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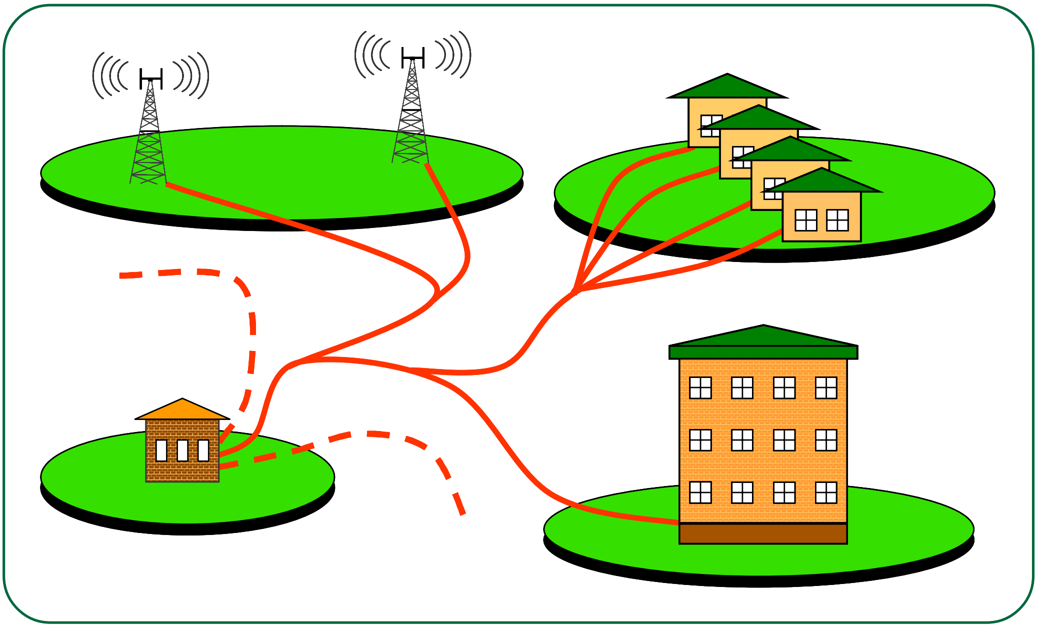

Sami Lallukka & Pertti Raatikainen

Passive Optical Networks

Transport concepts

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ISP	Internet Service Provider
IST	Information Society Technologies
ITU-T	International Telecommunications Union - Telecommunications
L1VPN	physical layer (layer-1) VPN
L2TP	Layer-2 Tunnelling Protocol
L2VPN	link layer (layer-2) VPN
L3VPN	network layer (layer-3) VPN
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LDC	Linear Divider Combiner
LDP	Label Distribution Protocol
LLID	Logical Link ID
LSP	Label Switched Path
LSR	Label Switching Router
MAC	Medium Access Control
MBGP	Multi-protocol Border Gateway Protocol
MDU	Multi-Dwelling Unit
MPCP	Multi-Point Control Protocol
MPEG-2	Moving Picture Experts Group 2
MPLS	Multi-Protocol Label Switching
NAB	Non Assured Bandwidth
NASA	National Aeronautics and Space Administration
NBAN	Next-generation Broadband Access Network
NMS	Network Management System
NNI	Network-to-Network Interface
NRZ	Non-Return to Zero
NSP	Native Service Processing
NSR	Non Status Reporting

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Abstract

The optical access is gaining more interest as the demand for higher and higher bandwidth is getting stronger. The major drivers for larger bandwidth are the increasing processing power of user terminals and development of services that require substantially larger bandwidth than available in present day access networks. The prevailing access techniques, such as the digital subscribes line systems and cable modems, are capable of supporting up to few tens of Mbit/s access rates per user, but the transport distance is limited. The optical access offers significantly higher bit rates and longer transport distances.

The high cost has been the foremost factor that has been slowing down penetration of the optical access. A number of alternative transport concepts have been developed to tackle the cost problem as well as the technical ones. The passive optical network techniques are largely anticipated to be the most economical solutions. This publication surveys the state of the art of the optical access concentrating on explaining more thoroughly some of the best known concepts. The survey is complemented with an assessment of the viability of the most well known concepts. Finally network costs of some optical transport concepts are compared based on the utilisation of the transport channel capacity.

Preface

This publication presents results obtained in a co-funded research project that has concentrated on the optical access technologies. The chosen viewpoints reflect the needs of the project parties highlighting the requirements to offer optical access to residential users as well as to connect base stations of a mobile telecommunications network to base station controllers or radio network controllers. The work has been funded by National Technology Agency of Finland (Tekes), Nokia Oyj, Teleste Oyj, Liekki Oy and Technical Research Centre of Finland (VTT).

Contents

List of acronyms and symbols

AAL5	ATM Adaptation Layer 5
AES	Advanced Encryption Standard
AIX	Ames Internet Exchange
AN	Access Node
ANSI	American National Standard Institute
AON	Active Optical Network
A-PON	ATM based Passive Optical Network
APS	Automatic Protection Switching
ASB	Assured Bandwidth
ASON	Automatic Switched Optical Network
ASTN	Automatic Switched Transport Network
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Gratings
BEB	Best Effort Bandwidth
BGP	Border Gateway Protocol
BoD	Bandwidth on Demand
BPI	Baseline Privacy Interface
B-PON	Broadband Passive Optical Network
CAC	Connection Admission Control
CAIDA	Cooperative Association for Internet Data Analysis
CATV	Community Antenna Television
CDMA	Code Division Multiple Access
CE	Customer Edge
CEP	Circuit Emulation over Packet
CID	Channel ID

CM	Cable Modem
CMTS	Cable Modem Termination System
CO	Central Office
CRC	Cyclic Redundancy Check
DBA	Dynamic Bandwidth Assignment
DBRu	Dynamic Bandwidth Report upstream
DES	Data Encryption Standard
DFB	Distributed Feedback
DH	Distribution Hubs
DHCP	Dynamic Host Configuration Protocol
DLCI ID	Data Link Connection Identifier
DOCSIS	Data Over Cable Service Interface Specification
DoS	Data over SDH
DSL	Digital Subscriber Line
DSLAM	Digital Subscribe Line Access Multiplexer
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fibre Amplifiers
EFM	Ethernet in the First Mile
EFMA	Ethernet First Mile Alliance
E-LAN	Ethernet LAN Service
ELS	Ethernet Line Service
EMS	Ethernet Multipoint Service
EMT	Ethernet Multitap
ENM	Ethernet Node Modem
EoC	Ethernet over Coax
EPM	Ethernet POP Modem
E-PON	Ethernet Passive Optical Network
ERMS	Ethernet Relay Multipoint Service

ERS	Ethernet Relay Service
EttH	Ethernet-to-the-Home
EWO	Ethernet Wall Outlet
EWS	Ethernet Wire Service
FEC	Forward Error Correction
FN	Fibre Nodes
FSAN	Full Service Access Networks
FTTB	Fibre-To-The-Building
FTTC	Fibre-To-The-Curb
FTTH	Fibre-To-The-Home
FXB	Fixed Bandwidth
GEM	G-PON Encapsulation Method
GFP	Generic Framing Procedure
G-PON	Gigabit capable Passive Optical Network
GPRS	General Packet Radio Service
GRE	Generic Routing Encapsulation
GSM	Global System for Mobile communications
HDLC	High-level Data Link Control
HDTV	High Definition Television
HE	Head-End
HEC	Header Error Control
HFC	Hybrid Fibre Coaxial
HVPLS	Hierarchical VPLS
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IPLS	IP-only LAN-like Service
IPsec	Secure Internet Protocol
ISDN	Integrated Services Digital Network

OAM	Operation, Administration and Maintenance
OAMPDU	OAM Protocol Data Units
OCDM	Optical Code Division Multiplexing
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Terminal
OTN	Optical Transport Network
OTP	Optical Terminating Points
P2P	Point-to-point
PCBd	Physical Control Block downstream
PCM	Pulse Code Modulation
PDH	Plesiochronous Digital Hierarchy
PE	Provider Edge
PLOAM	Physical Layer Operation, Administration and Maintenance
PLOAMu	Physical Layer OAM overhead upstream
PLOu	Physical Layer Overhead upstream
PLSu	Power Levelling Sequence upstream
P-MAC	Provider MAC
PMD	Physical Media Dependent
PON-ID	PON Identification label
POTS	Plain Old Telephony Service
PPP	Point-to-Point Protocol
PSN	Packet-Switched Network
PW	Pseudo Wire
PWE	Pseudo Wire Emulation
QoS	Quality of Service
RTP	Real-time Transport Protocol
RTT	Round-Trip Time

SAN	Storage Area Network
SAToP	Structure-Agnostic TDM over Packet
S-CDMA	Synchronous CDMA
SCM	Sub-Carrier Multiplexing
SCMA	Sub-Carrier Multiple Access
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SDU	Service Data Unit
SIM	Subscriber Identity Module
SLA	Service Level Agreement
SNI	System Network Interface
SONET	Synchronous Optical Network
SPD	Start of Packet Delimiter
SR	Status Reporting
STM-1	Synchronous Transport Mode 1
TC	Transmission Convergence
T-CONT	Transmission Container
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UNI	User Network Interfaces
VC	Virtual Concatenation
VCI	Virtual Connection Identifier
VLAN	Virtual Local Area Network
VLAN ID	Virtual Local Are Network Identifier
VMAN	Virtual Metropolitan Area Network

VoD	Video on Demand
VoIP	Voice over IP
VPI	Virtual Path Identifier
VPLS	Virtual Private LAN Service
VPN	Virtual Private Networks
VPWS	Virtual Private Wire Service
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WLAN	Wireless Local Area Network
WPON	WDM PON
WRPON	Wavelength Routed PON

$\overline{l_{dbru}}$	average number of DBRu fields in an upstream G-PON frame
C_k	total transport capacity of segment S_k
K_E	number of E-PON segments
K_{Eth}	number of Ethernet segments
K_{EttH}	number of EttH segments
K_G	number of G-PON segments
l_{cm}	length of a control message
l_{dbru}	number of DBRu fields in a G-PON frame
l_{Eo}	Ethernet frame overhead
l_{Ep}	Ethernet payload
l_{Ep}	length of Ethernet payload
l_{EPo}	E-PON frame overhead
l_{EPp}	E-PON payload
l_{GEM}	length of a GEM frame
l_{GEMo}	GEM framing overhead for Ethernet payload
l_{GPdo}	length of G-PON downstream frame overhead

l_{GPua}	upstream allocation overhead length in G-PON downstream frame
l_{plou}	G-PON upstream physical layer overhead
l_{plou}	length of physical layer overhead on G-PON upstream link
M_{ot}	number of optical interfaces in an optical network segment
M_T	total number of optical interfaces in an optical network
N	size of user population
N_k	number of users in segment S_k
$n_{k,i}$	number of users connected to all ONUs in segment S_k
N_{ONU}	number of ONUs in a network segment
N_T	aggregate number of users connected to all K segments
R_{EPbr}	nominal bit rate of an E-PON link
R_{GPbr}	nominal bit rate of a G-PON link
R_k	total bit rate available for user data in segment S_k
r_o	transport capacity of one end-user
R_T	aggregate bit rate of all K segments
S_k	network segment k
t_{AGC}	Automatic Gain Control (AGC) time
t_{CDR}	Clock and Data Recovery (CDR) time
t_{ct}	cycle time
t_D	G-PON delimiter time
t_{DZ}	E-PON dead zone
t_{EON}	E-PON laser on-time
t_G	G-PON guard time
t_{GB}	E-PON guard band
t_{GON}	G-PON laser on-time
t_{GPdf}	duration of a G-PON downstream frame
t_P	G-PON preamble time
t_{TU}	G-PON timing uncertainty

β	percentage of connected users that operate during a busy hour
γ	"broadband access" take-rate
η_E	E-PON to G-PON cost ratio
η_{Eth}	Ethernet to G-PON cost ratio
η_{EttH}	EttH to G-PON cost ratio
ρ_{EPd}	utilization of an E-PON downstream link
ρ_{EPu}	utilisation of an E-PON upstream link
ρ_{Eth}	utilisation of 100 Mbit/s Ethernet link
ρ_{GPd}	utilisation of a G-PON downstream link
ρ_{GPu}	utilization of a G-PON upstream link

1. Introduction

Real broadband customer access, supporting tens or even hundreds of Mbit/s data rates, is foreseen to be based on optical transport. Several solutions are being developed, but the problem in most solutions is the high installation and running cost. Most customer premises are connected to the nearest central office with twisted copper wires and to obtain real broadband these wires need to be replaced or supplemented with fibres.

Installation of an entirely new infrastructure is costly to carry out. To keep the installation cost in reasonable limits, various solutions are being studied to find the most economical optical transport concepts. Basically the studied solutions can be categorised to point-to-point and passive optical concepts. The point-to-point concepts represent the conventional approach, e.g., Synchronous Digital Hierarchy (SDH) and Ethernet. The passive optical networks (PONs), such as Ethernet PON (E-PON) and Broadband PON (B-PON), are newcomers enabling some simplifications in the physical network architecture. However, the transport of data requires more complex medium access control schemes than in the point-to-point concepts.

This publication starts with a state-of-the-art survey of the optical networking techniques that are applicable to broadband user access. Viability of these techniques is evaluated based on the status of standardisation as well as on various technical characteristics and aspects related to network construction. The most viable solutions are studied in more depth, e.g. to find out the most economical network topologies and virtual network implementation methods.

1.1 Terminology

At the time of writing this document, the PON standardisation still continues and the used terminology may vary, depending on the context. To avoid misapprehensions, it is worth of clarifying the meaning of some terms, constantly used throughout the document. The goal is to use terminology, adopted by the standards and recommendations, but when these are not specified, the most commonly known industry terms will be used.

When speaking about the telephone and data networks, conceptual terms such as distribution, access and feeder network can have different meanings. As this document concentrates on defining the PONs and future data networking, the terminology of the document shall be the same as used in data networking as depicted in Figure 1.

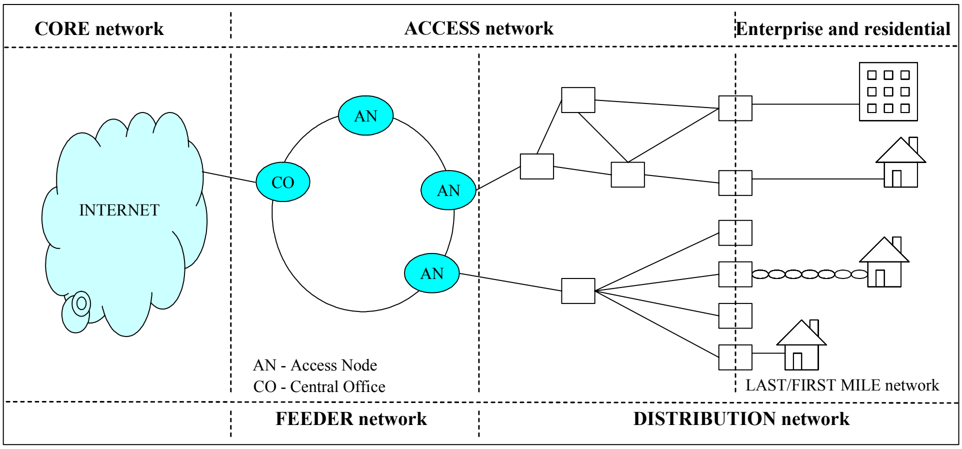

Figure 1. Construction and terminology of a broadband data network.

In a data network environment, the access network is composed of feeder and distribution networks. The first mile (also called as the last mile) network is the last leg of the distribution network. PONs can be seen as optical access networks or optical feeder and/or optical distribution networks depending on the origination and destination of the optical signal. In ITU-T recommendation G.983.1, the starting point of a PON is named as Optical Line Termination (OLT) and the ending point as Optical Network Termination (ONT) or Optical Network Unit (ONU). In the industry terminology, the starting point is also referred to as Central Office (CO) and the endpoint as ONU. In this document, we prefer to use the terms OLT and ONU.

2. Passive optical network technologies

The Passive Optical Network (PON) is a network, which carries data in the optical domain between the OLT and the ONU or ONT[1] and the transport path of the optical signal is passive. This implies that the optical network devices (between the transmitter and receiver) are non-powered, i.e. no electrical devices are used. The basic PON principle is summed up in [1] by the following phrase:

"*The basic principle of PON is to share the central Optical Line Termination (OLT) and the feeder fibre over as many Optical Network Units (ONUs) as is practical given cost effective optics.*"

2.1 Standard development

The first PON activity was in the 1980s when many of the largest carriers around the world worked together to introduce optical access solutions into their networks. However, these remained only as trial applications due to the high cost and relatively low demand at the time. The Internet became common in the 1990s, which brought out the need for efficient broadband access. A group of seven major network operators established the Full Service Access Networks (FSAN) consortium in 1995 to derive a common set of requirements for optical access systems [2]. In 1998, this resulted in ITU-T Recommendation G.902 and, in 1999, ITU-T adopted the new specifications as the 155 Mbit/s PON system (ITU-T Recommendation G.983 series). This was named as the Broadband PON (B-PON) or more commonly as Asynchronous Transfer Mode (ATM) based PON (A-PON or ATM-PON) [3].

While FSAN and ITU-T were actively improving B-PON, Ethernet was gaining more and more popularity. Institute of Electrical and Electronics Engineers (IEEE) established the Ethernet in the First Mile (EFM) study group, which later developed to IEEE 802.3ah task force. This task force had an E-PON sub-task force, which focused on standardising the Ethernet based 1 Gbit/s symmetrical PON system. The work has been finalised and the first version of the standard

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[1] An ONT is an ONU used for FTTH that includes the User Port function. [G.984.1]

was approved in summer 2004 [4]. Ethernet First Mile Alliance (EFMA) started to promote standards-based Ethernet as the first mile technique.

The FSAN consortium was also active and initiated, in 2001, a new effort to standardise PON networks operating at bit rates above 1 Gbit/s [2]. The work was based on the earlier B-PON and the recently developed Generic Framing Procedure (GFP) standards. The work was finished at quick pace. In 2003, the first draft documents of ITU-T Recommendation G.984 or Gigabit-capable PON (G-PON) standard were published.

2.2 Characteristics

As stated earlier, the PON research is focusing on two areas: EFMA/IEEE is defining Ethernet based PON and FSAN/ITU-T is defining ATM and GFP based PONs. The main differences between these two standardisation efforts are the operating principles and medium access control protocols to be developed. The PON network itself has some characteristics, which do not depend on the operating protocol and are handled similarly in both standardisation efforts. These characteristics are largely related to the physical layer issues, network structure and terminology, which all are driven by the basic philosophy behind the PON solutions – the cost-efficiency. The common PON characteristics are discussed next.

2.2.1 Low-cost optical components

The main sources of cost in running an existing network are the maintenance and powering of active network equipment. The idea of PON is to use passive components, which have no requirements for power or maintenance. These components are responsible for traffic distribution to several fibres between an OLT and several ONUs. Two types of components can be used for the purpose. The optical splitter/combiner is used with Time Division Multiplexed (TDM) PON networks. It divides the optical power, originating from the OLT, to all ONUs and combines the upstream signals coming from the ONUs into a single fibre. In Wavelength Division Multiplexed (WDM) networks, Arrayed Waveguide Gratings (AWG) devices are used for the traffic distribution. An

AWG device can separate wavelengths and route them to different fibres. In the upstream direction, the wavelengths are combined into a single fibre towards the OLT.

Although transport links of a PON network can do without electronic components, powered transceivers are needed at the terminating ends of the fibre, i.e. at the OLT and ONUs. Cost-efficiency is still maintained, because the OLT side needs only one transceiver to communicate with the ONUs. Power feeding does not usually cause additional expenses, since the OLT and ONUs are located in places where electric power is available.

2.2.2 Simple network architecture

The PON concept specifies an Optical Distribution Network (ODN), where traffic is transported optically between an OLT and several ONUs, as illustrated in Figure 2. Three different PON schemes have been defined. These have slightly different service requirements depending on the ending point of the fibre. Fibre-To-The-Curb (FTTC) concept provides the end-users with asymmetric and symmetric broadband access as well as Plain Old Telephony Service (POTS) and Integrated Services Digital Network (ISDN) access together with Digital Subscriber Line (DSL) services. Fibre-To-The-Building (FTTB) concept for Multi-Dwelling Units (MDUs) provides POTS and ISDN together with the asymmetric and symmetric broadband access. FTTB for businesses provides also private line services. The third scheme, Fibre-To-The-Home (FTTH) provides asymmetric and symmetric broadband access together with POTS and ISDN for homes directly connected to the fibre.

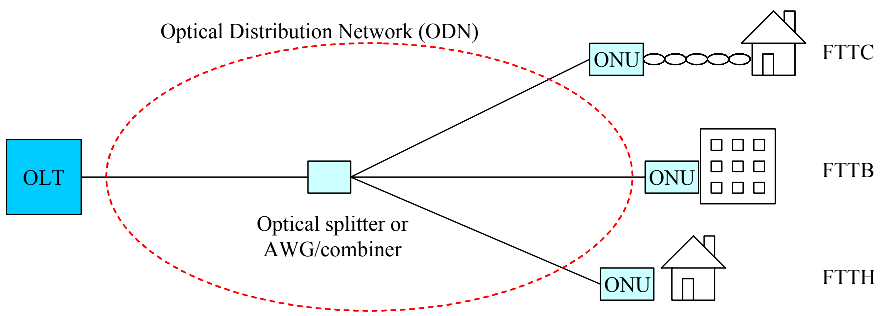

Figure 2. General PON architecture and terminology.

2.2.3 Cost-effective data transport

In a PON network, data signals are carried from one to many in the downstream direction and from many to one in the upstream direction. Thus the power of the downstream signal is divided in a splitter and delivered to all ONUs, connected via fibre links to the splitter. The number of ONUs that can be connected to a splitter is limited by the power loss, introduced in the splitter and on the OLT-to-ONU fibre links. When the power is divided uniformly between the ONU-links, the longest link sets the limit, because the power loss is a function of the transport distance. One could use Linear Divider Combiner (LDC) components to adjust the signal power to be equal at each ONU input interface. However, LDCs are in the development phase and therefore different multiplexing techniques, commonly referred to as WDM-PONs, are used instead. WDM-PONs are discussed later in this document.

The broadcast nature of the PON concept allows an efficient way to offer one-way broadcast services, such as cable TV. However, when two-way data services are concerned the PON solution requires some extra investigation. In the two-way transport, the most critical point is the optical splitter/combiner, which does only passive optical operations. In the upstream direction, this means that data streams from different ONUs are combined for transmission towards the OLT. If not synchronised, signals from the different ONUs may overlap at the combiner, which causes signal deterioration and data loss in the receiver. The standardisation bodies, working on the issue, have overcome this problem by defining specific request and grant procedures to be used between the OLT and ONUs for delay calculations. As a result, all the three standards or recommendations use TDM technique for the downstream traffic and Time Division Multiple Access (TDMA) technique for the upstream traffic. This transportation principle is demonstrated in Figure 3.

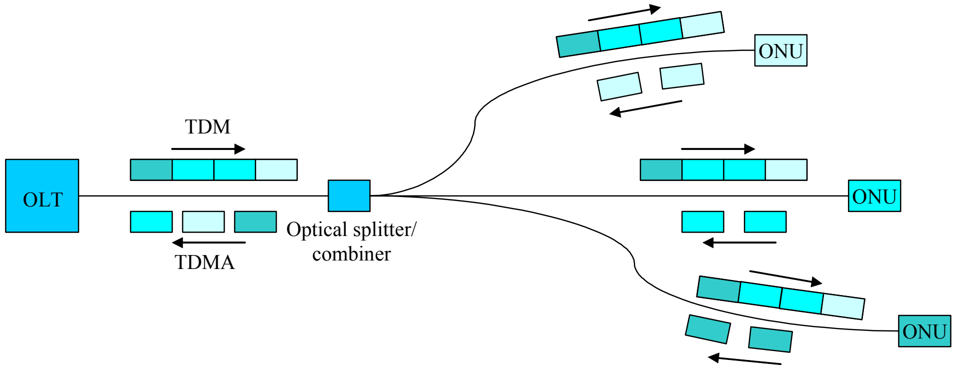

Figure 3. PON transportation principle.

Upstream and downstream signals cannot be carried on the same wavelength in the same fibre without difficulties, e.g. due to crosstalk. This implies that it is more convenient to direct the upstream and downstream traffic to separate fibres if they occupy the same wavelength. If a single fibre is used, the downstream and upstream traffic must occupy separate wavelengths. The PON standards commonly reserve the 1490 nm wavelength for the downstream and 1310 nm wavelength for the upstream traffic. The standards support WDM by defining different wavelengths for the different services. Today, PONs operate at bit rates up to 2.5 Gbit/s, which is remarkable considering the difficult transport environment. The main technical difficulty is to construct burst mode optics that can recover the signal level and bit level timing from multiple end-stations [10].

As the downstream transport in a PON is from one to many, the security of communication becomes a critical issue. Several encryption techniques have been proposed to solve the security problem in the downstream direction. In the upstream direction, data is transferred from point to point and security of communication is not as critical. One way to provide secure transfer is to allocate a separate wavelength for each end-user. However, this solution cannot be considered a common solution, because the number of wavelengths does not scale well with the number of end-users. As regards to the network availability and Quality of Service (QoS), protection of the network connections may also be an important matter. In PONs, the protection is usually provided with extra fibres and protection switching.

2.3 ATM based passive optical network (ATM-PON)

The name ATM-PON was first used to describe the ATM based passive optical network system, developed by FSAN, but it was later named as Broadband Passive Optical Networks (B-PON) by ITU-T. The name ATM-PON or the broadly used A-PON resulted in misunderstanding that the system supports only ATM services, which was not the case. Consequently, FSAN decided to change the name to B-PON to better describe the system's capability to provide broadband services including the Ethernet access, video distribution and high-speed leased line services. However, the acronyms A-PON and ATM-PON are still more commonly used to describe the ATM based PONs than the B-PON acronym.

2.4 Broadband passive optical network (B-PON)

ITU-T standard series G.983 defines a broadband optical access system, which is based on the passive optical network concept. This standard is named by ITU-T as the B-PON standard. Some parts of the standard are relatively old, but updates have recently been announced and some recommendations are still in the draft phase. All the newly developed features are compatible with the older recommendations. Enhancements have been developed to update the standard to better serve the WDM based broadband service delivery. The B-PON standard is optimised for lower line rate applications and builds on the strengths of ATM for multi-service delivery [5]. B-PON is already widely in use in Asia and several plans to utilise it in USA have also been made.

2.4.1 Transmission convergence layer

The B-PON transmission convergence layer exploits TDM technique in the downstream direction and TDMA technique in the upstream direction. The physical layer specifications define the maximum distance between an ONU and OLT to be at least 20 km [5]. The logical reach of the B-PON Medium Access Control (MAC) protocol is limited to 20 km between the nearest and the farthest ONU and it can identify up to 64 separate ONUs. Currently, the following nominal line rates have been defined for the downstream / upstream traffic:

- 155.52 Mbit/s / 155.52 Mbit/s
- 622.08 Mbit/s / 155.52 Mbit/s
- 622.08 Mbit/s / 622.08 Mbit/s
- 1244.16 Mbit/s / 155.52 Mbit/s
- 1244.16 Mbit/s / 622.08 Mbit/s.

The B-PON standard defines specific wavelength allocation schemes for the downstream and upstream traffic. In the case of a dual fibre system, the older B-PON standard reserves the 1260–1360 nm wavelength window for both the downstream and the upstream traffic. In the case of a single fibre system, the 1480–1580 nm window is used for the downstream direction (see Figure 4). The new wavelength allocation was made to improve B-PON's support for broadcast and multicast of economical video delivery services, including possibility to have varied deployment scenarios and modulation schemes, and possibility to implement a wide range of high-speed digital services. In the new wavelength allocation scheme [6], the downstream wavelength window is divided into the normal downstream band (1480–1500 nm) and enhancement band. The enhancement band has two options, 1539–1565 nm window for additional digital services and 1550–1560 nm window for video distribution and services alike. Separate guard bands are left between the reserved wavelength windows and some bands are reserved for the future use.

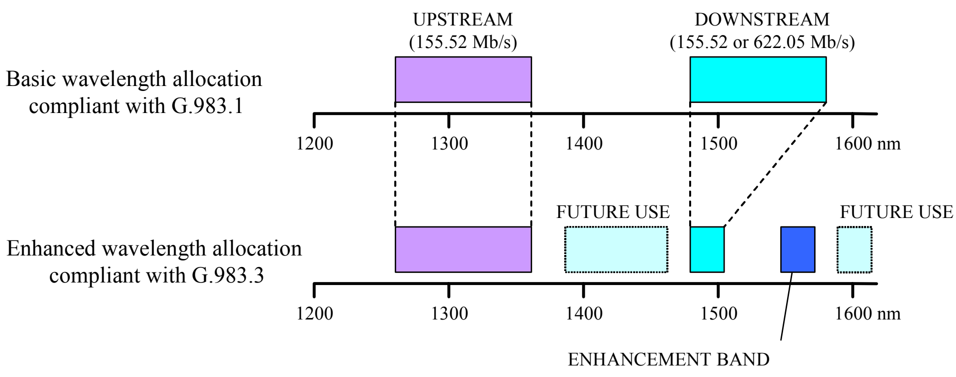

Figure 4. Wavelength allocation for a single fibre B-PON.

2.4.2 Medium access control protocol

B-PON uses standard ATM cells to carry user data and Physical Layer Operation, Administration and Maintenance (PLOAM) information. The B-PON MAC protocol has the ATM functionality with PON dedicated Operation, Administration and Maintenance (OAM) message delivery and additionally it supports broadcast. The protocol is fully compliant with the standard ATM, because the PLOAM cells are not passed to the ATM layer. The PLOAM cells are used in ONU synchronisation, in transmitting grant and alarm indications and in carrying Automatic Protection Switching (APS) messages in failure conditions. The upstream and downstream PLOAM messages have different structures.

The B-PON frame structure builds up with the line rates as shown in Figure 5. The basic frame format is defined for the STM-1 line rate of 155 Mbit/s [5]. In the downstream direction, the frame consists of 56 cells and each cell is 53 octets long. Every frame starts with a PLOAM cell followed by 27 ATM cells. The 29th cell is again a PLOAM cell followed by another sequence of 27 ATM cells. The higher standardised line rates are four and eight times the STM-1 rate and, consequently, the corresponding frame sizes are four and eight times the basic frame size.

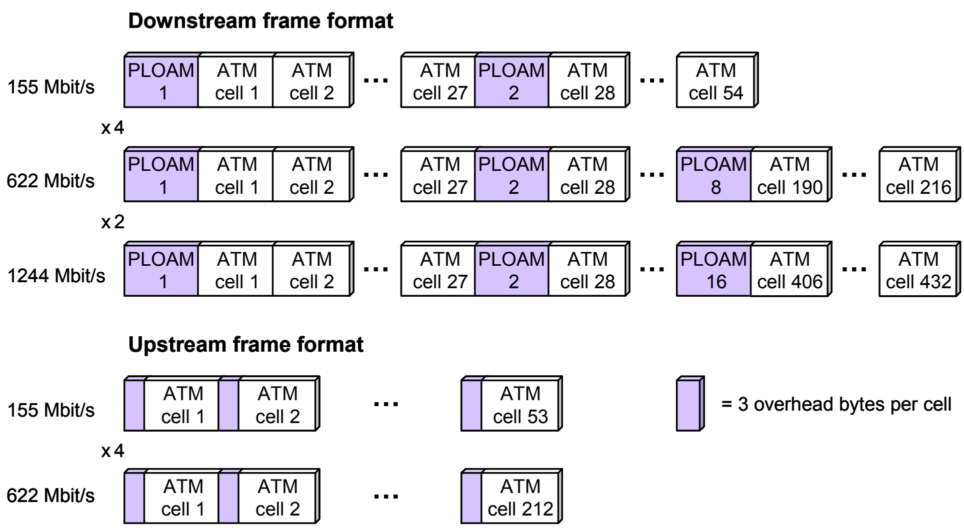

Figure 5. B-PON frame and super-frame structure (ITU-T G.983.1).

In the upstream direction, 53-octet ATM cells are added with three additional guard band octets resulting in 56-octet mini frames. At the STM-1 rate, the frame length is defined to be 53 mini frames and 212 mini frames at the STM-4 rate. The programmable three-octet guard band is needed to allow specific guard time between adjacent cells and to include a synchronisation pattern to every cell. Notice that there are no regularly running PLOAM cells in the upstream direction. The upstream ATM cells can be replaced with PLOAM cells whenever necessary.

In normal network conditions, ONUs are located at different distances from the OLT. This results in transmission phase differences and the OLT may receive overlapping transmissions from the different ONUs. The B-PON concept has a specific method for synchronising the ONU transmissions, called ranging [5]. First, an ONU synchronises itself to the downstream PLOAM frame headers and waits for the ranging window to open. When the window opens, the network enters into the ranging procedure, during which the delay and phase differences between the OLT and all active ONUs are determined. As a result, the ONUs adjust their transmission phases and grants accordingly.

The overall ranging scheme is presented in Figure 6. The ranging is operated by the OLT, which opens a ranging window between configurable time periods. This means that the OLT sends a ranging grant and stops the traffic in the network and waits for the ONUs to send their ranging PLOAMs. The ranging window should be large enough to cover propagation and processing delays of all the ONUs, including the farthest ONU. The window size can be programmed to support transport distances up to 20 kilometres.

During the ranging procedure, each active ONU receives a PON-ID from the OLT, which uses the IDs to send data to each ONU individually. Moreover, the OLT measures the arrival phases of the ONU ranging cells, calculates the required equalisation delays and communicates the information to the ONUs. The ONUs adjusts their transmission phases according to the determined values. After initialisation, each active ONU can transmit data according to the given grants.

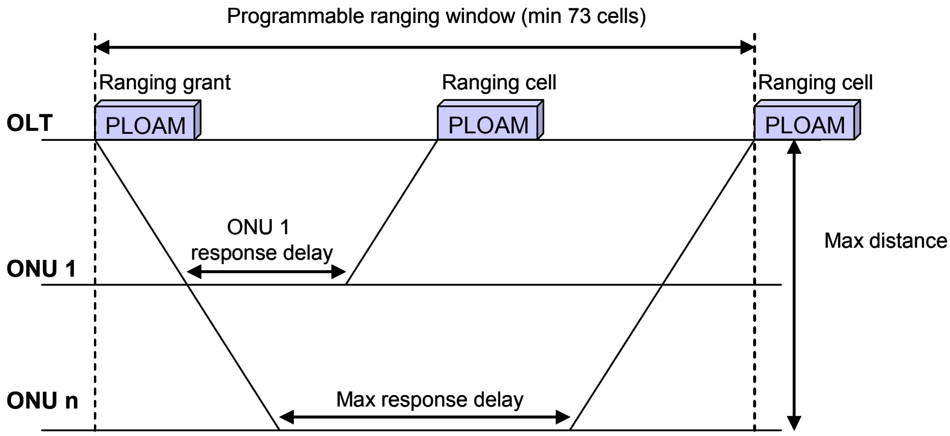

Figure 6. B-PON ranging scheme.

The B-PON concept manages the upstream bandwidth by exploiting a Dynamic Bandwidth Assignment (DBA) procedure, which is a collection of protocols and algorithms that are used for assigning bandwidth to users (ONUs) in real-time [7]. The DBA procedure uses a special transport entity, called Transmission Container (T-CONT), for carrying user data. T-CONT is a traffic prioritisation mechanism, allowing four priority classes between an OLT and an ONU. The priority classes are Fixed Bandwidth (FXB), Assured Bandwidth (ASB), Non Assured Bandwidth (NAB) and Best Effort Bandwidth (BEB). FXB always guarantees the assigned bandwidth, NAB and BEB assign bandwidth only if there is any vacant bandwidth available and ASB assigns bandwidth only when T-CONT requests for the bandwidth.

The OLT reserves bandwidth, i.e. a specific number of cell slots, for each T-CONT during a bandwidth assignment period. The bandwidth assignment is based on reports sent by the ONUs or on traffic monitoring. The ONUs can report their buffer status by sending programmable-sized mini-slots. The OLT can also base its allocation decisions on the portion of the idle frames coming from an ONU, e.g. if the upper threshold of idle frames is reached, the OLT allocates less bandwidth to the ONU and if the lower threshold is reached, the OLT allocates more bandwidth to the ONU.

The downstream payloads are churned by 14-bit codes in the OLT and the ATM headers are transported non-churned. The churning key is provided by the ONU on request from the OLT. The churning for ranged or non-ranged ONUs starts immediately after the first churning key is received. However, churned virtual paths of previously active ONUs should be restored when an ONU is reactivated. The churning encrypts the data carried between the OLT and an ONU and the other ONUs cannot see the original payloads. Optionally, the Advanced Encryption Standard (AES) scheme may be used instead of churning to offer advanced link security with longer encryption keys.

2.4.3 Transport concepts

When considering only the PLOAM messages and ATM cell overhead, the maximum link utilisation is about 87 % in the downstream direction. In the upstream direction, the maximum link utilisation is 86 % when only the overhead bytes are considered. Since the ONUs send upstream PLOAM messages regularly, the real utilisation of the upstream bandwidth is lower. Furthermore, the ranging window assignments may have an impact on the downstream and upstream transport efficiency.

In B-PON networks, bandwidth for the downstream and upstream traffic is allocated in a similar way as in ATM. ONUs may have different queues for the different types of T-CONT traffic and the transport capacity can be prioritised accordingly, providing QoS for the system. In B-PON, the cell variation requirements are the same as in ATM and the transport delay caused by an ONU and the OLT should be less than 1.5 ms to ensure highest quality voice transport.

Reliable performance of a network entails fault tolerant systems and use protection mechanisms to recover established connections in case of faults. The fault tolerance implies the network's ability to continue its intended operation in case of a failure or multiple failures. A fault tolerant system usually implements methods to recover from faults, e.g. redundant equipment, links or software modules and in the extreme cases rebooting of the system or parts of the system. Protection of established connections includes additional paths and functionality of network nodes to direct traffic from corrupted paths to reserve paths. The B-PON recommendation defines four different protection schemes that are based on Automatic Protection Switching (APS) [8]. APS uses forced switching, controlled by the OLT, automatic switching and a selection of revertive/non-revertive modes.

B-PON OAM fulfils the general operation, administration and maintenance principles defined in ITU-T Recommendation I.610. However, the point-to-multipoint nature of the physical medium entails that some notifications sent by the OLT to ONUs are obsolete, because the ONUs are essentially slaves to the OLT and the ONUs cannot make use of the notifications. OAM signals are mapped into the message fields of PLOAM cells. Furthermore, the OAM functionality in B-PON supports configuration, performance, fault and security management.

2.5 Ethernet passive optical network

The Ethernet passive optical network (E-PON) concept was developed in IEEE 802.3ah Ethernet in the First Mile (EFM) task force, and the standard was published in September 2004 [9]. The E-PON portion of the standard concentrates on defining Ethernet based point-to-multipoint fibre networks.

2.5.1 Transport convergence layer

The E-PON transport protocol is based on the standard Ethernet frame structure and it exploits TDM technique for the downstream and TDMA technique for the upstream communication. The transmission speed is symmetrical 1 Gbit/s with 8B10B block coding, resulting in 1.25 Gbit/s line rate. The protocol sets no limits to the maximum logical distance between the ONUs and OLT. The data traffic is carried in Ethernet frames and each ONU receives only the frames addressed to it. In the upstream direction, each ONU is allocated a specific timeslot, during which the ONU can transmit its data frames. The ONU identification, point-to-point emulation and point-to-multipoint emulation are accomplished by using a 2-byte tag, called Logical Link ID (LLID).

E-PON defines a single fibre network, operating at the wavelength of 1490 nm to the downstream and 1310 nm to the upstream direction [9]. This leaves the 1550 nm wavelength window open for additional services, such as private WDM networks and Community Antenna television (CATV) networks [10]. The E-PON Physical Media Dependent (PMD) layer defines two alternative optical ranges: 10 kilometres for short reach and 20 kilometres for long reach. This allows intermixing of different PMD types and results in a wide range of splitting ratios and transport distances. E-PON transceivers use Distributed Feedback (DFB) or Fabry-Perot or Vertical Cavity Surface Emitting lasers (VCSEL), prices of which are expected to decline when the market and technology matures.

2.5.2 Medium access control protocol

The E-PON Medium Access Control (MAC) mechanism is based on an extension of the Ethernet's MAC Control sub-layer, called the Multi-point MAC Control sub-layer. It provides real-time control of the MAC sub-layer function, such as multi-point transmission control, ranging functionality and enables dynamic bandwidth allocation.

The E-PON frame is based on the standard Ethernet frame. The difference can be found in the preamble field, which has been modified to carry a 2-byte Logical Link identification (LLID) field, Start of Packet Delimiter (SPD) that is transmitted as 0xD5 and the CRC8 field, which is calculated over the first bit of the SPD through the last bit of the LLID. The first bit of the LLID field is a mode indicator (point-to-point or broadcast mode) and the remaining 15 bits are for ONU identification [9]. The LLID tag exists only within the E-PON network and is inserted and removed by the emulation sub-layer, which resides below the Ethernet MAC layer. The E-PON frame structure is presented in Figure 7.

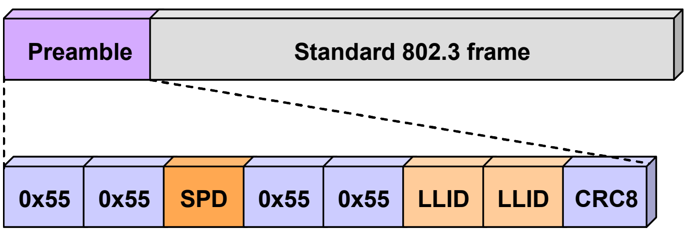

Figure 7. E-PON frame structure.

In the upstream direction, the unique traffic co-ordination requirements are handled by Multi-Point Control Protocol (MPCP) [10]. It is a frame-based protocol that uses 64-byte MAC control messages. MPCP includes messages for bandwidth request and assignment, negotiation of parameters, management, ranging, auto discovery and registration of ONUs. It also has the ability to test ONU lasers to find out whether they are aged or not. The MPCP functions are enabled with an extension in the MAC control sub-layer, called the multipoint MAC control sub-layer. This layer is required for point-to-multipoint operations and five new control messages are under consideration for the Ethernet standard: GATE, REPORT, REGISTER, REGISTER_REQUEST and REGISTER_ACK.

The OLT and ONUs use 32-bit counters to calculate local timestamps [9]. The counters are incremented every 16 ns. During the ranging period, shown in Figure 8, the OLT inserts a timestamp in the ranging message and the receiving ONU resets its counter according to the timestamp. After this the ONU generates a ranging message, which includes the ONU's current timestamp, and sends the message to the OLT. Then the OLT calculates the Round-Trip Time (RTT) and uses this value to determine when to assign grants to this ONU. If the OLT wants to receive a message at time *T*, it will send a GATE message to the ONU with a command to start transmission at time *T* - RTT.

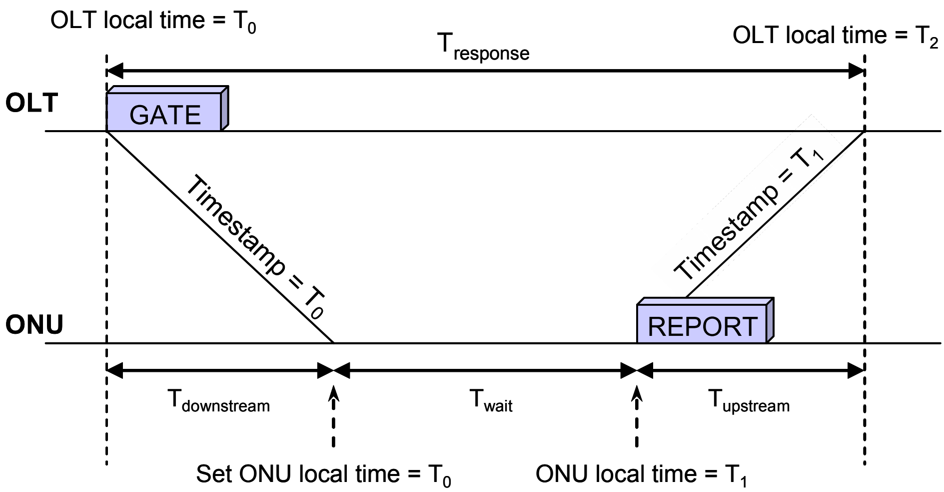

Figure 8. E-PON ranging and timing.

Based on the predefined parameters and policies, the OLT assigns timeslots for each registered ONU, which can then transmit as much data as is possible during that time frame. The data is transported in variable size Ethernet frames and it is possible that the timeslots are not fully utilised as depicted in Figure 9 [11]. This feature brings more challenge to the network planning, especially when the utilisation degree of the network is high. The length of a timeslot should be designed so that the transported frames can occupy the whole slot, leaving minimum amount of unused space.

After the network is initialised, the OLT starts to adjust the timeslots for each ONU by using the available ONU queue status information. This bandwidth allocation can be static or dynamic and no packet fragmentation is allowed within the upstream timeslots. In the downstream direction, ONUs will accept only those frames for further processing that carry their LLID tag. The security of communication is obtained by encryption mechanisms.

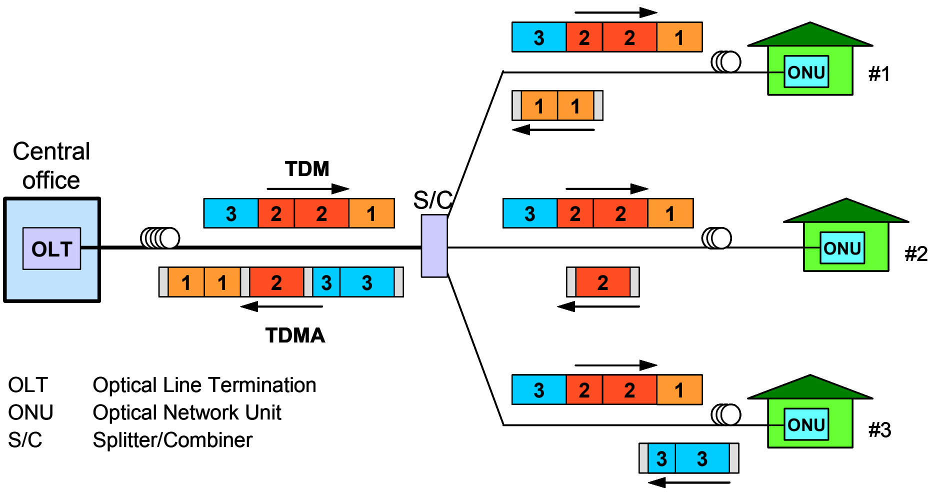

Figure 9. E-PON transport principle.

2.5.3 Transport concepts

E-PON is an extension of the Ethernet standard with some modifications in the preamble to enable point-to-point emulation. In this way, E-PON can utilise the already developed Ethernet functionality, such as bandwidth management and 802.1p priority queuing. In the point-to-multipoint networks, the security of communication becomes a problem, which will be solved by implementing some encryption mechanism, probably AES. The efficiency of E-PON depends greatly on the network characteristics and transported traffic, which both can vary a lot.

On network's throughput point of view, the most critical point is the length of the allocated timeslots. The number of unused bits in a timeslot should be minimised, which might be a hard task, considering the variable packet length. Of course, the size of the transported packet has also significance to the transport efficiency, because smaller packets have relatively large overhead. The control traffic should also be taken into account.

E-PON applies G.975 type of Forward Error Correction (FEC) scheme, which uses Reed-Salomon algorithm [12]. In the FEC process, an E-PON frame is encapsulated into a FEC frame carrying parity and other FEC bits. The protection schemes for E-PON are still for further study.

The OAM functionality in E-PON provides the operators with the ability to monitor the health of the network and quickly determine the location of failing links or fault conditions [10]. The OAM information is carried in the slow protocol frames, called OAM Protocol Data Units (OAMPDUs), containing appropriate control and status information for monitoring, testing and troubleshooting in OAM-enabled links. OAMPDUs are exchanged between OAM entities, which reside at the opposite ends of a PON link, i.e. in the OLT and ONUs, and are not forwarded further to the network by MAC clients (e.g., bridges or switches).

2.6 Gigabit-capable passive optical network (G-PON)

The new ITU-T recommendation series G.984 is targeting to describe a flexible fibre access network capable of supporting bandwidth requirements of business and residential services. It is named as Gigabit-capable PON (G-PON) [13] and it aims to improve the B-PON system by reconsidering the supporting service, security policy and optical fibre infrastructure. It also tries to maintain as many characteristics as possible from the B-PON recommendation to promote backward compatibility with the existing B-PON networks.

2.6.1 Transport convergence layer

The G-PON transport protocol exploits TDM technique in the downstream and TDMA technique in the upstream direction. The G-PON standard defines the following nominal system line rates (downstream/upstream):

- 1244.16 Mbit/s / 155.52 Mbit/s
- 1244.16 Mbit/s / 622.08 Mbit/s
- 1244.16 Mbit/s / 1244.16 Mbit/s
- 2488.32 Mbit/s / 155.52 Mbit/s
- 2488.32 Mbit/s / 622.08 Mbit/s
- 2488.32 Mbit/s / 1244.16 Mbit/s
- 2488.32 Mbit/s / 2488.32 Mbit/s.

In the G-PON Transmission Convergence (TC) layer, the maximum logical reach between an OLT and an ONU is 60 km, while the maximum differential fibre distance between the farthest and the nearest ONU is 20 km [14]. This differential distance is limited to 20 km to keep the ranging window size within the limit allowed by the service quality requirements. As for the split ratio, the TC layer supports split ratio up to 128 anticipating the future evolution of the optical modules. It also supports transport of an 8 kHz clock signal as well as delivery of a 1 kHz reference signal, both provided by the OLT to ONUs by means of a control signal. G-PON defines two options for physical reach: 10 or 20 km, where the 10 km reach is the maximum distance for high bit rates, such as 1.25 Gbit/s and above. The ONU addressing scheme allows up to 253 ONUs to be identified in the same network. An overlay wavelength may be used to provide enhanced services to subscribers. Accordingly, G-PON must vacate the enhancement band defined in G.983.3 [6].

2.6.2 Medium access control protocol

G-PON Encapsulation Method (GEM) [15] is intended for carrying circuit and packet switched data in G-PON networks. The G-PON frames carry also ATM traffic as shown in Figure 10. GEM is embedded into the PON section and is independent of the type of System Network Interface (SNI) in the OLT or the types of User Network Interfaces (UNI) in the ONU, following the same principles as the newly developed Generic Framing Procedure (GFP) (see 3.2.1). The maximum signal transfer delay should be limited to 1.5 ms to support all feasible services. The G-PON standard aims to support all the currently transport services as well as the services to be developed in the future.

In the downstream direction, G-PON uses similar frame structure as the SDH concept. One frame is transmitted to upstream and downstream in every 125 µs, allowing the clock distribution and synchronous data transfer. The frame size is determined by the transmission speed, being 19440 bytes for 1.24 Gbit/s and 38880 bytes for 2.5 Gbit/s [15]. The downstream Physical Control Block (PCBd), which is located in front of each downstream frame, has the same length range for both the above data rates and depends on the number of allocation structures per frame [16]. The downstream frame, shown in Figure 10, is scrambled and Non-Return to Zero (NRZ) line coded before transmission on the outbound transport link. The functions of the downstream frame fields are the following:

- **Psync field** carries the synchronisation pattern 0xB6AB31E0. ONUs receive this pattern in the physical control blocks (PCBd) and synchronise to the bit pattern.
- **Ident field** – The ident field is used for indication of larger frame structures and the least significant 30 bits of the field contain a super-frame counter, which is incremented by one in each super-frame. To provide error tolerance, every ONU must implement a local super-frame counter.
- **PLOAMd field** carries a PLOAM message.
- **Plend field** carries the payload length, which is sent twice for error robustness. It has a separated 12-bit field for the length of the bandwidth map (BWmap) and for the ATM section. The actual BWmap length is 8 times the provided value and the length of the ATM map is 53 times the provided value. The last 8 bits are for the Cyclic Redundancy Check (CRC).
- **BWmap field** is a scalar, which specifies when an ONU can start to transmit, which type of traffic (T-CONT type) it can transmit and when to stop transmission.
    - **AllocID** is an allocation identifier of a T-CONT.

- **Flags field** defines the required control messages to be sent during the allocated timeslot. The alternative messages are Power Levelling sequence (PLSu), PLOAMu and indication to use FEC and DBRu.
- **SStart field** contains the starting time of a transmission. The time is measured in bytes, starting with zero at the beginning of an upstream frame.
- **SStop field** contains the ending time of a transmission.

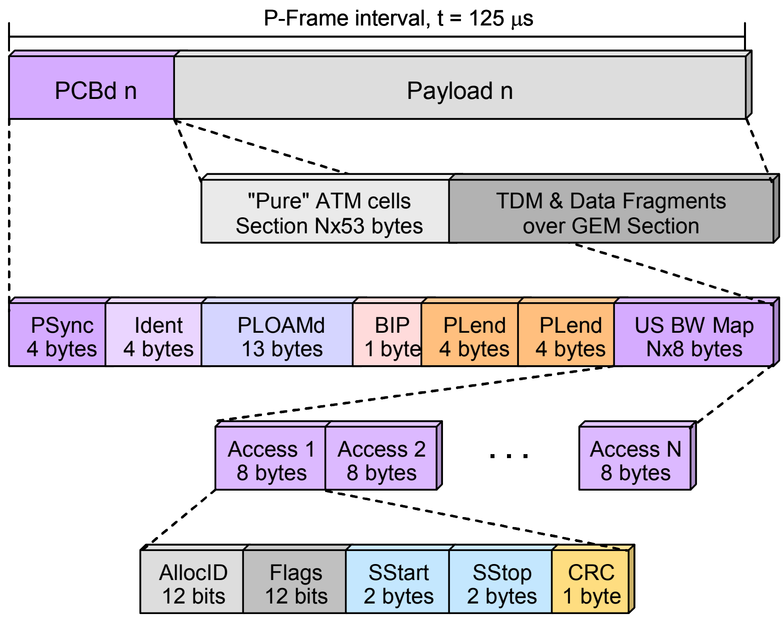

Figure 10. G-PON downstream frame.

In the upstream direction, several ONUs can send data during one frame period according to the timeslot allocations done by the OLT. The upstream frames can carry four types of overhead: Physical Layer Overhead (PLOu), Physical Layer OAM overheads (PLOAMu), Power Levelling Sequence upstream (PLSu) and Dynamic Bandwidth Report upstream (DBRu) [15][16]. The OLT indicates by using the downstream frame's flag field, whether the PLOAMu, PLSu or DBRu information should be sent during each allocation. Figure 11 demonstrates the upstream frame and frame overhead. The functions of the upstream frame fields are the following:

- **PLOu field** contains the programmable physical layer overhead (preamble and delimiter) and three additional fields for transmitting ONU indication. ONU-ID identifies the transmitting ONU and the indication field carries ONU's real time status report to the OLT.
- **PLOAMu field** contains a PLOAM message.
- **PLSu field** is 120 bytes long and is used in power control measurements by ONUs. The optical dynamic range seen by the OLT can be adjusted based on the measurements.
- **DBRu field** carries information related to a T-CONT entity and the DBA field contains the traffic status of a T-CONT in question.
- **Upstream payload**, which follows the last upstream overhead filed, carries ATM cells, GEM-delineated frames or DBA reports.

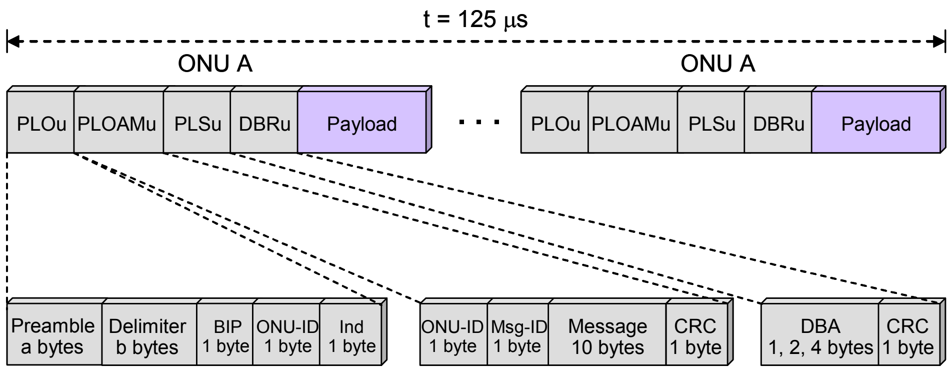

Figure 11. G-PON upstream frame and overheads.

The ranging procedure in G-PON is similar to that in B-PON. An ONU has 8 different states, each serving some specific function. The normal operation state is reached after passing the initial, standby, power range set up, ONU-ID assigning and ranging states. There are also some states for specified network failure conditions.

The G-PON transmission convergence system performs media access control for the upstream traffic. In the basic concept, the downstream frames inform the ONUs during which timeslot they can transmit. The downstream frames also carry synchronisation information to the ONUs [15], [16]. The MAC concept is illustrated in Figure 12. The OLT sends pointers in PCBds, and these pointers indicate the time at which each ONU may start and stop its upstream transmission. In this way, only one ONU can access the medium at a time, and there is no overlapping in normal operation. The pointer values are given in the number of bytes, allowing the OLT to control the medium at the bandwidth granularity of 64 kbit/s. However, it is possible to set the pointer values to a larger granularity and achieve fine-grained bandwidth control via dynamic scheduling.

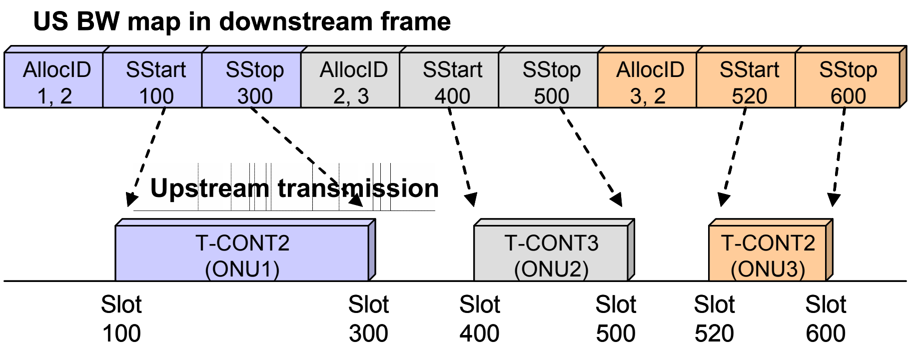

Figure 12. Simplified presentation of GTC MAC control.

As in B-PON, G-PON's data transport entity is named as Transport Container (T-CONT). It supports five priority classes and is updated to support ATM and GEM service multiplexing as shown in Figure 13. An ONU can support either one or both of the service multiplexing schemes and one T-CONT type must be allocated to each multiplexing scheme and priority class.

G-PON DBA supports two modes for every T-CONT: Status Reporting (SR) mode and Non Status Reporting (NSR) mode. The OLT must support both modes, but ONUs can be made simpler since the DBA reporting function is optional. When transporting ATM traffic, the bandwidth assignments are determined by the volume of ATM cells similarly as is done in B-PON. In the case of GEM traffic, the bandwidth assignments are determined by the number of fixed size GEM cells [15].

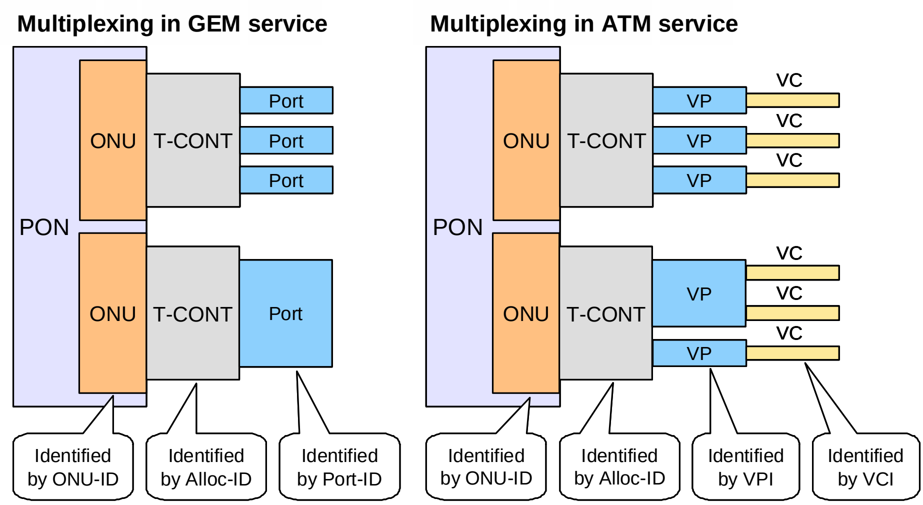

Figure 13. ATM and GEM service multiplexing in G-PON.

2.6.3 Transport concepts

G-PON provides capacity allocation at a minimum granularity of 64 kbit/s and it has built in support for five priority classes, composed of different T-CONTs like in B-PON. The ATM part of G-PON is similar to that of B-PON, but G-PON deals with many technical matters in a different way and the two systems are not interoperable. The security of communication is supplied with Advanced Encryption System (AES) that uses 128 bit keys. The keys are generated in ONUs on request of the OLT. The transport link utilisation depends on the network characteristics, set-up and used transport methods. G-PON is a relatively good concept for carrying ATM traffic and excellent for data traffic. G-PON also offers high efficiency for native voice traffic and multiservice support with GEM encapsulation [16].

Automatic switching and forced switching are considered for protection schemes in G-PON. Protection is an optional feature and enhances the reliability of the network [16]. In error-prone environments, the reliability of communication can also be improved by the optional Forward Error Correction (FEC) methods. The use of a FEC results in an increased link budget by approximately 3–4 dB, which enables higher bit rates, longer OLT-to-ONU distances as well as higher split ratios for a single PON tree.

G-PON has strong OAM capabilities supporting end-to-end service management. These capabilities are similar to those of the B-PON and SDH networks and are discussed more closely in [17].

2.7 Wavelength Division Multiplexed PONs

The WDM-PON acronym is commonly used to describe passive optical networks that exploit the Wavelength Division Multiplexing (WDM) techniques. Some research work has also been carried out to clarify applicability of other multiplexing and wavelength managing techniques to the PON networks. WDM-techniques have most commonly been applied in the downstream direction and they can be divided roughly into broadcast and select PONs (WPONs) and wavelength routed PONs (WRPONs). In WPONs, all wavelengths are transmitted to all PONs through an optical splitter and selection between the wavelengths is done in the ONU. In WRPON, the wavelength channels are routed to ONUs with the help of AWG. The PON standards and recommendations define wavelength windows for specific services that can make use of the WPON technique. The basic ideas of WRPON and WPON are demonstrated in Figure 14.

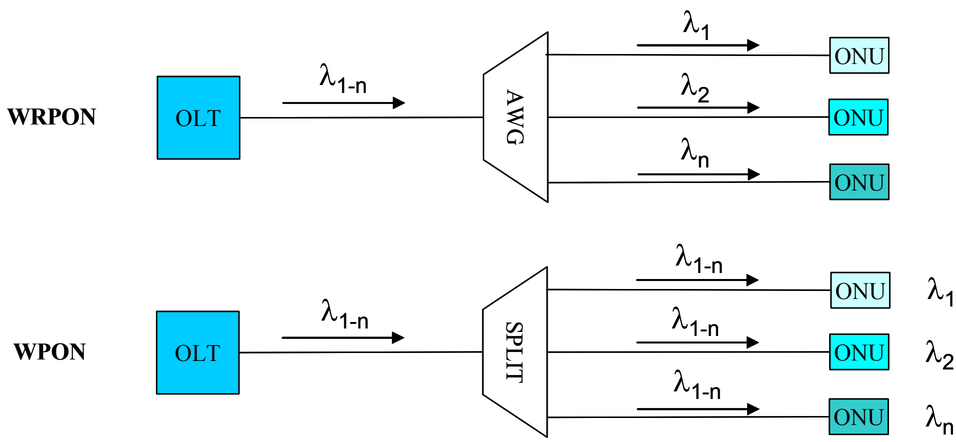

Figure 14. WRPON and WPON techniques.

The WDM-PON technique to be used in the upstream direction can be determined separately from the downstream direction. The most common solution is to deploy a single wavelength together with the TDMA technique. However, this combination is not capable of supporting symmetrical data rates. If symmetry is required, the wavelength-routed alternative might be a more desirable solution also for the upstream direction. PONs can also apply several other multiplexing techniques and some of them are described in the following. More information on WDM-PONs can be found in [18], [19] and [20].

Sub-carrier multiplexing (SCM) is used for multiplexing several data channels independently into the same optical channel. In addition to the independence of the channels, SCM gives flexibility with respect to the modulation format and synchronisation of the different channels. The disadvantage of the Sub-carrier multiple access (SCMA) systems is the need for analogue electronics, which are less integrated and more expensive than digital electronics.

Optical Code Division Multiplexing (OCDM) implies scrambling of the optical signal in the time and/or spectral domain. The aim is to multiplex several data signals into the same wavelength channel, giving each signal the whole modulation bandwidth of the transmitter and receiver. No inter-signal synchronisation or ranging is needed and the capacity of each channel can be set independently.

Space Division Multiplexing (SDM) is a term sometimes used when data streams are multiplexed each into its own fibre, creating a large number of point-to-point connections. If dark fibre is available, SDM may be the most cost-efficient solution, especially, when optical amplification is not needed.

2.8 Super-PON

SuperPON is a network structure similar to a PON, but supports a much higher splitting ratio by exploiting optical amplifiers. The downstream direction uses Erbium Doped Fibre Amplifiers (EDFAs/1.5μm) and the upstream direction Semiconductor Optical Amplifiers (SOAs/1.3μm). SuperPON is not standardised, but it can be adapted to any of the above described PONs. The split ratio of 1:2048 and downstream bit rate of 2.4 Gbit/s and upstream bit rate of 311 Mbit/s have been demonstrated using the B-PON architecture as described in [21].

2.9 Summary

Currently three different Passive Optical Network (PON) techniques have been standardised. Broadband PON (B-PON) and Gigabit capable PON (G-PON) are developed by the telephone operators and Ethernet PON (E-PON) by the Ethernet community. The medium access control protocols used by these systems are based on ATM, GFP and Ethernet. G-PON provides the highest bit rates and largest service support, E-PON does not support legacy services and B-PON was the first developed PON technique. Table 1 summarises characteristics of the various PON concepts.

Table 1. Summary of PON concepts.

	BPON	EPON	GPON
Bit rates Upstream (max) Downstream (max)	 622 Mbit/s 1244 Mbit/s	 1000 Mbit/s 1000 Mbit/s	 2488 Mbit/s 2488 Mbit/s
Logical split ratio	1:64	1:32768	1:253
Max physical distance OLT-ONU	 10 km / 20 km	 10 km / 20 km	 10 km / 20 km
Max logical distance OLT-ONU ONU-ONU	 N/A 20 km	 Not limited N/A	 60 km 20 km
Max link utilisation[1)] Upstream Downstream	 85,71 % 87,33 %	 98,00 % 98,27 %	 97,44 % 98,53 %
Line coding	Scrambled NRZ	8B10B	Scrambled NRZ
Data priority classes	4	8	5
Security	Churning, AES	Encryption (fs)	AES
ONU TX power adjustment	Yes	N/A	Yes
Protection	APS	N/A	APS
FEC	NO	G.975	G.975

[1)] 32 ONUs, one priority class, no overhead in transported traffic, no OAM or other control messages, 1500-byte Ethernet payload, 1 Gbit/s (not practical)
(fs) – for further study
N/A – Not Announced

3. Point-to-point techniques

This chapter gives a brief review of typical point-to-point techniques that can be applied in offering optical access to residential and business users. Some of the presented techniques can also be applied as local area solutions, i.e. to carry data beyond the ONUs.

3.1 Plesiochronous Digital Hierarchy

Plesiochronous Digital Hierarchy (PDH) is an older technique developed for conventional voice transport. PDH is still widely used, e.g. in mobile networks to transport data between the base stations and base station controllers. The PDH concept has a hierarchical structure with line rates of 64 kbit/s, 2.048 Mbit/s, 8.448 Mbit/s, 34.368 Mbit/s and 139.264 Mbit/s, which are known as E0, E1, E2, E3 and E4, respectively. The standard Pulse Code Modulation (PCM) technique is used to decode the analogue voice signal to digital form. One digital PCM coded voice channel is carried in one E0.

3.2 Synchronous Digital Hierarchy

Synchronous Digital Hierarchy (SDH) and its American counterpart Synchronous Optical Network (SONET) are widely used in transport networks worldwide. Although these techniques were developed already in 1980's, it seems that they are not going to be replaced for a long time. One reason for this is the recent enhancements made to the standards and another reason is the large investment made in these techniques. For these reasons operators are not willing to replace their SDH/SONET networks with other solutions in a short time scale. SDH is a hierarchical transport concept with line rates of 155.52 Mbit/s, 622.08, 2488.32 Mbit/s and 9953.28 Mbit/s, named as STM-1, STM-4, STM-16 and STM-64, respectively. Each line rate has its own frame format and the OAM functionality is an integral part of the frame structure. Irrespective of the line rate, transmission of each frame lasts exactly 125 µs.

3.2.1 Next-generation SDH

The conventional SDH is optimised for transporting voice channels, which sets quite different requirements for the network than data transport. It has been predicted that enterprises will move to packet based voice services in a few years, and the number of conventional voice-service-users will eventually decrease close to zero. The technique enabling the packet based voice services is called Voice over Internet Protocol (VoIP), which has gained a lot of interest. This implies that in the future the legacy SDH cannot support the growing data service demand. It is also good to keep in mind that the legacy service users are not going to vanish over night. The next-generation SDH has a transport mechanism, which enables the concurrent existence of the legacy and new services over the same network, without interfering each other.

The technique behind the next-generation SDH is commonly known as the Data over SDH (DoS) concept. DoS is a transport mechanism that provides means to accommodate various data interfaces efficiently into SDH. Most importantly, the allocation of bandwidth between these interfaces can be done without disturbing the existing SDH traffic, enabling the use of legacy services together with new services provided by DoS. The DoS scheme consists of three techniques: Generic Framing Procedure (GFP), Virtual Concatenation (VC) and Link Capacity Adjustment Scheme (LCAS) all standardised by ITU-T and American National Standard Institute (ANSI). Several interfacing techniques have already been standardised for DoS and will be defined when the need emerges [22].

- **Generic Framing Procedure (GFP)** provides a simple encapsulation mechanism for frame-based data traffic (Ethernet, IP/PPP, RPR, Fibre Channel, ESCON etc.) over a TDM transport path, e.g. SDH/SONET or Optical Transport Network (OTN).
- **Virtual Concatenation (VC)** provides a flexible bandwidth allocation scheme, moving granularity and utilisation of SDH link capacity that is close to that of Ethernet.
- **Link Capacity Adjustment Scheme (LCAS)** provides end-to-end signalling for dynamic adjustment of capacity when using VC on SDH links.

3.3 Ethernet

While the electrical 10 and 100 Mbit/s Ethernet connections are used in the access network, the optical 1 and 10 Gbit/s Ethernet (GbE) connections are becoming more popular in the core network. Presently, 1 GbE signals can be carried electrically and optically, but the 10 GbE signals only optically. However, the electronic 10 GbE version is under development (standard approval expected in July 2006). IEEE has recently defined also an optical 100 Mbit/s interface for the subscriber access [9]. 1 GbE links exploit 8B10B block-coding resulting in 1.25 Gbit/s line rate and 10 GbE uses 64B66B block-coding resulting in 10.3 Gbit/s line rate. OAM functionality requires an additional control protocol.

The reasons for Ethernet's popularity are the relatively low-cost equipment, ease of use and installation and the use of Ethernet in the residential data transport. Ethernet is deployed in the core network mainly by new service providers not having existing network infrastructure and by other providers not supporting legacy voice transport, e.g. cable operators.

3.3.1 Ethernet access services

Ethernet access services are a logical evolution towards packet based user access. These services offer configurable bandwidth (more flexibility than available in E1 or STM-1 transport), can be used over fibre or copper lines and have a simple interface to subscriber equipment. Most importantly, the Ethernet access services enable scalable revenue model for carriers as they can sell almost any size data pipes to customers and many types of services can be provided to customers over the same physical connection. In addition, services can be added or improved without any changes to the customer interface. However, one thing is certain. In order to support the Ethernet access services, the underlying network has to support the Ethernet transport services [23].

3.3.2 Ethernet transport services

The Ethernet transport services are also known as the Ethernet Wide Area Network (WAN) services. Basically, these services can be classified into point-to-point and multipoint-to-multipoint services. Despite the categorisation, some scalability and reliability challenges are present in the all-Ethernet metro networks [24], [25] as given in the list below.

- **Restrictions on the number of customers** – Virtual Local Are Network identifier (VLAN ID) used for traffic identification is 12 bits and thus restricts the carrier to 4096 customers.
- **Service monitoring** – Ethernet does not have embedded mechanism for service monitoring.
- **Scaling the L2 backbone** – Spanning tree protocol does not scale for bandwidth, but blocks some number of ports to prevent loops in ring topologies.
- **Service provisioning** – VLAN tag needs to be carried over the whole network, which is not an easy task and results in impossible network scaling.
- **Interworking with legacy deployments** – Frame Relay is widely deployed and there is a need for functionality enabling Ethernet and Frame Relay services to work together.

Point-to-point service – This is also known as Ethernet Line Service (ELS) and it can be divided into two types of service: Ethernet Wire Service (EWS) and Ethernet Relay Service (ERS). EWS is the Ethernet analogue to the private line or private wire service [24], where a single physical connection is established between two sites. Depending on the used transport method (frame encapsulation or native entity transport), different functionality can be provided between the end-points. ERS is the Ethernet analogue to FR service [24], where multiple point-to-point connections are established between two sites. This requires the co-ordination of Ethernet VLAN IDs and enables service multiplexing between sites. As a result, it offers Hub-and-Spoke enterprise connectivity as well as Internet Service Provider (ISP) to customer connectivity.

Multipoint-to-multipoint service – This is also known as Ethernet LAN Service (E-LAN) and it can also be divided into two categories: Ethernet Multipoint Service (EMS) and Ethernet Relay Multipoint Service (ERMS). EMS is the WAN analogue to the multipoint Ethernet LAN capability [24]. Unicast frames are delivered using standard self-learning and forwarding capabilities of the Ethernet bridges and broadcast frames are replicated to all sites. For example, EMS is a good way to connect multiple campuses together. ERMS is a combination of EMS and ERS and it enables simultaneous use of multipoint layer-2 services and Internet access over the same UNI. It is exploited by ISPs that are interested in offering service multiplexed multipoint-to-multipoint services.

3.4 Optical Transport Network

SDH cannot fully exploit the possibilities of the WDM technique. To ease the management tasks in the WDM networks, ITU-T study group 15 has defined a set of recommendations (G.709.x) for optical transport [26]. These include architectural, interfacing and management issues, which all are described by a single term Optical Transport Network (OTN). Since OTN can be considered as an improved version of the SDH concept, it has many similarities with SDH, such as hierarchical network structure and frame format. OTN has methods to manage and monitor optical paths and channels in a similar way as SDH does in electrical transport systems. OTN defines frame mappings for multiple optical layer client signal types, e.g., SDH and GFP. Moreover, Automatic Switched Optical Network (ASON) specification G.8080 following the Automatic Switched Transport Network (ASTN) recommendation G.807/Y.1302 has been created to enable automatic provisioning of OTN. Currently, the OTN hierarchical structure defines line rates of 2666 Mbit/s, 10709 Mbit/s and 43014 Mbit/s for OTU-1, OTU-2 and OTU-3, respectively.

3.5 Summary

Although PDH and SDH are the most widely used point-to-point techniques, they do not fit well for data transport. The DoS concept has been developed to enhance data transport capabilities of SDH and most lately it has been extended also to PDH [27]. The enhancements improve performance of the legacy transport concepts and therefore PDH and SDH can be considered equally good competitors to Ethernet. In the long run, issues like wavelength channel management and automatic network configuration will gain importance in the optical access networks. These are not supported by the above mentioned techniques and OTN can be seen as the solution. Table 2 summarises some characteristics of the point-to-point techniques.

Table 2. Summary of point-to-point techniques.

	PDH	**SDH / NG-SDH**	**Ethernet**	**OTN**
Optical line rates (Mbit/s)	2.048 (E1) 8.448 (E2) 34.368 (E3) 139.264 (E4)	155.52 (STM-1) 622.08 (STM-4) 2488.32 (STM-16) 9953.28 (STM-64)	100 1000 10000	2666 (OTU-1) 10709 (OTU-2) 43014 (OTU-3)
Line signal coding	Line code + scrambling	Line code + scrambling	Block-coding	Line code + scrambling
Wavelength management	No	No	No	Yes

4. Last mile techniques

This chapter gives a brief introduction to the most commonly used last mile techniques and other solutions to implement data access services.

4.1 Wireless access

The popularity of wireless access is forecasted to grow in the future as multifunctional mobile terminals become common. This affects the connection requirements between the base stations and other network equipment, because technique-specific control and bandwidth management is required. Common wireless technologies together with their maximum channel bit rate are listed in Table 3 [28].

Table 3. Maximum downstream bit rates of some wireless access techniques.

Technique	Bit rate per channel
GSM	14.4 kbit/s
HSCSD	57.6 kbit/s
GPRS	115.2 kbit/s
EDGE	384 kbit/s
UMTS (Rel99)	2 Mbit/s
CDMA2000	3 Mbit/s
Wi-Fi (IEEE802.11b)	11 Mbit/s
WLAN (IEEE802.11g)	54 Mbit/s

4.2 Digital subscriber line

The Digital Subscriber Line (DSL) techniques are being studied intensively. The standard ADSL is the most commonly used techniques in residential broadband connections. The DSL techniques can offer quite large bandwidth, but for a short range. While bit rates of the DSL techniques grow up, the signal range gets shorter and combination of fibre and copper line transport becomes a relevant alternative. One of the proposed solutions is the hybrid PON-DSL network. PON is used to carry large bandwidth signals to a curb site or to a building and DSL to distribute the signals to the end-users. The most common DSL techniques are presented in Table 4 [29].

Table 4. Summary of most common xDSL techniques.

Technique	Supported data rates
ADSL	~1 Mbit/s upstream and ~8 Mbit/s downstream (6 km)
HDSL	1.544 Mbit/s symmetric
SDSL	up to 2.32 Mbit/s symmetric
VDSL	~13 Mbit/s upstream and ~22 Mbit/s downstream (14.5 Mbit/s up to 1.5 km and 58 Mbit/s up to 0.3 km)

4.3 Hybrid fibre coax network

The Hybrid Fibre Coaxial (HFC) networks combine fibre and coaxial cable transmission and are commonly deployed in Community Antenna TV (CATV) networks. TV signals are transmitted from a central point and carried along fibre lines up to a point, which converts the signals to electronic form. From this point the electronic signals are carried in coaxial cables to residential users. The optical part of the network enables improved signal quality and lowers the number of electronic amplifiers thus offering a cost-effective way to carry TV signals long distances [30]. The number of homes connected to a network segment is usually around 2000 homes, but can go as high as 20 000 homes in densely populated areas, such as major cities. The cabling architecture of a typical HFC network is presented in Figure 15.

The HFC network consists of three parts. At the top we have the head-end (HE), which delivers optical broadcast signals to (about ten) distribution hubs (DHs). These forward the optical broadcast signals to (about 40) fibre nodes (FNs), which transform the optical signals to electronic form and distributes the signals to (2–8) coaxial cable bus segments, each connected to 500–1000 homes.

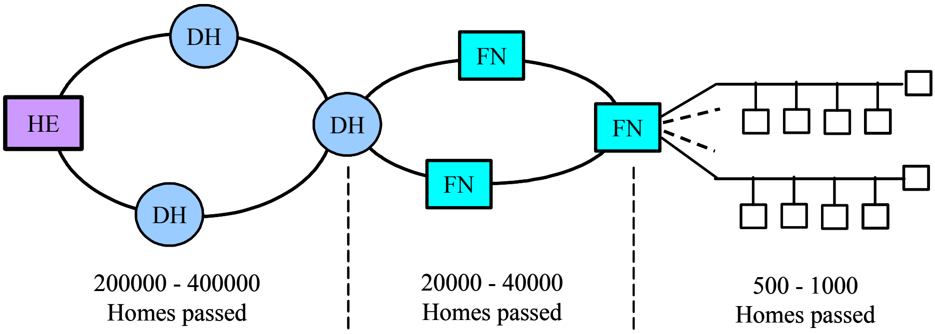

Figure 15. Hybrid Fibre-Coax (HFC) network.

Characteristics of the optical signal from the HE to FH are unique. It represents the only widespread use of analogue modulation of communications lasers. The technique is called Sub-Carrier Multiplexing (SCM). The signal is prepared in the distribution centre exactly as though it was to be fed directly into the cable. That is to say that many RF sub-carriers are mixed and a single composite stream with a bandwidth of 500 MHz is produced. This stream is then used to modulate a laser transmitter by means analogue modulation [30].

The HFC networks also support data access services. In the cable part of the network, the data is transported upstream and downstream by using a dedicated technique, called Data Over Cable Service Interface Specification (DOCSIS). Additionally, a more advanced technique, called Ethernet-to-the-Home (EttH), is currently available.

4.3.1 Data-over-cable service-interface specification

In CATV networks, delivery of data services is currently based on the DOCSIS specification, developed by a consortium of North American cable operators. The European counterpart of the standard is called euroDOCSIS, which uses slightly different frequency bands than DOCSIS. Both standards occupy frequencies above the TV channels for the downstream and frequencies below the TV channels for the upstream transmission. Due to the present CATV frequency allocation schemes, the available upstream band is more limited than the downstream one. Furthermore, the upstream band suffers from disturbances, caused for example by household appliances, degrading quality of the upstream data communications. The upstream frequency band problem has recently been issued by DOCSIS 2.0 specification, which provides up to 30 Mbit/s throughput in the upstream and 50 Mbit/s throughput in the downstream direction [31], [32]. The available downstream bandwidth is almost unlimited, because the unused broadcast channels can also be utilised for data transport. Recently, the Cable Labs consortium has started the development of DOCSIS 3.0 standard, which is said to enable 100 Mbit/s upstream and 200 Mbit/s downstream data rates for end-users [33].

The DOCSIS architecture is presented in Figure 16. The cabling structure between the HE and customers is similar to that presented in Figure 15. The optical links between the HE and optical nodes utilise Ethernet transport and the DOCSIS transport is used between the optical node and customers. An optical node includes a cable modem termination system (CMTS) for transmitting and receiving signals to and from the customers. The customer sites have cable modems (CM) to connect to the network. Residential data devices, such as PCs, are connected to standard Ethernet interfaces of the modems.

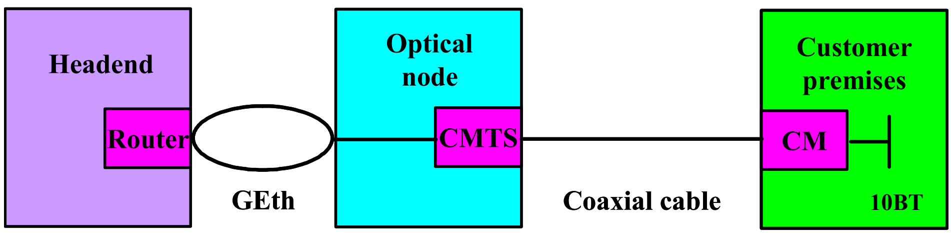

Figure 16. DOCSIS architecture.

4.3.2 Ethernet to the home

Ethernet to the Home (EttH) is a newly introduced technique by Teleste Oyj. The target has been to overcome the bandwidth limitation present in the DOCSIS systems [34]. The EttH concept uses the virtual fibre and remote subscriber access techniques, which allow separation of the most interference sensitive network part from the rest of a cable network segment. Efficient modulation and the virtual fibre technique enable a two-way 100 Mbit/s data pipe to be carried between an optical node and customer premises.

The EttH architecture is presented in Figure 17. The HE transmits data over Gigabit Ethernet links to the optical nodes. An optical node, acting as an Ethernet switch, distributes the data frames to a number of coaxial cable segments. Each segment interface implements an Ethernet Node Modem (ENM) that modulates and transmits a 100 Mbit/s Ethernet signal to the coaxial cable attached to it. In the reverse transfer direction, the ENM receives and demodulates a corresponding 100 Mbit/s Ethernet signal coming from the customer site. The demodulated signal is further multiplexed with signals coming from the other coaxial segments to form an aggregated stream of Ethernet frames. This data stream is further transmitted over an optical Gigabit Ethernet link to the HE.

The modulated Ethernet signal from ENM is terminated at an Ethernet POP Modem (EPM), which provides a local 100 Mbit/s Ethernet interface to an Ethernet Multitap (EMT) or to any other subscriber access system that supports Ethernet transport. The EMT acts as an Ethernet switch that is connected to a number of 10 Mbit/s Ethernet links. The remote subscriber access refers here to the capability of accessing the Internet through the HFC carrier network with a standard Ethernet interface, i.e. EttH offers Ethernet over Coax (EoC) service.

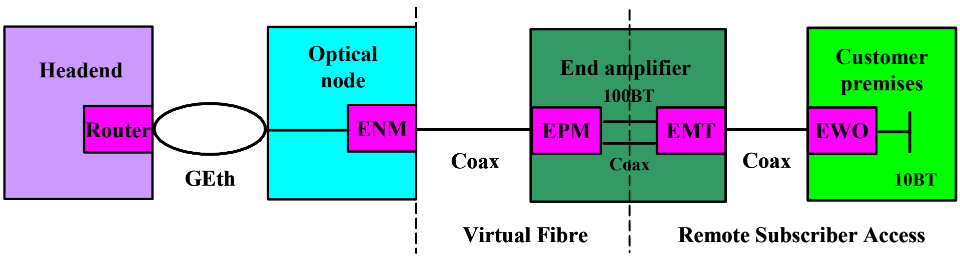

Figure 17. Ethernet-to-the-Home architecture.

Each 10 Mbit/s Ethernet signal is carried along with the TV signals over the addressed residential coaxial cable. At the customer site, the TV signals are received from a conventional CATV wall-outlet and the standard Ethernet signal from an Ethernet Wall Outlet (EWO). In the reverse direction, the EWO passes the standard Ethernet signal to the coaxial cable to be carried to the EMT. Thus the EWO provides the end-user with a standard 10 Mbit/s Ethernet interface.

4.3.3 Next-generation broadband access network

The Next-generation Broadband Access Network (NBAN) system, described in [35], is an enhancement to the existing cable networks. It exploits the unused coaxial cable frequency spectrum from 909 to 2466 MHz, enabling two 100 Mbit/s and two 1 Gbit/s Ethernet channels as illustrated in Figure 18. It can also provide additional services like Dynamic Host Configuration Protocol (DHCP), Connection Admission Control (CAC), topology servers and Network Management System (NMS). The legacy cable network amplifiers do not support the NBAN frequencies and adoption of this system requires either upgrade of the existing amplifiers or installation of new ones.

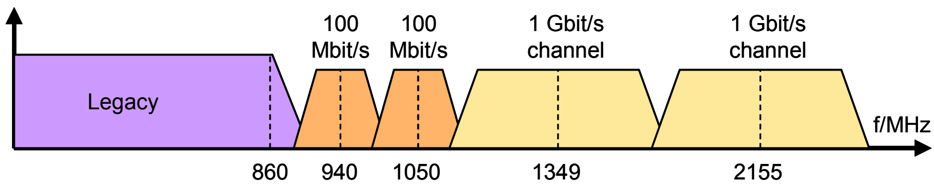

Figure 18. NBAN frequency allocation.

Normally, the cable network segments are using amplifiers at maximum power and the only possible way to implement NBAN is to replace all of the existing amplifiers with new ones. This is expensive and therefore the NBAN is not widely used.

4.4 Summary

Wireless access is getting more popular as techniques evolve and the available bandwidth increases. The same type of development can be seen in the DSL market as well. In the wireless and DSL access, high bandwidth can be supported only for short ranges. This means that the base stations and Digital Subscribe Line Access Multiplexers (DSLAMs) need to come closer to the end-user to enable high-bit-rate access. This could be obtained by exploiting hybrid PON solutions, i.e. PON techniques are used for carrying data signals close to the end-users and wireless or DSL solutions to distribute the signals to the end-user terminals.

Approaching competition can also be seen between the cable network and telephone network operators as the separate legacy networks start to converge. Older DOCSIS solutions cannot be considered competitive enough and thus new solutions are needed. One way of offering higher bandwidth for the data-users in the cable television network is to decrease the size of the CATV segments. However, the segments cannot be reduced endlessly. DOCSIS 2.0 offers enhanced features and increased bandwidth, but currently the EttH solution seems more promising and competitive. The situation may change when DOCSIS 3.0 is published, but it is worth noticing that the development work around the EttH concept continues as well. The next generation EttH is expected to offer ten times higher access bit rates than the current version. Table 5 lists some essential characteristics of today's data delivery techniques deployed in the cable networks. Notice that the downstream bit rate is given for an 8 MHz channel and the upstream bit rate for a 60 MHz band. In practice the downstream occupies several 8 MHz bands and the total bit rate surpasses that of the upstream direction.

Table 5. Summary of cable network data delivering solutions.

	DOCSIS 1.0	DOCSIS 1.1	DOCSIS 2.0	ETTH	NBAN
Bit rates					
Upstream	184 Mbit/s [1)]	184 Mbit/s [1)]	276 Mbit/s [3)]	392 Mbit/s [4)]	1100+cable
Downstream	56 Mbit/s [2)]	56 Mbit/s [2)]	56 Mbit/s [2)]	56 Mbit/S [2)]	1100+cable
Priority classes	no	8	8	8	8
Security	BPI (DES)	BPI+	DES	Switched	N/A
ONU TX power adjustment	yes	yes	yes	no	no
Protection	no	no	no	no	no
FEC	yes	yes	yes	no	no

1) Theoretical maximum for euroDocsis (16QAM, 3.2 MHz/channel and 60 MHz total bandwidth)

2) Theoretical maximum for euroDocsis and ETTH (256QAM and 8 MHz channel bandwidth)

3) Theoretical maximum for SCDMA based euroDocsis with TCM (128QAM, 6.4 MHz/channel and 60 MHz total bandwidth)

4) Theoretical maximum for ETTH (256QAM, 8 MHz/channel and 60 MHz total bandwidth)

5. Roadmap of optical transport concepts

This chapter evaluates the feasibility and survivability of the optical transport concepts, presented in the previous chapters. The evaluation bases on the requirements that are presented in the next section.

5.1 Requirements for the future optical access network

In order to find the requirements for the future optical access networks, we need a vision of the future access services, applications and end-users' needs. Some work has been done to define the future directions for optical networking in an EU funded Information Society Technologies (IST) thematic network project, called OPTIMIST (Optical Technologies in Motion for the IST Programme) [36]. The results of the project have played an important role in defining the following definitions.

5.1.1 Network performance

Residential customers – If the customers are using TV-focused services such as high definition TV (HDTV), Video on Demand (VoD), picture in picture, broadcast TV, personal video recorder, TV/audio jukebox, picture/video exchange and interactive TV telephony, downstream bit rates up to 20 Mbit/s may be required. This is the case only if one television channel is delivered at a time. Provided that several simultaneous television channels are needed, a lot more bandwidth is required. If the customers are using PC-focused services, such as high speed Internet access, live TV on PC, VoD interactive games and picture/video exchange, downstream bit rates up to 5 Mbit/s may be required. To ensure service operability and data exchange in both the above user scenarios, the peak rates up to 2 Mbit/s are required in the upstream direction.

Business customers (small enterprises) – Potential services for small businesses include high-speed Internet access, virtual private networks (VPNs), LAN extensions, video conferencing and server based email. To enable these services up to 10 Mbit/s bit rate is required per user in both transfer directions.

Business customers (large enterprises) – When large enterprises use Storage Area Networks (SANs), leased lines or VPN services, they require symmetrical transport channels and the bandwidth requirement can go up to 10 Gbit/s. If the service supply is limited only to voice, video conferencing and Internet access, 1 Gbit/s access rate in both transfer directions might be enough.

Quality of Service (QoS) – Voice and video conferencing are two-way services requiring low end-to-end delays. For example, VoIP communication requires that the end-to-end delay does not exceed 150 ms (400 ms in international calls) [37]. The legacy networks have ways to guarantee low end-to-end delay, but the key method in packet networks is the packet differentiation.

Granularity – Granularity reflects the size of the smallest allocation unit of the network's transport capacity and in some networks it determines the minimum cycle time, i.e., the delay between successive transmission turns of a networking device. Small granularity is important for efficient service support, especially in the access networks. It can also help to obtain low delays and to increase utilisation of network's transport resources.

Availability – Component malfunctions or cable/fibre failures may result in link unavailability. Depending on the network requirements, network users may want to wait for the repairer to fix the problem or they may want their traffic to be directed over an alternative path without even knowing that anything happened. In the latter case, a network protection scheme needs to be implemented beforehand resulting in better network availability but usually at extra cost.

5.1.2 Network services

Triple play – The vision of a single network that provides converged voice, data and TV services is still vivid throughout the industry. Some has even argued that as soon as the fibre reaches homes, this could finally be possible. Considering only the required bandwidth, this triple play might already be possible. However, some issues need further effort to be publicly agreed and legislated, like the following items.

Open access – Open access is the key to enable future network service models. The idea behind the open access is to give all service providers a way to use the existing infrastructure in accessing the end-users. This requires Service Level Agreements (SLAs) between the network operators and service providers and it is usually not prevented by the underlying transport technique. Advances in this matter can be seen continually.

Virtual path provisioning – The demand for virtual network connections, such as Virtual Private Networks (VPNs), is rising and networks should be capable of establishing, maintaining and terminating these connections in short time periods and in different situations. One challenge is to sustain connections in mobile networking. Virtual connections can also be used for switching, which offer a faster way to route traffic between two sites than IP or Ethernet based routing.

Security – Network security is a special concern to all of us. How to prevent possible misuse and still allow enough freedom is something that network designers need to consider beforehand. The security features must allow privacy and sufficient bandwidth at all times.

Scalability – The future networks should support remote and dynamic reconfiguration in order to respond efficiently to the varying demand for network resources. Bandwidth on demand (BoD) is an example of services that cause dynamic variation of network resources. Furthermore, the structure and design of a network should allow ease of upgrades and scalability to respond to changes in the number of network connections.

5.1.3 Cost-efficiency

Network components – The major part of the access network cost is tied to the physical network connections and their installation. Network components, such as concentrators and switches, may also have an outstanding contribution to the total network cost. Installation cost at the end-users premises also plays an important role when implementing new services. To keep the networking costs on a reasonable level, the future network components should be cheap, long lasting and easy to install. Additionally, the network and component complexity as well as the need for power, cooling and physical room should be minimised.

Ease of maintenance – Maintenance need of the network components should be minimised and the required maintenance operations, such as control, monitoring and provisioning, should be possible through remote configuration and automation. Furthermore, the networks should support plug-and-play capability.

Adaptability – Network environment tends to change in the course of time and it is more cost-effective to adapt to these changes within the existing infrastructure than to build a new network. Even re-use of at least some of the older equipment and network parts can result in cost savings. Network providers can easily follow this type of “pay as you grow” -guideline, if the network update scenario is designed in advance.

5.1.4 Network convergence

Heterogeneous networking – Network convergence bases on Internet Protocol (IP) and means that networks deploying different transport technologies will work together. In order for the various networks to interoperate properly a number of technical questions have to be solved. These include for example seamless roaming, vertical handover and micro-mobility [38]. The transport network connecting the various sites of the mobile networks should be able to support heterogeneous networking.

Interoperability – The advent of new and network independent services will strengthen the need for the interoperability. This is partly a result of mobile revolution, which is forcing us to think differently. A key technical issue is how to do fast handover between different wireless technologies. Another problem is related to the layering and signalling overhead in the circuit-based systems. To allow efficient interoperability solutions, the underlying transport technique should support packet as well as circuit switched connections.

Packet transport capability – Some has argued that in the future, a converged network will transport all traffic in IP packets (preferably IPv6). The packet transport could provide the transparency needed to enable efficient mobile service handover between various transport technologies. Furthermore, there is a need to provide different services over a single network, and currently the packet-based transport seems to be the most suitable solution for that purpose.

5.2 Evaluation of passive optical network techniques

The PON techniques are striving for Mbit/s data rates. ITU-T's Draft Recommendation H.fsv-opreq [39] states that for a wide range of services FTTH should provide a minimum bandwidth of 10/2 Mbit/s (downstream/upstream). On the other hand, the FTTH council [40] has set its target to 100 Mbit/s data rate. As always, foreseeing the future is difficult and currently FTTH's main promotion is its scalability, implying that once the fibre is built to the home almost any data rate is possible.

5.2.1 Broadband passive optical network

The ITU-T series of recommendations for B-PON has been completed and the development of G-PON continues from there. Meanwhile B-PON is turning into a mature technique and new world-wide implementations are made continuously, especially in Asia and USA.

Performance – B-PON offers data rates up to 1.244 Gbit/s in the downstream and up to 622 Mbit/s in the upstream direction, covering the needs of residential users and small businesses. The ATM-based solution offers low delay and small granularity, so allocation of bandwidth for differentiated traffic and running the network at full load should not be a problem. B-PON also defines four standard protection schemes that utilise Automatic Protection System (APS) [1].

Services – Like ATM, B-PON transports legacy voice and other delay sensitive services very efficiently and does not introduce much overhead to the packet transport. ATM virtual paths and connections can be exploited in transport capacity provisioning.

Security communication is offered by applying methods that use secret key encryption, based on Advanced Encryption Standard (AES). These methods guarantee sufficient security for residential data connections. B-PON supports several line rate configurations for the upstream and downstream traffic and the maximum supported splitting ratio is 32, resulting in sufficient scalability.

Cost-efficiency – Due to the strict delay and performance requirements, the B-PON physical components have relatively high quality constraints, which naturally have an effect on the component prices. The prices of the optical components have been declining continuously and this will continue if the PON solutions are deployed widely. Additionally, B-PON supports remote maintenance and has some plug-and-play functionality.

Convergence – The adaptive ATM transport layer is supporting network convergence and packet based transport. However, the ATM adaptation layer is not as flexible as the GFP based solution and does not extend to the GFP capabilities.

5.2.2 Ethernet passive optical network

The E-PON standard has been ratified in summer 2004. The standard does not specify any algorithm for dynamic bandwidth assignment (DBA) but instead leaves this choice for the equipment manufacture. Some or simply one of the proposed DBA algorithms might eventually turn into a de Facto standard, but in the meanwhile manufacturers support several different algorithms. Moreover, efficient resource allocation requires more complex algorithms in E-PON than in G-PON or B-PON. This picture is based on the fact that B-PON and G-PON support packet fragmentation while E-PON does not. To have an efficient DBA algorithm, the sizes of the upstream packets need to be known by the OLT, before it can allocate grants for the ONUs. As this is a challenge for the manufacturers, E-PON’s timeslot allocation can also be managed more easily by allocating fixed timeslots for all ONUs. Utilisation of the transport capacity is lowered but E-PON manages with a very simple DBA algorithm.

Performance – Most of today’s residential data are carried in Ethernet packets, which is a major advantage for E-PON. E-PON provides adequate bandwidth for residential and small businesses, but the bandwidth demand of larger enterprises can only be partly covered with the current 1 Gbit/s standard. E-PON has the Ethernet-like flexibility with variable granularity (variable packet size) and priority queue based traffic differentiation, all optimised for packet based data transport. The variable size packet transport may result in fluctuating end-to-end delays, affecting the quality of service. However, with efficient DBA, the delays can be kept in reasonable limits. How E-PON operates in network exhaustion situations, depends also much on the implemented DBA algorithm. One disadvantage of E-PON is the 25 % line rate overhead resulting from the 8B10B block coding. E-PON has the best logical scalability but it does not specify any protection methods to be used.

Services – Like the packet based data services, Ethernet supports also transport of legacy voice services. Voice information is mapped into fixed size Ethernet packets, in a similar way as is done in ATM, but resulting in poorer efficiency [41]. The more favoured approach is VoIP, which is already in world-wide use. If the new Ethernet transport services fulfil expectations, efficient VLAN provisioning can be supported by E-PON as well. Ethernet has always been scalable, which also holds in the case of E-PON. Security of communication is based on data encryption in a similar way as in other PONs.

Cost-efficiency – In the E-PON development, cost-efficiency has been one of the key factors from the very beginning. The physical requirements of the optical components are not as strict as in the B-PON and G-PON systems and due to this some amount of efficiency, especially in the upstream direction, is lost. Hence, the E-PON components can be made cheaper. Additionally, E-PON follows Ethernet's plug-and-play functionality and remote maintenance. Ethernet uses OAM frames for management information and new management features are easy to implement.

Convergence – E-PON is totally based on Ethernet, which supports pure packet based transport. Since the entity carried inside the Ethernet frame is an IP packet, E-PON can be said to support heterogeneous networking as well.

5.2.3 Gigabit capable passive optical network

G-PON has been developed from B-PON to support higher bit rates, but due to different technical solutions, it is not backward compatible with B-PON. It supports legacy network services and could be used as an enhancement to or replacement of the SDH networks.

Performance – Like B-PON, G-PON supports several line rates for the upstream and downstream directions. Of the three PONs discussed, it offers the highest bit rate of 2.5Gbit/s for both transfer directions. It also supports legacy ATM and any packet-based transport. It even has an efficient Ethernet transport capability, i.e. some of the Ethernet overhead is extracted during the encapsulation process. Additionally, G-PON supports packet fragmentation, enabling efficient utilisation of transport media. QoS and protection schemes follow the same principles as in B-PON. G-PON provides adequate bandwidth and QoS for the residential customers and small businesses and some of the larger enterprise services can also be supported. With these metrics, G-PON provides the best performance of the three considered PONs.

Services – G-PON is planned to support efficiently all legacy, current and future services. This is enabled by the GEM adaptation method, which can be enhanced to support future technologies. In respect to scalability, G-PON overcomes E-PON with several line rate options and, especially, with the larger offered bandwidth. Security can be implemented with different encryption techniques, among which AES is the most advanced one. G-PON offers QoS in a similar way as B-PON and supports the same wavelength allocation standard as B-PON. As for the traffic provisioning, G-PON uses 12-bit port IDs as are used for the Ethernet VLAN and ATM virtual channel identification.

Cost-efficiency – In respect of cost, G-PON cannot compete with E-PON, due to the tighter physical requirements of the transport components. So the performance has its price. G-PON is the most complex of all the compared PONs bringing challenges to the maintenance. The remote maintenance follows the same standard as is used in SDH/SONET networks, already familiar to operators world-wide. With the support of B-PON transport, G-PON can be considered as an adaptive solution, supporting the "pay as you grow" guideline.

Convergence – G-PON has the best support of all the PONs for heterogeneous networking. The most important advantage of G-PON is the GFP based adaptation layer, which is capable of supporting any service whether it is packet or circuit oriented.

5.2.4 Wavelength division multiplexed passive optical network

WDM-PON offers ways to provide services over several wavelengths. High transport capacity is obtained by implementing multiple wavelength channels, each of which can be assigned, e.g., for certain services or for certain customers. The use of light paths results in remarkable benefits compared to conventional electrical transport, e.g., attenuation factor of fibre is 0.5 dB/km and that of copper cable about 30 dB/km. Furthermore, the wavelength converters are passive and low cost components and even cheaper solutions are continually being developed [42].

5.2.5 Super passive optical network

SuperPON, also known as Active Optical Network (AON), is a different optical networking approach, offering more flexibility and scalability for network planning. Active components enable the network reach or splitting ratios to be as high as necessary and no compromise, due to the lack of signal power, is needed. In SuperPON, the desired cost-efficiency can be obtained by using an optimum combination of active and passive optical components that implement several wavelengths. In this way, the best features of both approaches can be utilised in a single network. SuperPON's drawback is that active components are more expensive than the passive ones and they require powering and possibly cooling in the cabinet. A good point is that the high cost can be shared among a larger user population.

5.2.6 Conclusions

Currently, all the three surveyed PON solutions seem to provide efficient data transport capabilities for the future access networks and probably they all will be used at least to some extent. Which one to choose, depends mainly on the type of traffic to be carried. If one wants to support legacy services, the B-PON or G-PON systems might be the most convenient solutions. If only Ethernet services are provided, E-PON might be the solution. But clearly if legacy services and Ethernet transport should be supported, G-PON handles this combination most effectively. G-PON also offers the best performance, but E-PON is the most cost-efficient one. The expected low cost is the reason why the industry seems to have great expectations on E-PON and the other two concepts are not so eagerly promoted. In publicity, E-PON has a major lead, because its marketing and promotion has been active already from the beginning.

5.3 Evaluation of point-to-point techniques

5.3.1 Plesiochronous and synchronous digital hierarchies

The PDH technique as such is designed for legacy voice transport and cannot be considered as survivable concept concerning the requirements stated earlier. The same conclusion can be made for the legacy SDH, but with different justification. The legacy SDH supports packet based data transport by applying ATM or Point-to-Point protocol (PPP) encapsulation. These result in relatively high overhead, but the main reason for its lack of survivability is the inefficiency of supporting data services, i.e. bandwidth allocation and flexibility. The next-generation SDH introduces improvements that make it a respectable competitor on the data transport services' market and thus the following discussion focuses only on the next-generation SDH.

Performance – The next-generation SDH provides the necessary capacity for the small businesses and even for some large enterprises by employing point-to-point links. The SDH technique supports only symmetrical connections and asymmetric residential connections can be supported efficiently only by using hybrid solutions (e.g. SDH supplemented with PON or xDSL). SDH offers efficient protection capabilities having the restoration delay within 50 ms, resulting in high availability. Allocation of the network resources cannot be done as easily as is done by VLAN tagging in Ethernet, but adequate allocation capabilities can be provided.

Services – The next-generation SDH offers almost Ethernet like granularity by deploying the virtual concatenation and link capacity adjustment scheme, supporting remote provisioning and scalable bandwidth allocation. Security of communication is not a problem, because the SDH traffic is carried entirely in the operator's own network and manipulated by the operator's own equipment. The next-generation SDH can be applied as the core network technique in hybrid systems, providing transport services for example between B-PON, E-PON, and G-PON access networks.

Cost-efficiency – The next-generation SDH is still more expensive than the Ethernet technique, but offers an advanced adaptation layer, capable of supporting any service. The multi-service support added with the capability of transporting native services is a definitive advantage of the next-generation SDH. The legacy SDH services can be carried as such in the next-generation SDH networks thus giving more time for the conventional networks and allowing gradual network upgrades without affecting the existing services.

5.3.2 Point-to-point Ethernet

Performance – The point-to-point Ethernet offers enough bandwidth for large enterprises and it can also be considered for small businesses. For residential customers, it might be too expensive, if the given bandwidth is not shared between several homes.

Services – Ethernet supports packet based services and protection capabilities are supplied only for the Resilient Packet Ring (RPR) networks. Furthermore, Ethernet offers switching and bandwidth assignment capabilities for network resource provisioning.

Cost-efficiency – The Ethernet technique has less strict jitter and power level constraints, so the Ethernet components can be made cheaper than the OTN or SDH components. The Ethernet devices are not as complex as those of SDH and OTN, resulting in lower efficiency and network utilisation.

Convergence – Ethernet is a packet based transport technique and supports IP centric network convergence.

5.3.3 Optical transport network

Performance – OTN cannot be considered for residential customers or small businesses, due to the high capacity and high cost. Some large enterprises might find it usable in the future.

Services – OTN offers wavelength management, strong forward error correction and tandem connection monitoring levels, transparent transport of client signals and switching capability [26]. It also has efficient protection and restoration capabilities.

Cost-efficiency – OTN is designed for the management of multiple high-speed wavelength channels and thus requires complex and expensive equipment.

Convergence – OTN supports heterogeneous networking and interoperability of different sorts of network. OTN is capable of carrying various client signals that are based on different transport technologies, e.g., ATM, Ethernet and IP.

5.3.4 Conclusions

The point-to-point techniques can be used efficiently in providing symmetrical high-speed connections for large enterprises. However, these techniques cannot be considered for residential users, due to the poor provisioning capabilities and high cost. Small businesses might consider the point-to-point Ethernet connections, if the cost-to-performance ration is competent. On the whole, the point-to-point techniques are best suited for the core network connections. Of the three discussed techniques, Ethernet seems to have the cheapest components and OTN provides the most advanced services.

5.4 Evaluation of access techniques

5.4.1 Cable television access

Performance – Cable TV networks have a limited frequency band for the upstream direction, total of 60 MHz in Europe and 37 MHz in USA [43]. Part of this band is also responsive to disturbances caused by normal household appliances. The disturbances prevent the use of efficient modulation techniques, resulting in low upstream data rates. In DOCSIS 2.0 this has been addressed with advanced Synchronous Code Division Multiple Access (SCDMA) and TDMA techniques [44], giving approximately three times the upstream data rate available in DOCSIS 1.1. (see Table 5). In the Ethernet-to-the-Home (EttH) approach, the end-amplifier separates the subscriber network from the rest of the cable network (see Fig. 17), thus preventing the disturbances from spreading all over the network. The disturbance free transport, enables almost 1.5 times the theoretical data rate of DOCSIS 2.0 [34]. EttH provides the customers also with a standard 10 Mbit/s Ethernet wall outlet. The Next-generation Broadband Access Network (NBAN) is not widely used and due to its expensive realisation it cannot be considered as the mainstream technique.

The number of customers connected to a cable segment has a major impact on the performance of a cable network system. The lower the number of customers per segment, the large is the bandwidth per user. The use of very small segments enables sufficient bandwidth even in the DOCSIS 1.x. systems. If very small segments are not possible, residential and small business users can obtain more bandwidth by adopting DOCSIS 2.0 or EttH. Large enterprises can also choose the NBAN solution.

When a DOCSIS modem has data to send, it first enquires Cable Modem Termination System (CMTS) to allocate a transmission timeslot, or it can try to use open slots available for all modems. The conversation with CMTS takes time and may result in relatively long waiting times, limiting TCP efficiency [45]. DOCSIS 1.1 and 2.0 support priority based packet scheduling and security issues have been solved by using the specifically designed Baseline Privacy Interface (BPI) concept along with Data Encryption Standard (DES). EttH uses Ethernet switching allowing customers to receive only those frames that are addressed to them and separate encryption is not necessary. NBAN is a point-to-point system and security of communication is an inherent part of that solution.

Cost-efficiency – A lot of investment is tied to the cable network infrastructure and operators want to utilize that investment as thoroughly as possible. The network also implements a number of amplifiers, requiring external power. The network devices are relatively complex, supporting different frequencies and modulation techniques, and thus replacement of the existing devices with new ones is expensive. When the network is getting obsolete, one way to lower the upgrade cost would be to replace at least some part of the network with an optical one and avoid purchasing of an excessive number of expensive electronic devices. The EttH technique offers also the possibility to get rid of the end-user modem, which is a necessary device in the DOCSIS based systems.

Convergence – DOCSIS, EttH and NBAN all support Ethernet packet transport and comply with the IP based network convergence.

5.4.2 Wire line access

Performance – xDSLs provide usually asymmetric bandwidth, more for the downstream and less for the upstream. However, usable symmetrical bandwidth can be supported only for short distances and thus it is suitable for residential and small business users that reside close to the DSLAM. The xDSL techniques cannot offer the required bandwidth for larger enterprises.

The xDSL solutions support differentiated services by deploying Ethernet over ATM and ATM virtual channels are used for allocation of transport capacity. Since the DSLAMs direct data packets to the addressed links, security of communication is sustained and eavesdropping becomes very difficult.

Cost-efficiency – The costs to acquire the required equipment is left for the customer who needs to buy or rent a DSL modem. The twisted copper-pair wires are already installed to every home and the use of the xDSL services does not prevent the usage of the conventional telephone. DSLAMs and other network devises add the operator’s networking costs.

Convergence – Since xDSLs support Ethernet transport over ATM, they also comply with the IP based network convergence.

5.4.3 Wireless access

Performance – The third generation (3G) technologies, such as Universal Mobile Telecommunications System (UMTS), offer theoretically adequate bandwidth for the Internet- and low resolution TV services along with video conferencing. However, the number of users within the reach of a base station may be so high that the bandwidth per user is not adequate. Wireless LANs (WLANs) and systems alike that utilise high frequency bands are a solution to this problem. They support high access data rates, but due to the high frequency band the reach of a WLAN base station is short. Thus these systems are best suited for small area coverage, such as hotspots and cafeterias. Additionally, the WLAN technique can be considered an access solution for the residential users and small businesses.

In the wireless access, support of mobility comes first. In current standards (GSM, GPRS, UMTS), the mobility is provided through complex systems that are hard to manage. However, it has been anticipated that this situation will change in the coming years [38]. Another problem related to WLANs is billing, i.e., how to change customers for the use of the wireless access. One proposed solution is to exploit the GSM-based Subscriber Identity Module (SIM) card for identification and billing in the WLAN systems [47].

Cost-efficiency – As regards to the GSM, GPRS and UMTS, we can say that these complex systems cannot meet the cost-efficiency requirement [46]. A better solution would be a WLAN that supports Ethernet transport. However, it is difficult to offer similar functionality over Ethernet based WLAN as is available in the mobile networks.

Convergence – Interoperability between wireless technologies is becoming more important and it should be possible to switch between technologies without closing the ongoing connection or call. Currently, the signalling and complex systems make this type of performance impossible and therefore the network structure needs to be changed in the future. The handsets are also going to use more advanced techniques for finding the available network resources.

5.4.4 Conclusions

The frequency bandwidth that can be carried over copper wires has been continuously increasing, due to the advances in digital signal processing and progress in the integrated circuit technologies. Today the twisted copper pair wires can be considered a serious media in carrying broadband services to residential users. The extra capacity has mainly been obtained by harnessing higher frequencies, which cannot propagate as long distances as those utilised by the earlier applications. This is why the large bandwidth can be guaranteed only for relatively short distances.

The last mile techniques are mainly intended for carrying residential data between the home and core network and they serve this purpose quite well. The current and future access techniques provide quite good performance, but the problem is how to bring the devices closer to customers to support even larger bandwidth. One simple and relatively low cost solution is to use the PON network to carry high bandwidth signals closer to the customer and then distribute the signals by using wireless or electronic wire line access techniques. Such hybrid solutions could use efficient statistical multiplexing and the bandwidth could be managed in a very efficient way. It has been stated in [48] that the use of the xDSL techniques in delivering up to 26 Mbit/s bit rate per customer is cheaper than the use of FTTH technology.

5.5 Summary

The future access network should be capable of carrying high bit rates, up to 100 Mbit/s downstream and at least 10 Mbit/s upstream, to support the coming broadband services. An additional requirement is the support of QoS with low delay and bit rate guarantees thus allowing prioritization of the carried data traffic. The developed new solutions should be adaptable to enable support of legacy, current and new access network services, while allowing ease of updates, IP-based network convergence as well as cost-efficiency.

Of the introduced PON techniques BPON offers good performance with average cost, EPON fair performance with affordable cost and GPON premium performance with the highest cost. Point-to-point solutions, such as PDH, SDH, Next-generation SDH, Ethernet and OTN, are capable of offering high bit rates and low delay, but are considered expensive solutions.

The electronic wire line and wireless access solutions do not introduce as high bit rates as the optical ones. However, if the transmission distance is short, they can support relatively high bit rates. In CATV networks, data delivery is based on the DOCSIS standard that offers almost unlimited downstream capacity, but has serious limitations in the upstream direction. Improvements have been introduced in DOCSIS 2.0 and more is to be expected when DOCSIS 3.0 will be announced. An alternative solution to exploit the CATV network and obtain more bandwidth for data transport is the EttH concept.

The various xDSL solutions exploit the twisted copper pairs and are capable of carrying high bit rates only for short distances. As for the wireless solutions, WLANs and other similar systems support relatively high access bit rates. However, the access rates are shared by a number of users leaving moderate bit rates per user. The access bit rates of the mobile telephone networks are even more moderate. Nonetheless, direct optical access to the various terminals is rare and hybrid solutions that implement PONs in the core and metro networks and electronic solutions in the terminal device access are foreseen to be the most optimal ones.

6. Virtual private network service provisioning

VPNs have become a lucrative business for network operators, which provide their customers with secure transport paths to connect separate LAN sites together. Establishment of these paths through the operator's network is referred to as VPN provisioning. Market forecasts show that VPN services are becoming more popular and the current mainstream transport systems do not meet the latest VPN service provisioning requirements [49]. This has resulted in efforts to find new methods to offer up-to-date VPN services. Since it has been estimated that over 90 percent of the IP traffic originates from Ethernet-LANs [50], we focus on the Ethernet based VPN services but discuss briefly about the other VPN solutions as well.

6.1 Establishment of virtual private networks

A VPN can be defined as restricted communication between a set of sites, making use of a backbone that is shared with other traffic not belonging to that communication [51]. Service providers have been looking for advanced ways to provide VPN services to enterprise customers for some time. They combine requirements such as efficient use of the packet-switched core network, large amount of automation in the creation and management of VPNs and ability to offer different services over the same infrastructure.

The VPN approaches are classified according to the management responsibility, resulting in customer-managed and provider-provisioned approaches [51] (see Figure 19). The standardisation has focused on the latter approach, which is further classified based on the location of the VPN-specific equipment. The division is made between customer edge (CE)-based VPNs and provider edge (PE)-based VPNs. The PE-based VPNs are also known as network based VPNs and they have been further classified to layer-1 VPNs (L1VPNs), layer-2 VPNs (L2VPNs) and layer-3 VPNs (L3VPNs).

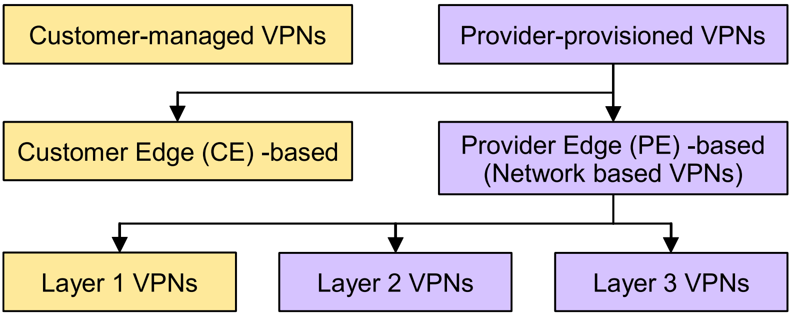

Figure 19. Virtual Private Network classification.

6.1.1 Layer-1 virtual private networks

ITU-T study group 13 has developed requirements and high level architectural models for L1VPNs, which have reached a high degree of maturity [52]. L1VPNs utilise and enhance common control and management techniques from L2VPNs and L3VPNs, and apply them to the layer-1 network, creating VPN services over TDM and OTN. L1VPNs are however out of the scope of this document.

6.1.2 Layer-2 virtual private networks

The traditional layer-2 VPNs have been presented in the form of leased line VPNs and customer-premises-based secure VPNs. In the leased line VPNs, the customer sites are interconnected over manually provisioned static virtual channels through a separate layer-2 backbone network. In the customer premises-based VPNs, all the VPN functions are implemented in the customer equipment and the provider is only responsible for the connection between the customer sites. Technically, the traditional layer-2 services can be classified in the following way.

Ethernet LAN – The standard 802.1Q tag, carrying a VLAN ID, offers a simple way to separate traffic from different LANs. VLAN ID is a 12 bits long tag enabling support of 4094 separate LANs.

ATM virtual circuits – ATM has been the mainstream VPN provisioning technique for some time. Depending on the interface, there are either 24 or 28 bits in the ATM header to be used for virtual circuit identification. These bits are divided into two fields: 16 bits for the Virtual Channel Identifier (VCI) field and the rest 8 bits in User-to-Network Interface (UNI) and 12 bits in Network-to-Network Interface (NNI) for the Virtual Path Identifier (VPI) field. These give 256 UNI or 4096 NNI virtual paths and 65536 virtual channels inside each path to be used in the network.

Frame Relay – Frame Relay is also a widely used and mature technique for transparent transport overlay solutions. Frame Relay Data Link Connection Identifier (DLCI ID) provides selectable 10, 17 or 24 bits to be used for virtual path identification, supporting up to 17 million possible VLANs.

6.1.3 Layer-3 virtual private networks

Layer-3 VPNs are offered over Multi-Protocol Label Switching (MPLS) or IP networks, i.e. IP tunnelling over a packet-switched network (PSN), under the administration of one or a group of co-operating service providers. The L3VPN functionality is implemented in the provider edge devices and routed over VPN-unaware provider core devices (core IP routers, MPLS switches or label switching routers, LSRs) in VPN tunnels. Technically, layer-3 VPN services can be classified to the following approaches.

GRE-based VPNs – Generic Routing Encapsulation (GRE) technique is a method to encapsulate an IP packet inside another IP packet and in this way provide virtual tunnels over the network. For large-scale deployment of IP VPNs, the industry has gradually moved towards MPLS L3VPNs [53].

MPLS-based VPNs – MPLS encapsulation is a recently developed technique to equip any packet or frame with an MPLS label and route the packet across an MPLS network accordingly [54]. In this way, the efficient protection and restoration and good scalability of MPLS can be utilised in VPN provisioning.

IPsec-based VPNs – Secure IP (IPsec) is another technique to provide IP based VPN encapsulation. It has useful features, like strong end-to-end encryption, but it is not directly related to Ethernet VPNs and is therefore out of the scope of this document [49].

6.1.4 Issues in virtual private network provisioning

From the above presented VPN techniques, the ATM and Frame Relay layer-2 services dominate the revenues of the largest service providers [55]. However, these services are commonly offered over extensive dedicated L2 networks, with very expensive provisioning as well as configurations and management. On the other hand, they enable transparent transport between selected sites, leaving traffic management to customers. This might be important to enterprises willing to ensure that their traffic is secure and properly managed. Alternatively, it can also be considered as a shortcoming, because all customers do not want to hire separate IT-management staff to run their IT services.

Currently, the industry is addressing the complexity, hard management and high cost issues by developing Ethernet based layer-2 transport services. Ethernet has been used to implement LAN interconnections for some time, but the expansion of the VPN requirements has made the conventional VLAN and MAC solutions incompetent. The major problems faced include MAC address table explosion in the provider switches, limited VLAN ID space, isolation and interaction of the provider and customer control protocols, realisation of various traffic management functions to meet contracted SLAs and design of efficient OAM tools [50]. These problems are broadly referred to as the metro Ethernet scalability issues.

Layer-3 VPNs give more scalability and ease of provisioning by tunnelling IP packets over the IP or MPLS networks. MPLS, especially, offers excellent multiplexing capabilities, a large amount of automation and very good traffic engineering properties. The scalability of MPLS is also good, because there is no need to know the existence of other sites, and the enterprise edge routers need to communicate only with their neighbours. With the MPLS scheme, enterprises cannot control their own routing, which forces the service provider to participate and manage the customer’s IP addresses as is typically done when IP services are sold. This means that MPLS cannot be used in selling just network overlay L2VPN services.

6.2 Ethernet protocol extensions

The scalability issues in the Ethernet VLAN provisioning are addressed in the proposed Q-in-Q and MAC-in-MAC enhancements [50], [55], which allow multiple consecutive VLAN tags or MAC addresses to be inserted in an Ethernet frame. Also a new tag, called Virtual MAN (VMAN) tag, has been proposed to replace the Ethernet frame's VLAN tag. All these enhancements aim for enabling better scalability in the Ethernet networks.

Q-in-Q – Q-in-Q technique, a.k.a. stacked VLAN or VLAN stacking, is standardised in IEEE 802.1ad and commercial products are already available. The Q-in-Q concept manages VLAN IDs either as separate IDs, making a clear distinction between the provider and customer VLANs or combines the VIDs allowing the use of a larger VLAN space. Only the first scheme is backward compatible with the 802.1Q standard, which restricts the number of VLAN customers to 4094. Stacking of two VIDs enables each of the 4094 customers to implement up to 4094 virtual connections [56]. Figure 20 illustrates the Q-in-Q encapsulation and service VLAN tag information fields, i.e. Priority Code Point (PCP), Drop Eligible Indicator (DEI) and VLAN ID (VID) [89].

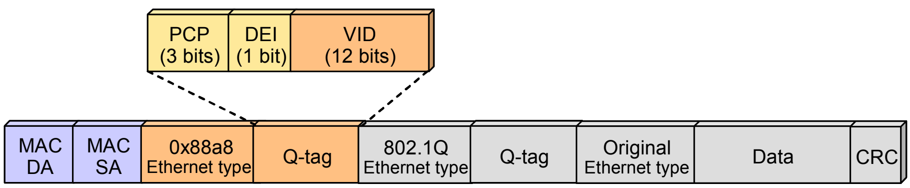

Figure 20. Q-in-Q encapsulation.

Virtual MAN (VMAN) tag – The VMAN solution introduces a new tag, known as the VMAN tag. The principle is similar to the VLAN tag, but this time the tag is larger. The initial VMAN proposal introduced 24 bits for the virtual path provisioning in metropolitan networks [56].

MAC-in-MAC – The MAC-in-MAC concept, a.k.a. MAC address stacking (MAS) with VLAN stacking, is similar to Q-in-Q. The basic idea in increasing scalability is to have separate customer and provider MAC (P-MAC) addresses (see Figure 21). This scheme enables subscriber control protocol transparency and service identification. It is also scalable, but introduces enlarged overhead [56].

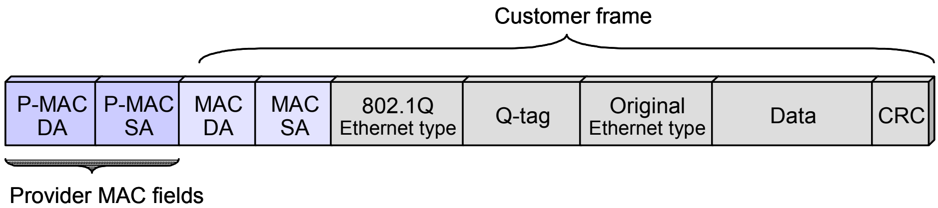

Figure 21. MAC-in-MAC encapsulation.

Ethernet frame header expansion - Currently, IEEE 802.3 Frame Expansion Study Group [57] is investigating expansions to the Ethernet frame. The expansions allow all or some of the previously defined protocol extensions and characteristics, such as Ethernet MPLS encapsulation, 802.1AE MACSec frame and 802.1ad tagged frame.

The Ethernet protocol extensions bring improvements to Ethernet's scalability. The Q-in-Q enables network layering, but is still restricted to 4094 VLAN customers. The MAC-in-MAC tackles the MAC address table explosion by avoiding huge MAC address entries in the core switches [56]. Both concepts introduce some extra transport overhead, which affects especially the delay sensitive services that use small packet sizes, e.g. VoIP and TDM over Ethernet. It is worth of noticing that not all of the proposed enhancements are compatible with the Ethernet standard, and extensions to the current standard are on their way [57].

6.3 Layer-2 virtual private networks over packet switched networks

There is a high level of interest in methods for delivering L2 services over Packet Switched Networks (PSNs). There are already standardisation efforts for carrying layer-2 traffic over the existing IP and MPLS networks. Internet Engineering Task Force (IETF) is working on the issue in the "Pseudo Wire Emulation Edge to Edge (PWE3)" [58] and "Layer-2 Virtual Private Networks (l2vpn)" [59] working groups. They present proposals for emulating Ethernet, ATM, SDH/SONET and Frame Relay circuits over PSN. These proposals are based on the transport of layer-2 encapsulated traffic over a network which offers end-to-end Pseudo Wire (PW) connections.

6.3.1 Pseudo wire connections

In the IETF proposals, VPN tunnels emulate the behaviour of a connection or a wire over a connectionless infrastructure and the tunnels are called Pseudo Wires (PWs) or packet leased-lines [60]. A PW is a connection between provider edge (PE) devices that connect two attachment circuits. These circuits can be Frame Relay DLCIs, ATM VPI/VCIs, Ethernet ports, VLANs, HDLC links, PPP connections on a physical interface, PPP sessions on a L2TPv3 (Layer-2 Tunnelling Protocol version 3) tunnel, MPLS LSPs, etc. [61]. PWs are two-way connections over the PSN as depicted in Figure 22. The connections can be set up by configuring them manually or by using signalling protocols, such as Border Gateway Protocol (BGP), LDP [63] or signalling capabilities of L2TPv3 [62]. PWs must be set up before the emulated circuit is established and torn down when the emulated circuit does no longer exist. It is possible to establish multiple PWs between end-points and then allocate these PWs for different sorts of traffic, or establish only one PW and use identifiers and switching to differentiate traffic.

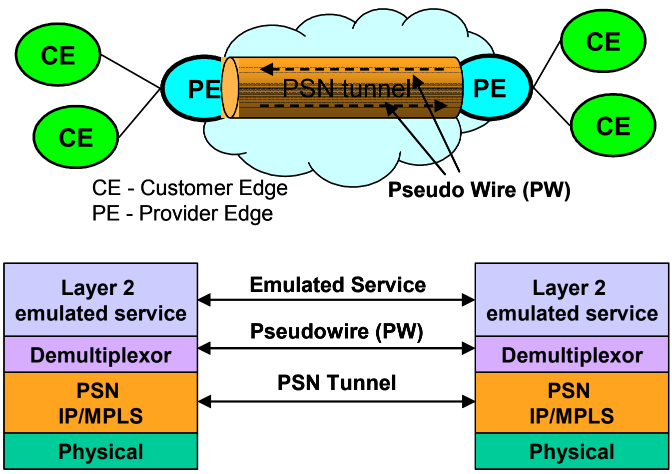

Figure 22. Pseudo Wire connections in a PSN tunnel.

When emulating the layer-2 service over the PSN network, the layer-2 payload is first equipped with a PW header, consisting of a multiplexer field, which is used to identify the particular PW on which the packet travels. To travel from a PW end-point to another PW end-point, the packet needs to go through a PSN tunnel and requires an additional PSN header for that purpose. Data encapsulation examples for PW emulation (PWE) over IP and MPLS are presented in Figure 23.

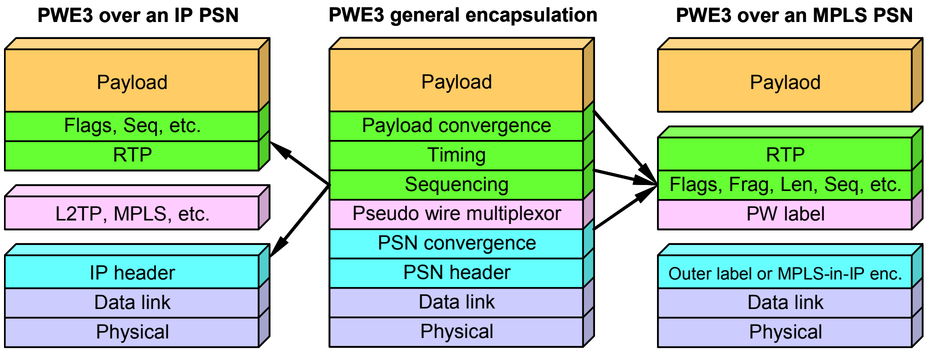

Figure 23. Pseudo Wire encapsulation.

The IETF specification does not exclude any PSN to be used as the transport layer, as long as it is capable of transporting PW encapsulation headers. L2TP is used to set up PWs in IP networks and LDP in MPLS networks [53]. L2TPv3 is an extension to L2TP and allows more flexibility and scalability in carrying other than PPP traffic. The MPLS L2 traffic encapsulation is commonly referred to "draft-Martini" encapsulation in reference to the author of the original Internet draft [64]. With draft-Martini encapsulation, PWs are constructed by building a pair of unidirectional MPLS virtual connections between the end-points, one for the outgoing traffic and another for the incoming traffic. The MPLS L2 encapsulation is currently defined for ATM, Ethernet, Frame Relay and SDH/SONET networks. These methods are further discussed in the following.

6.3.2 Ethernet over packet switched network

Ethernet over IP – Ethernet PWs over the IP network are set up as L2TPv3 sessions. Provisioning of an Ethernet port or a VLAN and its association with a PW triggers the establishment of a session. The type of a PW can be either an Ethernet port or an Ethernet VLAN, allowing a connection between two physical ports or Ethernet LANs. Each PW is associated with a PW ID that identifies the actual PW.

The entire Ethernet header, excluding the preamble, is encapsulated in L2TPv3, regardless of the presence of the 802.1Q tag. For the Ethernet port type of PW, the frames are transported between ports without modifications to the header.

VLAN tags can be manipulated in the Native Service Processing (NSP) functions after the frame has travelled through the PW.

Ethernet over MPLS – Ethernet PWs over an MPLS network are set up as MPLS virtual connections by using targeted LDP [64] ("draft Martini" encapsulation). The encapsulation is similar to the L2TPv3 encapsulation except that the port type of PW is called the raw mode PW and the VLAN type of PW is called the tagged mode PW. The addition of the MPLS header to the Ethernet frame is shown in Figure 24.

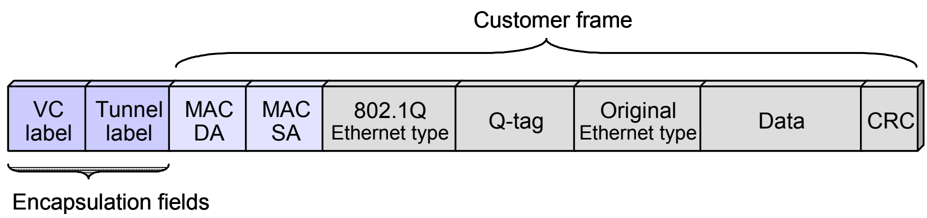

Figure 24. Ethernet MPLS layer-2 encapsulation.

6.3.3 ATM over packet switched network

ATM over IP – ATM PWs over an IP network are set up as L2TPv3 sessions [65] and ATM service payload can be transported in two modes: AAL5-SDU (ATM Adaptation Layer 5 - Service Data Unit) mode and cell mode. In the AAL5-SDU mode, each AAL5 virtual circuit is mapped to an L2TP session. AAL5 service data units are assembled without trailer or padding bytes. In the cell mode, ATM cells are transported over an L2TP session either as separate cells or as concatenated cells inserted into a single packet. The ATM cells are carried without Header Error Control (HEC) field and the amount of concatenated cells in a single packet is determined by the maximum transport unit size of the session.

ATM over MPLS – ATM PWs over an MPLS network are set up as MPLS virtual connections by targeted LDP ("draft Martini" encapsulation) [64] and the transport of ATM service payload can be based on two encapsulation methods: one-to-one and N-to-one mode. The only required mode is the N-to-one mode, which maps several ATM virtual connections or paths to one PW. The one-to-one mode maps one virtual connection to one PW. Two optional methods have also been defined for the transparent AAL5 encapsulation: the service data unit and payload data unit encapsulation.

The general format of the ATM encapsulation over PSN is presented in Figure 25. The PSN header depends on the underlying transport network and the pseudo wire headers are outlined in Figure 23. The ATM control word includes some flags and indication of the PW payload type. It is optional to the cell mode ATM transport.

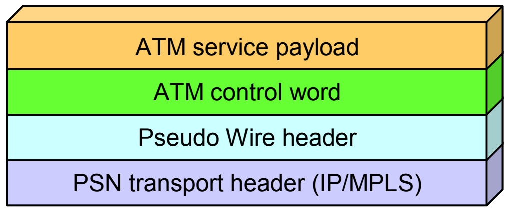

Figure 25. General format of ATM encapsulation over PSN.

6.3.4 TDM over packet switched network

TDM circuit emulation has been studied in IETF and two different approaches have been defined for TDM over PSN in [66]: structure-aware and structure-agnostic transport. The structure-aware transport is considered for TDM with any level of structure imposed by frame alignment and the structure-agnostic transport for unstructured TDM. The unstructured TDM implies that all bits are available for user data.

The structure-agnostic TDM over packet (SAToP) protocol describes a method for encapsulating TDM bit-streams (E1, T1, E3, T3) as pseudo wires over PSN [67]. The protocol completely disregards any structure that may possibly be imposed on these signals, in particular the structure imposed by standard TDM framing. This emulation suits for applications where provider's network devices have no need to interpret TDM data or to participate in the TDM signalling.

The structure-aware methods are classified into three categories: structure-locking [68], structure-indication [66] and structure-reassembly [66]. The structure-locking method requires each packet to begin at the start of a TDM structure, and to contain an entire structure or integral multiples thereof. The structure-indication allows packets to contain arbitrary fragments of the basic structures, but employs pointers to indicate where each structure begins.

The framework considering the SDH/SONET circuit emulation over packet (CEP) is based on the previously discussed TDM over PSN methods [69]. Figure 26 illustrates the CEP encapsulation method.

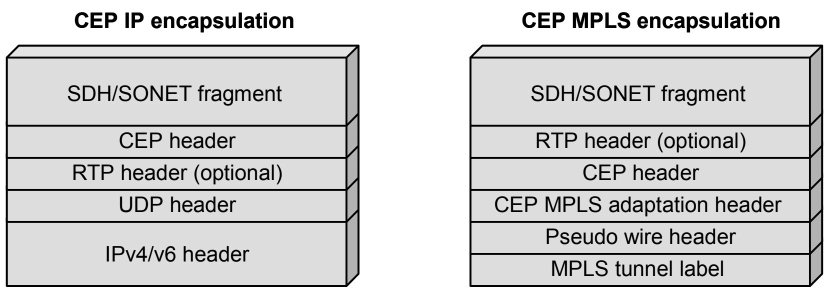

Figure 26. SDH/SONET circuit emulation over packet (CEP) encapsulation.

6.3.5 Everything over Ethernet

MPLS over Ethernet – The MPLS encapsulation scheme allows transport of a variety of different protocols. To exploit this in the Ethernet transport, IETF is defining a dedicated Ethernet frame type for MPLS and MPLS encapsulation method. The general principle of the MPLS over Ethernet encapsulation is presented in Figure 27.

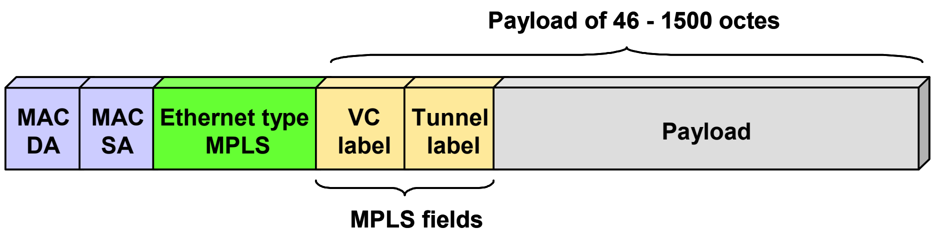

Figure 27. MPLS over Ethernet encapsulation.

L2TP tunnels over Ethernet – L2TP tunnels can be established over IP and this approach results in Ethernet/IP/L2TP tunnel transported traffic protocol stack.

Directly over Ethernet – The MPLS and IP over Ethernet techniques result in relatively large overhead. For this reason, several techniques have been studied to carry different sorts of traffic over the Ethernet transport networks. However, none of them is currently under standardisation. Dedicated protocols for the ATM over Ethernet transport have been investigated in [70], [71] and TDM over E-PON transport in [41].

6.3.6 Layer-2 virtual private network services

The IETF l3vpn group is defining framework for provider provisioned L2VPNs aiming at standardised protocols and interoperable L2VPNs [72]. The framework includes Virtual Private Wire Service (VPWS), Virtual Private LAN Service (VPLS) and IP-only LAN-like Service (IPLS). Service requirements are further investigated in [73].

Virtual Private Wire Service (VPWS) – The L2VPN VPWS defines a point-to-point service between CEs. This type of service has been available over the ATM and Frame-Relay backbones for some time, but VPWS defines a way to provide similar service over the IP and/or MPLS networks.

Virtual Private LAN Service (VPLS) – The L2VPN VPLS emulates a LAN that provides full learning and switching capabilities between different customer locations. VPLS reference model is illustrated in Figure 28, where both VPLS A and VPLS B are emulated LANs over a PSN.

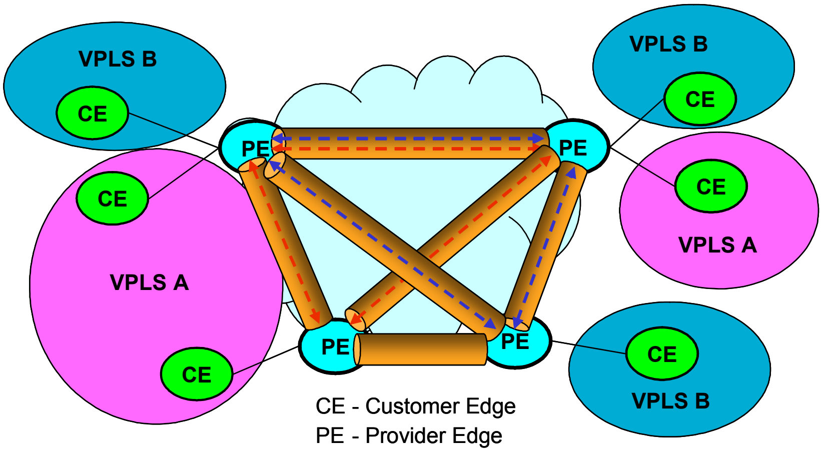

Figure 28. Virtual Private LAN Service reference model.

The VPLS LAN emulation is flexible, but it has all the limitations of the Ethernet protocol, including MAC addresses, learning, broadcast and flooding. Broadcast storms or loops in VPLS can be avoided only by forming a full mesh between all the PE devices participating in the VPLS. In small networks, this can be acceptable, but scalability problems can be expected in larger networks. The scalability problem can be dealt with Hierarchical VPLS (HVPLS), which allows scaling of VPLS by introducing Central Offices (CO) or HUBs in the network. These COs are connected in full mesh and several PEs can be connected to one CO [49], [53]. In this way, the number of COs can be kept low and the service stays scalable. The principle of HVPLS is illustrated in Figure 29.

A VPLS can be established and maintained by using Multi-protocol Border Gateway Protocol (MBGP) signalling, as described in [74]. BGP requires a separate control plane to distribute reachability information, but no separate control plane is required when pseudo wires are used to implement VPLS over MPLS [75]. In this case, the reachability information is obtained by standard learning bridge functions of the data plane.

MAC addresses must be associated with pseudo wires. Since static configuration is not possible, PEs should have the capability to learn MAC addresses dynamically and to forward and replicate packets across the physical ports and pseudo wires. No spanning protocol is required as the use of full-mesh and split-horizon forwarding is enough to establish loop free topology.

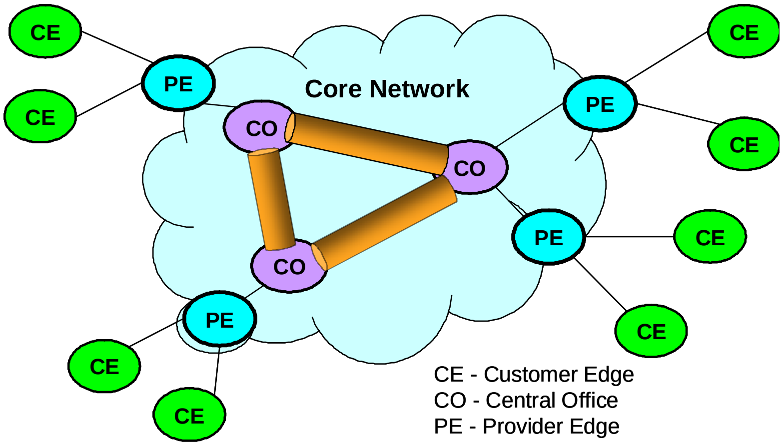

Figure 29. Hierarchical Virtual Private LAN Service.

IP-only LAN-like Service (IPLS) – The VPLS interconnections are LAN switches, however it is possible to provide the same service by IP hosts or IP routers with certain simplifications [76]. This simplified mode is called IPLS and the difference to VPLS is that MAC forwarding tables are maintained via signalling rather than via MAC learning procedures, and ARP messages are proxied rather than carried transparently. IPLS is a functional subset of VPLS, allowing it to run on certain hardware platforms that cannot support the full VPLS functionality.

6.3.7 Discussion

This section discussed several ways to supply L2VPN services over PSN. With the help of these services it is possible to provide a variety of existing data and voice services over the Ethernet network. These services are not limited to Ethernet as the transport technique, but any PSN technique capable of supporting pseudo wires can be used. MPLS based VPLS looks especially promising. Services can be provided over PSN with MBGP or with LDP over pseudo wires. MBGP requires a separate control plane to distribute reachability information, but standard learning bridge functions can be used with LDP, enabling simpler operation. Although the VPLS scales in theory, it has not been shown in practice whether it can scale to very large networks. Furthermore, the efficiency of the introduced solutions may suffer from large overhead. For example, establishment of a VPLS service over an Ethernet network by using MPLS based pseudo wires results in a minimum of 42 octets of overhead per transported MAC client. Establishment of a VPLS service over an Ethernet network by using L2TP pseudo wires produces even larger overhead as shown in Figure 30.

Ethernet does not have any mechanism that fits for service monitoring and therefore additional control plane intelligence is required [55]. The Ethernet VPLS scheme greatly benefits from the advanced features of MPLS, e.g. traffic engineering, rich OAM functionality, fast protection against node or link failures and bandwidth guarantees through appropriate signalling mechanisms [56].

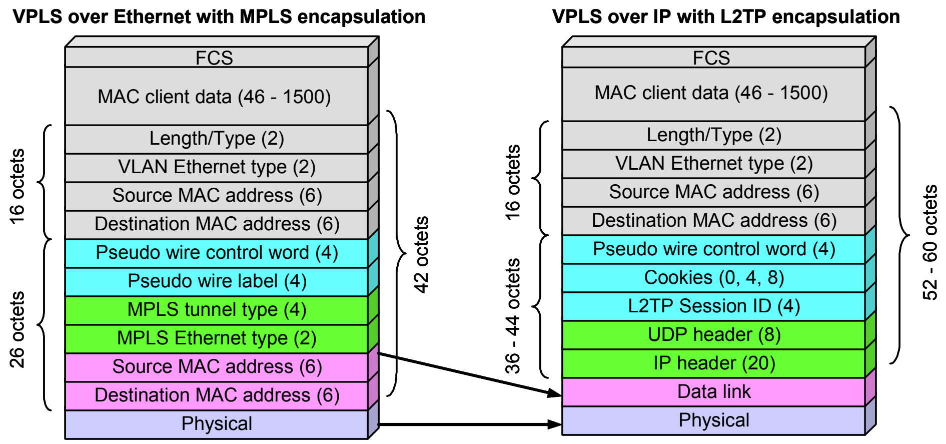

Figure 30. Frame structures and overhead when establishing VPLS service over Ethernet using MPLS or L2TP.

6.4 Layer-2 virtual private network provisioning in optical access technologies

In general, two types of provisioning are needed in the optical access. First, the optical link is identified by a technique-specific link ID or routing tag/identifier, and in the electrical part of the network, traffic is further allocated by using virtual path identifiers. All PONs have similar provisioning techniques, but the size of the used identifiers varies. The point-to-point technologies have their own specific provisioning methods. Technique specific provisioning IDs are further discussed in the following.

6.4.1 Next generation PDH and SDH/SONET

In the next-generation PDH and SDH/SONET, the logical point-to-point links are provisioned by using an 8-bit Channel ID (CID), located in the GFP point-to-point extension header [77]. Further provisioning is done by higher layer technologies, such as Ethernet or L3VPNs. In addition to the legacy PSTN transport, GFP offers an efficient transport method: the transparent mapped GFP (GFP-T) [78]. GFP-T maps 8B10B block-coded data into 64B65B code blocks, enabling native transport of original 8B10B coded signals over the SDH/SONET links, while occupying less bandwidth than the original signal. This method can be applied to several technologies including Ethernet and most of the storage area network (SAN) techniques [22].

6.4.2 Point-to-point Ethernet

In point-to-point (P2P) Ethernet, link end-points are identified by link device MAC addresses. As the links are physical ones, no separate link ID is needed. For virtual path provisioning, Ethernet uses a standard 12-bit VLAN ID and several non-standard enhancements. The Q-in-Q and MAC-in-MAC alternatives utilise stacking of multiple VLAN IDs or MAC addresses, supporting provisioning on multiple layers [50]. A new tag has been proposed for Ethernet giving a 24-bit VMAN ID for traffic provisioning in metropolitan area networks [79]. These techniques and others are currently being studied for inclusion to the Ethernet 802.3 frame extension [57].

6.4.3 Broadband passive optical network

A B-PON OLT implements ATM virtual path cross-connection functionality, allowing all the 12 bits of a virtual path identifier (VPI) to be used for virtual path provisioning in a B-PON tree. B-PON has an 8-bit PON ID, but only 64 optical links can be supported. The PON ID is used to address management information cells and data cells are identified by VPI. This is possible due to the broadcast type of transport to the downstream direction and allows efficient use of ATM multicast. The PON ID is not required in the upstream direction, since the OLT allocates the transmission timeslots and always knows which ONU is transmitting.

6.4.4 Ethernet passive optical network

The E-PON optical links are identified by a 15-bit Logical Link ID (LLID), allowing 32768 ONUs to be addressed. Virtual path provisioning can exploit all the former mentioned Ethernet standard techniques. Like the other Ethernet versions, E-PON does not support legacy services or other native transport, except Ethernet transport. E-PON ONUs receive only frames labelled with their specific LLIDs or broadcast ID. Multicasting utilises MAC layer multicast filtering, i.e., frames with a multicast MAC address are equipped with a specific LLID tag and broadcast to all ONUs, which then identify multicast frames and process them further.

6.4.5 Gigabit capable passive optical network

G-PON optical links are identified by an 8-bit ONU ID, allowing 254 different ONUs to be addressed. For the virtual path provisioning, G-PON uses a 12-bit GEM port ID and a B-PON based 12-bit ATM VPI. ONU IDs are used only for carrying control information and ONUs utilise port IDs or VPIs to identify data frames. However, GEM does not support multicast data transport. G-PON is fully compatible with B-PON, offering ease of update possibility for the B-PON networks. It also supports legacy PSTN and Ethernet transport in a similar way as the next-generation SDH/SONET, but does not provide GFP-T like transparent transport. The frame based Ethernet transport over the next-generation PDH, SDH/SONET or G-PON does not increase overhead, because part of the Ethernet frame, i.e., inter-frame gap, preamble and start of frame indicator, are replaced with an equal size GFP or GEM header. Removed fields are returned at the optical link termination point.

6.4.6 Discussion

The previously discussed identifiers are presented in Figure 31. Link level provisioning in the point-to-point concepts is based on link IDs, i.e., GFP CID and Ethernet MAC. Ethernet MAC has significant scalability over GFP CID, which limits the number of the next-generation PDH and SDH/SONET point-to-point links to 256. GFP's advantage is that it does not require as complex routing as the Ethernet MAC and does not introduce as much overhead.

Link level provisioning in PONs is based on ONU IDs. In B-PON and G-PON, the ONU ID is mainly used to distribute management information between OLT and ONUs and virtual path identifiers are used for data identification. In E-PON, ONU ID is used for unicast identification and a multicast is identified by a MAC multicast address.

Technology	Link ID	Size (b)	Virtual ID	Size (b)
Next-generation SDH	GFP CID	8		
P2P Ethernet	MAC		VLAN ID	12
BPON	PON ID	8	VPI	12
EPON	LLID	15	VLAN ID	12
GPON	ONU ID	8	GEM Port ID	12

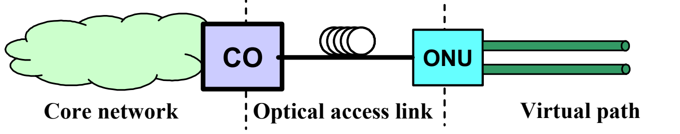

Figure 31. Optical access provisioning identifiers.

Originally E-PON was to support multiple LLIDs per ONU, which was later considered troublesome and currently only one LLID per ONU is supported. A more straightforward addressing scheme could be obtained by using LLID for the management operations and the standard Ethernet addresses for data identification.

The link ID address space varies from PON to PON. B-PON supports only 64 ONUs, which is not enough for large superPON solutions. This restriction is caused by the B-PON functionality, not by the 8-bit ID. G-PON has also an 8-bit address space for ONU identification and it uses that space more effectively than B-PON being able to address 253 separate ONUs. E-PON has a 15-bit address space for ONU identification, which looks overwhelming when considering the practical split ratios. Some of those ID bits could be used for other functionality.

Basically, all PON standards use 12-bits for virtual path provisioning in a PON tree. Technically, G-PON can double that number by exploiting the B-PON like ATM transport. E-PON with its new enhancements can even go beyond G-PON. The Q-in-Q technique and VMAN ID seem to be the most useful ones, due to their simplicity and usability. The MAC-in-MAC scheme is a complex one and may result in MAC address table explosion in routers. It also requires large amount of extra overhead.

Ethernet's triumphal march in residential networks has meant that almost all data access is Ethernet based. In order to survive, other transport techniques need to support Ethernet. As an example, the next-generation PDH, SDH/SONET, B-PON and G-PON are profiled only for transport service and are giving up access functionality to Ethernet. GFP has the most extensive support for Ethernet transport, due to its transparent transport mode. GEM together with ATM also supports Ethernet frame transport.

Multicasting is an important capability also in the optical access. B-PON supports standard ATM multicast and E-PON as well as the other Ethernet techniques supports standard Ethernet multicast. The current GFP and G-PON standards do not mention multicast. However, if they are used in connection with Ethernet, multicast addressing is not necessarily needed, due to Ethernet's efficient multicast support.

6.5 Summary

VPN provisioning in the optical access networks is based on mechanisms available in layer-2, i.e., link and virtual path identification. All covered PON concepts and P2P Ethernet have 12 bits for virtual path identification. Next-generation PDH and SDH/SONET do not support the path level provisioning. Link level provisioning is supported by all PONs. E-PON has the largest identifications address space and B-PON the smallest. P2P Ethernet does not support link level provisioning, while next-generation PDH and SDH/SONET use 8 bits for this purpose.

Although Ethernet is not the best solution in all respect, it has the most extensive support for virtual path identification. Considering Ethernet's strong position in local area networks, it can be seen as an evident transport concept for the optical access network. Due to this progress, other transport concepts are being developed to adapt to the Ethernet transport. In the future, more attention should be paid on issues such as automatic VPN provisioning and control of VPNs that are provisioned in multiple protocol layers.

7. Comparison of transport concepts

This chapter evaluates the performance of the most promising optical access techniques. According to the previous chapters, the most viable solutions seem to be E-PON, G-PON and EttH. These three concepts and the 100 Mbit/s point-to-point optical Ethernet are included in the evaluation. Since residential data networks are usually based on Ethernet, the analysis assumes that all information, composed of data, video and music, are transported over Ethernet.

7.1 Technical considerations

The evaluation of the chosen access techniques considers only the performance of the link layer, which is pure Ethernet in the EttH and 100 Mbit/s Ethernet case. E-PON uses modified Ethernet frames and G-PON encapsulates Ethernet traffic in GEM frames. The comparison assumes that the PON solutions implement 16 ONUs per network segment and the line rates are symmetrical, i.e. 1250 Mbit/s for E-PON and 1244.16 Mbit/s for G-PON both in the upstream and downstream directions. The corresponding nominal bit rates are 1000 Mbit/s for E-PON and 1244.16 Mbit/s for G-PON.

In the assumed constellation, E-PON and G-PON implement 17 optical terminating points (OTPs), one OLT and 16 ONUs. A 100 Mbit/s point-to-point optical Ethernet link implements two optical terminating points (OTPs), one at each end of the optical link. An EttH segment connects a head-end (HE) to an optical node (ON) with a 1 Gbit/s link in both transfer directions (see Figure 17). The optical node supports up to 8 Ethernet Node Modems (ENM) and each of these connects to a separate Ethernet POP Modem (EPMs) (refer to section 4.3.2 for more details of EttH) with a 100 Mbit/s virtual or physical fibre. Thus the total capacity of an EttH network segment is 800 Mbit/s. Provided that the ENM-to-EPM links are realised with physical fibres then the maximum number of OTPs in an EttH segment is 18, i.e. one at both ends of the HE-to-ON link and one at both ends of each ENM-to-EPM link. If the ENM-to-EPM links deploy coaxial cable then only two OTPs are needed. Table 6 summarises some characteristics of the evaluated access concepts.

Table 6. Summary of evaluated techniques.

Technique	Line rate (Mbit/s)	Nominal bit rate (Mbit/)s	OTPs	Encapsulation
100 Mbit/s Ethernet	125	100	2	Ethernet
EttH	modulated	800	18	Ethernet
E-PON	1250	1000	17	Ethernet
G-PON	1244	1244	17	GEM

When assessing the transport efficiency of the selected techniques, the overhead information involved with the data encapsulation has a crucial role. All the Ethernet based solutions have a similar frame structure from which the G-PON frame structure differs substantially. The E-PON frame structure was presented in section 2.5.2 and the G-PON frame structure in section 2.6.2. The standard Ethernet frame, deployed in 100 Mbit/s Ethernet and EttH, is illustrated in Figure 33. In the access network, Ethernet switches differentiate data flows by VLAN ID tags and therefore Ethernet frames are considered to be equipped with VLAN IDs. This is also the case when transporting Ethernet over G-PON.

The utilisation (ρ_{Eth}) of a 100 Mbit/s Ethernet and an EttH link can be calculated using (1), where l_{Eo} is the Ethernet frame overhead and l_{Ep} the Ethernet payload both given in bytes or bits.

$$\rho_{Eth} = \frac{l_{Ep}}{l_{Eo} + l_{Ep}} \tag{1}$$

The PON techniques share the transport link among a number of ONUs and require some management functions for efficient network usage. Also a registration period between programmable time intervals is used for registration of newly powered ONUs. However, this is not required when all ONUs are active and is therefore not considered in this analysis.

Successful transmission of data in the upstream direction entails support of processes like clock recovery and start of burst delimitation [80]. The laser *on-off* -times and timing drift tolerance should also be taken into consideration. All these contribute to the E-PON's guard band and G-PON's upstream physical layer overhead. The E-PON guard band (t_{GB}) consist of the laser *on*-time (t_{EON}), Automatic Gain Control (AGC) time (t_{AGC}), Clock and Data Recovery (CDR) time (t_{CDR}) and additional dead zone (t_{DZ}), which is needed to allow timing variability (see Figure 32). The G-PON upstream physical layer overhead (l_{plou}) consist of the preamble time (t_P), delimiter time (t_D) and guard time (t_G), which is the laser *on*-time (t_{GON}) added with timing uncertainty (t_{TU}).

The G-PON upstream physical layer overhead is fixed to be 192 bits (i.e., 154 ns) for the bit rate of 1.244 Gbit/s. This requirement is not easy to obtain and requires accurate transceiver components. G-PON employs also power level adjustment in fine-tuning the power levels of its transmitters. The E-PON guard band depends on the quality of the used components. E-PON's t_{AGC} and t_{CDR} are negotiable up to 400 ns and the laser *on-off* -time up to 512 ns.

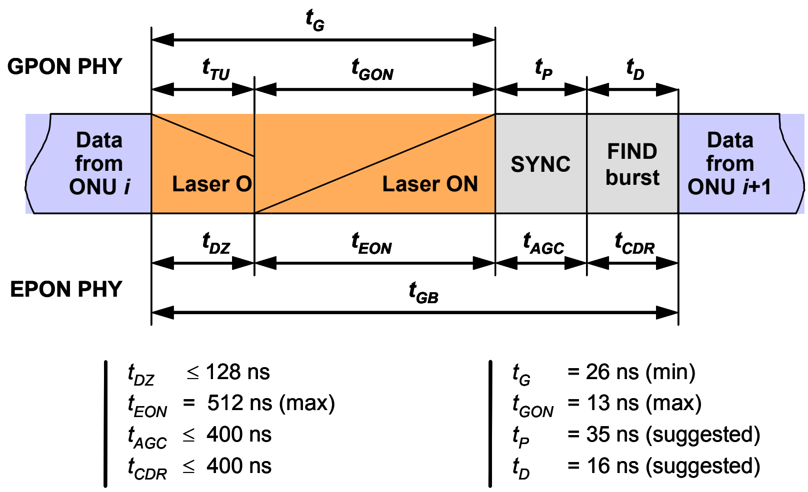

Figure 32. G-PON and E-PON upstream physical layer overhead.

The E-PON and G-PON standards do not explicitly specify any DBA algorithm to be used for the upstream timeslot allocation. Only a framework is defined for the whole DBA process and its implementation is left for the designers. Several DBA algorithms have been developed for E-PON [81], [82], [83] and algorithms suitable for G-PON should follow the principles outlined in [7] and [16].

In general, the same principles apply for E-PON and G-PON DBA. An efficient DBA algorithm allocates bandwidth in a fair manner also for the prioritized traffic and it uses the ONU queue reports to fully exploit the upstream timeslots. It should guarantee low access delay by adapting quickly to traffic changes and keeping the cycle time and polling interval in reasonable limits. ITU-T specifies the maximum access delay to be 1.5 ms, which can be guaranteed by adopting maximum polling interval of 500 μs [7]. E-PON's DBA algorithm does not allow complete utilisation of the upstream timeslots, but in the comparison it has been assumed that it can do so.

In an E-PON system, bandwidth allocation requires transport of special messages. ONUs send queue reports to the OLT to require bandwidth, and the OLT responds by sending bandwidth allocation messages to the ONUs. One control message is carried to and from each ONU during one cycle time. Utilization of an E-PON downstream link (ρ_{EPd}) is given in (2), where l_{EPo} is the E-PON frame overhead, l_{EPp} the E-PON payload, R_{EPbr} the nominal bit rate of an E-PON link, N_{ONU} the number of ONUs in a network segment, l_{cm} the length of the control message and t_{ct} the cycle time.

$$\rho_{EPd} = \frac{\frac{l_{EPp}}{l_{EPo} + l_{EPp}}\left[t_{ct} \times R_{EPbr} - N_{ONU} \times l_{cm}\right]}{t_{ct} \times R_{EPbr}} \tag{2}$$

Utilisation of an E-PON upstream link (ρ_{EPu}) is given in (3), where t_{GB} is the physical layer overhead, i.e., the guard band.

$$\rho_{EPu} = \frac{\frac{l_{EPp}}{l_{EPo} + l_{EPp}}\left[t_{ct} \times R_{EPbr} - N_{ONU}\left(l_{cm} + t_{GB} \times R_{EPbr}\right)\right]}{t_{ct} \times R_{EPbr}} \tag{3}$$

The G-PON encapsulation method (GEM) supports transparent transfer of the Ethernet frames [14] (see Figure 33). This means that the Inter Frame Gap (IFG) and Preamble fields of an Ethernet frame are extracted in the transmitting end and automatically added in the receiving end. TDM data can also be encapsulated into GEM frames by removing ingress control overhead and inserting, e.g. 32 bytes of an E1 frame into the GEM frame.

When GEM frames are deployed in transporting data, the control overhead of the downstream frames is 30 bytes and the upstream bandwidth-mapping field (US BW Map) carries a separate 8-byte record for each upstream bandwidth allocation. Thus the utilisation of a G-PON downstream link depends on the number of timeslot allocations assigned for an upstream frame. The most efficient way to transport data is to allocate the whole upstream frame for one ONU. However, this is not possible when supporting PSTN type of delay sensitive connections. PSTN requires consecutive frame transmissions every 125 µs, which means that in the worst case every ONU needs to access the upstream link during a single 125 µs period.

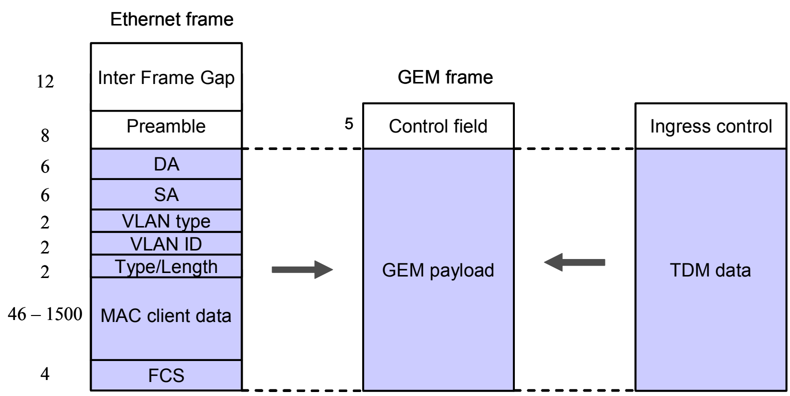

Figure 33. GEM encapsulation for Ethernet and TDM traffic.

Utilisation of a G-PON downstream link (ρ_{GPd}) can be calculated using (4), where l_{GEMo} is the GEM framing overhead for Ethernet payload, l_{Ep} is the length of Ethernet payload, t_{GPdf} is the duration of a G-PON downstream frame, R_{GPbr} is the nominal bit rate of a G-PON link, l_{GPdo} is the length of G-PON downstream frame overhead and l_{GPua} is the length of the upstream allocation overhead.

$$\rho_{GPd} = \frac{\frac{l_{Ep}}{l_{GEMo} + l_{Ep}} \left[t_{GPdf} \times R_{GPbr} - l_{GPdo} - l_{GPua} \times \left\lceil \frac{N_{ONU} \times t_{GPdf}}{t_{ct}} \right\rceil \right]}{t_{GPdf} \times R_{GPbr}} \quad (4)$$

Utilization (ρ_{GPu}) of a G-PON upstream link is given in (5), where l_{plou} is the length of physical layer overhead (incl. PLOAMu field) and $\overline{l_{dbru}}$ is the average number of DBRu fields in an upstream G-PON frame.

$$\rho_{GPu} = \frac{\frac{l_{Etp}}{l_{GEMfo} + l_{Etp}} \left[t_{GPdf} \times R_{GPbr} - \left\lceil \frac{N_{ONU} \times t_{GPdf}}{t_{ct}} \right\rceil \left(l_{plou} + \overline{l_{dbru}} \right) \right]}{t_{GPdf} \times R_{GPbr}} \tag{5}$$

Since an ONU can send several GEM frames during its time slot and only the first one of them carries the PLOu field and all frames carry the DBRu field, $\overline{l_{dbru}}$ is approximated by

$$\overline{l_{dbru}} = \frac{\left\lfloor \frac{t_{ct} \times R_{GPbr}}{N_{ONU}} - l_{plou} \right\rfloor}{l_{dbru} + l_{GEM}} \tag{6}$$

where $l_{GEM} = l_{GEMo} + l_{Ep}$ and l_{dbru} is the number of DBRu fields in a G-PON frame.

7.2 Broadcast video transport

One of the mainstream services in the access networks is CATV, where TV channels are broadcast using Moving Picture Experts Group 2 (MPEG-2) streams. Currently, most CATV channels are carried over a dedicated CATV network infrastructure, owned by a cable TV operator. This service area attracts other operators too and some of them are already providing TV channels over IP networks. The following investigates the performance of the selected techniques in transporting MPEG-2 video streams over Ethernet. The calculations are presented only for broadcast downstream traffic.

Video transport over IP networks is discussed in [84] and [85]. The most convenient way in carrying MPEG-2 video streams is to use User Datagram Protocol (UDP) over IP, which does not retransmit lost frames unlike Transmission Control Protocol (TCP). UDP does not guarantee packet delivery and the receiver needs to rely on the upper layer protocols, such as Real-time Transport Protocol (RTP), to detect packet losses and reorder the received frames. The resulting protocol stack to carry MPEG-2 encoded video over the Ethernet network is ETH/IP/UDP/RTP.

An MPEG-2 frame is 188 bytes long and thus seven MPEG-2 frames can be encapsulated into one Ethernet frame. The size of the Ethernet payload (l_{Ep}) when all contributing protocols (IP+UDP+RTP+7xMPEG-2) are considered is 1356 bytes. For illustrative calculations, we selected to use t_{GB}= 1440 ns (corresponding to 180 bytes) for the maximum laser on-off time, l_{dbru}=7 bytes for the reporting functionality in G-PON and t_{ct}=2 ms for the maximum G-PON cycle time with 16 ONUs. The rest of the parameters were R_{EPbr}=1000 Mbit/s, R_{GPbr}=1244.16 Mbit/s, l_{Eo}=42 bytes, l_{EPo}=42 bytes, l_{cm}=88 bytes, l_{GEMfo}=27 bytes, l_{plou}=15 bytes, t_{GPdf}=125μs, l_{GPdo}=30 bytes and l_{GPua}=16 bytes. The results are presented in Figure 34, where network utilisation and the number of supported video channels are shown as a function of the required channel bit rate.

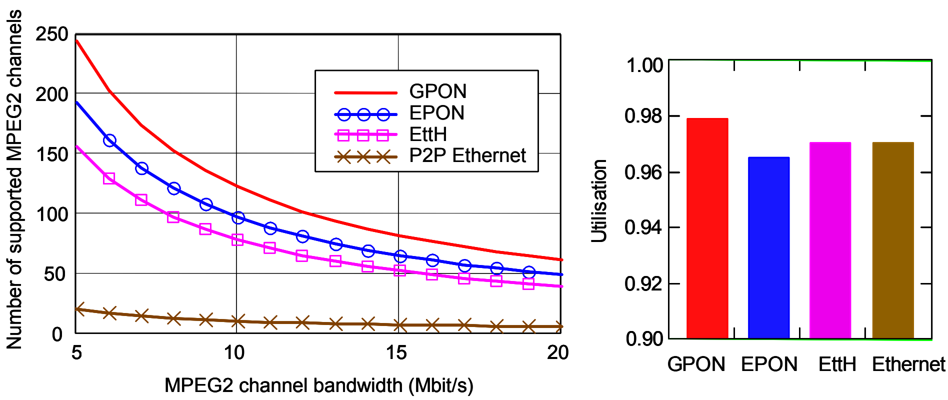

Figure 34. Number of supported MPEG-2 channels and link utilisation.

7.3 Voice transport

The voice services can be transported over IP networks by using VoIP and over PDH, SDH and ATM networks by using the legacy PCM technique. The PCM systems require network synchronisation and a coded voice sample of each voice connection is transmitted every 125 μs. VoIP techniques utilise more efficient compression techniques but result in longer delays due to the packet assembly, packet reordering and reassembly delays as well as longer network transmission delays [37]. The performance of VoIP depends highly on the packet assembly delay (usually 20 ms), because the VoIP packet is always assembled/reassembled with large overhead, resulting from IP/UDP/RTP protocol headers. A PCM codec operates much faster than a VoIP codec.

There are several VoIP codecs available, and two of them were selected for the evaluation. The first one, called G.729, transmits data at the rate of 8 kbit/s and introduces 10 ms packet assembly delay, indicating that a 10-byte payload is carried in every VoIP frame and a frame is sent every 10 ms. The other codec, called G.728, is recommended to be used in cable transport. Its transport rate is 16 kbit/s and the packet assembly delay is 625 µs. This means that VoIP frames with a 10-bit payload are sent every 625 µs.

Figure 35 gives the maximum number of VoIP connections supported by a single E-PON, G-PON, Ethernet and EttH link. The parameter values used in the calculations were the same as in chapter 7.2. Only the cycle time (t_{ct}) was selected to be 625µs in the case of G.728 and 10 ms in the case of G.729 allowing all ONUs to send VoIP frames in respective 625 µs and 10 ms intervals.

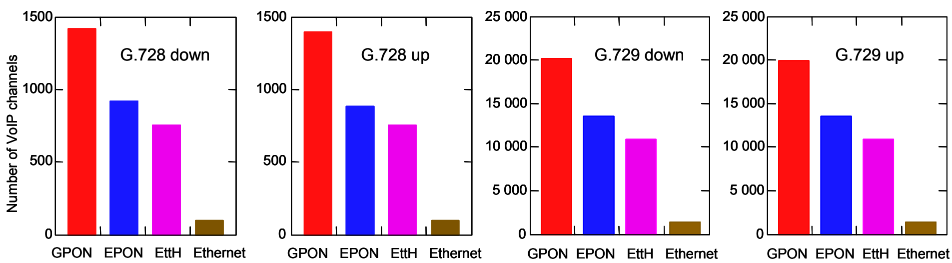

Figure 35. Number of supported VoIP connections.

7.4 Variable size data packets

In order to make realistic network performance evaluations, statistical information about the IP packet size distribution in the access network is required. The Cooperative Association for Internet Data Analysis (CAIDA) [86] provides information about Internet statistics. In their CoralReed project [87], measurements from National Aeronautics and Space Administration's (NASA) Ames Internet exchange (AIX) in Mountain View CA were made, and the resulting IP packet distributions are shown in Figure 36. The distribution of IP packet size is outlined for packet lengths from 0 to 1500 bytes. IP packet sizes larger than 1500 octets are not included, because they represent only 0,005 % of the total traffic [88]. The measured IP packet size distribution reflects the one found in the Internet and is applied in the following calculations.

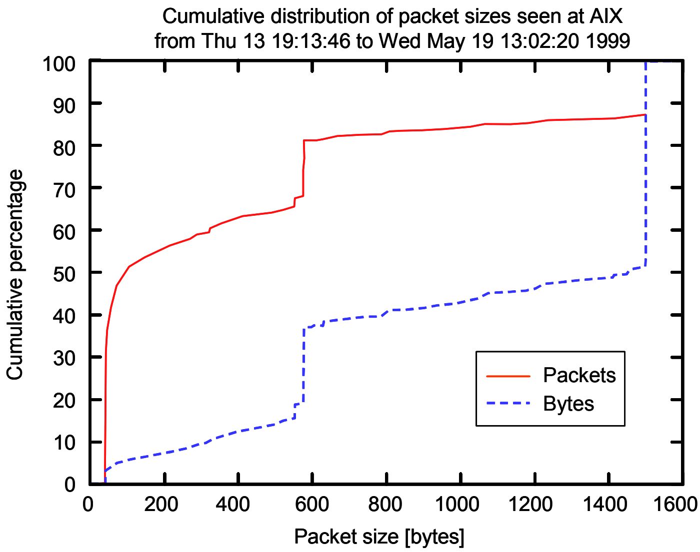

Figure 36. IP packet size distribution measured in CoralReef project [87].

From Figure 36 we can derive an easy-to-use estimation about the IP packet size distribution. We can find peaks close to packet size 44, 580 and 1500 octets. The increase of the cumulative percentage between these peaks is close to linear for which reason the intervals between the peaks can be estimated using the average packet sizes of 320 and 1040 bytes. The percentage of the selected IP packet size from the whole IP traffic can then be determined visually. The derived values are presented in Table 7.

Table 7. Estimated IP packet size distribution.

Percentage [%]	IP packet size [bytes]
50	44
16	320
15	580
6	1040
13	1500

The derived IP packet size distribution estimates the situation in which management and control traffic coexists with data traffic. Applying the obtained packet lengths to formulas (1)–(6) and setting the cycle time (t_{ct}) to 2 ms, we can calculate the transport channel utilisation in the case of variable length packets (Internet access traffic). The results for the upstream and downstream directions are shown in Figure 37.

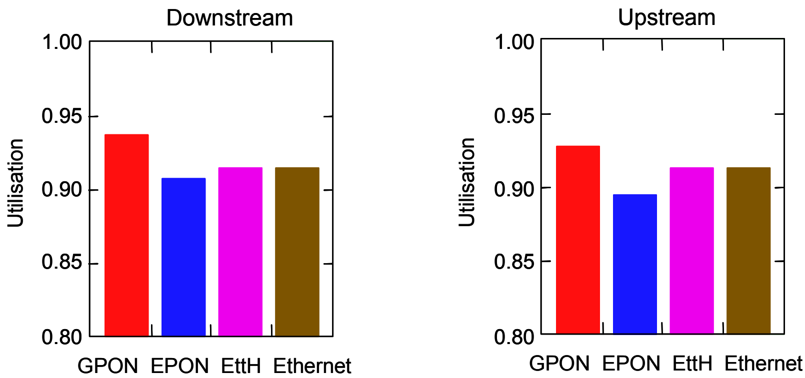

Figure 37. Link utilisation for variable size data packets.

7.5 Bandwidth per user and segmentation need

The cost of the access network has a significant contribution to the overall cost of a telecommunications network and thus it is justifiable to compare the access network cost of the various optical access techniques. The total cost is access technology dependent, but common to all techniques is that the cost depends strongly on the number of connected customers and on the offered bandwidth per customer. These two together contribute to the number of required network segments.

Figure 38 illustrates a typical PON network layout, showing that the access network is divided into network segments and each segment supports a number of customers. The price of a PON segment is usually much higher than that of an EttH or a 100 Mbit/s point-to-point Ethernet segment, but a PON segment support a much larger number of end-users than the two. Provided that the size of the population, penetration of the optical access, percentage of users accessing the network during a busy hour and the minimum transport capacity per user, are known, it is possible to calculate the required number of network segments for each access technique.

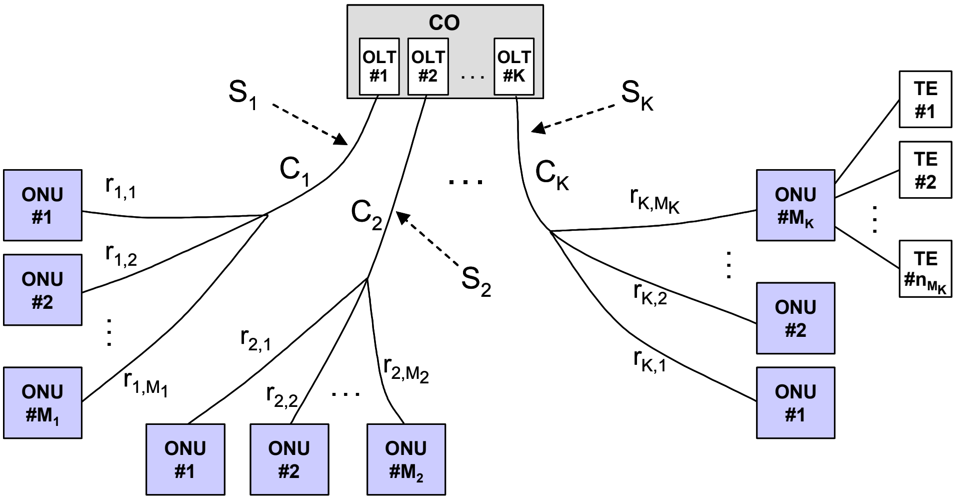

Figure 38. PON network layout.

Assume that the total transport capacity of segment S_k is C_k and utilization of the transport channel is ρ, then the total bit rate R_k available for user data (excluding line coding) in segment S_k is

$$R_k = \rho\, C_k. \tag{7}$$

The total bit rate of each segment is the sum of the traffic from all ONUs, connected to segment S_k, i.e.

$$R_k = \sum_{i=1}^{M_k} r_{k,i} \tag{8}$$

and the aggregate bit rate R_T of all the K segments is

$$R_T = \sum_{k=1}^{K} R_k \tag{9}$$

The number of users in segment S_k is N_k, which is the sum of users ($n_{k,i}$) connected to all ONUs in segment S_k, i.e.

$$N_k = \sum_{i=1}^{M_k} n_{k,i} \tag{10}$$

and the aggregate number N_T of users connected to all the K segments is

$$N_T = \sum_{k=1}^{K} N_k \tag{11}$$

If we assume that one end-user should have transport capacity of r_o then segment S_k is able to support up to

$$m_k = \frac{R_k}{r_o} \tag{12}$$

simultaneous users and all the K segments support up to

$$m_T = \sum_{k=1}^{K} m_k \tag{13}$$

simultaneous users.

Let's suppose that in the target area all segments offer the same transport capacity C, the size of the population is N and the "broadband access" take-rate is γ ($0 < \gamma \leq 1$). Provided that we also know the percentage β of the connected users that operate during a busy hour, we get the number of required segments K. From (7) and from the above assumptions we get that

$$R_T = K\rho C = \gamma\beta N r_o \tag{14}$$

and from this we can solve the number of segments to be

$$K = \frac{\gamma\beta N r_o}{\rho C} \tag{15}$$

Each segment serves $\gamma N/K$ customers that are connected to the ONUs of that segment.

Figure 39 gives an example showing how the number of simultaneous users per segment develops as a function of the offered bit rate per user. The various network parameters used in the calculations were the same as in the previous examples. The EttH system is scaled to 20 Mbit/s user bit rate, although the present version does not yet support access rates over 10 Mbit/s. As the figures show, G-PON is able to support the largest number of users at every offered bit rate. However, the difference diminishes as the offered bit rate increases.

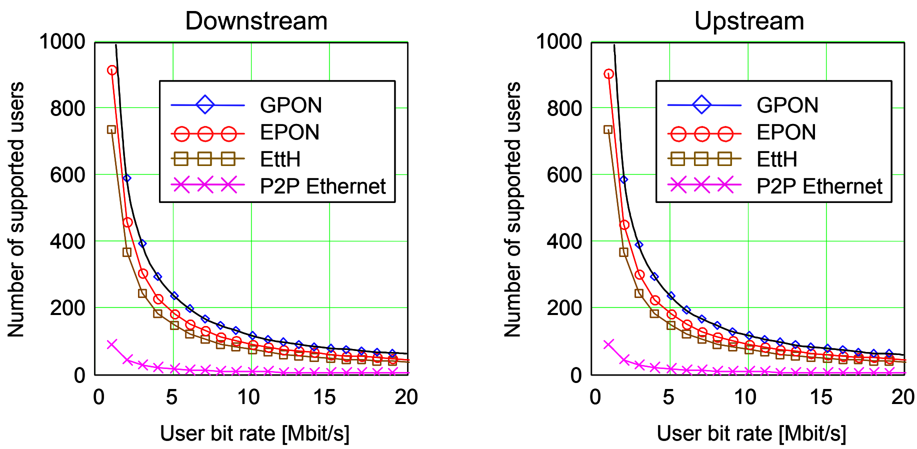

Figure 39. Number of simultaneous users as a function of access bit rate.

The number of required network segments to support a known customer population can be calculated as a function of the required user bit rate for given broadband access take rates when the percentage of connected users that operate simultaneously during a busy hour is known. As an example, Figure 40 illustrates how the number of segments develops for a population of 10 000 users as a function of the user bit rate in three take rate cases: 30 %, 50 % and 70 %. The curves are drawn for the downstream direction using the assumption that the percentage of simultaneous active users is 10 % and all those users send data continuously. The utilisation values were obtained from Figure 39. Notice that the calculations assumed that $\gamma N/K$ users can be connected to an ONU. Notice also that OAM traffic was not considered.

The graphs show that G-PON manages with the lowest number of network segments, but the difference between G-PON and E-PON is not an outstanding one. EttH requires roughly 30 % more network segments than G-PON and point-to-point Ethernet needs a substantially higher number of network segments than the other compared optical access concepts. Notice that EttH has been scaled to offer 100 Mbit/s user bit rates to allow linear comparison.

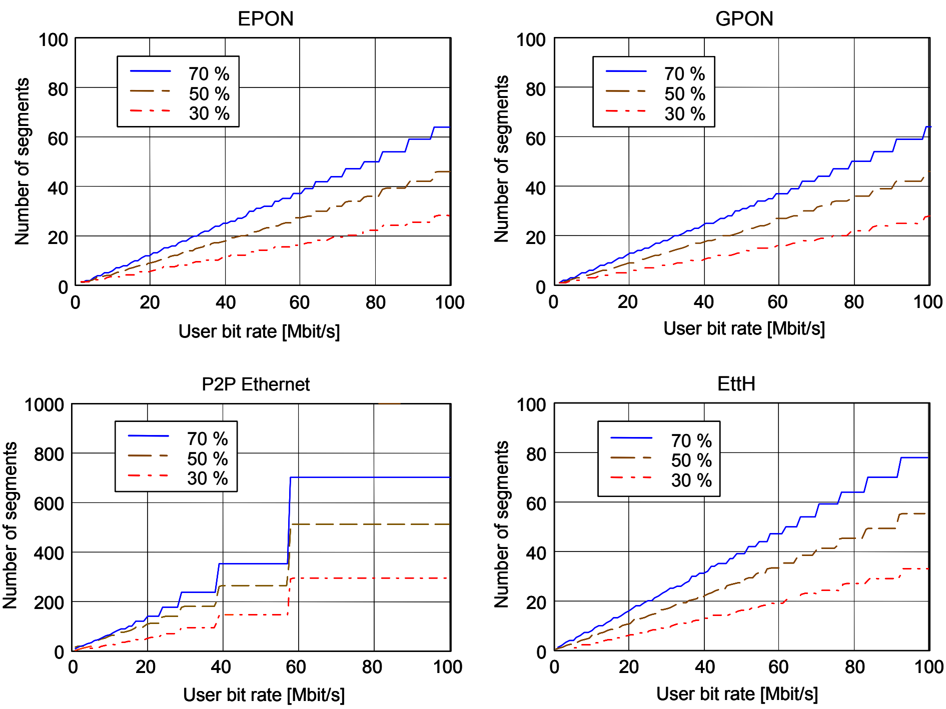

Figure 40. Number of segments required to support 10 000 households as a function of user bit rate.

7.6 Number of optical interfaces

When comparing the costs of different network solutions that cover the same area and population and use the same dimensioning parameters, relevant measures for the comparison are the number of network segments and the number of optical interfaces (i.e. ONUs and OLTs). Equation (15) can directly be used in evaluating the number of required segments. It includes several parameters and, by varying one parameter at a time and keeping the others fixed, we can study how *K* develops as a function of the selected parameter. The total number of optical interfaces, needed in a large network, can be calculated when knowing the number of ONUs and OLTs per segment. Provided that the average number of optical interfaces in a network segment is M_{ot}, then the total number (M_T) of the interfaces is given by

$$M_T = M_{ot} K \tag{16}$$

Figure 41 illustrates how the total number of optical interfaces develops in the previous example case as the function of the user access bit rate. Notice that the curves have been calculated for the theoretical case, when one ONU can connect to a large number of users corresponding to the FTTB or FTTC type of optical network layout. When the user access rate is low (less than 1 Mbit/s) the practical number of users connected to an ONU is clearly less than the theoretical number and thus the total number of network segments as well as the total number of optical interfaces is clearly larger than given by the formulas. If the user access rate is high (at least several Mbit/s per user) formulas (15) and (16) give adequate information to compare the access techniques.

As figures 40 and 41 show the 100 Mbit/s point-to-point Ethernet is the most expensive solution. EttH yields a clearly lower network cost, but is more expensive than E-PON and G-PON. G-PON manages slightly better than E-PON when focusing only on the number of required network segments and the number of optical interfaces. In practice, E-PON optical interfaces are cheaper than those of G-PON and the obtained difference in the number of segments and interfaces implies how much cheaper the E-PON interfaces should be to obtain the same system cost as G-PON.

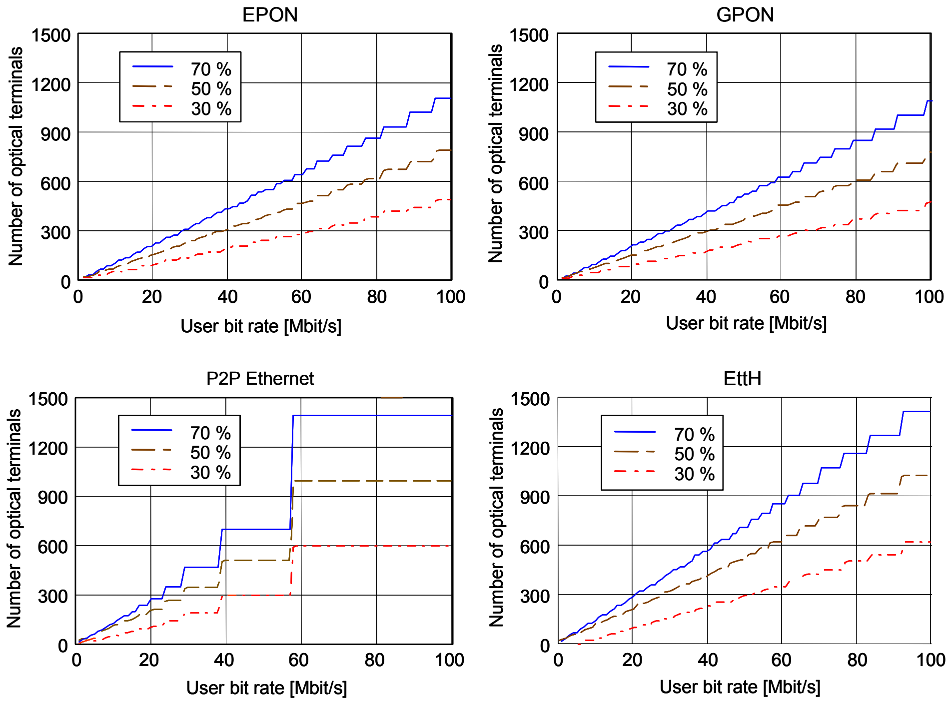

Figure 41. Total number of optical interfaces required to support 10 000 households in point-to-point Ethernet, EttH, E-PON and G-PON solutions.

7.7 Summary

This chapter compares transport efficiency of E-PON, G-PON, EttH and point-to-point Ethernet. The efficiency, a.k.a. utilization of the transport capacity, was further used to evaluate costs of the four transport concepts to build an optical access network for a known user population. The number of network segments and the number of optical interfaces were used as the cost measures. The utilization of the transport capacity was analysed on the IP traffic's point of view, illustrating how large portion of the link's capacity is actually used for carrying users' IP traffic. The analysis assumed that all the four concepts carry IP traffic in Ethernet frames and all additional information, added to the IP bit stream by Ethernet and other lower protocol layers, were considered as overhead. In addition to the framing overhead, loss of transport capacity, caused by exchange of transmission turns of the users' end devices, was considered.

The utilization was analysed for different sorts of traffic: short frame sizes (VoIP), long frame sizes (streaming video) and mixed traffic (reflecting real Internet traffic). G-PON turned out to be the most efficient transport concept of the four compared ones. EttH and point-to-point Ethernet share the next place surpassing E-PON slightly. When the number of supported data channels and number of supported users were analysed, G-PON was the obvious winner due to the best utilisation performance and the highest nominal bit rate. E-PON became second, since its nominal bit rate is higher than that of EttH and point-to-point Ethernet. The difference between E-PON and EttH was not a great one. Point-to-point Ethernet was clearly the worst solution as was expected.

When comparing the number of network segments and the number of optical interfaces, G-PON became first and E-PON took the second place. The difference between E-PON and G-PON was a marginal one. EttH took the third place requiring slightly more segments and optical interfaces than the two PONs. Point-to-point Ethernet was clearly the worst solution requiring more segments and optical interfaces than the other compared optical access concepts thus being also the most expensive alternative. Although G-PON manages with a lower number of network segment and optical interfaces in serving a known customer population, E-PON may still be a lower cost solution, because prices of the E-PON interfaces are lower that those of G-PON.

8. Concluding discussion

While new services, such as high-definition TV, requiring real broadband are maturing, the demand for optical access is strengthening. The required access bit rates start from few tens of Mbit/s per user, but the commonly anticipated target to provide real broadband is 100 Mbit/s per user. Today's most commonly implemented broadband access solutions are based on the various DSL techniques and cable modems. DSLs are capable of supporting few tens of Mbit/s access rates but only for short distances. The cable modems operate in CATV networks and the offered bit rate becomes very modest when the number of users per network segment is large. This is the case also for the arriving DOCSIS 3.0 concept. Wireless access solutions, such as WLANs, promise bit rates that approach the 100 Mbit/s limit, but the transport distance is very limited. When combining these techniques with the optical transport, clearly larger bandwidth can be carried longer distances up to the end-users.

The optical access has not yet been mushrooming, because the fibre installation cost is high and cost-efficient terminal solutions are still awaited. The conventional point-to-point solutions, e.g. SDH and point-to-point Ethernet, are able to offer adequate bandwidth, but are inherently high-cost solutions. New techniques, such as passive optical networks (PONs), have been developed to overcome the cost problem while maintaining high throughput of the optical fibres. This publication introduces the basics of PONs and surveys technical details of the best known concepts: B-PON, E-PON and G-PON.

In order to demonstrate the cost-efficiency of the PONs, a comparison is made between the E-PON, G-PON, point-to-point Ethernet and newly developed EttH concept. EttH has been developed to provide data services in CATV networks. It combines optical and electronic transport but can be implemented as an all optical solution corresponding to the PON solutions. The number of network segments and the number of optical interfaces that need to be implemented to serve a known geographical area and user population are evaluated by using the utilisation of the transport link capacity. These measures are further used in assessing the network cost relations of the compared access solutions.

The analysis showed that G-PON has the best utilisation and it also manages with the lowest number of network segments and optical interfaces in serving a known customer population with a known access bit rate requirement. EttH and point-to-point Ethernet have identical utilisation performance and manage slightly better than E-PON. However, E-PON offers higher nominal bit rate than these two and therefore E-PON manages with a lower number of network segments and optical interfaces. EttH comes next and point-to-point Ethernet clearly needs the highest number of network segments to serve the same number of customers than the other compared concepts.

The number of required network segments and the number of optical interfaces reflect directly the cost to build an access network. Although the calculations do not give concrete network cost for any of the studied access concepts, the calculations illustrate the cost relation of the different techniques. Based on the carried out comparisons, the PON solutions are obviously low cost solutions. The difference between E-PON and G-PON was a marginal one and due to E-PON's cheaper optical interfaces it may be the cheapest solution in practice.

Other aspects worth of considering when assessing survivability of an optical access concept are interoperabity, scalability to very large installations and the OAM complexity and cost. In view of the interoperability, the question is how well an optical access concept supports other transport concepts. G-PON includes inherent support for a number of other transport concepts while the Ethernet based concepts support only Ethernet based transport. On OAM point-of-view, the point-to-point systems are usually easiest to manage.

Scalability has many dimensions and when speaking about optical access the provisioning of transport capability becomes an important measure. All the studied systems support Ethernet type of virtual private networks (VPN) that can be used to provide network capacity effectively. The only problem is that the available address space for VPNs is limited in all introduced concepts. However, new approaches and extension to the VPN address space are being developed. On scalability point-of-view, one should also remember that in very large installations the point-to-point concepts may become unrealistic due the very large number of optical transceivers needed in the central office. When considering this physical limitation, it looks that PONs really will have a future.

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Passive Optical Networks
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Abstract

The optical access is gaining more interest as the demand for higher and higher bandwidth is getting stronger. The major drivers for larger bandwidth are the increasing processing power of user terminals and development of services that require substantially larger bandwidth than available in present day access networks. The prevailing access techniques, such as the digital subscribes line systems and cable modems, are capable of supporting up to few tens of Mbit/s access rates per user, but the transport distance is limited. The optical access offers significantly higher bit rates and longer transport distances.

The high cost has been the foremost factor that has been slowing down penetration of the optical access. A number of alternative transport concepts have been developed to tackle the cost problem as well as the technical ones. The passive optical network techniques are largely anticipated to be the most economical solutions. This publication surveys the state of the art of the optical access concentrating on explaining more thoroughly some of the best known concepts. The survey is complemented with an assessment of the viability of the most well known concepts. Finally network costs of some optical transport concepts are compared based on the utilisation of the transport channel capacity.

Keywords
passive optical networks, access networks, transport technology, virtual private networks, optical access technologies, transport concepts, Ethernet, cable networks, wireless access, packet switched networks

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