in PONs. Accordingly, the P-t-P Ethernet system also provides 32 user connections. The only exception is the TDM/WDM PON which contains 32 WDM channels and each channel is split on additional 32 subscribers that are equipped with TDM ONUs. Therefore, the considered TDM/WDM PON connects 33 × 32 = 1024 users. The results of power consumption are firstly given in power per user for technologies providing 1 Gbit/s bit rates (1G) and secondly for technologies providing 10 Gbit/s data rates (10G). For a better evaluation, the 1 Gbit/s advanced networks such as pure WDM or TDM/WDM PONs are compared with state-of-the-art PONs, i.e., GPON and EPON, and 1GE P-t-P network. This can be seen in Figure 4.14. The consumption per user of WDM PON is lower then that of P-t-P network but higher then the one of GPON. The P-t-P network consumes the most energy while EPON is the most efficient in terms of consumption per user. TDM/WDM PON is almost as power-efficient as EPON while providing 32 times more user. This corresponds to the results obtained in Subsection 4.1. Due to the higher number of connected subscribers, it is understandable that the hybrid PON provides lower consumption per subscriber then WDM PON.

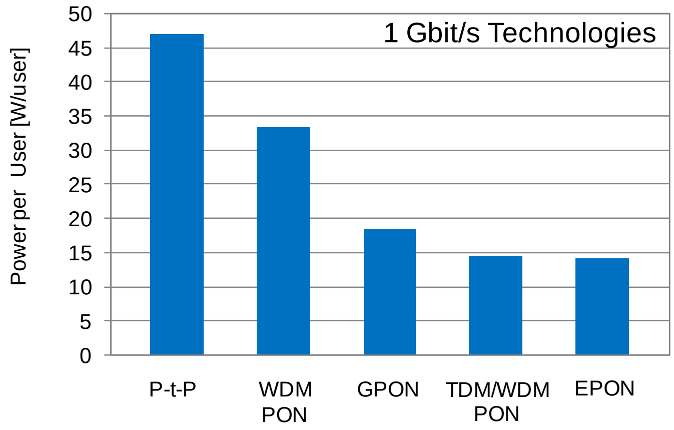


Figure 4.14 Power consumption per user in 1 Gbit/s advanced and state-of-the-art networks

A similar distribution of power per user can be observed for 10 Gbit/s network options that are shown in Figure 4.15. The 10 Gbit/s options include 10GE P-t-P, WDM PON, TDM/WDM PON and 10G-EPON. It is evident from the Figure that TDM/WDM PON and 10G-EPON are the most power efficient solution among them.

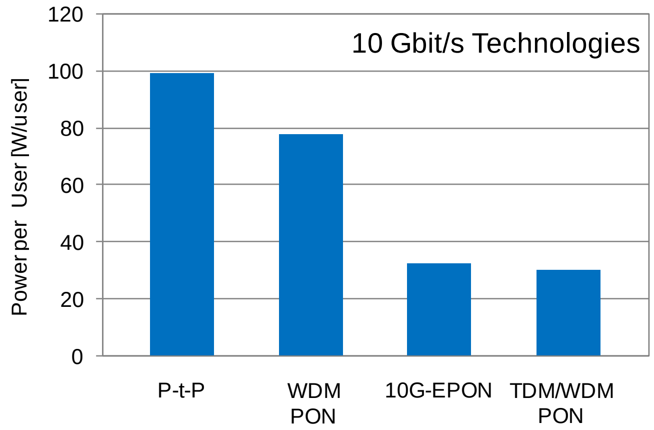


Figure 4.15 Power consumption per user in advanced access networks providing 10 Gbit/s bit rates

The access solutions providing 1 Gbit/s access rate have actually different total capacities. The total capacity of the network model is calculated as a sum of the total DS bit rate and the total aggregate US bit rate for all users in the network. The considered systems differ in the principle of bit rate distribution and therefore they offer different bandwidths per user. P-t-P links and WDM channels provide dedicated symmetrical user bandwidth while in TDM PON solutions, the available bandwidth is always shared among users. The mentioned total capacity is a theoretical and unlimited value obtained under the assumption that the CO equipment can always transport this total aggregate capacity toward the core network. The values of the theoretical bidirectional capacities as well as the DS and US bit rates per user are listed in Table 4.7 for all considered access technologies.

The following results concern the power consumption in W per user and per Gbit/s. For ease of simplicity, the unit of power consumption per user and per Gbit/s will be written as W/Gbit/s, where W comprises the consumption per user. The same results can be expressed in terms of energy consumption given in nJ per bit per user. The unit transformation is more descriptive by the following equation:

$$\frac{W}{Gbit/s} \equiv \frac{W/user}{Gbit/s} = \frac{W \cdot s}{user \cdot Gbit} = \frac{nJ/bit}{user} \qquad (3)$$

Figure 4.16 shows the comparison of so called 1G technologies (see Table 4.7) in terms of power consumption per user and per Gbit/s. The corresponding total capacity is written over each bar representing a particular technology. In contrast to Figure 4.14, which shows only the power per user, Figure 4.16 andFigure 4.17 show the power efficiency of advanced network concepts, i.e., TDM/WDM PON, WDM PON, and P-t-P network, in comparison to the state-of-the-art PONs. EPON exhibits the lowest efficiency in term of W/Gbit/s since it offers a relatively low total bandwidth for the same number of users. In the group of technologies providing 64 Gbit/s of total capacity, the P-t-P network features the highest consumption.

	Technology	Users	DS rate/user [Gbit/s]	US rate/user [Gbit/s]	Throughput [Gbit/s]
1G technologies	EPON	32	1/32	1/32	2
	GPON	32	1/32	2.5/32	3.5
	1GbE P-t-P	32	1	1	64
	1G WDM PON	32	1	1	64
	1G TDM/WDM PON	1024	32/1024	32/1024	64
10G technologies	10GbE P-t-P	32	10	10	640
	10G-EPON asym.	32	10/32	1/32	11
	10G-EPON sym.	32	10/32	10/32	20
	10G WDM PON	32	10	10	640
	10G TDM/WDM PON	1024	320/1024	320/1024	640

Table 4.7 Overview of data rates per user and total theoretical bidirectional throughput

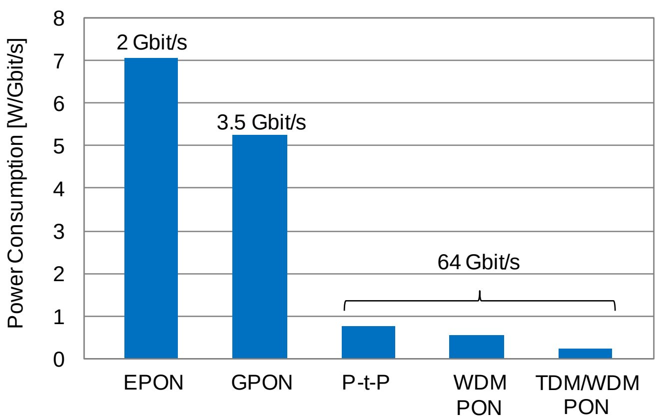


Figure 4.16 Power consumption per user and per Gbit/s for 1G technologies with different total bidirectional capacity

The results for power consumption per user and per Gbit/s are also given for so called 10G technologies. Figure 4.17 shows a higher efficiency of 10G technologies compared to 1G technologies. The two 10G-EPON options have the highest consumption in W/Gbit/s among advanced 10 Gbit/s network concepts. This result is analog to the power efficiency of EPON and GPON among 1G technologies. Figure 4.17 also specifies the corresponding capacity for each network type.

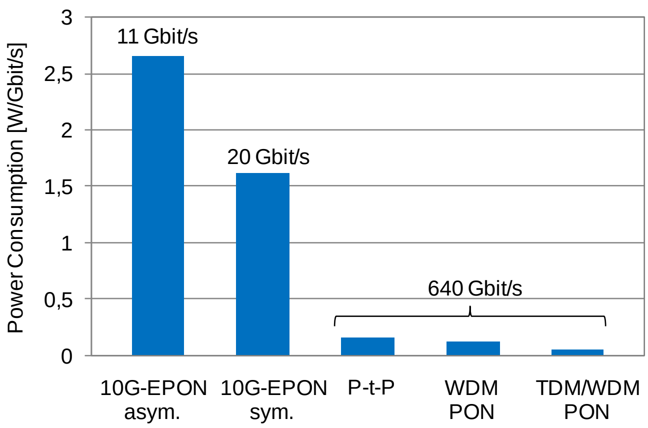


Figure 4.17 Power consumption per user and per Gbit/s for 10G technologies with different total bidirectional capacity

The next option in advanced access networks includes the reach extension. As described in Subsection 4.2.1 different reach extenders have been considered. With use of REs, the transmit distances can be increased up to 3 times in case of 10G-EPON and 2 times in case of WDM PON. Figure 4.18 shows the relative power consumption increase per user for three different RE options, namely EDFA, SOA and OEO repeater. The Figure gives the comparison between TDM/WDM PON and WDM PON. There is no significant difference between the results obtained for EDFA and SOA. The third option provides the highest power consumption increase. This inefficiency results from the fact that each WDM channel needs an OEO repeater. In contrast EDFA and SOA can amplify all 32 signals simultaneously.

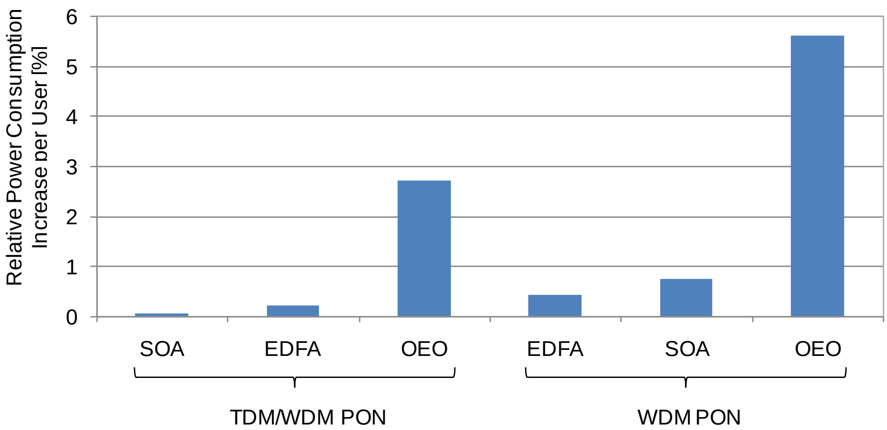


Figure 4.18 Relative increase of power consumption per user in % for different reach extenders, EDFA: Erbium-doped fiber amplifier, OEO: Optical-electrical-optical repeater, SOA: Semiconductor optical amplifier

Figure 4.19 shows the relative increase of power consumption per user when reach extension is applied. It depicts the results for a number of 1G access options. The highest relative consumption growth exhibits a P-t-P network when SOAs are used for implementing RE. P-t-P network was also modeled with OEO repeaters as REs, which consume less power then SOAs. Almost 15% of the consumption increase per user in P-t-P networks relies on the fact that each P-t-P link requires a separate RE. Since PON is a P-t-MP topology, it requires only one RE, whose cost is shared among 32 users. EDFA is the most suitable amplifier for WDM PON options. The most efficient solution is the hybrid PON with a negligible consumption growth per user. The EPON shows a relatively high increase in power consumption of 7% compared to other considered PON solutions. P-t-P network extended with SOA exhibits the highest power consumption growth per user.

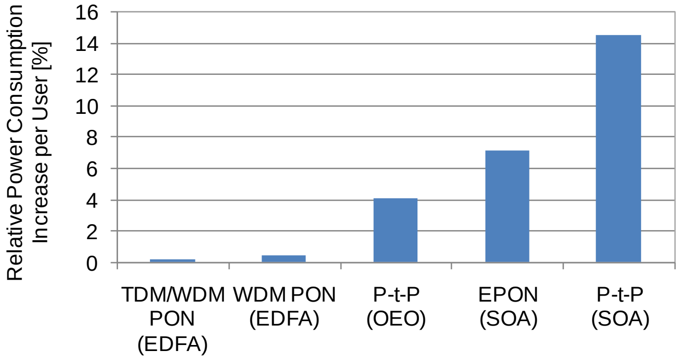


Figure 4.19 Relative increase of power consumption per user in the case of reach extension

According to the presented results, a general conclusion about considered advanced FTTH solutions can be made. In the case of an achievable maximum capacity in which every user can exploit the upper limits of the available bandwidth, the most energy efficient solution is the hybrid TDM/WDM PON using optical amplification since it provides the lowest consumption per user and Gbit/s. This is the case for both standard network architecture and long reach network option.

In order to give a better comparison among the considered networks and regarding power efficiency, it makes sense to additionally consider a realistic situation in which the CO equipment will have a limited throughput toward core network. This limited uplink throughput can be estimated using the following scenario. The scenario assumes a 10-hop, 80 channel WDM metro ring providing 40 Gbit/s per wavelength channel and 1000 users per CO. The total capacity of the ring is then 3.2 Tbit/s and the average data rate per user in one direction is 320 Mbit/s, according to the following calculation:

$$\frac{40\ Gbit/s\ \cdot 80\, wavelengths}{10\, COs\ \cdot 1000\, users} = \frac{3.2\ Tbit/s}{10000} = 320\ Mbit/s \tag{4}$$

This scenario makes sense especially for a network providing dedicated bandwidth per user, i.e., for P-t-P Ethernet networks, WDM PONs and TDM/WDM PONs, while state-of-the-art PONs and 10G-EPON have already standardized limited capacity per network. In Figure 4.20 one can see the overall comparison of 1G technologies for both cases, Case A and B. The first considered option with maximum theoretical throughput is named Case A and Case B is the option with limited throughput in the assumed scenario. The same results for 10G technologies are shown in Figure 4.21. Among 1G technologies EPON is characterized by the highest power consumption per Gbit/s since it has a relatively limited transmission capacity compared to other options. Besides EPON, among both 1G and 10G technologies, the highest power consumption can be observed for P-t-P network. It also provides high difference in use with or without RE as well as the largest differences between Case A and Case B. Generally the most power efficient solution is the hybrid TDM/WDM PON.

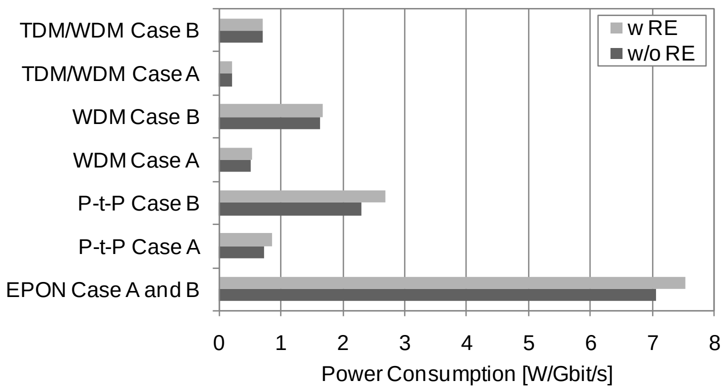


Figure 4.20 Overall comparison of power consumption of 1G technologies with and without RE for Case A: Theoretical maximum throughput and Case B: Assumed limited throughput

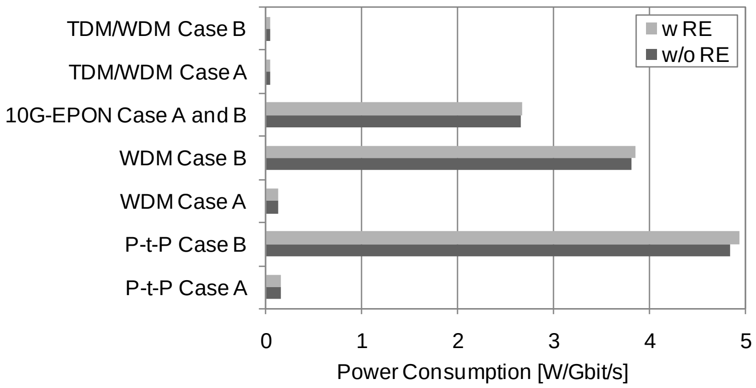


Figure 4.21 Overall comparison of power consumption of 10G technologies with and without RE for Case A: Theoretical maximum throughput and Case B: Assumed limited throughput

4.2.3 Power Consumption of 100 Gbit/s Ethernet

100GbE is being intensely researched recently. Its standardization is expected in mid-2010. 100 Gbit/s Ethernet does not concern directly the access network since it is way too many Gigabits for an access link that is currently having the best-case capacity up to 1 Gbit/s. Thus 100GbE will be deployed in metro network nodes that aggregate the transmit capacities of many access networks. Considering the 100 Gbit/s Carrier Ethernet in the power consumption estimation represents one step further from access networks toward the core network. The power consumption of 100GbE systems located in metro networks is described in this subsection.

Till now different realization options of 100GbE have been proposed. For the implementation of high-speed Ethernet various advanced technologies are considered. They concern higher-order modulation schemes, multicarrier schemes, dispersion compensation methods and digital signal processing. Since all implementations of high-speed optical Ethernet till now are only experimentally realized it is self-evident that many concerned components are not available on the market. The data about components' power consumptions are taken from technical specifications, but also from research papers and online documents made by the IEEE 802.3ba 40 Gbit/s and 100 Gbit/s Ethernet Task Force. [53] For the calculation of power consumption three most discussed 100GbE physical layer realization options are taken into account. These PHY options include one serial and two parallel implementations as follows:

a) 10 × 10 Gbit/s – 100 Gbit/s transport over 10 parellel wavelength channels, i.e., virtual lanes, each carrying 10 Gbit/s (see Figure 4.22)
b) 4 × 25 Gbit/s – 100 Gbit/s transport over 4 parellel wavelength channels, i.e., virtual lanes, each carrying 25 Gbit/s (see Figure 4.23)
c) 1 × 100 Gbit/s – 100 Gbit/s transport over 1 serial channel (see Figure 4.24)

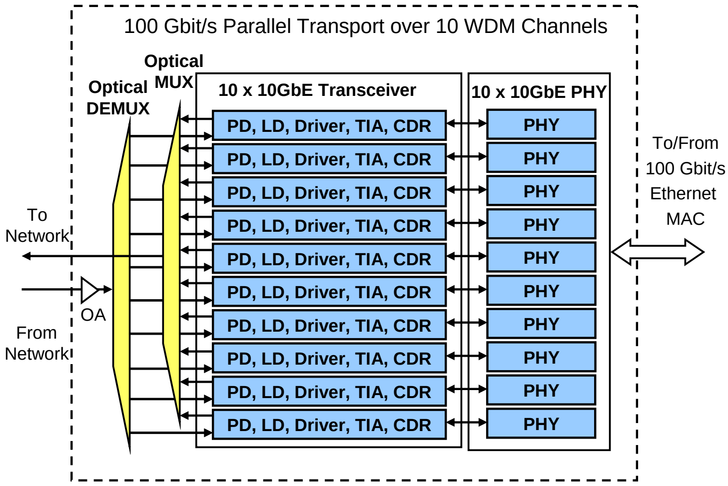


Figure 4.22 10 x 10 Gbit/s parallel PHY realization option for 100GbE

Block diagram in Figure 4.22 shows the 10 × 10 Gbit/s realization with the row of parallel transceivers and PHY components. The transceiver includes a photo detector (PD), a transimpedance amplifier (TIA), a clock and date recovery (CDR) unit, laser diode (LD) and a laser driver. An optical amplifier (OA) is placed in front of the optical demultiplexing unit to preamplify the optical signal before reception. The 10 × 10 Gbit/s realization is specified in the 100GBASE-ER10 part of the future IEEE 802.3ba standard.

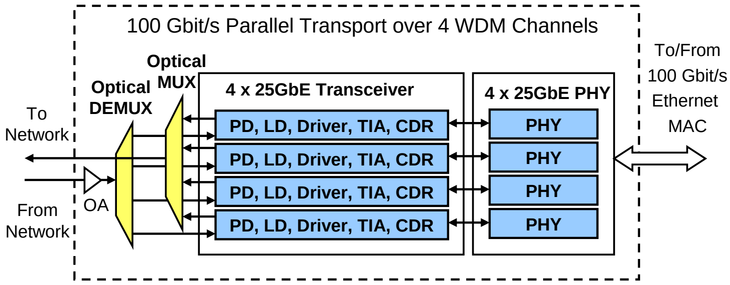


Figure 4.23 4 x 25 Gbit/s parallel PHY realization option for 100GbE

Similarly to the 10 × 10 Gbit/s option, Figure 4.23 represents the block diagram of the 4 × 25 Gbit/s parallel option. This realization is specified in the 100GBASE-ER4 part of the future IEEE 802.3ba standard.

Finally, Figure 4.24 shows the architecture of the serial 100GbE transceiver and physical layer. This implementation considers the single-polarization differential quadrature phase shift keying (DQPSK) modulation format, which has already been successfully demonstrated in a field trial [66].

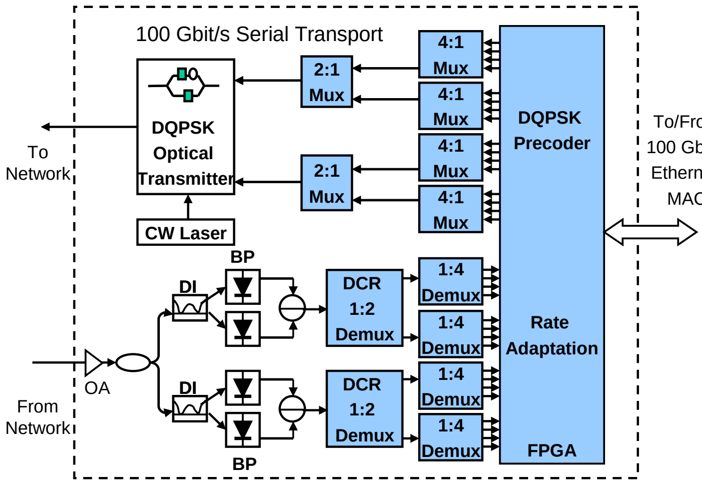


Figure 4.24 1 x 100 Gbit/s serial PHY realization of 100GbE [67]

Considering the described transceiver options and other necessary Ethernet line card components, one can specify a generic structure of a 100GbE line card. The power consumption relies on the model of such an Ethernet line card, as depicted in Figure 4.25. Besides transceiver and PHY, every line card includes a 100 Gbit/s MAC implemented in an FPGA device. The packet processing, classifying and forwarding function is accomplished by a network processor. The line card includes also a fabric interface, central processing unit (CPU), dynamic random access memory (DRAM) and ternary content addressable memory (TCAM). Since today, not many components running on 100 Gbit/s are available. The corresponding power consumption of some 100 Gbit/s components is estimated by parallelizing a number of lower rate components of same art. The lists of components with their consumption values are given in Tables B8, B9 and

B10, which are included in Appendix B. The tables contain also the names of components' manufactures that either sell the concerned product or have published a research study about it. The power levels in Figure 4.26 show clearly that the 4×25 Gbit/s option has the lowest power consumption and the serial 100 Gbit/s solution the highest one.

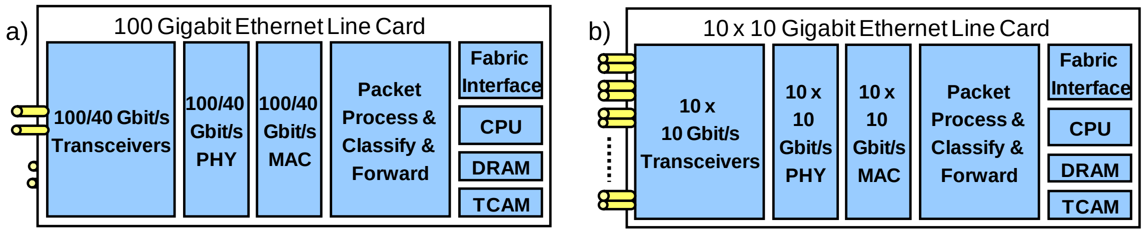


Figure 4.25 100GbE line card models used for power consumption calculation a) 100G line card b) 10x10G line card [68]

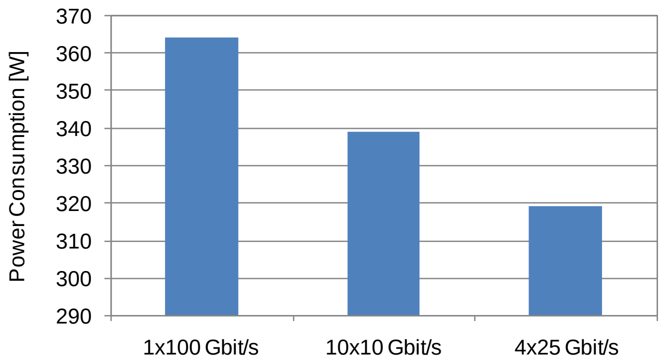


Figure 4.26 Absolute power consumption of three different 100GbE line card realization options

The 100GbE switch model comprises a number of line cards slots. In order to achieve a certain aggregate data rate of the switch, different numbers of the three line cards options can be scaled. The considered model of the 100 Gbit/s Ethernet switch can be seen in Figure 4.27. Besides the line cards, it includes following parts:

- Interconnects
- Switching fabrics
- Implementation of the management and control planes

The very large switching fabrics are mostly realized using either Benes or Clos network of smaller packet switch devices. In this study, the switching fabrics include a strictly non-blocking Clos arrangement of switching elements having 32×32 ports at 10 Gbit/s each. The line cards options that are considered in the switch model are the three 100GbE options and state-of-the-art 10GbE line cards. Such a switch would provide Tbit/s capacities. The switch architecture shown in Figure 4.27 represents an example of a combination of *M* 100 Gbit/s cards and *N* 10×10 Gbit/s cards.

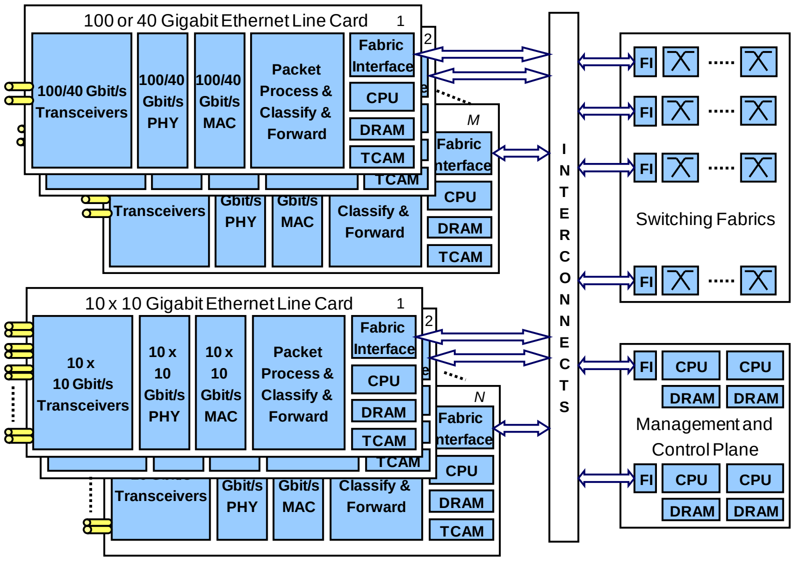


Figure 4.27 Generic structure of a 100GbE switch considered for the power consumption estimation [68]

Figure 4.28 shows the power consumption comparison of three switches, each equipped with a number of same line cards. Scaling different numbers of line cards one can obtain different switch capacities. Figure 4.28 gives the comparison up to 110 Tbit/s. It can be observed that the solution with serial 100 Gbit/s transmission consumes more energy than the other two solutions. The most energy efficient switch model is the one equipped with 4×25 Gbit/s line cards. For smaller aggregate data rates of the switch the difference in consumption between the three options is negligible. For 100 Tbit/s the power consumption varies from 319 W for the most efficient solution to 364 W for the least efficient solution. It should be mentioned at this point that parallel 100G options are designed for distances up to approximately 40 km while the serial option allow transmission distances of several hundreds kilometers.

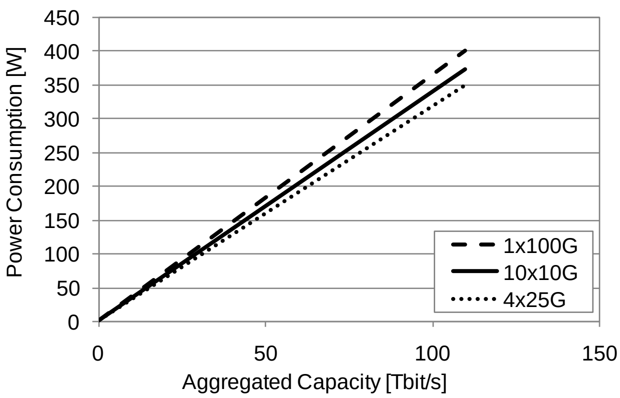


Figure 4.28 Comparison of power consumption of 100GbE switches with three different realization options

The considered switch model can also have *M* 100GbE line cards of any of the three realizations, while the rest of the slots is occupied by 10GbE line cards. One can also vary the ratio of 100GbE cards to the 10GbE cards and observe if different ratios influence the power consumption. Figure 4.29 depicts two groups of curves. Each group contains three curves corresponding to the three realization options. One bunch of curves represents the solution with only M = 2 slots occupied by 100GbE cards and the other one represents the switch with M = 16 slots carrying 100GbE line cards. All other slots are occupied by 10GbE line cards to achieve the given capacity. The diagram gives the relative savings of power in % when using novel 100GbE technology instead of the current 10GbE solution. The savings for a given capacity in Tbit/s are calculated as follows:

$$S = \left(1 - \frac{Power\ of\ the\ switch\ with\ M\ 100GbE\ slots}{Power\ of\ the\ switch\ with\ all\ 10GbE\ slots}\right) \cdot 100 \quad (5)$$

The switches equipped with a large number of 100GbE ports improve the power efficiency and could offer up to 25% power savings in comparison to pure 10GbE switches. On the other hand, if using more 10GbE ports the power efficiency decreases. However for large capacities over 20 Tbit/s, the savings are below 3%.

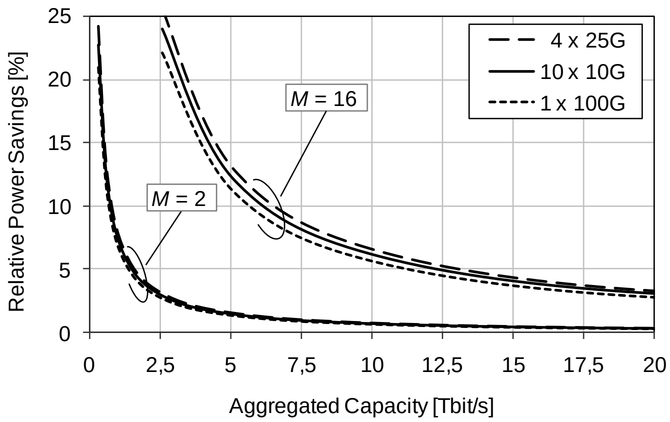


Figure 4.29 Relative power savings when using new 100G line cards instead of existing 10G line cards to achieve the same aggregate capacity. The savings are shown for two cases: 1) when only M=2 slots are occupied by 100G line cards and 2) when M=16 slots are occupied by 100G line cards. In both cases, the remaining slots contain 10G line cards.

Since the IEEE 802.3ba standard discusses also the 40 Gbit/s Ethernet, it makes sense to compare the power consumption of possible 100GbE switches with that of potential 40GbE switches. Such a comparison is given in [69]. The comparison shown in Figure 4.30 includes the three 100GbE realizations and two 40GbE realizations. Moreover it takes into account a state-of-the-art 10GbE switch. One 40GbE option comprises the parallel transport over four 10 Gbit/s lanes and the other option stands for serial 40 Gbit/s transmission. All Ethernet switches are modeled to provide an aggregate data rate capacity of 10 Tbit/s. Their consumption is expressed in terms of energy per bit. Since nJ/bit = kW/(Tbit/s) and the switches offer 10 Tbit/s throughput, the consumption of each switch can easily be converted in kW. For example, the 1x40G switch consumes about 60 kW. Remarkably higher energy consumption per bit can be observed for a 10GbE switch in comparison to all other novel realizations. The Figure 4.30 shows that the level of the 10G switch is in average 30% higher of all other levels. Therefore, it can be expected that the new high-speed Ethernet technologies will contribute to higher power efficiency in Carrier Ethernet networks.

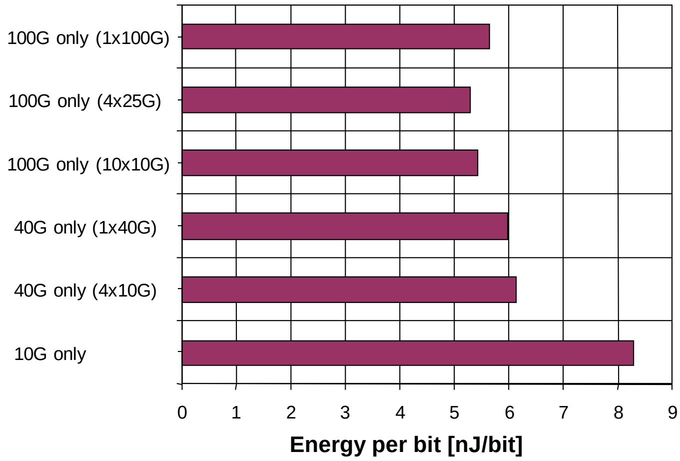


Figure 4.30 Comparison of 40GbE and 100GbE switches with the 10GbE switch in terms of energy per bit [69]

Chapter 5

5 Summary and Conclusions

5.1 Summary

This thesis is dedicated to estimation of power consumption in the access network area, which seems to be the largest contributor to power consumption of the complete information network infrastructure. The study realized within the framework of this thesis concerns mainly the wired access technologies. Current wired state-of-the-art access networks and advanced access networks as well as novel standards for the access and metropolitan area are described and compared in terms of power consumption. The work firstly contains a technical overview of copper-based access technologies, which are different types of digital subscriber line (DSL) and hybrid fiber-coax (HFC). Secondly, it describes the major technical features of current optical access networks, i.e., passive optical network (PON) and 1 Gbit/s point-to-point optical Ethernet network. Additionally, it introduces the most important characteristics of WiMAX, which is the only wireless access option considered within this work. The description of all above mentioned state-of-the-art access networks is given in Chapter 2. The subsequent Chapter 3 provides the overview of considered advanced access networks. It contains the highlights of the novel 10 Gigabit Ethernet PON (10G-EPON) standard, as well as different concepts for wavelength-division multiplexed PON (WDM PON). Different realization options for the so called colorless ONUs used in WDM PONs are also presented. The advanced access options include also long-reach PONs. For these PONs different types of reach extenders, i.e., amplifiers were considered and compared in terms of performance and suitability. The last topic presented in Chapter 3 concerns the emerging 40 Gbit/s and 100 Gbit/s Ethernet standard, i.e., IEEE 802.3ba standard.

The analysis of power consumption is done according to a generic model, whose description is included in Chapter 4. The mentioned networks are compared in terms of power consumption per user. Their power efficiency, in terms of Watt per Gbit/s, is also evaluated. The diagrams with the results are contained in Chapter 4.

Data about power consumption of state-of-the-art network devices, which were used in the considered network model, were mostly available in manufacturers' data sheets. For advanced network elements that are not commercially available yet, a model of network elements was created. The model includes all necessary electronic and optical components. Power consumption values of those chips and components were collected from numerous data sheets and research paper. The obtained data base was the basis for power consumption calculations. Tables containing these data are included in Appendices A and B.

A better overview of mentioned access networks is given in Figure 5.1. It shows the historical development of the most significant access and metro network technologies. The currently most deployed and the most promising future optical technologies are depicted on the trend lines. The supported bit rates are also given. The framed names in Figure 5.1 refer to the technologies considered in this thesis. The star represents the hybrid TDM/WDM PON, which is according to the results of this study the most power-efficient access solution.

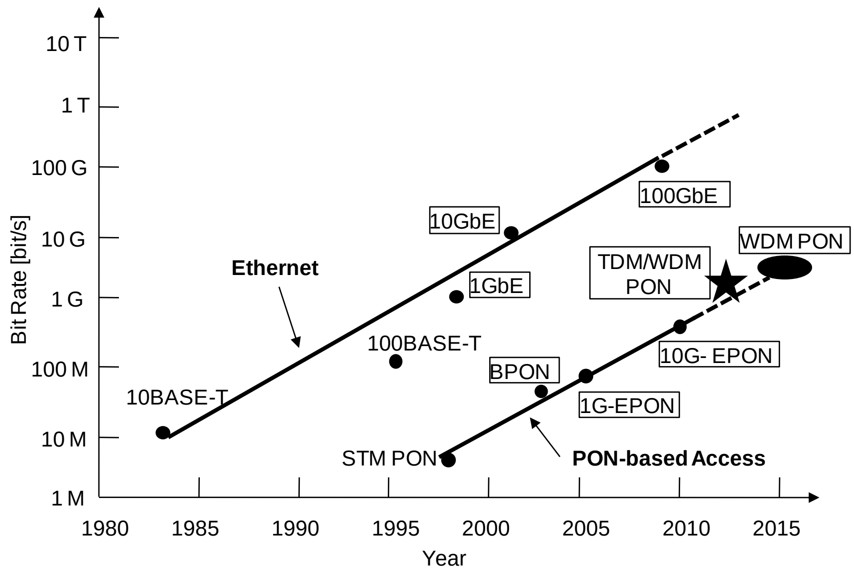


Figure 5.1 Overview of historical evolution and capacities of different optical technologies used in access and metro network area [70]

5.2 Conclusions

The comparison of various access technologies in terms of power consumption has lead to the conclusion that optical technologies are promising candidates for the next generation access networks. PON provides the lowest power consumption among all state-of-the-art access networks and moreover, it offers a high aggregate data rate. Copper-based access networks, i.e, xDSL and HFC networks, provide lower aggregate data rates and have remarkably higher power consumption per user. Apart from PON, P-t-P Ethernet network is the other FTTH solution, which in contrast to PON delivers a dedicated high data rate to the user. However, this solution consumes twice the power of the PON for an average access rate of 10 Mbit/s. For a significantly higher access data rate of 1 Gbit/s, which is the theoretical maximum of the current state-of-the-art PON, the PON becomes even more power-consuming than the P-t-P Ethernet network. In conclusion, one can say that users requiring high bit rates up to 1 Gbit/s should be served by P-t-P optical links in order to achieve the highest power efficiency. According to current bandwidth demand this may concern only business customers, while for residential customers, the newest broadband access trends approach slowly 100 Mbit/s of dedicated data rate per user. Therefore it is more efficient in terms of power consumption to serve the residential users by PONs. Among all state-of-the-art access networks, WiMAX, as the only considered wireless technology, consumes the most power, but it offers a relative high-speed access and supports mobility which can not be provided by any of the wired access technologies.

The advanced access technologies were divided in two groups. The first group supports data rates up to 1 Gbit/s and the second group up to 10 Gbit/s. The results that are given in Watt per Gbit/s showed a higher energy efficiency of higher-speed access technologies, i.e., 10G technologies. Hence, the 10G-EPON is more efficient than the 1G-EPON., although it has a higher absolute power consumption for the same number of users. P-t-P networks have generally the lowest power efficiency. Power consumption of advanced access networks was analyzed for two cases. Case A refers to a theoretical unlimited maximum throughput in the aggregation node. Case B comprises a more realistic model in which the assumed throughput toward the core is limited. This reflects on a limited maximum access data rate per user. P-t-P network exhibits the highest difference in power efficiency for the two cases. Evidently, the model of Case A, which allows very high uplink throughput, provides higher power efficiency per bit/s.

The overall conclusion for the advanced access networks, which are all based on a fiber-to-the-home architecture is that the hybrid TDM/WDM PON is the most promising candidate in terms of power efficiency. It can support a very large number of users, large transmission distance and sufficiently high data rates.

Power consumption analysis included also reach extension options. The results have lead to the conclusion that the use of amplifiers for reach extension does not remarkably influence the power efficiency. On the other hand a reach extender can provide longer transmission distances and larger coverage area, but unfortunately it destroys the passiveness of the optical distribution network.

Since it is expected that both average access rate and number of users will increase in the near future, bandwidth requirements on aggregation switches will become higher. According to [51], core network links typically require 4-10 times the bandwidth of the highest-speed user service interface to provide adequate performance. The technology that promises to satisfy these needs in the near future is the 100 Gbit/s Ethernet (100GbE). The 100GbE switch model that is used in this work for the estimation of power consumption comprises three PHY realization solutions as proposed by the 40 Gbit/s nd 100 Gbit/s Ethernet Task Force [53] as well as in recently published research papers [66]. One line card model included the serial 1 × 100 Gbit/s PHY option, and the other two comprised parallel options, i.e., 10 × 10 Gbit/s and 4 × 25 Gbit/s, which involves 10 parallel wavelength channels at 10 Gbit/s each and 4 parallel wavelength channels at 25 Gbit/s, respectively. The power consumption estimation of 100GbE switches showed that the serial line card option consumes the highest power, while the parallel 4 × 25 Gbit/s option is the most power-efficient. These results reflect proportionally on the results obtained for the switch models comprising a number of line cards of different types.

Finally, it can be stressed that fiber-based access promises more in terms of power efficiency than the copper-based access. However from a capacity point of view one may argue about why should an existing hybrid fiber-twisted pair network be replaced by an all-optical network? Taking into account the technoeconomical aspect, this evolutional step might seem unnecessary. According to [23], the combination of DSL and PON access (FTTN) can provide 50 Gbit/s of shared bandwidth in each direction. This is much more than the bandwidth provided by the state-of-the-art standardized FTTH solutions, e.g., GPON and EPON. This difference in speed offered by these different solutions exists not because copper wire has a larger bandwidth but because GPON and EPON do not exploit the whole capacity of optical fibers. Besides wide bandwidth, optical fiber offers other advantages that make it very attractive for high-speed access networks. It provides low attenuation, longevity and low maintenance cost. These properties together with growing popularity of bandwidth-hungry applications will render fiber the medium of choice in access networks.

5.3 Outlook for the Future

Since different factors influence the power consumption of the access network, different power-saving approaches and methods have to be considered. The solutions for power-efficiency improvements can have direct or indirect impact on the power savings [68]. Reducing the power consumption of network components such as switches, base stations and modems, influences directly the power consumption of the whole network. Although the home networking equipment have not been included in the power consumption estimations within this work, reducing the consumption of those devices, e.g. PCs and printers, would lead to significant power savings. Other measures like optimization of production processes and more efficient energy management through the use of special applications should be taken in order to provide an indirect impact on global power consumption of networks. The router efficiency can be further improved by more energy-aware routing protocols. Controlling energy in access networks by introducing different operational power-modes, e.g. sleep-mode in modems, enables a dynamic energy management that also increases energy efficiency of the whole network. At the chip level, power consumption can be decreased by improving the process technology. For example, the network processor realized in 90 nm process geometry has half the power consumption of the previous 130 nm process geometry.

Finally, the increased use of optical technology, which is generally more energy-efficient than the electronics, should lead to power saving within network elements. It is expected that due to its unique properties, the optical fiber will replace the access copper wires in the near future. But the wireless counterparts of optical access networks will exist over the next decades [23]. Moreover, future broadband access networks tend to a fiber-wireless convergence. The *fiber-wireless* (FiWi) networks combine the broad bandwidth of the optical fiber with the ubiquity and mobility of wireless networks. Today’s wireless backhaul suffers from the emerging bandwidth bottleneck due to increasing traffic caused by new applications, e.g., the smart phone. Future broadband access solutions have the potential to change the way we live and work by providing the convenient option of telepresence and teleworking. This could not only save the time previously used for transportation but also impact the environment by reducing fuel consumption.

Appendix A

Data Base of Network Components Used for State-of-the-Art Access Networks

A.1 DSL

Product	Vendor	Number of Lines						Power [W]	Power per Line [W]
		ADSL2/2+	ADSL	VDSL2	VDSL	SHDSL	G.SHDSL		
AAM1212-51/53	ZyXEL	12						25	2.08
ALC1248G-51/53	ZyXEL	48						70	1.46
ALC1272G-51	ZyXEL	72						95	1.32
Surpass hiX ADSL2+	NSN	72						110	1.53
D500 line card	NSN		48					62.4	1.30
NCT1901	NetComm		48					49	1.02
Mean Power Consumption per ADSL/2/2+ Line									**1.45**
VLC1224G-41	ZyXEL			24				80	3.33
Surpass hiX VDSL2	NSN			24				74	3.08
Surpass hiX VDSL2	NSN			48				84	1.75
D500 line card	NSN				24			48	2.00
VLC1124L	ZyXEL				24			30	1.25
Mean Power Consumption per VDSL/VDSL2 Line									**2.28**
D500 line card	NSN					24		45.6	1.90
SLC1248G-22	ZyXEL					48		60	1.25
Surpass hiX SHDSL	NSN					48		85	1.77
SAM1008	ZyXEL						8	8.6	1.08
SAM1216-22	ZyXEL						16	25	1.56
Mean Power Consumption per SHDSL/G.SHDSL Line									**1.51**
Mean Power Consumption per Line for all DSL Types									**1.73**

Table A1 Power consumption of commercially available DSL line cards and their mean consumption per DSL line

Product	Vendor	DSL Type					WLAN	Power [W]
		VDSL2	VDSL	ADSL2/2+	ADSL	SHDSL		
HCL-VM-10	HCL		×					4
ASM-61	RAD		×					4.6
H335G	Dasan	×						5.5
MVM204	Millinet	×						6
ASM-60	RAD		×					6
P-870M-I	ZyXEL	×						7
SMC7800A/VCP	SMC	×						7
P-871H	ZyXEL		×					7
VC2 - M/S	Dynamix	×						7.5
NV-600R	Netsys	×						7.5
Netopia 7340-44	Motorola	×						9.6
VF200F6	NEC		×					10
VM-120	Roomweb		×					12.5
Mean Power Consumption of VDSL/2 Modems								**7.25**
VER170M	Versa Tech.			×				5
VER170P	Versa Tech.			×				5
Linksys WAG54G2	Cisco			×			×	5
DG834GBGR	Netgear			×			×	5
VX-VER170WR	Versa Tech.			×				5.8
TEW-635BRM	Trendnet			×				6
S519	Sangoma			×				8
Linksys WRT54G	Cisco			×			×	10
P-2602R-D1A	ZyXEL			×			×	10
P-663H-51	ZyXEL			×				12.5
CellPipe 22A	Lucent				×			15
Mean Power Consumption of ADSL2/2+ Modems								**7.94**
3300	Corecess					×		4
ASMi-52L	RAD					×		6
ASMi-52L	RAD					×		8
Mean Power Consumption of SHDSL Modems								**6**
Mean Power Consumption of all DSL Modems								**7.36**

Table A2 Power consumption of commercially available DSL modems

Product	Vendor	Max. No. of Lines	Number of Ports per Card						Uplink Capacity [Gbit/s]	Power [W]	Power per Line [W]
			ADSL2/2+	ADSL	G.lite	VDSL2	SHDSL	G.SHDSL			
IES-1000M/ AAM1212-51	ZyXEL	24	24	×	×				0.4	50	2.08
VX1000MD	Versa Tech.	24	24	×	×				0.01	40	1.67
IES-1248	ZyXEL	48	48	×					2	90	1.88
IES 5005/ ALC1248G-51	ZyXEL	192	48						2	342	1.78
G400 hiX5625	NSN	288	72			×	×	×	8	480	1.67
M400 hiX5625	NSN	360	72			×	×	×	4	600	1.67
M600 hiX5630	NSN	576	72			×	×	×	8	952	1.65
G1100 hiX5635	NSN	1008	72			×	×	×	8	1600	1.59
M1100 hiX5635	NSN	1080	72			×	×	×	4	1650	1.53
Mean Power Consumption per Line of ADSL2/2+ DSLAMs											**1.72**
EDN 612	Ericsson	12	×	×		12			2	45	3.75
VES-1616F-34	ZyXEL	16				16			4	75	4.69
VES-1616FA-54	ZyXEL	16				16			4	100	6.25
VES-1624FA-54	ZyXEL	24				24			4	120	5.00
VES-1624FT-55A	ZyXEL	24	×			24			2	64	2.67
MicroRAM 24V	ECI	24				24			1	75	3.13
V5924C-R	Dasan	24	×			24			4	88	3.67
IES 5005/ VLC1324G-51	ZyXEL	96				24			2	256	2.67
Mean Power Consumption per Line of VDSL/2 DSLAMs											**3.98**
IES-708-22	ZyXEL	8					8	×	0.2	13	1.63
IES-1000M/ SAM1008	ZyXEL	16					16		0.2	17.18	1.07
6724	Corecess	24					24		0.1	45	1.88

Product	Vendor	Max. No. of Lines	Number of Ports per Card						Uplink Capacity [Gbit/s]	Power [W]	Power per Line [W]
			ADSL2/2+	ADSL	G.lite	VDSL2	SHDSL	G.SHDSL			
IES-1000M /SAM1216-22	ZyXEL	32						32	0.4	50	1.56
IES 5005/ SLC1248G-22	ZyXEL	192					48	×	2	254	1.32
Mean Power Consumption per Line of SHDSL/G.SHDSL DSLAMs											**1.49**
Mean Power Consumption per Line for all DSLAMs											**2.48**

Table A3 Power consumption of commercially available DSLAMs and their mean power consumption per line

A.2 HFC

In CMTS channels can be bonded to obtain higher data rate. Thus the configuration of a CMTS and the number of served subscribers is variable according to the distribution of resources, which is influenced by customers' needs. Accordingly, it is not accurate to give the consumption per line of HFC network equipment and no mean value is calculated. All devices support also the corresponding EuroDOCSIS standard. The devices' size, i.e., their height is given in rack units (RU) since all of them fit into 19 inch chassis.

Product	Vendor	DOCSIS Version			Size [RU]	Uplink Capacity [Gbit/s]	Power [W]
		3.0	2.0	1.1			
C2200	Casa Systems	×			1	4	400
C3200	Casa Systems	×			3	12	700
C4c 7.1	Arris	×			7	20	1350
C10200	Casa Systems	×			12	12	1600
C4 7.1	Arris	×			14	12	2800
BRS2000	Motorola		×		1	2.4	150
C3	Arris		×		1	2	87
uBR7246VXR	Cisco		×		6	2	800
C4 5.1	Arris		×		14	2	2800
CS-BT-CMTS-1x1	Bloder Tongue			×	1	0.1	34
C600	C9 Networks			×	2	0.1	100
C800	C9 Networks			×	2	0.1	100
uBR10012	Cisco			×	18	4	3344

Table A4 Power consumption of commercially available CMTSs for HFC networks, RU: rack units

Product	Vendor	DOCSIS Version				Power [W]
		3.0	2.0	1.1	Euro	
DPC3000	Cisco	×				6
SMCD3CM	SMC	×			×	6.5
SB6120	Motorola	×			×	9
WBM760C	Arris	×				9
TM722A	Arris	×				10
U10C035	Ubee	×				10
BRG-35503	Hitron	×			×	12
Mean Power Consumption DOCSIS 3.0 Modems						**8.93**
DCM-202	D-Link		×		×	6
EPC2100	Scientific Atlanta		×		×	6
SB5101	Motorola		×		×	9
Mean Power Consumption DOCSIS 2.0 Modems						**7**
DPX 100	Scientific Atlanta			×		6
#6000	U.S. Robotics			×		6
PCX1100	Toshiba			×		8
Mean Power Consumption DOCSIS 1.1 Modems						**6.67**
Mean Power Consumption of all Modems						**7.88**

Table A5 Power consumption of commercially available cable modems

A.3 PON

Product	Vendor	Number of Ports				ONU Type	Data Rate [Mbit/s]	Power [W]	Power per Mbit/s [W]
		10/100BASE-TX	100/1000BASE-T	POTS	RF Video Port				
ONT1120GE	Motorola		4			SFU	4000	15	0.004
ONT1000GT2	Motorola		1		1	SFU	1000	20	0.020
ONT-G1000iX	Enablence		1			SFU	1000	5.5	0.006
ONT-G221X	Enablence	2		2		SFU	200	13	0.065
ONT-G1321X	Enablence	3	1	2	1	SFU	1300	13	0.010
T063G	Ericsson		4	2		SFU	4000	20	0.005
T065G	Ericsson		4			SFU	4000	15	0.004
1600-702	Tellabs		1	2	1	SFU	1000	24	0.024
ZNID-2511	Zhone	4		2	1	SFU	400	12	0.030
AMN1220 SFU	Hitachi		2	2	1	SFU	2000	14.4	0.007
ZNID-7310	Zhone		1	8		SOHO	1000	7.2	0.007
ONT1500GT	Motorola		2		1	SOHO	2000	42	0.021
Mean Power Consumption of SFU/SOHO GPON ONUs								**16.76**	**0.017**
V2524G	Dasan		4			MDU	4000	36	0.009

Product	Vendor	Number of Ports				ONU Type	Data Rate [Mbit/s]	Power [W]	Power per Mbit/s [W]
		10/100BASE-TX	100/1000BASE-T	POTS	RF Video Port				
V2824	Dasan	24				MDU	2400	16	0.007
ONT-G880	Enablence	8		8	1	MDU	800	36	0.045
AMN1220 MDU	Hitachi	12	1	24	1	MDU	2200	75	0.034
Mean Power Consumption of MDU GPON ONUs								**40.75**	**0.024**

Table A6 Total power consumption and power consumption per Mbit/s of GPON ONUs. (SFU – Single Family Unit, SOHO – Small Office / Home Office, MDU – Multiple Dwelling Unit)

Product	Vendor	Number of Ports					ONU Type	Data Rate [Mbit/s]	Power [W]	Power per Mbit/s [W]
		10/100BASE-TX	100/1000BASE-T	1000BASE-SX	POTS	RF Video Port				
FA2132	Fujitsu	1	1				SFU	1100	8	0.007
EE29000-02	AD-net	1	1				SFU	1100	10	0.009
ONT-E221	Enablence	1			2	1	SOHO	100	11.5	0.115
ONT-E1321X	Enablence	3	1		2	1	SOHO	1300	13	0.010
AN 5006-02	Fiberhome	2				1	SFU	200	10	0.050
AN 5006-05	Fiberhome	2			2	1	SFU	200	10	0.050
3804T	Corecess	4					SFU	400	11	0.028
6040 B-22	ZyXEL	4					SFU	400	18	0.045
home4000	Alloptic	4			4	1	SFU	400	18	0.045
Xgen1000	Alloptic	4			2		SFU	400	20	0.050
ONT-E1800i	Enablence	8	1				SFU	1800	5	0.003
Xgen8000	Alloptic		1		2		SFU	1000	18	0.018
Mean Power Consumption of SFU/SOHO EPON ONUs									**12.71**	**0.036**
AN 5006-06	Fiberhome	4			8		SOHO	400	30	0.075
ONT-E888	Enablence	8			8	8	MDU	800	36	0.045
2024-21	ZyXEL	24		1			MDU	3400	22	0.006
Xgen6000	Alloptic	24			2	1	MDU	2400	25	0.010
V2524G	Dasan		4				MDU	4000	36	0.009
V2824	Dasan	24					MDU	2400	16	0.007
Mean Power Consumption of MDU EPON ONUs									**27.5**	**0.025**

Table A7 Total power consumption and power consumption per Mbit/s of EPON ONUs. (SFU – Single Family Unit, SOHO – Small Office / Home Office, MDU – Multiple Dwelling Unit)

Product	Vendor	No. of PONs		Uplink Capacity [Gbit/s]	Power [W]	Power per PON [W]
		GPON	1G-EPON			
V5812G	Dasan	4		8	45	11.25
BBS 1000+	UTStarcom	8		4	100	12.5
V5848G	Dasan	16		13.2	276	17.25
AMN1220	Hitachi	32		16	1336	41.75
AXS-1800	Motorola	48		20	1500	31.25
Mean Power Consumption per GPON port						**22.8**
AN-OLT-01	AD-net		1	1	40	40
edge200/202	Alloptic		2	2.2	60	30
AN-5116-03	Fiberhome		2	4	38	19
CC65000-4	AD-net		4	4	70	17.5
CM7700S	NEC		8	4	100	12.5
1308S-22	ZyXEL		8	4	90	11.25
egde2000	Alloptic		16	12	480	30
FA2232U	Fujitsu		16	16	400	25
AN-5116-02	Fiberhome		32	7	600	18.75
Mean Power Consumption per 1G-EPON port						**22.67**

Table A8 Power consumption of commercially available PON OLTs and their mean power consumption per PON port

A.4 1 Gbit/s P-t-P Optical Ethernet

Product	Vendor	Number of 1GE and 1FE ports				Power [W]	Power per Mbit/s [W]
		Network interface		User interface			
		1GE	1FE	1GE	1FE		
CVT-3012SFP	Connection Tech.	1	×	1	×	4	0.0040
TC3300	TC Communic.	1	×	1	×	4	0.0040
79119	DKTComega	1	×	1	×	5	0.0050
FTTH CPE	Microsens	1	×		4	15	0.0150
ETX-201	RAD	2	×	1	×	6.1	0.0031
ETX-202	RAD	2	×	4	×	9	0.0045
ETX-201A	RAD	2	×		4	15	0.0075
ETX-202A	RAD	2	×	4	×	18.5	0.0093
ETX-102	RAD		2		4	6.1	0.0305
Mean Power Consumption of Ethernet Optical Modems						**9.19**	**0.0092**

Table A9 Power consumption of Ethernet optical modems, i.e. P-t-P CPE, 1GE: 1 Gbit/s Ethernet, 1FE: 100 Mbit/s Ethernet or Fast Ethernet

Product	Vendor	Downlink Capacity [Gbit/s]	Uplink Capacity [Gbit/s]	Power [W]	Power per 1GE port [W]
V2524G	Dasan	24	2	36	1.50
V5524XG	Dasan	24	20	65	2.71
EX4200-24F-DC	Juniper	24	20	190	7.92
V5548G	Dasan	48	20	190	3.96
V5848G	Dasan	48	40	276	5.75
4503	Cisco	N/A	72	466	N/A
Mean Power Consumption per port of 1GE optical Switches					**4.37**

Table A10 Power consumption of available 1 Gbit/s Ethernet switches with optical interfaces

A.5 WiMAX

The devices listed in Table A12 and Table A11 support the mobile WiMAX standard (802.16e-2005).

Product	Vendor	CPE type		Power [W]
		Outdoor	Indoor	
BreezeACCESS SU-EZ	Alvarion	×		25
CPEo 400	Motorola	×		45
ExcelMAX FD-FDD CPE3210	Axxcelera	×		15
ExcelMAX H-FDD/TDD CPE	Axxcelera	×		10
OD200	AWB	×		28
ExcelMAX CPE	Axxcelera		×	15
ExcelMAXCPE	Axxcelera		×	10
Mean Power Consumption of WiMAX CPE				**21.14**

Table A11 Power consumption of commercially available WiMAX CPE

Product	Vendor	No. of Sectors	Network Capacity [Mbit/s]	Power [W]	Power per sector [W]
StarMAX 6400 16e	Telsima	1	32	285	285
BroadOne WX300	Fujitsu	1	32	235	235
MacroMAXe BS	Airspan	3	96	705	235
WAP400	Motorola	4	128	1300	325
BS-PS-AC-VL	Alvarion	6	192	450	75
ExelMAX	Axxcelera	6	192	810	135
StarMAX 6400 16e	Telsima	8	256	2280	285
Mean Power Consumption per sector of WiMAX base stations					**201.67**

Table A12 Power consumption of commercially available WiMAX 802.16e-2005 base stations. The base station configuration includes necessary antennas for all sectors

Appendix B

Data Base of Network Components Used for Advanced Access Networks

B.1 10 Gbit/s P-t-P Optical Ethernet

	Component	**Vendor**	**Power [W]**
Switch	Transceiver	SET SCP6G74	1
	PHY	Vitesse VSC8211	0.7
	µProcessor	Broadcom BCM1280	17
	Switch + MAC	Fulcrum FM3112	24
NTU	Transceiver	SET SCP6G74	1
	PHY	Vitesse VSC8211	0.7
	µProcessor	PMC-Sierra RM5231A	0.9
	1GE MAC	Broadcom BCM53242M	4.1

Table B1 Power consumption of components used for the 1GbE P-t-P network model

	Component	**Vendor**	**Power [W]**
Switch	Transceiver	SET SCP6G74	1
	PHY	Puma AEL1002	0.8
	Switch + MAC	Fulcrum FM3208	16
	µProcessor	Intel IXP 2855	32
NTU	Transceiver	SET SCP6G74	1
	PHY	Puma AEL1002	0.8
	Switch + MAC	Fulcrum FM3104	13
	µProcessor	Broadcom BCM1255	13

Table B2 Power consumption of components used for the 10GbE P-t-P network model

B.2 10G-EPON

	Component	Vendor	Quantity	Power per Unit [W]
OLT	APD	NTT	1	0.18
	Burst Mode TIA	Vitesse VSC7716	1	0.08
	DFB/EAM	Northlight	1	0.84
	Laser Driver	Vitesse VSC7982	1	1
	PHY (CRD+LA)	Vitesse VSC8479	1	1.15
	Switch+MAC	Fulcrum FM3208	8	16
	µProcessor	Intel IXP 2855	1	32
ONU	APD+TIA	NTT	1	0.18
	PHY (CRD+LA)	Broadcom BCM8705	1	1.1
	DFB/EAM	Northlight	1	0.84
	BM Cont+Driv	MAX3643	1	0
	Switch+MAC	Fulcrum FM3103	2	11.5
	µProcessor	Broadcom BCM1255	1	13

Table B3 Power consumption of the components used for the asymmetrical 10G-EPON model

	Component	Vendor	Quantity	Power per Unit [W]
OLT	BM Receiver	Research paper [64]	1	0.76
	DFB/EAM	Northlight	1	0.84
	Laser Driver	Vitesse VSC7982	1	1
	PHY (CRD+LA)	Vitesse VSC8479	1	1.15
	OLT MAC	PMC Sierra PM3392	1	8.47
	Switch	Fulcrum FM3103	1	11.5
	µProcessor	Intel IXP 2855	1	32
ONU	APD+TIA	NTT	1	0.18
	PHY (CRD+LA)	Vitesse VSC8479	1	1.15
	DFB/EAM	Northlight	1	0.84
	BM Cont+Driv	MAX3643	1	1.26
	BM Tx (DFB+Driver)	Reasearch paper [63]	1	1.6
	Switch+MAC	Fulcrum FM3104	2	13
	µProcessor	Broadcom BCM1255	1	13

Table B4 Power consumption of the components used for the symmetrical 10G-EPON model

B.3 WDM PON

	Component	Vendor	Quantity	Power per Unit [W]
OLT	WDM Transceiver	SET	32	1
	PHY	Vitesse VSC8601	32	0.6
	OLT MAC	Broadcom BCM53242M	16	4.1
	Switch	Broadcom BCM5324M	16	3.5
	µProcessor	Xelerator X10q-w	1	9.5
	SLED	DenseLight DL-CS5403A	1	7.16
	APD+TIA	NTT	1	0.18
ONU	PHY (CRD+LA)	Vitesse VSC8479	1	1.15
	RSOA	Potomac	1	0.48
	BM Contr.+Driver	MAX3643	1	1.26
	ONU MAC	Broadcom BCM53242M	1	2.05
	Switch	Broadcom BCM5324M	1	3.5
	µProcessor	Broadcom BCM1255	1	13

Table B5 Power consumption of the components used for the 1 Gbit/s WDM PON model

	Component	Vendor	Quantity	Power [W]
OLT	WDM Transceiver	Cisco	32	3.5
	PHY	Puma AEL1002	32	0.8
	OLT MAC	PMC Sierra PM3392	32	8.47
	Switch	Fulcrum FM3208	8	16
	µProcessor	Intel IXP 2855	1	32
	SLED	DenseLight DL-CS5403A	1	7.16
	APD+TIA	NTT	1	0.18
ONU	PHY (CRD+LA)	Vitesse VSC8479	1	1.15
	RSOA	Potomac	1	0.48
	BM Contr. +Driver	MAX3643	1	1.26
	ONU MAC	PMC Sierra PM3393	1	8.36
	Switch	Fulcrum FM3104	2	13
	µProcessor	Intel IXP 2855	1	32

Table B6 Power consumption of the components used for the 10 Gbit/s WDM PON model

Component	Vendor	Power [W]
EDFA	Cisco	25
	MRV	15
	Greatway	50
SOA	Alphion SAO29p	4
	Alphion PON extender	30
	Alphion SAS26p	4
OEO repeater	NEC OD-B1226-N21x	1
	NEC OD-B1228-L2x	1

Table B7 Reach extender used for the estimation of power consumption

B.4 100 Gbit/s Ethernet

Assumption: 100Gbit/s MAC and TCAM is assumed the same for all options. Since the exact power consumption of a commercially available 10GbE MAC or TCAM could not be found, the value of 30W and 10W, respectively, was assumed according to data estimated in various research papers.

Component	Vendor / Researcher	Quantity	Power [W]	
			Per Unit	Per Function
DQPSK Optical Transmitter	SHF 46214A	1.0	20.5	20.50
2:1 Mux	SHF 408	2.0	1.0	2.00
4:1 Mux	SHF 404	4.0	3.6	14.20
CW Laser	EM4 DFB Laser	1.0	1.1	1.13
Balanced Photodetector	u2t	2.0	0.56µ	0.00
DCR + 1:2 Demux	Fraunhofer	2.0	1.7	3.30
1:4 Demux	SHF 423	4.0	3.5	14.00
DQPSK Precoder	Xilinx	1.0	16.1	16.11
100 Gbit/s MAC	See Assumption	1.0	25.0	30.00
NP	Xelerator x10q-w	6.0	9.5	57.00
Fabric Interface	AMCC PRS C192X	20.0	9.0	180.00
TCAM	See Assumption	1.0	10.0	10.00
DRAM Memory	Samsung K4H641638N	16.0	1.0	16.00
Power Consumption of 1x100Gbit/s line card				**364.24**

Table B8 Power consumption of the components used for the 1x100Gbit/s Ethernet line card model

Component	**Vendor / Researcher**	**Quantity**	**Power [W]**	
			Per Unit	**Per Function**
10G Transceiver	Opnext TRF7052XN-GA00	10.0	3.5	35.0
10G PHY with CDR	Broadcom BCM8705	10.0	1.1	11.0
100 Gbit/s MAC	See Assumption	1.0	30.0	30.0
NP	Xelerator x10q-w	6.0	9.5	57.0
Fabric Interface	AMCC PRS C192X	20.0	9.0	180.0
TCAM	See Assumption	1.0	10.0	10.0
DRAM Memory	Samsung K4H641638N	16.0	1.0	16.0
Power Consumption of 10x10 Gbit/s line card				**339.0**

Table B9 Power consumption of the components used for the 10x10Gbit/s Ethernet line card model

Component	**Vendor / Researcher**	**Quantity**	**Power [W]**	
			Per Unit	**Per Function**
25G Trasceiver	Opnext	4.0	3.8	15.0
10G PHY with CDR	Broadcom BCM8705	10.0	1.1	11.0
100 Gbit/s MAC	See Assumption	1.0	25.0	30.0
NP	Xelerator x10q-w	6.0	9.5	57.0
Fabric Interface	AMCC PRS C192X	20.0	9.0	180.0
TCAM	See Assumption	1.0	10.0	10.0
DRAM Memory	Samsung K4H641638N	16.0	1.0	16.0
Power Consumption of 4x25 Gbit/s line card				**319.0**

Table B10 Power consumption of the components used for the 4x25Gbit/s Ethernet line card model

List of Abbreviations

µP	Microprocessor
AAL	ATM Adaptation Layer
ADSL	Asymmetric Digital Subscriber Line
ANSI	American National Standards Institute
APD	Avalanche Photo Diode
AS	Asymmetric channel (description used in ADSL)
ASE	Amplified Spontaneous Emission
ASN	Access Service Network
ATM	Asynchronous Transfer Mode
ATU-C	ADSL Transmission Unit – Central office
ATU-R	ADSL Transmission Unit – Remote end
AWG	Arrayed Waveguide Grating
BA	Basic Access
BER	Bit Error Rate
BRI	Basic Rate Interface
CAP	Carrierless Amplitude/Pulse modulation
CATV	Community Antenna Television or popularly “Cable TV”
CCITT	Comité Consultatif International Téléphonique et Télégraphique
CDR	Clock and Data Recovery
CMTS	Cable Modem Termination System
CPE	Customer Premises Equipment
CPU	Central Processing Unit
CSN	Core Service Network
DBA	Dynamic Bandwidth Allocation
DEMUX	Demultiplexer
DFA	Doped Fiber Amplifier
DFB/EAM	Distributed Feedback / Electro-Absorption Modulation
DMT	Discrete MutiTone
DRAM	Dynamic Random Access Memory

DS	Downstream
DSL	Digital Subscriber Line
ECH	Echo Cancellation Hybrid
EDFA	Erbium-Doped Fiber Amplifier
EMI	Electromagnetic Interference
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FEC	Forward Error Control
FiWi	Fiber-Wireless
FPGA	Field Programmable Gate Array
FSAN	Full Service Access Network
FTTH	Fiber-To-The-Home
FTTN	Fiber-To-The-Node
FTTx	Fiber-To-The-x
GEM	GPON Encapsulation Method
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTC	GPON Transmission Convergence
HDSL	High bit rate Digital Subscriber Line
HFC	Hybrid Fiber Coax
ICT	Information and Communication Technology
IDSL	ISDN Digital Subscriber Line
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISDN	Integrated Services Digital Network
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
LA	Limiting Amplifier
LS	Low Speed channel (description used in ADSL)
LTU	Line Termination Unit
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MPN	Mode Partition Noise
MUX	Multiplexer
NAP	Network Access Provider
NG-PON	Next Generation Passive Optical Networks
NIM	Network Interface Module
NP	Network Processor

NRZ	Non Return-to-Zero
NSP	Network Service Provider
NT	Network Termination
NTU	Network Termination Unit
ODN	Optical Distribution Network
OEO	Optical-Electrical-Optical
OLT	Optical Line Termination
OMCC	ONT Management and Control Channel
OMCI	ONT Management and Control Interface
ONT	Optical Network Termination
ONU	Optical Network Unit
OPEX	Operational Expenditure
PIM	PON Interface Module
PLOAM	Physical Layer Operation, Administration and Maintenance
PMD	Physical Medium Dependent
PON	Passive Optical Network
POTS	Plain Old Telephone System
PRI	Primary Rate Interface
PSTN	Public Switched Telephone Network
PTM	Packet Transfer Mode
P-t-MP	Point-to-multipoint
P-t-P	Point-to-point
QAM	Quadrature Amplitude Modulation
RE	Reach Extender
RSOA	Reflective Semiconductor Optical Amplifier
SDSL	Single-Pair Digital Subscriber Line
SLED	Superluminescent Light Emitting Diode
SNI	Service Node Interface
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SRA	Seamless Rate Adaptation
STM	Synchronous Transfer Mode
TCAM	Ternary Content Adressable Memory
T-CONT	Transmission Container
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TIA	Transimpedance Amplifier

UMTS	Universal Mobile Telecommunication System
UNI	User Network Interface
US	Upstream
VC	Virtual Circuit
VDSL	Very high bit rate Digital Subscriber Line
VoD	Video on Demand
WDM	Wavelength Division Multiplexing
WiMAX	Worldwide Interoperability for Microwave Access

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