IEEE 802.3 Ethernet Working Group Communication

From: IEEE 802.3 Ethernet Working Group[1]

Subject: Industry Connections Feasibility Assessment for the Next Generation of EPON

CC: Paul Nikolich, Chair, IEEE 802 LMSC, <p.nikolich@ieee.org>

Date: 13th of March 2015

Approval: Agreed to at IEEE 802.3 Plenary meeting, Berlin, Germany, 12th of March 2015

In order to maintain an ongoing understanding of the industry trends, the IEEE 802.3 Next Generation Ethernet Passive Optical Network (NG-EPON) Ad Hoc was created. The scope of this ad hoc was to focus on gathering information that would enable an assessment of operator requirements, technical and economic feasibility, bandwidth needs for different types of applications served with EPON, including, but not limited to, residential and business customers.

The attached assessment is the culmination of the open industry assessment performed by the ad hoc in 2014 and the first quarter of 2015. It includes a summary of the data brought forward by individuals throughout the EPON ecosystem, including operators, system integrators, chip vendors, optics suppliers, and others. All contributed information is solely the perspective of the respective contributors. It should be noted that all submitted data should be considered a snapshot of the perceived requirements for next generation EPON at the time of submission.

Sincerely,

David Law

Chair, IEEE 802.3 Ethernet Working Group

<david_law@ieee.org>

[1] The views expressed in this document solely represents the position of the IEEE 802.3 Working Group, and do not necessarily represent a position of the IEEE, the IEEE Standards Association, or IEEE 802.

IEEE 802.3 Industry Connections Feasibility Assessment for the Next Generation of EPON

Prepared by the

IEEE 802.3 Ethernet Working Group

This is a report on the feasibility assessment for the Next Generation of Ethernet Passive Optical Network (EPON).

This report can be found at the following URL:
http://www.ieee802.org/3/ad_hoc/ngepon/ng_epon_report.pdf

Second printing: 19th March 2015

Participants

The following individuals were officers and members of the IEEE 802.3 working group when this report was approved. Individuals may have not voted, voted for approval, disapproval or abstained on this report.

David J. Law, *IEEE 802.3 Working Group Chair*
Adam Healey, *IEEE 802.3 Working Group Vice-Chair*
Pete Anslow, *IEEE 802.3 Working Group Secretary*
Steven B. Carlson, *IEEE 802.3 Working Group Executive Secretary*
Valerie Maguire, *IEEE 802.3 Working Group Treasurer*

Howard Frazier, *IEEE 802.3 Industry Connections NG-EPON Ad Hoc Chair, Phase 1*
Marek Hajduczenia, *IEEE 802.3 Industry Connections NG-EPON Ad Hoc Chair, Phase 2*
Kevin Noll, *IEEE 802.3 Industry Connections NG-EPON Ad Hoc Editor*

Ghani Abbas
John Abbott
David Abramson
Shadi Abughazaleh
Faisal Ahmad
Michel Allard
Dale Amason
J Michael Andrewartha
Pete Anslow
Oleksandr Babenko
Kwang-Hyun Baek
Amrik Bains
Koussalya Balasubramanian
Thananya Baldwin
Denis Beaudoin
Christian Beia
Yakov Belopolsky
Michael Bennett
Gary Bernstein
Vipul Bhatt
William Bliss
Brad Booth
Martin Bouda
Edward Boyd
David Brandt
Ralf-Peter Braun
Theodore Brillhart
Paul Brooks
Alan Brown
David Brown
Matthew Brown
Thomas Brown
Phillip Brownlee
Mark Bugg
Juan-Carlos Calderon
J. Martin Carroll
Clark Carty
Mandeep Chadha
David Chalupsky
Jacky Chang
Xin Chang
David Chen
Wheling Cheng
Ahmad Chini
Golam Choudhury
Peter Cibula
Christopher R. Cole
Keith Conroy
Eugene Dai
Shaoan Dai
John D'Ambrosia

Mike Darling
Yair Darshan
Piers Dawe
Fred Dawson
Ian Dedic
William Delveaux
John Dickinson
Chris Diminico
Thuyen Dinh
Curtis Donahue
Dan Dove
Mike Dudek
David Dwelley
Hesham Elbakoury
David Estes
John Ewen
Josef Faller
Arash Farhoodfar
Shahar Feldman
German Feyh
Alan Flatman
Richard Frosch
Michael Furlong
Andrew Gardner
Mike Gardner
Ali Ghiasi
Joel Goergen
Zhigang Gong
Steven Gorshe
James Graba
Robert Grow
Mark Gustlin
Bernie Hammond
Jeffrey Heath
Carl Herman
David Hess
Yasuo Hidaka
Riu Hirai
Thomas Hogenmueller
Brian Holden
Rita Horner
Bernd Horrmeyer
Victor Hou
Rui Hua
Liang-wei Huang
Scott Irwin
Kazuhiko Ishibe
Hideki Isono
Tom Issenhuth
Mitsuru Iwaoka
Kenneth Jackson
Jack Jewell
Wenbin Jiang
Andrew Jimenez
Chad Jones
Antony Joseph
Yasuaki Kawatsu
Michael Kelsen
Yong Kim
Jonathan King
Scott Kipp
Michael Klempa
Avi Kliger
Curtis Knittle
Shigeru Kobayashi
Keisuke Kojima
Paul Kolesar
Tom Kolze
Glen Kramer
Albert Kuo
Hans Lackner
Efstathios Larios
Wayne Larsen
Ryan Latchman
Mark Laubach
Greg Le Cheminant
Arthur Lee
Andre Lessard
David Lewis
Lei Li
Mike Peng Li
Shaohua Li
Thomas Lichtenegger
Ru Jian Lin
Robert Lingle
James liu
Zhenyu Liu
William Lo
Miklos Lukacs
Kent Lusted
Jeffery Maki
James Malkemus
Yonatan Malkiman
Edwin Mallette
Arthur Marris
Chris Mash
Kirsten Matheus
Erdem Matoglu
Laurence Matola
Brett Mcclellan
Thomas Mcdermott
John McDonough
Richard Mei
Richard Mellitz
Bryan Moffitt
Leo Montreuil
Paul Mooney
Charles Moore
Andy Moorwood
Thomas Mueller
Ron Muir
Dale Murray
Henry Muyshondt
Edward Nakamoto
Gary Nicholl
Paul Nikolich
John Nolan
Ronald Nordin
Mark Nowell
David Ofelt
Ichiro Ogura
Tom Palkert
Sujan Pandey
Sesha Panguluri
Carlos Pardo
Moon Park
Pravin Patel
Petar Pepeljugoski
Gerald Pepper
Ruben Perez De Aranda Alonso
Michael Peters
John Petrilla
Rick Pimpinella
Neven Pischl
Rainer Poehmerer
William Powell
Richard Prodan
Rick Rabinovich
Saifur Rahman
Adee Ran
Ram Rao
Alon Regev
Duane Remein
Victor Renteria
Michael Ressl
Poldi (Pavlick) Rimboim
Christopher Roth

Salvatore Rotolo
Hisaya Sakamoto
Vineet Salunke
Sam Sambasivan
Yasuo Sasaki
Fred Schindler
Stefan Schneele
Peter Scruton
Alexander Seiger
Naoshi Serizawa
Megha Shanbhag
Masood Shariff
Stephen Shellhammer
Bazhong Shen
Mizuki Shirao
Kapil Shrikhande
Jeff Slavick
Scott Sommers
Yoshiaki Sone
Xiaolu Song
Tom Souvignier
Bryan Sparrowhawk
Edward Sprague
Peter Stassar
Leonard Stencel
Robert Stone
Ken-Ichi Suzuki
Steve Swanson
Andre Szczepanek
William Szeto
Bharat Tailor
Akio Tajima
Takayuki Tajima
Tomoo Takahara
Satoshi Takahashi
Kiyoto Takahata
Alexander Tan
Toshiki Tanaka
Mehmet Tazebay
Brian Teipen
Geoffrey Thompson
Alan Tipper
Pirooz Tooyserkani
Nathan Tracy
David Tremblay
Albert Tretter
Stephen Trowbridge
Wen-Cheng Tseng
Yoshihiro Tsukamoto
Mike Tu
Alan Ugolini
John Ulm
Ed Ulrichs
Musa Unmehopa
Sterling A. Vaden
Stefano Valle
Paul Vanderlaan
Robert Wagner
Robert Wang
Tongtong Wang
Xiaofeng Wang
Xinyuan Wang
Zhong Feng Wang
David Warren
Markus Weber
Brian Welch
Yang Wen
Matthias Wendt
Oded Wertheim
Natalie Wienckowski
Ludwig Winkel
Peter Wu
Yu Xu
Lennart Yseboodt
Liquan Yuan
Hayato Yuki
Garold Yurko
Andrew Zambell
Jin Zhang
Yan Zhuang
George Zimmerman
Helge Zinner
Pavel Zivny
Gaoling Zou

Trademarks and Disclaimers

IEEE believes the information in this publication is accurate as of its publication date; such information is subject to change without notice. IEEE is not responsible for any inadvertent errors.

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Notice and Disclaimer of Liability
Concerning the Use of IEEE-SA Industry Connections Documents

This IEEE Standards Association ("IEEE-SA") Industry Connections publication ("Work") is not a consensus standard document. Specifically, this document is NOT AN IEEE STANDARD. Information contained in this Work has been created by, or obtained from, sources believed to be reliable, and reviewed by members of the IEEE-SA Industry Connections activity that produced this Work. IEEE and the IEEE-SA Industry Connections activity members expressly disclaim all warranties (express, implied, and statutory) related to this Work, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; quality, accuracy, effectiveness, currency, or completeness of the Work or content within the Work. In addition, IEEE and the IEEE-SA Industry Connections activity members disclaim any and all conditions relating to: results; and workmanlike effort. This IEEE-SA Industry Connections document is supplied "AS IS" and "WITH ALL FAULTS."

Although the IEEE-SA Industry Connections activity members who have created this Work believe that the information and guidance given in this Work serve as an enhancement to users, all persons must rely upon their own skill and judgment when making use of it. IN NO EVENT SHALL IEEE OR IEEE-SA INDUSTRY CONNECTIONS ACTIVITY MEMBERS BE LIABLE FOR ANY ERRORS OR OMISSIONS OR DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS WORK, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Further, information contained in this Work may be protected by intellectual property rights held by third parties or organizations, and the use of this information may require the user to negotiate with any such rights holders in order to legally acquire the rights to do so, and such rights holders may refuse to grant such rights. Attention is also called to the possibility that implementation of any or all of this Work may require use of subject matter covered by patent rights. By publication of this Work, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. The IEEE is not responsible for identifying patent rights for which a license may be required, or for conducting inquiries into the legal validity or scope of patents claims. Users are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. No commitment to grant licenses under patent rights on a reasonable or non-discriminatory basis has been sought or received from any rights holder. The policies and procedures under which this document was created can be viewed at http://standards.ieee.org/about/sasb/iccom/.

This Work is published with the understanding that IEEE and the IEEE-SA Industry Connections activity members are supplying information through this Work, not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought. IEEE is not responsible for the statements and opinions advanced in this Work.

TABLE OF CONTENTS

FIGURES

TABLES

1 Introduction

IEEE Std 802.3™ [4], and published, EPON-specific amendments to this standard (IEEE Std 802.3bk™ [5]), include specifications for the Data Link and Physical layers for Ethernet Passive Optical Networks (EPON) operating at 1 Gb/s (1G-EPON) and 10 Gb/s (10G-EPON).

The demand for high-speed data services has driven the market for residential service offerings reaching 1 Gb/s and business service offerings towards multi-Gb/s speeds. In response to this market demand, service providers are moving 10G-EPON quickly towards commercial deployment. 1G-EPON will soon become a de-facto legacy technology, providing lower-bandwidth services. At the same time, anticipating the demand for high-speed data services to continue growing in the foreseeable future, service providers are exploring the market potential and technology options for a next generation of EPON. NG-EPON would operate at aggregate data rates above 10 Gb/s to provide higher per-subscriber data rates and at the same time minimize the physical footprint and power consumption of the access network

To support this exploration, the NG-EPON Industry Connections group worked toward raising awareness in the industry and collected input regarding the desired features and options for a next generation of EPON. Several distinct markets and applications currently rely on EPON. The largest application areas for EPON include residential and commercial subscriber access (for voice, video and data), and mobile backhaul, offered in triple- and quad-play packages. The largest geographical areas of EPON deployments can be found today in Asia and the Americas. Equipment vendors and operators serving all of these markets are interested in exploring the technologies available for the next generation of EPON, allowing them to provide cost-effective solutions to the ever-increasing demand of the end-customers, as well as addressing the requirements of customer applications. The dominant applications for EPON include triple-play packages for Internet access voice, and video offered to residential and commercial subscribers, private network access for commercial subscribers, and mobile backhaul for carriers. The largest geographical areas of EPON deployments can be found today in Asia and the Americas. Equipment vendors and operators serving all of these markets are interested in exploring the technologies available for the next generation of EPON, allowing them to provide cost-effective solutions to the ever-increasing demand for higher bandwidth from subscribers, as well as addressing the requirements of subscriber applications.

2 Abbreviations

This document contains the following abbreviations:

ADC	Analog-Digital Conversion
AP	Access Point
APD	Avalanche Photo-Diode
AWG	Arrayed Wave Guide
BE	Best Effort
BER	Bit Error Ratio
CAGR	Compounded Annual Growth Rate
CAPEX	Capital Expenses
CATV	Cable Television, Community Access Television, Community Antenna Television
CD	Chromatic Dispersion
CD-OFDM	Coherent Detection OFDM
CDM	Code Division Multiplexing
CDN	Content Delivery Network
CDR	Clock Data Recovery
CO	Central Office
CPE	Customer Premises Equipment
CWDM	Coarse Wavelength Division Multiplexing
CWL	Center Wavelength
DAC	Digital-Analog Conversion
DBA	Dynamic Bandwidth Allocation
DC	Dispersion Compensation
DD-OFDM	Direct Detection OFDM
DFB	Distributed Feedback
DIA	Direct Internet Access
DPoE	DOCSIS Provisioning of EPON
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
EML	Externally Modulated Laser
E-LINE	Ethernet Line
E-TREE	Ethernet Tree
E-LAN	Ethernet LAN
EP-LINE	Ethernet Private Line
EP-TREE	Ethernet Private Tree
EP-LAN	Ethernet Private LAN
EPON	Ethernet Passive Optical Network
EVC	Ethernet Virtual Circuit
EVPL	Ethernet Virtual Private Line
EV-LINE	Ethernet Virtual Line
EV-TREE	Ethernet Virtual Tree
EV-LAN	Ethernet Virtual LAN
FBT	Fused Biconical Taper
FFT	Fast-Fourier Transform

FP	Fabry Perrot
FSR	Free Spectral Range
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTD	Fiber to the Desktop
FTTH	Fiber to the Home
FTTLA	Fiber to the Last Active
FTTN	Fiber to the Node
FTTP	Fiber to the Premises
FTTU	Fiber to the Unit
FTTx	Fiber to the X (home, business, etc.)
FWHM	Full-Width Half Maximum
GPON	Gigabit PON
HD	High Definition
IFFT	Inverse Fast-Fourier Transform
IL	Insertion Loss
I/Q	In-Phase/Quadrature
LAN	Local Area Network
L2CP	Layer-2 Control Protocol
LD	Laser Diode
LPF	Low Pass Filter
LSB	Least Significant Bit
MAC	Media Access Control
MDU	Multi Dwelling Unit
MEF	Metro Ethernet Forum
MEMS	Micro-Electro-Mechanical systems
MPCP	Multipoint Control Protocol
MSB	Most Significant Bit
MSD-WDM-PON	Multiple Scheduling Domain WDM-PON
MSO	Multiple-System Operator
MTU	Maximum Transmit Unit
MZI	Mach-Zehnder Interferometer
NRZ	Non Return to Zero
NRZ-OOK	Non-Return to Zero On-Off Keying
O/E	Optical-Electrical
OADM	Optical Add-Drop Multiplexer
OCM	Optical Channel Monitor
ODN	Optical Distribution Network
OFDM	Optical Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Network Unit
OPEX	Operational Expenses
OTT	Over The Top
P2MP	Point To Multi Point
P2P	Point To Point
PAM	Pulse Amplitude Modulation
PD	Photo Detector/Photo Diode

PDL	Polarization Dependent Loss
PHY	Physical Layer
PLC	Planar Lightwave Circuit
PON	Passive Optical Network
PSC	Passive Splitter / Coupler
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RF	Radio Frequency
RFoG	Radio Frequency over Glass
RN	Remote Node
RTE	Real-Time Entertainment
SD	Standard Definition
SFU	Single Family Unit
SLA	Service Level Agreement
SMF	Single-Mode Fiber
SNR	Signal to Noise Ratio
SoC	System-on-Chip
SSD-WDM-PON	Single Scheduling Domain WDM-PON
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDR	Time Domain Reflectometry
TV	Television
UTP	Unshielded Twisted Pair
UHD	Ultra High Definition
UNI	User Network Interface
VLAN	Virtual LAN
WA-PON	Wavelength Agile PON
WBF	Wavelength Blocking Filter
WDD	Wavelength Division Duplex
WDM	Wavelength Division Multiplexing

This document makes frequent use of the following terms:

1G-EPON	An EPON architecture operating at the effective data rate of 1 Gb/s in both downstream and upstream directions, first specified in IEEE Std 802.3ah and now part of IEEE Std 802.3 [4].
10G-EPON	An EPON architecture operating at the effective data rate of 10 Gb/s in either downstream or both downstream and upstream directions, first specified in IEEE Std 802.3av and now part of IEEE Std 802.3 [4]. This term collectively refers to 10/10G-EPON and 10/1G-EPON architectures.
10/10G-EPON	An EPON architecture operating at the effective data rate of 10 Gb/s in both downstream and upstream directions (symmetric rate), first specified in IEEE Std 802.3av™ and now part of IEEE Std 802.3 [4].
10/1G-EPON	An EPON architecture operating at the effective data rate of 10 Gb/s in downstream direction and 1 Gb/s in upstream direction (asymmetric rate), first specified in IEEE Std 802.3av and now part of IEEE Std 802.3 [4].

3 Taxonomy of PON-based Access Network Technologies

There are a number of PON-based access architectures providing layer-2 (L2) connectivity between the location of the Optical Line Terminal (OLT), and the demarcation point (Optical Network Unit, or ONU). Depending on the actual location of the ONU, there are several classes of fiber access networks, namely (adapted from [10]):

- *FTTN / FTTLA (fiber-to-the-node, -neighborhood, or -last-amplifier)*: Fiber is terminated in a street cabinet, with the drop section between the cabinet and customer premises typically implemented using either coaxial or twisted pair cabling. FTTN is often considered to be an interim step toward FTTH.
- *FTTC (fiber-to-the-curb, -closet, or -cabinet)*: An architecture that is very similar to FTTN. The difference between FTTN and FTTC is that the termination point (ONU) is located nearer the customer premises - typically within 1000 ft (300 m).
- *FTTB (fiber-to-the-building, -business, or -basement)*: Fiber is terminated at a selected location within the building, such as the basement in a multi-dwelling unit, with the drop section between the termination point (ONU) and customer premises typically implemented using either coaxial or twisted pair cabling.
- *FTTH/FTTU (fiber-to-the-home/fiber-to-the-unit)*: An architecture in which the fiber is terminated directly on the premises of a residential customer. FTTU refers to this architecture when applied to individual units in a multi-tenant/multi-dwelling unit (MDU/MTU). FTTH refers to this architecture when applied to stand-alone offices or homes.
- *FTTP (fiber-to-the-premises)*: An architecture that includes both FTTH and FTTB architectures.
- *FTTD (fiber-to-the-desktop)*: An architecture where fiber extends all the way to a fiber media converter near the user's desk.

Optical access architectures can be classified by their logical connectivity options. One distinguishing factor is the number of independent connections (or channels) that exist between the OLT and an ONU. Another factor is the nature of each logical channel: a channel can be dedicated to a single ONU or shared among multiple ONUs.

There exist several physical means of creating the channels. A simple way is to use separate fiber strands for each connection. Another method involves chromatic separation of channels using Wavelength-Division Multiplexing (WDM) techniques. Other methods include carrier frequency separation (e.g., Orthogonal Frequency Division Multiplexing channel) and signal coding (e.g., Code Division Multiplexing channel).

Figure 1 illustrates the mentioned connectivity options using separate optical fibers (ODNs). The top left quadrant represents a dedicated point-to-point connection from the OLT to each ONU, a so-called “home run” architecture. The top right quadrant represents a typical TDM-PON architecture, i.e., EPON or GPON.

The two quadrants at the bottom represent point-to-point and TDM-PON access architectures with dual homing (e.g., for fault protection and/or extra bandwidth).

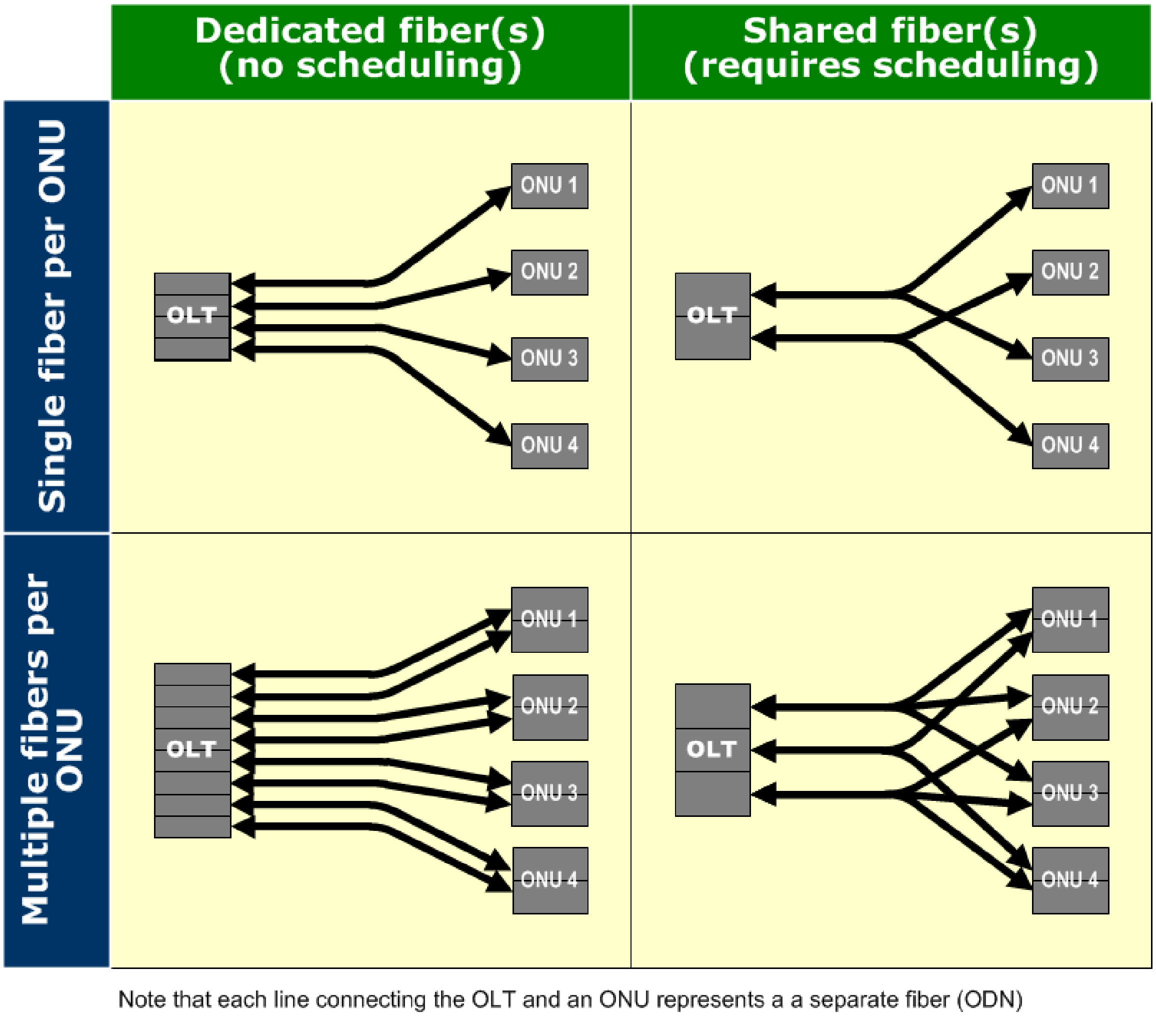


Figure 1: Optical access architectures using multiple ODNs

Figure 2 illustrates the same logical connectivity options, but this time the channel separation is achieved using WDM techniques.

In the scenarios shown in the two quadrants on the left, an ONU has one or more pairs of dedicated wavelength channels (one downstream, one upstream), forming a Wavelength-Division Multiplexing PON (WDM-PON). In the scenarios shown in the two right quadrants, an ONU shares one or more pairs of wavelength channels with other ONUs using a Time-Division Multiplexing (TDM) scheme, resulting in a Hybrid-PON. Depending on the order in which WDM sharing and TDM sharing is applied to these wavelength channels, Hybrid-PON can be further divided into Single-Scheduling Domain WDM-PON (SSD-WDM-PON) and Multiple-Scheduling Domain WDM-PON (MSD-WDM-PON).

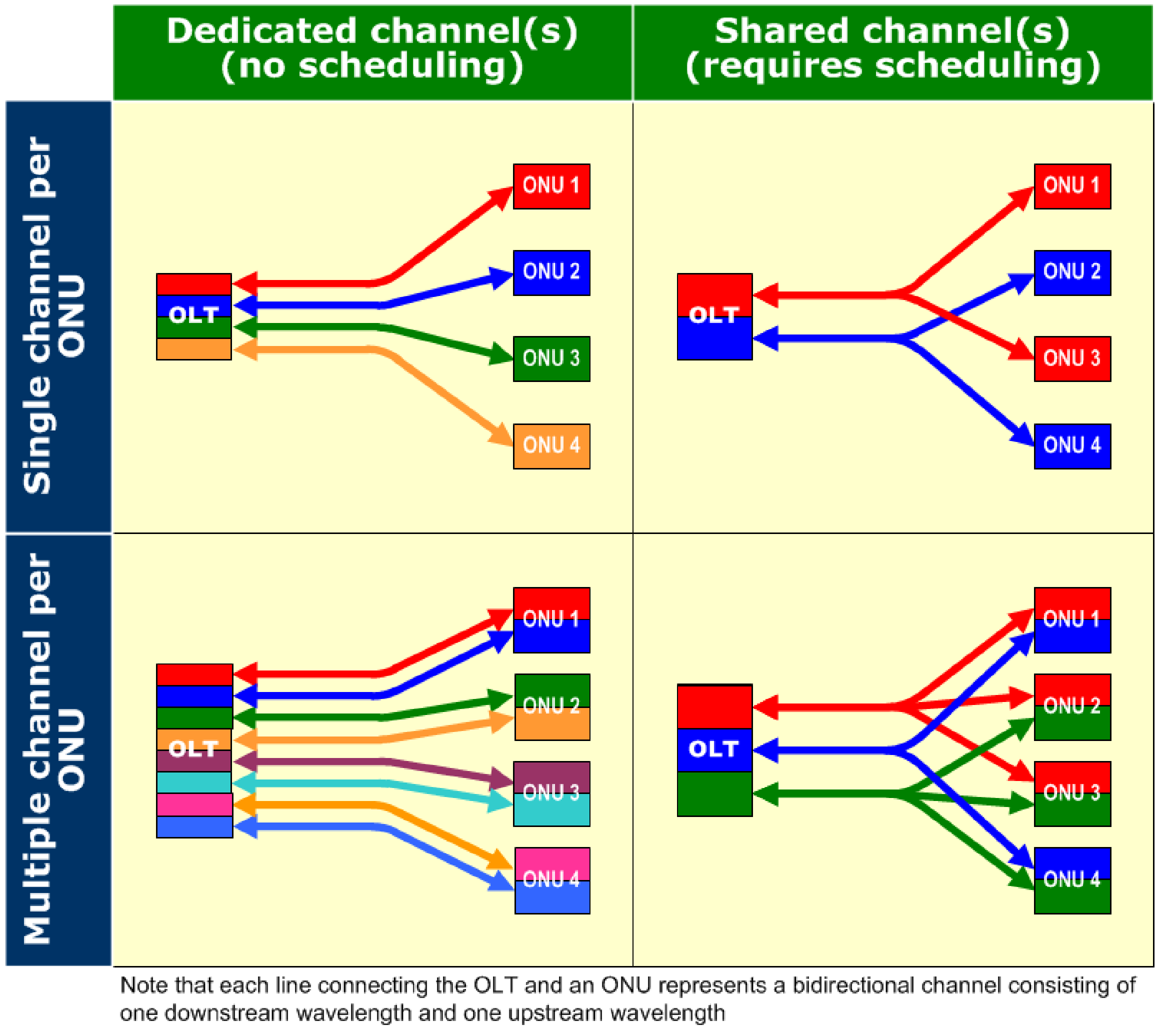


Figure 2: Optical access architectures using WDM

This taxonomy of optical access architectures is presented in Table 1.

3.1 TDM-PON

A TDM-PON provides all ONUs with the same wavelength pair (one downstream and one upstream) over a single fiber. This provides virtual point-to-point (P2P) links to each ONU over a point-to-multipoint (P2MP) media by multiplexing data to each ONU in both directions in time, hence the term TDM-PON. A TDM-PON has a single scheduling domain. Most PONs deployed to date, including 1G-EPON and 10G-EPON, fall into this category.

3.2 WDM-PON

A WDM-PON provides each ONU (and subscriber(s) connected to such an ONU) with at least one dedicated pair of wavelength channels (one downstream and one upstream) creating logical P2P data connections between the OLT and the ONU. This means that no multiple access techniques are required for the upstream direction as a dedicated upstream wavelength channel is continuously available to each ONU. Furthermore, each wavelength channel is transparent to data rate and Media Access Control (MAC) frame format, allowing each wavelength channel to run at a different data rate (e.g., 10 Mb/s, 100 Mb/s, 1000 Mb/s, or higher) and/or a different MAC frame format (Ethernet, IP over glass), depending on subscriber demand and requirements.

Table 1: Taxonomy of Optical Access Architectures

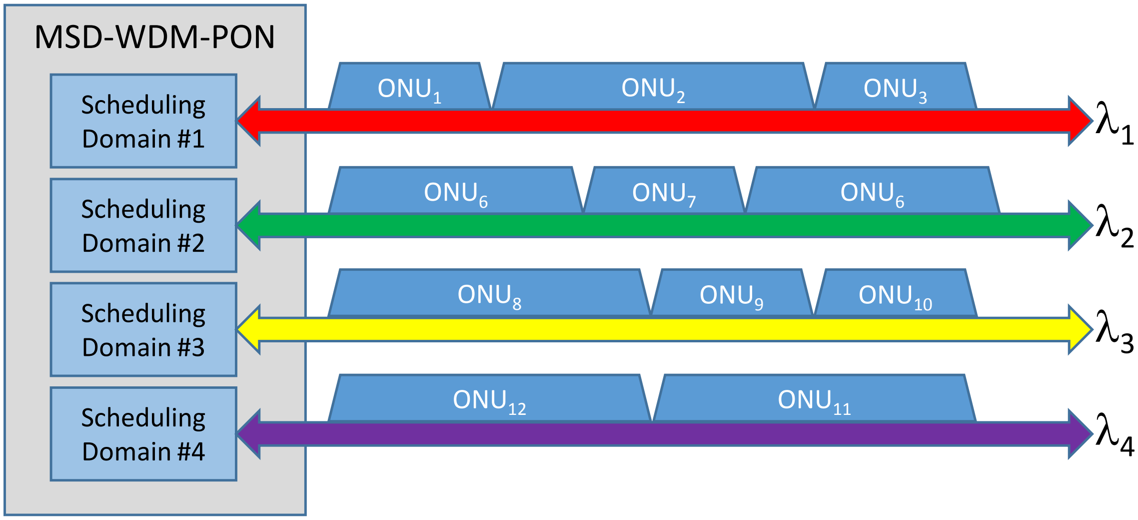
PHY Channels per PON per direction {one/many}	PHY Channels per ONU per direction {one/many}	PHY Channel Connectivity Type {P2P/P2MP/Mix}	Type/Name of Network
One	One	P2P	P2P Link
		P2MP	EPON, 10G-EPON, GPON, XG-PON
Many	One	P2P	WDM-PON
		P2MP	MSD-WDM-PON
	Many	P2P	WDM-PON
		P2MP	SSD-WDM-PON, WA-PON

3.3 Hybrid-PON

A Hybrid-PON provides a group of ONUs (and subscriber(s) connected to such an ONU) with at least one pair of wavelength channels, (one downstream and one upstream), shared among ONUs in a TDM fashion. In this way, P2MP connections between the OLT and specific group of ONUs are created. Depending on the way a group of ONUs shares the assigned wavelength channels, Hybrid-PON is further classified into MSD-WDM-PON, SSD-WDM-PON, and Wavelength Agile PON (WA-PON). For brevity, the difference between MSD-WDM-PON, SSD-WDM-PON, and WA-PON is explained only for the upstream direction.

Upstream transmissions from ONUs that share assigned wavelengths in a TDM fashion may collide at the OLT receiver. A scheduling protocol is required to arbitrate upstream transmissions to prevent collisions from occurring. In the downstream direction, the medium is continuously available for transmission, since the OLT is the only device allowed to transmit data towards ONUs. Over the years, various medium access protocols have been designed, with various generations of EPON and GPON representing the most popular P2MP medium access protocols for optical access.

3.3.1 MSD-WDM-PON



[1] Figure is exemplary and does not show all possible arrangements of ONU transmission

Figure 3: Upstream Channel in MSD-WDM-PON

In a MSD-WDM-PON, upstream and downstream wavelength channels are assigned (dynamically or statically) to a group of ONUs.

In the upstream direction, the OLT then grants access to the assigned wavelength channel to a specific ONU, allowing the ONU to transmit its queued data. The duration of such access to the upstream wavelength channel granted to the given ONU depends on the operation of a Dynamic Bandwidth Allocation (DBA) mechanism. No other ONU sharing the same wavelength channel is allowed to transmit during the same window of time. On a MSD-WDM-PON, each ONU transmits on one and only one upstream wavelength at a time, as illustrated in Figure 3.

The OLT is the only device with access to the downstream wavelength channel and transmits data without needing arbitration.

3.3.2 SSD-WDM-PON

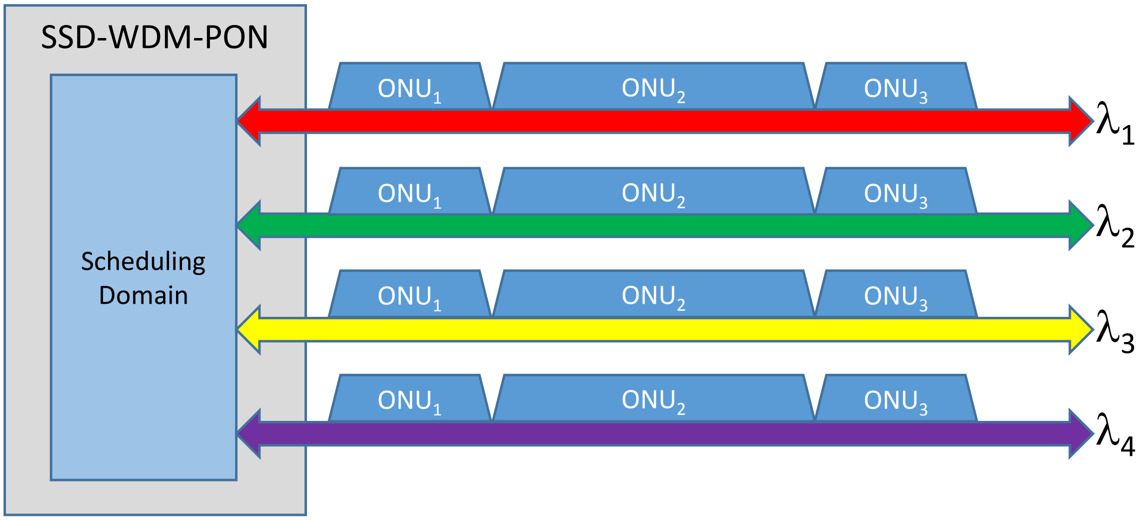


Figure 4: Upstream Channel in SSD-WDM-PON

In an SSD-WDM-PON, all upstream and downstream wavelength channels are accessible to all ONUs connected to the given OLT.

In the upstream direction, the OLT grants access to all available upstream wavelength channels to a specific ONU, allowing it to transmit its queued data. The duration of such access to all upstream wavelength channels granted to the given ONU depends on the operation of a DBA protocol. No other ONU is allowed to transmit during the same window of time. On an SSD-WDM-PON, each ONU simultaneously transmits on all upstream wavelength channels as illustrated in Figure 4.

The OLT is the only device with the access to the downstream wavelength channel and transmits data without further arbitration on all available downstream wavelength channels.

3.3.3 WA-PON

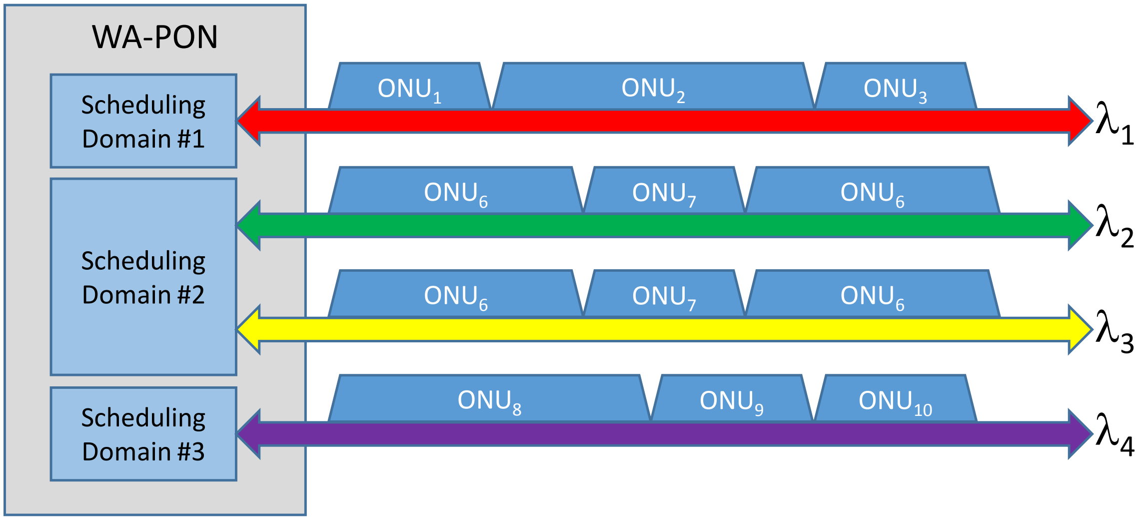


Figure 5: Upstream Channel in WA-PON

In a WA-PON, more than one upstream and downstream wavelength channel is assigned (dynamically or statically) to a group of ONUs connected to the given OLT. The allocation of downstream and upstream wavelength channels to the given ONU may change dynamically over time, under the control of the OLT. The OLT may change the number of downstream and/or upstream wavelength channels assigned to the given ONU. Their placement in the available wavelength grid depends on the configuration selected by the operator, capacity planning, and other factors.

In the upstream direction, the OLT grants access to the assigned upstream wavelength channels to a specific ONU, allowing it to transmit its queued data. The duration of such access to the assigned upstream wavelength channels granted to the given ONU depends on the operation of a DBA mechanism. No other ONU is allowed to transmit on the same wavelength channels during the same window of time. Effectively, in WA-PON, each ONU transmits on its allocated upstream wavelengths simultaneously with other ONUs as shown in Figure 5.

The OLT is the only device with access to the assigned downstream wavelength channels and transmits data to a group of ONUs without needing arbitration.

In order to meet the full flexibility of a wavelength agile PON, a WA-PON ONU needs to support tunability of its receivers and transmitters, allowing such an ONU to receive and transmit on different wavelengths selected by the OLT.

3.4 ODN Topologies

Generally, modern access networks are designed to provide *P2MP connectivity*: a device in the central office can communicate with multiple subscribers, but the subscribers are prevented from communicating directly with each other. In PON, all transmissions are performed between the OLT and ONUs located at or near the subscriber premises.

There are several PON-based Optical Distribution Network (ODN) topologies that offer point-to-multipoint connectivity suitable for the access network. These include *passive tree*, also known as *trunk-and-branch* (Figure 6), *passive bus* (Figure 7), or *passive ring* (Figure 8). In all the cases, the topology is passive. Instead of active (powered) devices, all junction points are built using 1×2 or 2×2 optical tap couplers, or *M*×*N* optical splitters.

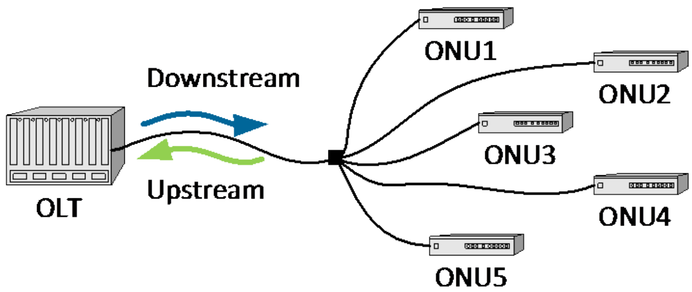


Figure 6: Tree Topology using 1×N Splitter

In a tree topology (Figure 6), a single trunk fiber is connected to a 1×N splitter that fans out the signal to a number of (typically, 16 or 32) branches. Various branches may in turn be connected to another splitter that fans out to yet more branches. Two very common ODN configurations use a 1×32 splitter or a 1×4 splitter followed by four 1×8 splitters. In this topology, the upstream and downstream optical signals propagate in opposite directions in the same fiber.

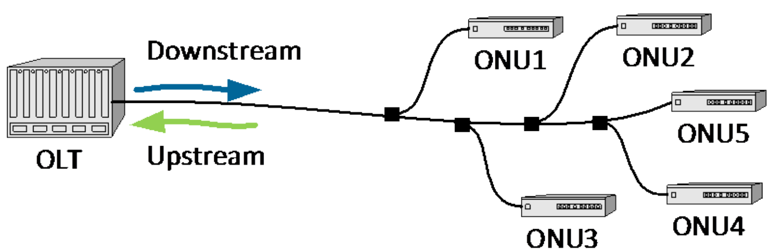


Figure 7: Bus Topology using 1×2 Tap Couplers

A bus topology (Figure 7) is similar to the tree topology in that the upstream and downstream optical signals propagate in the opposite directions in the same fiber. However, instead of using a 1×N splitter, the bus topology employs 1×2 tap couplers that divert a small portion of the signal away from the main bus toward an ONU. The couplers may have a fixed or progressive tapping ratio. The couplers with fixed ratio divert a constant fraction of power away from the main bus. The ONUs that are attached to the PON bus nearer to the OLT gets higher power than the ONUs that are attached at the far end of the bus. To alleviate this problem, the tap couples with progressive ratio may be used. In this case, a tap nearer the OLT diverts a smaller fraction of power than a tap farther away, resulting in each ONU receiving approximately equal optical input power from the OLT.

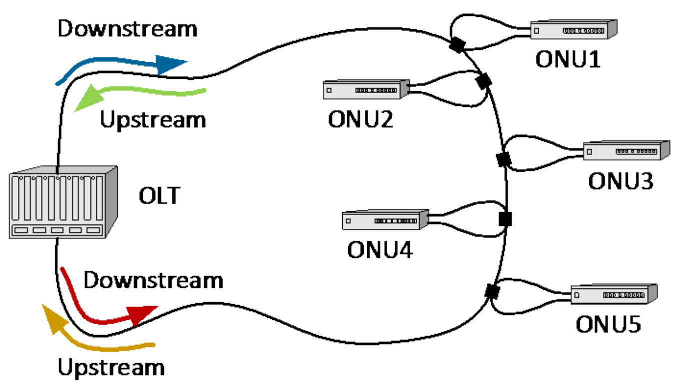


Figure 8: Ring Topology using 2×2 Tap Couplers

A ring topology (Figure 8) utilizes 2×2 couplers to connect ONUs to a fiber ring. The fiber ring can be constructed with co-propagating or contra-propagating downstream and upstream signals. It is also possible to construct a ring with two downstream and two upstream channels, with one downstream/upstream pair propagating clockwise and another propagating counter-clockwise.

An added advantage of the ring topology compared to the bus or the tree is that the OLT receives its own transmission signal. This allows the OLT to detect a failure in the fiber ring almost instantaneously rather than waiting for a protocol timeout while communicating with the ONU.

The topologies described above can be used with either WDM-PONs or TDM-PONs. The ODN can be constructed using wavelength mux/demux devices to enable operation of WDM-PONs.

The WDM-PON ODN can be further categorized as wavelength-selected or wavelength-routed.

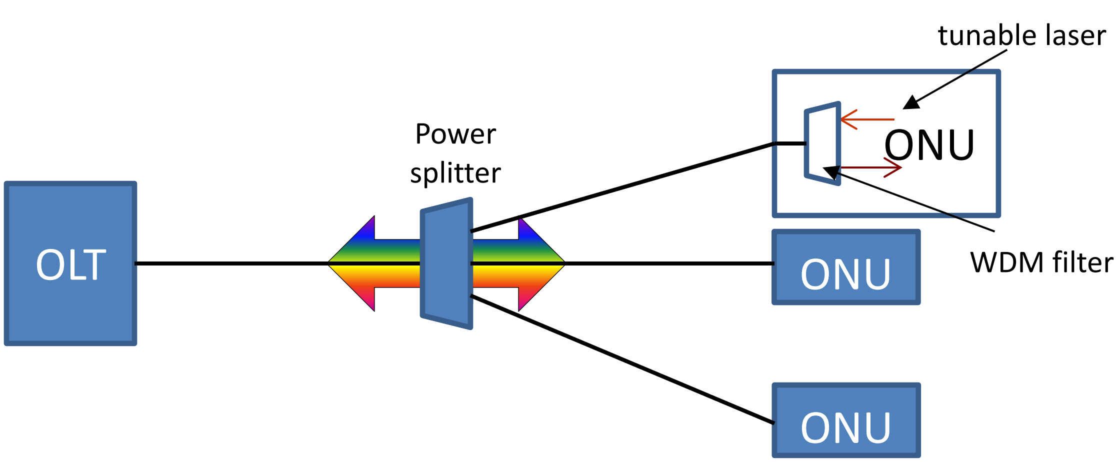


Figure 9: Wavelength Selected WDM-PON

A wavelength-selected WDM-PON (shown in Figure 9) utilizes power splitters in the ODN. The ONU, however, must have wavelength filter to select the desired downstream wavelength. A tunable laser is used in the ONU to produce the correct upstream wavelength.

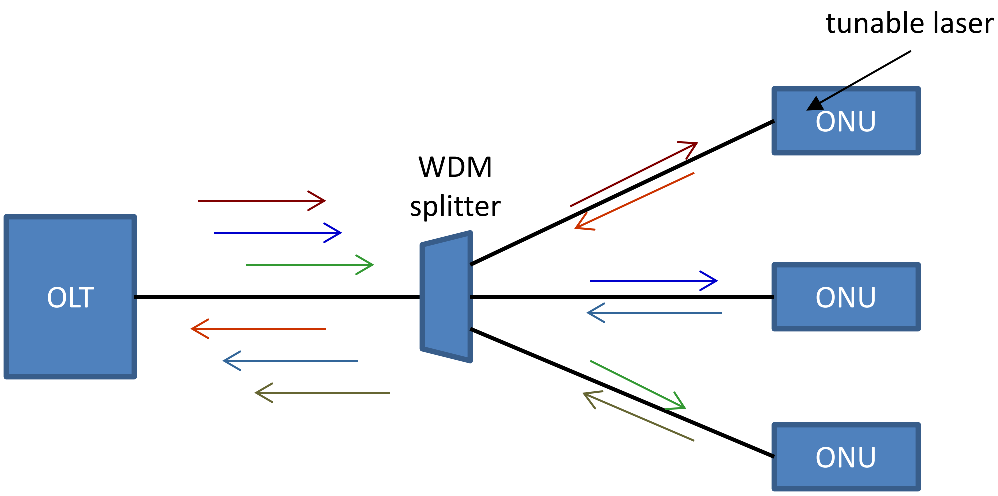


Figure 10: Wavelength Routed WDM-PON

The wavelength-routed WDM-PON (shown in Figure 10) utilizes WDM mux/demux components in the ODN in lieu of power splitters. A wideband receiver can be used in the ONU since the desired downstream wavelength is determined by the ODN. A tunable laser is used to produce the correct upstream wavelength.

A wavelength routed ODN has an advantage over a power-split ODN when compared on the basis of power-loss budgets. Symmetrical power splitters exhibit insertion loss of approximately $3 \times N$ dB for a 2^N split, whereas a wavelength mux/demux will exhibit an insertion loss between 1 dB and 4 dB with the exact value dependent upon manufacturing technique, tolerances, and other factors.

There are at least two disadvantages to wavelength routed ODNs. The first is the difficulty, if not impracticality, of deploying cascaded splitter architectures, already widely deployed by operators. The second is that the passband of a wavelength mux/demux is strongly dependent upon operating temperature. Therefore, special measures must be taken to ensure thermal stability in a typical field deployment.

4 Motivation for NG-EPON

4.1 Background and Market Drivers

With the first trials of first generation of EPON (1G-EPON) taking place in December 2004, EPON quickly emerged as the market-leading optical access technology in multiple application areas in different countries around the world.

In Japan, as of the end of September 2011, there were 21.4 million EPON subscribers, of which 12.9 million represented FTTUs and 8.5 million represented FTTBs.

NTT has 74.4% share of EPON subscribers in Japan. Most of the rest are served by KDDI, the second largest carrier in Japan. Generally, 100 Mb/s or 200 Mb/s services are offered, with KDDI offering 1 Gb/s service in some areas. The immediate target of NTT is to achieve 20 million FTTH subscribers [58].

Korea Telecom (KT) began EPON deployments in Korea in 2006. As of April 2012, EPON serves more than 3.2 million FTTH, and 1 million FTTB subscribers, which together represent 53% of all KT's broadband subscribers. EPON service contracts generally provide 50−100 Mb/s of bandwidth and may include IPTV and VoIP services [58].

China Telecom started a comprehensive EPON interoperability program in 2006. Interoperability tests were first conducted among the chip vendors and then among the system vendors. As part of the interop tests, China Telecom demonstrated in 2007 a large-scale, comprehensive chip-level and system-level interoperability among EPON devices. With more than 60 million households passed and 20 million active broadband subscribers, China Telecom is today the largest and fastest growing FTTx network operator. They are on track to deploy fiber within reach of 30 million subscribers in 2012, of which half are expected to subscribe to the new fiber-based services [58].

In July 2009, China Telecom launched a new interoperability-testing program, this time focused on 10G-EPON, including both symmetric (10G/10G) and asymmetric (10G/1G) EPON ASICs and systems. This sustained and extensive program continued through 2011 and culminated in the introduction of fully interoperable, commercial quality equipment from a large number of suppliers.

In December of 2011 NTT demonstrated a field trial of long-reach dual-rate 10G-EPON in Japan. The demonstrated technology supported both 10G/10G ONUs and 1G/1G ONUs, between the cities of Sapporo and Chitose [30].

Responding to the increasing demand for higher bandwidth from its subscribers in Korea, Korea Telecom was planning a pilot deployment of 10G-EPON by the end of 2012 [31].

Intending to significantly enhance access to broadband applications and extend mobile Internet penetration, China [9] has plans to introduce FTTB for urban households and broadband access by 2015 in rural districts. Expected take rates for fixed broadband reaching 50% and the fraction of villages provided with broadband services is expected to reach 95%. Public institutions such as schools, libraries, hospitals, etc., are expected to have nearly universal broadband access. The minimum offered broadband access rates for urban and rural families are set at 20 Mb/s and 4 Mb/s, respectively, while they can reach 100 Mb/s in some developed cities.

China expects broadband applications to be deeply integrated into day-to-day life and mobile Internet access to be universally available and accepted by 2020. Under the same strategy, China plans for 98% of villages to have access to broadband services with 70%–85% take-rates for fixed and mobile broadband access. The minimum offered broadband access rates for urban and rural families are set at 50 Mb/s and 12 Mb/s, respectively, while they can reach 1 Gb/s in some developed cities.

Bandwidth targets for individual types of FTTx subscribers and adoption timelines are included in [9].

4.2 Regional Consumption of Internet Traffic

At the end of the first half of 2014 the median Internet data usage (per subscriber) in the North American fixed access network was on the order of 17.4 GB downstream and 1.4 GB upstream per month [37], while the mean reaches almost 43.8 GB downstream and around 7.6 GB upstream. Top users consistently exceeded 5 TB of monthly data usage, typically shared among multiple devices at home. Most service providers observe a steady data consumption growth of more than 30% per year irrespective of the access technology they use in their first mile networks (see section 4.3 for an example of operator data). The large growth in the mean and median data consumption in fixed access networks (when compared with 2011 numbers as published by the same source) is mainly attributed to the growing use of Real-Time Entertainment (RTE) services. RTE services are responsible for about 63% of peak data consumption during busy hours [37].

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	36.35%	Netflix	31.62%	Netflix	28.18%
2	HTTP	6.03%	YouTube	18.69%	YouTube	16.78%
3	SSL	5.87%	HTTP	9.74%	HTTP	9.26%
4	Netflix	4.44%	BitTorrent	4.05%	BitTorrent	7.39%
5	YouTube	3.63%	iTunes	3.27%	iTunes	2.91%
6	Skype	2.76%	MPEG - Other	2.60%	SSL	2.54%
7	QVoD	2.55%	SSL	2.05%	MPEG - Other	2.32%
8	Facebook	1.54%	Amazon Video	1.61%	Amazon Video	1.48%
9	FaceTime	1.44%	Facebook	1.31%	Facebook	1.34%
10	Dropbox	1.39%	Hulu	1.29%	Hulu	1.15%
		66.00%		76.23%		73.35%

Figure 11: Top 10 Peak Period Applications—NA, fixed access [37]

In North America (see Figure 11), Netflix continues to be the main contributor to downstream data consumption, accounting for more than 34% of downstream traffic during the peak period.

Moreover, with the introduction of 4K Super High-Definition (HD) content [38], Netflix is expected to continue to drive data consumption in the downstream, increasing its overall share as 4K TVs become more popular. When combined with other similar services (YouTube, Amazon Video, and Hulu, and others), more than 65% of downstream traffic is consumed by RTE services focused on video delivery.

The same source [37] also provides numbers for Internet data consumption in fixed access networks in Europe, Africa, Latin America, and Asia-Pacific regions.

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	48.10%	YouTube	28.73%	YouTube	24.21%
2	YouTube	7.12%	HTTP	15.64%	BitTorrent	17.99%
3	HTTP	5.74%	BitTorrent	10.10%	HTTP	13.59%
4	Skype	4.96%	Facebook	4.94%	Facebook	4.65%
5	Facebook	3.54%	Netflix	3.45%	Netflix	3.33%
6	Netflix	2.83%	MPEG - Other	3.10%	MPEG - Other	2.57%
7	SSL	2.47%	RTMP	2.82%	RTMP	2.42%
8	eDonkey	1.12%	Flash Video	2.56%	Skype	2.32%
9	Dropbox	1.12%	SSL	1.91%	Flash Video	2.16%
10	RTMP	0.85%	PutLocker	1.25%	SSL	2.03%
		77.83%		73.23%		75.25%

sandvine

Figure 12: Top 10 Peak Period Applications—Europe, fixed access [37]

In Europe the median values are smaller than in North America (around 7 GB downstream and less than 1 GB upstream), with the mean values reaching roughly half of the data consumption reported for North America-based fixed access subscribers. European countries with limited access to RTE content have typically higher volume of file-sharing traffic (see Figure 12), the fact that was observed before in North America when the RTE services were in their infancy.

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	29.70%	YouTube	36.82%	YouTube	33.29%
2	YouTube	14.70%	HTTP	20.01%	HTTP	18.10%
3	Facebook	8.55%	BitTorrent	7.63%	BitTorrent	11.14%
4	HTTP	8.01%	Facebook	6.22%	Facebook	6.59%
5	Ares	5.61%	SSL	2.81%	SSL	2.88%
6	SSL	3.22%	MPEG - Other	2.68%	MPEG - Other	2.36%
7	Skype	2.81%	Flash Video	2.23%	Flash Video	1.99%
8	SPDY	1.00%	Netflix	2.17%	Netflix	1.94%
9	RTMP	0.97%	RTMP	1.79%	RTMP	1.66%
10	eDonkey	0.77%	SPDY	1.22%	Ares	1.64%
		75.34%		83.57%		81.60%

sandvine

Figure 13: Top 10 Peak Period Applications—Latin America, fixed access [37]

It is expected that as Over The Top (OTT) RTE services become more generally accessible (both technically, as well as economically), the traffic distribution becomes more similar to the one observed in North America, decreasing the share of file sharing services and increasing the share of RTE services.

Interestingly enough, these numbers for Latin America (Figure 13) are only around 25% lower when compared to North America, indicating that local service providers are quickly closing the technology gap and migrating their subscribers to higher speed links. It is also interesting to note that the upstream data consumption is larger, implying that more digital content is being created and shared online. Despite this lower overall data usage per subscriber, the habits of the digital content consumption in Latin America are very similar to that observed in North America and in Europe. Unsurprisingly, RTE services generate the majority of the downstream traffic during peak hours, while the share of web browsing and file sharing services is dropping continuously as RTE OTT services become more available and accessible to the average consumer. At this time YouTube dominates downstream data consumption. The recent emergence of proxy caches allows Netflix to be consumed in regions without official Netflix support. This development has supported a 5% growth of Netflix streaming in Latin America where the rate observed prior to the first half of 2013 was less than 1%.

	Upstream		Downstream		Aggregate	
Rank	Application	Share	Application	Share	Application	Share
1	BitTorrent	35.72%	YouTube	31.22%	YouTube	23.30%
2	QVoD	14.10%	BitTorrent	14.25%	BitTorrent	21.18%
3	YouTube	6.65%	HTTP	10.48%	HTTP	8.08%
4	RTSP	5.00%	QVoD	4.51%	QVoD	7.61%
5	Thunder	4.03%	Facebook	4.45%	Facebook	3.57%
6	HTTP	3.04%	MPEG - Other	3.65%	RTSP	3.24%
7	Skype	2.03%	RTSP	2.40%	MPEG - Other	2.62%
8	Facebook	1.74%	iTunes	1.70%	Thunder	2.20%
9	PPStream	1.30%	Dailymotion	1.69%	iTunes	1.28%
10	Funshion	1.17%	Flash Video	1.67%	Dailymotion	1.21%
		74.78%		76.03%	0.00%	74.28%

sandvine

Figure 14: Top 10 Peak Period Applications—APAC, fixed access [37]

A unique characteristic of the Asia-Pacific region (Figure 14) is the popularity of peer casting applications, such as PPStream and QVoD that are not used anywhere else around the world at a similar scale. These applications allow users to stream live events. Simultaneously, users participate in distribution of other data streams to viewers, providing distributed caching capabilities. Both of these features of peer casting applications drive the observed high upstream data consumption. File sharing applications remain strong, especially in the upstream, contributing to roughly 45% of the volume of transmitted data. Similar to other regions, the lack of well-established OTT RTE services skews the traffic distribution towards free YouTube content and file sharing applications, providing access to video content not available through other digital channels.

4.3 Residential Bandwidth Consumption

Operator data on bandwidth consumption varies greatly from operator to operator, depending on the data collection methodology, type of examined subscribers, and observation period. The following bandwidth consumption and peak rates are intended to be an example of the trends observed for residential subscribers over the period of approximately 3.5 years. The presented data includes Internet traffic and managed unicast video, but does not include managed broadcast and multicast linear television (TV) (i.e., traditional scheduled non-time-shifted television service).

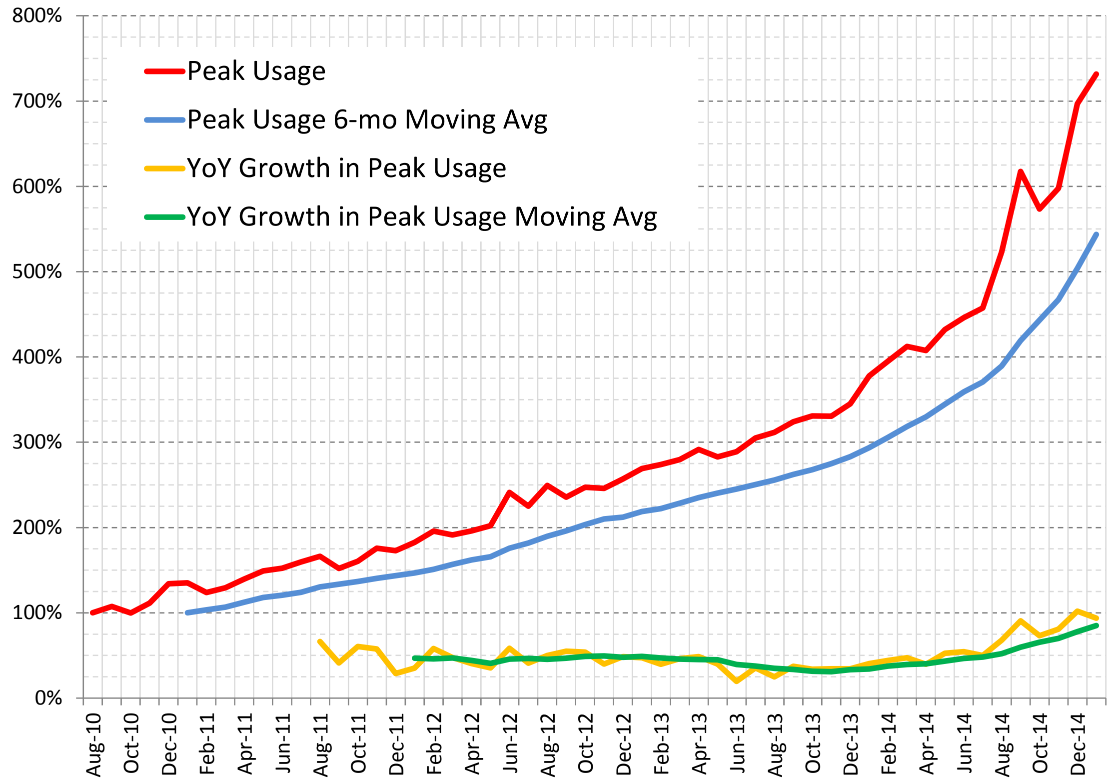


Figure 15: Peak Bandwidth Trends Over a 4-year Period

Figure 15 presents the peak data rate per connected subscriber presented on a month-to-month basis, calculated per month and as a 6 months' moving average, as well as the year-to-year peak usage and a moving average. It is important to note that over the period of 3.5 years the observed peak data rate increased ~6 times, trending very closely to ~50% compounded annual growth rate (CAGR) per year. CAGR in the last 6 months has increased and it is right now reaching almost 100%.

Trending the peak data rate into the future under the assumption of ~50% CAGR year-to-year growth, the peak rate at the year 2020 shows ~70 fold growth when compared with August 2010 peak data rate. For example, if the peak data rate per subscriber in 2010 is around 1 Mb/s, in 2020 the same subscriber would be expected to generate the peak data rate around 70 Mb/s. Note that this compound growth accounts only for a steady increase in the subscriber bandwidth, resulting from increased consumption of digital content, emergence of new subscriber applications, increase in the quality and resolution of video content, etc. Obviously, it does not account for new, revolutionary networked applications that do not exist today and their emergence is very hard to predict in any quantifiable manner.

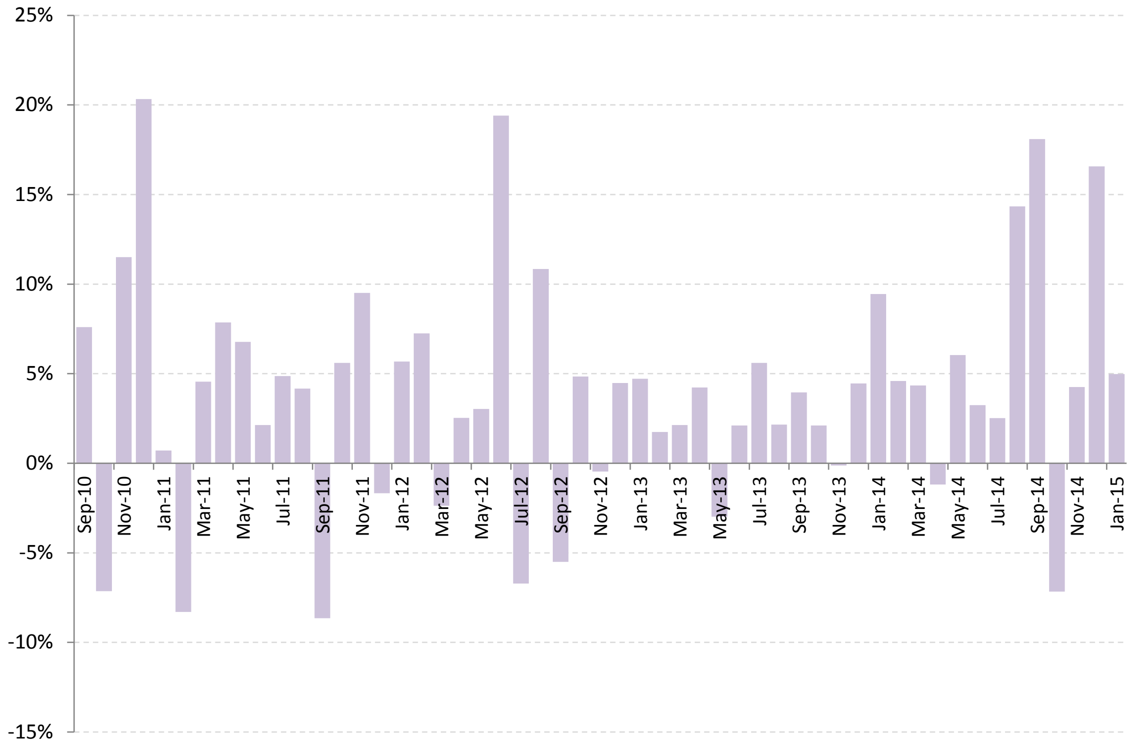


Figure 16: Average Subscriber Month-to-Month Change in Peak-Hour Data Rate

Figure 16 presents the month-to-month variations (as a percentage) of the peak-hour data rate consumed by an average subscriber in the examined network. The two major positive changes observed in December 2010 and June 2012 are the result of two events: changes in the offered subscriber data rates (increase) to a larger number of subscribers in the network footprint. The August/September 2014 change is mainly related to network architecture changes and are due to a new direct connect to Netflix Content Delivery Network (CDN), dramatically improving video quality and generating more traffic on average without increase in the number of connected subscribers or offered data rates. Overall, there is a steady trend to see month-to-month increase in peak data rate consumed per connected subscriber, mainly attributed to more diverse, video-rich content, rather than increase in the number of connected subscribers, which increased only by ~20% over the examined period of time.

4.4 Bit Rate Trends

There has been a clear historical trend of steadily increasing bandwidth consumption for residential and business subscribers. Figure 17, which shows maximum offered Internet bandwidth of North American cable operators, is indicative of this trend. Similar curves could be also drawn for other access media, including twisted pair, as well as fiber. The observed increase is primarily motivated by both evolutionary and revolutionary end-user applications, requiring online connectivity, and attracting larger quantities of individual consumers as well as driving the bandwidth consumption per single user.

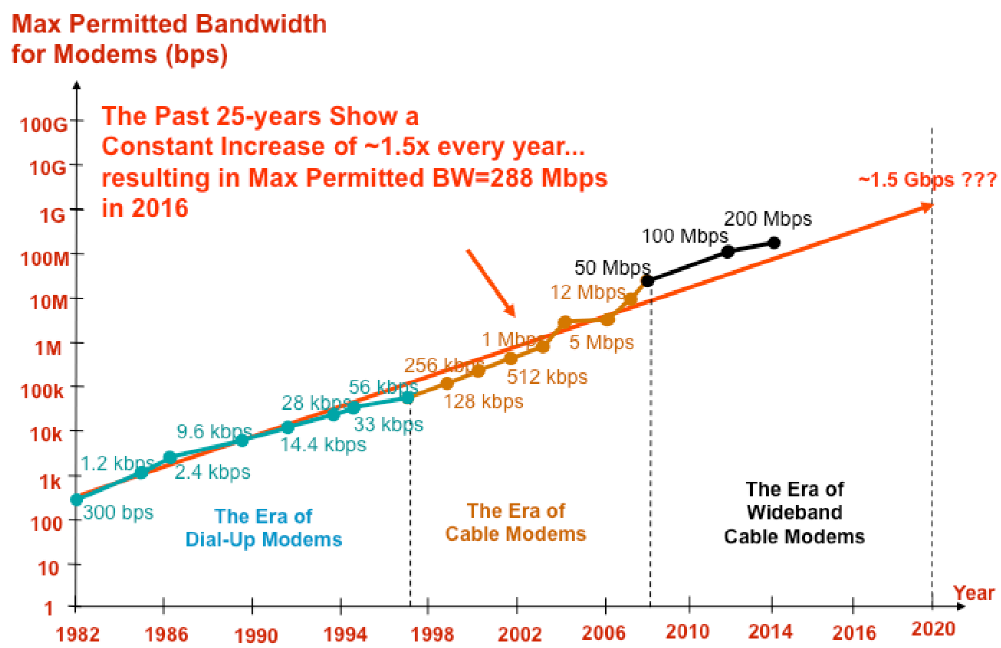


Figure 17: Advertised (maximum permitted) bandwidth [39]

Web 2.0 with its video-oriented and interactive content is one good example of a revolutionary change in the online services consumed by a large pool of users. The transition from Standard Definition (SD) to HD quality for streaming video services is an example of evolutionary change in the online services. Today (in 2014) we observe this transition as well, with some streaming platforms (for example, Netflix) beginning to offer 4K resolution content to their subscribers. It is expected that with the increasing popularity of 4K-compatible TV sets, the volume of 4K content is expected to become much larger, further increasing the average bandwidth consumption observed in the access network.

However, it is also necessary to remember that the number of simultaneous sessions established between the subscriber LAN and individual services, as well as the duration of such sessions also affect the total bandwidth consumed in the access network. In the era of dial-up modems, connections were typically made on demand, when the user needed to download and/or upload some data, resulting in short sessions, and typically very few simultaneous sessions established during such a connection. Along with the start of the era of broadband access devices and always-on network connectivity, the number and duration of individual data sessions increased substantially. Individual users started streaming data (music, video, and other content) directly off the web, rather than from local storage. There are also many more users online at any point of time, sharing a single access link and generating much more traffic on average than in the case of on-demand dial-up connections.

Various studies forecast that the average number of devices connected to the Internet (at any one time) per household can reach 5 by 2017 and 10 by 2020, comprising mostly portable personal electronic devices (tablets, smartphones, etc.) and smart home systems (home appliances, air conditioning, home security systems, etc.) [46], [47]. The rapidly emerging trends for the use of cloud storage and cloud computing systems [49] only add to offered load both in downstream and upstream directions, as content is now not only consumed by devices connected to the subscriber LAN, but also generated by subscribers and uploaded to the remote cloud storage for distribution to other connected devices.

More recently, even more content is being stored in the cloud (not on local LAN storage devices), requiring more downstream bandwidth, as well as improved upload capabilities, when compared to the previous generation of access networks. The increase in quality/resolution of multimedia content stored in the cloud, as well as close integration of cloud-based storage services with newer generations of computer operating systems provides a clear view of the always-connected future, where local storage would be mostly used for caching purposes only.

The current projections, shown in Figure 17, in terms of offered load per household (in residential applications) calls for approximately 300 Mb/s around end of year 2016. If the same trend in bandwidth consumption (~1.5 increase per year, following closely Nielsen's Law [50]) is observed in the following years close to 600 Mb/s per subscriber is expected to be demanded around 2020.

In the business application space, bandwidth requirements are typically quite different when compared to residential scenarios. This is primarily due to:

- Delivery of bandwidth symmetric services, where downstream and upstream bandwidth available to a connected subscriber is the same.
- Delivery of guaranteed bandwidth, where the purchased amount of bandwidth is allocated exclusively to the given subscriber and not shared with other subscribers.
- More stringent frame delay and frame delay variation requirements, especially for advanced applications like cellular backhaul and fronthaul.

It is worth noting that with the rapid adoption of FTTx services, the distinction between residential and business services is beginning to blur as far as bandwidth symmetry and quality requirements are concerned. With FTTH, it is not uncommon for operators to provide symmetric bandwidth, especially to higher subscriber tiers, to allow more streamlined usage of cloud-based services. There are also new business application products, where only part of the provisioned bandwidth is guaranteed, and the remainder is provided on a shared and best-effort basis.

The mobile cell backhaul—one of the business applications served today with EPON—has been steadily increasing bit rate requirements over the last few years. The bit rate increase is the direct result of several evolutionary changes in the cellular technology: migration from 2G to 3G and now 4G (LTE), increase in the number of mobile devices connected (on average) to a single cell tower, increase in the cell tower density per geographical area and resulting decrease in the area covered by a single cell tower to increase data rates and resulting capacity, as well as increase in data rates offered to each connected mobile device. Many studies (including [37]) demonstrate an explosive growth in the mobile traffic around the world, resulting in a steady increase in data rates per individual cell.

In order to cope with the increasing data rates served to wireless devices, cell tower operators also need to increase backhaul capacity to be able to receive data from the Internet and transmit user data to the Internet. As an example, a typical cell tower housing three different mobile service providers served with a third-party backhaul link aggregating traffic from all antennas on the cell tower was served with 100 Mb/s by the end of 2013. In order to cope with the increase in the mobile traffic, the very same cell tower had to be served with ~350 Mb/s circuit by the end of 2014, and it is further expected to be migrated to ~500 Mb/s circuit by the end of 2015. With the evolution towards bonding multiple LTE bands, it is likely that in 2016 the industry would see backhaul capacity grow in excess of 1 Gb/s per cell tower. Note that this trend is visible across the whole footprint of cell tower backhaul network, though might observe different timelines. For example, cell towers in large urban areas are upgraded more quickly, as their backhaul capacity is exhausted more rapidly, while cell towers in rural areas with lower customer density will see the backhaul capacity exhaustion take more time.

4.5 Forecasting Advertised Bandwidth for Residential Access

This section presents a forecast model for advertised bandwidth in residential access, which is independent from the actual observed offered load.

The most well-known method for forecasting advertised bandwidth over residential access systems comes from extrapolating “Nielsens’ Law of Internet Bandwidth” [50], which claims that a high-end user’s connection speed grows by 50% per year. This assertion is based (in recent years) on premium service levels offered over DOCSIS Hybrid Fiber-Coax (HFC) networks to J. Nielsen in the U.S. It is problematic to apply this “Law” to FTTH networks, as it has already failed, by an order of magnitude, to account for the recent proliferation of Gigabit offerings. Further, it only applies to the offered speed of Internet connections, excluding the connectivity for managed linear pay-TV, which represents a much larger component of a user’s traffic on all-IP video networks. Accordingly, an alternative method for forecasting maximum service level offerings is presented here.

Operators will only offer access speeds that can be realized using existing in-home networking solutions and also successfully verified by a subscriber. 1 Gb/s (and slower) wired Ethernet and wireless Ethernet solutions (cabling and terminals) remain predominant in most homes due to the low availability of 10 Gb/s Ethernet in home networking equipment. This means, in practice, that the current gigabit rate offerings already match the theoretical maximum network throughput of user terminals and home networks, leaving little justification for further increase in offered data rates.

A reasonable assumption can be made that operators will not offer tiers exceeding 1 Gb/s until home-networking equipment is available that can exceed this data rate.

Therefore, we posit that once advertised bandwidths reach the maximum capability of subscriber end terminals in the home network (which has already happened for FTTH networks), the maximum advertised bandwidth will be governed by the maximum bandwidth capability of subscriber end terminals in the home network. The latter is examined next.

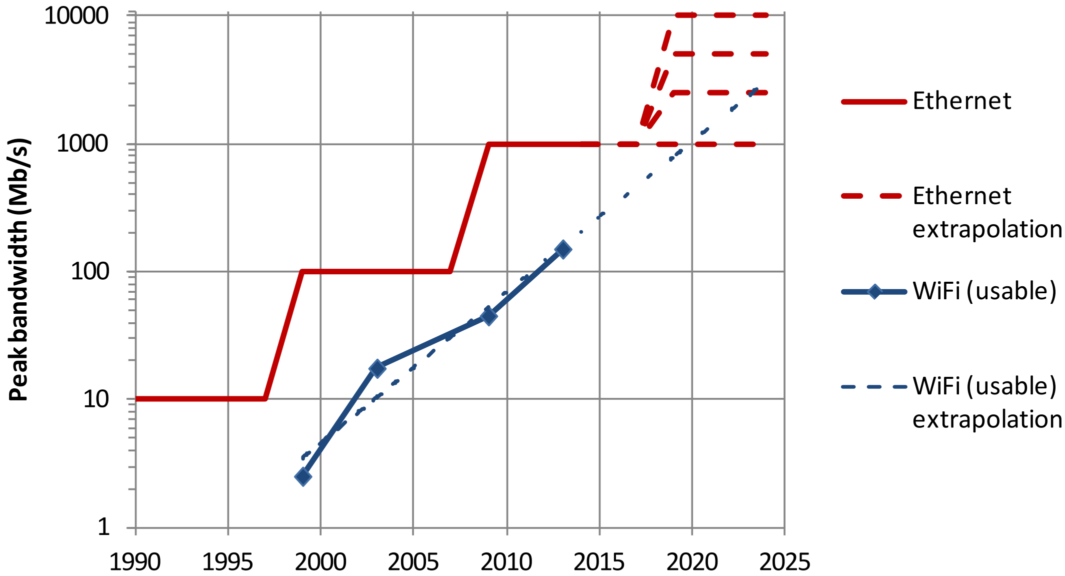


Figure 18: Evolution of Residential Home-Network Bandwidth

The solid red line in Figure 18 approximates the adoption of bandwidths supported by Ethernet LAN over unshielded twisted pair (UTP) in the home. Extrapolating this adoption trend predicts 10 Gb/s Ethernet over UTP in the home within the next 10 years. Alternatively, intermediate Ethernet speeds over cat-5 UTP are under consideration in IEEE 802.3 Working Group: 2.5 Gb/s and 5 Gb/s. Finally, it is possible that none of these higher speed technologies gain significant traction in the home, maybe because of the proliferation of wireless devices at the expense of wired devices. The dashed red lines in Figure 18 represent these four possibilities.

Figure 18 also shows the evolution of wireless Ethernet (802.11) speeds in home LANs, covering 802.11b, 802.11g, 802.11n, and early 802.11ac devices. A linear extrapolation (shown with a dashed blue line) indicates that a 3 Gb/s peak data rate should become available for the use in wireless home LANs within the next 10 years. However, at this time there is no demonstrated 802.11 technology able to support such data rates within wireless home LANs and it is not clear whether sustained 1 Gb/s data rates over wireless LAN are practical.

Accordingly, in 10 years maximum peak residential home network bandwidth will probably be limited to somewhere between 1 Gb/s and 10 Gb/s. Following the logic above, that operators won't offer speeds that can't be realized and verified in the home, the maximum advertised bandwidth will also be somewhere between (today's) 1 Gb/s and 10 Gb/s. In the context of defining NG-EPON, it makes sense to plan for the high end of that range, i.e., 10 Gb/s offered peak bandwidth. However, there is a good chance that this is overly aggressive in light of a preference for wireless connectivity in the home.

4.6 Downstream Bandwidth Consumption Forecast—Residential Access

4.6.1 FTTH

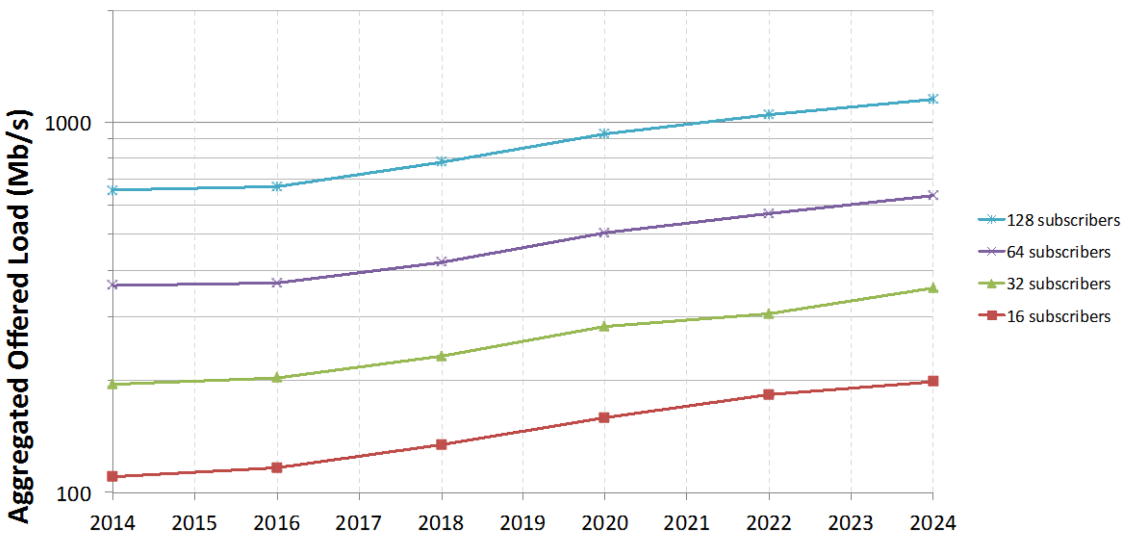


Figure 19: Forecasted Downstream Offered Load—Moderate Scenario on FTTH

The bandwidth requirement for a TDM-PON is a function of the aggregated offered load of all the subscribers on that PON. A statistical model, described in [16] and [18], forecasts aggregate residential downstream offered loads. The model attempts to bound the forecast with a “moderate” set of inputs and a “heavy” set of inputs. The heavy inputs, in relation to the moderate inputs, assume a larger number of concurrent video streams per home, relatively higher penetration of HD and UHD displays and higher availability of HD and Ultra-HD (UHD) content, lower video compression ratio for improved video quality, and faster growth in bursty traffic. In both examined scenarios, NG-EPON needs to be able to support the worst-case bandwidth consumption, where all video traffic, including all linear TV (i.e., traditional scheduled non-time-shifted television service), is transmitted as unicast to individual subscribers. The forecasts for aggregate offered load at peak-hours for both the moderate and heavy demand scenarios are presented in Figure 19 and Figure 20, respectively.

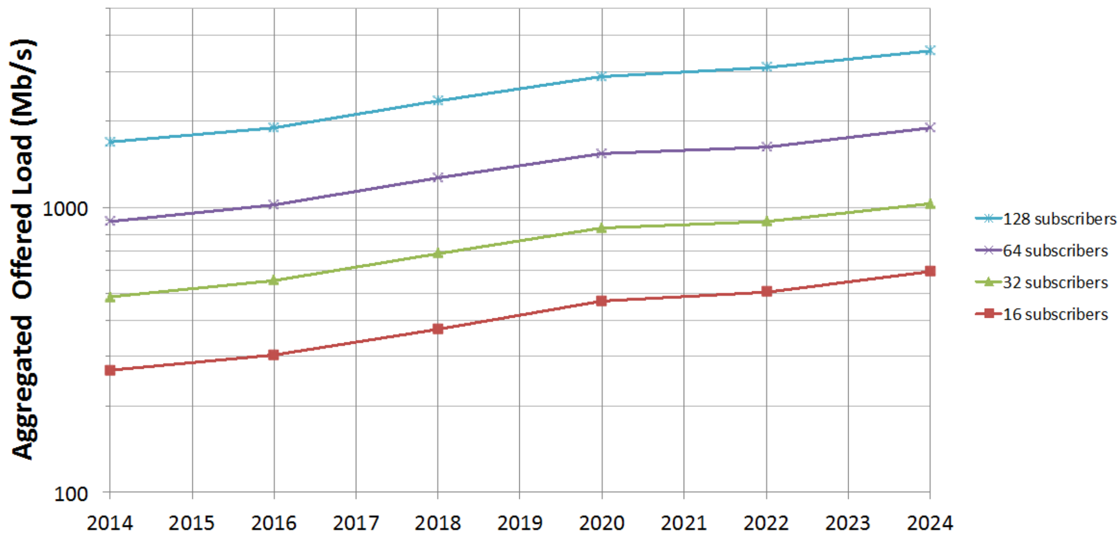


Figure 20: Forecasted Downstream Offered Load – Heavy Scenario on FTTH

The aggregated downstream offered load shown in Figure 19 and Figure 20 includes peak-hour sustained downstream offered load and peak-hour average burst downstream offered load. By far, most of the demand results from managed plus OTT video traffic.

Finally, it is necessary to add the maximum individual peak burst demand. Typically this is estimated based on the assumption that users will attempt to verify the network's ability to deliver the service to which they have subscribed.

For example, in 2024, it is expected that under the heavy demand scenario and with 32 subscribers the average offered load on a PON would be approximately 1 Gb/s of downstream peak hour traffic. If a 1 Gb/s service is offered over this PON, then 1 Gb/s of bandwidth headroom is required to support peak bursts of 1 Gb/s, resulting in the total aggregate downstream offered load of 2 Gb/s during peak hours. Using the model described above and these assumptions and a maximum advertised bandwidth of 1Gb/s, it can be concluded that, up to the year 2024, 10G-EPON can support the estimated offered load in residential access.

A worst-case example might assume a 10G-EPON network with 32 subscribers each consuming 4 simultaneous streams of UHD-2 "8K" video at 50 Mb/s each. Even with this additional offered load, the operator would still have enough headroom to support bursts, and therefore a service offering, of more than 2 Gb/s.

The maximum service levels supported by different FTTH technologies (both existing and emerging) by the year 2024 are shown in Figure 21 for the heavy-use scenario. These are determined by simply subtracting the forecasted aggregate demand in Figure 20 from the TDM-PON MAC downstream bandwidth capacity (minus network overheads).

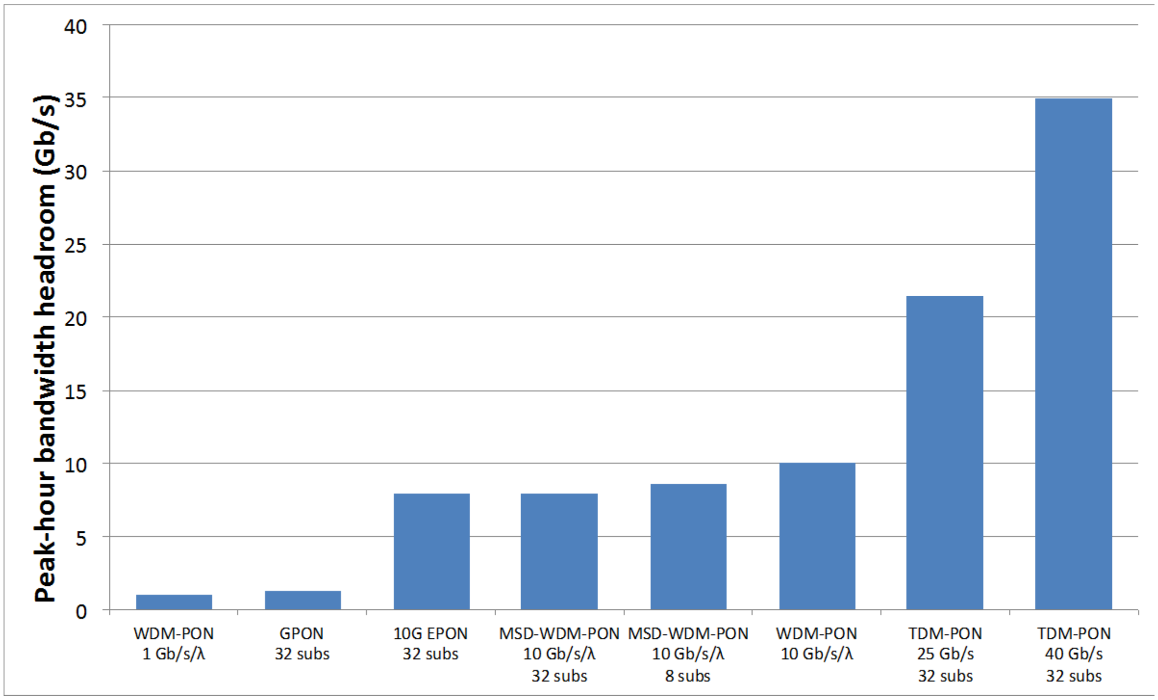


Figure 21: Peak-hour downstream bandwidth headroom for FTTH

Figure 21 indicates, from a residential downstream bandwidth point of view, that to significantly differentiate itself from existing 10G-EPON, an NG-EPON system will need to support more than 10 Gb/s service. In other words, a TDM-PON MAC must support an aggregate bit rate or a WDM-PON must support a per-wavelength bit rate of more than 10 Gb/s. Failing that, NG-EPON would not support significantly superior bandwidth service than can already be provided by 10G-EPON.

4.6.2 FTTB

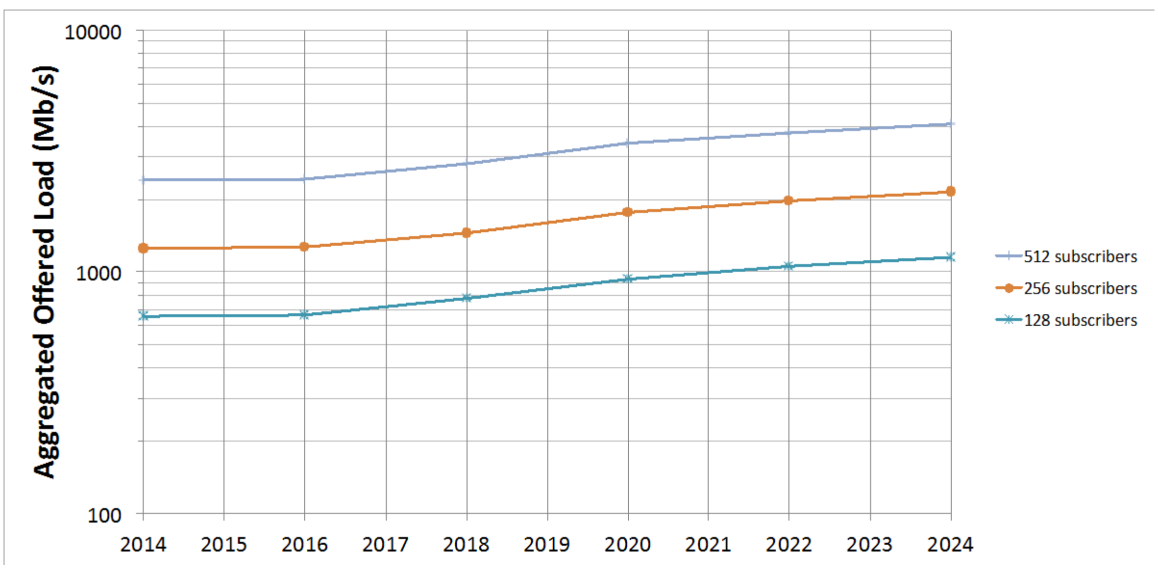


Figure 22: Forecasted Downstream Demand—Moderate Scenario on FTTB

The same methodology applies for analyzing FTTB. The difference is that multiple subscribers are served by a single ONU, and therefore there will typically be a larger number of subscribers per PON compared to FTTH (where the number of subscribers is limited by optical splitting). Subscriber aggregates of 128 to 512 are considered. The forecasts for aggregate bandwidth demand at peak-hours for both the moderate and heavy demand scenarios, for FTTB, are presented in Figure 22 and Figure 23, respectively.

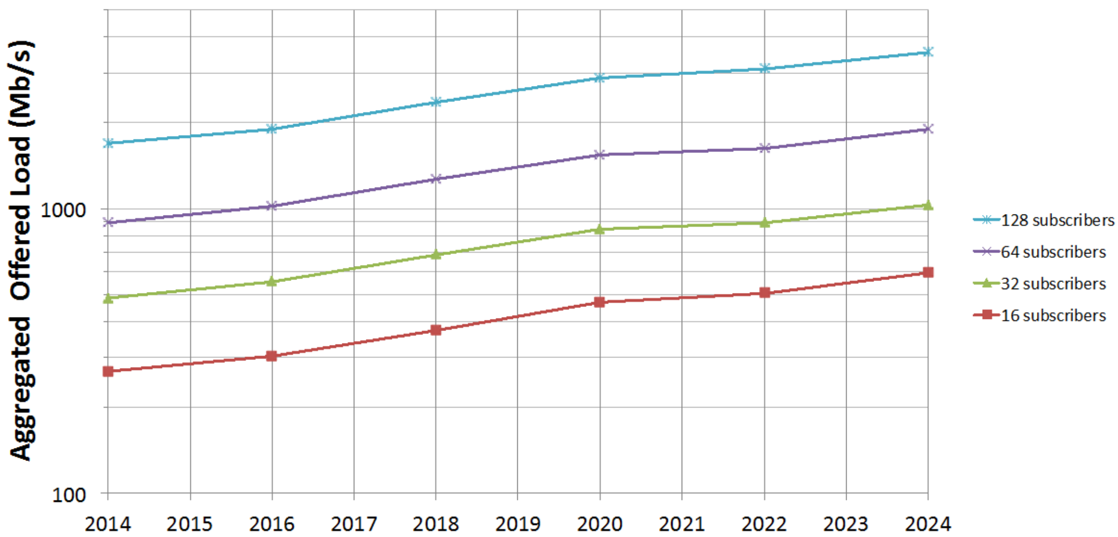


Figure 23: Forecasted Downstream Demand—Heavy Scenario on FTTB

These results indicate that 10G-EPON can support offered load in residential access up to the year 2024 in the moderate scenario, with sizable headroom. However for the heavy demand scenario, 512 subscribers will exhaust the capacity of 10G-EPON before 2018 (assuming 1 Gb/s headroom is required). This can be solved by either (1) limiting the number of subscribers per 10G-EPON via split ratio reduction, or (2) NG-EPON. Examples of NG-EPON implementations that could address this are: a higher speed TDM-PON (e.g., 25 Gb/s downstream); two 10 Gb/s wavelengths of hybrid PON; or logical PTP connections of more than 1 Gb/s (depending on the number of subscribers per ONU), either PTP fiber or a WDM-PON.

4.7 User Population/Split Ratio

ODN splitter architectures can be grouped into two categories: pay-as-you-grow approach and capital-expenditure (CAPEX) first approach.

In the pay-as-you-grow approach, the fiber drop (the fiber connecting from the last splitter to the ONU location) is connected to the splitter only when service is activated. An OLT port, feeder fiber, and splitter are all activated based on demand, and subscribers are connected only when service request comes in. Once the splitter is filled, a second OLT port, feeder fiber, and splitter are activated. This approach maximizes utilization of OLT and ODN resources and leads to relatively high fill ratios for splitters.

In the CAPEX-first approach, every possible potential user is pre-connected to a splitter port, and all splitters and OLT ports are pre-activated. This approach requires higher initial capital investment and typically leads to relatively lower splitter fill (on average, equal to the take rate), though has lower operational expenses (OPEX), as no truck rolls to the splitters are required to connect subscribers as they request service.

At this time, there are no consistent studies of the average number of subscribers connected to a single OLT port in FTTx architectures around the world. Using data on ONU and OLT port shipments around the world [35], it is possible to conclude that a rather low split ratio is most commonly used, ranging from 1:4 to 1:16, depending on the number of actual OLT ports brought into service. Most new FTTx projects assume 1:16 or 1:32 split ratios, primarily to offset CAPEX (electronics and fiber infrastructure) and future OPEX related primarily with fiber infrastructure. The number of actual connected and active subscribers is typically lower than the number of splits in the ODN connected to a single OLT port. Depending on the adopted deployment model, demographics, and local competition, take rates between 20 % and 90 % are common. Take rates of 100 % can only be achieved in communities where fiber is connected to all homes in the community and included in a contractual package for residents [48]. It is, therefore, typically very hard to predict with any level of confidence how many active subscribers are present on the access platform once it is deployed, at least as far as residential access is concerned. This deployment model also requires the operators to deploy the capacity first (CAPEX-first) and add subscribers on demand, as services are requested.

5 Requirements for NG-EPON

5.1 PON Capacity

NG-EPON aggregate system capacity requirements are driven by a number of factors, including the mix of services offered by the given service provider, subscriber population and demographics, etc. The evolution of existing services, as well as anticipated future service types, drive the need for different sustained and peak data rates, as well as different symmetry ratios between upstream and downstream data rates.

To address a cost-effective delivery of differentiated services over optical access networks, service providers expect to deliver services to both residential and business subscribers on the same access platform. In this case, requirements for the aggregate bandwidth supported by NG-EPON are primarily driven by business subscribers and their growing demand for higher bandwidth. Business subscribers are typically provided with symmetric service rates, while residential subscribers are typically provided with asymmetric service rates, thus NG-EPON is expected to support both symmetric and asymmetric data rates.

Projecting based on premium-tier offerings and market drivers in the business services market, NG-EPON is expected to support the aggregate capacity of at least 40 Gb/s in the downstream and upstream directions. Given that it is impossible to precisely predict future service evolution within the next decade, especially in terms of emergence of new disruptive services, NG-EPON needs to be designed in a scalable fashion to support also higher data rates up to at least 100 Gb/s.

5.2 ONU Capacity

Operators expect to use NG-EPON to provide service to two general classes of users: residential users and business users. Residential users tend to use data services asymmetrically (more downstream than upstream) and tolerate best-effort delivery. Business subscribers typically demand committed symmetrical data rates with frame-loss and delay limits. NG-EPON should support each of these user classes by enabling flexible ONU configurations.

In the short term, an NG-EPON ONU will need to support currently emerging 1 Gb/s residential Internet access services. By the year 2020 consumer grade electronics are expected to incorporate interfaces supporting data rates exceeding 1 Gb/s. An NG-EPON ONU will need to support delivery of up to 10 Gb/s burst rates to support the capabilities of those devices.

In contrast, an NG-EPON ONU supporting a business user will need to support at least 10 Gb/s, and provide options to enable delivery of flexible rates up to 40 Gb/s. By the year 2020, an NG-EPON ONU will need to support delivery of rates varying from 10 Gb/s up to 100 Gb/s to business users.

NG-EPON is expected to support such flexible ONU configurations and the coexistence of varying configurations on the same PON.

5.3 Split Ratios

Today operators deploying PON typically require the support for the split ratio of at least 1:32. NG-EPON is expected to support at least the same split ratio as 1G-EPON and 10G-EPON and should support a higher split ratio to increase subscriber density per OLT port. These target split ratios are applicable for all supported power budgets.

5.4 Nominal Reach

The target distance in EPON has always been limited by a combination of three factors: ODN loss, transmission impairments (mainly dispersion in 10G-EPON), and target split ratio. The combination of optical transmitters and receivers operating at the specific data rate can support a specific power budget, which the operator can trade for distance, split ratio, or a combination of both.

The target distance for optical access largely depends on the architecture of existing aggregation and metro networks, as well as placement of OLTs relative to population centers. Some operators prefer to maintain a relatively dense network of smaller OLT locations, allowing them to reach a large share of the local population using short access optical links. Other operators have chosen to actively consolidate their access infrastructure into fewer OLT locations, each location serving a larger geographical area. Obviously, in the second approach, the average distance to a connected subscriber is larger than in the first case, but operators justify the longer distances with OPEX savings gained by facility consolidation.

NG-EPON is expected to support the nominal reach of at least 20 km (between the OLT and the furthest ONU), and differential reach of at least 10 km. The nominal reach is the basis for the definition of a power budget for NG-EPON devices.

NG-EPON is expected to support the nominal reach greater than 20 km, where available power budget is traded for higher transmission penalties. This effectively means that the distance between the OLT and the furthest ONU may be longer than 20 km, in which case the available power budget may be decreased due to increased transmission penalties. Operation at a distance exceeding the nominal reach would not be guaranteed by the standard, but would not be precluded by the management and control plane.

5.5 Power Budgets

It is expected that NG-EPON can coexist with 1G-EPON and/or 10G-EPON (EPON) on the same ODN. It is therefore necessary for the NG-EPON to support the same power budgets as defined for EPON today. They are:

- Low-power budget class, which supports PON ODN with the insertion loss of ≤ 20 dB. The low-power budget is typically implemented in the form of PON ODN with the split ratio of at least 1:16 and the reach of at least 10 km.
- Medium-power budget class, which supports PON ODN with the insertion loss of ≤ 24 dB. The medium-power budget is typically implemented in the form of PON ODN with the split ratio of at least 1:32 and the reach of at least 10 km.

- High-power budget class, which supports PON ODN with the insertion loss of ≤ 29 dB. The high-power budget is typically implemented in the form of PON ODN with the split ratio of at least 1:32 and the reach of at least 20 km.
- Extended-power budget class, which supports PON ODN with the insertion loss of ≤ 33 dB. The extended power budget is typically implemented in the form of PON ODN with the split ratio of at least 1:64 and the reach of at least 20 km.

The power budget supported by the pair of ONU and OLT PHYs allows an operator to trade distance for split ratio and vice versa, just like EPON today. Operators may therefore implement a PON ODN with the maximum distance between the OLT and the ONU exceeding the nominal reach associated with the given power budget class, while decreasing the implemented split ratio to compensate for increased insertion loss and dispersion penalty.

5.6 Optical Distribution Network

It is expected that NG-EPON can coexist with 1G-EPON and/or 10G-EPON (EPON) on the same ODN. It is necessary for the NG-EPON to operate over the same single-mode fiber used by EPON today, i.e., IEC 60793–2 B1.1 and B1.3 [24], ITU-T G.652 [19], and/or ITU-T G.657 [20] in any combination. Moreover, NG-EPON is expected to operate over the same passive splitters/couplers and other passive elements of the ODN, including connectors, splices, etc.

Given the large number of deployed PON ODNs following requirements established for EPON, the wavelength allocation plan selected for NG-EPON is not expected to require replacement of existing ODN elements. This is especially critical for operators with already deployed EPON infrastructure, where any changes to the ODN are labor intensive and typically very expensive.

EPON ODN is deployed today in different architectures (see section 3.4 for more details), depending on the redundancy requirements, fiber trunk availability, and operator preferences. It is expected that NG-EPON operates over already deployed EPON ODN architectures and does not put additional requirements for a specific ODN architecture to operate properly.

5.7 Backward Compatibility and Coexistence

Many operators expect that NG-EPON will maintain the ability to coexist and be backward compatible with the two previous generations of EPON.

A gradual evolution from 1G-EPON systems towards 10G-EPON, while allowing operators to take full advantage of deployed active equipment, was one of the cornerstone requirements during the development of 10G-EPON technology [14]. The resulting development of a dual-rate OLT (capable of operating in 1G-EPON and 10G-EPON mode in the upstream and downstream directions) provided a clear evolution and migration path to 10G-EPON.

5.7.1 Coexistence of 1G EPON and 10G-EPON

Figure 24 presents the starting point for the evolution from 1G-EPON to 10G-EPON, where all active devices in the TDM-PON are of the 1G-EPON type.

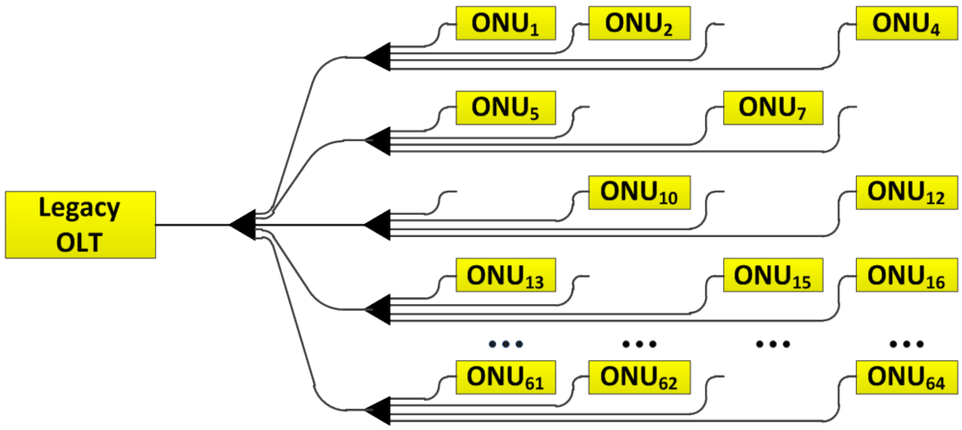


Figure 24: EPON Access: Starting Point with 1G-EPON Devices

During a maintenance window, an operator would replace the line card on the OLT, converting a dedicated 1G-EPON line card to a dual-rate line card capable of operating at 1G-EPON and 10G-EPON modes simultaneously. This situation is presented in Figure 25. All ONUs connected to this port continue to operate in 1G-EPON-mode only.

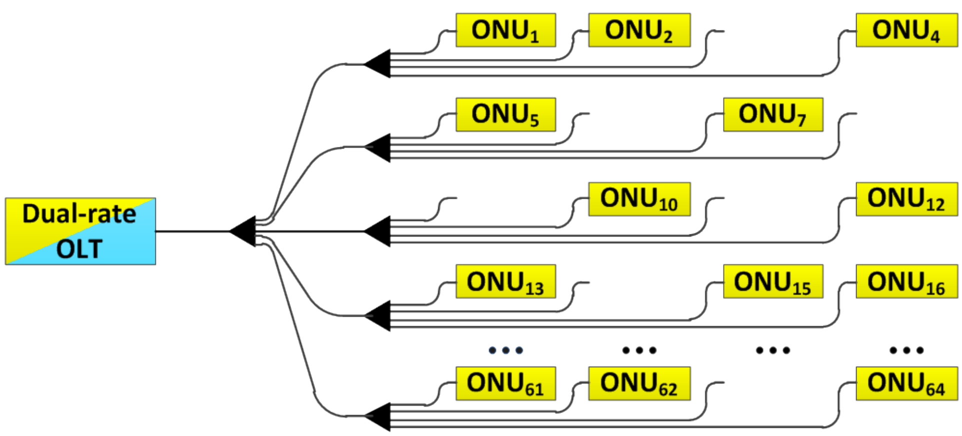


Figure 25: EPON Access: Dual-Rate OLT Port

Once the maintenance on the OLT port has been completed, new subscribers may be connected to currently unoccupied ports on the splitter(s) and be served with 10G-EPON ONUs. It is also possible to upgrade some of the existing subscribers served with 1G-EPON ONUs to higher speed 10G-EPON ONUs. Such a decision is typically driven by a demand for higher tier services purchased by selected subscribers. This scenario is shown in Figure 26, where 1G-EPON and 10G-EPON ONUs coexist on the same PON.

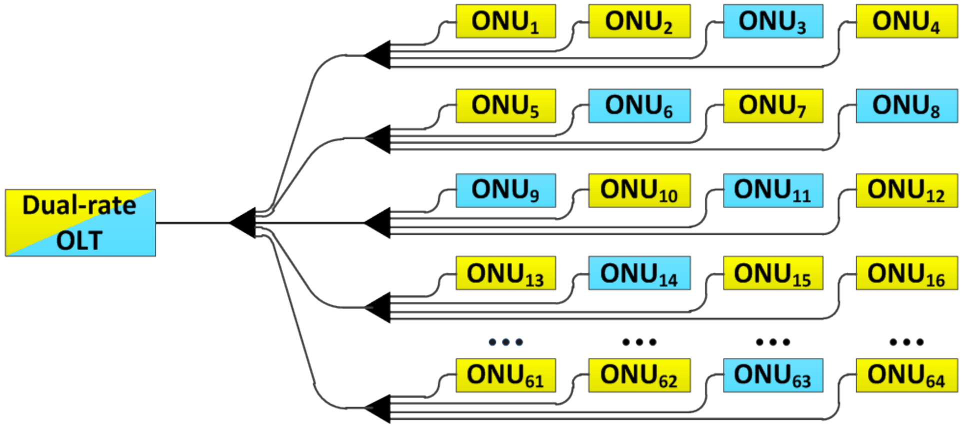


Figure 26: EPON Access: 1G-EPON and 10G-EPON ONUs Coexist on the Same ODN

Over time most of the existing ONUs get upgraded to 10G-EPON, as the cost of 10G-EPON devices decreases and approaches the cost of 1G-EPON devices. This scenario is shown in Figure 27. Note that the resulting network may operate in a dual-rate mode for a very long time, since the transition from 1G-EPON to 10G-EPON is primarily motivated by the service upgrades for existing subscribers, as well as cost decrease of 10G-EPON devices.

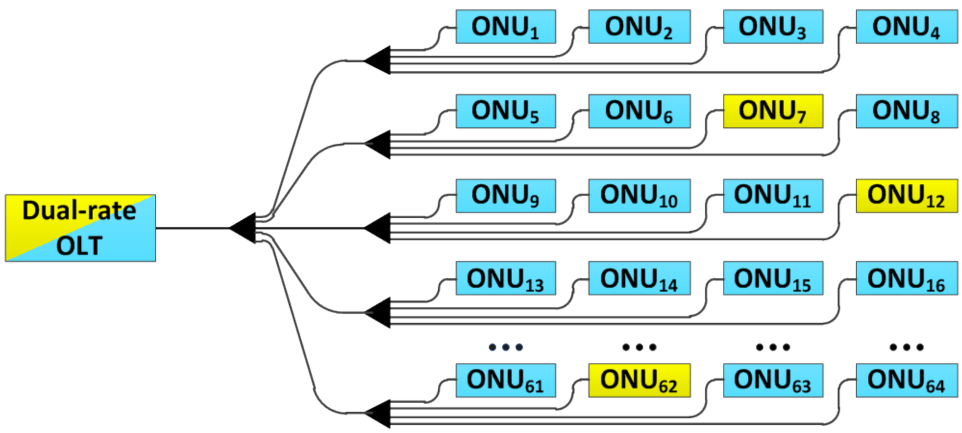


Figure 27: EPON Access: 1G-EPON and 10G-EPON ONUs Coexist on the Same ODN

The evolution scenario described above assumes the deployment of a dual-rate OLT, capable of operating at 1G-EPON and 10G-EPON modes simultaneously. This requires that 1G-EPON and 10G-EPON transmissions be time-interleaved in the upstream using a dual-rate burst mode receiver at the OLT as described in IEEE Std 802.3-2012 [4].

A drawback of this approach is that the ability to support 1G-EPON is essentially paid for twice—once with the purchase of the 1G-EPON ports and then with the purchase of the dual-rate port capable of supporting 1G-EPON and 10G-EPON. The other potential drawback is the practical aspect of dual-rate 1G-EPON/10G-EPON OLT ports, which provide lower port density per line card when compared with dedicated 1G-EPON or 10G-EPON line cards.

However, it is also possible for an operator to deploy separate 1G-EPON and 10G-EPON OLT ports, and then combine downstream 1G-EPON and 10G-EPON wavelengths and split the respective upstream wavelengths using a discrete wavelength splitter/combiner device external to the OLT ports. This solution provides a higher OLT port density per line card, and eliminates the need to repurchase the OLT ports, though the operator needs to make sure that 1G-EPON and 10G-EPON upstream wavelengths can be WDM-separated into dedicated OLT ports. In practice, this requires the use of 1G-EPON ONUs equipped with more narrow-band upstream transmitters, typically centered around 1310 nm with 40 nm or even 20 nm band rather than 100 nm band allowed by 1G-EPON equipment compatible with [4].

5.7.2 Migration to NG-EPON and Coexistence with 1G-EPON and 10G-EPON

When evaluating migration scenarios for NG-EPON, NG-EPON designers need to assume that the access network will include a mixture of 1G-EPON and 10G-EPON devices. They should also assume that these devices will be deployed in either of the coexistence modes discussed in section 5.7.3. Assuming that 1G-EPON ONUs remain in the network and coexist on the same ODN with both 10G-EPON as well as NG-EPON ONUs, a triple-rate OLT may need to be deployed first, preparing the given ODN for NG-EPON ONUs.

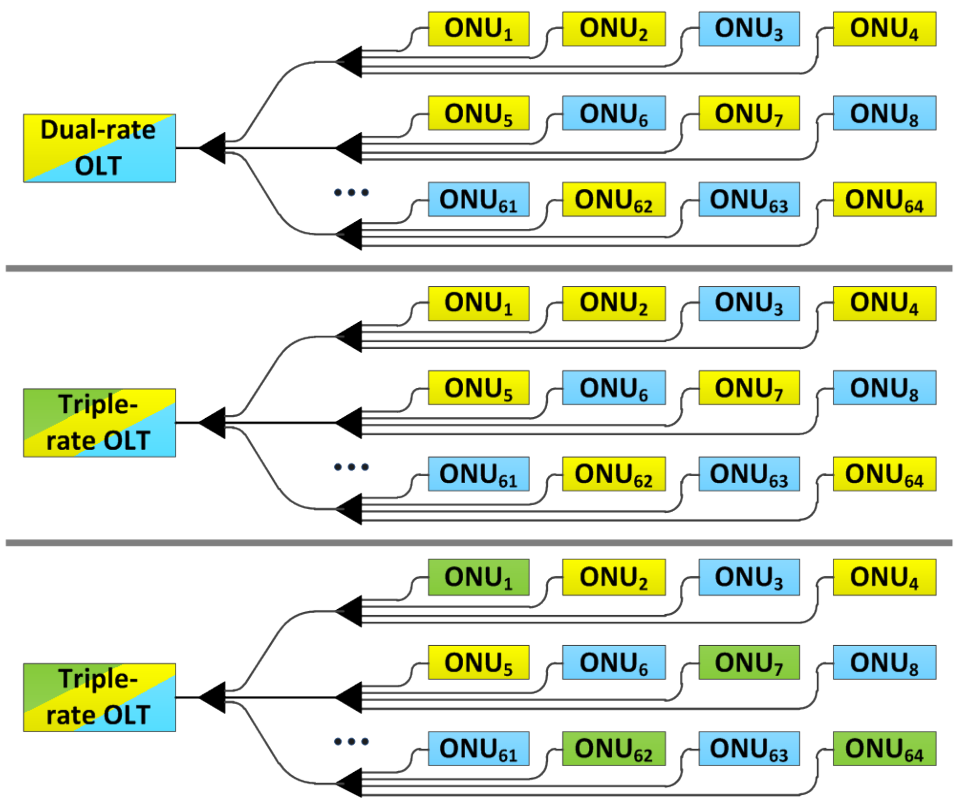


Figure 28: Evolution from 1G-EPON and 10G-EPON Network to Three-Generation EPON Access

Only when the NG-EPON OLT port becomes available, may NG-EPON ONUs be connected to the ODN, occupying previously unoccupied drop fibers, or replacing 1G-EPON or 10G-EPON ONUs, as service requirements for selected subscribers exceed the capacity of 1G-EPON or 10G-EPON systems. This evolutionary approach becomes increasingly complex, especially because of the exhaustion of the fiber spectrum. It is also inefficient for the operator to repurchase 1G-EPON and 10G-EPON OLT port that has been already paid for by the time 1G-EPON and 10G-EPON have been deployed.

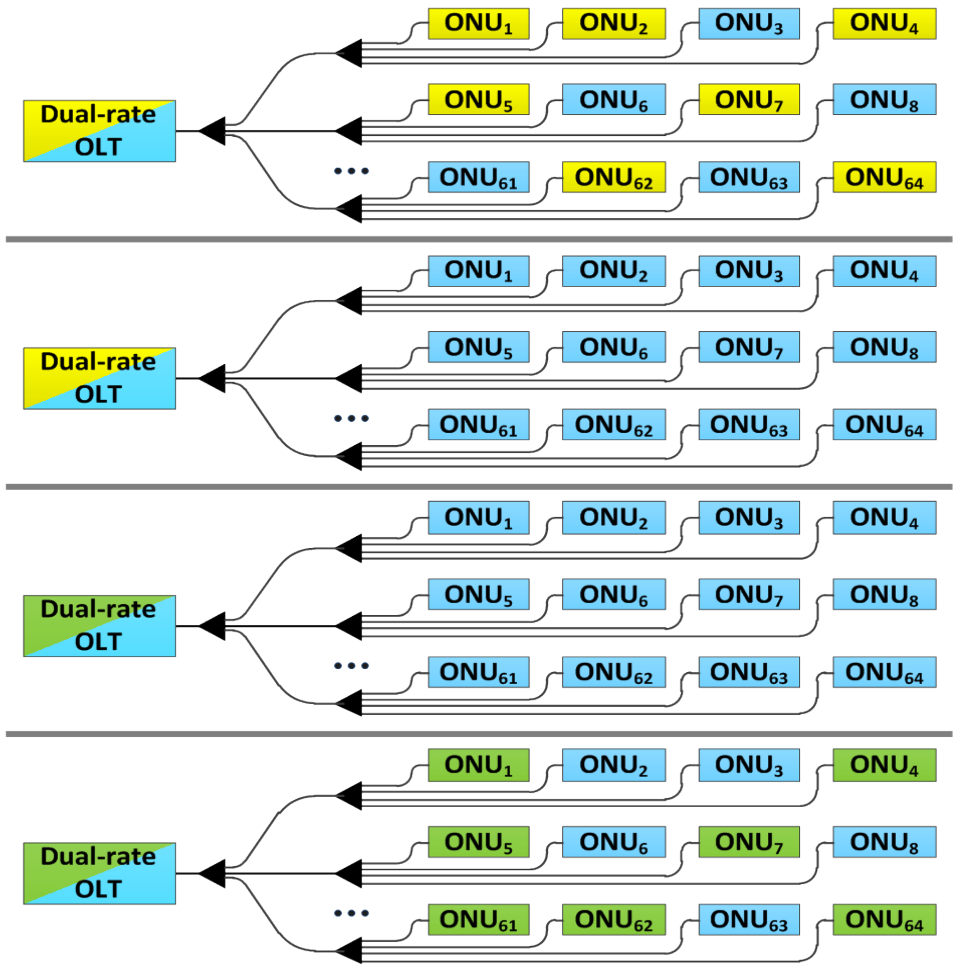


Figure 29: Evolution from 1G-EPON and 10G-EPON Network to Two-Generation EPON Access

An alternative approach (see Figure 29) assumes coexistence of only two EPON generations on the same ODN. Before deploying NG-EPON devices, the operator upgrades all 1G-EPON ONUs to 10G-EPON ONUs, replacing the dual-rate OLT port operating in 1G-EPON and 10G-EPON with a dual-rate OLT port capable of operating in 10G-EPON and NG-EPON modes. Once the OLT port upgrade is done and all 1G-EPON active devices have been removed from the given ODN, the NG-EPON ONUs can be deployed. In this particular scenario, the NG-EPON may partially or completely reuse 1G-EPON downstream and/or upstream spectrum, assuming that TDM or WDM separation between 10G-EPON and NG-EPON upstream channels is possible. Once all 1G-EPON active devices have been removed from the given ODN, the NG-EPON may partially or completely reuse 1G-EPON downstream and/or upstream spectrum, assuming that TDM or WDM separation between 10G-EPON and NG-EPON upstream channels is possible.

5.7.3 Coexistence and Backward Compatibility

Some operators consider a critical characteristic of NG-EPON to be backward compatibility and coexistence with 1G-EPON, 10G-EPON, and RF overlay systems on the same ODN. There are several deployment scenarios for NG-EPON systems, with different coexistence and backward compatibility requirements. The resulting wavelength allocation for NG-EPON needs to account for these different deployment scenarios, while observing technical and economic feasibility.

Note that there are two main types of deployed RF overlay systems, as follows:

- Unidirectional (downstream-only, with center wavelength at 1550 nm) RF overlay with digital return channel.
- Bidirectional (with downstream center wavelength at 1550 nm and upstream center wavelength at 1610 nm or 1310 nm) RF overlay [53] with analog return channel.

The bidirectional RF overlay scheme is defined by SCTE in [53] and is referred to as RFoG.

Unidirectional RF overlay and the 1610 nm variant of RFoG can coexist with 1G-EPON and 10G-EPON on the same ODN. The 1310 nm variant of RFoG cannot coexist on the same ODN with 1G-EPON or 10G-EPON. This variant is rarely, if ever, used and is excluded from the following analysis.

5.7.3.1 NG-EPON in Green-Field Scenario

When deployed in the green-field scenario, NG-EPON does not have any specific coexistence and backward compatibility requirements. The wavelength allocation plan selected for NG-EPON for this scenario needs to make the most optimum use of the available SMF spectrum.

5.7.3.2 NG-EPON Coexisting with 1G-EPON and Optional RFoG

When deployed in a brown-field scenario on the ODN carrying 1G-EPON and optional RFoG, there are several requirements that the NG-EPON needs to meet, as follows:

- NG-EPON downstream channel does not overlap with and impact the downstream 1G-EPON channel and downstream RF channel.
- NG-EPON upstream channel does not overlap with and impact the upstream 1G-EPON channel and optional RF upstream (return) channel.
- NG-EPON upstream and downstream channels do not require any changes in the design of wavelength blocking filters in 1G-EPON ONUs and RFoG ONU already deployed in the field.

Effectively, the wavelength plan selected for NG-EPON needs to avoid the wavelength bands allocated to 1G-EPON and RFoG, and simultaneously use wavelength bands rejected by the wavelength blocking filters in deployed 1G-EPON and RF ONUs devices.

5.7.3.3 NG-EPON Coexisting with 10G-EPON and Optional RFoG

When deployed in a brown-field scenario on the ODN carrying 10G-EPON and RFoG, there are several requirements that the NG-EPON needs to meet, as follows:

- NG-EPON downstream channel does not overlap with and impact the downstream 10G-EPON channel and downstream RF channel.

- NG-EPON upstream channel does not overlap with and impact the upstream 10G-EPON channel and optional RF upstream (return) channel.
- NG-EPON upstream and downstream channels do not require any changes in the design of wavelength blocking filters in 10G-EPON ONUs and RFoG ONU already deployed in the field.

Effectively, the wavelength plan selected for NG-EPON needs to avoid the wavelength bands allocated to 10G-EPON and RFoG, and simultaneously use wavelength bands rejected by the wavelength blocking filters in deployed 10G-EPON and RF ONUs devices.

5.7.3.4 NG-EPON Coexisting with 1G-EPON, 10G-EPON, and Optional RFoG

When deployed in a brown-field scenario on the ODN carrying 1G-EPON, 10G-EPON, and optional unidirectional/bidirectional RFoG, NG-EPON needs to simultaneously meet requirements listed in sections 5.7.3.2 and 5.7.3.3.

5.7.3.5 NG-EPON Coexisting with 1G-EPON, 10G-EPON, but no RFoG

Given the ongoing migration from RF delivery systems towards all-IP delivery paradigm in some networks, it is likely that by the time NG-EPON is deployed in the field, RFoG is not likely to be actively deployed anymore in such networks. The aggregate capacity of NG-EPON is expected to further stimulate the migration to all-IP delivery model, and in case of some operators this process would release the downstream and upstream RFoG channels for the use by digital transmission systems.

Some operators expect NG-EPON to support coexistence with 10G-EPON on the same ODN in the following manner:

- WDM coexistence in the downstream direction, i.e., NG-EPON operates in a wavelength band that does not overlap or impact downstream 10G-EPON wavelength band.
- WDM or TDM coexistence in the upstream direction, where the WDM coexistence is preferred. The TDM coexistence mode builds on the principle of dual-rate burst-mode operation supported by 10G-EPON when sharing the upstream channel with broad-spectrum 1G-EPON ONU transmitters. The WDM coexistence mode builds on the principle of wavelength filtering, for example, when narrow-band (40 nm or even 20 nm) optics is used in deployed 1G-EPON ONU transmitters.

NG-EPON is expected to support coexistence with 1G-EPON on the same ODN in the following manner:

- WDM coexistence in the downstream direction, i.e., NG-EPON operates in a wavelength band that does not overlap or impact downstream 1G-EPON wavelength band,
- WDM or TDM coexistence in the upstream direction, where the WDM coexistence is preferred. The TDM coexistence mode builds on the principle of dual-rate burst-mode operation supported by 10G-EPON when sharing the upstream channel with broad-spectrum 1G-EPON ONU transmitters. The WDM coexistence mode builds on the principle of wavelength filtering when narrow-band (40 nm or even 20 nm) optics is used in deployed 1G-EPON ONU transmitters.

5.7.3.6 NG-EPON and 10G-EPON ONUs

It is highly desired that an NG-EPON OLT allow a 10/10G-EPON ONU to register and operate as if it were connected to a 10G-EPON OLT.

5.7.3.7 Wavelength Allocation for NG-EPON

Requirements for backward compatibility and coexistence are also expected to drive the process of selecting the target wavelength allocation plan for NG-EPON. For multi-wavelength PONs (WDM-PON or Hybrid-PON), in order to alleviate inventory and logistical tasks for service providers, it is highly desirable that the allocation of the downstream and/or upstream wavelength channels to an ONU be configurable dynamically via the OLT. The operation of the wavelength configuration protocol needs to be reliable and prevent a situation in which an ONU after a reboot/reset impacts other subscribers by transmitting on incorrect upstream wavelength channels.

The specific number of downstream and upstream channels allocated within the selected wavelength windows depends on the aggregated bandwidth per OLT port, wavelength grid spacing, as well as wavelength stability at the ONU. The allocation of transmission windows and individual channel assignments would be addressed by the future NG-EPON Task Force, taking into consideration many aspects of PHY operation, including requirements for coexistence and backward compatibility, aggregate capacity, etc.

5.8 Pluggable Optics

For a residential-class and a business-class ONU, it is highly desirable that pluggable PON optics is supported.

In case of fixed wavelength optics, pluggable PON optics limits inventory problems, allowing an operator to reuse the same ONU model in different locations and equip it with required fixed wavelength transceivers on demand.

In case of tunable optics, pluggable PON optics simplifies the deployment process and limits inventory problems, allowing the ONU to be upgraded to support larger number of wavelength channels (provided that electronic front end is designed accordingly).

5.9 Power Saving

Power conservation and reduction of the carbon footprint of access networks is globally recognized as one of the technical targets for the optical access networks. The objectives of the power-saving mechanisms are to reduce ecological impact, reduce operating cost, and extend battery backup time (if supported by the given product), while minimizing any degradation of network performance to maintain the configured service level agreement (SLA).

It is expected that NG-EPON supports power-saving mechanism available today for 1G-EPON and 10G-EPON systems, defined in [5], providing decreased power consumption for ONUs while maintaining the configured SLA. The power-saving mechanism needs to be fully configurable on a per-ONU or per-OLT port basis, providing the operator with full control of the sleep period, detection threshold for ONU inactivity, and other parameters. The NG-EPON OLT is expected to support a mix of ONUs with enabled power-saving mechanism and with disabled power-saving mechanism on the same OLT port. The NG-EPON OLT is expected to support different configuration parameters for the power-saving mechanism for different groups of ONUs on the same OLT port.

At the same time, it is also expected that NG-EPON OLT implements more advanced power-saving mechanisms, disabling inactive OLT ports, inactive wavelengths on OLT ports, whole line cards (when inactive), etc. OLT power saving mechanisms become increasingly important for high-density optical access platforms to avoid substantial increase in drawn power, but also in cooling/ventilation necessary to keep the OLT within its operating conditions.

5.10 Service Types

NG-EPON is expected to support all the mechanisms necessary to implement differentiated QoS. It is highly desirable that NG-EPON be able to support both residential and business subscribers on the same OLT through properly defined QoS enforcement mechanisms that can be configured to support target SLAs for each subscriber type.

Many operators support prioritized traffic management for voice and managed IPTV services. Internet access is usually provided best-effort (BE) service, with an associated service profile that specifies the peak bandwidth and a number of other operating parameters.

A typical business service is provided with guaranteed bandwidth, where the minimum guaranteed and peak bandwidth parameters in the associated SLA profile are set to the same value. Subscribers with such service profiles are therefore guaranteed access to the medium, and careful network engineering prevents oversubscription of OLT ports that such users are connected to. Such services are typically provided for cell tower backhaul, larger enterprise business subscribers, dedicated Internet access (DIA) circuits for educational institutions, etc.

Smaller business subscribers or business subscribers with less stringent SLA requirements are offered a medium-effort service type, where the SLA profile provides the subscriber with both guaranteed and best-effort bandwidth components. However, in the case of medium-effort services, the guaranteed bandwidth component is set to a value smaller than peak bandwidth, still providing guaranteed bandwidth but in the amount necessary to maintain basic network connectivity.

The following sections are examples provided by network operators of services and deployments of EPON.

5.10.1 Residential services

In this service type, IP connections from subscribers' customer premises equipment (CPE) connected to the ONU are carried across the PON and then routed to the public Internet across the converged transport network.

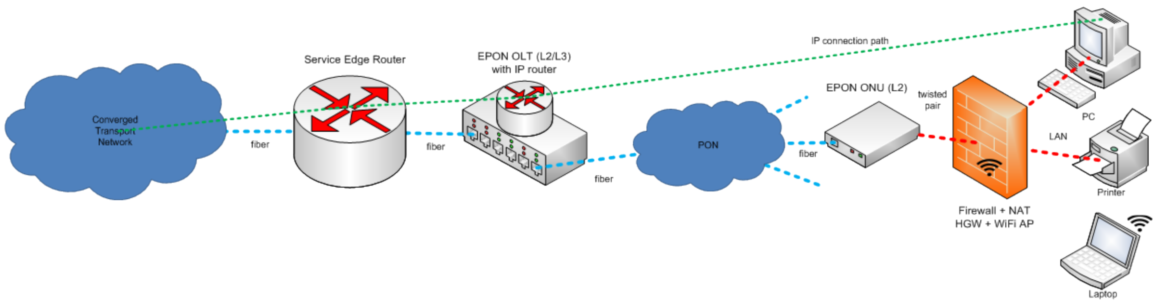


Figure 30: Architecture of a Residential FTTH Services

In many cable operator-specific access networks providing residential services, the provisioning processes are derived from their DOCSIS counterparts, following the DPoE service and provisioning models. This means that all the existing tools and backoffice procedures developed over the years to deploy, manage, and bill DOCSIS-based residential subscribers are directly applicable to residential subscribers served over EPON. The obvious differences are the physical media (fiber rather than coax) and the possible bandwidth tiers—providing up to 1 Gb/s symmetric services today (over 1G-EPON) and soon to exceed this value once 10G-EPON is deployed commercially.

5.10.2 Direct Internet Access

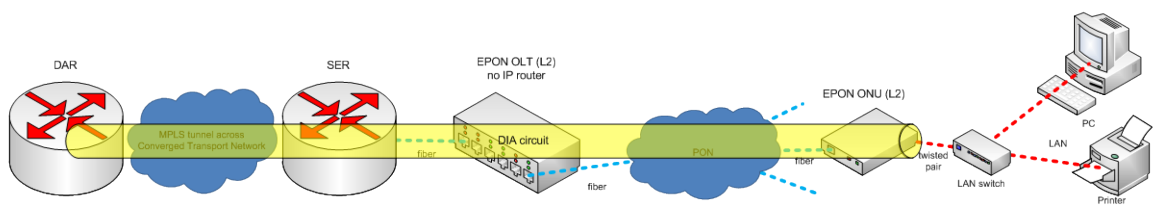


Figure 31: Architecture of DIA service

Direct Internet Access (DIA) is a type of business service in which the subscriber receives a connection to the public Internet. Often, when implementing DIA, the OLT does not operate in the routed mode. Instead all Internet data between the subscriber CPE and the Internet is carried within a L2 tunnel based on a pre-configured combination of IEEE Std 802.1Q [2] VLAN tags to an IP router. Figure 31 presents an example of a typical DIA service implementation over EPON.

5.10.3 MEF services

Metro-Ethernet Forum (MEF) services are used to interconnect two or more subscriber locations across the service provider's network. Similar to DIA the OLT does not operate as an IP router, and data generated by the subscriber at one site is transported to the other location in a dedicated L2 tunnel, less locally significant layer-2 control protocol (L2CP) traffic. This L2 tunnel is designed based on a pre-configured combination of IEEE Std 802.1Q [2] VLAN tags.

There are several types of MEF services that can be supported over the EPON, namely: E-LINE, E-TREE, and E-LAN. These individual MEF service types can be demonstrated using Figure 32 as the reference access network architecture.

An E-LINE service spans between a user-network interface (UNI) (UNI1, UNI2, or UNI3) on any of the ONUs connected to the OLT, and a single remote UNI. Effectively, each E-LINE creates a simple point-to-point tunnel between the selected MEF UNIs.

An E-TREE service creates a rooted multipoint service that connects a number of UNIs providing sites with hub and spoke multipoint connectivity. Each UNI is designated as either 'root' or 'leaf'. A root UNI can communicate with any leaf UNI, while a leaf UNI can communicate only with a root UNI. An E-TREE root could be located at the OLT, and individual leaf sites at UNI1, UNI2, or UNI3. Alternatively, the root could be located at the remote UNI4, and individual leaf sites at UNI1, UNI2, or UNI3.

An E-LAN service creates a multipoint-to-multipoint service that connects a number of UNIs (2 or more) providing full mesh connectivity for those sites. Each UNI can communicate with any other UNI that is connected to that Ethernet service. In the architecture shown an E-LAN could be created among UNI1, UNI2, and remote UNI4.

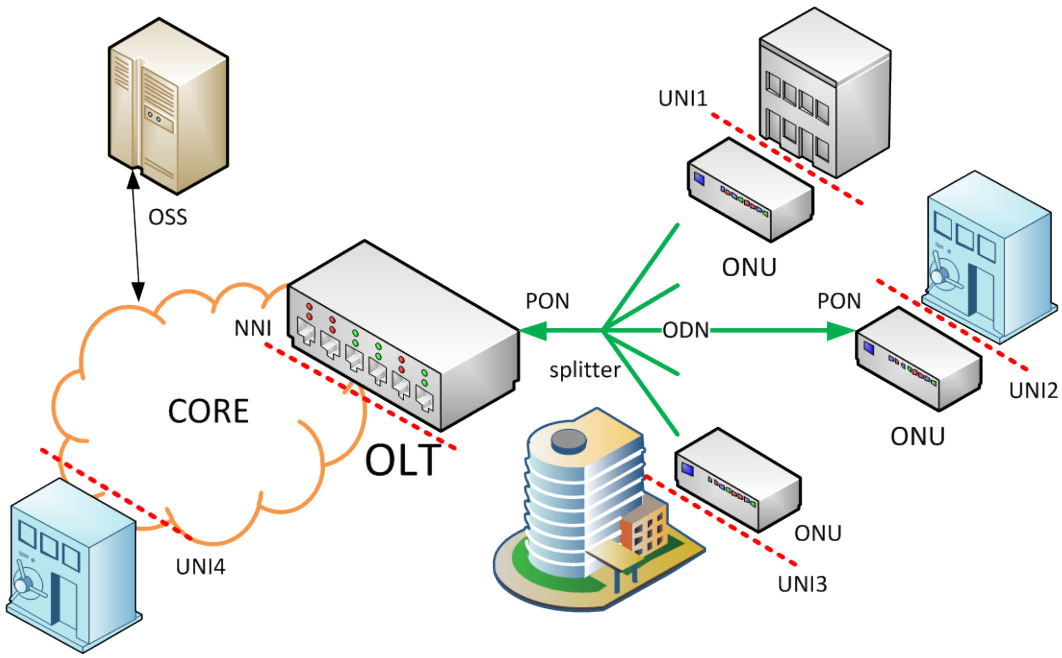


Figure 32: Reference Scenario for Description of MEF Service Types

Each MEF service type can be further sub-divided into Private and Virtual service. Therefore, we have the following:

- EP-LINE: Ethernet Private Line
- EV-LINE: Ethernet Virtual Line
- EP-LAN: Ethernet Private LAN
- EV-LAN: Ethernet Virtual LAN
- EP-TREE: Ethernet Private Tree
- EV-TREE: Ethernet Virtual Tree

In a Private service type, each UNI is associated with one and only one service delimitating VLAN tag. All users connected to such a MEF UNI share a single MEF service instance.

In a Virtual service type, each UNI is associated with at least two service delimiting VLAN tags, effectively creating multiple MEF Ethernet Virtual Circuits (EVC) on a single physical UNI. In such an arrangement, each MEF service is connected to at least one other UNI.

From a provisioning perspective, the difference between private and virtual MEF services lies only in association of individual services (service flows) to individual UNIs on the ONU:

- Multiple instances of virtual services are assigned to one and the same physical UNI, sharing its bandwidth.
- A single private service instance is always assigned to one dedicated physical UNI; no other service instances share this particular UNI.

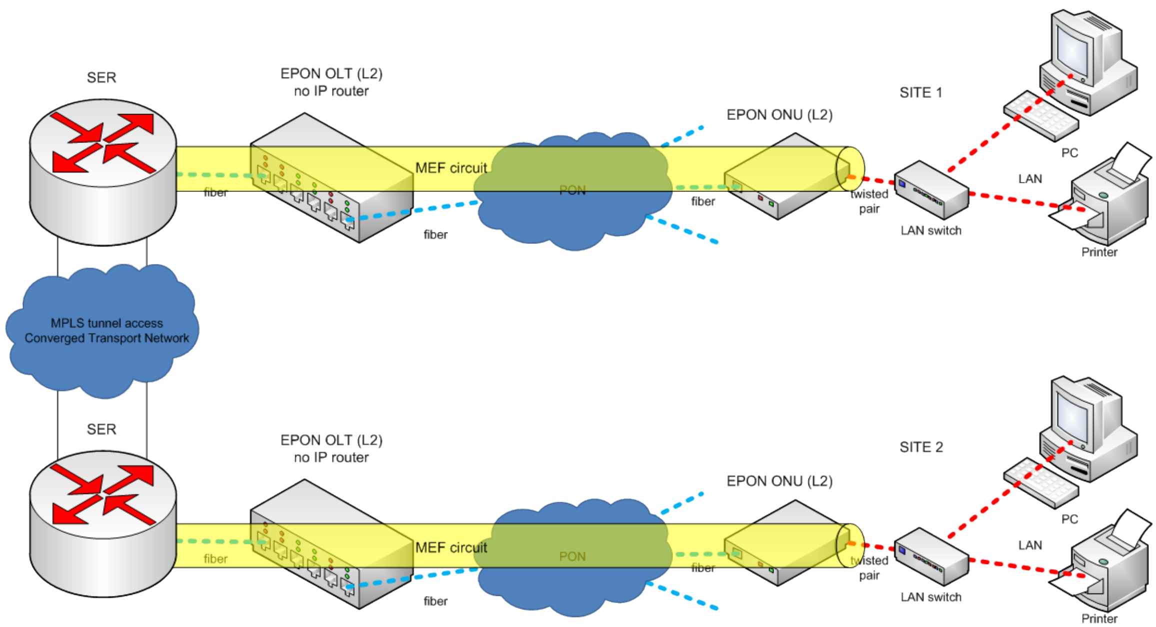


Figure 33: Architecture of MEF Services

Figure 33 shows an example of a simple MEF service, with an L2 tunnel interconnecting two subscriber sites: SITE1 and SITE2. Dedicated MEF tunnels are built at both sites across ONU and OLT operating in L2 mode only. There is no routing involved within deployed MEF circuits.

5.10.4 Public WiFi Backhaul

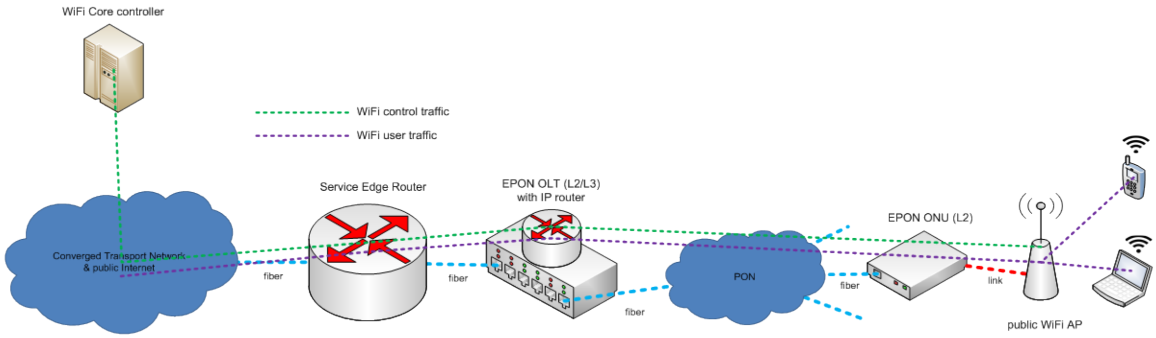


Figure 34: Architecture of Public WiFi Backhaul Service

The public WiFi backhaul service (see Figure 34) is very similar to the residential service, in that a WiFi access point (AP) is treated as a CPE device connected to an EPON ONU. In one arrangement, a stand-alone EPON ONU is used, and the WiFi AP is then connected using standard twisted pair (at least CAT5e-class) cable. Alternatively, a small-format-pluggable ONU (SFP-ONU) can be plugged directly into the WiFi AP. The second configuration is preferred for all new deployments, lowering the resulting power consumption.

During the initialization phase, the WiFi AP acquires an IP address and then establishes a communication path with the WiFi core controller. The said controller configures the WiFi AP with specific service parameters, including SSID, bandwidth profiles, and other parameters required for its proper operation. All the control and subscriber data is transmitted in-band across the public Internet.

5.10.5 Cellular Backhaul

Cellular backhaul is a very specific type of business service in which digital data generated by the radio interfaces on a cellular base station is then backhauled into a metro/core network, as shown in Figure 35. Apart from this one distinction, the service model is very similar to a point-to-point P2P Ethernet Virtual Private LAN MEF circuit.

For redundancy purposes, a network interface device (NID) located between the EPON ONU and the cellular tower (NID_A) creates two independent VLANs transported by the ONU and the OLT. One of the VLANs is injected into the primary dense wavelength division multiplexing (DWDM) transport ring, while the other VLAN is injected into the secondary DWDM transport ring. This arrangement provides redundancy north of the OLT.

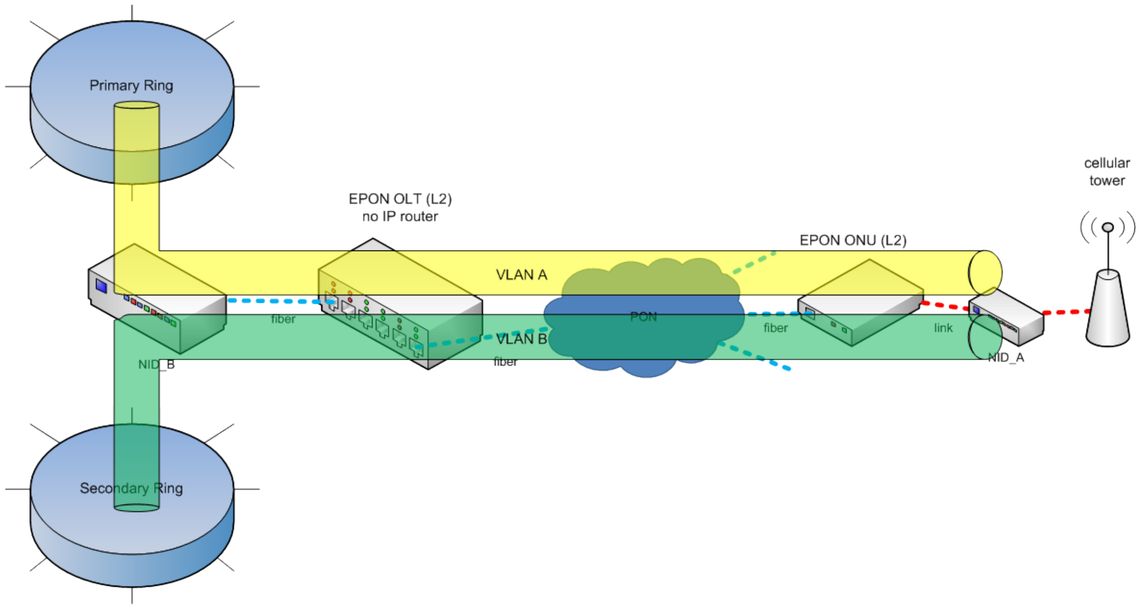


Figure 35: Architecture of Cellular Backhaul Service

5.10.6 Service Requirements for NG-EPON

NG-EPON is expected to support all application types supported today on 1G-EPON and 10G-EPON platforms, while allowing at least the same SLA levels to be implemented. Improved jitter and delay characteristics are important for time-sensitive applications, such as cellular backhaul. Support for cellular fronthaul is highly desired, though a technical feasibility study might be required before specific requirements for aggregate bandwidth, timing, and jitter are narrowed down.

Native support for improved time distribution at the physical layer is highly desired, to eliminate the need for operation of higher layer protocols such as IEEE Std 802.1as™ [7] or IEEE Std 1588™v2 [6].

5.11 Maximum Transmission Unit (MTU)

There is a demonstrated operator demand to carry frames with sizes exceeding 2 kB. To address this demand, NG-EPON is expected to support the ability to transfer frames of at least 9 kB (often referred to as *Jumbo Frames)*, either natively (through increased MAC frame size), or through a fragmentation mechanism at the ONU and the OLT.

5.12 System Cost

Given the need to compare three different generations (1G-EPON, 10G-EPON, and NG-EPON) of access equipment, the most effective manner is to examine the relative cost of providing symmetric dedicated (committed information rate (CIR) only) 1 Gb/s of subscriber bandwidth, irrespective of the actual OLT architecture, number of ports supported by the OLT, port density per line card, etc. It is assumed that the cost for 1 Gb/s for the given OLT is calculated in a fully loaded architecture, i.e., all uplink and PON cards are accounted for and populated with the necessary optics. The cost of corresponding ports on the edge router is not accounted for in this comparison.

Using data provided by [35] and assuming the cost of dedicated (CIR only), symmetric 1 Gb/s of bandwidth provided by a 1G-EPON OLT in the first quarter of 2008 as a unit (100%), the first generation of 10/1G-EPON OLTs (around the third quarter of 2011) exhibited the bandwidth cost of approximately 37%. The bandwidth cost for 1G-EPON in the third quarter of 2011 also decreased to roughly 45%. The bandwidth cost for both 1G-EPON and 10G-EPON systems have decreased since then, with bandwidth cost of 1G-EPON at 22% and of 10G-EPON at 21% at the end of the third quarter of 2014.

It is expected that the bandwidth cost in NG-EPON (when such systems become commercially available) is at most at the similar level to 1G-EPON and 10G-EPON at the time, while providing higher density (higher number of connected subscribers) and higher aggregate capacity.

5.13 Expected Availability Timeframe

The anticipated timeline for the commercial availability of NG-EPON systems depends on a number of factors, including the target application for the access system, operator’s investment in EPON technology so far, technical condition of the existing ODN, and others.

For residential applications, 10/10G-EPON is expected to address the offered load from power users until at least 2018−2020 timeframe, when the next generation access solution may be needed. The need for NG-EPON for residential access will be mainly driven by the power users, primarily for SOHO applications generating substantial volume of traffic in both downstream and upstream directions. In this scenario, the coexistence of NG-EPON with 10G-EPON and likely with 1G-EPON on the same ODN for extended period of time is likely to be required to avoid the need to repurchase OLT ports that were already paid for.

For business applications, 10/10G-EPON is expected to run out of bandwidth around 2017 for the majority of typical L2 applications, including cell tower backhaul, MEF services, and DIA. Some of the emerging business-class applications, such as cell tower fronthaul, are expected to push forward the development and then deployment of NG-EPON. The economics of using PON architecture for such high data rate services are expected to be mainly driven by the need for fiber conservation and ever increasing cost of civil construction, especially in densely populated areas. The more efficient use of ODN spectrum when compared to typical coarse wavelength division multiplexing (CWDM) P2P links is expected to be the main advantage of a multi-wavelength NG-EPON architecture.

6 Technical Feasibility of NG-EPON

6.1 System Capacity

The aggregate system capacity (expressed as aggregate bandwidth supported per port) can be increased using several approaches including the following:

- Increase the line rate relative to that used in 10G-EPON
- Apply advanced modulation techniques to increase the number of bits carried per Baud
- Increase the number of wavelength channels used to transmit in the upstream and/or downstream direction
- Implement a hybrid approach that increases the number of wavelengths per transmission direction, while simultaneously employing a more advanced modulation scheme to increase the effective data rate per wavelength channel

The requirements for NG-EPON capacity for both residential and business applications are listed in sections 5.1 and 5.2 for the OLT and ONU, respectively.

6.2 Architectures

There are several possible architectures for NG-EPON, including higher-speed, single wavelength TDM-PON, Hybrid-PON systems, as well as more exotic solutions like OFDM-PON systems. The following sections focus on technical challenges of individual solutions, especially in terms of component maturity and ability to reach the total system capacity in excess of 10 Gb/s.

6.2.1 TDM-PON

Commercial PON systems have been deployed for about two decades, and virtually all of them have used TDM-PON technology. With one wavelength channel in each direction, TDM-PONs provide multiple access using TDM in the downstream direction and time division multiple access (TDMA) in the upstream direction. On average, commercially deployed TDM PON bit rates tend to double once every two years if plotted over the last 20 years as shown in Figure 36 [17].

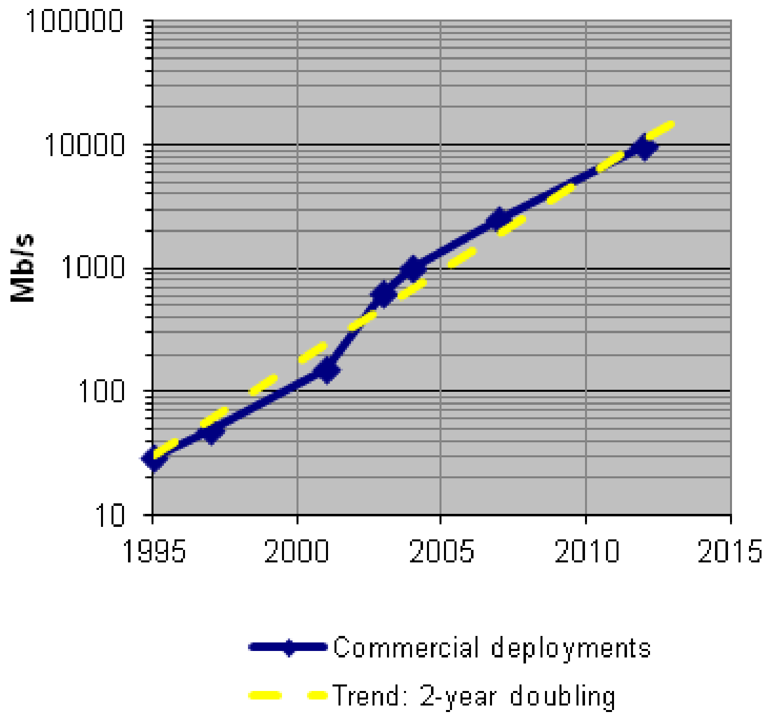


Figure 36: Evolution of TDM-PON Downstream Data Rate

At each increase in speed, TDM-PON has needed to overcome three main challenges without resorting to WDM: (1) higher speed electronics, aided by Moore's Law, (2) more optical transmit power and improved receiver sensitivity to sustain signal-to-noise ratio (SNR), and optionally, (3) mitigation of chromatic dispersion (CD). For an NG-EPON based on TDM-PON, these challenges need to be addressed again.

For increased aggregate system capacity with respect to 10G-EPON, an NG-EPON based on TDM-PON would require either

- Non-return to zero (NRZ) modulation at bit rates above 10 Gb/s, or
- Multi-level modulation with higher spectral efficiency and reduced bandwidth requirements, or
- A combination of the two above options.

6.2.1.1 High-speed bit interleaving

TDM-PON ONUs currently process the shared aggregate downstream signal at line rate regardless of how much traffic is actually being sent to the ONU. This may lead to a higher power consumption compared to a case where the ONU processes only the signal representing data destined to that ONU. A dynamic bit-interleaving protocol has been proposed [56],[57] wherein a decimator in the clock-data recovery (CDR) circuit extracts only a small proportion of the downstream bits containing the ONU payload. The ONU's optical receiver operates at the full line rate however the ONU's digital processing circuitry and its power consumption may be reduced to operate at the decimated rate. Time interleaving is in practicality limited to downstream framing. The upstream data path still follows a TDMA framing. However, by the very principle of the TDMA, only the relevant upstream packets are processed, and therefore energy proportionality to traffic load is already provided.

ONUs cost-optimized for residential services might be limited to a fraction of the downstream bit rate, say 10 Gb/s. ONUs optimized for business services might be designed to have access to the full line rate, say 25 or 40 Gb/s. Both ONUs could be mixed on a PON and their bandwidths allocated dynamically, analogously to dynamic bandwidth allocation protocols already used in the upstream direction.

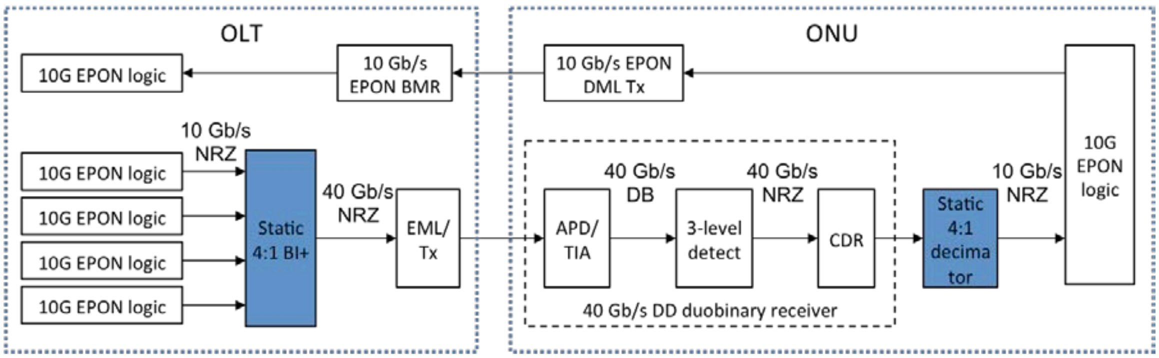


Figure 37: Example of simple static bit-interleaved PON

These benefits come with the cost of the added complexity of the dynamic bit-interleaving protocol. A simpler static bit interleaving could also be devised, although with reductions in power efficiency compared to dynamic bit interleaving. In this case the decimator ratio would be fixed, and its bit phase would be configured for each ONU. For example, a 40 Gb/s downstream / 10 Gb/s upstream OLT and ONU could be implemented with 10G EPON logic, as shown in Figure 37. The down-side of static bit interleaving is that the ONU maximum downstream bandwidth is limited to the fixed decimation ratio (10 Gb/s in this example). This static implementation is analogous to wavelength-stacking in TWDM PONs, except a single OLT transceiver provides the full aggregate bandwidth and no wavelength agility or management is required. Any changes to the MAC required to implement bit interleaving need to fit within/conform to the Ethernet protocol stack.

6.2.2 WDM-PON

WDM-based access solutions achieve higher aggregate system capacity by using more than one downstream and upstream wavelength channel in parallel. In such an access system, each wavelength channel is typically dedicated to a single subscriber. The total number of connected subscribers and the aggregate system capacity is proportional to the number of wavelength channels operated in parallel. There are many different ways to implement a WDM-PON access solution, depending on the complexity of light sources, target distance, supported line rates, and other factors. Amitabha, et al. [26] provides a detailed survey of available WDM-PON access solutions, their advantages, and technical challenges.

In order to achieve an aggregate system capacity of 100 Gb/s, a WDM-PON system operating at 10 Gb/s (using, for example, 10GBASE-LR optics) would require 10 wavelength channels in the downstream and 10 wavelength channels in the upstream, but would be able to connect only 10 ONUs (subscribers).

One of the obvious drawbacks of the WDM-PON architecture, especially for residential applications, is that each ONU is provided with dedicated data channel to the OLT, which remains idle most of the time, apart from periods of peak activity when bursty data is being exchanged. The potential advantage, though, is that some subscribers can be serviced with lower-cost P2P optics running at 1 Gb/s or even 100 Mb/s.

6.2.3 Hybrid-PON

Hybrid-PON access systems combine features of both TDM-PON as well as WDM-PON allowing the access system to achieve high aggregate capacity (100 Gb/s and more) while still taking advantage of the TDM-based sharing of a wavelength channel among connected subscribers.

In the simplest form, a hybrid-PON system can be implemented by stacking multiple TDM-PON systems, each operating at a different wavelength in the downstream and upstream directions. Depending on the way scheduling domains are created across available wavelength channels, MSD-WDM-PON, SSD-WDM-PON, and WA-PON can be supported.

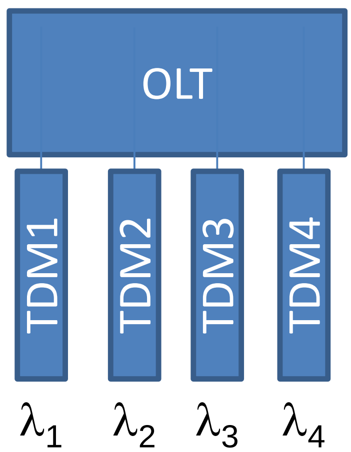


Figure 38: MSD-WDM-PON with Multiple TDM domains [11]

Figure 38 shows an example of a simple MSD-WDM-PON system, with four scheduling domains, where each wavelength channel is TDM-shared among a number of connected subscribers. In this scheme, each ONU has access to only one wavelength pair at a time, transmitting and receiving on pre-assigned upstream and downstream wavelength channels. The assignment can be either fixed (fixed optics) or dynamic (tunable optics), depending on the requirements for the ONU's flexibility, ability to move between individual TDM domains for load balancing, etc. Each TDM domain is scheduled independently by the dynamic bandwidth allocation (DBA) process on the OLT. The number of connected ONUs could vary per wavelength channel.

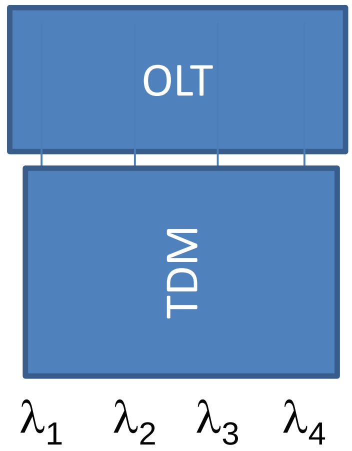


Figure 39: SSD-WDM-PON [11]

It is also possible to create just one large scheduling domain, where all connected ONUs have access to all downstream and upstream wavelength channels at the same time, and are scheduled via a single DBA process on the OLT (see Figure 39). In this way, an SSD-WDM-PON system is created. In this scheme, the ONU can utilize fixed optics, but its electronics need to process all data transmitted by the OLT.

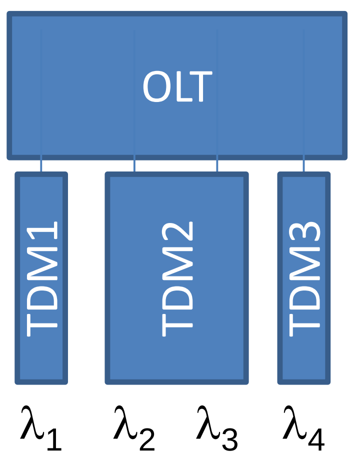


Figure 40: WA-PON [11]

A more flexible Hybrid-PON approach is shown in Figure 40, where two wavelength channels are combined to create a larger scheduling domain with the aggregate throughput exceeding the throughput of a single wavelength channel. In the WA-PON scheme, advantages of the first MSD-WDM-PON system are applicable, while it is also possible to support subscribers with services requiring throughput exceeding the capacity of a single wavelength channel. This particular arrangement can support both residential and business services on a single access platform.

Hybrid-PON access systems stack multiple 10G-EPON systems in either symmetric or asymmetric configurations. Given the flexibility of this scheme, it is possible to operate some wavelength channels in the asymmetric 10/1G-EPON configurations and dedicate these wavelengths for residential access. Simultaneously, it is possible to aggregate multiple wavelength channels of 10/10G-EPON to create symmetric data channels with aggregate throughput exceeding 10 Gb/s. Such data channels can provide multi-Gb/s access service to business subscribers.

If TDM sharing is used, simulation models have shown that due to statistical multiplexing (see 6.10), it is possible to serve the same number of ONUs (compared with WDM-PON) with fewer wavelength channels, while simultaneously observing similar SLAs.

6.3 Modulation Techniques

Historically, at each increase in speed, TDM-PON technologies have needed to overcome the following four main challenges without resorting to WDM:

- Higher speed optics and electronics
- Higher optical transmit power
- Improved receiver sensitivity
- Mitigation of chromatic dispersion

While it may be possible to achieve the next step in speed with NRZ transmission, penalties resulting from increasing line rate could be offset to some extent by using more advanced, non-NRZ modulation schemes that allow more than one bit to be encoded into a single Baud. To meet the requirements of low cost, only direct detection systems are considered in the following sections.

6.3.1 NRZ modulation

NRZ modulation is the simplest and lowest cost way to transmit data over optical fiber. As bit rates increase however, mitigation of increased chromatic dispersion is required. One method to mitigate chromatic dispersion is to use directly-modulated distributed-feedback (DFB) lasers rather than Fabry-Perot lasers. At 10 Gb/s, directly-modulated lasers (DML) are adequate in the O-band, but it is necessary to move to electro-absorption modulated lasers (EMLs) for transmission at longer wavelengths.

For bit rates of 10 Gb/s and above, for example 25 Gb/s and 40 Gb/s, additional steps are required for dispersion mitigation. The dispersion tolerance (@1 dB dispersion penalty) for 25 GB/s and 40 Gb/s using EML transmitters (using the model in [54]), and the corresponding usable spectrum in ITU-T G.652 fibers (20 km length) without dispersion compensation (DC) is shown in Table 2.

Table 2: NRZ Usable Spectrum

NRZ bit rate	Dispersion tolerance (EML)	Usable spectrum (20 km, no DC)
10 Gb/s	1000 ps/nm	All of O-, E-, S, C, and L bands
25 Gb/s	190 ps/nm	1260–1410 nm
40 Gb/s	75 ps/nm	1290–1340 nm

If the NG-EPON downstream and/or upstream signal can be limited to the O-band, then 25 Gb/s NRZ transmission is viable without DC up to 20 km. If it could be further limited to the spectrum between 1290-1340 nm, then even 40 Gb/s NRZ transmission without DC is viable. On the other hand, if neither is possible, e.g., due to co-existence requirements, then 25 Gb/s or 40 Gb/s NRZ can be used with DC in the S, C and/or L-bands. Even in that case, for actual ODNs of <20 km length, DC might be dispensed with. For example, 5 km ODNs would not require DC for 25 Gb/s at any wavelength, and 40 Gb/s would work out to 1490 nm without DC.

We can extrapolate from 10 Gb/s the required NRZ receiver sensitivity for 25 GB/s and 40 Gb/s, and the corresponding OLT minimum launch powers. For APD receivers, using the model $P_{\min} \propto B^{7/6}$ [55], 25 Gb/s requires 4 dB more power, and 40 Gb/s requires 7 dB more power. Referring to Table 3, 25 Gb/s and 40 Gb/s receiver sensitivities are extrapolated from a 10GBASE-PR(X)-U4. Required launch powers for PR30 loss budget (29 dB) are then shown. 25 Gb/s requires 5 dBm launch power, which is about the maximum that can be obtained from unamplified EMLs. 40 Gb/s requires 8 dBm launch power, which would probably require a post amplifier, usually an SOA. These pose no problem for OLT transmitters.

Table 3: NRZ Power Requirements, Downstream

NRZ bit rate [Gb/s]	Rx sensitivity, downstream [dBm]	Required transmit power, PR30 [dBm]
10	-29.5	1
25	-25.5	5
40	-22.5	8

In the upstream direction, the 10GBASE-PR(X)-D4 receive sensitivity is 0.5 dB worse, so ONU launch powers will need to be 0.5 dB higher.

The above extrapolation assumes that high speed 25 Gb/s and 40 Gb/s APDs will have the same multiplication gain as 10 Gb/s APDs. Maintaining gain at very high speeds is a challenge for APDs, and to the extent that lower performance is obtained, the required launch powers need to be adjusted upwards.

Another consideration is the availability of low-cost 25 Gb/s and 40 Gb/s optical transmitters and APDs. It is possible to piggyback onto the 25 Gb/s technologies commercialized for 100GBASE-ER4, although those components most likely have a significant price premium compared to 10 Gb/s components in the near to medium term. For 40 Gb/s, a 40 Gb/s APD is a new component. An alternative would be a combination Erbium-Doped Fiber Amplifier (EDFA) pre-amp and 40 Gb/s PIN detector.

Because of this decreased dispersion tolerance and need for higher speed components, NRZ may not be the most practical way to implement speeds above 10 Gb/s. Instead, it may be more practical to implement higher order modulations with narrower signal bandwidth, as described in the next sections.

6.3.2 Duobinary

Compared to higher multi-level modulation schemes, duobinary implementations for modulation and for demodulation are relatively simple. As described in [25], duobinary data can be generated by sending NRZ On-Off Keying (NRZ-OOK) data through an electrical “delay-and-add” filter, creating a 3-level signal. This filter has a z-transform of $1 + z^{-1}$, which can be approximated by a low-pass filter (LPF) in the electrical domain. Duobinary coding is a *correlative* coding method, so to avoid error propagation, pre-coding of the data at the transmitter is needed [40]. An example of a simple duobinary decoder is an electrical circuit that includes a splitter, 2 comparators, and an XOR gate [40].

The duobinary signal generated by a LPF is compared to NRZ in the time and frequency domains in Figure 41.

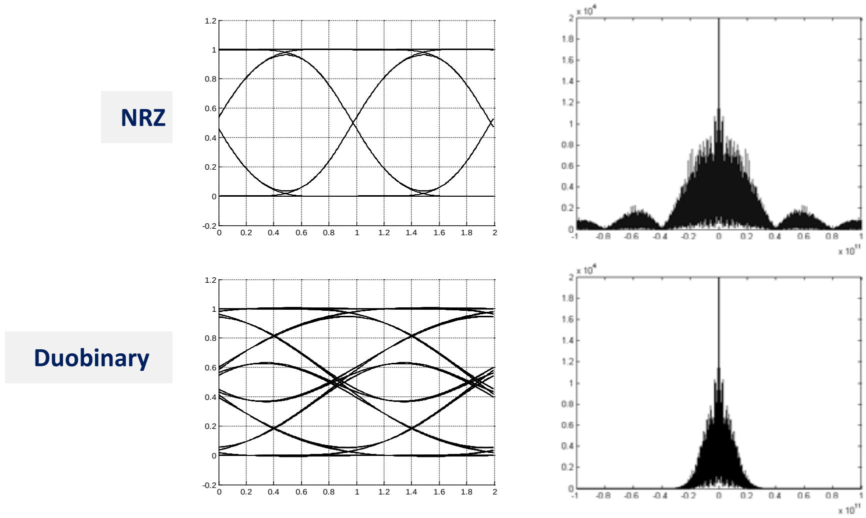


Figure 41: NRZ and Duobinary (LPF) Signals in the Time and Frequency Domains

Table 4: Duobinary LPF encoding bandwidths compared to NRZ

Signaling Rate / Modulation	10 Gb/s	25 Gb/s	40 Gb/s
NRZ	7 GHz	17.5 GHz	28 GHz
Duobinary	(not in scope)	7 GHz	11 GHz

The payoff for these simple electronic circuits is, compared to NRZ, a reduction in signal spectrum of approximately 60% and an increase in CD tolerance by approximately a factor of 2. These characteristics of duobinary mitigate the need for higher speed components and increased dispersion tolerance, while semiconductor optical amplifier (SOA) post-amplifiers, where required, can answer the needs for higher power.

The duobinary LPF encoding can be realized by the bandwidth roll-off of either the transmitter or the receiver. The required bandwidths of the LPF are shown in Table 4.

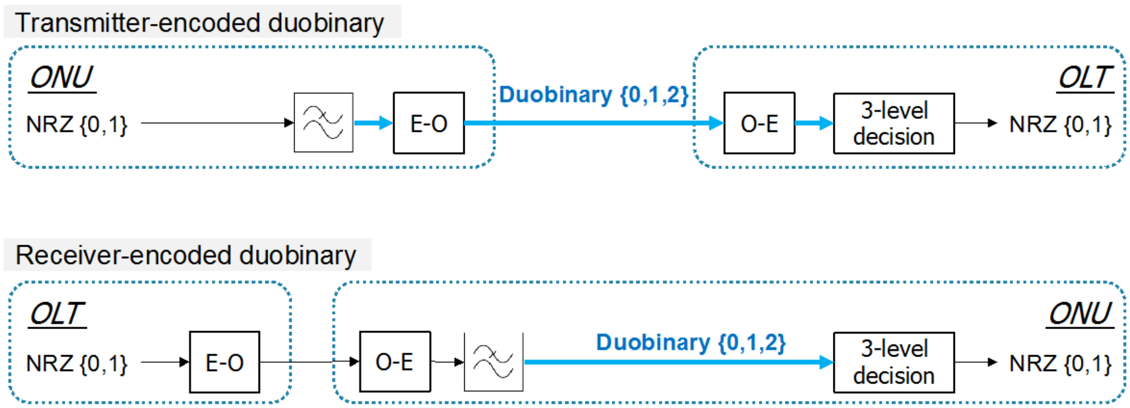


Figure 42: Partitioning Duobinary Functions in TDM-PON

A TDM-PON can be cost-optimized by placing low bandwidth components in the ONU. When using duobinary encoding, this would imply that the encoding is performed at the ONU receiver for downstream transmission and by the ONU transmitter for upstream, as indicated by Figure 42. The values in the table indicate that a 25 Gb/s symmetric ONU only requires a 10 Gb/s transmitter and receiver, the same kinds of components already commercially available in 10G-EPON NRZ systems. A 40 Gb/s symmetric ONU only requires 25 Gb/s components (which are actually overkill and would need to have their bandwidth reduced in the electrical domain). These components might be leveraged from the 25 Gb/s components in 100GBASE-ER4 Ethernet systems.

In the OLT, full-rate 25 Gb/s or 40 Gb/s components are required, but their higher cost is shared.

Using the duobinary modulation scheme,

- 25 Gb/s symmetric NG-EPON can be implemented with low cost 10 Gb/s optical components used in both the ONU and the OLT,
- 40 Gb/s symmetric NG-EPON can be implemented using 25 Gb/s components, and
- Asymmetric data rate NG-PON, supporting 25G/10G, 40G/10G, and 40G/25G, can be also implemented while optimizing the cost of the ONU transmitter and OLT receiver optics.

Experimental confirmation of receiver-encoded duobinary downstream PON transmission at 26 Gb/s [42] and 40 Gb/s [21] are reported. Upstream duobinary burst-mode transmission remains at this time to be experimentally verified.

While increasing the bit rate from 10 Gb/s to 25 Gb/s reduces the CD tolerance by a factor of 6, and to 40 Gb/s by a factor of 16, duobinary encoding provides partial mitigation by increasing the dispersion tolerance to CD by a factor of approximately 2 compared to NRZ. There are multiple paths to gaining the further required reductions in CD.

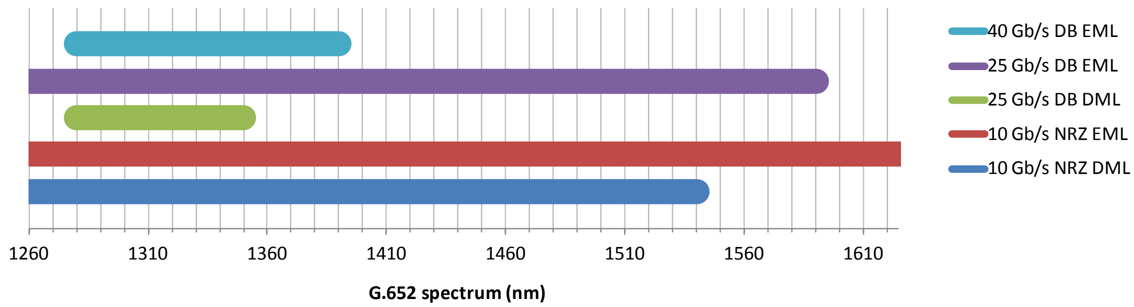


Figure 43: Estimated usable SSMF spectrum (20 km) without DC

Based on simulation, the usable spectrum for a 20 km G.652 standard single-mode fiber (SSMF) fiber that can be used without DC for the considered bit rates, laser sources, and encoding are summarized in Figure 43 (assuming 1 dB optical dispersion penalty).

- If both upstream and downstream transmission is in the O-band, no DC is required. Duobinary transmission up to 25 Gb/s can be achieved with DML lasers, and 40 Gb/s with EML lasers.
- Co-existence with 10G-EPON, GPON and 1G-EPON simultaneously is possible, if 1G-EPON upstream transmission is constrained to the same 1310 ± 20 nm window as GPON, using a DFB laser.
- 25 Gb/s duobinary transmission in the S, C, and L-bands: Allowing for a 2 dB optical penalty (instead of 1 dB), the following can be achieved without DC: (1) 20 km up to 1560 nm, and (2) at 1600 nm, up to 18 km.
- 40 Gb/s duobinary transmission in the S, C, and L-bands: Requires DC for wavelengths up to 1600nm and ODNs longer than 5 km.

For S, C, or L-bands, DC would only need to be implemented on those longer length ODNs. Available DC technologies include the following:

- DC fiber, which is low-loss (<3 dB) and low cost, although bulky.
- Fiber Bragg grating dispersion compensators for PON applications might be possible. Although they would be smaller they are likely to be more expensive.
- Electronic DC may be possible, but the improvement in dispersion tolerance for duobinary modulation has not yet been determined.

6.3.3 PAM-4 Modulation

Pulse amplitude modulation (PAM) encodes information into the amplitude of the transmitted signal. A PAM-M modulation encodes information into an M-level amplitude signal. PAM-2 is a binary signal, known as NRZ. Compared to NRZ, higher level PAM encodes $\log_2(M)$ more information per symbol, although with required SNR increasing with increasing M.

PAM-4 is a candidate for a good compromise between NRZ and higher level PAM for NG-EPON. The eye diagrams for NRZ and PAM-4, with the same bit rate, are compared in Figure 44. It is evident that the unit interval (UI) is twice as long for PAM-4, i.e., the symbol (Baud) rate is half that of NRZ.

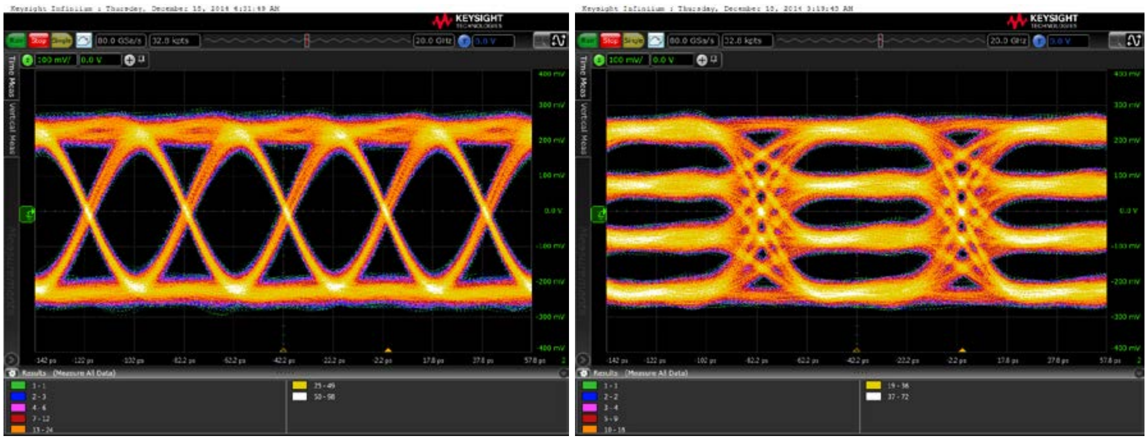


Figure 44: NRZ and PAM-4 Eye Diagrams

This leads to a signal with about half the signal spectrum, requiring components with about half the bandwidth (see Table 5), while improving dispersion tolerance with a manageable increase in complexity.

Table 5: NRZ and PAM-4 Required Receiver Bandwidth for Various Data Rates

Modulation	10 Gb/s	25 Gb/s	40 Gb/s
NRZ	7 GHz	17.5 GHz	28 GHz
PAM-4	(not in scope)	≈9 GHz	≈14 GHz

PAM-4 carries two bits/symbol. The PAM-4 signal is created by feeding the most significant bit (MSB) and least significant bit (LSB) streams into a digital-to-analog converter (DAC), which generates the 4-level signal. This signal is amplified and modulates the optical transmitter.

Since PAM-4 is not a binary signal like NRZ, transmitter non-linearity is an impairment causing a significant power penalty if not mitigated. For example, pre-distortion by the adjustment of level spacings may provide adequate mitigation (this is comparatively simple with respect to the pre-distortion used in CATV optical transmitters).

On the receive side, after the optical receiver, a 4-level decoding circuit is required to recover the original MSB and LSB signals.

6.3.4 PAM-4 vs. Duobinary Modulation

6.3.4.1 Back-to-Back Comparison, 25 Gb/s

Comparing duobinary's 3-level signal to PAM-4's 4 level signal, duobinary's larger vertical eye dimension results in an ideal 1.8 dB modulation advantage. For the same bit rate R, each signal has an optimal receiver bandwidth: approximately 0.27R for receiver-encoded duobinary and 0.35R for PAM-4. The wider bandwidth of the PAM-4 receiver will result in about a 1 dB receiver noise penalty. This ideally gives duobinary a 2.8 dB advantage when considering optimized receiver bandwidths.

In PON systems, ONU cost must be minimized. In the downstream direction, an ideal NG-EPON receiver would be based on high-volume low-cost 10 Gb/s APDs, as used in 10G-EPON ONUs today. 10 Gb/s APDs have about 7 GHz bandwidth, which is ideal for 25 Gb/s receiver-encoded duobinary. 25 Gb/s PAM-4 ideally requires about 9 GHz receiver bandwidth, but 7 GHz can yield good results.

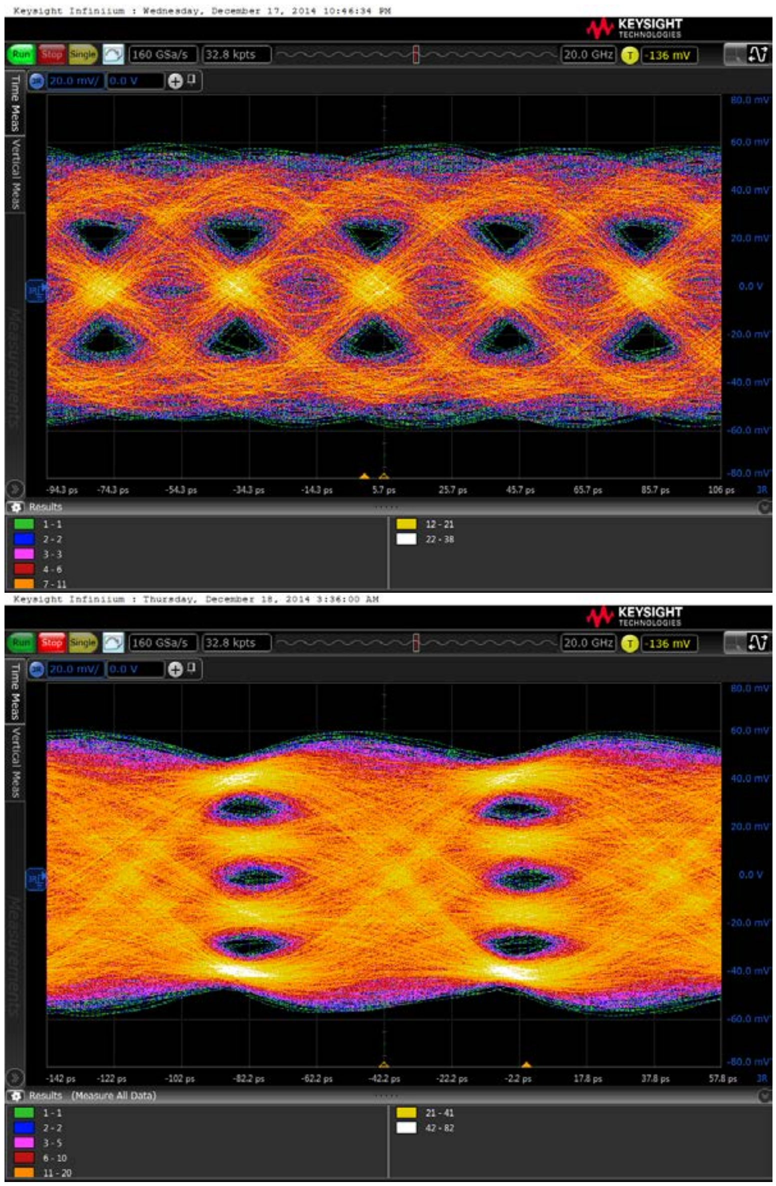


Figure 45: Received Eye Diagrams (shown at −18 dBm) for Duobinary and for PAM-4

An empirical comparison [21] at 25 Gb/s transmission into a 7 GHz avalanche photodiode (APD), using the exact same set-up for receiver-encoded duobinary and for PAM-4 modulations, has been performed. In this case, with an identical receiver, there is no receiver noise penalty for the PAM-4 signal, and we would expect to see only the 1.8 dB modulation penalty. In fact, the measured receiver sensitivities (@10^{-3} Bit Error Ratio) for duobinary and PAM-4 were −24.9 dBm and −21.5 dBm respectively, a 3.4 dB penalty. The observed eye diagrams are shown in Figure 45.

The additional 1.6 dB penalty can be explained by the following:

- The PAM-4 signal is sensitive to transmitter non-linearity. Pre-distortion was used to mitigate this effect, however at the cost of some transmitter noise penalty.
- Any latent uncompensated non-linear signal distortions at the transmitter.

Non-optimized receiver bandwidth for PAM-4 produces some additional signal distortion.

6.3.4.2 20 km Transmission, 25 Gb/s

PAM-4 has half the Baud rate as duobinary, which leads to superior dispersion tolerance. Simulations [22], again for 25 Gb/s into a 7 GHz APD receiver, has shown that PAM-4 achieves about 1.8x better dispersion tolerance (see Figure 46). For 20 km transmission, this gives about a 0.2 dB and 1.8 dB advantage to PAM-4 when transmitting in the O-band and at 1600 nm respectively.

Combining this with the back-to-back performance, it is concluded that receiver-encoded duobinary has a performance advantage of about a 3.2 dB and 1.6 dB over PAM-4 when transmitting in the O-band and at 1600 nm respectively, which bookends the full range of likely wavelengths to be considered for NG-EPON.

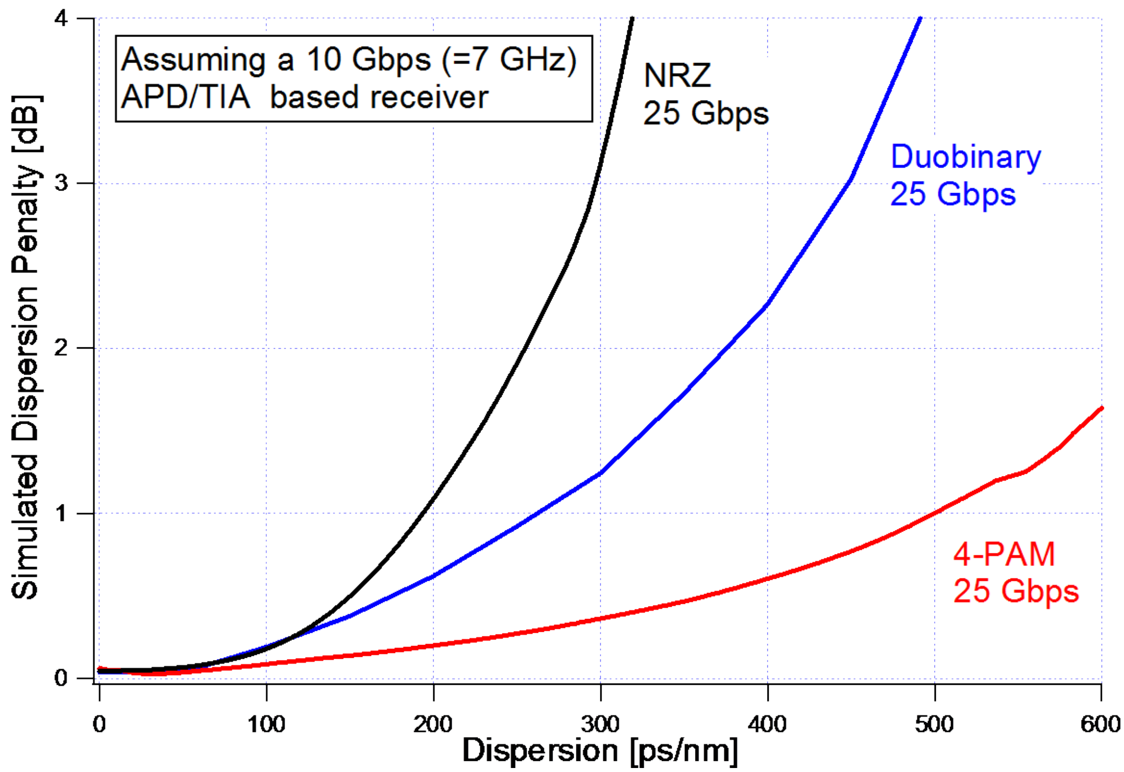


Figure 46: Simulated Dispersion Tolerance for Duobinary and for PAM-4

6.3.4.3 20 km Transmission, 40 Gb/s

For 40 Gb/s, an APD receiver with >>7 GHz bandwidth will be required. A 25 Gb/s 100GBASE-ER4 receiver is a likely candidate. In this case the receiver bandwidth can be optimized for both duobinary and for PAM-4. The relative increase in receiver noise for PAM-4 (due to wider PAM-4 receiver bandwidth vs. duobinary) is expected to be at least offset by reduced signal distortion, in which case the back-to-back advantage for duobinary would be expected to be less than the observed 3.4 dB and closer to the ideal 2.8 dB.

6.3.5 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) has been applied in many communication fields; in copper and wireless applications it is a mature technology with wide commercial availability. Since 2005, research on optical domain OFDM technology has been conducted and has become a very hot field. However, the need for high-speed DAC ADC components and the relatively high complexity has hampered its adoption in optical access networks.

Depending on the modulation, the optical domain OFDM technology is divided into Coherent Detection OFDM (CD-OFDM) and Direct Detection OFDM (DD-OFDM). DD-OFDM has lower cost and smaller packaging, so it is more likely to be adopted in optical access.

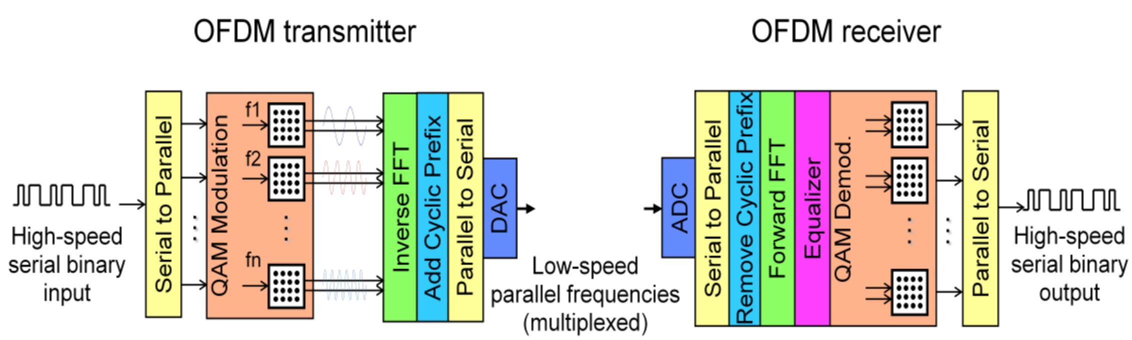


Figure 47: Base Electrical Physical Architecture of DD-OFDM

The basic electrical architecture for a DD-OFDM transmitter and receiver is shown in Figure 47.

In the transmit side, incoming serial data is converted to a parallel format, mapped to symbols from Quadrature Amplitude Modulation (QAM) constellation, and then applied to a n-point Inverse Fast Fourier Transform (IFFT) to generate a digital OFDM signal with n orthogonal subcarriers. A cyclic prefix is added to mitigate inter-symbol interference and then the output data is serialized and converted to an analog signal using high speed DAC technology. The analog signal is converted to an optical signal using a laser for optical domain applications.

In the receive-side, signal processing and data flow are opposite to the transmit-side. The incoming signal is first converted to an electrical signal using an O/E converter and then applied to an ADC. The serial ADC output is converted to parallel and the cyclic prefix is removed. A Fast Fourier Transform (FFT) is used to decode the n OFDM subcarriers, and an equalizer may be used to compensate for chromatic dispersion. After equalization and FFT the signal is sent to a QAM symbol detection module. Finally, the received signal is serialized to recover the transmitted data.

In normal practice the transmit-side uses two DAC chips and the receive-side two ADC chips. This is because the Inverse FFT output is complex signal (i.e., I+jQ), and it is divided into in-phase (I) component and quadrature (Q) component and each are transmitted through separate DAC channels. The question then becomes how to use a single laser to transmit the two signals. There are several methods to accomplish this. One method is to use an electrical analog I/Q modulator to combine the two signals into one. In this case, the receive-side can use a single electrical analog I/Q demodulator.

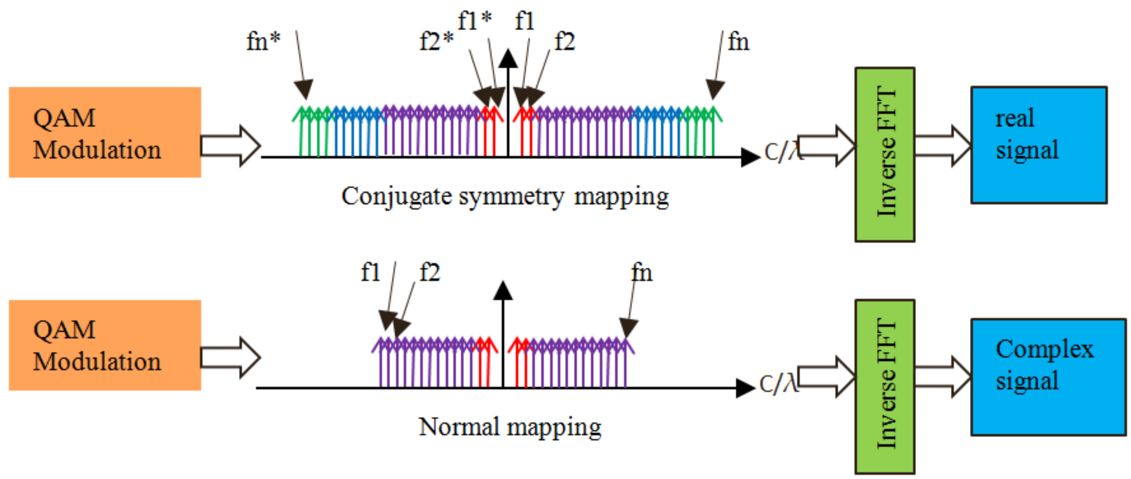


Figure 48: Two Mapping Method

There is one way to avoid the need for two DACs and ADCs. The Fourier transform of a real number sequence has conjugate symmetry, so when QAM symbols are applied to an Inverse FFT, they are mapped to half of the entire subcarriers set, and the other half is assigned as the conjugate of this set. The process is illustrated in Figure 48. Using conjugate symmetry method, a single DAC in the transmitter and single ADC in the receiver are needed.

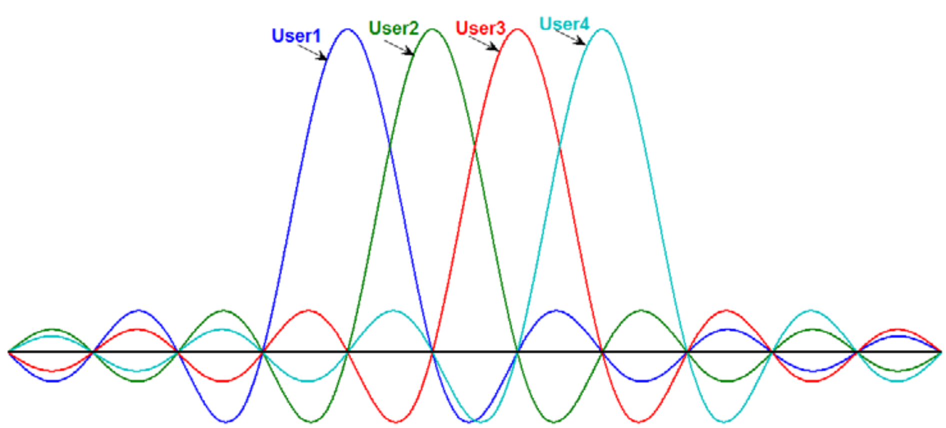


Figure 49: OFDM Multiplexing

In OFDM systems multiplexing can be accomplished in either the time domain or the frequency domain. In strict time domain multiplexing the entire OFDM frequency spectrum would be assigned to a single user for some number of symbols, in frequency domain multiplexing a user is assigned one or more subcarriers as illustrated in Figure 49. By assigning groups of users to different subcarrier sets, the advantages of both time and frequency domain multiplexing can be realized.

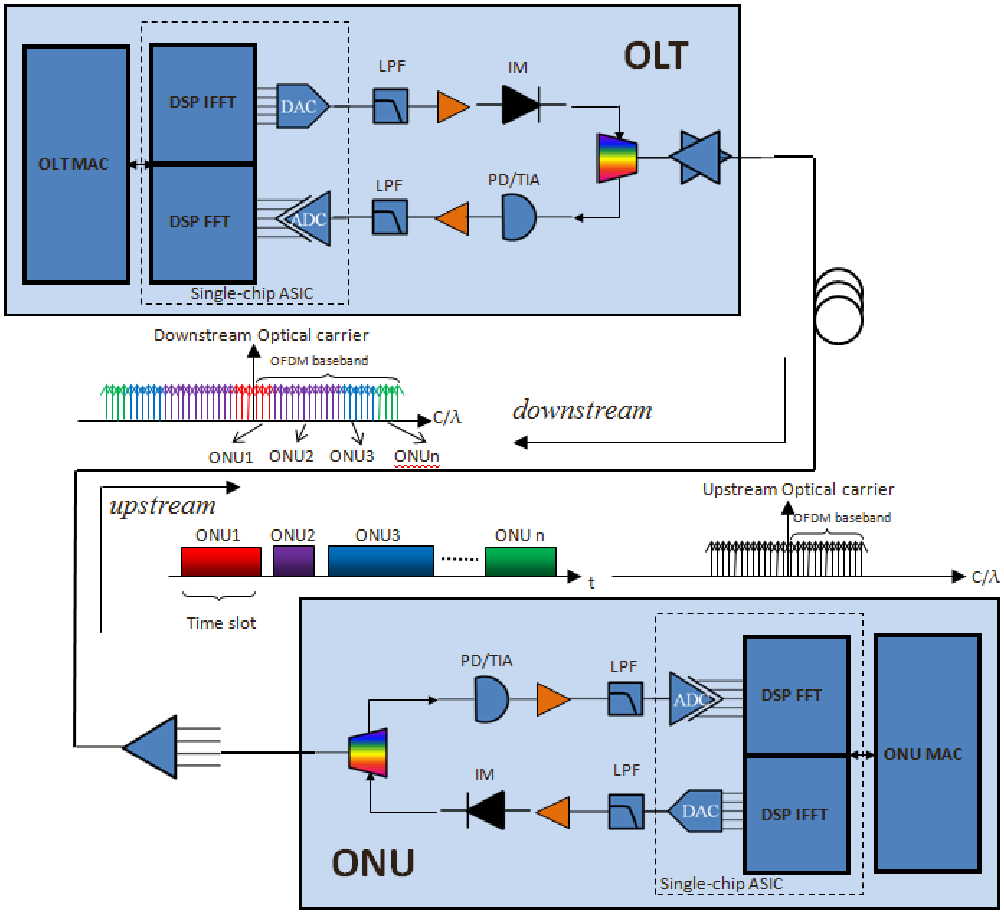


Figure 50: Architecture of DD-OFDM PON

One possible DD-OFDM PON architecture is shown in Figure 50, detailed component requirements are shown in Table 6.

Table 6: DD-OFDM Parameters

Modulation	10 Gb/s	25 Gb/s	40 Gb/s	100 Gb/s
Bandwidth (OFDM+16QAM)	2.5 GHz	6.25 GHz	10 GHz	25 GHz
LASER	2.5G DML/EML	10G DML/EML	10G DML/EML	25G DML/EML
PD	2.5G APD	10G APD	10G APD	25G APD
DAC	5GS/s	12.5GS/s	20GS/s	50GS/s
ADC	5GS/s	12.5GS/s	20GS/s	50GS/s

OFDM has higher spectral efficiency than NRZ, PAM4 and duobinary. For 40 Gb/s OFDM modulation, 10G optical components are sufficient, but component cost savings are transferred to electrical high-speed ADC/DAC components. This has become one of the major limitations of OFDM applications in access.

Another limiting factor is the optical power budget. OFDM has good dispersion resistance performance, better than PAM and duobinary, but has higher linearity requirements than either PAM or duobinary. Both the nonlinearity of the optical components and the electrical components affect the system performance and reduce the overall power budget.

For 40 Gb/s downstream transmission, the OLT minimum launch power can be set to +10 dBm after optical amplification. When the direct detection of optical APD receiver is employed at ONU, the achievable sensitivity at the BER (bit error rate) level of 1×10^{-3} (pre-FEC) is −21 dBm.

For 10 Gb/s upstream transmission, the pre-amplifier at OLT can be added to increase the received sensitivity and APD is employed for direct detection, the achievable sensitivity at the pre-FEC BER level of 1×10^{-3} is −26 dBm. FEC and equalizer can be used to reduce BER.

6.4 Outside Plant

6.4.1 Single-Mode Fiber Spectrum

The existing ODN designed for use with optical access networks is intended to carry multiple services, requiring allocation of specific wavelength bands (spectrum ranges) that need to coexist on the same fiber. At the same time, the fiber medium itself has specific regions that are more favorable for telecommunication applications, while other regions remain largely unused due to their less favorable transmission characteristics.

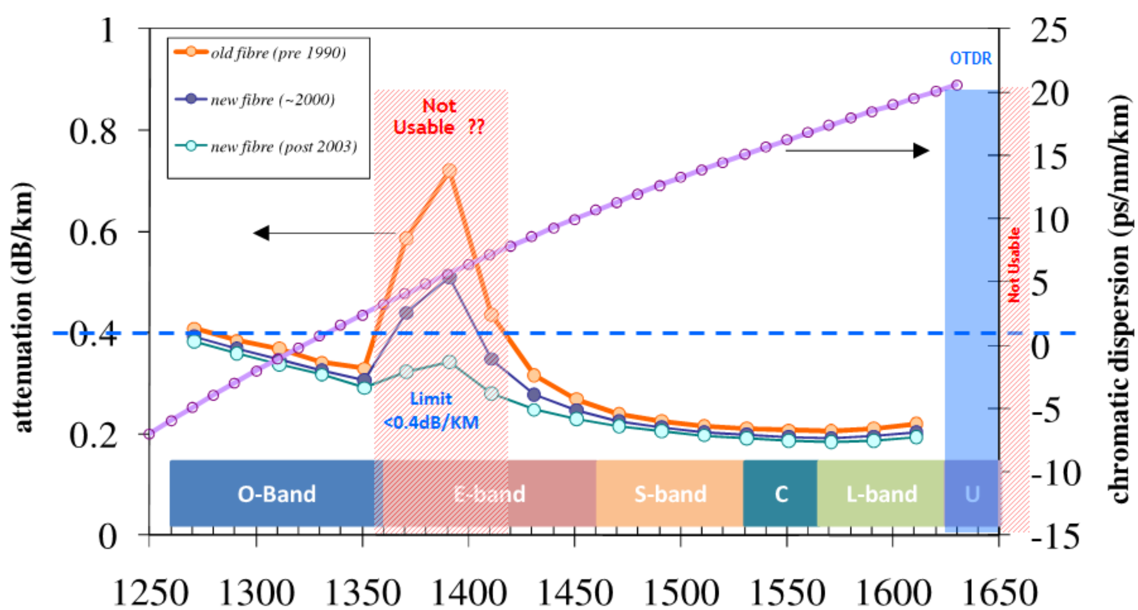


Figure 51: Attenuation and Chromatic Dispersion in Different Fiber Types [8]

Figure 51 presents attenuation and chromatic dispersion curves for the three most common single=mode fiber type found in existing ODNs designed for optical access. Reflected in Figure 51 is the definition of single-mode fiber types found in ITU-T G.652 [19]. Types A and B are defined for legacy fibers with unspecified loss in the E-Band (shown in Figure 51 as “pre-1990” and

"~2000"). Types C and D are defined for modern fiber types with low E-Band attenuation (shown as "post-2003").

Discussion on wavelength allocation plans for access systems can be found in 6.5.

6.4.2 Passive Splitter/Combiner for TDM-PON

A power splitter distributes all incoming signals evenly among all output ports, requiring a wavelength filter at each ONU. Insertion loss, loss uniformity, return loss, and operating temperature range are just a few of the important features of Passive Splitter/Combiner (PSC) units. The specifications of the splitter can be found in ITU-T G.671 [51] also specifies performance for PON splitters, including loss over 1260−1360 nm and 1480−1625 nm (but E-band performance is not specified). There are several manufacturing techniques for PSC, discussed briefly below.

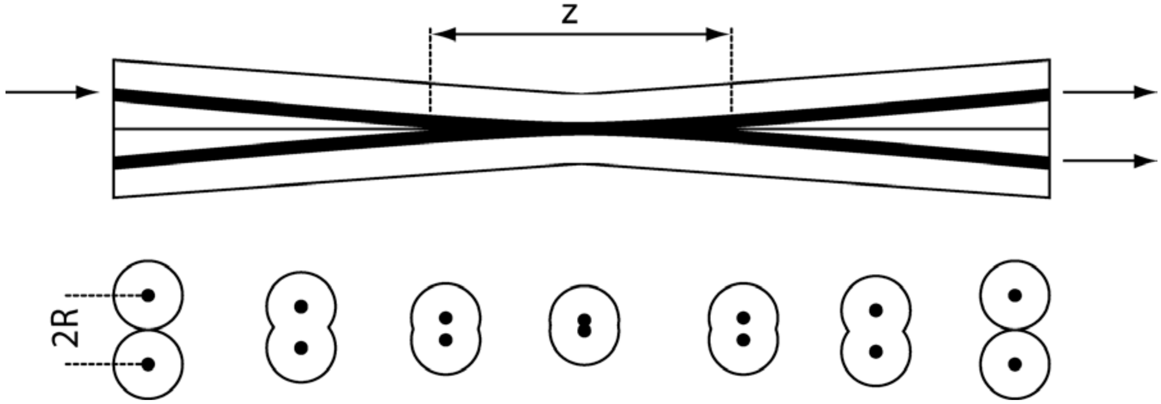


Figure 52: Fused Passive Coupler/Splitter

A fused coupler is a structure formed by joining two independent optical fibers (see Figure 52). The claddings of the fibers are fused in a small region (length *z*). FBT devices work as a result of an energy transfer by coupling proximity between optical fiber cores.

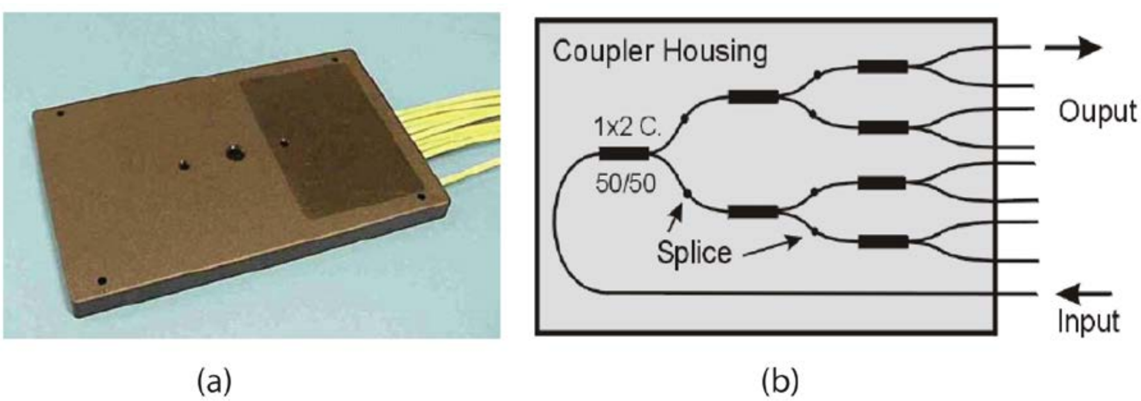


Figure 53: (a) Standard PON Multi–Port PSC, and its (b) Internal Structure

To create a more complex structure than 1x2 or 2x2 configurations, 1x2 fused coupler components are concatenated by splicing each output arm of the first coupler to the input arm of the second ones, and so forth. This is done repeatedly to achieve the desired output power ratio and number of ports required, and a set of cascaded fused couplers and splices are usually housed and protected in a robust, environmentally hardened plastic packaging (see Figure 53(a) for an example of an actual component, and Figure 53(b) with internal structure of such a PSC module).

6.4.2.1 Planar Lightwave Circuit (PLC)

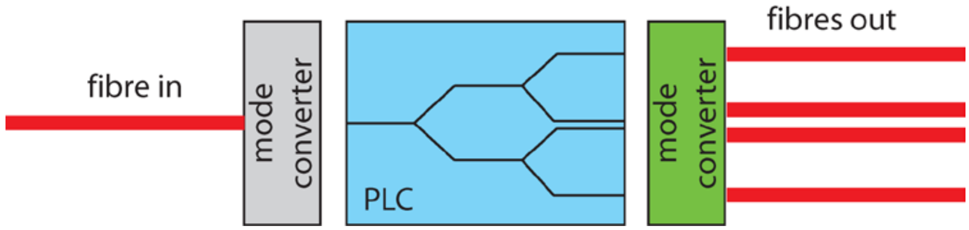


Figure 54: Planar Splitter Sub–Assemblies

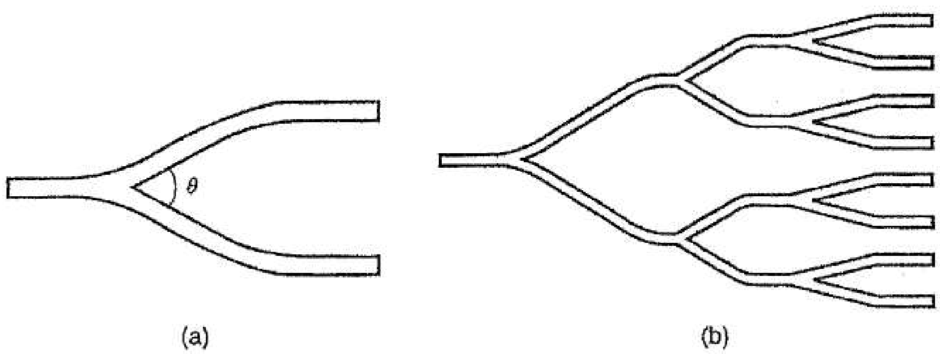


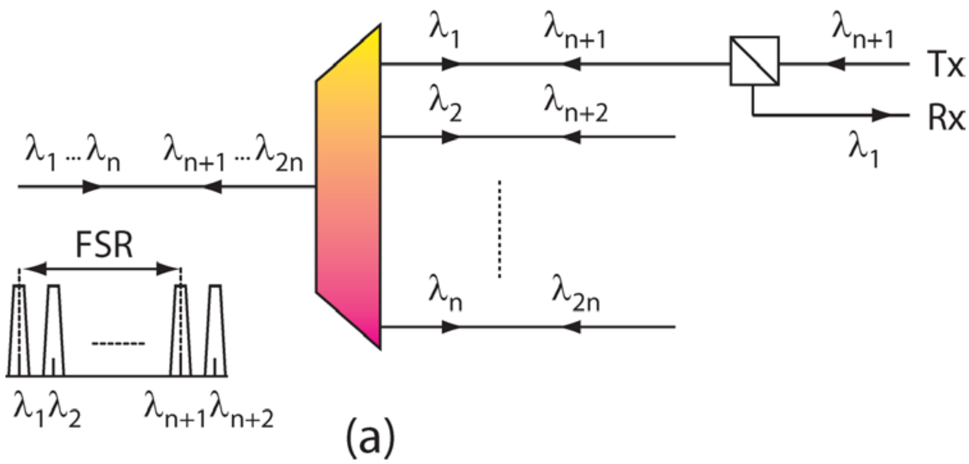
Figure 55: (a) Y-junction and (b) 1:8 PSC made by Combining Several Y-junctions

PSCs can be also manufactured using the planar lightwave circuit (PLC) technique, where power splitting/coupling function is achieved within a Y-junction [see Figure 55(a)]. Such a Y-function is fabricated inside the bulk material using photolithography techniques similar to the procedures used in the semiconductor industry or polymer processing techniques to imprint the Y-junction pattern into the base polymer material, which is then etched and treated accordingly, producing a custom design power splitter. When light is injected in the input end, its power is divided equally between its two branches, assuming that the Y-junction is perfectly symmetric around the axis of the input waveguide. In this sense, this device acts similarly to a standard fiber coupler, except that it has only three ports. Conceptually, it differs considerably from a fiber coupler since there is no coupling region in which modes of two different waveguides overlap.

Depending on the employed manufacturing scheme, PLC-based PSCs can achieve excess loss <0.2 dB per single Y-junction, providing much lower total loss for PSCs with higher power count when compared with typical manufacturing techniques [33], [34].

6.4.3 Wavelength Routers for WDM-PON

A WDM-PON system with multiple wavelength channels in downstream and upstream directions may either deliver all wavelengths to each ONU (wavelength selected) or perform wavelength routing within the ODN and deliver only selected downstream wavelength channel(s) to each ONU. In the wavelength-selected approach, the TDM-PON ODN can be reused, though it requires each ONU to be capable of selecting appropriate downstream and upstream wavelength channels and filter out all other wavelength channels. In the wavelength routed approach, the ODN needs to employ some of sort of a WDM router, placing specific wavelengths into selected output ports.



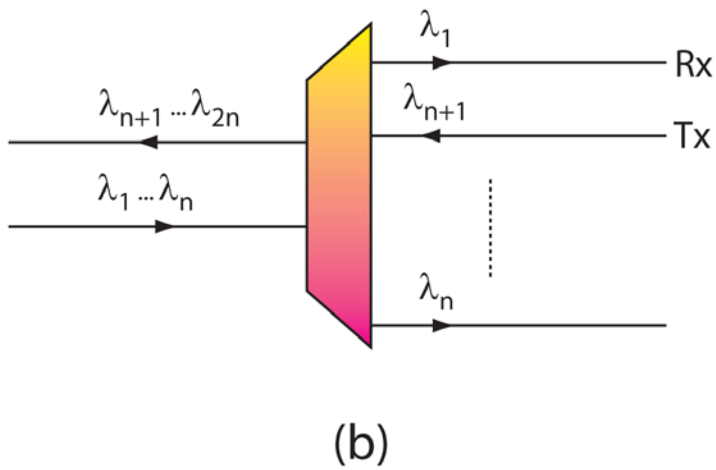


Figure 56: RN with (a) Bidirectional, or (b) Unidirectional Transceiver at the ONU

WDM filters for the use in WDM-PON systems are typically implemented in the form of an Arrayed Wave Guide (AWG). An AWG routes each specific wavelength to a unique output port, separating multiple wavelengths at the same time. Its cyclic wavelength property enables the AWG to be used at the Remote Node (RN), both as multiplexer and demultiplexer at the same time, as depicted in Figure 56. Providing that the upstream channel wavelengths differ from the downstream wavelengths by an integer multiple of the free spectral range (FSR) of the AWG, the same AWG output port can be assigned for both upstream and downstream transmissions, as presented in Figure 56.a. A CWDM filter is used at the ONU for separating the two signals. There are several reasons for using the aforementioned CWDM filter:

- It prevents the downstream signal from entering the Laser Diode (LD) at the ONU.

- The insertion loss of the filter is far less (~ 0.5 dB) when compared to a 1×2 splitter (~ 3.5 dB).
- It prevents the potential upstream signal from entering the Photodetector (PD) at the ONU.)

However, provided that both the downstream and upstream channels use the very same wavelength channel (e.g., in a shared source scenario), two different output ports need to be assigned to an ONU and a 2×N AWG should be used at the RN, as depicted in Figure 56(b).

The typical AWG insertion loss reaches 4 dB to 5 dB, regardless of the number of supported channels, which is significantly lower when compared with a standard PSC. However, a typical AWG's center wavelength shift of ~ 0.01 nm/°C makes it difficult to employ such components in ODN without additional active temperature stabilization. This temperature dependency originates from the index change of the silica waveguide, leading to a change in the optical length of the circuit of the AWG. Recently, athermal packaging of AWGs has been reported, where AWG is equipped with a temperature-compensating material with a temperature coefficient different from that a AWG lightwave circuit [28][29].

WDM filters can be also implemented using thin-film multicavity filters (TFMF) or multilayer interference filters. By positioning cascaded filters in the optical path, wavelengths can be demultiplexed, and vice versa. Each filter is designed to transmit a unique wavelength while reflecting others. This type of filter is better suited for CWDM channels, while the AWG is more adequate for implementing DWDM channels.

Recently, a new type of wavelength router, called a *bulk grating*, has been suggested for use in a DWDM system [36]. This bulk grating is based on a bulk-type diffraction grating and has lower insertion loss (less than 3 dB values are achievable) with narrower channel spacing and larger channel count when compared with the AWG. For instance, devices for 160 channels with 25 GHz channel spacing can be manufactured using the standard production techniques used currently for AWGs. The AWG has an apparent advantage for integration with other devices in thin structures, since it may be implemented on a silica-based PLC, while the bulk grating has a potential for temperature insensitivity and narrow channel spacing, but does not allow for significant size reduction and its integration remains problematic.

6.5 Existing Wavelength Allocation Plans for Optical Access Systems

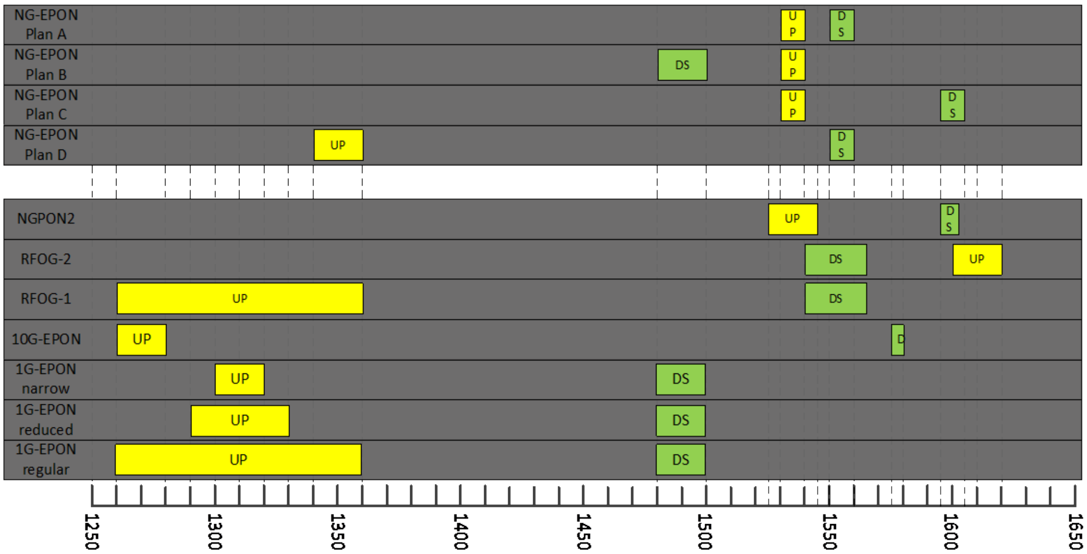


Figure 57: Spectrum Allocation Bands for Optical Access Defined in IEEE Std 802.3, SCTE, and ITU-T

Figure 57 presents a more detailed view of the existing spectrum allocation bands, covering not only optical access systems defined by IEEE 802.3 Working Group and SCTE systems, but also optical access technologies covered by ITU-T recommendations. The spectrum range above 1440 nm (the edge of the GPON guard band [52]) is already covered with either allocated transmission channels or guard bands for legacy systems. Any newly specified optical access standard needs to either operate within existing guard band regions, or displace one of the existing systems, which would potentially break backward compatibility across three generations of equipment.

The continued use of 1610 nm return channel for RFoG impedes deployment of next generation ITU-T systems, overlapping with the downstream channel of TWDM option.

Examples of wavelength allocation plans for several IEEE Std 802.3, SCTE, and ITU-T optical access systems are shown in Table 7. The 1260–1360 nm upstream band for 1G-EPON is defined in IEEE Std 802.3 [4], though it is possible to purchase commercially available 1G-EPON transmitters conforming to reduced or narrow upstream bands, defined for GPON.

Table 7: Wavelength Allocation Plans for Selected IEEE Std 802.3, SCTE, and ITU-T Optical Access Systems

<table>
<tr><th>System</th><th>Downstream (nm)</th><th>Upstream (nm)</th></tr>
<tr><td>1G-EPON</td><td>1480-1500</td><td>1260-1360[1]
1290-1330[2]
1300-1320[3]</td></tr>
<tr><td>10G-EPON</td><td>1575-1580</td><td>1260-1280</td></tr>
<tr><td>GPON</td><td>1480-1500</td><td>1260-1360 (regular)[1]
1290-1330 (reduced)[2]
1300-1320 (narrow)[3]</td></tr>
<tr><td>NGPON2 (TWDM)</td><td>1596-1603</td><td>1524-1544</td></tr>
<tr><td>NGPON2 (P2P WDM)</td><td colspan="2">1524-1625</td></tr>
<tr><td>RFoG 1 [53]</td><td rowspan="2">1540-1565</td><td>1260-1360</td></tr>
<tr><td>RFoG 2 [53]</td><td>1600-1620</td></tr>
</table>

[1] Typical for Fabry Perot lasers
[2] Typical for DFB lasers without temperature control
[3] Typical for DFB lasers with temperature control

6.6 Wavelength Allocation Plans for NG-EPON

1G-EPON, as first specified in IEEE Std 802.3ah™, now part of IEEE Std 802.3 [4], opted for a very cost-effective use of upstream wavelength and least challenging (as far as dispersion) portion of the fiber spectrum, allowing the use of the whole 100 nm region around 1310 nm. While initial generations of optical 1G-EPON transceivers based on FP laser diodes indeed took advantage of this whole spectrum, the development of cost-effective, temperature uncontrolled DFB designs allowed a quick reduction of the occupied upstream band to 40 nm. Today the progress of DFB technology allows for development of 20 nm upstream transceivers for EPON, with a limited or even absent temperature control loop.

10G-EPON [5] started off with a much more efficient use of fiber spectrum in both downstream and upstream directions, requiring only 5 nm spectrum in the downstream (1575–1580 nm) and 20 nm in the upstream (1260–1280 nm). Due to partial overlap with 1G-EPON upstream channel, a dual-rate burst-mode operation was defined in IEEE Std 802.3 [4], allowing for seamless coexistence of legacy 1G-EPON with 100 nm wide upstream and newer 10G-EPON devices.

Given a very constrained availability of free spectrum in deployed SMF (see 6.4.1 for more details), and the number of simultaneously coexisting transport technologies (1G-EPON, 10G-EPON, RFoG with or without return channel, TDR, and others) the decision on the placement and number of wavelength channels (if multiple-wavelength design is adopted) is non-trivial.

Examples of wavelength allocation plans are included in the following sections and shown in Figure 57.

6.6.1 Plan A

Figure 57 illustrates a wavelength plan for NG-EPON (Plan A) guaranteeing coexistence for 1G-EPON, 10G-EPON, and NG-EPON, when operated on the same ODN. The downstream NG-EPON wavelength band is 10 nm wide and placed between 1550 nm and 1560 nm, while the upstream NG-EPON wavelength band is also 10 nm wide and placed between 1530 nm and 1540 nm.

Effectively, in this particular wavelength allocation plan, the spectrum band currently reserved for the RFoG downstream is reused for NG-EPON.

Optical components for C-band are technically mature and are expected to be cost-efficient at this time, though they are typically designed for transport systems and support very limited power budgets. The dispersion in C-band is much higher when compared with O-band, and thus typically EML transmitters are used for high-bit rate and longer distance applications. There are currently no broadly available C-band components supporting power budgets in excess of 29 dB, which would make them capable of operating over the most common ODN designs deployed today.

6.6.2 Plan B

Figure 57 illustrates a wavelength plan for NG-EPON (Plan B) guaranteeing coexistence for RFoG downstream, 10G-EPON, and NG-EPON, when operated on the same ODN. The downstream NG-EPON wavelength band is 20 nm wide and placed between 1480 nm and 1500 nm, while the upstream NG-EPON wavelength band is 10 nm wide and placed between 1530 nm and 1540 nm. Effectively, in this particular wavelength allocation plan, the spectrum band currently reserved for the downstream 1G-EPON is occupied by the downstream NG-EPON, while the upstream NG-EPON band is placed between downstream 1G-EPON band and RFoG, effectively changing requirements for existing wavelength filters on 1G-EPON devices with RFoG downstream.

Observations about maturity of C-band components in 6.6.1 are also applicable to NG-EPON upstream band in this plan. The S-band optical PON-specific components are much more mature, given the long-term deployment of 1G-EPON operating in the same wavelength band in downstream. The transition from 1G to 10G lasers is expected to be relatively straightforward, given the maturity of laser drivers for 10G-EPON transceivers.

6.6.3 Plan C

Figure 57 illustrates a wavelength plan for NG-EPON (Plan C) guaranteeing coexistence for RFoG downstream, 1G-EPON, 10G-EPON, and NG-EPON, when operated on the same ODN. The downstream NG-EPON wavelength band is 10 nm wide and placed between 1595 nm and 1605 nm, while the upstream NG-EPON wavelength band is also 10 nm wide and placed between 1530 nm and 1540 nm. Effectively, in this particular wavelength allocation plan, the NG-EPON wavelength bands are located in areas currently not used by 1G-EPON, 10G-EPON, or RFoG downstream.

Observations about maturity of C-band components in 6.6.1 are also applicable to NG-EPON upstream band in this plan. Off-the-shelf optical L-band DFB lasers and APD receivers achieving 33 dB optical budgets compatible with this wavelength plan have been demonstrated.

6.6.4 Plan D

Figure 57 illustrates a wavelength plan proposed in [12] for NG-EPON (Plan D) guaranteeing coexistence for 1G-EPON, 10G-EPON, and NG-EPON, when operated on the same ODN. The downstream NG-EPON wavelength is 10 nm wide and placed between 1550 nm and 1560 nm, effectively reusing the RFoG downstream band. The upstream NG-EPON wavelength band is

20 nm wide and placed between 1340 nm and 1360 nm, overlapping with the IEEE 802.3-defined 1G-EPON upstream wavelength band.

Coexistence with 1G-EPON and 10G-EPON in the downstream direction is achieved via WDM, where 1G-EPON, 10G-EPON, and NG-EPON wavelength bands are non-overlapping, and separated sufficiently to implement low-cost wavelength filters. Furthermore, given the reuse of the RFoG downstream band, 1G-EPON and 10G-EPON ONUs are already equipped with the appropriate wavelength rejection filters to make sure that downstream NG-EPON transmissions do not affect their receivers.

The coexistence with 10G-EPON in the upstream direction is achieved via WDM, where 10G-EPON and NG-EPON wavelength bands are non-overlapping, and separated sufficiently to implement low-cost wavelength filters. Coexistence with 1G-EPON in the upstream direction is achieved via WDM or TDM schemes. The TDM coexistence mode extends to the concept of TDM coexistence defined for 1G-EPON and 10G-EPON to a triple-rate burst mode operation mode. This mode of operation is only required when the operator uses 1G-EPON ONUs with broad-spectrum (100 nm) transmitters. The WDM coexistence mode is supported when the operator uses 1G-EPON ONUs with reduced-band or narrow-band transmitters, and 1G-EPON and NG-EPON transmissions can be WDM-filtered.

The optical components for the downstream channel are available today, requiring minimum changes to the manufacturing process to support the required power budgets. The optical components for the upstream channel can build on upstream components for 10/10G-EPON, requiring minimum changes to shift the transmission wavelength from 1260–1280 nm band to 1340–1360 nm band.

6.6.5 Comparison of Different Wavelength Allocation Plans

Table 8: Comparison of Different Wavelength Allocation Plans for NG-EPON

<table>
<tr><th>Wavelength Plan</th><th>A</th><th>B</th><th>C</th><th>D</th></tr>
<tr><td>Downstream band (nm)</td><td>1550–1560</td><td>1480–1500</td><td>1595–1605</td><td>1550–1560</td></tr>
<tr><td>Upstream band (nm)</td><td colspan="3">1530–1540</td><td>1340–1360</td></tr>
<tr><td>Number of channels (in 100 GHz grid)</td><td>10 / 10</td><td>20 / 10</td><td>10 / 10</td><td>10 / 20</td></tr>
<tr><td>Maturity of optics Downstream / Upstream</td><td colspan="3">High / Moderate</td><td>High / High</td></tr>
<tr><td>Overlap with 1G-EPON</td><td>No</td><td>Yes</td><td colspan="2">No</td></tr>
<tr><td>Overlap with 10G-EPON</td><td colspan="4">No</td></tr>
<tr><td>Overlap with RFoG 2</td><td>Yes</td><td>No</td><td colspan="2">Yes</td></tr>
<tr><td>Overlap with OTDR</td><td colspan="4">No</td></tr>
</table>

Table 8 presents a comparison of different wavelength allocation plans for NG-EPON, summarizing the key characteristics of specific plans presented in the previous sections. Table 8 includes wavelength overlaps with legacy technologies, but avoids concluding that wavelength non-overlap is the same as achieving co-existence. Filter bandwidths and NEXT/FEXT must be considered before drawing such a conclusion.

6.7 Optical Transmitters

While current optical transmitters could be used, new development might be beneficial. The following sections describe areas for study for an NG-EPON.

6.7.1 Raman Mitigation in downstream NG-EPON

Downstream 10G-EPON transmitters operate at higher power levels than 1G-EPON, causing interaction between analog RFoG and digital EPON carriers, as discussed in [41]. In effect, analog modulated RFoG carriers are depleted into high power digital carriers of 10G-EPON, causing SNR degradation and in extreme cases – service outage.

As NG-EPON is expected to support the same power budgets as 10G-EPON and take advantage of multiple-wavelength access systems, Raman-effect mitigation techniques become increasingly important. The toolset (channel link model, see [15]) developed under IEEE P802.3av *10G-EPON PHY* Task Force accounts for the Raman effect and remains applicable to future NG-EPON development effort, though further analysis is needed in the case that multiple co-propagating wavelengths in the downstream and upstream are required.

6.7.2 Tunable Transmitters

If NG-EPON is specified as a WDM-PON or hybrid-PON, then tunable lasers will provide a number of advantages when used in the ONU, including the following:

- A single time provisioning process performed on demand, when the new station comes online and it is provisioned by the OLT.
- A single ONU type (model) used for deployment, irrespective of the actual wavelength used by the ONU in the access network (port). This eliminates inventory and warehouse problems related with maintaining different types and models of ONUs, as well as deploying specific ONU models on specific ODN ports.

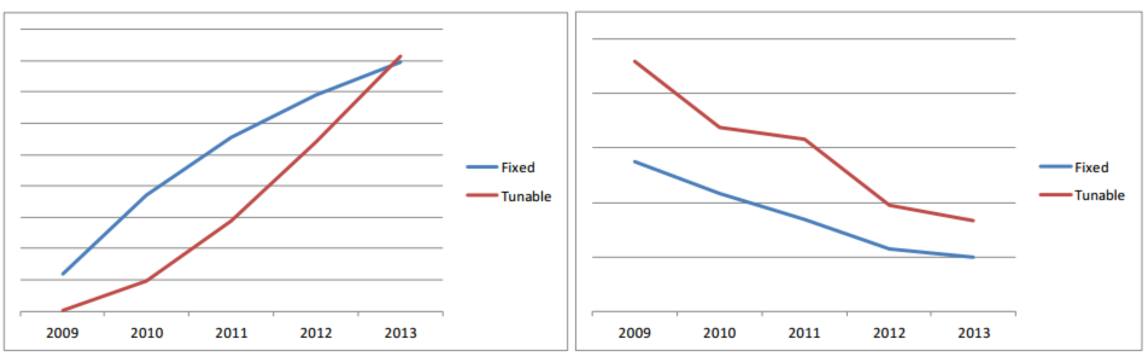


Figure 58: Trajectory of Fixed and Tunable Transceiver Shipments (left image) and Relative Cost of Fixed and Tunable Transceivers (right image)

As of the time of writing, tunable lasers are relatively mature as far as typical transport applications are concerned, employing monolithically integrated Semiconductor Optical Amplifier (SOA) and Mach-Zender (MZ) modulators, as well as automated testing (individual components, as well as resulting transceiver assembly). The manufacturing yield/efficiency has significantly improved in recent years, resulting in substantial decrease in prices of commercially available tunable lasers, as shown in Figure 58. It can be concluded that the total volume of tunable transceivers shipped in 2013 exceeded the volume of shipped fixed wavelength transceivers, while the cost of tunable transceivers continues to decrease more rapidly than fixed wavelength devices. As of the end of 2013, the cost of tunable XFP-format transceiver reached less than 2 times the cost of a fixed wavelength XFP-format transceiver, providing support for the same distance, as well as power budget [44].

To be successful in access applications, the tunable transceivers require further cost decrease, especially if they are planned for use in ONUs. It is expected that increased volumes generated by NG-EPON deployments in the future, as well as relaxed specifications (center wavelength tolerance, band size, etc.) results in a decreasing cost of such devices, especially when combined with steady progress in automated assembly and testing.

6.8 Optical Receivers

While current optical receivers could be used, new development might be beneficial. The following sections describe areas for study for NG-EPON.

Tunable optics enable wavelength tuning features in optical communications systems such as WDM/TWDM based access networks. Tunable receivers work with tunable transmitters to provide access network flexibility and extendibility on legacy ODNs. Furthermore, *colorless* ONUs are highly desirable in optical access networks in order to lower OPEX and enable high-volume deployments.

6.8.1 Tunable Receivers

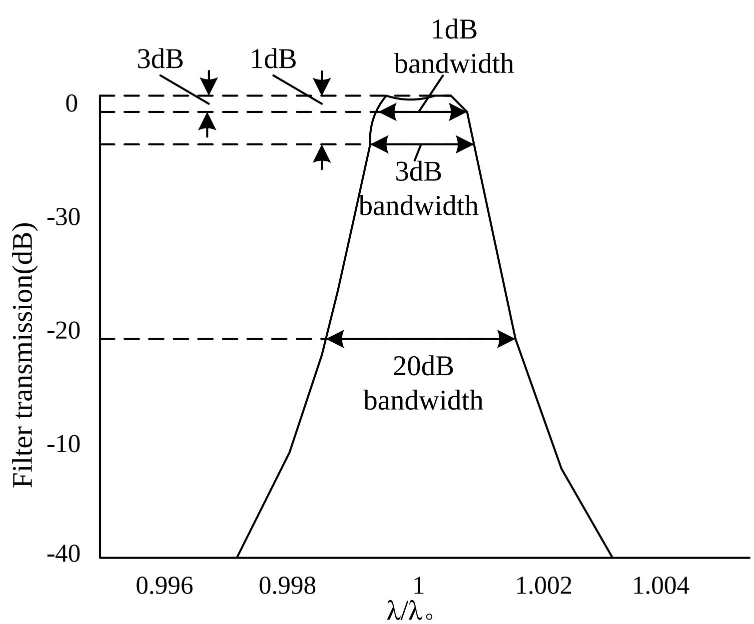


Figure 59: Tunable filter and its characteristics

Tunable filters are a critical element of a tunable receiver, required in some candidate architectures for NG-EPON. An ideal tunable filter is a device that can isolate an arbitrary spectral band at an arbitrary wavelength over a broad, continuous spectral range, preferably with a response function that is identical in form at all wavelengths.

Table 9: Different Tunable Filter Options

Filter Types		Tuning Range (nm)	IL (dB)	FWHM (nm)	Channel Spacing/ Isolation	Tuning Speed	Power[2]	Cost[3]	Size
Fabry-Perot	Thermal Optical FP Filter	40	2	<0.5	100 GHz/ 25 dB	s	Mid	Low	Small
	Liquid Crystal FP Filter	30	3	<0.5	100 GHz/ 20 dB	ms	Low	Mid	Mid
	MEMS FP Filter	221	1.5	<0.5	100 GHz/ 20 dB	ms	Low	High	Small
Waveguide	MZI Filter[3,4]	15	4	<0.5	100 GHz/ 10 dB	µs	Mid	Mid	Small
	Micro Ring Filter	20	5.2	<0.5	100 GHz/ 60 dB	ms	Low	Mid	Small
Micro-motor	Angle Adjustment Filter	80	0.5	<0.5	100 GHz/ 25 dB	ms	Low	High	Large
	Linear Variable Filter	380	2	CWL*1%	100 GHz/ 25 dB	ms	Low	High	Large
	Cavity Length Adjustment Filter	60	2	<0.5	100 GHz/ 20 dB	ms	Low	High	Large

[1] Power and cost estimates include a TEC, if required for operation under extended temperature conditions
[2] Power and cost estimates include a TEC, if required for operation under extended temperature conditions
[3] Large Crosstalk
[4] Large Insertion Loss

The set of typical parameters used to characterize an optical filter is shown in Figure 59 and described in the following list:

- *Insertion Loss (IL)*: ratio of output optical power and input optical power in dB.
- *Polarization Dependent Loss (PDL)*: the ratio of the maximum and minimum transmission of an optical device with respect to all polarization states.
- *Return Loss*: the ratio of input optical power and returned optical power at the same test point.
- *Tuning Speed*: the speed at which the filter can tune to the target wavelength.
- *Tuning Range*: the difference between the shortest and longest wavelength to which the filter can tune.
- *Passband*: the width of the band around the center wavelength where the filter causes minimum loss on the transmitted signal.
- *Power Consumption*: the power consumption of the wavelength tuning mechanism in the filter.
- *High-volume production capacity*: characterizes the ability to mass-produce the device/mechanism in a cost-efficient manner.

- *Control Mechanism*: the method whereby the filter frequency is changed.

There are three major types of tunable filters: Fabry-Perot filters, waveguide filters, and micro-motor filters. A summary of the features of different tunable filter types is shown in Table 9.

6.8.2 Fabry-Perot filters

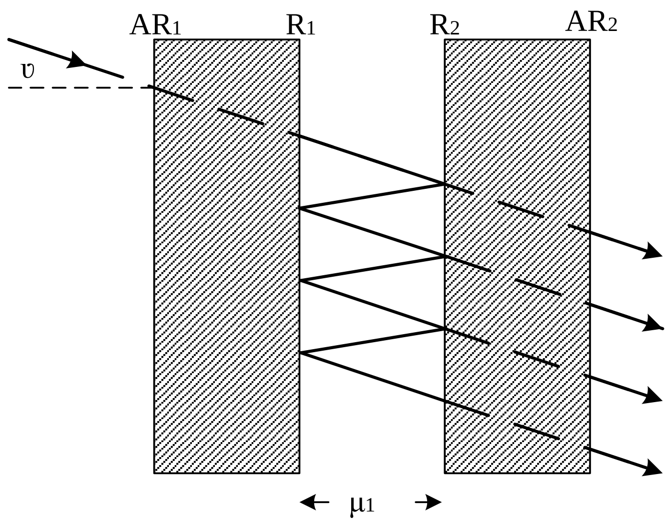


Figure 60: Fabry-Perot Filter

The Fabry-Perot filter is an optical resonator that confines and stores light energy at selected frequencies. This optical transmission system incorporates feedback, whereby the light is repeatedly reflected within the system and thus circulates without escaping the system. A simple Fabry-Perot filter is comprised of two parallel planar mirrors (R_1 and R_2) spaced a fixed distance apart (see Figure 60), and equipped with anti-reflective exterior coatings (AR_1 and AR_2).

The rays travelling between the mirrors are kept perpendicular to the plane of the mirrors via a two-lens system. The lenses are placed outside the mirrors to serve two purposes: first, to establish parallel rays inside the resonance cavity between the mirrors; and second to focus the output light onto the detector following the Fabry-Perot filter.

Table 10: Features of Tunable Filters

Filter type	Advantages	Disadvantages
Thermal optical	Small size, easy for integration Low cost materials Tuning range can reach 40+ nm Mature technology with broad application and mature industry chain	Heat induced wavelength tuning and stabilization, driving high power consumption Slow tuning speed, depending on heater power and heating method
Liquid crystal	Mature technology with broad application and mature industry chain Tuning range can reach 30 nm Low power consumption Fast tuning speed	Polarization dependent Temperature sensitivity (needs thermoelectric cooler or heater) Large size
MEMS	Fast tuning speed (µs level) Low power consumption Large tuning range Small size	Complex process, high cost, need to manufacture in high volume capacity Poor anti-shock performance

Currently, Fabry-Perot filters implemented in thermal optical, liquid crystal, and Micro-Electro-Mechanical Systems (MEMS) have already seen commercial applications and are widely used in optical communications. Thermal optical tunable filters use heating or cooling to control the device's temperature and thus change the refractive index of the Fabry-Perot filter cavity. Liquid crystal tunable filters are optical filters that use electronically controlled liquid crystal elements to transmit a selectable wavelength of light and exclude others. Often, the basic working principle is based on the Lyot filter, but many other designs can be used. This filter type has been applied in optical communications and used in optical channel monitors (OCM), optical add-drop multiplexors (OADM), and wavelength division duplexing (WDD) devices. Features of the primary tunable optical filter types are in Table 10.

6.8.3 Waveguide Filter

Waveguide tunable filters are based on waveguide structures, including Mach-Zehnder Interferometer (MZI) and micro-ring tunable filter.

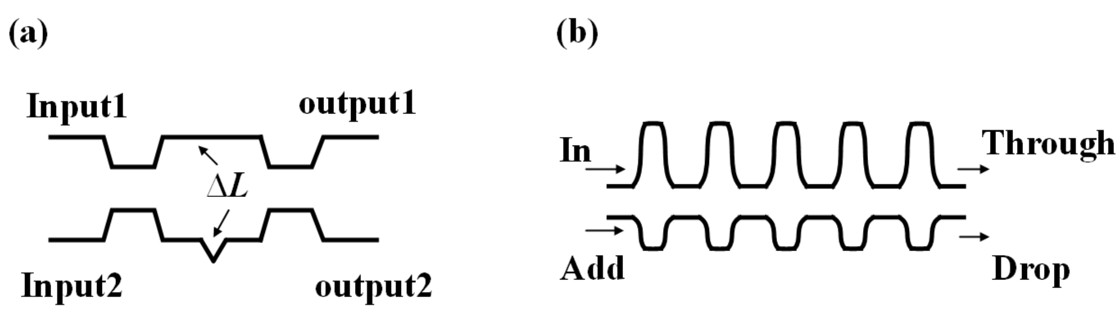


Figure 61: MZI filter schematic diagram

MZI (see Figure 61) uses the difference in the length of optical paths to decompose the incoming optical signal and perform selective filtering. The transmission spectrum of single MZI is very wide, so multiple MZI are cascaded to achieve a much narrower spectrum filtering capability. The resulting large crosstalk, as well as technical challenges in the manufacturing process, make this technology unsuitable for large-scale application in access networks.

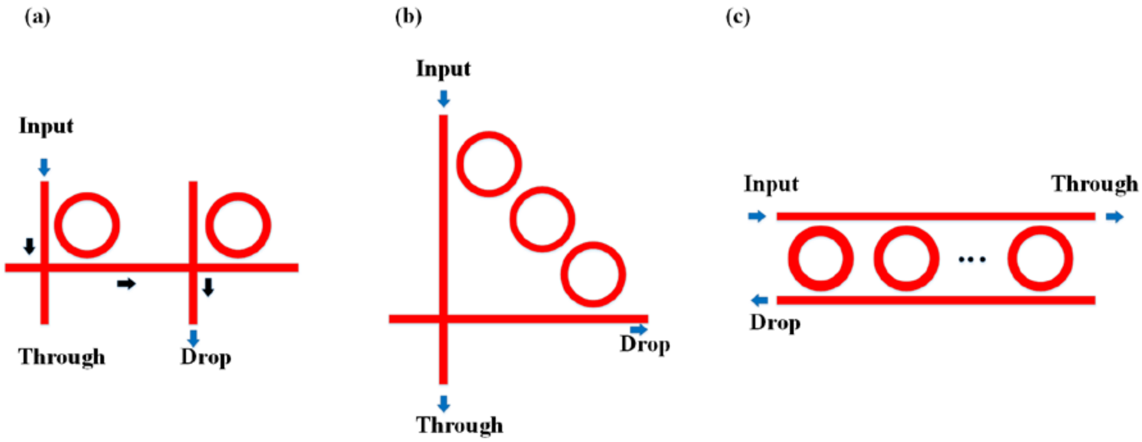


Figure 62: Three topologies of micro ring tunable filters

Micro-ring tunable filters (see Figure 62) are based on a waveguide resonator principle. This filter type has the same characteristic wide spectrum as MZI; thus, it is necessary to cascade multiple micro-ring resonators to achieve narrow spectrum filtering capabilities, using one of the available topologies (cascade, serial coupling, or parallel coupling).

Table 11: Advantages and drawbacks of the three micro-ring topologies

Topology	Advantages	Disadvantages
Cascading	Expansion of FSR Reduced crosstalk	Loss increase due to center wavelength mismatch
Series coupling	Expansion of FSR Flattop pass band	Small fabrication tolerance
Parallel coupling	Flattop pass band	Small fabrication tolerance

Advantages are disadvantages of individual topologies of the micro-ring filters are summarized in Table 11.

6.8.4 Micro-motor Filter

A micro-motor filter includes a micro-mechanical element (typically an electrical motor), changing the properties of the filtering cavity. There are several types of micro-motor filters, including linear variable, angle adjustment, and cavity length adjustment filters.

Linear variable micro-motor filters change the transmission (pass-band) characteristics of the filter along with the spatial location of the filtering element. This technology is relatively mature and features a large tuneability range, low insert loss and millisecond-level tuning speed. Drawbacks include large size, high cost, and large full width at half maximum.

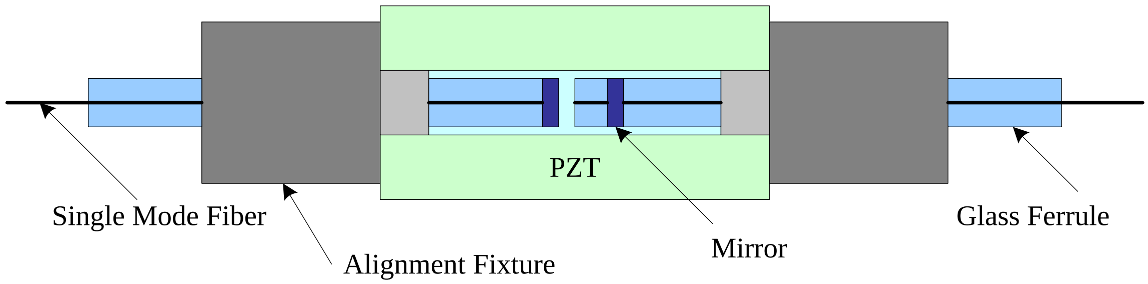


Figure 63: Cavity length adjustment tunable filter

Angle adjustment tunable filters feature a special thin-film filter, which is tuned using a micro-motor to adjust the angle of incident light. The characteristics of this filter type include relatively mature technology, large tuning range, low insert loss, large size, and high cost.

Cavity length adjustment tunable filters use a micro-motor to change the length of the filter cavity to adjust the filtering wavelength (see Figure 63). These filters have low insertion loss, thermal stability, high reliability, and relatively large size.

6.9 Support for Larger MTU

There is a high demand in the industry to support frames larger than 1986 octets as specified in IEEE Std 802.3 [4]. Observing that the vast majority of enterprise and carrier-grade Ethernet products support frames of at least 9kB (often called *Jumbo Frames)* in length easily establishes the widespread demand for larger MTU support in Ethernet. The demand to support larger Ethernet frames is driven by applications like the following:

- Cellular backhaul and fronthaul
- Distributed database and cloud applications
- Home automation and M2M communication

There is also a growing interest from the end users to minimize the transmission overhead not at layer 2 and above.

There are two ways NG-EPON could address the need to carry frames exceeding the size of envelope frames:

- Frame fragmentation
- Increasing the MTU size for OLT and ONU

The fragmentation approach could take advantage of the work of the IEEE P802.3br *IET* Task Force. At the time of writing, this Task Force is working on defining the extended MAC architecture to support interspersing express traffic. This Task Force is going to add also a framework for MAC frame fragmentation. Such a framework could be reused in NG-EPON for packet fragmentation purposes, where large incoming Ethernet frames would be fragmented into 2 kB segments and then transmitted to the link peer and then reassembled. The advantage of this solution is related with its scalability to any size of MTU, making NG-EPON independent of any future changes in the MTU size required by the end-applications. There are drawbacks, though, mainly related with the increased cost and complexity of OLT and ONU due to fragmentation / reassembly at high data rates.

The alternative approach assumes the extension of the size of the MAC frame size to 9 kB and development of mechanisms to carry such larger frames through Ethernet networks, including NG-EPON. The drawback of this approach is the fixed size of the MTU, which might be further increased in the future, requiring revision of the NG-EPON specifications. Additionally, the minimum grant size would have to be increased to the size of a maximum frame (9 kB), negatively affecting the delay and jitter through the system.

At this time, the progress of IEEE P802.3br *IET* Task Force and their resulting framework for MAC frame fragmentation seem to be the most scalable and future proof approach to supporting MTU exceeding 2 kB in the optical access.

6.10 Bandwidth Allocation: Static versus Dynamic

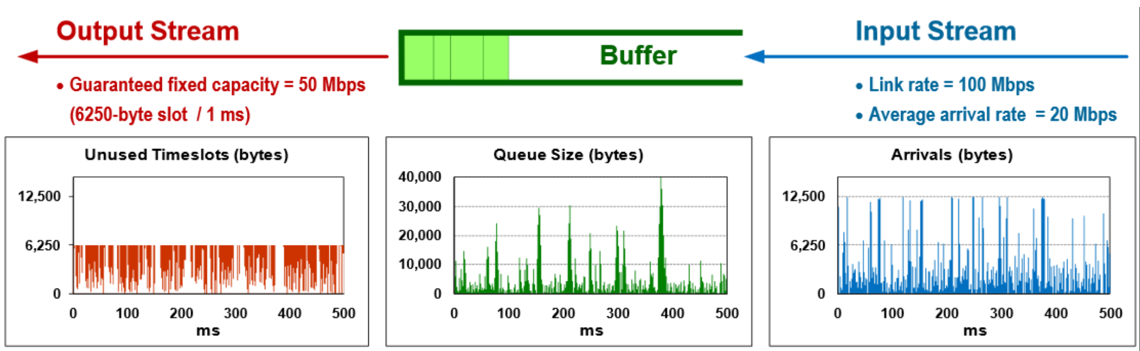


Figure 64: Bursty traffic and strict traffic shaping with fixed slot allocation

Static bandwidth allocation is an inefficient resource allocation scheme in access networks. Statically allocated (fixed size) transmission slots are almost always not large enough to accommodate queued bursty traffic, and in between individual data bursts, the allocated transmission slots are underutilized. For example, a bursty data stream with the average data rate of only 20 Mb/s is fed at the line rate of 100 Mb/s into a queue, granted with a fixed guaranteed bandwidth of 50 Mb/s (6250 bytes per slot per 1 ms). Given that the interarrival times for individual packets are self-similar and do not follow traditional Poisson models used to model traffic arrival in voice circuits, and that the egress capacity is 2.5 times larger than the average ingress data flow, the queue size still grows to 40 kB, resulting in excessive delay for queued packets, and potentially lost, if the buffer size was set to some smaller size. This scenario is presented in Figure 64.

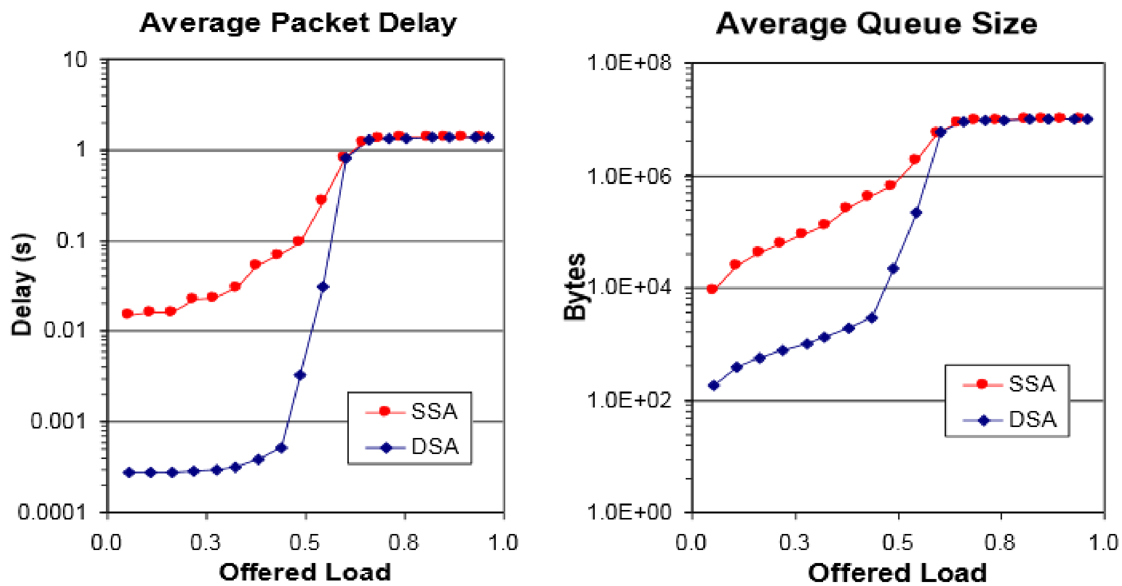


Figure 65: Comparison of Static and Dynamic Slot Assignment in EPON

Through the efficient use of the dynamic bandwidth granting based on the operation of the Multi Point Control Protocol (MPCP), EPON provides very low delay until the upstream channel congestion point is reached, and the packet queues on the ONUs start to fill up quicker than data can be retrieved from them and transmitted upstream. What is even more interesting is that a properly designed dynamic bandwidth allocation (marked as DSA in Figure 65) protocol can outperform static bandwidth allocation (marked as SSA in Figure 65) in terms of average queue size and average packet delay, until the uplink saturation point is reached. At that time, both mechanisms exhibit similar performance, clearly indicating that there is no observable advantage to SSA in the optical access for self-similar traffic typical in modern IP networks.

7 Economic Feasibility of NG-EPON

The economic feasibility of NG-EPON systems is influenced by a number of factors, including costs of equipment (OLT and ONU), costs of outside plant (ODN), costs of installation of the OLT in the chosen facility, and at the target ONU location, as well as operational costs incurring on daily basis by operator using this technology.

7.1 Costs of Outside Plant

The cost of deploying and maintaining the ODN infrastructure for EPON (1G-EPON, 10G-EPON) is well known and understood by operators using this technology today. Given the expectation that the NG-EPON operates over the very same ODN as the previous generations of EPON, the material and installation costs of fiber plant, splitters, and other passive components of the ODN remain unchanged.

Furthermore, the reuse of the very same ODN design allows operators to take advantage of the experience of field technicians, design teams, and civil construction teams, resulting in more agile and cost-optimized deployment process. Network design, installation, and maintenance costs are minimized by preserving the already existing network architectures, management, and software, as well as processes internal to individual operators. The ability to build on existing deployment and maintenance mechanisms is crucial for quick roll-out and successful integration into already existing network architectures.

Last but not least, the ability to support multiple generations of EPON on the same ODN extends the life span of the already deployed ODN, allowing operators to provide services to subscribers for a longer period of time without having to reinvest money into the PON infrastructure.

7.2 Costs of Installation

The costs of installation are primarily related with the complexity of the deployment of the OLT in its target facility, deployment of individual ONUs at their target locations (depending on the selected PON architecture), and configuration process for services once the active devices are in place. Given that the deployment model for NG-EPON does not change when compared with previous generations of EPON, the costs of installation of active devices remain well understood.

If NG-EPON employs hybrid- or WDM-PON technology, then depending on the wavelength agility of NG-EPON ONUs, the service configuration process might require to allocate specific wavelength channels to particular ONUs, though it is expected that the extended MPCP protocol (to be developed by the future NG-EPON Task Force) makes this process semi-automatic, requiring no dedicated (colored) optics on the ONU side. If NG-EPON employs TDM-PON technology, then there is no change to existing configuration processes.

7.3 Costs of Active Equipment

The costs of NG-EPON ONU and OLT devices are hard to predict with any level of certainty. Figure 66 presents the relative price of 1G-EPON and 10/10G-EPON active devices (ONU and OLT) over time, based on data from [35].

The price of 1G-EPON ONU in the first quarter of 2008 is assumed to be equal to 1 unit (100%). The chart shown in Figure 66 represents the erosion in the price of 1G-EPON ONU over time. The price of 10/1G-EPON ONU is presented relative to the price of 1G-EPON ONU in the first quarter of 2008. It is worth noting that when the first commercial 10G-EPON ONUs were included in an OVUM report [35] in the first quarter of 2011, their price was almost 2.5 times higher than the price of 1G-EPON ONU in 2008, though they did provide much more bandwidth. Since then, by the first quarter of 2014, the report indicates the price of 10/1G-EPON ONU stabilizing around 1.5 the price of 1G-EPON ONU. It is expected that the price of a single wavelength NG-EPON ONU be comparable to the price of 10/10G-EPON ONU, with the premium attributed primarily to the tunable optics (if used by operators). The price of higher capacity ONUs using multiple wavelengths largely depends on the progress of optical integration and availability of higher speed system-on-chip (SoC) capable of handling more than 10 Gb/s. It is probably reasonable to expect the first generation of multi-wavelength NG-EPON ONUs will cost 4 times more than current 10/10G-EPON ONUs, with additional premium for tunable optics (if used by operators).

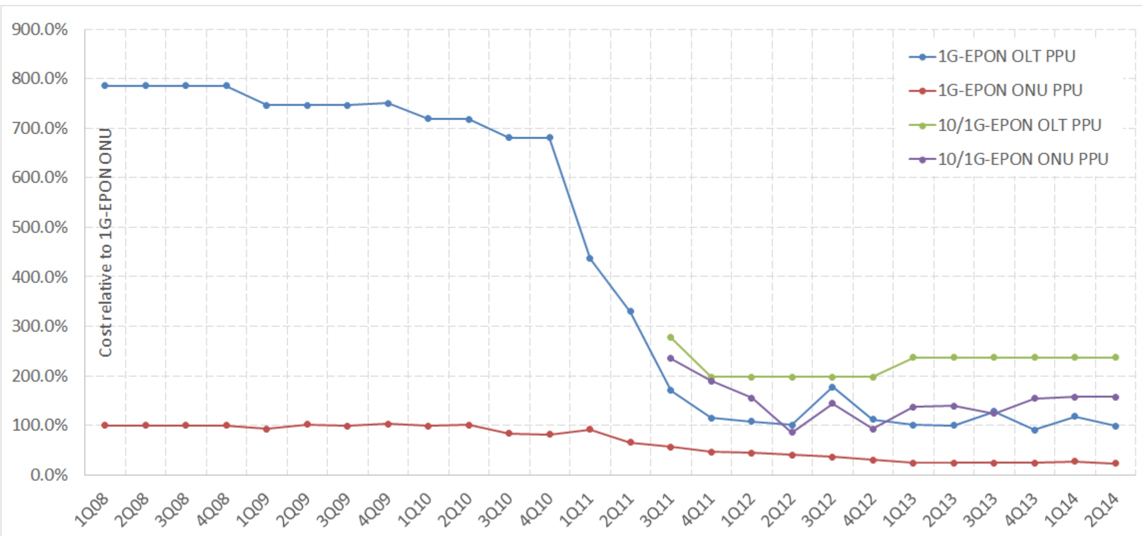


Figure 66: Relative Cost of 1G-EPON and 10/1G-EPON ONU and OLT Devices over Time

The price of 1G-EPON OLT has also decreased over time, as shown in Figure 66. The price of the 10/1G-EPON OLT port relative to the price of 1G-EPON ONU port has been low in the first quarter of 2011, and remains only slightly higher when compared with 1G-EPON OLT port. The cost of NG-EPON OLT port largely depends on the progress of optical integration, and at this time it is hard to speculate on the relative cost of such a device.

Figure 67: Relative Cost for 1 Gb/s of Bandwidth

The cost of 1 Gb/s of raw bandwidth has been used recently as a representation of the system's ability to provide high speed data services in a cost-effective manner. Figure 67 presents the relative cost of 1 Gb/s of bandwidth in 1G-EPON and 10G-EPON, taking the cost of such bandwidth unit in the first quarter of 2008 as 1 unit. The steady erosion in the cost of this bandwidth unit is visible, but what is more interesting is the fact that 10/1G-EPON remains competitive with 1G-EPON when it comes to the cost of 1 Gb/s of bandwidth.

8 Conclusions

The telecommunications and cable network operators have deployed 1G-EPON on a large scale and the 10G-EPON deployments are ramping up around the world. The following distinct markets and applications currently rely on EPON:

- Residential subscriber access providing voice, video, and data services
- Commercial (business) subscriber access providing primarily voice and high-grade/high-reliability data services
- Mobile (cellular) backhaul

The observed ~50% annual growth in volume of Internet traffic in residential applications is driving the migration from legacy to fiber-based access technologies. For the residential subscribers served by EPON, the speed of residential wired or wireless LANs becomes the primary gating factor for the bandwidth demand. While being predominantly in the range between 100 Mb/s and 1 Gb/s today, the interface speeds of the customer equipment (PCs, laptops, set-top boxes, TVs, security cameras, personal storage farms, etc.) are expected to increase to 2.5– 5.0 Gb/s within the target timeframe for the NG-EPON technology. The stochastic nature and the temporal profiles of the residential traffic make statistical multiplexing techniques especially beneficial to the performance of the residential access networks, while at the same time relaxing the aggregated capacity targets, compared to the business access environment.

The bandwidth demand in the business access market is being driven by the following two major factors:

- An increase in the average bandwidth demand per business subscriber.
- An increase in the number and density of business subscribers that provides strong incentives for the network operators to migrate customers currently served with point-to-point solutions to a PON-based solution.

The simultaneous increase in bandwidth demand per business subscriber and aggregation of multiple subscribers on a single PON lead to much higher bandwidth requirements for NG-EPON in business access markets, compared to the residential markets. Higher-grade service level agreements and an abundance of time-sensitive circuit-like flows in the business access environment give higher priorities to user isolation and hard performance guarantees per business customer. This drives providers to provision less capacity sharing for business subscribers then is typically used for residential subscribers.

A very similar transformation is taking place in the mobile backhaul market. To serve an increasing number of mobile devices, wireless operators are increasing the density of antenna deployments with the corresponding reduction is cell size. At the same time the traffic volume per individual cell is increasing steadily. A typical cell tower has moved from being served with 100 Mb/s circuit at the end of 2013 to ~350 Mb/s circuit at the end of 2014, and it is expected to increase to ~500 Mb/s by the end of 2015. With the evolution towards bonding multiple LTE bands, it is likely that in 2016 the industry would see backhaul capacity grow in excess of 1 Gb/s per cell tower.

The growing number of subscribers, ever-increasing bandwidth consumption, and the continued demand for new, higher-speed services in both residential and business environments create an impetus for the industry to initiate the development of the standard for the next generation of EPON systems.

While unified in the common trend to support more subscribers with a higher data rates, the residential access, business access, and mobile backhaul markets have different bandwidth targets and technical performance requirements. Not only are the technical requirements different in all these markets, but also the cost-to-performance objectives are different. To address these diverse requirements the following solutions merit further consideration:

- A multi-wavelength (per-direction) EPON PHY (i.e., hybrid PON) with an aggregate downstream capacity of at least 40 Gb/s (40G-EPON), with an evolutionary path to 100 Gb/s (100G-EPON).
- A single wavelength (per direction) EPON PHY (i.e., TDM-PON) that supports symmetric downstream and upstream line rates of at least 25 Gb/s (25G-EPON) or 25 Gb/s downstream / 10 Gb/s upstream line rate (25/10G-EPON).

The new PHYs need to consider the coexistence with the deployed EPON technologies and reuse functions and components of 10G-EPON to the extent possible.

The findings of this report substantiate a recommendation that a Study Group be formed within the IEEE 802.3 Working Group to develop a Project Authorization Request, Criteria for Standards Development and objectives for a new standard for the next generation of EPON PHYs.

9 Citations

[1] IEEE Standard for Service Interoperability in Ethernet Passive Optical Networks (SIEPON), IEEE Std 1904.1™-2013.

[2] IEEE Standard for Local and Metropolitan Area Networks - Virtual Bridged Local Area Networks Amendment 5: Connectivity Fault Management, IEEE Std 802.1ag™ - 2007. (Amendment to IEEE Std 802.1Q™-2005 as amended by IEEE Std 802.1ad™-2005 and IEEE Std 802.1ak - 2007).

[3] IEEE Standard for Local and metropolitan area networks—Bridges and Bridged Networks, IEEE Std 802.1Q-2014 (Revision of IEEE Std 802.1Q-2011).

[4] IEEE Standard for Ethernet, IEEE Std 802.3-2012 (Revision to IEEE Std 802.3-2008).

[5] IEEE Standard for Ethernet Amendment 1: Physical Layer Specifications and Management Parameters for Extended Ethernet Passive Optical Networks, IEEE Std 802.3bk-2013 (Amendment to IEEE Std 802.3-2012).

[6] IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, IEEE Std 1588-2008 (Revision of IEEE Std 1588-2002),.

[7] IEEE Standard for Local and Metropolitan Area Networks—Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks, IEEE Std 802.1as-2011.

[8] Joe Smith, Bill Powell, "Optical Wavelength Considerations for NG-EPON," http://www.ieee802.org/3/ad_hoc/ngepon/public/jan14/powell_ngepon_01A_0114.pdf, January 2014, Indian Wells, CA, USA.

[9] "State Council issue notice of 'Broadband China' strategy and implementation plan," issued by Chinese State Council, August 17, 2013.

[10] "Fiber to the x", http://en.wikipedia.org/wiki/Fiber_to_the_x

[11] Marek Hajduczenia, "Ready to give up on TDM?", http://www.ieee802.org/3/ad_hoc/ngepon/public/may14/bhn_ngepon_1_0514.pdf, May 2014, Norfolk, VA, USA.

[12] Marek Hajduczenia, Michel Allard, "Wavelength allocation plan for NG-EPON," http://www.ieee802.org/3/ad_hoc/ngepon/public/sep14/bhn_and_cogeco_ngepon_1_0914_R03.pdf, September 2014, Kanata, Ontario.

[13] Glen Kramer, "Taxonomy of PON,",http://www.ieee802.org/3/ad_hoc/ngepon/public/jan14/kramer_ngepon_01_0114.pdf, January 2014, Indian Wells, CA, USA.

[14] Multi-author contribution "10Gb/s PHY for EPON—Call for Interest," http://www.ieee802.org/3/cfi/0306_1/cfi_0306_1.pdf , March 2006.

[15] IEEE P802.3av, Draft Standard for Channel Link Model, version 2.3, http://www.ieee802.org/3/av/public/tools/3av_0804_linkmodel_v2_3.xls.

[16] E. Harstead, R. Sharpe, "Forecasting of Access Network Bandwidth Demands for Aggregated Subscribers using Monte Carlo Methods," *IEEE Communications Magazine*, March 2015.

[17] E. Harstead, R. Sharpe, "Future Fiber-To-The-Home bandwidth demands favor Time Division Multiplexing Passive Optical Networks," *IEEE Communications Magazine*, November 2012.

[18] E. Harstead, R. Sharpe, "Bandwidth demand forecasting (for section 4.2.2),"http://www.ieee802.org/3/ad_hoc/ngepon/public/sep14/harstead_ngepon_01a_0914.pdf September 2014.

[19] ITU-T G.652, "Characteristics of a single-mode optical fibre and cable," 2011 with errata and amendments.
[20] ITU-T G.657, "Characteristics of a bending-loss insensitive single-mode optical fibre and cable for the access network," 2010 with errata and amendments.
[21] V. Houtsma, D. van Veen, A. Gnauck and P. Iannone, "APD-Based DuoBinary Direct Detection Receivers for 40 Gb/s TDM-PON," 2014, unpublished.
[22] V. Houtsma, D. van Veen, E. Harstead, "PAM-4 vs. duobinary modulation @25 Gb/s," http://www.ieee802.org/3/ad_hoc/ngepon/public/15jan/ngepon_0115_houtsma_01.pdf , Jan. 2015.
[23] Minghui Tao, Lei Jing, "Feasibility of high speed TDM in NG-EPON," http://www.ieee802.org/3/ad_hoc/ngepon/public/may14/tao_ngepon_01_0514.pdf , May 2014, Norfolk, VA, USA.
[24] IEC 60793–2, Edition 7.0, Optical fibres—Part 2: Product specifications—General, 2011.
[25] A. Lender, "The Duobinary Techniques for High-Speed Data Transmission," IEEE Trans. Consumer Electronics, vol. CE-82, pp. 214–218, May 1963.
[26] Amitabha Banerjee, Youngil Park, Frederick Clarke, Huan Song, Sunhee Yang, Glen Kramer, Kwangjoon Kim, and Biswanath Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: a review," http://networks.cs.ucdavis.edu/~amitabha/papers/jonnov2005.pdf .
[27] FTTH Council, "Passive Splitters for FTTH-PON Applications," White Paper, 2004.
[28] K.-D. Langer, J. Vathke, K. Habel, and C. Arellano, "Recent Developments in WDM-PON Technology," presented at ICTON'06, 2006.
[29] J. Hasegawa and K. Nara, "Ultra low loss athermal AWG module with a large number of channels," Furukawa, vol. 26, 2004.
[30] M. Fujiwara, T. Imai, K. Taguchi, K. Suzuki, H. Ishii, and N. Yoshimoto, "Field Trial of 79.5-dB Loss Budget, 100-km Reach 10G-EPON System Using ALC Burst-Mode SOAs and EDC," in Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America, 2012), paper PDP5D.8.
[31] H. Yoon, et al., "10G-EPON System Engineering and Deployment Strategy," in Technical Digest of OECC 2012, July, Busan, 2012.
[32] B. L. Booth, J. E. Marchegiano, C. T. Chang, R. J. Furmanak, D. M. Graham, and R. G. Wagner, "Polyguide(tm) Polymeric Technology for Optical Interconnect Circuits and Components," DuPont, White Paper, available on-line at: http://www.opticalcrosslinks.com/pdf/photonics97.pdf, 1997.
[33] T. Xu, Z. Lai, Y. Yang, M. Bachman, and G. P. Li, "A low-cost injection-molded polymeric channel waveguide," presented at Optical Fiber Communications Conference (OFC), 2003.
[34] T.-D. Ni, D. Sturzebecher, A. Paolella, and B. Perlman, "Novel polymer optical couplers based on symmetry mode mixing," IEEE Photonics Technology Letters, vol. 7, pp. 1186 – 1188, 1995.
[35] OVUM "Market Share Report 2Q14 FTTx, DSL, and CMTS," 2014.
[36] P. Rigby, "Lightchip launches AWG killer," Light Reading, 2002.
[37] Sandvine, "2H 2013 Global Internet Phenomena Report," https://www.sandvine.com/downloads/general/global-internet-phenomena/2013/2h-2013-global-internet-phenomena-report.pdf , Fall 2013.
[38] J. Smith, "Netflix Now Streaming in Ultra HD 4K," http://blog.netflix.com/2014/05/netflix-now-streaming-in-ultra-hd-4k.html, 2 May 2014.

[39] T. Cloonan, "Maximum Permitted Bandwidth on Cable Modems," http://www.ieee802.org/3/ad_hoc/ngepon/public/15jan/ngepon_0115_cloonan_01.pdf, Jan 2015.

[40] Sinsky et al., "High-Speed Electrical Backplane Transmission Using Duobinary Signaling," IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 1, January 2005, p.152.

[41] Sergey Y. Ten, Silvia Pato, "Non-linear effects in PON fiber channel," http://www.ieee802.org/3/av/public/2006_11/3av_0611_ten_1.pdf , November 2006.

[42] D. van Veen, V. E. Houtsma, P. Winzer, and P. Vetter, "26-Gb/s PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver," in European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optical Society of America, 2012), paper Tu.3.B.1.

[43] ITU-T Y.1731, OAM functions and mechanisms for Ethernet based networks, 2006 with errata and amendments.

[44] Wen Li, "Tunable Lasers – Technologies, Cost, and Applications," http://www.ieee802.org/3/ad_hoc/ngepon/public/mar14/li_ngepon_01_0314.pdf, March 2014, Beijing, PRC.

[45] Zhiming Fu, Yong Guo, Liquan Yuan, "NG-EPON Coexistence scenarios and wavelength plan," http://www.ieee802.org/3/ad_hoc/ngepon/public/mar14/yuan_ngepon_01_0314.pdf , March 2014, Beijing, PRC.

[46] iControl Networks, "2014 State of Smart Home," report available online at: http://www.icontrol.com/insights/2014-state-smart-home/.

[47] "Internet Connected Devices Surpass Half a Billion in U.S. Homes," available online at https://www.npd.com/wps/portal/npd/us/news/press-releases/internet-connected-devices-surpass-half-a-billion-in-u-s-homes-according-to-the-npd-group/.

[48] Shalini Ramachandran, "Bright House to Build Ultrafast Broadband Network," available online at: http://www.myultrafi.com/wp-content/uploads/2014/03/Wall-Street-Journal-Article_03-12-14.pdf, Wall Street Journal, March 2014.

[49] APPIRIO, "State of the Public Cloud: The Cloud Adopters ' Perspective," available at: http://thecloud.appirio.com/rs/appirio/images/State_of_the_Public_Cloud_Results_FINAL-102910.pdf, October 2010.

[50] J. Nielsen, "Nielsen's Law of Internet Bandwidth," available online at: http://www.nngroup.com/articles/law-of-bandwidth/.

[51] ITU G.671, "Transmission characteristics of optical components and subsystems," 2012 with errata and amendments.

[52] ITU G.984.5, "Gigabit-capable passive optical networks (G-PON): Enhancement band," 2014 with errata and amendments.

[53] SCTE 174 2010, Radio Frequency over Glass Fiber-to-the-Home Specification, http://www.scte.org/documents/pdf/standards/SCTE 174 2010.pdf .

[54] G. Agrawal, P. Anthony, T. Shen, "Dispersion penalty for 1.3-μm Lightwave systems with multimode semiconductor lasers," J. Lightwave Technology, volume 6, number 5, 1988.

[55] "Fiber communication system ," Beijing University of Posts and Telecommunications Publishing Group, page 183.

[56] D. Suvakovic, H. Chow, D. van Veen, J. Galaro, B. Farah, N. P. Anthapadmanabhan and P. Vetter, "Low Energy Bit-Interleaving Downstream Protocol for Passive Optical Networks," 2012 IEEE Online Conference on Green Communications (GreenCom), p.26-p31 (2012).

[57] D. Suvakovic, et. al., “A Low-Energy Rate-Adaptive Bit-Interleaved Passive Optical Network,” IEEE J. Selected Areas in Communications, v. 32, n. 8, Aug. 2014.
[58] G. Kramer, L. Khermosh, F. Daido, A. Brown, et. al., “The IEEE 1904.1 standard: SIEPON architecture and model,” IEEE Communications Magazine, v. 50, n. 9, Sep. 2012.