Fiber-to-the-Premises
- A Next Generation Access Network Solution

by

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Tutorial Outline

Part I

- Fiber-to-the-Premises Technology
- Next Generation Passive Optical Networks

Part II

- PHY/MAC Layer Issues
- Studies on WDM-Based Passive Optical Networks

Part - I

Fiber-to-the-Premises Technology

Presentation Outline

- Introduction
- Evolution of fiber-based broadband access
- PON Architectures and Enabling Technologies
- ITU-T/IEEE Standard Configurations
- Deployment Scenario and State-of-the art
- Field Trials and Test Bed Studies
- Summary

Introduction

Access Network is the last (or first) mile of the telecom infrastructure between the central office and the user

Dial-up through PSTN using DSL and Cable-modem technologies were primary methods for broadband access

Desire to access the Internet with a high-speed connection and multimedia services requires >1Mbps/user (broadband)

Paradigm shift from Telco-centric (circuit-switched) to IP-centric (packet-switched) transport

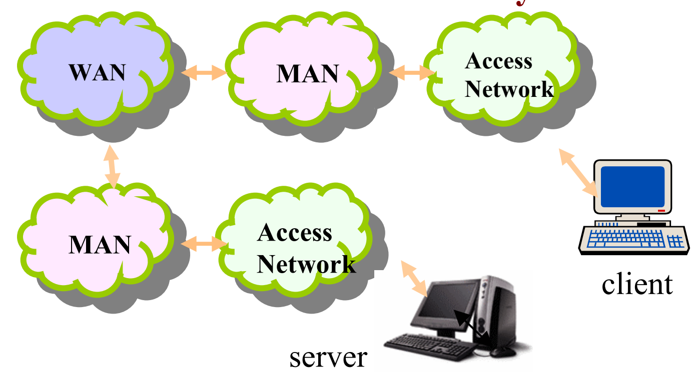
Lack of optical RAM rules out simple extensions to electronic counterparts

Support for heterogeneous traffic:

- bursty/constant bit rate/real time/non real-time
- digital video, telecommuting, multimedia interactive services
- efficient and high speed IP service: multicast /broadcast
- narrow and broadband analog services

Need for capability to internetwork with network core to support end-to-end connectivity

Telecom Connectivity



Existing Access Technologies

Technology	Speed	Typical Range
ADSL	2 Mbps	5.5 Km
VDSL	20 Mbps	1.0 Km
Coax	2 Mbps	0.5 Km
WiFi	54 Mbps	0.1Km
WiMax	28 Mbps	15 Km
3G Cellular	10/6 Mbps	few Km
3G LTE	100 Mbps	10-15 Km

Classification of Access Networks

Service Bandwidth – Narrow band (33.6 Kbps voice modem)

- Mid band (ADSL-9/0.8 Mbps ; VDSL-50/2 to 25 Mbps)
- Wide band (FTTH & PON)

Symmetry – Symmetric (Telephony)

- Asymmetric (Internet, Video)

Broadcast/Switched – Broadcast (cheaper, NIU identical, Intelligence in NIU)

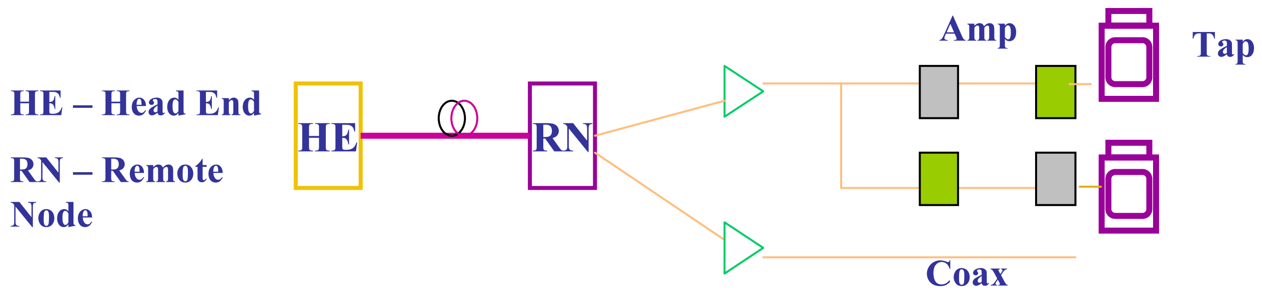
- Switched (Security, fault location, Intelligence in n/w)

Shared/Dedicated – Shared (Bursty traffic, NIU operates at aggregate rate)

- Dedicated (CBR Traffic, QoS, NIU operates on fixed BW)

Network Services - Telephone, Broadcasting or Cable TV, xDSL
WiMax for BWA, Cellular telephony
FTTH, LAN / WLAN

Fiber based Access Networks



- **HFC (Hybrid fiber coax)**

  - Up gradation of analog coaxial services

  - Unidirectional and simple management

  - Star coupler based tree topology

  - NIU separates telephone and video signals

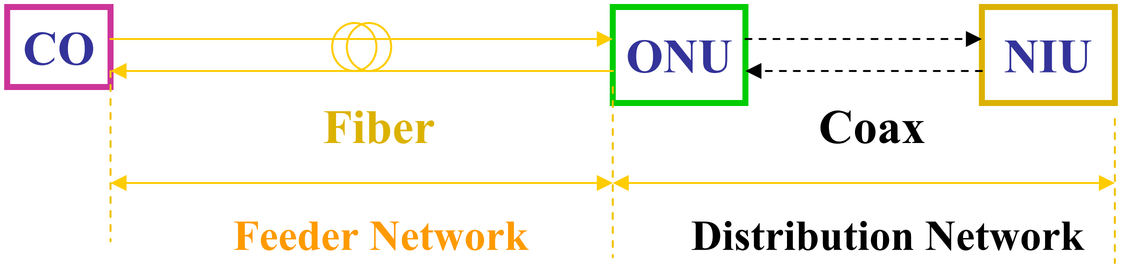
  - Supports digital information transfer

    Video - 5 to 550 MHz, AM-VSB, 6MHz TV signals

    Data - 30 Mbps (downlink) & 5-40 MHz band (uplink)

  - Limited upstream BW and powered amp. sections

Fiber based Access Networks



CO - Central office

ONU – Optical Network Unit

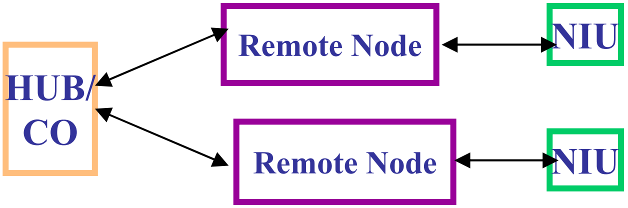
NIU – Network Interface Unit

Depending on the fiber proximity - FTTH, FTTC architectures evolved

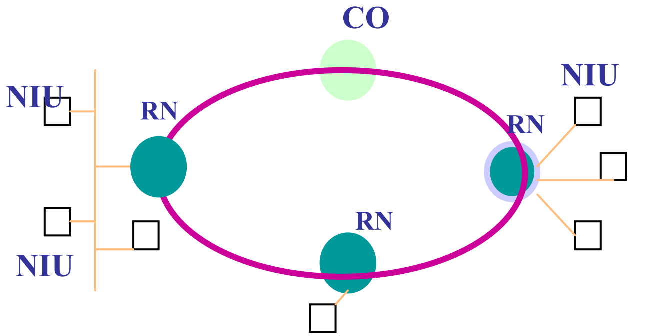
- FTTC (Fiber to the Curb)
  - Data digitally transmitted
  - CO to ONUs - feeder ; ONU to NIUs - distribution
  - ONUs share BW using TDM or ATM techniques
  - ONU serves 8-64 homes (NIUs)
  - Needs an overlay HFC network for analog video
  - Attractive to new entrants

Common Topologies

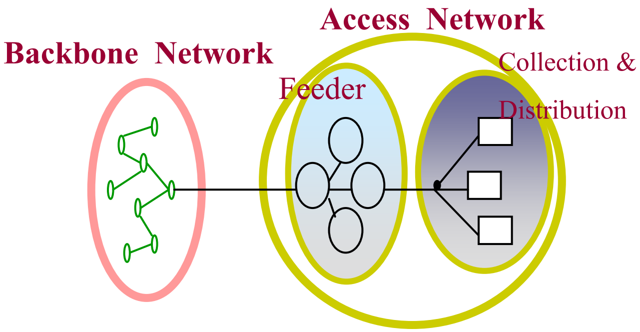
- **Star - Local /Rural telephone network**
  - **Simple subscriber equipment**
  - **Scalability straight forward**



- **Tree - Multiple bus network**
  - **TDM equipment necessary**
  - **Good scalability**



- **Ring – Minimal amount of cable**
  - **TDM for broadband transport**
  - **Limited scalability**



NIU: Network Interface Unit

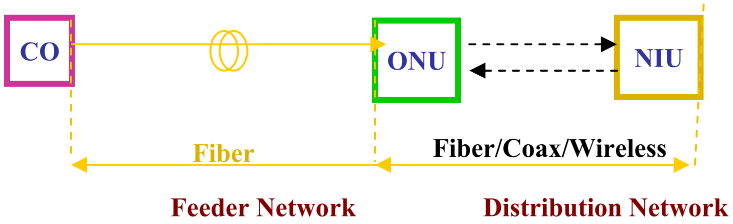
RN: Remote Node

CO: Central Office

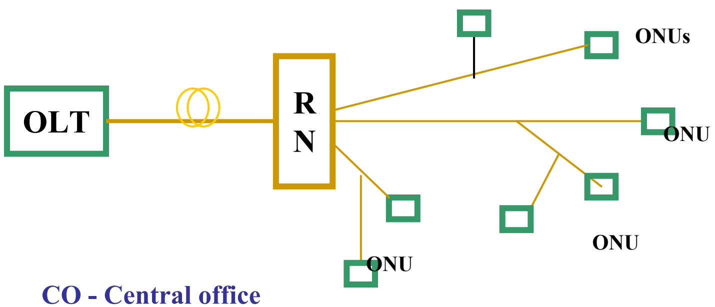
Fiber to the Premises

- Fiber needs to be deployed close To The user Premises for broadband services ---FTTP
- Fiber Access supports triple play services (voice, video and data) and is scalable with tree topology
- FTTP is a cost sensitive segment and mandates network resources to be shared
- Passive , point-to-multipoint architectures called passive optical networks (PONs) are widely accepted
- Service providers are adopting content-based revenue as the business model as against BW-based model
- Easy to install, provision, maintain and troubleshoot
- Reliable, high BW platform and smoothly integrates into any CO equipment or out-side plant

Fiber-based Access Network



Passive Optical Network (tree-based)



CO - Central office

ONU – Optical Network Unit

NIU – Network Interface Unit

OLT – Optical Line Terminal

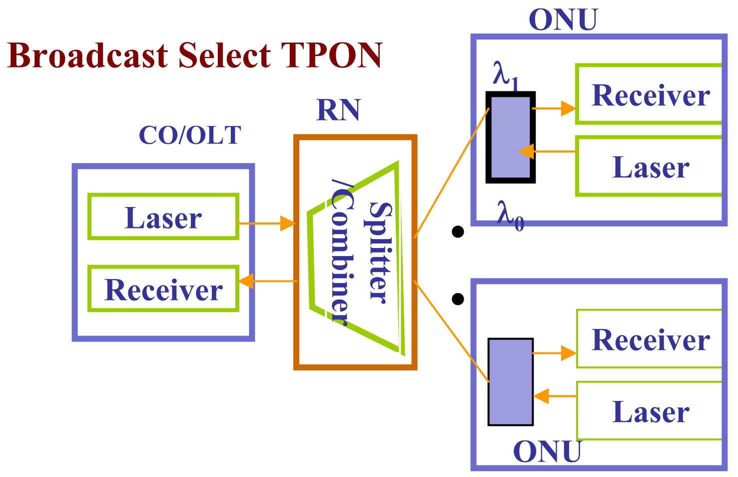
RN–Remote Node

Variants of PONs

Time Division Multiplexing PONs (TDMPON):

- TDMPON uses Passive splitter devices for channel distribution and aggregation through the remote nodes

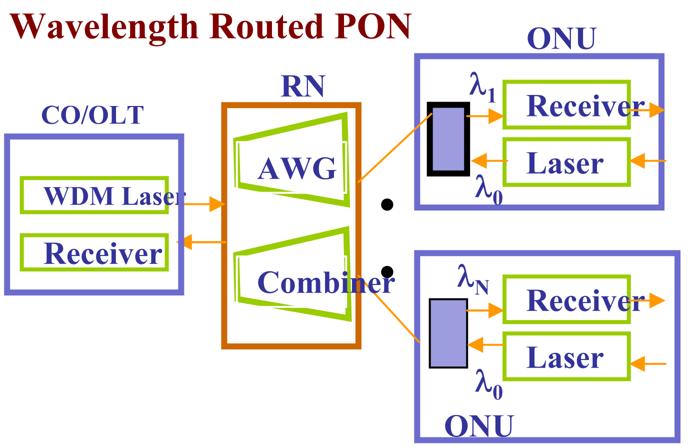
- IEEE/ITU-T standardized PONs (G. 983/4 series) are single carrier-based and employ ATM/TDM
    - ATM, BPON
    - Ethernet PON, GEPON
    - GPON



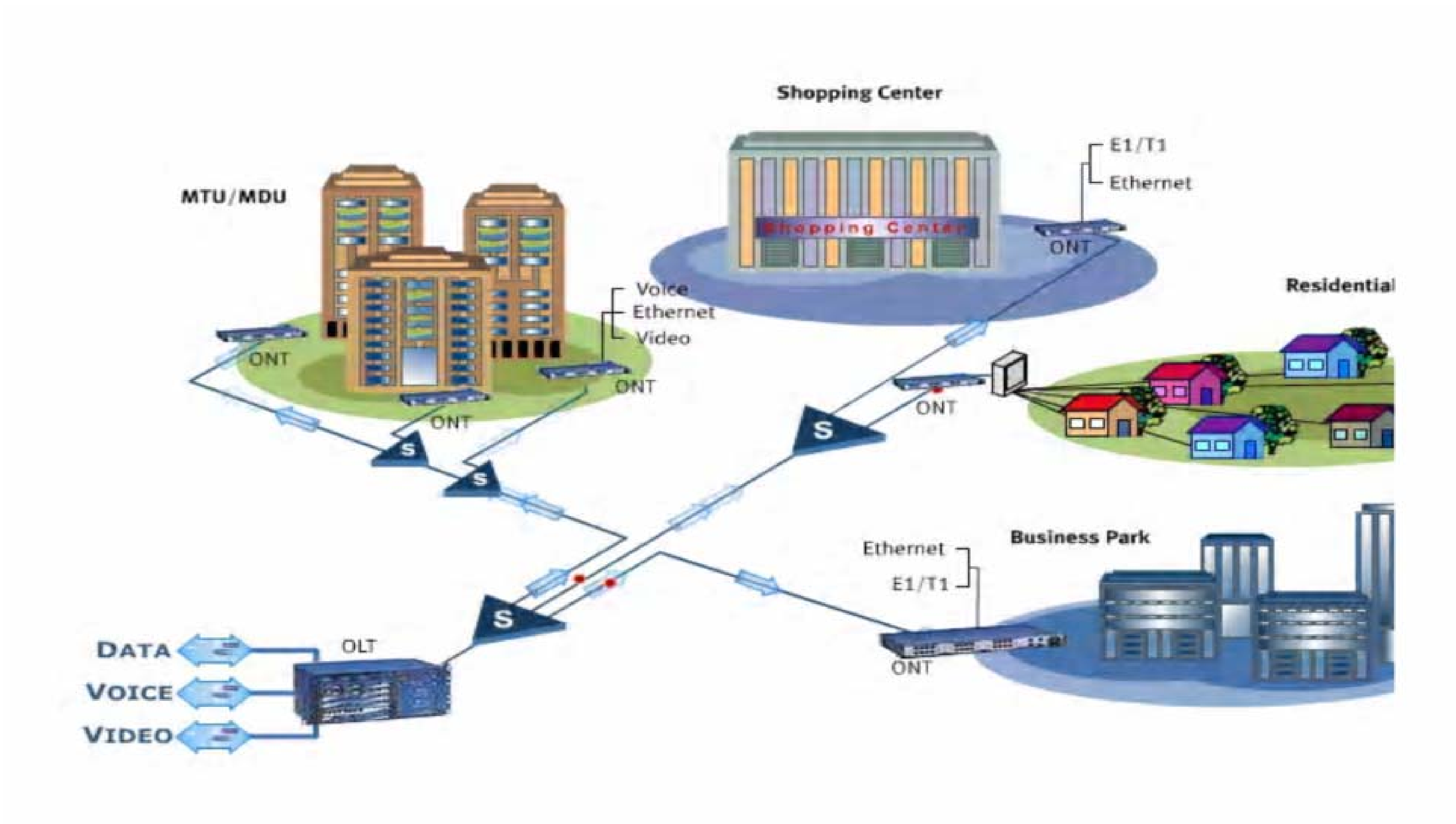
Wavelength Division Multiplexing PON (WDMPON):

- WDMPON ensures high bandwidth, dynamic service provisioning and transparency

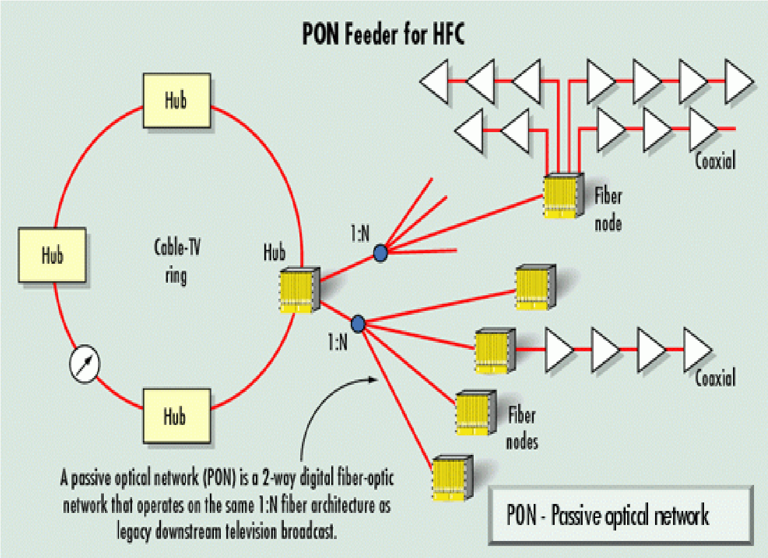
- WDMPON uses Routing devices for channel distribution and aggregation



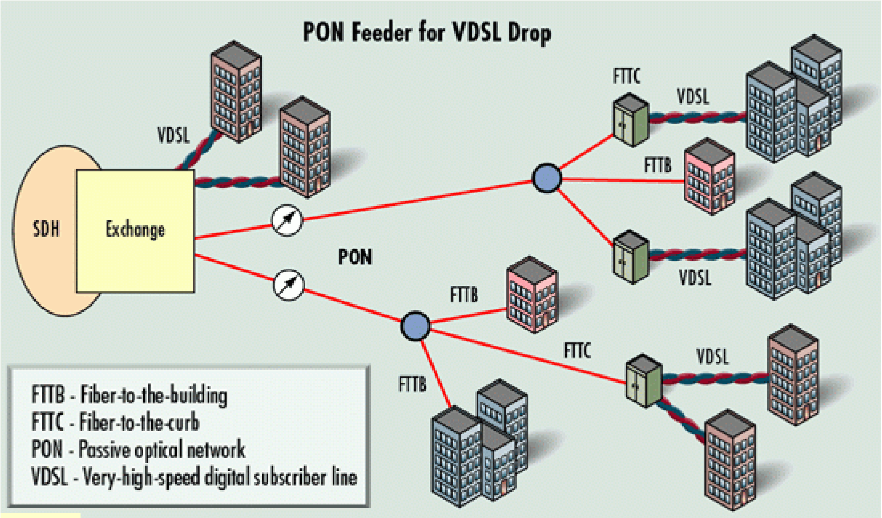
A Typical FTTP Deployment



PON Application - Feeder Configurations

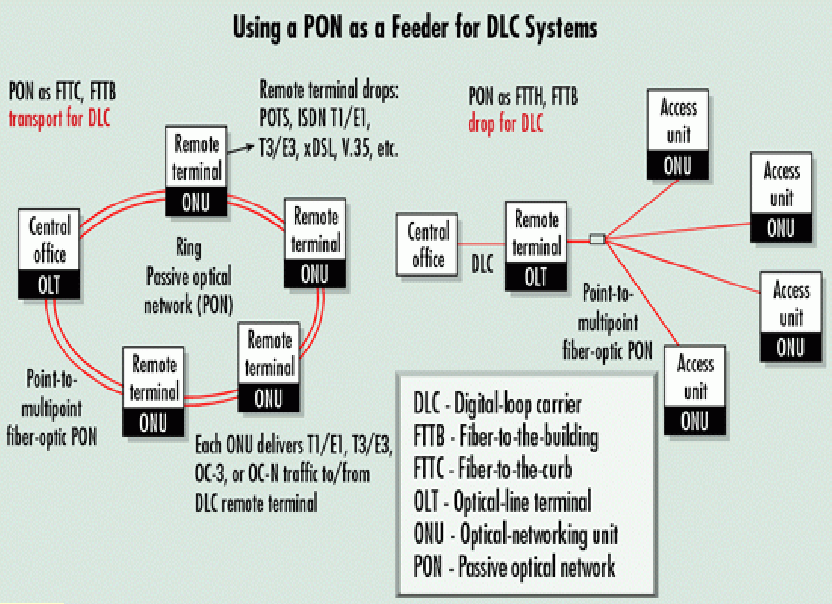


A PON between the hub and multiple fiber nodes offers a low-cost method for adding fault-tolerant, bidirectional digital transport in a cable-TV network.

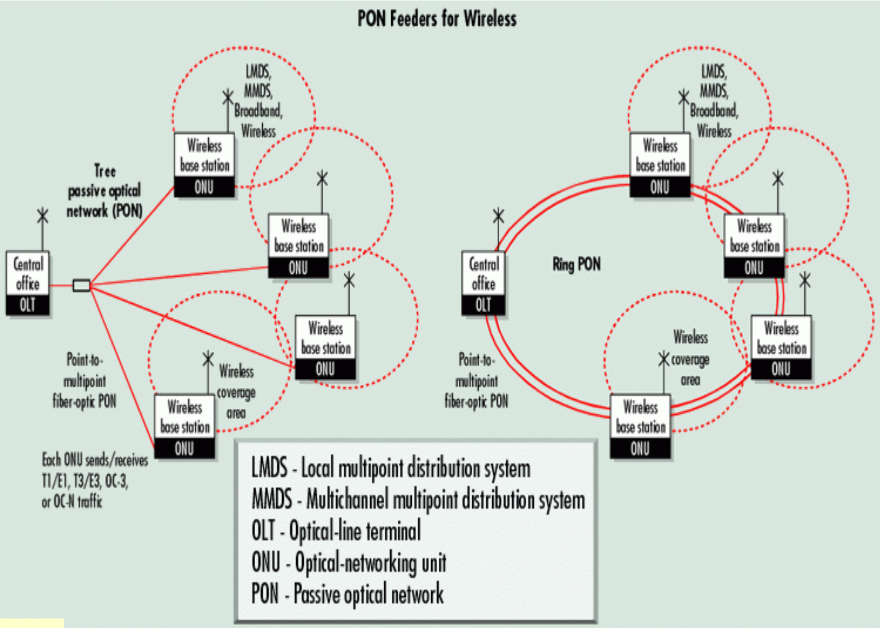


VDSL technology supports 50-Mbit/sec transmission over copper but only over short distances of less than 1000 ft; therefore, an optical-fiber feeder network such as a PON is required. This network topology, referred to as the full-services access network (FSAN), is backed by most of the world's major telephone companies.

PON Applications- Feeder Configurations



The passive optical network lowers the digital-loop-carrier network cost, while enabling fault-tolerant broadband service.



A PON can aggregate traffic from the wireless base stations back to the CO. Wireless base stations deliver broadband services in a surrounding area that is typically 5 km.

Desirable Features for the PONs

- High BW, QoS and smooth connectivity within/amongst user-clusters
  - -Dynamic bandwidth allocation, separate MAC protocols
  - - service differentiation in WDMOAN

- Cost-effective deployment
  - - Passive architectures with shared fiber segments

- Scalability and Resource Provisioning
  - - Hybrid access/multiplexing technology (WDM/TDM/SCM/OCDM)

- Security, fault tolerance and support for bursty traffic
  - - Encoded access schemes like OCDMA; unpowered PON less prone to failures
  - - maximize resource utilization with scalability in W-OCDMA PON

- Service transparency, link upgradeability and network reconfiguration
  - - WDM and wavelength routing in the optical layer (WR-WDMPONs)
  - - assessment of signal quality in WDMPON

Deployment Scenario

Global:

• Approximately 76% of the world's FTTH subscribers reside in the Asia/Pacific region. By 2006, Japan had FTTx connectivity to 67 million domestic subscribers

• The Asia/Pacific region, Latin America and the Middle East/Africa regions will see very high growth rates

• By year-end 2010, the US will have had over 179 million broadband subscribers.

•Total worldwide DSL subscribers will have reached 371 million at year-end 2010

•Mobile wireless broadband subscribers continue to grow rapidly as service providers roll out 3G and 4G services

• North America continues to be the largest market for cable modem services.

India:

•India announced a National Broadband Plan of connecting close to 160 million households (existing10.3 M connections)

•As part of the NBP, TRAI hopes to have 60 M wireless broadband, 22 M DSL and 78 M Cable Internet users, by 2014

•State Optical Fiber Agencies (SOFA) in each state under a National Optical Fiber Agency (NOFA) Speeds of upto 10 Mbps downlink are expected in cities.

Standards Forums

The Broadband Forum:

• Central organization driving broadband wire line solutions
• Empowers converged packet networks for vendors, service providers and customers
• Develop multi-service packet network specifications: interoperability, architecture and management.

Full Service Access Network:

• Task group studies evolution of optical access systems beyond GPON.
• NGA task group studies technology and architecture options for NGOANs (e.g. 10 Gbit/s, reach/split)

FTTH Council:

• Consists of providers of FTTH services and companies involved in planning/building FTTH networks.
• The Council members share knowledge and build industry consensus on key issues surrounding fiber to the home.
• Educate the public about FTTH solutions and to promote the deployment of fiber to the home

Study Groups

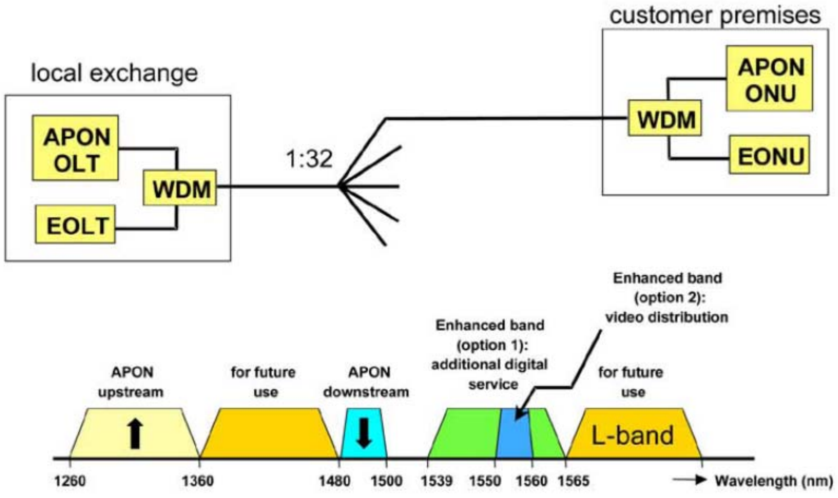
- **IEEE 802.3 Ethernet Working Group:**
  - IEEE Std 802.3z-1998, Gigabit Ethernet
    - IEEE Std 802.3ae-2002, 10Gb/s Ethernet
    - IEEE Std 802.3ah-2004, Ethernet in the First Mile
  - IEEE Std 802.3av-2009, 10Gb/s PHY for EPON

- **ITU-T Study Group 15 (2009-12):**
  - Optical transport networks and access network infrastructures
  - Study Group 15 works on DSL and optical access and backbone technologies.
  - SG15 standards (ITU-T Recommendations) relating to passive optical networks (PONs).

Standard Configurations-APON/BPON

APON (ATM Passive Optical Network)/BPON

- A G.983 Standard adopted by ITU-T in 1999
- 155Mbps/622 Mbps downstream; 20 Km
- Bursts of ATM cells at 155 Mbps upstream
- OAM features (auto ranging, BER monitoring, security, auto-discovery)
- Named BPON after adding broadcast video overlay on 1550 nm
- BPON defined in ITU Rec. G.983.1/2/3

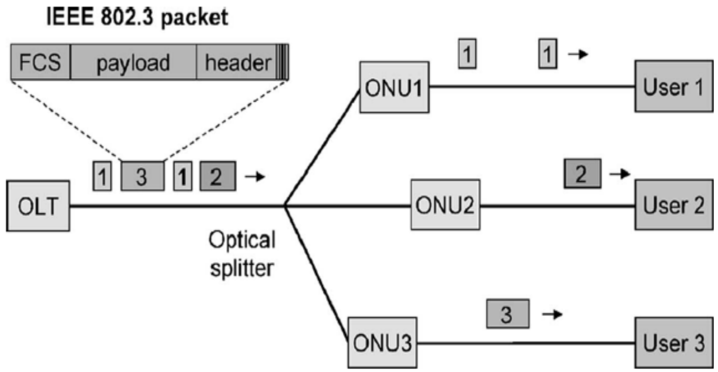


WDM enhancement G.983.3.

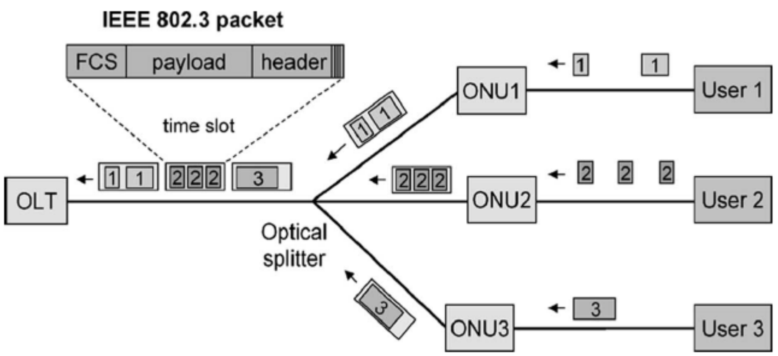
Standard Configurations-EPON

EPON (Ethernet PON)

- An effort to accommodate IP dominant traffic in the year 2001
- Extension to IEEE 802.3 MAC (sub layer with a family of PHY layers)
- Point to multipoint topology with passive splitters
- Work within IEEE Ethernet in the First Mile group and standardized in Sept. 2004



Downstream traffic in an EPON.

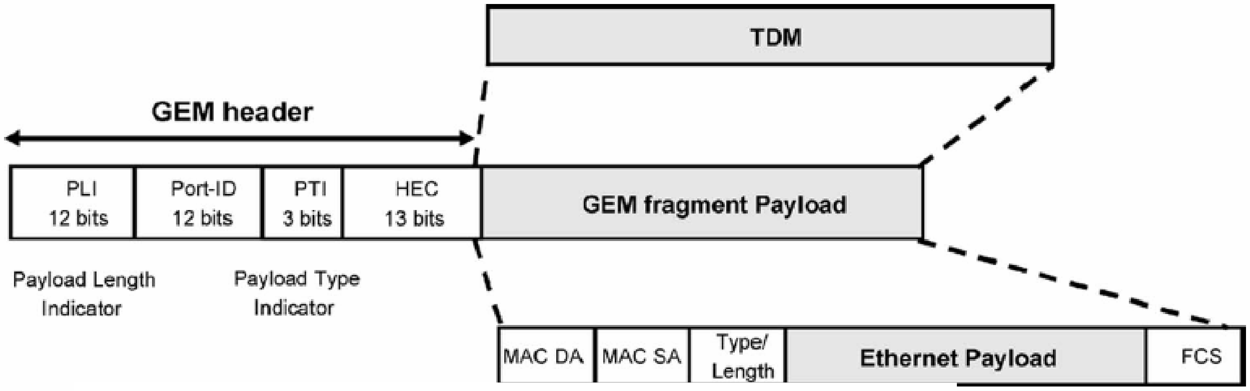


Upstream traffic in an EPON.

Standard Configurations-GPON

GPON (Gigabit Passive Optical Network)

- Efforts of FSAN and ITU-T in 2001
- Full service support (Voice, Ethernet, ATM, Leased lines)
- Symmetric 622 Mbps or Asymmetric 2.5/1.25 Gbps ; 20-60 Km
- Transport frames encapsulated to enable fragmentation
- QoS implemented taking SLAs into consideration
- ITU adopts GPON spec.s as Rec. G.984x



GPON encapsulation method according to ITU-T Rec. G.984.3.

WDMPON Configurations

- **WDM-based PON ensures very high bandwidth, flexible service provisioning and transparency**

- **ONUs operate at individual data rates; OLT –Array/tunable lasers**

- **Architectural Choice:**

  Broadcast star
  - good connectivity, inherent multicast feature
  - splitting losses, security risk

  Wavelength routing
  - reliable, dedicated high capacity paths
  - no λ sharing , no splitting losses, limited connectivity

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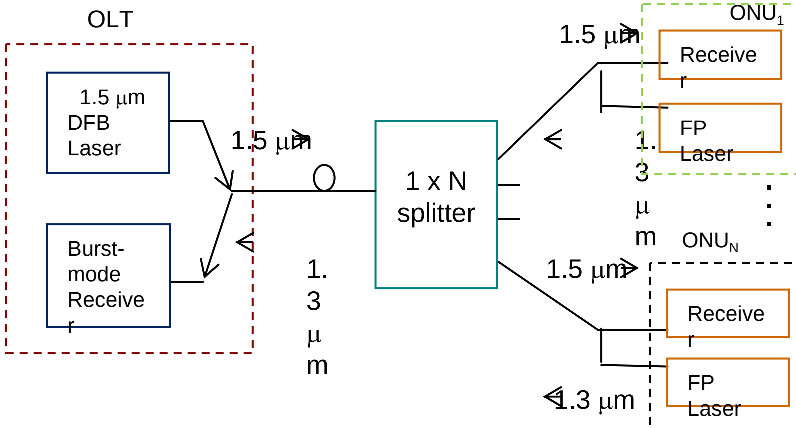
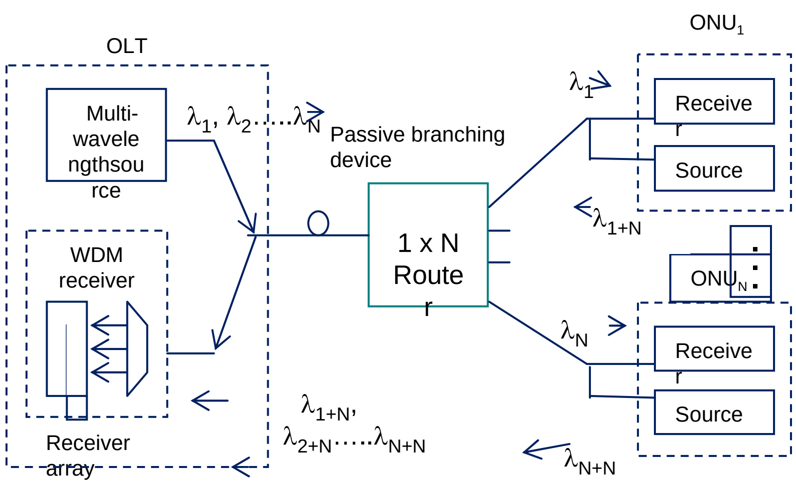


Power splitter-based WDMPON architecture



Routed-based WDMPON architecture

Some Test-bed Studies

• NGI-ONRAMP (MIT, Nortel Networks, AT&T, JDS Uniphase ..)

- Focuses on feeder network and uses power-splitting and TDMA in distribution

• SONATA (European Union)

- Centrally scheduled all traffic (WDM/TDM) and is not easily scalable

• SUCCESS (Stanford University)

- Half duplex mode communication limits the channel rate

• CPON, PSPON (British Telecom Labs)

- Splitting loss in the downstream and burst mode transceivers in the upstream

•LARNET, RITENET (AT& T Labs)

- Double-fiber connectivity and spectrum slicing loss in LARNET and round trip losses in RITENET

• AWG-Based WDMPONs (S. Korea, Japan)

- Suitable choice and merits from low loss and configurability

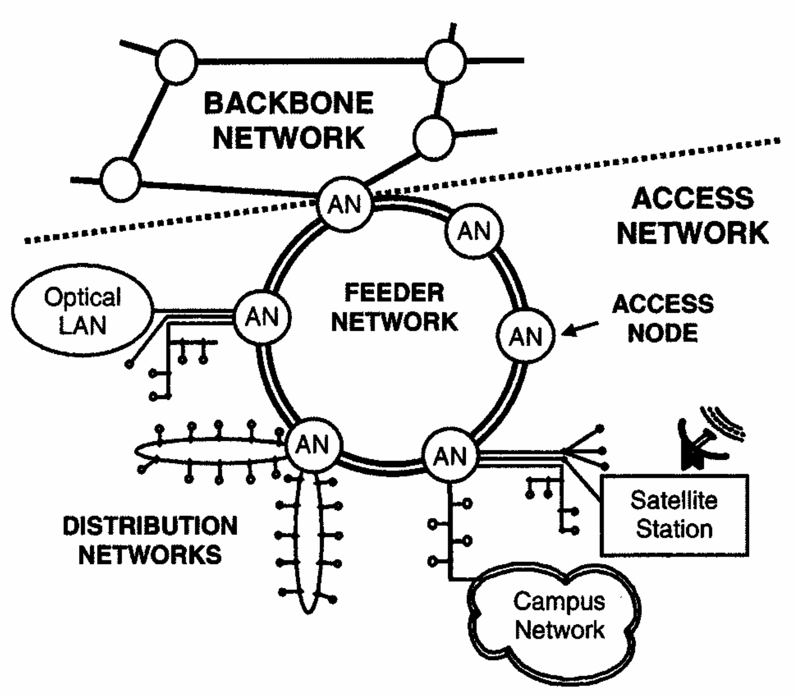
Field Trials and Test-Bed Studies

- Larger areas and higher subscriber density
- Collection & distribution network : Passive star/ tree/ bus
- Feeder network : Configurable WDM ring/ mesh ;wavelength-routed
- Access node : Electronic/Optical switching

  Electronic switch - IP, ATM, SONET, FR Protection, QoS

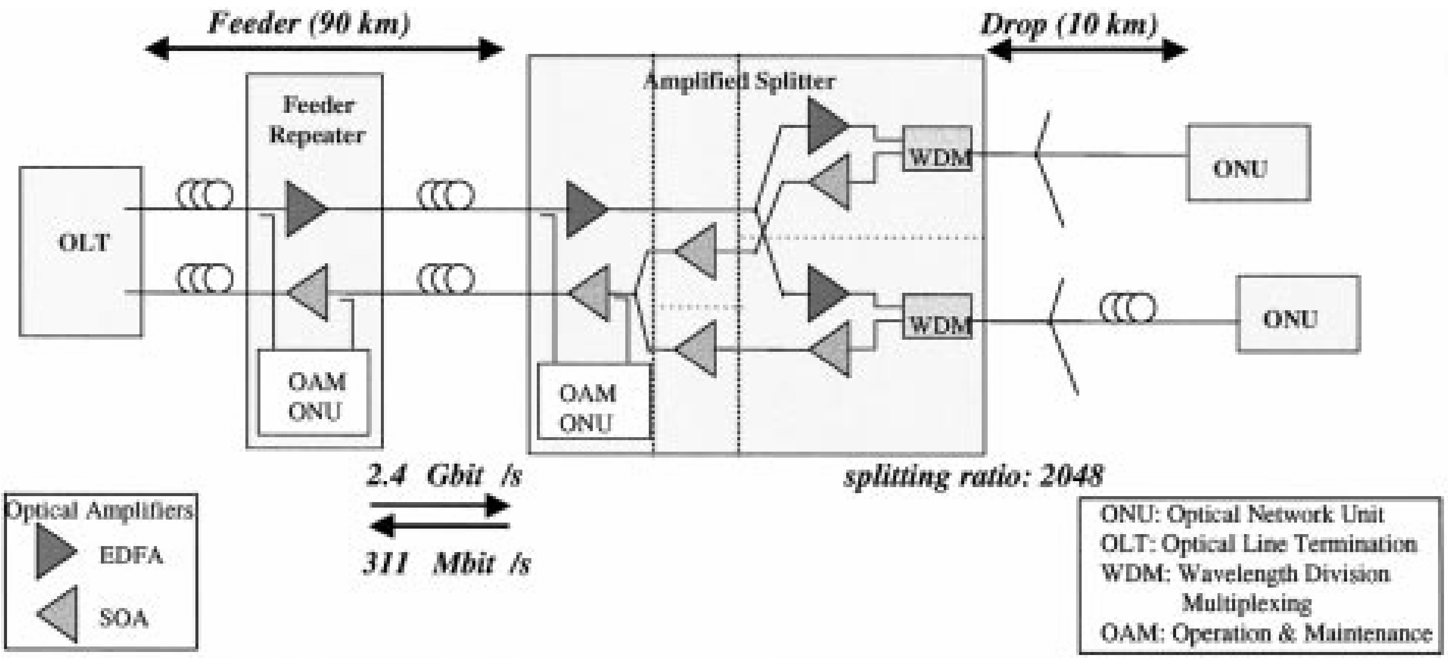
  Optical switch - Reconfigurability; Differentiated QoS, Traffic grooming, Optical Protection and restoration, n/w management & control
- Traffic: Intra cluster from C/D n/w

  Inter cluster from Feeder n/w



NGI-ONRAMP
(Next Generation Internet -Optical Network for Regional Access using Multi-wavelength Protocols)

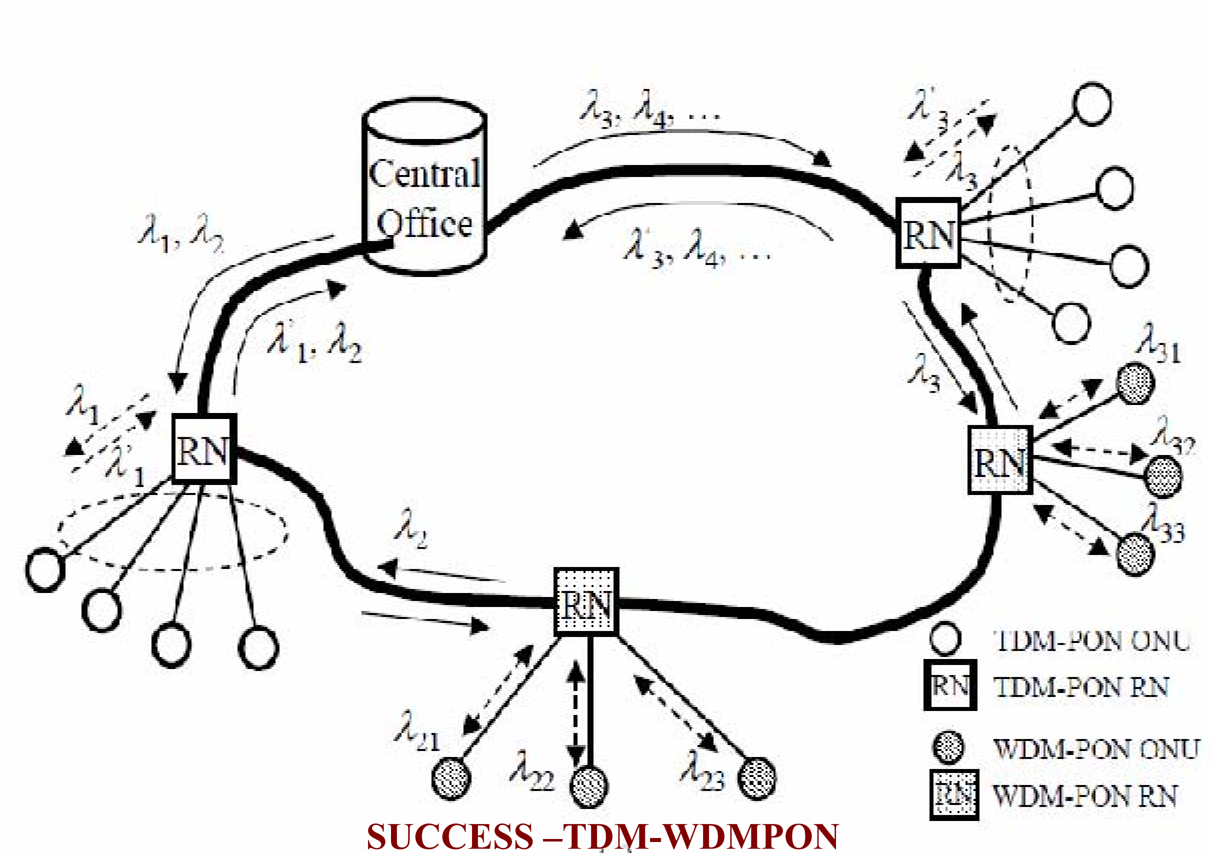
Field Trials and Test-Bed Studies



ACTS-PELICAN SUPERPON

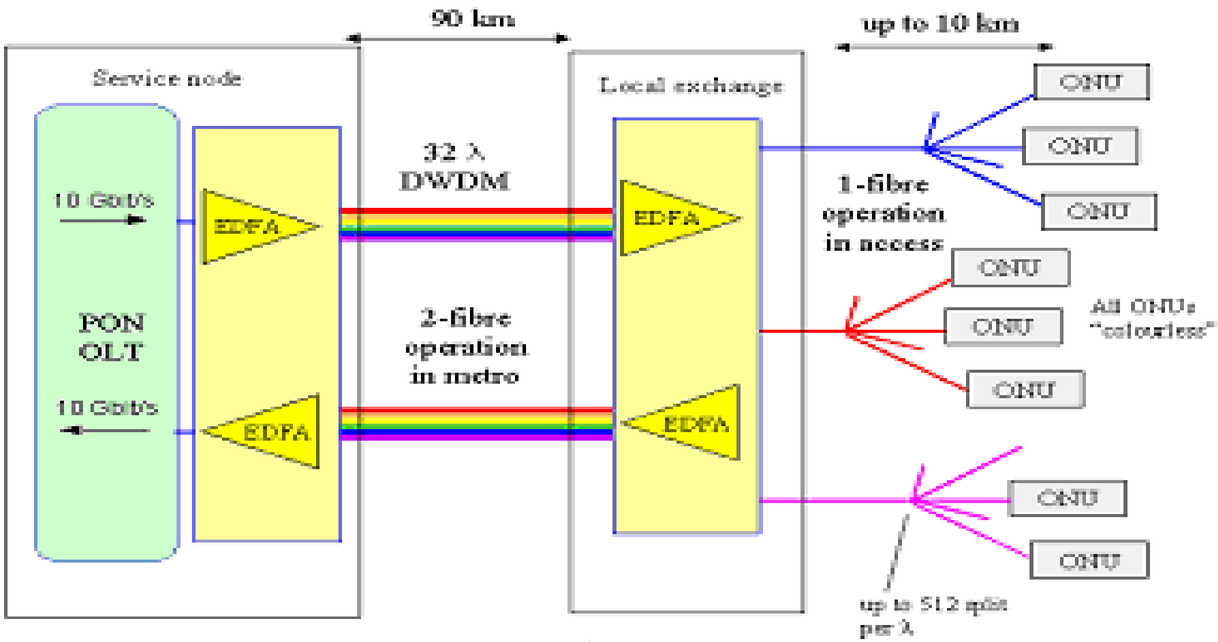
• An access network, based on the ATM-based SuperPON approach, connected via an ATM switch to a metropolitan/regional transport ring network and a meshed core network

Field Trials and Test-Bed Studies



SUCCESS –TDM-WDMPON

Field Trials and Test-Bed Studies



PIEMAN

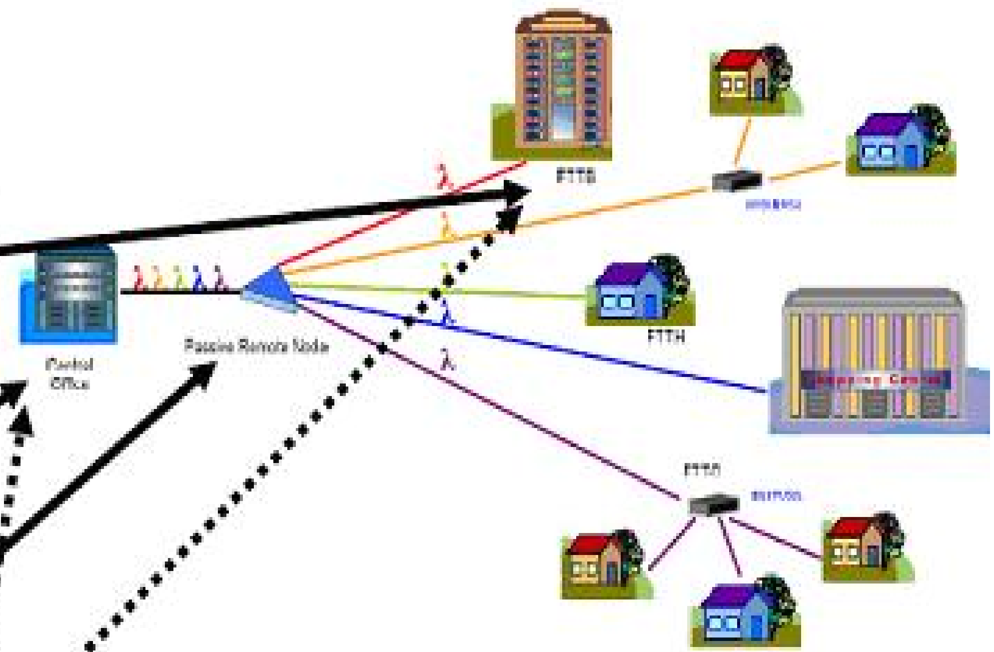
- **WP 2 - 10 Gbit/s PON optoelectronics: focuses on upstream burst mode operation at 10 Gbit/s with amplified reach of 100km.**

- **WP2-Tunable ONU: investigates a wavelength tunable 10 Gbit/s transmitter capable of achieving access cost targets when manufactured in volume.**

- **WP3 -Reflective ONU: design, develop and characterize a reflective ONU**

Field Trials and Test-Bed Studies

The project has 4 major development parts with one Work Package defined for each:



1. **Tuneable Laser, WP 2,** - A low cost tuneable laser for the colourless home unit at all end users FTTx.
2. **Fixed Laser Arrays, WP3**, for low cost integration to cover 64 channels.
3. **Athermal AWG, WP4**, - A low loss, industry temperature range, athermal AWG for the Remote Node
4. **Hybridisation of photonic components , WP4,** Integration of Optical Components or - Hybridisation for high scale integration of home unit (OLT) silicon bench with transmit and receive filter and Central Office units (ONT)
(64 channels in one hybrid for CO) using Silica on Silica with the AWG as substrate

Gigawam

TDM-Based PONs

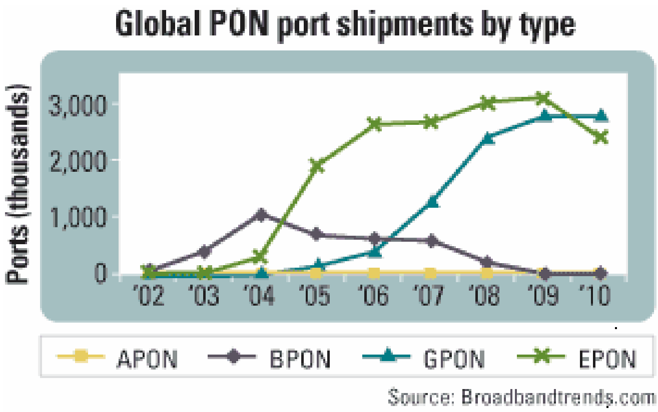
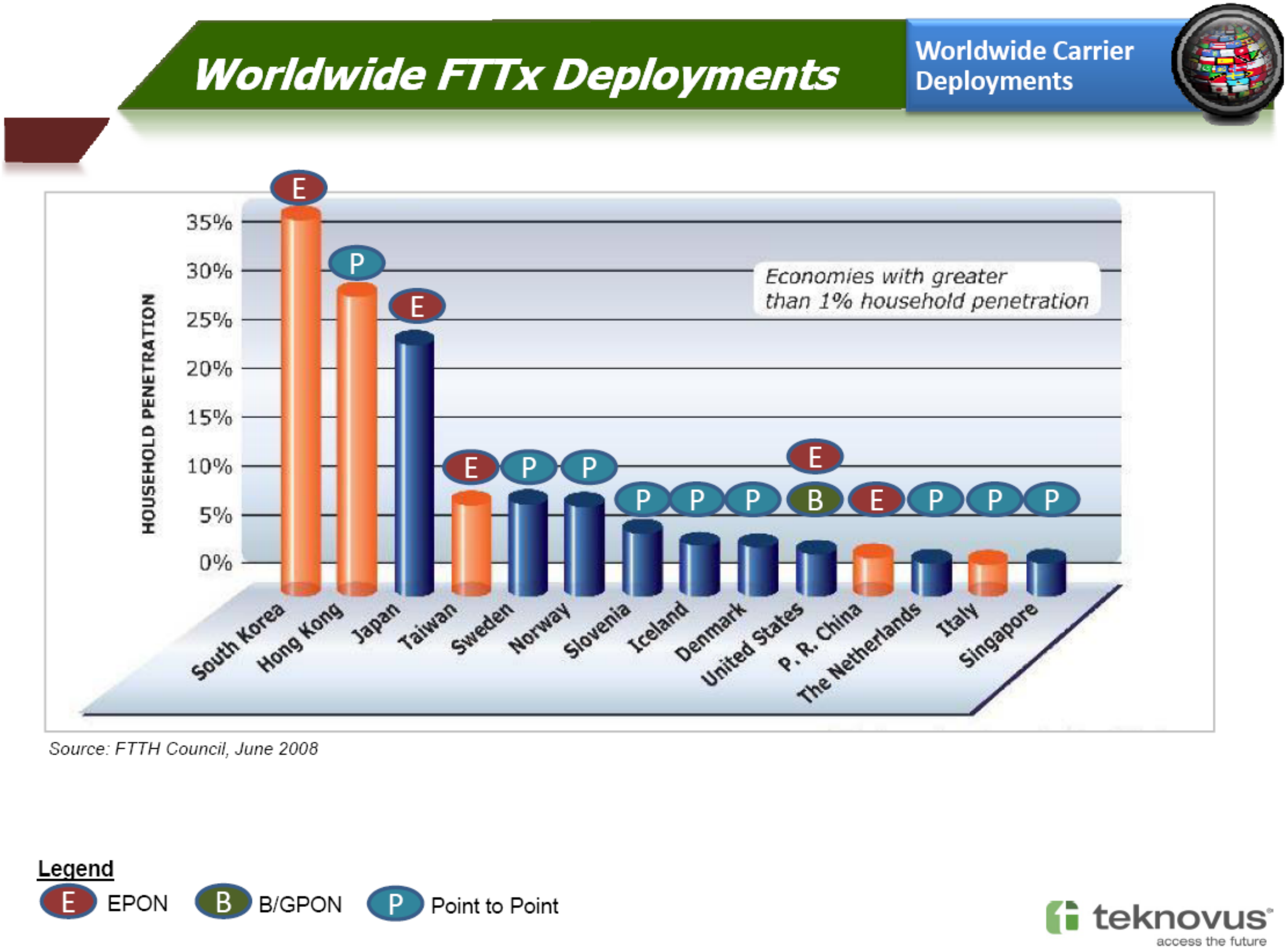


TABLE II
TDM-PON COMPARISON

	EPON	BPON	GPON
Standard	IEEE 802.3 ah	ITU G.983	ITU G.984
Framing	Ethernet	ATM	GEM/ATM
Max Bandwidth	1 Gb/s	622 Mb/s	2.488 Gb/s
Users / PON	16	32	64
Avg. Bandwidth / User	60 Mb/s	20 Mb/s	40 Mb/s
Video	RF / IP	RF	RF / IP
Estimated Cost	Lowest	Low	Medium

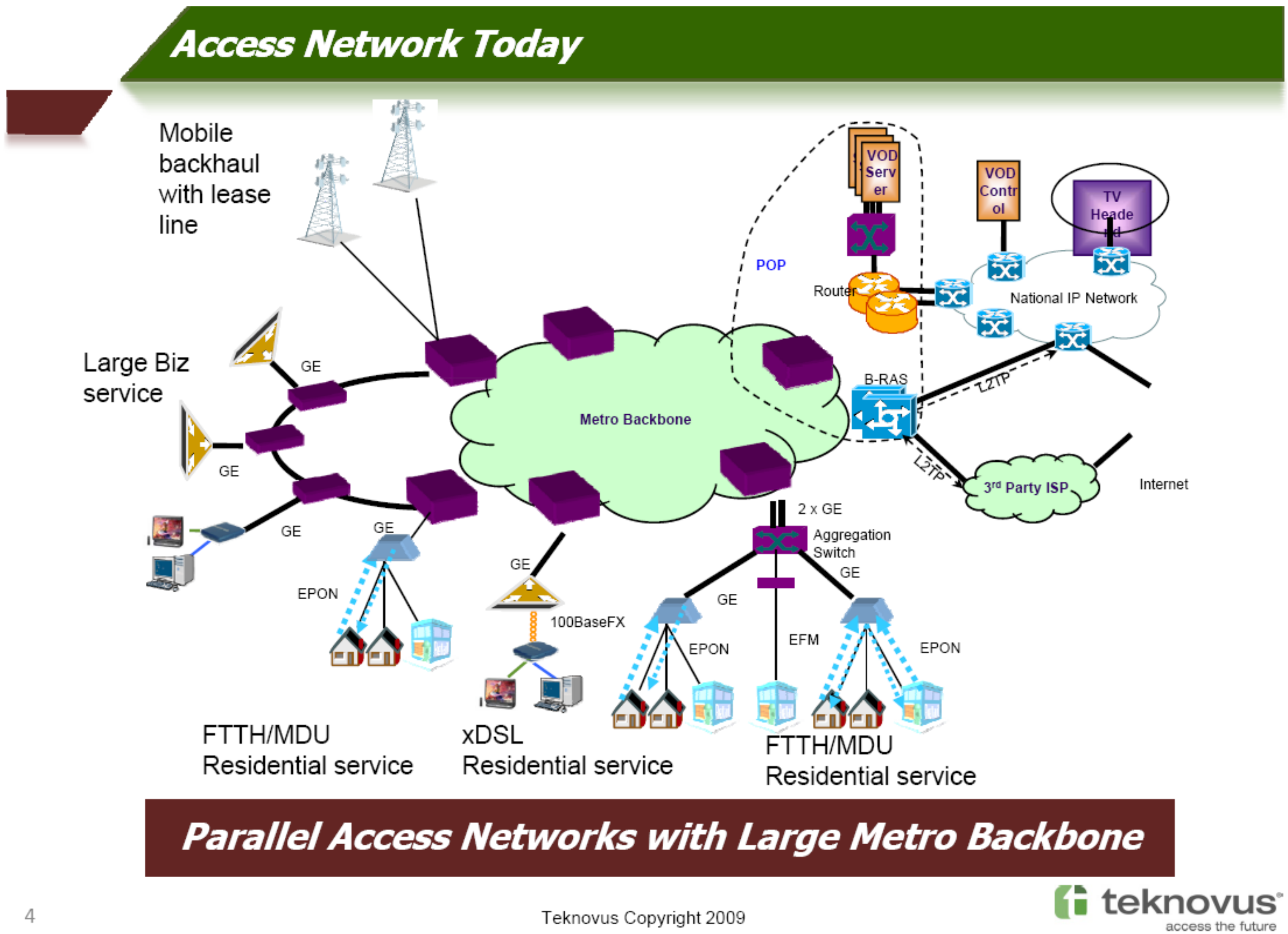
* Bandwidth depends on the number of users, and the number listed here is typical values.

Current Deployment Statistics



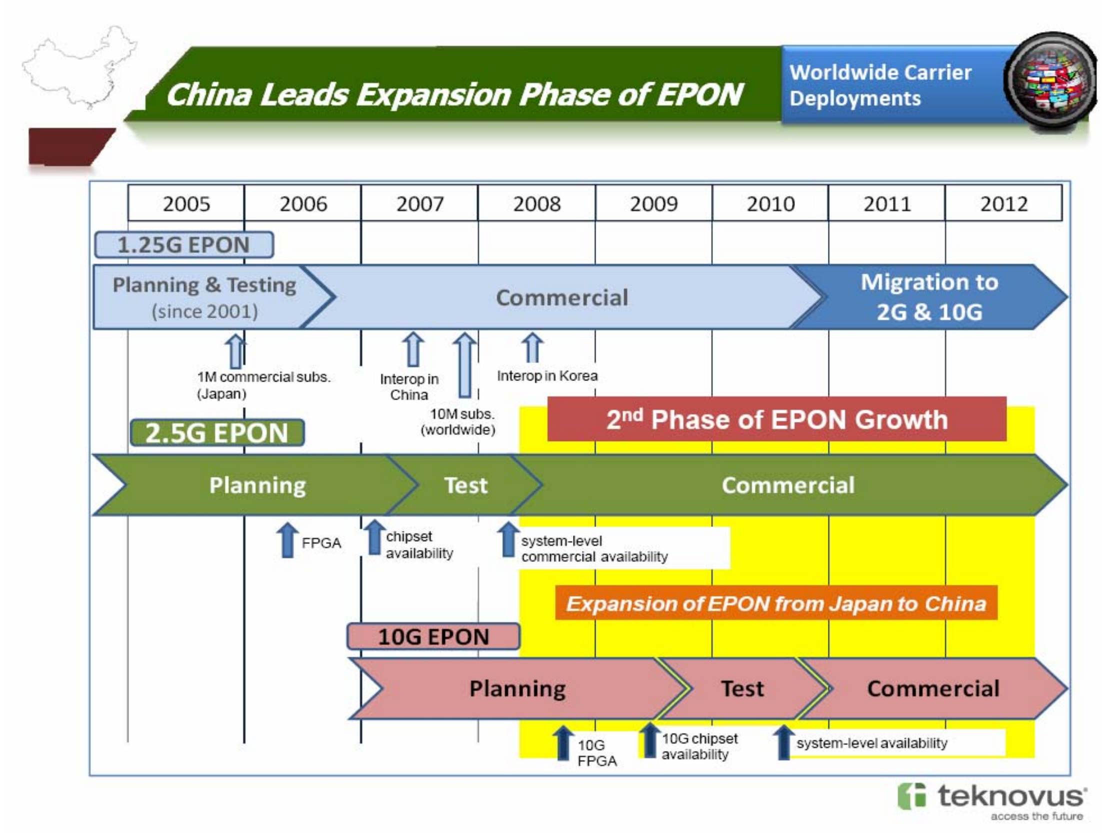
Source: FTTH Council, June 2008

Current/ Near Future Deployment Scenario



PON Projected Deployment

- Massive Chinese PON equipment orders drive 16% market gain in 2Q09
- Asia Pacific PON port shipments tripling 2008 to 2013



Next Generation PONs

Presentation Outline

- Access Solutions with Evolutionary Approach (XGPONs)
- Access Solutions with New Approach (WDMPONs)
- Futuristic Convergent Access Solution (FiWi Access)

NGPONs - Need

• FTTH- low cost, low energy technology (50% reduction in lifetime emissions)

•NG-PONs are expected to deliver: new and legacy services, both analog (e.g, QAM-subcarrier multiplexed video) and digital, in a single converged conduit

•Including new services - mobile backhaul networks with high accuracy of the clock timing for mobile services

•Optimized technology combinations in terms of cost, performance and energy saving

•Longer reach and higher splitter ratios-PHY issues in NG-PONs – role of optical amp.s

•Traffic pattern has been asymmetric and hubbed-this may be changing

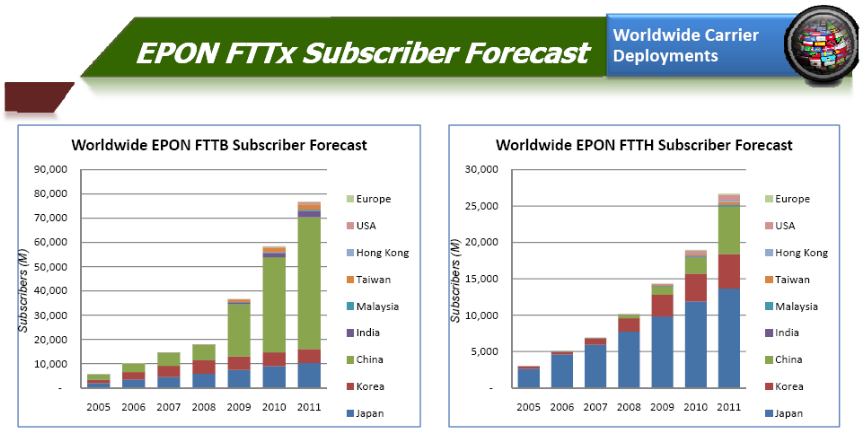
Driving Factors

- Advances in photonic technologies
- Worldwide deployment of optical fiber
- Consolidation of xPON technologies
- Expected popularity of HDTV, video-on-demand, interactive-learning etc.
- Estimated demand: 30 Mb/s guaranteed BW per u

TABLE I
BANDWIDTH/USER AND MAX REACH OF VARIOUS ACCESS TECHNOLOGIES

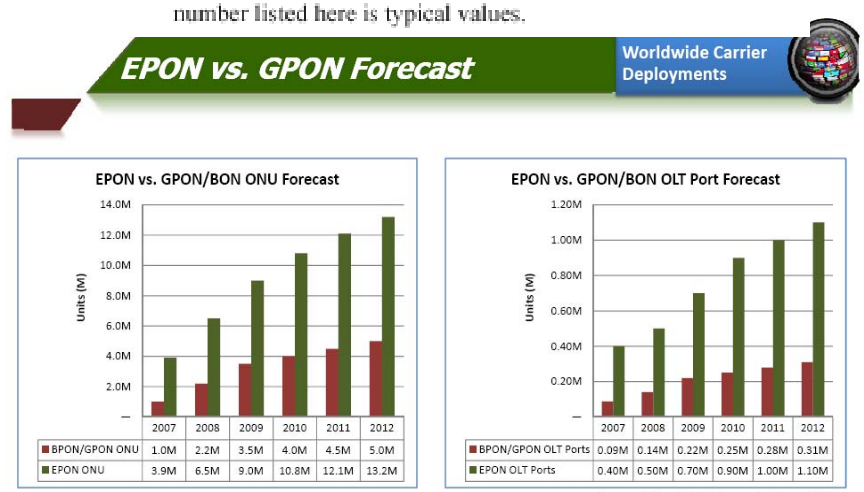
Service	Bandwidth/user	Max Reach
ADSL	2 Mb/s (typical)	5.5 km
VDSL	20 Mb/s (typical)	1 km
Coax	2 Mb/s*	0.5 km
Wi-Fi	54 Mb/s (max)	0.1 km
WiMax	28 Mb/s (max)	15 km
BPON	20 Mb/s*	20 km
EPON	60 Mb/s*	20 km
GPON	40 Mb/s*	20 km

* Bandwidth depends on the number of users, and the number listed here is typical values.



Source: TK Research, 2008

- EPON is the technology of choice for FTTx for Several Asian Carriers
- While Japan leads in FTTH, China will denominate MDU/FTTB deployments
- USA Cable MSO's considering EPON to compete against Telco's

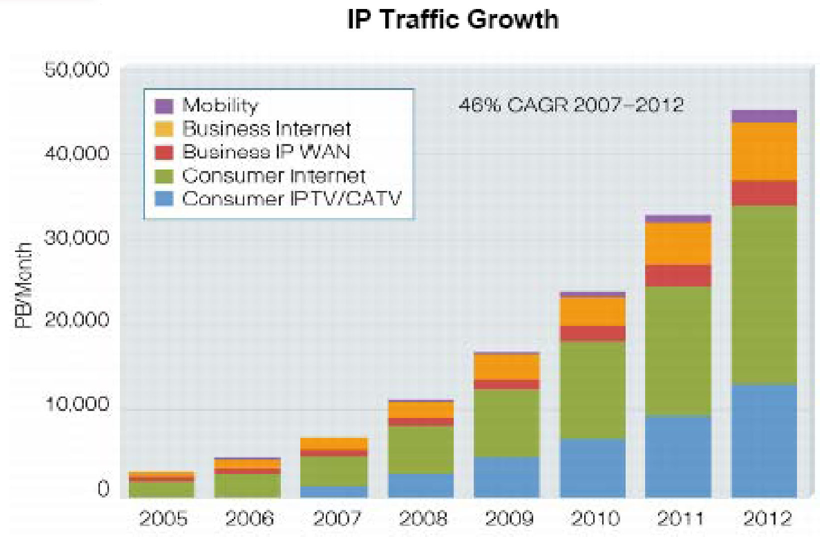


Source: Linley Market Research Group, 2008

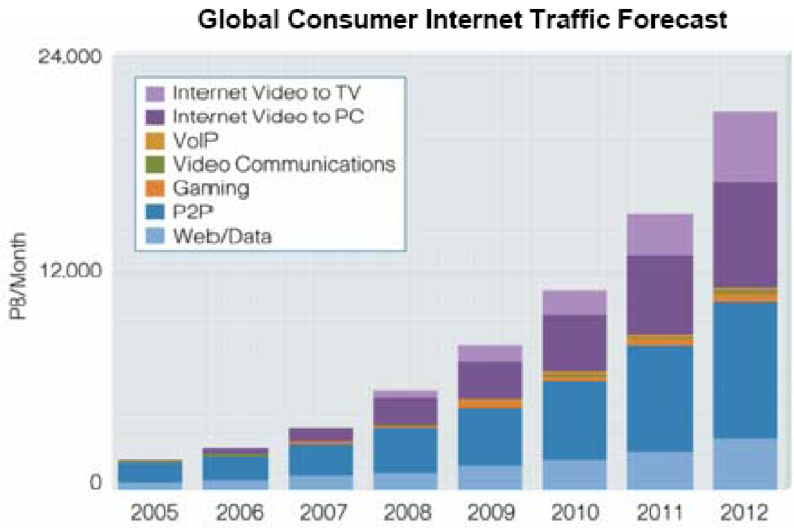
- EPON ONU Shipments will grow at 30% CAGR
- EPON units dwarf BPON/GPON by a factor of 3:1

teknovus
access the future

Driving Factors



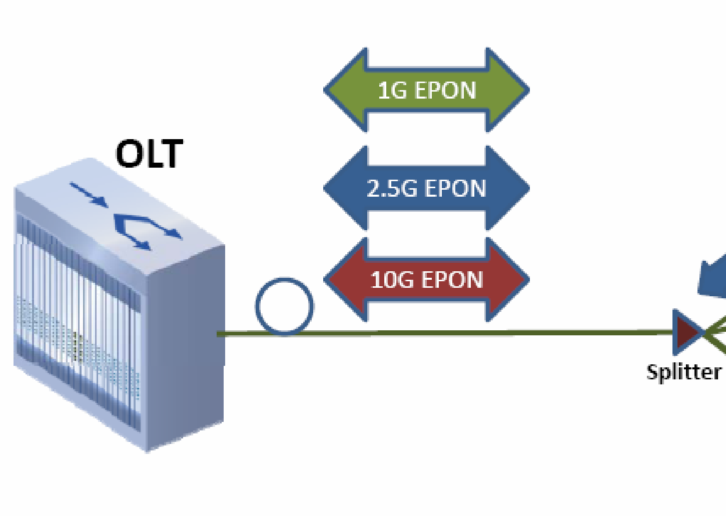
Source: Cisco Systems, 2008

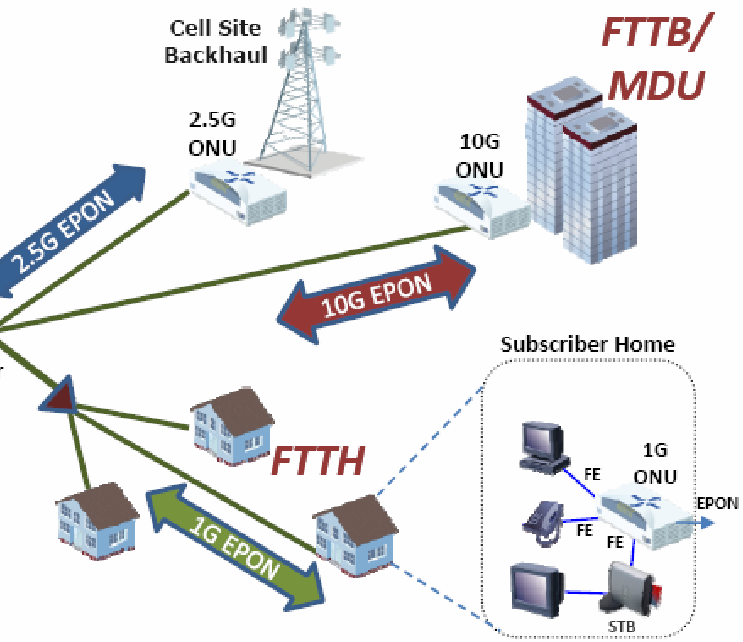


- Global IP traffic will nearly double every two years through 2012
- The Internet in 2012 will be 75 times larger than it was in 2002
- P2P is growing in volume, but declining as a percentage
- Internet video is now approximately one-quarter of all consumer Internet traffic
- The sum of all forms of video (TV, VoD, Internet, and P2P) will account for close to 90% of consumer traffic by 2012

teknovus
access the future

Access Scenario in Near Future





Time Frame	Subscriber Bandwidth Requirements
Bandwidth Demand (DS) Short Term: 2008-2010	IPTV: 1Ch HDTV: 6 – 10 Mbps 2 Ch SDTV: 4 – 6 Mbps Video Communication: 1 – 2 Mbps High Speed Internet: 2 – 4 Mbps 2Ch VoIP 0.2 Mbps Internet Gaming: 0.3M - 0.8 Mbps **Total Bandwidth: 13.5M-23 Mbps** **Average B/W: 16M-18 Mbps**
Medium Term 2010-2012	20M-30 Mbps
Long Term 2012-2015	50M-100 Mbps

Source: China Telecom, 2008

1G, 2.5G, 10G EPON Co-Existence

Triple Play Service
Internet
VoIP
IPTV

Roadmap for NGPONs

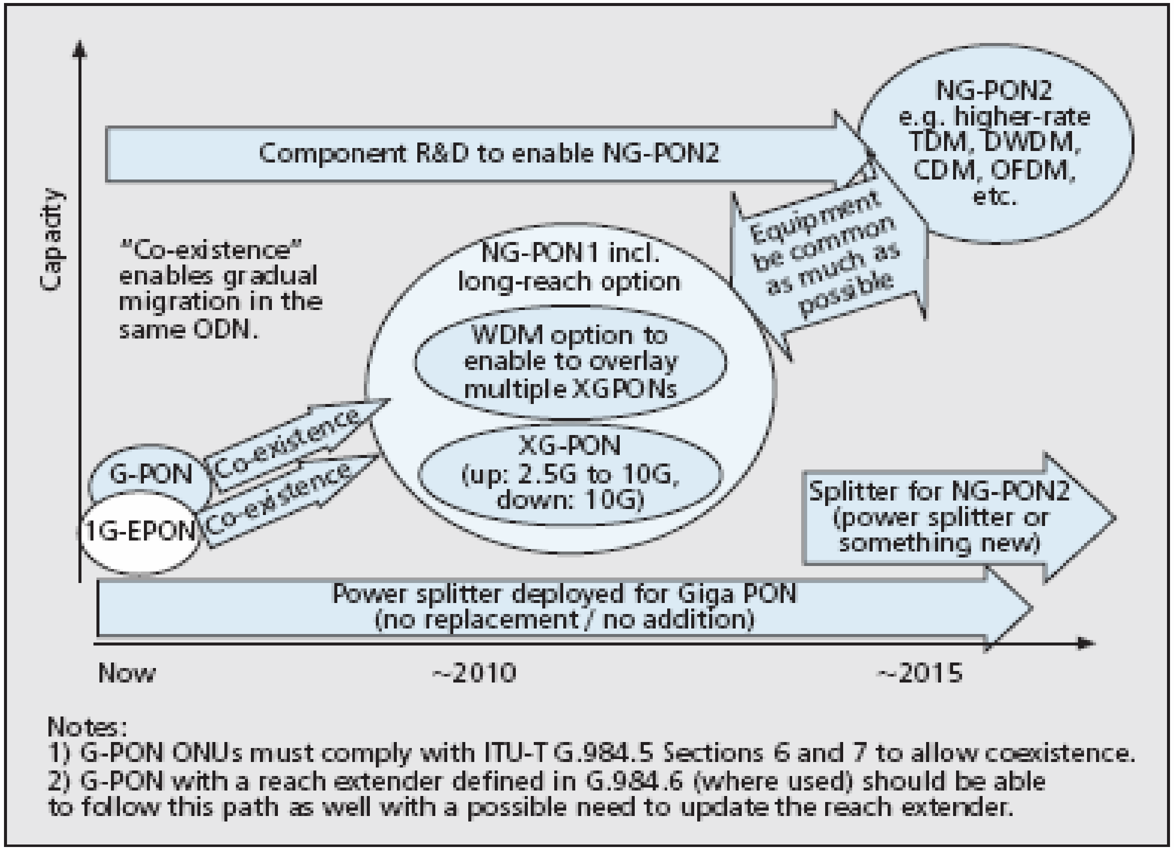


Figure 1. *NG-PON roadmap.*

[EMPP09]

General Requirements for NGPONs

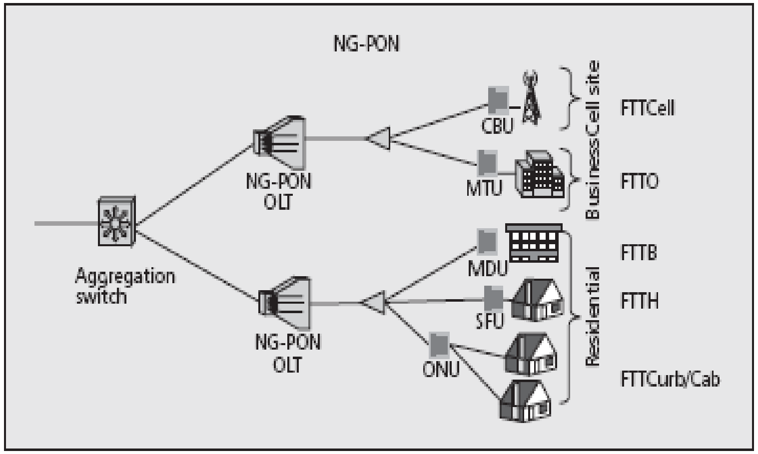
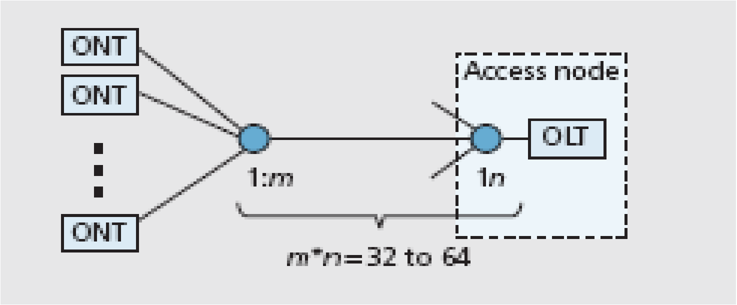


Figure 3. *NG-PON use cases.*

- Services
  - Support business/residential and mobile backhaul
  - support legacy POTS/T1/E1 as well as Ethernet
- Architecture
  - FTTx (x:cell/office etc.)
  - Splitter location
  - Resilience (protect high value services)
- Physical Layer
  - Data rate (2.5 - 10.0 Gbps)
  - Power budget (28.5-31 dB)
  - split ratio (1:64/32 and economics-based)
  - Reach (20/extended 60)
- System
  - Power saving (OPEX reduc. and green tech.)
  - QoS and Traffic Mgmnt. (BW for RT and priority class for NRT)
  - Synch. with mobilebackhaul



NGPON Architectures - Evolutionary

I. Asymmetric XGPON

- Avoids burst mode transceivers
- Multiple ch.s for ONUs with TDMA

  -spectrum compatibility and complexity of TDMA hardware
- Asymmetry typically 4:1 or 2:1 (GPON like)
- Dispersion in downstream channels

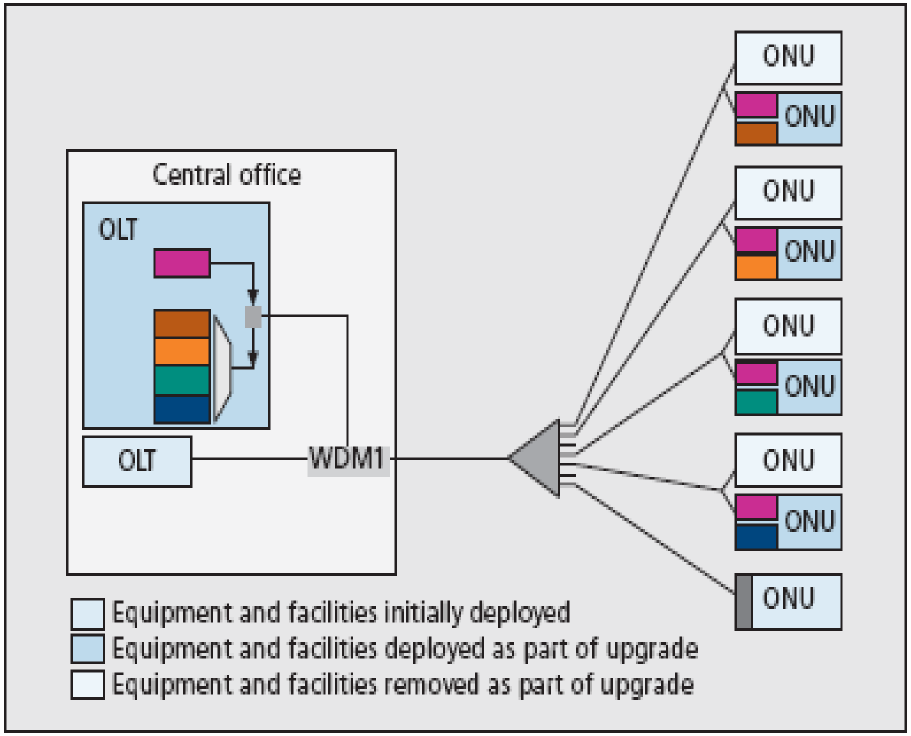


Figure 1. *XG-PON1: 10 Gb/s downstream, Nx2.5 Gb/s upstream.*

[EMPP09]

NGPON Architectures - Evolutionary

II. Symmetric XGPON

- More challenging PHY
- Analogous to WDM txmn. Links
- Link budget 8dB worse than 2.5 Gbps ch.s
- Needs FEC, APDand OAs
- Uses G.652fiber at 1310 nm with DCF

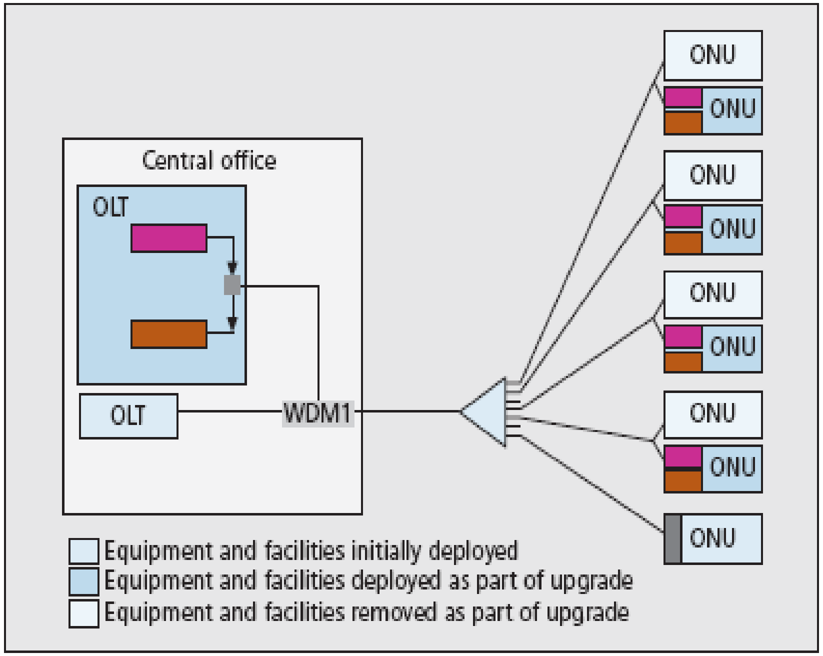


Figure 2. *XG-PON2: 10 Gb/s symmetrical.*

[EMPP09]

NGPON Architectures - Evolutionary

III. Hybrid DWDM/XGPON

- DWDM technology, colorless ONUs & WDM filter
- Split ratio upto 1000 and aims for CAPEX/OPEX savings
- Used when feeder fiber is at premium
- 10Gbps DS and 2.5 Gbps US
- Seed-light injected RSOA and tunable LD

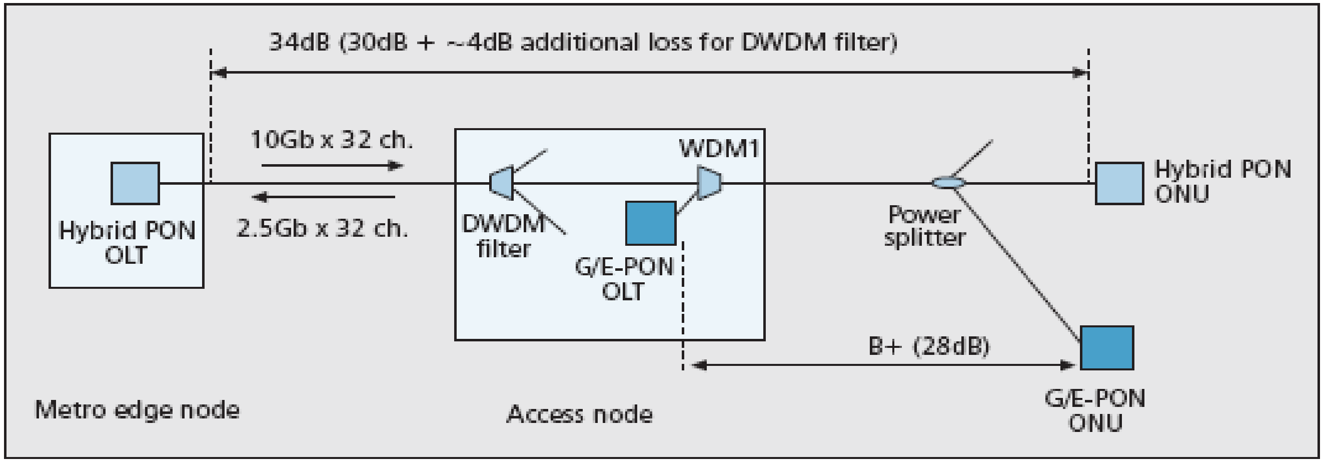


Figure 3. *Architecture of a hybrid DWDM/XG-PON.* **[EMPP09]**

NGPON Architectures - Evolutionary

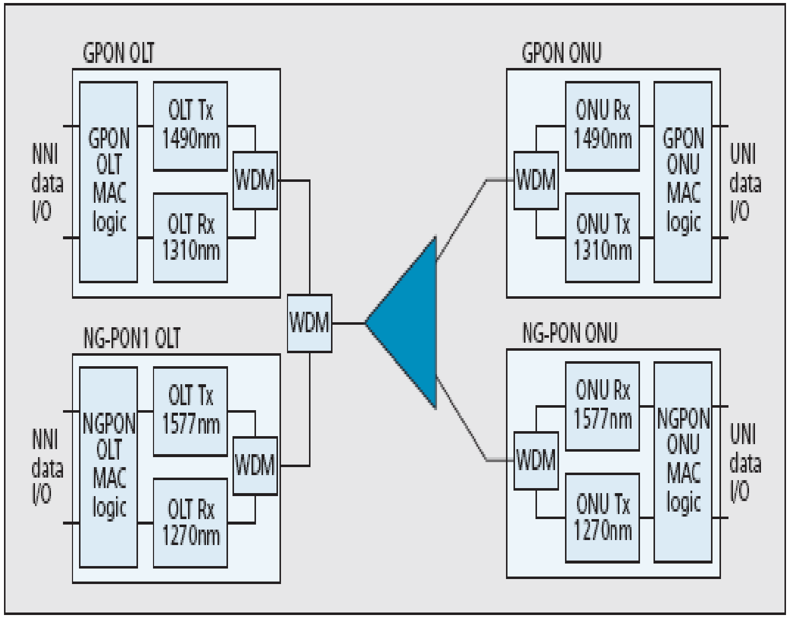


Figure 7. *G-PON and NG-PON1 coexistence using WDM for both directions.*

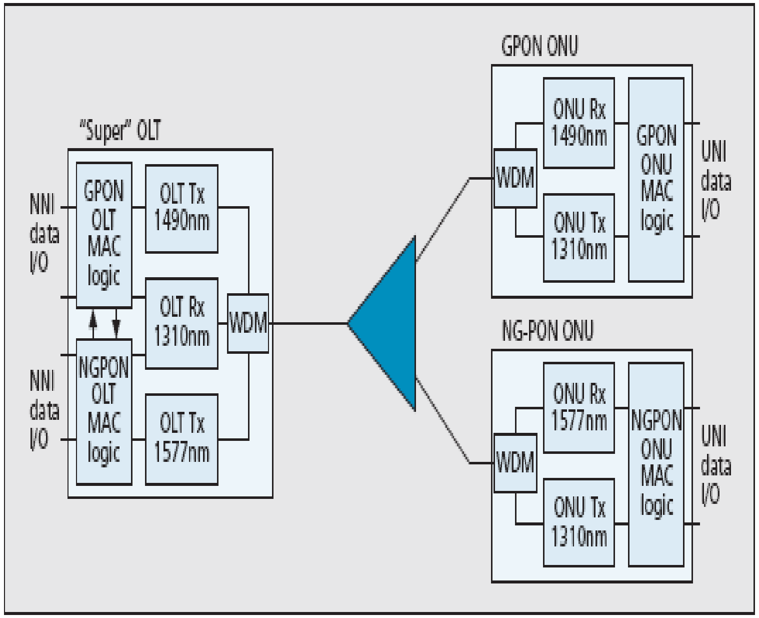


Figure 8. *G-PON and NG-PON1 coexistence using WDM downstream and TDMA upstream.*

[EMPP09]

- WDM in both directions
- GPON ONUs must have a λ-filter to block NGPON λs
- Addl. Preplacement WDM filter protects GPON OLT from service outage and NGPON signals

- WDM in DS and TDMA in US
- Employed when earlier system uses widest spectrum upstream (eg., 1260-1360nm)

NGPON Architectures (Revolutionary) -WDMPONs

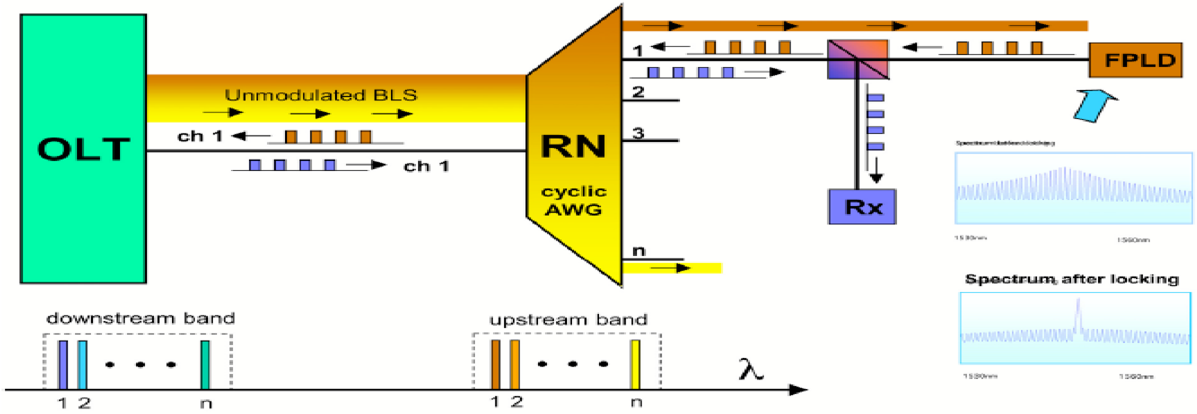


Figure 2. Basic operation principle for a wavelength-locked WDM-PON

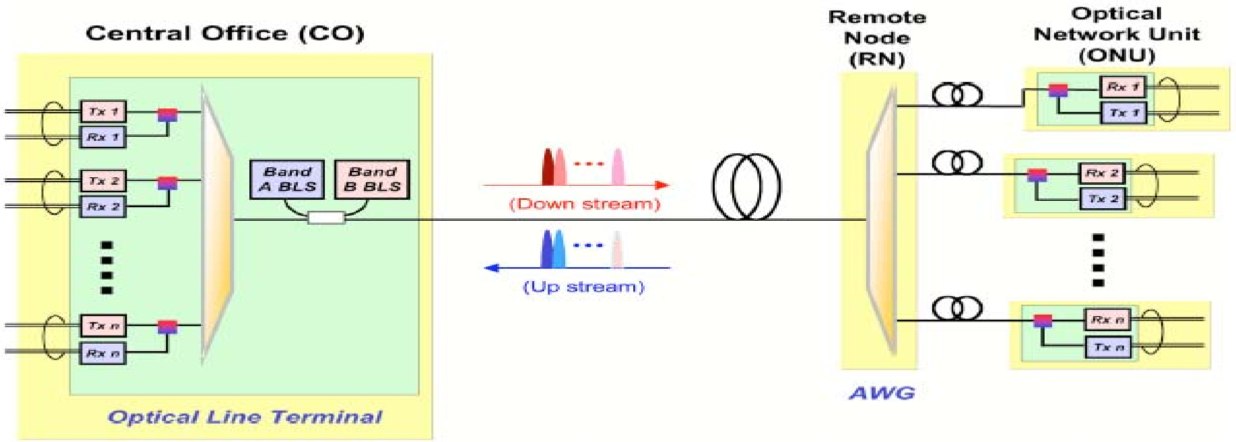
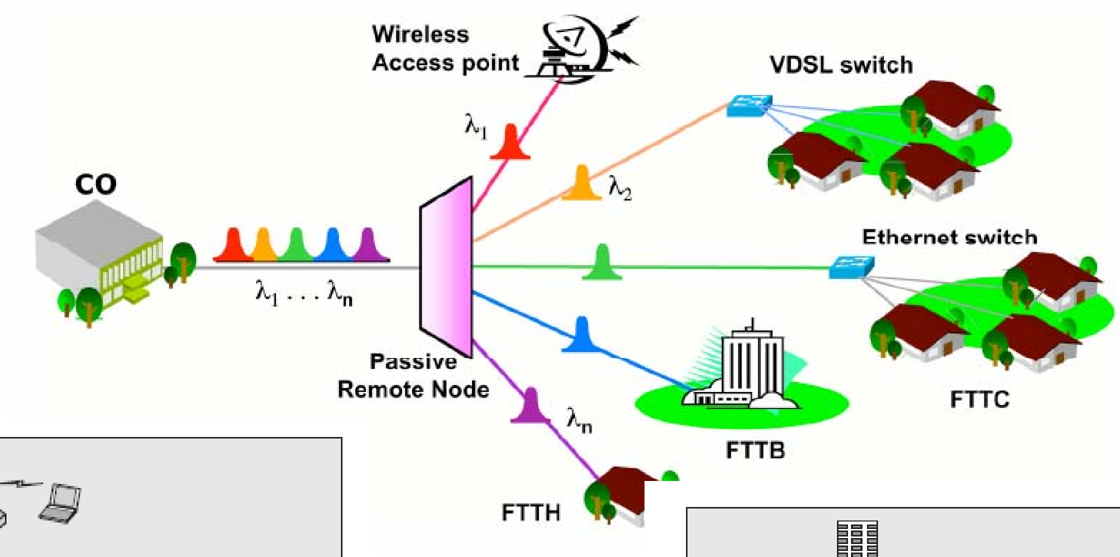
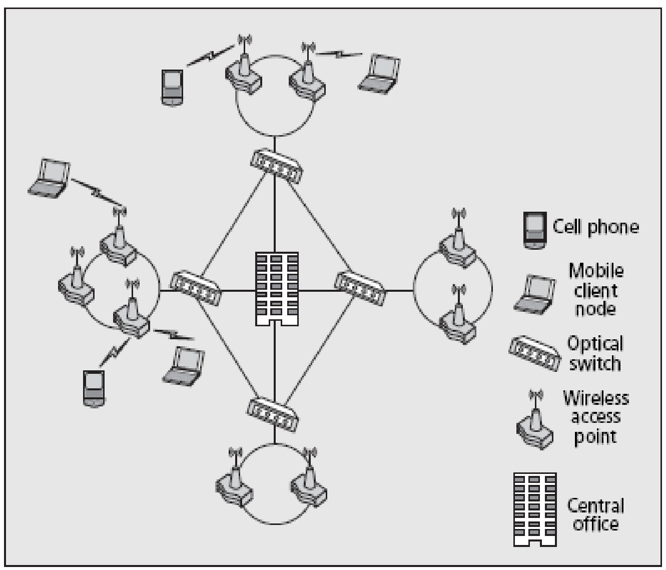


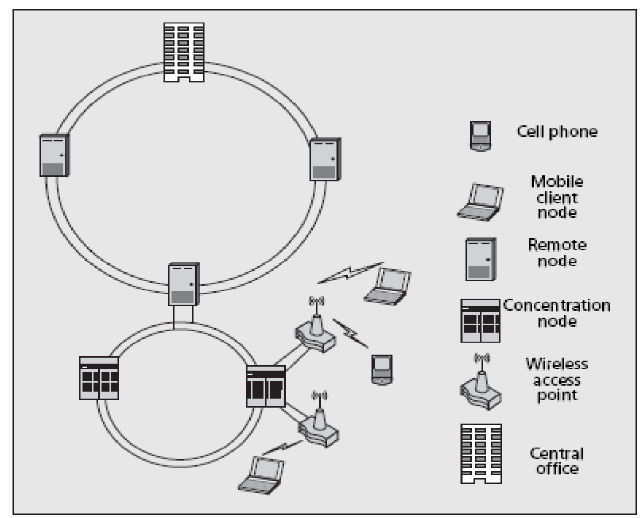
Figure 3. A wavelength-locked WDM-PON system

NexGen Hybrid Access Solution (FiWi)





■ Figure 4. *Optical hybrid star-ring network integrated with WiFi-based wireless access points.*



■ Figure 3. *Optical interconnected bidirectional fiber rings integrated with WiFi-based wireless access points.*

Part – II

PHY/MAC Issues in NGPONs

Studies on WDM-Based Access Networks

Presentation Outline

- PHY/MAC Issues in Next Generation PONs

- MAC Protocols for Real-time/Non-real-time traffic in a WDMOAN

- Transmission Impairments in a WDMPON

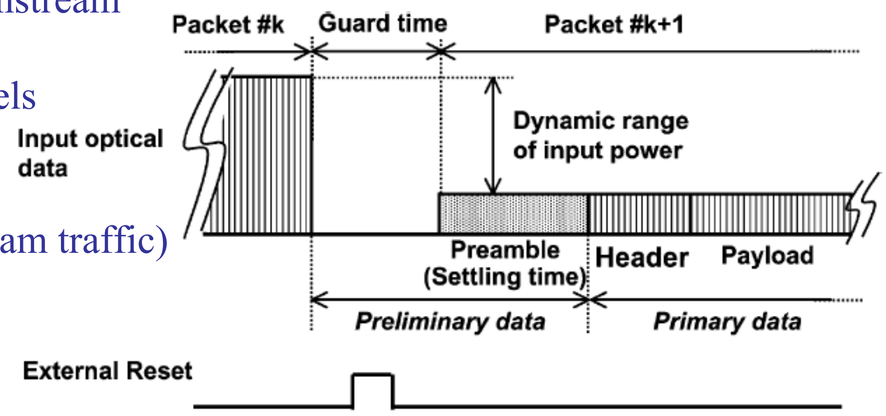
- Resource Provisioning in a Hybrid WDM-OCDMA PON

PHY Layer Issues - TDMPONs

Transceivers:

• OLT
– Continuous mode transmitters for broadcast-downstream traffic
- Burst mode receivers to handle varying power levels

• ONU
– Burst mode transmitters (limited activity in upstream traffic) during pre-assigned time slots
- Continuous mode receivers for downstream traffic



• Burst mode laser drivers:
- Fast on/off speed (6-13bits at 1.25 Gbps)
- power suppression during idle period (<-45dBm in EPON)
- Stable emission during on-period (feedback control by PD)

• Burst mode receivers:
-High sensitivity, Wide dynamic range & Fast response time
-Dynamic sensitivity recovery
- Level recovery thro’ feedback/forward structures
- Clock recovery thro PLL (ONUs lock to OLT clock)

PHY Layer Issues - WDMPONs

- **Transceivers**

TABLE IV
WDM-PON APPROACH COMPARISON SUMMARY

Approach	Communication	Key Components	Advantages	Disadvantages
Tunable lasers	• Full-duplex • Gbit/s	**ONU:** tunable laser **OLT:** WDM demux	• Dynamic wavelength management • Can share fiber from ONU to RN if using tunable receivers for downstream	• Very high cost for access networks
BLS w/spectral slicing	• Full-duplex • Few Mbit/s	**ONU:** LED BLS **RN:** AWG **OLT:** WDM demux	• Inexpensive BLS	• High slicing power loss limits network reach • Incoherent output • BLS spectrum width limits number of users per RN • High crosstalk limitations • No fiber sharing from ONU to RN
Injection-Locked FPLD	• Full-duplex • Few Gbit/s	**ONU:** FPLD + circulator **RN:** AWG **OLT:** ASE source	• Inexpensive FPLD	• Limited locking range • Back scattering and reflection
Centralized Light Sources	• Half-duplex or Full-duplex • 1-2 Gbit/s	**ONU:** SOA + circulator or RSOA **RN:** AWG **OLT:** WDM lasers, WDM demux	• No light source at ONU • SOA can simultaneously act as a detector	• ASE noise • Rayleigh backscattering and reflections need to be minimized. • No fiber sharing from ONU to RN
Shared Resources (HPON, DWA)	• Half-duplex or Full-duplex	**ONU:** Fixed Lasers or RSOA **OLT:** Tunable Lasers **OLT or RN:** AWG	• Allow smooth transition from TDM to Hybrid TDM/WDM to full WDM	• Resource sharing require scheduling algorithms

PHY/MAC Issues - GPON

- Wavelength plan

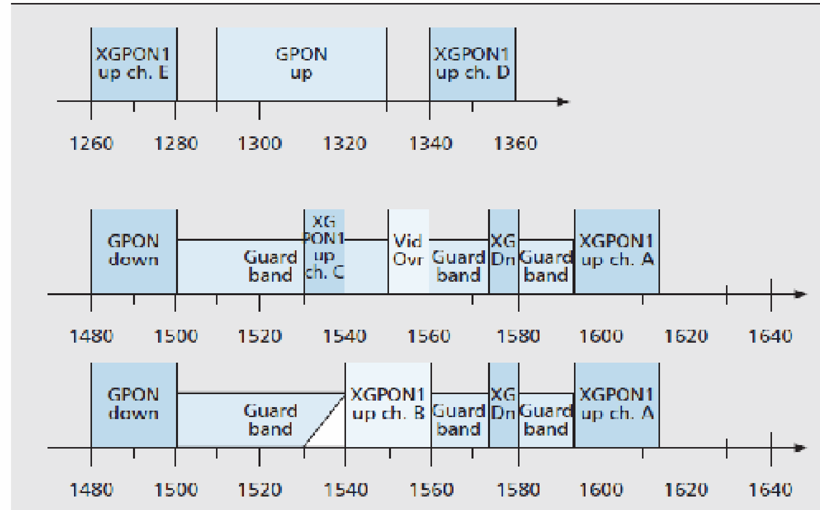
- Mandatory FEC for high loss budget RSC (255,223)
  -13% overhead; 64B66B line encoding of FEC

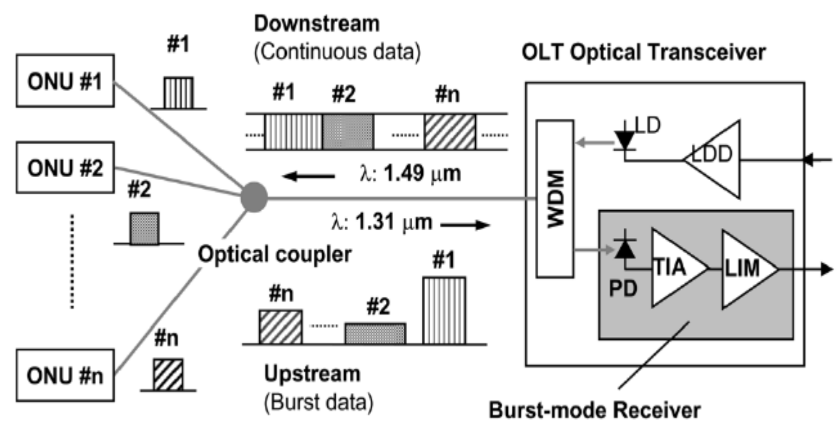
- Multi-rate burst mode reception

- A spectrally flat preamble pattern

- Word-aligned framing concept
  - 5 byte GEM header and 13 byte PLOAM message do not align with typical data transfers

- Expansion of the G-PON encapsulation method -GEM
  - protocol support -features, such as an expanded ONU and T-CONT address space,
  - improved signaling methods
  - more precise bandwidth reporting



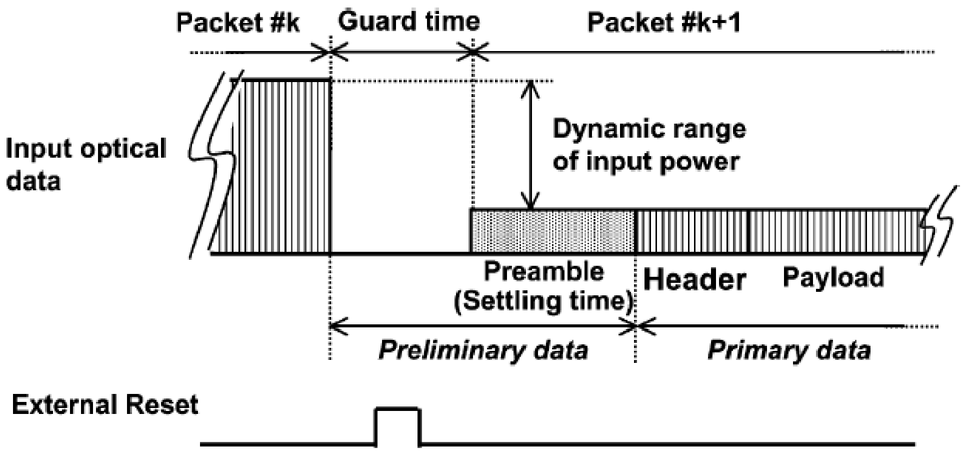


ONU: optical network unit, OLT: optical line terminal, WDM: wavelength division multiplexing, TIA: transimpedance amplifier, LIM: limiting amplifier, LDD: LD driver

PHY /MAC Issues in NGPONs

Long-reach NGPONs:
• Network protection
• Signal integrity with OA (especially SOA) against power variations at 10's of microsec
• Multiplexing several PONs at the reach extenders

Backhaul for Mobile:
•NG-PON shall provide an accurate transfer capability to the phase and time information from OLT to ONUs
• Takes all propagation delay and processing delay into account



MAC Layer Issues – EPON/GPON

- **To drive the PON cost down, an efficient, and scalable solutions are important**
  - Dynamic bandwidth allocation based on an interleaved polling scheme with an adaptive cycle time
  - In-band signaling that allows a single wavelength for both downstream data and grants transmission

- **Access Mechanism**
  - Data and Control Channels
  - Sharing Mechanisms
  - Ranging to Counter distance variation
  - Collision Control (preamble and guard time)

- **Security** (denial of service, eavesdropping, masquerading):
  - Encryption and Authentication specified in GPON Std. ITU G.984

- **Scheduling**
  - Dynamic Bandwidth Assignment
  - Priority Queuing for Differentiated services
  - Service Level Agreements

MAC Layer Issues

Include interrelated issues like:

• **Access Protocols with/without QoS awareness**

- OLT **p**olls ONUs and issues grants based on predetermined policies
- CSMA/CA with back-off medium access control

•**Scheduling Algorithms**

-guarantee bandwidth efficiency and fairness between up/down transmissions

- keep track of the status of all shared resources

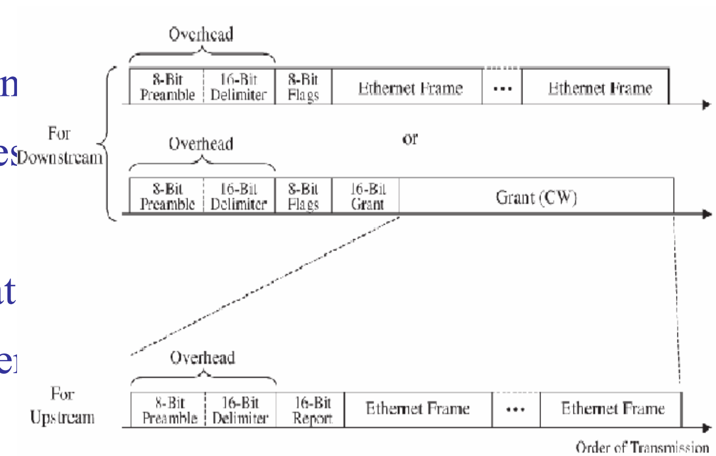
I. Sequential scheduling algo. using FIFO queuein

-simple to implement ;lacks efficiency   and fairnes

II. Batching earliest departure first algorithm

-allows prioritized transmissions;complex optimizat

-stored in virtual optical queues ;sent after batch pe

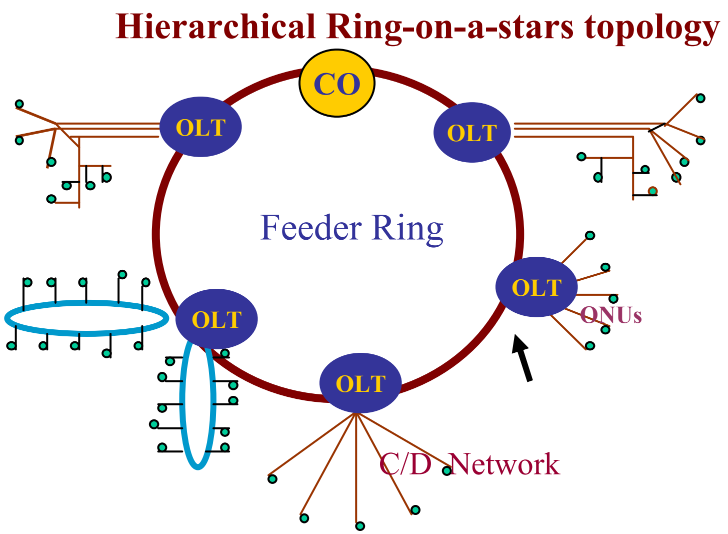


• **Provisioning (wavelength, time slots, signature codes) with traffic awareness**

Studies on WDM-Based Access Networks

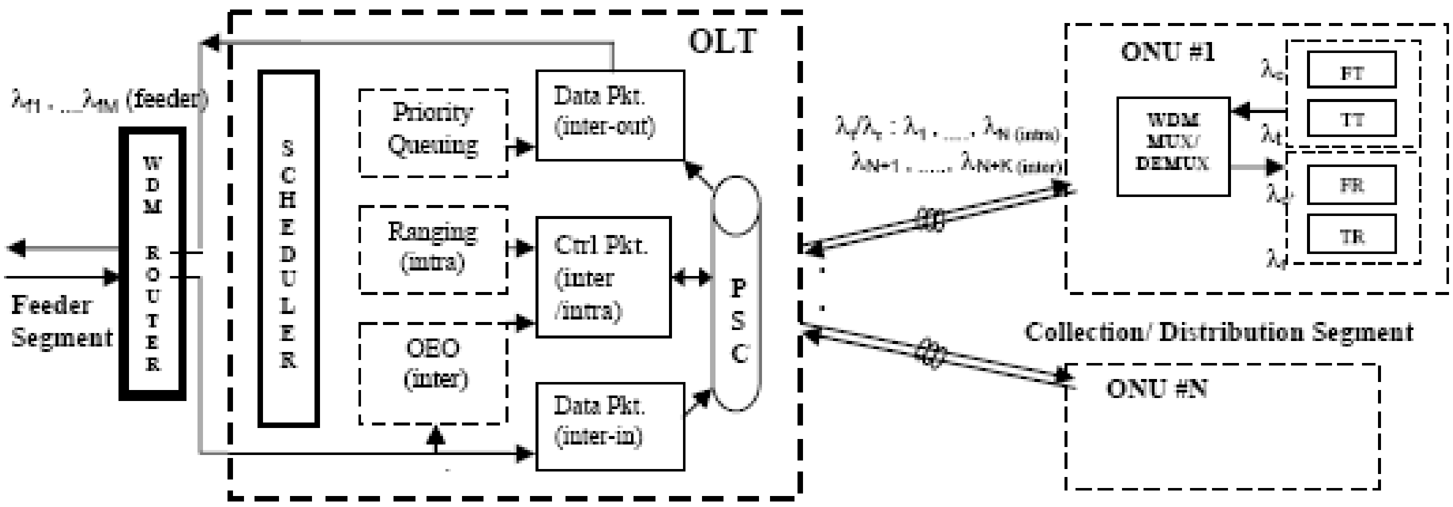
MAC Protocols for WDM-Based Optical Access Networks

WDMOAN with Ring-on-stars Topology



- Larger areas and BW intensive ONUs
- Collection & distribution (C/D) through Star Coupler
- Feeder network : Wavelength-routed WDM ring
- Access node : Router, Scheduler and a Passive Star Coupler
- Traffic: Intra cluster (C/D n/w); Inter cluster (Feeder n/w)

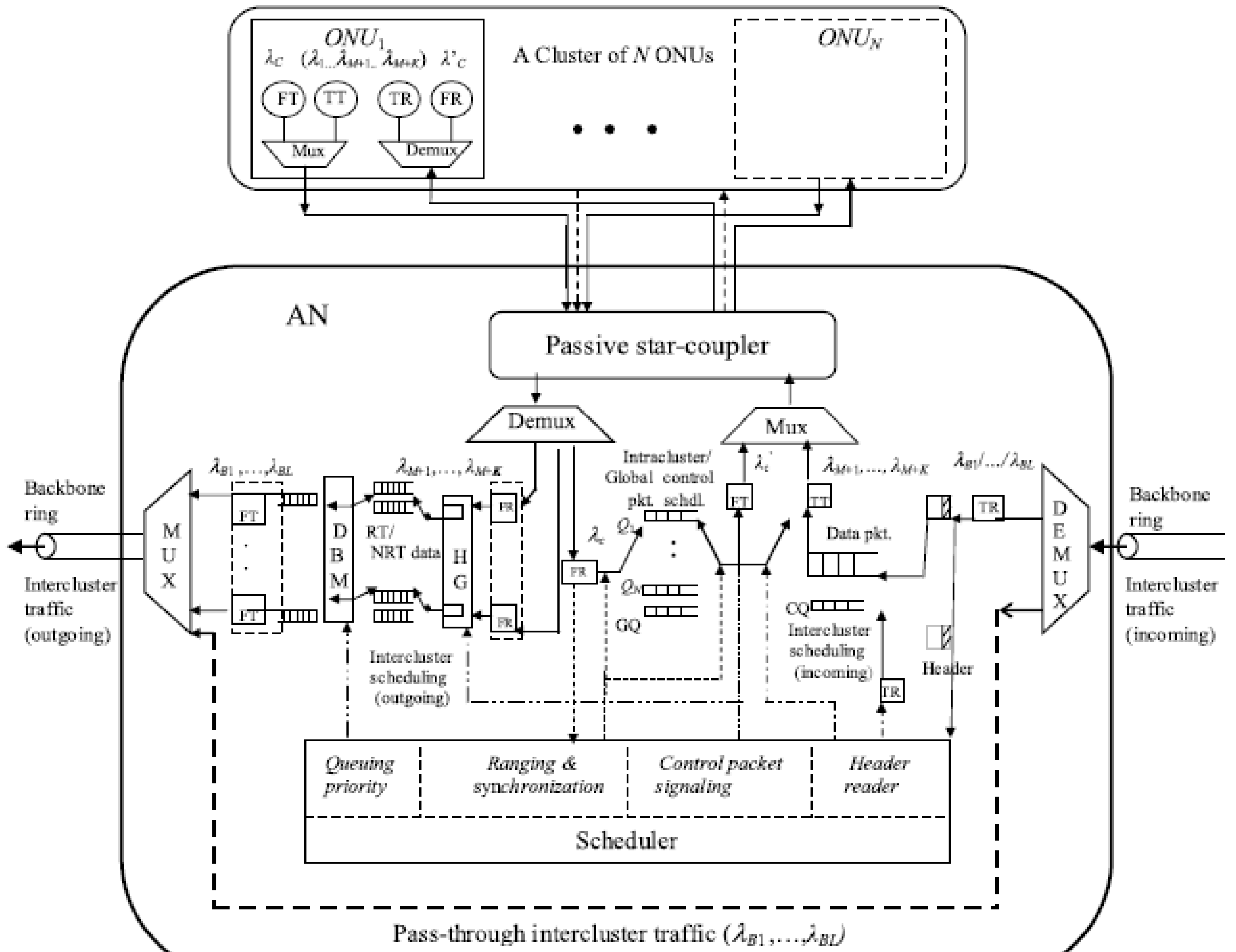
CO- Central office; ONU – Optical Network Unit ;
OLT – Optical Line Terminal; PSC-Passive Star Coupler



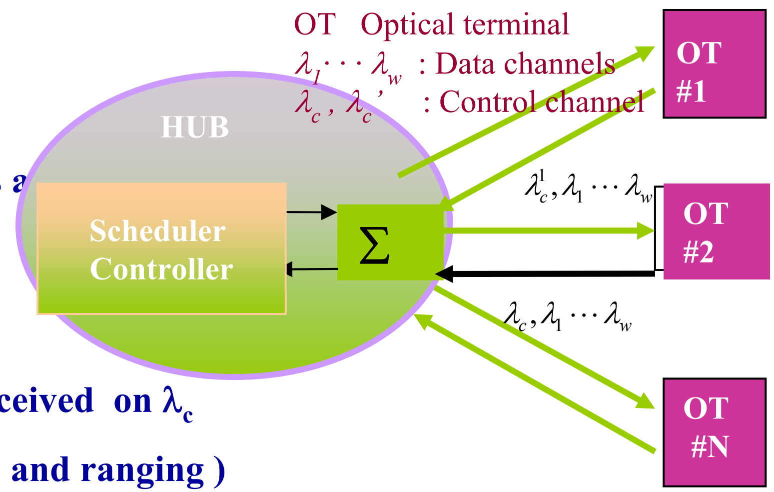
Salient Features of WDMOAN

- A Backbone ring supporting star-connected user-cluster communication
- Architecture is predominantly "active" with expensive ONUs
- Fixed Assignment (source-destination pair) wavelength routing of optical channels carrying feeder traffic
- Access Node consists of a Router, Scheduler and a Broadcast Star Coupler
- Scheduler-based MAC protocols in a WDM based Access Network
- Scheduler role in Intra cluster Communication:
  - Contention–based (Aloha) control trmn. for access requests on control channel
  - Ranging and Look-ahead features in access grants
  - Pre-transmission co-ordination based data transmission
- Scheduler role in Inter cluster Communication:
  - Separate queues for RT and NRT data packets
  - Priority queuing of traffic (Dynamic BW Management)
  - O-E-O conversion for mapping intracluster - λ traffic to feeder-λ traffic

Proposed Access Node (OLT) Architecture for WDMOAN



MAC protocol for Intra-Cluster Traffic



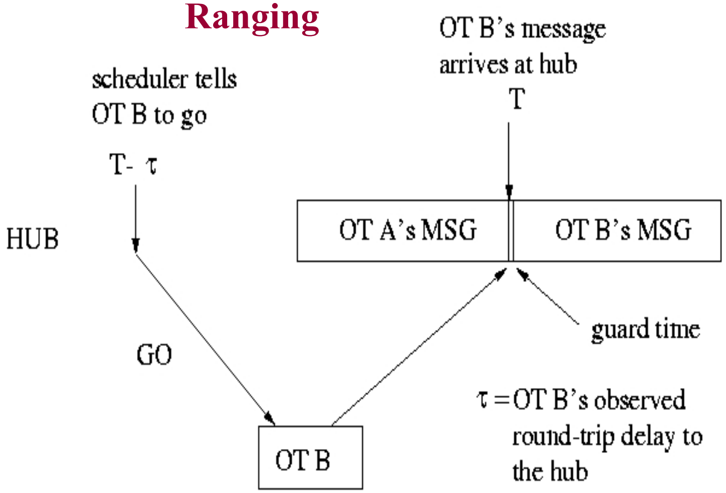
Pre-transmission coordination (PC):

- Aloha protocol for control channel (λ_c)
- OTs send reservation requests repeatedly; update requests a
- The requests contain the status of the queue

Master/Slave Scheduler-based transmissions:

- Hub issues permits on λ_c' after scheduling the requests received on λ_c
- Hub adjusts transmissions of λ_c'-packets (synchronization and ranging)
- Look-ahead to avoid head-of-line blocking

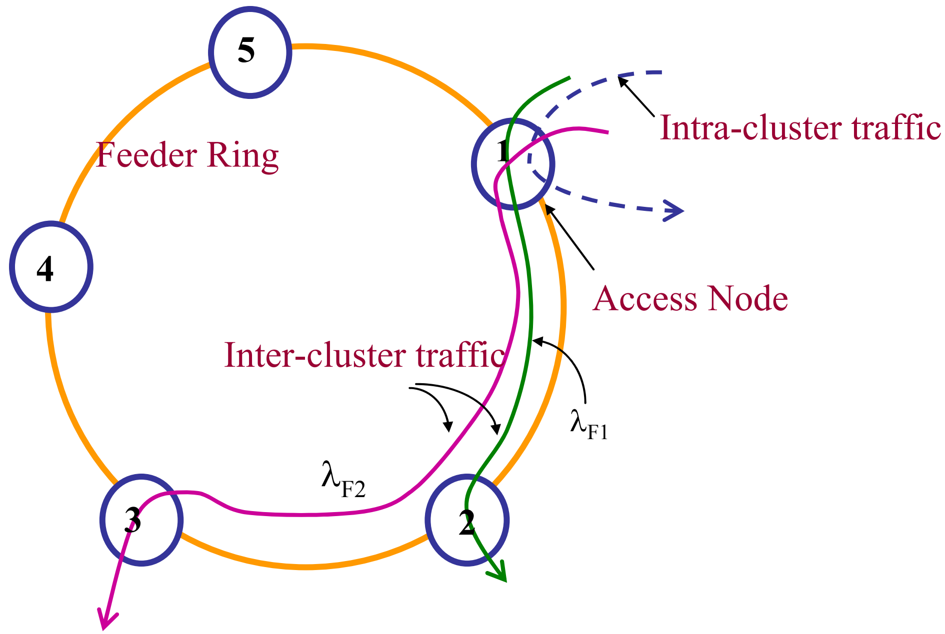
Ranging



Look-ahead Scheduling

Queue 1 (OT 1)	2	3	3*
Queue 2 (OT 2)	3	1*	3
Queue 3 (OT 3)	1	1	1

MAC protocol for Inter-Cluster Traffic

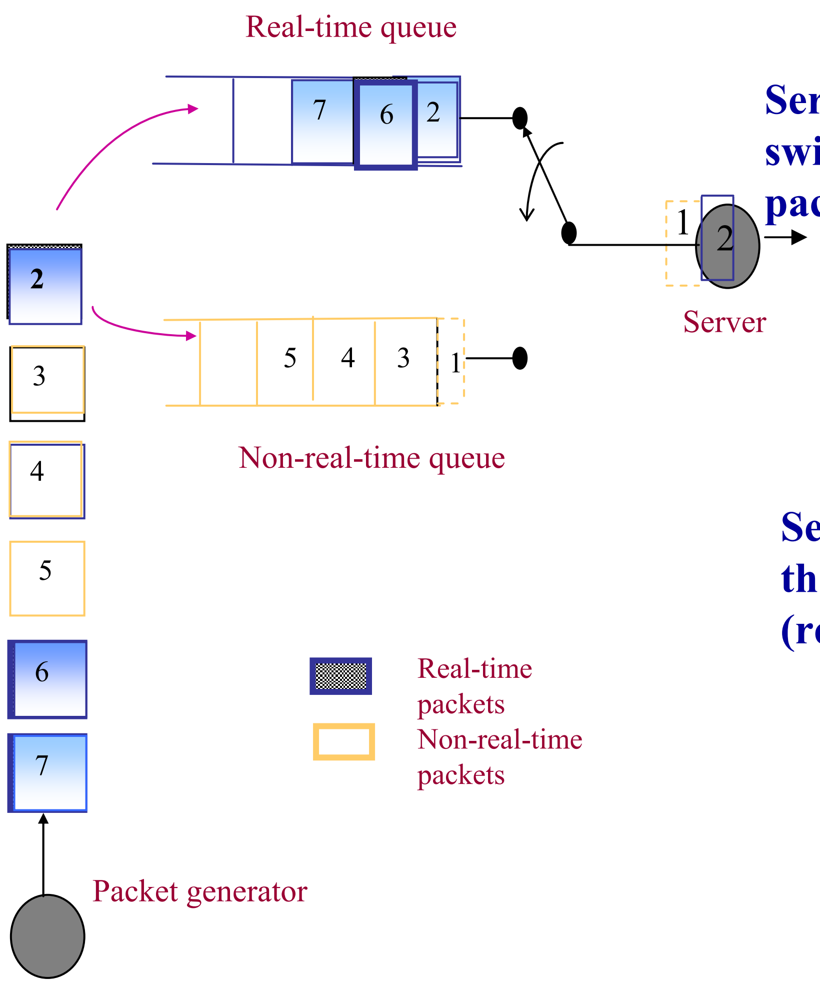


•**Bandwidth Management Schemes :**

- **Non-preemptive priority scheme**
- **Preemptive resume priority scheme**

• **Fixed Wavelength Assignment**: Priority-based real-time and non-real-time data packets multiplexed on same wavelength (for a given destination node)

Bandwidth Management Schemes (DBM)



Preemptive Resume Priority

Serving of packet 1(non-real) interrupted and switched over to real-time immediately after packet 2 (real-time) arriving

Non-Preemptive Resume Priority

Serving of packet 1(non-real) completed and then switched over to real-time after packet 2 (real-time) arriving

Delay Analysis for Intercluster Communication

Delay T is expressed in terms of mean residual time R, waiting time in the queue and average service time $1/\mu$ for real-time and non-real time data traffic using Little's theorem and Pollaczek Khinchin formulae

Non-preemptive resume priority queuing

Total delay for RT pkts., $T_{RT} = \dfrac{R}{(1-\rho_1)} + \dfrac{1}{\mu_1}$

Total delay for NRT pkts., $T_{NRT} = \dfrac{R}{(1-\rho_1)(1-\rho_1-\rho_2)} + \dfrac{1}{\mu_2}$

Preemptive resume priority queuing

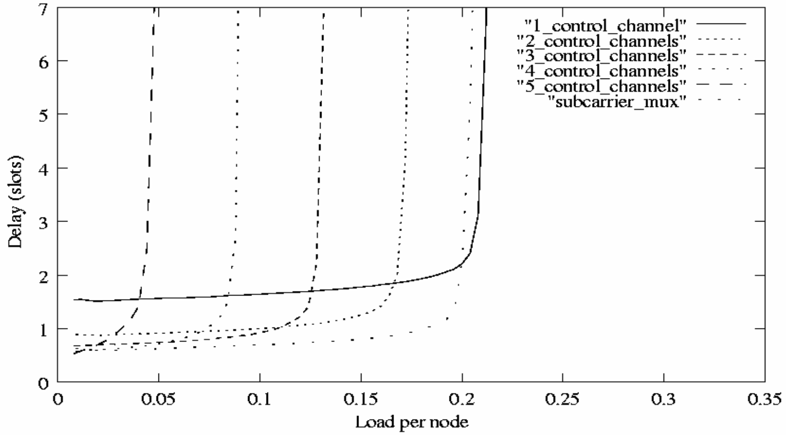
Total delay for RT pkts., $T_{RT} = \dfrac{\frac{1}{\mu_1}(1-\rho_1) + R_{RT}}{(1-\rho_1)}$

Total delay for NRT pkts., $T_{NRT} = \dfrac{\frac{1}{\mu_2}(1-\rho_1-\rho_2) + R_{NRT}}{(1-\rho_1)(1-\rho_1-\rho_2)}$

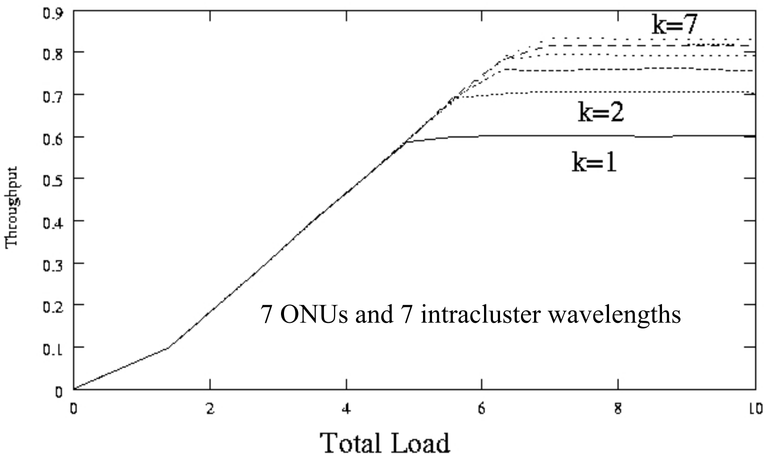
Simulation Results : Intra-cluster Traffic

Effect of control ch. count and look ahead

Nodes=21, Channels=6, 1 : 50 pkt. ratio, k=1



System throughput with look-ahead, k

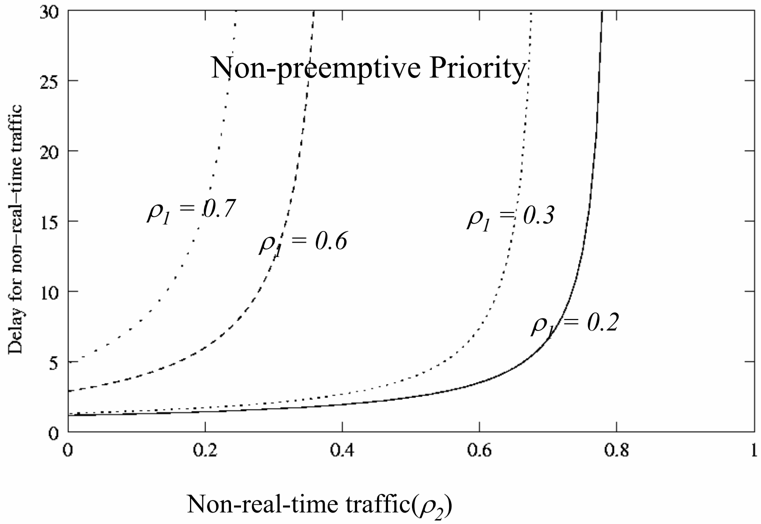


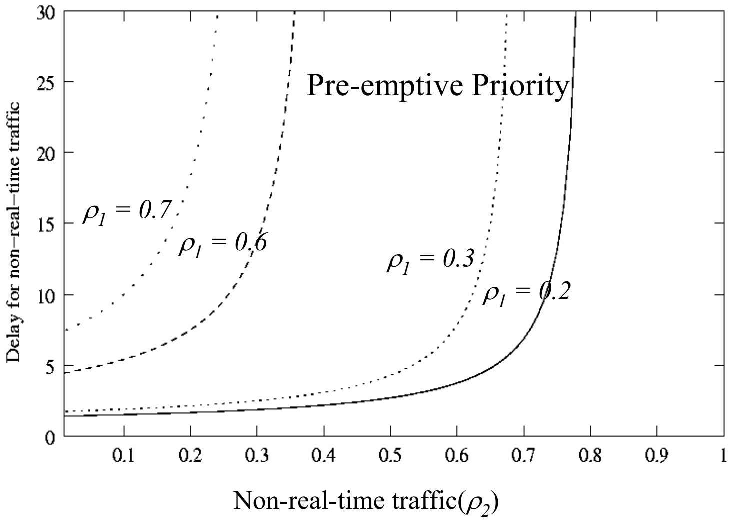
Observations:

- **More control channels can improve the delay performance until the load per ONU approaches the take-off point (load x ONU/ctrl. ch.s=1)**
- **Delay performance is much more improved with SCM**
- **With *k*=1 to 7, the effect of receiver contention is gradually overcome improving throughput (saturates when ONU-to-channel ratio becomes 1)**

Numerical Results: Inter-cluster Traffic

Delay characteristics of non real-time traffic



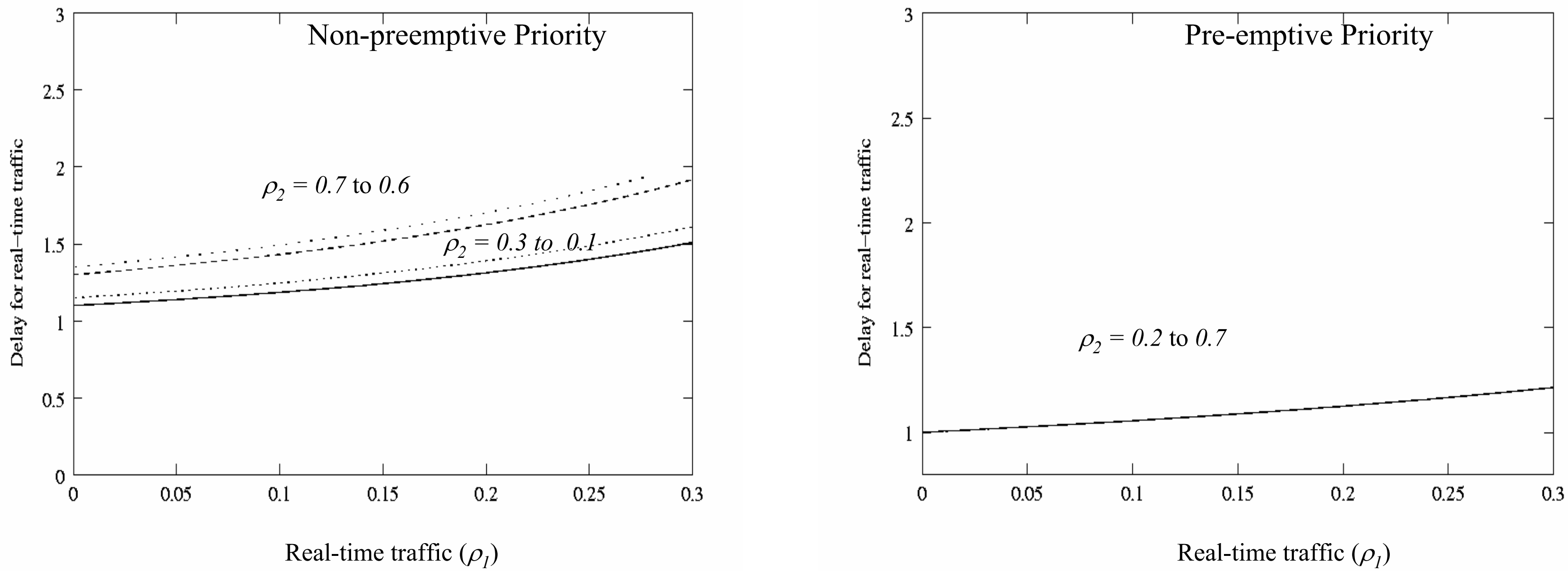


Observations:

- NRT delay profile is highly sensitive to the RT traffic in both schemes
- Take-off points take place in the vicinity of $\rho_2 = 1 - \rho_1$
- The delay for NRT packets is relatively high in premptive resume priority (for high RT traffic)

Numerical Results : Inter-cluster Traffic

Delay characteristics of real time traffic

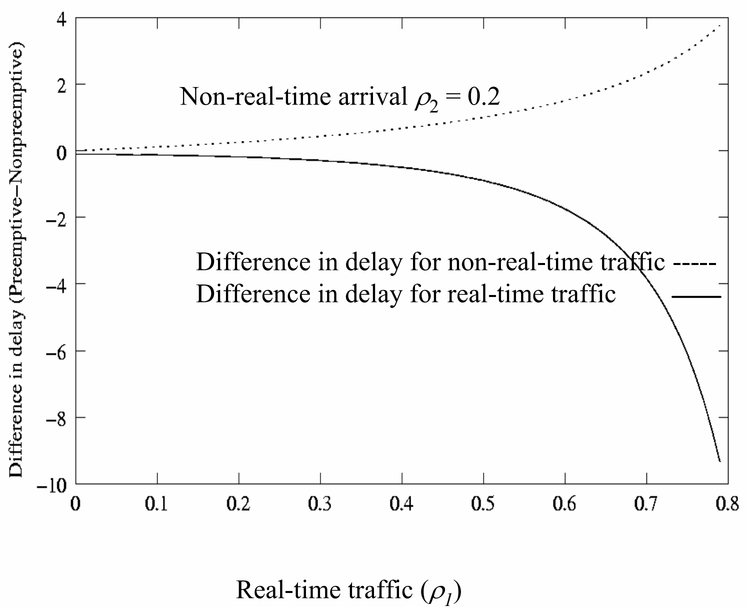


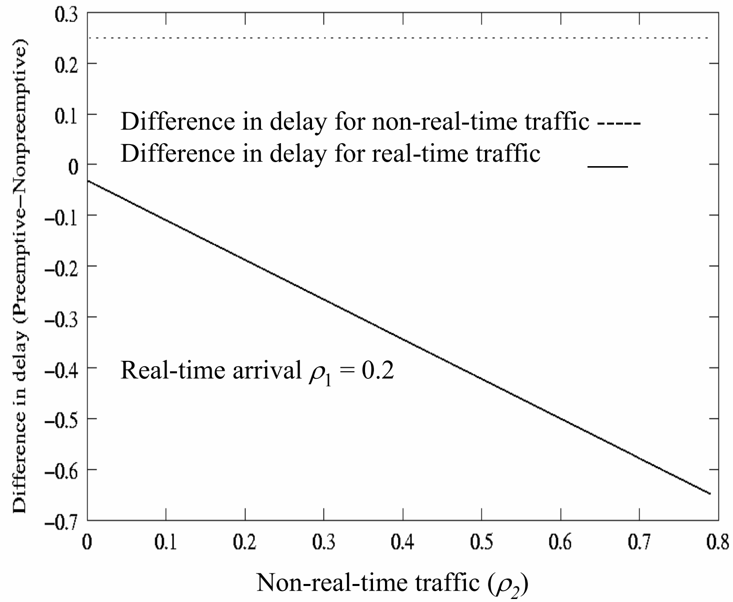
Observations:

- **In non preemptive resume priority scheme, the NRT traffic shows some impact on the RT packet delay**
- **In case of preemptive resume priority the delay for RT data packets is independent of arrival of NRT packets**

Numerical Results : Inter-cluster Traffic

Differential delay between the two schemes for RT/NRT traffic





Observations:

- **For a low NRT traffic: The delay difference for NRT data packets increases with increase in RT traffic, whereas for RT data packets, it decreases more significantly with knee portion around 0.6**

- **For a low RT traffic: The delay difference for NRT packets remains constant with varying NRT traffic whereas for RT data packets, it drops linearly with nominal decrease**

Conclusions

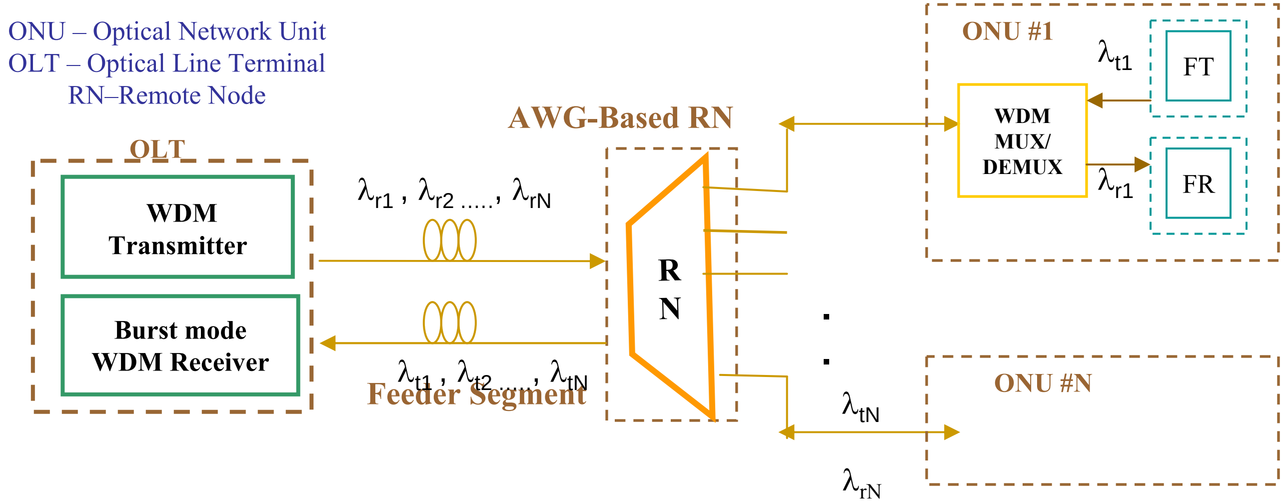
MAC protocols in a WDM-based optical access network with ring-on-stars topology for incorporating Dynamic Bandwidth Allocation based service differentiation

- Scheduling improved with more control channels, sub-carrier multiplexing and look ahead feature
- Real time services (voice, video) benefit in preemptive priority queuing at high real-time traffic
- Non real-time service (data, image) quality not affected by preemptive queuing for low real-time traffic

Transmission Impairments in a WDMPON

System Architecture of AWG-based WDMPON

Arrayed Waveguide Grating-Based Wavelength Routed Passive Optical Network



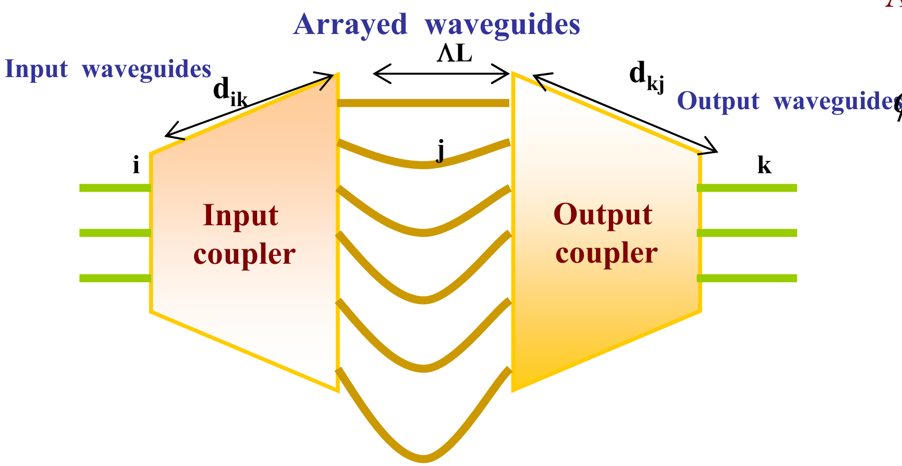
Salient Features:

- Architecture is predominantly "passive" with inexpensive ONUs
- Distribution with one or more stages of AWG-based RNs
- Wavelength Routing-based Demultiplexing

System Considerations:

- Tunable Laser Source in OLT ; Fixed tuned transceiver in ONU
- $\lambda_{up} - \lambda_{dn}$ = n x FSR of AWG ; AWG-based demultiplexer in RN
- OLT-ONU: 20 Km; IM-DD signal transmission

Enabling Device Technology- Arrayed Waveguide Grating



Arrayed Waveguide Grating Device (AWG)

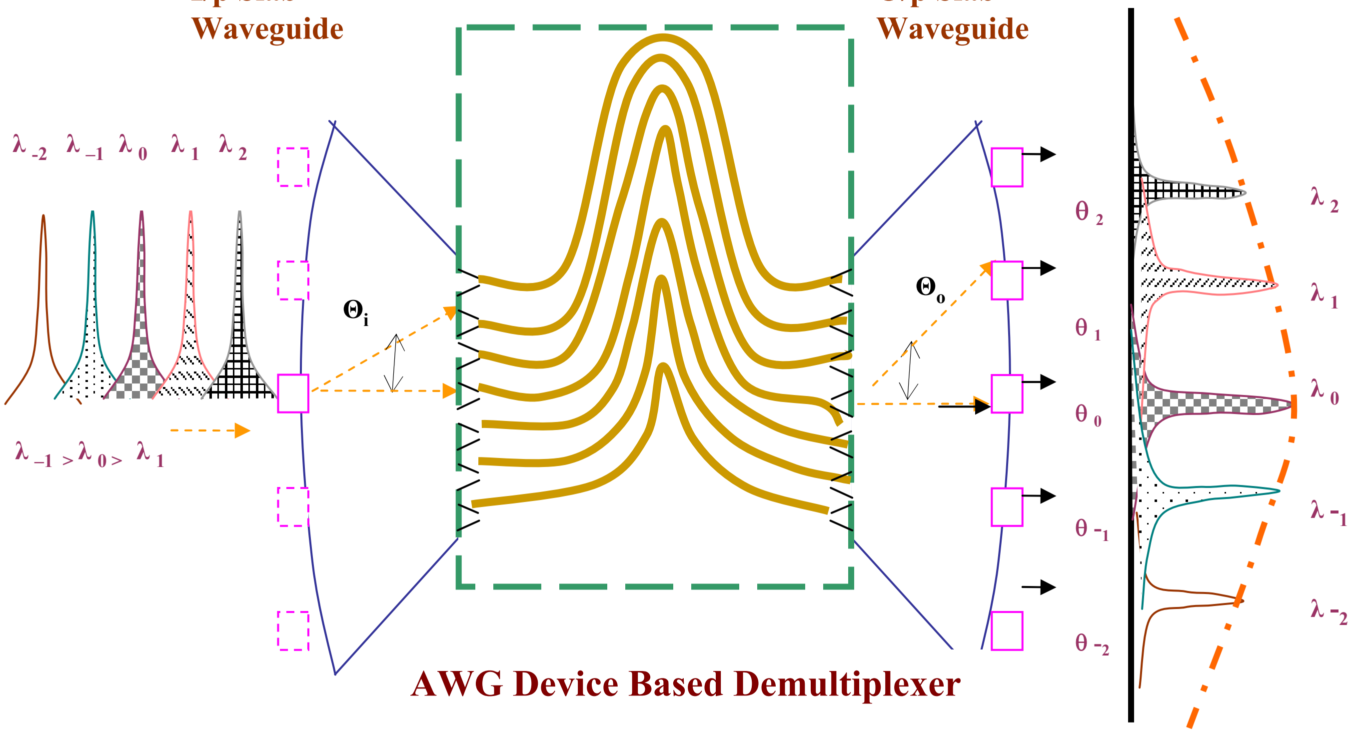
$$\phi_{ijk} = \frac{2\pi}{\lambda}\left(n_1 d_{ik}^{in} + n_2 k \Delta L + n_1 d_{kj}^{out}\right) \quad k = 1,..m$$

Condition to be met for signal on λ from i^{th} port to appear at k^{th} port

$$\phi_{ijk} = \quad p\, x\, 2\pi \quad \text{p is an integer}$$

- **Principle:** Light signal after diffraction in i/o slab waveguide is subjected to λ dependent progressive phase delay in slab regions and w/g array. After constructive interference it is routed to a unique o/p port
- AWG is less lossy with flat pass band and polarization independence
- Easy to realize on integrated optic substrate and amenable to mass fabrication

Wavelength Routing Mechanism in AWG



AWG Device Based Demultiplexer

Far Field Pattern of Routed Optical Channels in a AWG based Remote Node (considering the lorentzian laser emission Spectrum , dispersion and Gaussian focal field)

Factors affecting the optical channel

- **Laser related:** Laser linewidth, Laser transmit power
  Finite Laser Line-width due : Lorentzian Emission Spectrum
  - Spillover to adj. ch
  - Produces hetero wavelength crosstalk at o/p ports

- **AWG related:** Far-field image profile, Heterowavelength crosstalk and Dispersion
  Gaussian Far-field Pattern: Effect of dispersion in Slab waveguides
  - Results in non-uniform routed signal power at o/p Ports

- **Photo detector related :** Beat noise (between signal and cross talk)
  Beat Noise: By-product of constructive interference phenomenon in AWG

Performance Analysis – AWG Model

Far Field Distribution at the Image Plane of AWG (due to dispersion):

Optical Power at the ith output port, $P_o^i(\theta) = P_o\, e^{\frac{-2\theta_i^2}{\theta_w^2}}$

Lorentzian Power Spectral Density of the Laser at center frequency f_{oi}:

$$S_i(f) = \frac{A^2}{4\pi^2 N_O}\left[\frac{1}{1+\left(\frac{f+f_{oi}}{\pi N_o}\right)^2} + \frac{1}{1+\left(\frac{f-f_{oi}}{\pi N_o}\right)^2}\right]$$

where B_L (3*dB* laser line width); N_O – Laser freq. noise spectral density($= \frac{B_L}{2\pi}$)

Transformation from Spectral Domain to Radial (Angular) Domain:

$$\theta = \frac{D}{R_a}(f - f_o) \Rightarrow (f - f_o) \Leftrightarrow \frac{R_a\theta}{D}$$

$$f - f_{oi} = f - f_o - i\Delta f_{ch} \Leftrightarrow \frac{R_a\theta}{D} + i\frac{R_a\Delta\theta_{ch}}{D}$$

Performance Analysis - AWG Model:

Considering only the real frequencies in the PSD of the laser emission spectrum, the transformed Lorentzian power spectral density of the laser, operating at f_{oi}

$$S_i(\theta) = \frac{A^2}{\pi B_L}\left[\frac{1}{1+\left(\frac{2R_a\theta}{B_L D} - i\frac{2R_a\Delta\theta_{ch}}{B_L D}\right)^2}\right] = P_o^i \; S_n^i(\theta)$$

On integration, total optical signal power captured at the i_{th} port is given by:

$$P_{sig}^i = \frac{A^2}{2\pi} e^{\frac{-2(i\Delta\theta_{ch})^2}{\theta_w^2}} \left\{2\tan^{-1}\left(\frac{R_a \Delta\theta_{wg}}{B_L D}\right)\right\} = \frac{A^2}{\pi} e^{\frac{-2(i\Delta\theta_{ch})^2}{\theta_w^2}} \tan^{-1}\left(\frac{R_a \Delta\theta_{wg}}{B_L D}\right)$$

On integration, total inter-channel (hetero-wavelength) crosstalk at the i_{th} port is given by::

$$P_{xt}^i = \frac{A^2}{2\pi} e^{\frac{-2(\overline{i+1}\Delta\theta_{ch})^2}{\theta_w^2}} \left\{\tan^{-1}\left(\frac{2R_a}{B_L D}\left(\Delta\theta_{ch} + \frac{\Delta\theta_{wg}}{2}\right)\right) - \tan^{-1}\left(\frac{2R_a}{B_L D}\left(\Delta\theta_{ch} - \frac{\Delta\theta_{wg}}{2}\right)\right)\right\}$$

$$- \frac{A^2}{2\pi} e^{\frac{-2(\overline{i-1}\Delta\theta_{ch})^2}{\theta_w^2}} \left\{\tan^{-1}\left(\frac{2R_a}{B_L D}\left(\Delta\theta_{ch} - \frac{\Delta\theta_{wg}}{2}\right)\right) - \tan^{-1}\left(\frac{2R_a}{B_L D}\left(\Delta\theta_{ch} + \frac{\Delta\theta_{wg}}{2}\right)\right)\right\}$$

Performance Analysis – BER Evaluation

Transmission Impairments:

Direct Noise Components

Thermal Noise Variance, $\sigma_{th}^2 = \eta_{th} B_e = \dfrac{4KTB_e}{R_L}$

Thermal Noise Variance, $\sigma_{th}^2 = \eta_{th} B_e = \dfrac{4KTB_e}{R_L}$

Shot Noise Variance for “0” bit, $\sigma_{sh0}^2 = 2q\varepsilon q_{\lambda} P_{sig}^i B_e$

Shot Noise Variance for “1” bit, $\sigma_{sh1}^2 = 2qR_{\lambda} P_{sig}^i B_e$

Cross talk Variance from n adjacent channels, $\sigma_{xt}^2 = 2q\, R_{\lambda} P_{xt}^i\, n_{adj}\, B_e\, p_{r-on}\ (n_{adj} = 2)$

Beat Noise Components

Signal - Cross talk Beat Variance, $\sigma_{sg\_xt}^2 = 2\xi_{pol} R_{\lambda}{}^2 P_{sig}^i P_{xt}^i\ p_{r-on}$

Cross talk - Cross talk Beat Variance, $\sigma_{xt\_xt}^2 = 2\xi_{pol} R_{\lambda}{}^2 P_{adj+1}^i P_{adj-1}^i p_{r-on}^2 (n_{adj} - 1)$

Performance Analysis – BER Evaluation

Various Noise factors and their standard deviations :

Without Beat Noise:

Total Noise Standard deviation for "0" bit, $\sigma_0^{'} = \sqrt{\sigma_{th}^2 + \sigma_{sh0}^2 + \sigma_{\mathrm{xt}}^2}$

Total Noise Standard deviation for "1" bit, $\sigma_1^{'} = \sqrt{\sigma_{th}^2 + \sigma_{\mathrm{sh1}}^2 + \sigma_{\mathrm{xt}}^2}$

With Beat Noise:

Total Noise Standard deviation for "0" bit, $\sigma_0 = \sqrt{\sigma_{th}^2 + \sigma_{sh0}^2 + \sigma_{\mathrm{xt}}^2 + \sigma_{xt\_xt}^2}$

Total Noise Standard deviation for "1" bit, $\sigma_0 = \sqrt{\sigma_{th}^2 + \sigma_{sh1}^2 + \sigma_{xt}^2 + \sigma_{xt\_xt}^2 + \sigma_{sig\_xt}^2}$

Optimized Decision Threshold:

Detection threshold independent of beat noise (practical), $I_{th1} = \dfrac{R_\lambda P_{sig} \sigma'_0 + \varepsilon R_\lambda P_{sig} \sigma'_1}{\sigma'_1 + \sigma'_0}$

Probability of Bit Error Rate:

$$P_e = \frac{1}{4}\left\{ erfc\left[\frac{R_\lambda P_{sig} - I_{th1}}{\sqrt{2}\sigma_1} \right] + erfc\left[\frac{I_{th1} - \varepsilon R_\lambda P_{sig}}{\sqrt{2}\sigma_0} \right] \right\}$$

System Considerations

- **Optical Channels (= port count) : 16; OLT Transmit power levels– Class B PONs**
  Laser Linewidths: 100 MHz-5 GHz range; Wavelength channel spacing: 100/50/25 GHz
  Data rates: 155/622 Mbps; Insertion loss of AWG is 6.5 dB; fiber span of 20 Km @0.25dB/Km

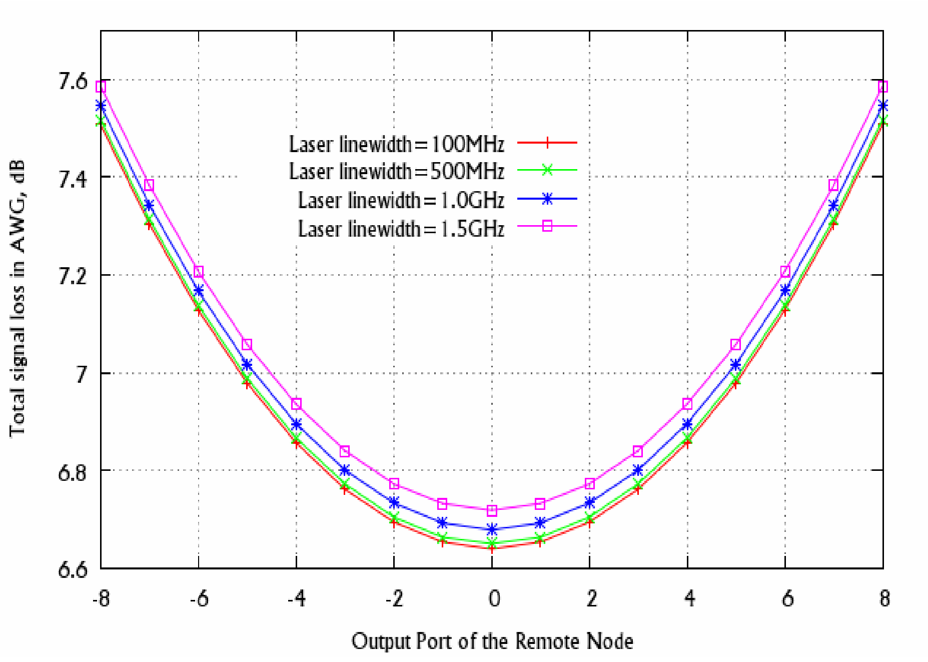
- **Thermal noise dominates the link budget of the wavelength channels in a WDMPON because of cost-effective photo-receivers (6pF capacitors)**

- **Full FSR has not been used. The output port-aperture is only a fraction of a FSR or the main focal spot**

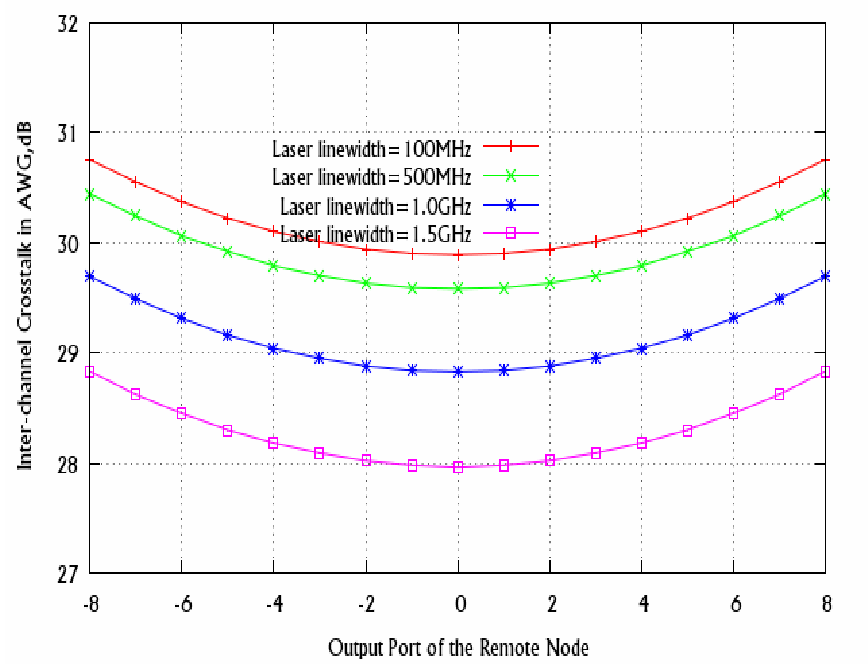
- **Receiver waveguide width is typically that of a SM fiber**

Numerical Results

Signal loss and Crosstalk variation at output ports



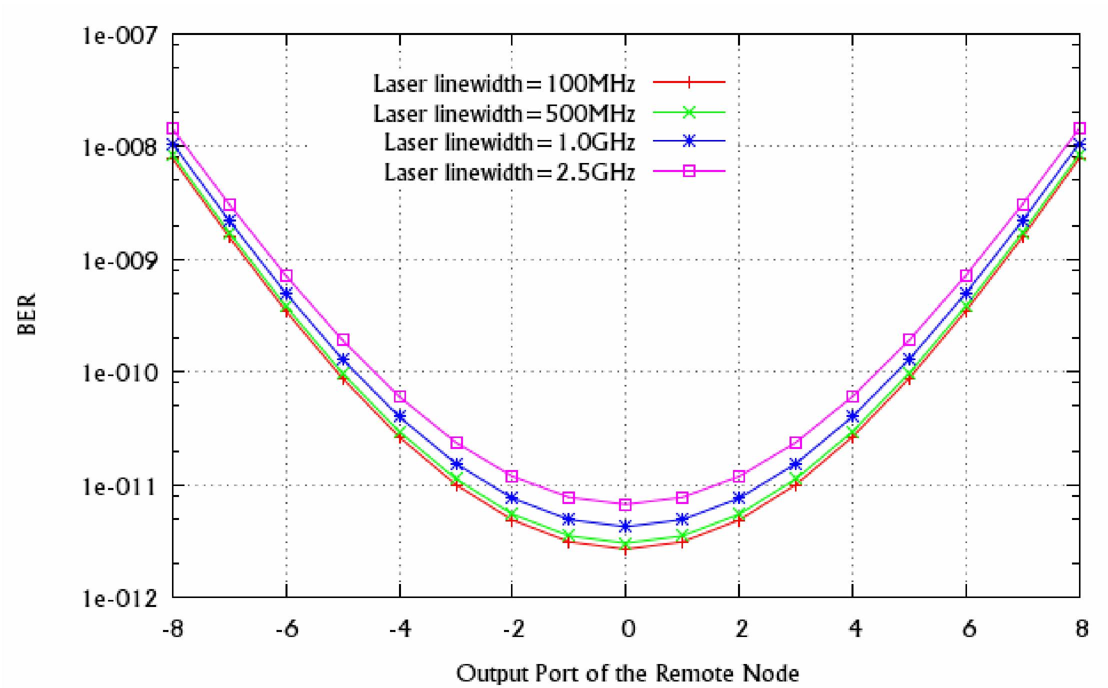
Loss Characteristics of AWG for different laser linewidths; R_b = 1.25Gbps; P_{OLT} = -6.0 dBm; AWG Insertion loss = 6.5 dB



Inter-channel Crosstalk Characteristics for 1.25Gbps channels; P_{OLT} = -6.0dBm

Numerical Results

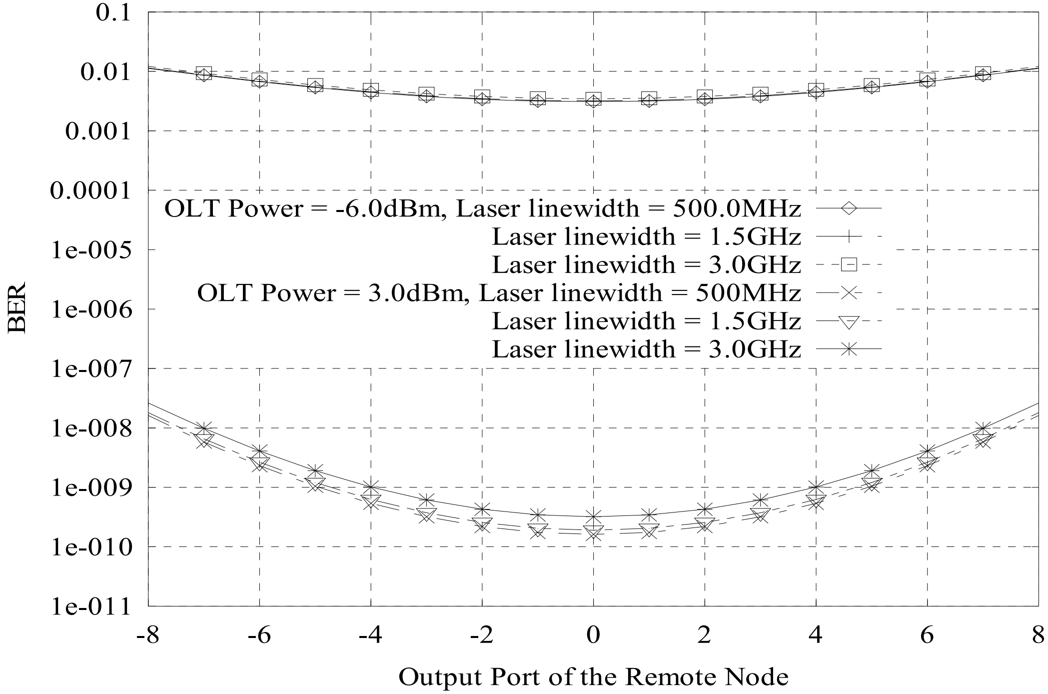
BER variation at output ports



BER characteristics of 1.25 Gbps channels for different laser linewidths without including beat noise: POLT=−6.0 dBm, ch =100 GHz.

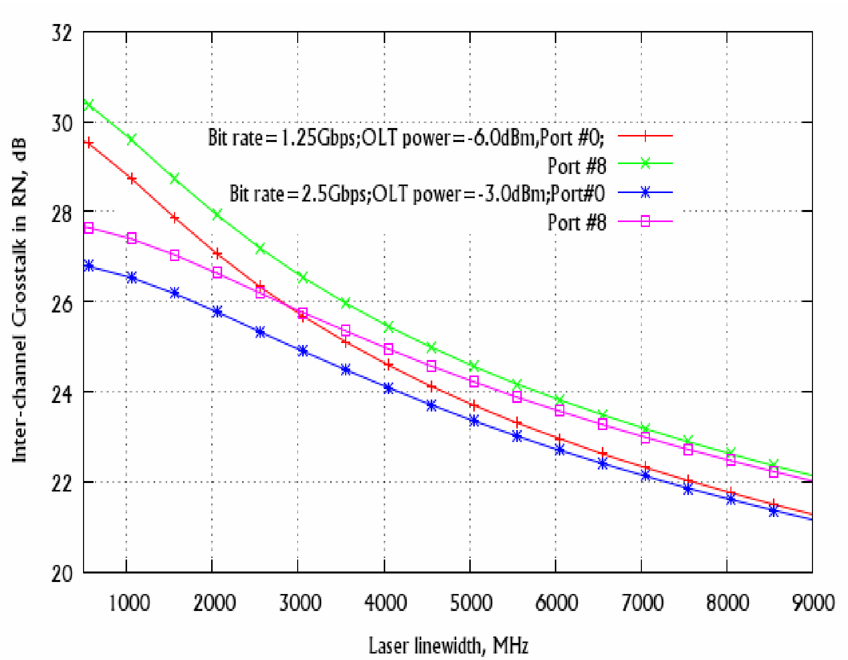
Numerical Results

Impact of OLT Transmit Power on BER variation at output ports

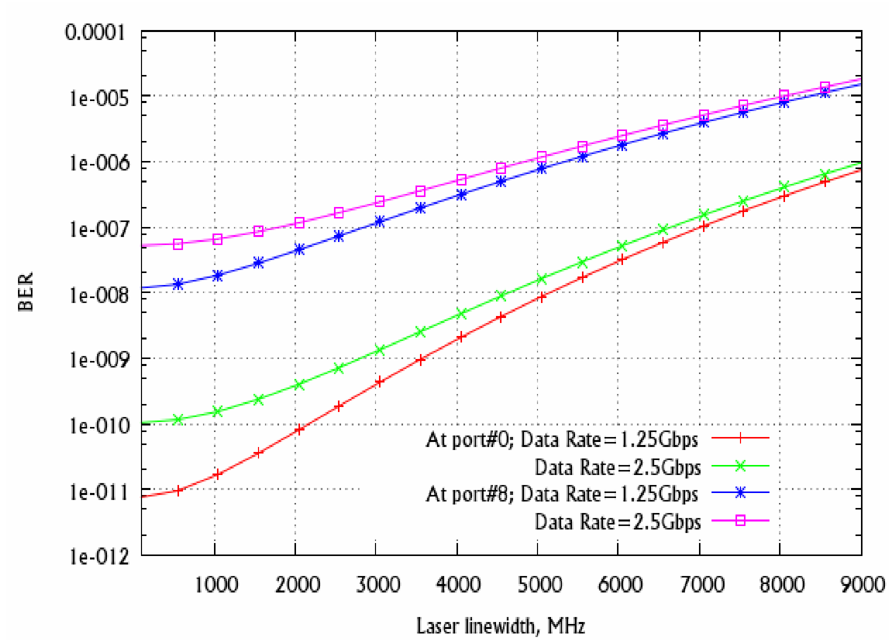


BER Characteristics of 10.0Gbps channels for different laser linewidths; P_{OLT} = +3.0 dBm; $\Delta\theta_{ch}$ =100GHz

Numerical Results

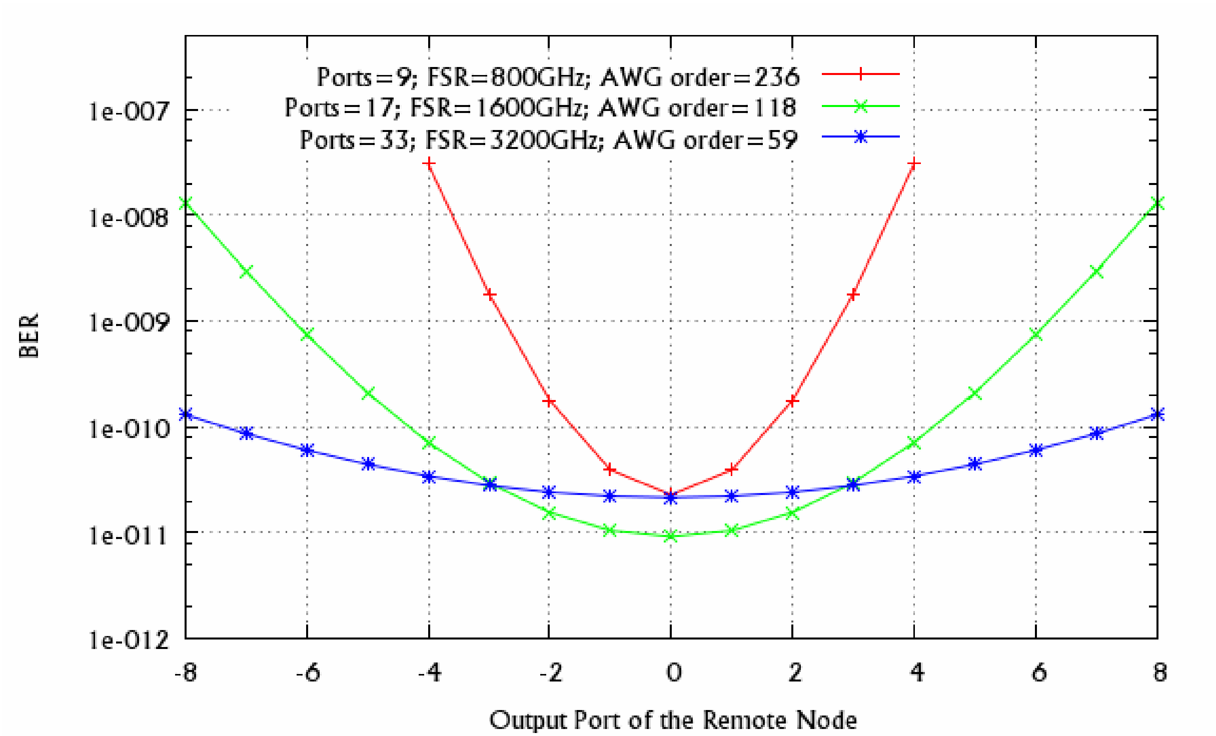


Comparative Crosstalk Characteristics for different data rates and port locations



BER versus laser linewidth for different data rates at Port #0; B_L = 500 MHz;

Numerical Results



BER performance of 1.25 Gbps channels including beat noise for different port counts: POLT=−6.0 dBm, BL=500 MHz, ch=100 GHz.

Conclusions

Impact of transmission impairments in an AWG-based PON

•Gaussian focal-field pattern of the AWG largely determines the signal strength of the demultiplexed channels at the output ports

•Beat noise effects become more conspicuous in PONs, for increasing values of laser linewidth especially at the inner ports

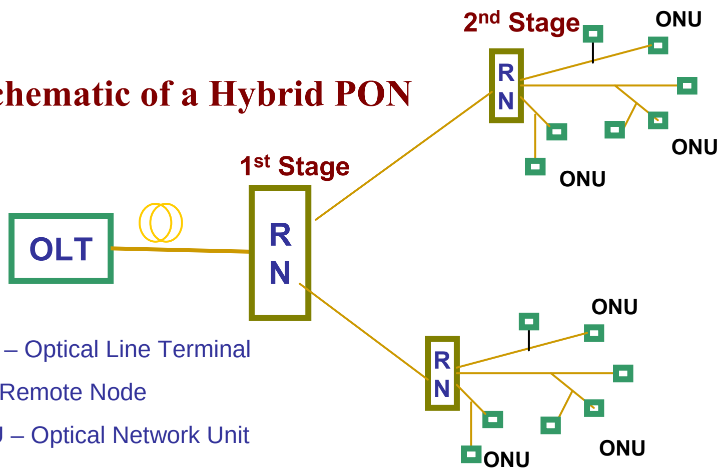
•Impairments bring a significant BER variation amongst the ONUs connected to the output ports of a AWG while employing DFB lasers at the OLT.

Resource Provisioning in a WDM-OCDMA PON

Impetus for a Hybrid WDMPON

- **Scalability and resource provisioning**
  - Modular scaling (in terms of clusters)
  - Increased resource pool (codes/time slots/RF sub-carriers etc.,)

Schematic of a Hybrid PON



OLT – Optical Line Terminal
RN–Remote Node
ONU – Optical Network Unit

- **Effective bandwidth utilization per wavelength**
  - Finer granularity in provisioning within a λ

- **Reduced ONU cost due to more sharing and less inventory**
  - Fewer port counts and transceiver with shorter tuning range
  - WDM transceiver common for all ONUs within a code-cluster

- **Derive combined strength of constituent access and MUX schemes**
  - Compensate limitations of independent schemes

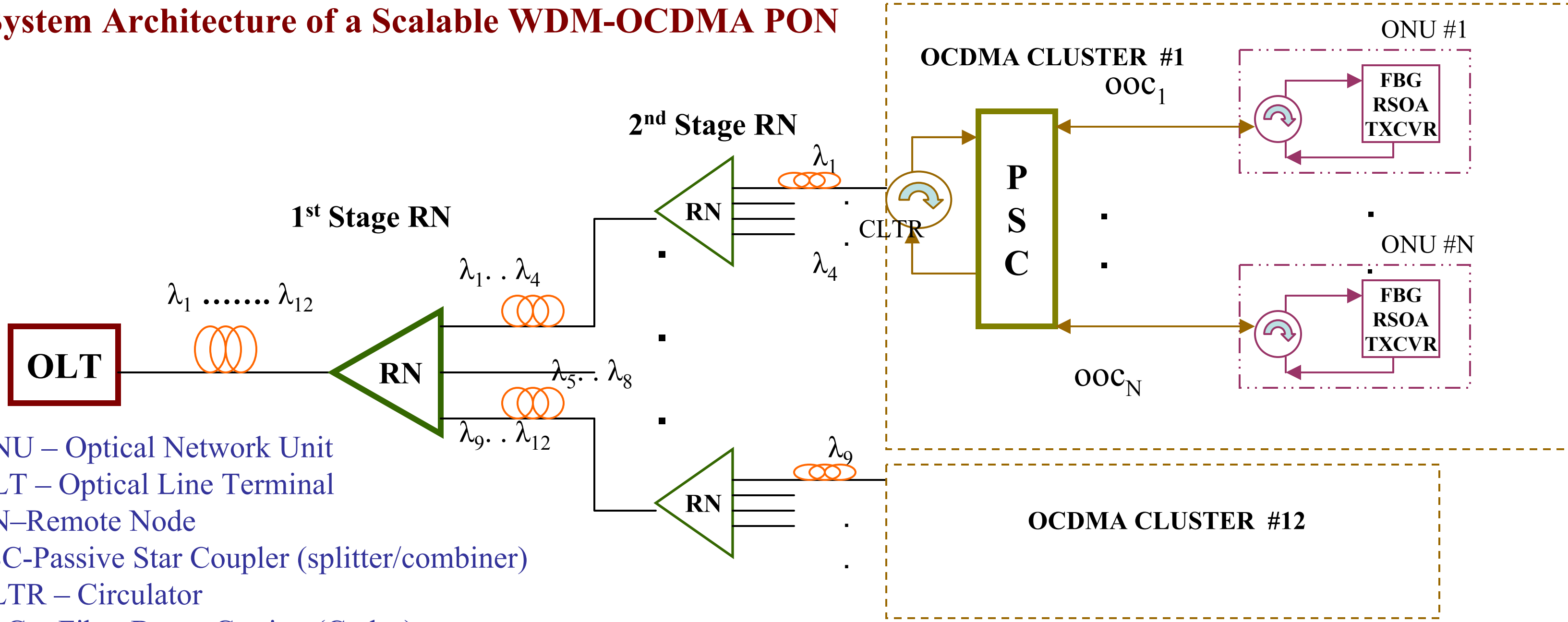
- **Better network resilience**
  - ONU less prone to failure (semi-passive)
  - Restoration cheaper (low inventory cost)

Salient Features of a WDM-OCDMA PON

- **Passive Architecture: Fiber Bragg Grating-based CODECs, Arrayed Waveguide Grating-based Mux/Demux, Circulator, Passive Star Coupler**
- **Asynchronous access: Free of time synchronization between ONU's and OLT**
  Ideal for bursty data traffic
- **Hybrid multiplexing and multiple access (WDM/OCDM techniques)**
- **Resource Optimization: Reduced no. of wavelengths (λ/cluster)**
  Reuse of a set of optical codes in several clusters
  No separate laser in the ONU (downstream laser power reused through Reflective Semiconductor Optical Amplifier-RSOA)
- **Scalability: Upstream codes reduced and downstream users increased**
- **Operating conditions: W-OCDM PON using (341,5,1) OOC with 17 codes; Asymmetric traffic with up:down ratio 0.25 to 0.9; PON span: 20-25Km; ONUs: 255 (=15 x 17)**

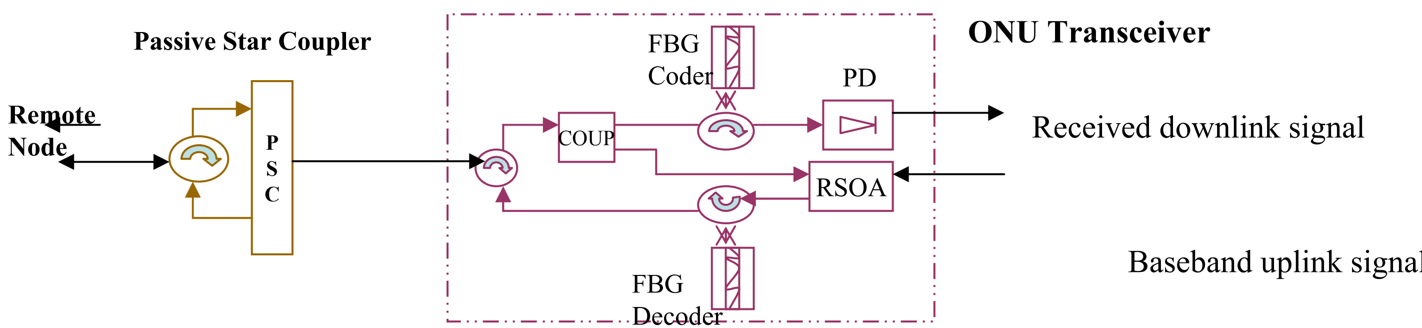
System Architecture of WDM-OCDMA PON

System Architecture of a Scalable WDM-OCDMA PON



ONU – Optical Network Unit
OLT – Optical Line Terminal
RN–Remote Node
PSC-Passive Star Coupler (splitter/combiner)
CLTR – Circulator
FBG – Fiber Bragg Grating (Codec)
RSOA- Reflective Semiconductor Optical Amplifier

Fiber Bragg Grating-based ONU Transceiver



Salient Features of W-OCDM PON

- **Hybrid Transmission Mechanisms :** -WDM/OCDM multiplexing downstream
  -WDMA/OCDMA multiple access upstream
  - N x M ONUs with unique wavelength-code combination

- **Passive Architecture :** Two stage distribution
  - PSC-based RN handles OOC-encoded ONU traffic
  - AWG-based RN handles aggregated WDM traffic
  - Fiber Bragg grating-based CODECs for ONUs

- **Asynchronous access:** - Free from time synchronization between ONUs and OLT
  - Ideal for bursty data traffic

- **Resource Optimization:** - Reduced no. of wavelengths i.e., simpler OLT
  - Reuse of optical codes in several clusters
  - No separate laser in the ONU (RSOA)

- **Provisioning:** - Each ONU-cluster allocated a wavelength
  - Every ONU allotted distinct code for downstream transmission
  - Shared codes for upstream transmission (code contention)
  - Traffic asymmetry accounted

- **Data Security:** Inherent coding mechanism enhances confidentiality in n/w

Resource Provisioning through a Code Allocation Scheme

- **Optical Orthogonal Codes (OOCs)**
  - Unipolar coding for IM data streams
  - Selection criteria: cluster size and data rate per user
- **Proposed Code Allocation Scheme**
  - Heuristic estimate based on traffic ratio β
  - Open search mode using deviation Δ for optimal solution
- **Major Impairments affecting the Performance**
  - Multiple user interference (MUI) and code contention
- **Performance Criteria**
  - Aggregate throughput in upstream and downstream directions
- **Operating conditions:**
  - OOC (364,4,1) i.e., cluster size M=30
  - Slotted ALOHA protocol
  - ONUs operate in duplex mode
  - Fiber link : 2.5 Gbps with 6.6 Mbps/channel
  - Data packet size P_{len} :150/ 75 /20 bytes
  - Binomial distributed traffic with β =0.25/ 0.5/0.75/0.9
  - PON span: 20-25Km ; Total ONUs: 30xN (N=λs)

Table 1. Some OOCs and their Characteristics

Code Family	Code Charact. $C=(n,w,\lambda)$	Code Size $\lvert C\rvert=[(n-1)/w(w-1)]$
$(n,3,1)$	(31,3,1)	5
	(63,3,1)	10
	(127,3,1)	21
	(255,3,1)	42
	(511,3,1)	85
	(1023,3,1)	170
	(2047,3,1)	341
	(4095,3,1)	682
$(n,4,1)$	(40,4,1)	3
	(121,4,1)	10
	(364,4,1)	30
	(1093,4,1)	91
	(3280,4,1)	273
$(n,5,1)$	(85,5,1)	4
	(341,5,1)	17
	(1365,5,1)	68
	(5461,5,1)	273

Resource Provisioning through a Code Allocation Scheme

Heuristic Code Allocation:

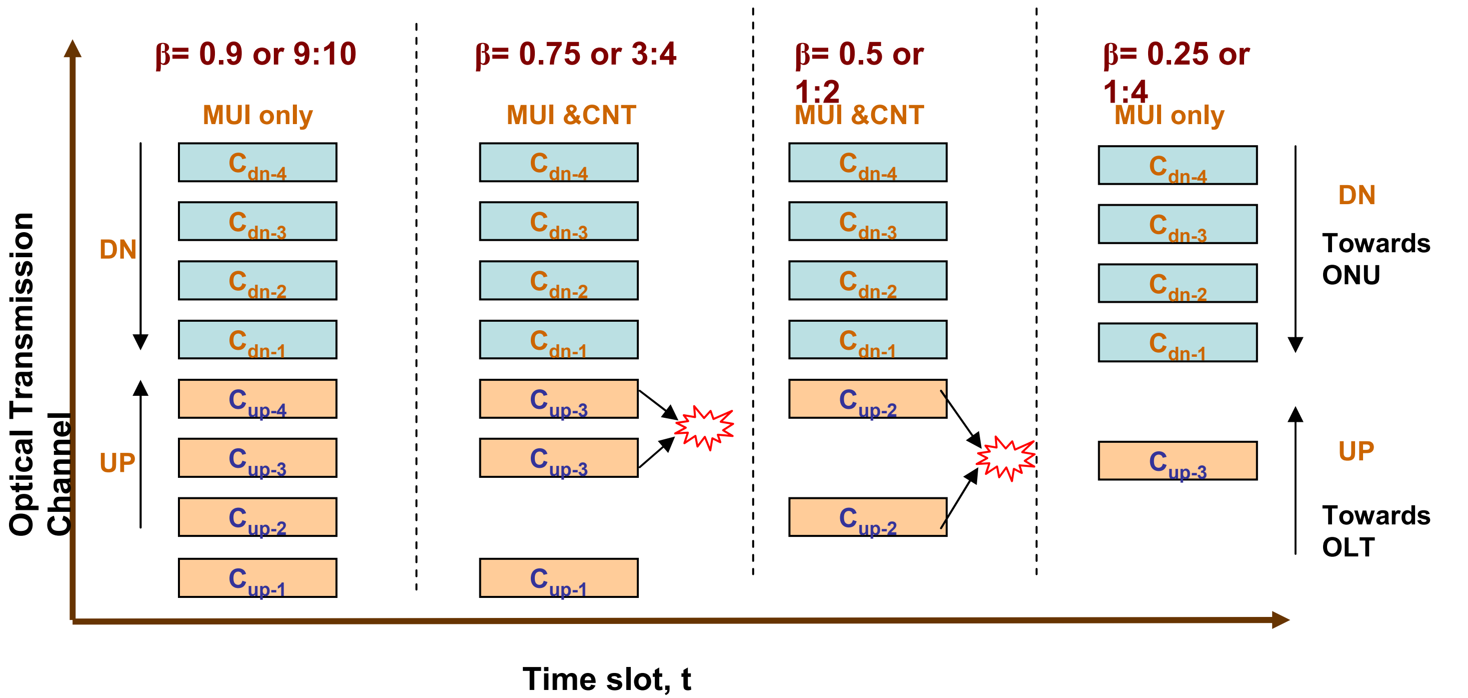
$$C_d = \frac{n-1}{w(w-1)} \quad ; \beta \sim \left(\frac{G_{up}}{G_{dn}}\right)$$

$$N_{up} = \left\lfloor \left[C_d \frac{\beta}{(1+\beta)} \right] \right\rfloor \quad ; \quad N_{dn} = (C_d - N_{up})$$

G_{up} /N_{up}= Pkt. traffic /Codes in upstream direction

G_{dn} /N_{dn}= Pkt. traffic/Codes in downstream direction

Packet Transmission under different traffic conditions



System Throughput in a Code-cluster

$$S = \sum_{k=1}^{k_{max}} S(k) = \sum_{k=1}^{k_{max}} k \,.\, f_N(k) \,.\, P_d(k) \,.\, P_c(k) \qquad (1)$$

where k = no. of packet transmissions

$f_N(k)$ = packet arrival probability

$P_d(k)$ = probability of distinct code usage

$P_c(k)$ = probability of correct packet transmission under MUI

k_{max} = maximum no. of transmissions in a direction

Upstream channels: $k = k_{up}$ & $k_{max} = N_{up}$

Downstream channels: $k = k_{dn}$ & $k_{max} = N_{dn}$

Packet arrival probability (upstream) :

$$f_{N_{up}}(k_{up}) = \binom{N_{up}}{k_{up}} \cdot \left(\frac{N_{up}}{N_{dn}}\right)^{k_{up}} \cdot \left(1 - \frac{N_{up}}{N_{dn}}\right)^{N_{up}-k_{up}} \quad \text{(Binomial)} \qquad (2)$$

Distinct code usage probability:

k_{int} = no. of interferers

g_m = no. of contenders for a upstream code

P_{len} = data packet length in bytes

$$P_d(k_{up}) = \frac{\left[\binom{N_{up}}{k_{up}} \cdot (g_m)^{k_{up}}\right]}{\binom{N_{dn}}{k_{up}}} \qquad (3)$$

Correct packet transmission probability under MUI:

$$P_C(k_{up}) = \left\{1 - \left[P_{len} \cdot f_{N_{dn}}(k_{dn}) . \sum_{i=w}^{k_{int}} \binom{k_{int}}{i} \left(\frac{w^2}{n}\right)^i \left(1 - \frac{w^2}{n}\right)^{k_{int}-i}\right]\right\} \qquad (4)$$

Performance Analysis of W-OCDM PON

With Code Contention:

▪ **Upstream throughput in an ONU-cluster:**

$$S_{binomial}^{up} = \left\{ \sum_{k_{up}=1}^{N_{up}} k_{up} \left[\binom{N_{up}}{k_{up}} \left(\frac{N_{up}}{N_{dn}} \right)^{k_{up}} \left(1 - \frac{N_{up}}{N_{dn}} \right)^{N_{up}-k_{up}} \right] \left\{ \frac{\left[\binom{N_{up}}{k_{up}} (g_m)^{k_{up}} \right]}{\binom{N_{dn}}{k_{up}}} \right\} \left\{ 1 - \left[P_{len} \left\{ f_{N_{dn}}(N_{dn}) \right\} \left\{ \sum_{i=w}^{k_{int}} \binom{k_{int}}{i} \left\{ \left(\frac{w^2}{n} \right) \right\}^i \left\{ \left(1 - \frac{w^2}{n} \right)^{k_{int}-i} \right\} \right\} \right] \right\} \right\} \quad (5a)$$

With Contention Avoidance:

$$S_{binomial}^{up} = \sum_{k_{up}=1}^{N_{up}} k_{up} \left\{ \binom{N_{up}}{k_{up}} \right\} \left\{ \left(\frac{N_{up}}{N_{dn}} \right)^{k_{up}} \right\} \left\{ \left(1 - \frac{N_{up}}{N_{dn}} \right)^{N_{up}-k_{up}} \right\} \left\{ 1 - \left[P_{len} \left\{ f_{N_{dn}}(N_{dn}) \right\} \left\{ \sum_{i=w}^{k_{int}} \binom{k_{int}}{i} \left\{ \left(\frac{w^2}{n} \right) \right\}^i \left\{ \left(1 - \frac{w^2}{n} \right)^{k_{int}-i} \right\} \right\} \right] \right\} \quad (5b)$$

where,

$$f_{N_{dn}}(N_{dn}) = \binom{N_{dn}}{k_{dn}} \left\{ \left(\frac{N_{dn}}{N_{dn}} \right)^{k_{dn}} \right\} \left\{ \left(1 - \frac{N_{dn}}{N_{dn}} \right)^{N_{dn}-k_{dn}} \right\} \text{ and } k_{\text{int}} = (k_{up} - 1 + N_{dn})$$

Performance Analysis of W-OCDM PON

- **Downstream throughput in an ONU-cluster:**

$$S_{binomial}^{dn} = N_{dn}\left\{1-\left[P_{len}\left\{f_{N_{up}}(k_{up})\right\}\left\{\sum_{i=w}^{k_{\text{int}}}\binom{k_{int}}{i}\left(\frac{w^2}{n}\right)^{i}\left(1-\frac{w^2}{n}\right)^{k_{int}-i}\right\}\right]\right\} \qquad (6)$$

where,

$$f_{N_{up}}(k_{up}) = \left[\binom{N_{up}}{k_{up}}\left\{\left(\frac{N_{up}}{N_{dn}}\right)^{k_{up}}\right\}\left\{\left(1-\frac{N_{up}}{N_{dn}}\right)^{N_{up}-k_{up}}\right\}\right] \text{ and } k_{\text{int}} = (k_{dn}-1+k_{up})$$

Important regions in performance curves:

- **Cut-off point vis-a-vis heuristic estimate**
  - extent of deviation from traffic-aware allocation
- **Over-provisioned region (cut-off point at +ve Δ)**
  - trade-off between per-user rate and reduced cluster size
- **Under-provisioned region (cut-off point at -ve Δ)**
  - scope for spare codes / scalability

Throughput Analysis of W-OCDM PON

Upstream Traffic:

$$\text{Upstream throughput, } S_{up} = \sum_{k_{up}=1}^{k_{max}} S(k_{up}) = \sum_{k_{up}=1}^{k_{max}} k_{up} \,.\, f_{N_{up}}(k_{up}) \,.\, P_d(k_{up}) \,.\, P_c(k_{up})$$

where $k_{up} =$ No. of upstream transmissions

$f_{N_{up}}(k_{up}) =$ Steady-State distribution Probability of k_{up} upstream packets

$P_d\ (k_{up}) =$ Probability of k distinct codes subject to code contention

$P_c(k_{up}) =$ Probability of correct txmn. of packets subject to multiple user interference

$k_{max} = N_{up}$

Downstream Traffic:

$$\text{Downstream throughput, } S_{dn} = \sum_{k_{dn}=1}^{k_{max}} S(k_{dn}) = \sum_{k_{dn}=1}^{N_{dn}} k_{dn} \,.\, f_{N_{dn}}(k_{dn}) \,.\, P_d(k_{dn}) \,.\, P_c(k_{dn})$$

where $k_{dn} =$ No. of downstream transmissions

$f_{N_{dn}}(k_{dn}) =$ Steady-State distribution Probability of k_{dn} downstream packets

$P_d(k_{dn}) =$ Distinct Code Probability subject to code contention $=1$

$P_c(k_{dn}) =$ Correct Packet Probability subject to multiple user interference

$k_{max} = N_{dn}$

Throughput Analysis of W-OCDM PON

Packet arrival probability:

$$f_{N_{up}}(k_{up}) = \begin{pmatrix} N_{up} \\ k_{up} \end{pmatrix} . \left(\frac{N_{up}}{N_{dn}} \right)^{k_{up}} . \left(1 - \frac{N_{up}}{N_{dn}} \right)^{N_{up} - k_{up}} \qquad \text{(Binomial distribution)}$$

Code Contention:

$$P_d(k_{up}) = \frac{P(k_{up})}{Q(k_{up})} = \frac{\left[\begin{pmatrix} g \\ k_{up} \end{pmatrix} . (g_m)^{k_{up}} \right]}{\begin{pmatrix} N_{dn} \\ k_{up} \end{pmatrix}} = \frac{\left[\begin{pmatrix} N_{up} \\ k_{up} \end{pmatrix} . (g_m)^{k_{up}} \right]}{\begin{pmatrix} N_{dn} \\ k_{up} \end{pmatrix}}$$

where $Q(k_{up})$ is the total combinations & $\mathrm{P}(k_{up})$ is the distinct combinations

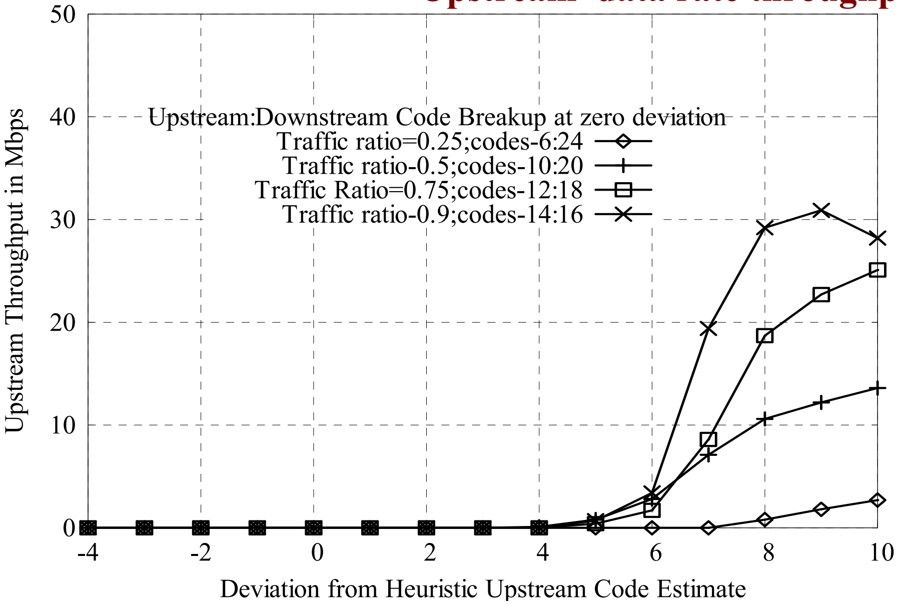
Correct packet probability under MUI:

Probability of correct packet transmission for a data packet length of $\mathrm{P}_{\mathrm{len}}$ is given by

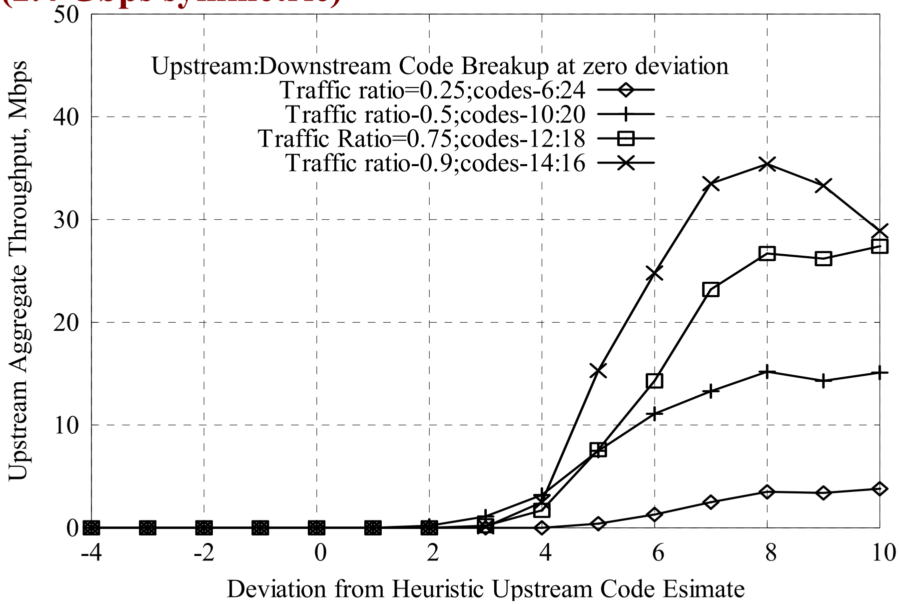
$$P_C(k_{up}) = \left\{ 1 - \left[P_{len} . f_{N_{dn}}(k_{dn}) . \sum_{i=w}^{k_{int}} \begin{pmatrix} k_{cnt} \\ i \end{pmatrix} \left(\frac{w^2}{n} \right)^i \left(1 - \frac{w^2}{n} \right)^{k_{int} - i} \right] \right\}$$

Numerical Results

Upstream data rate throughput (2.4 Gbps symmetric)



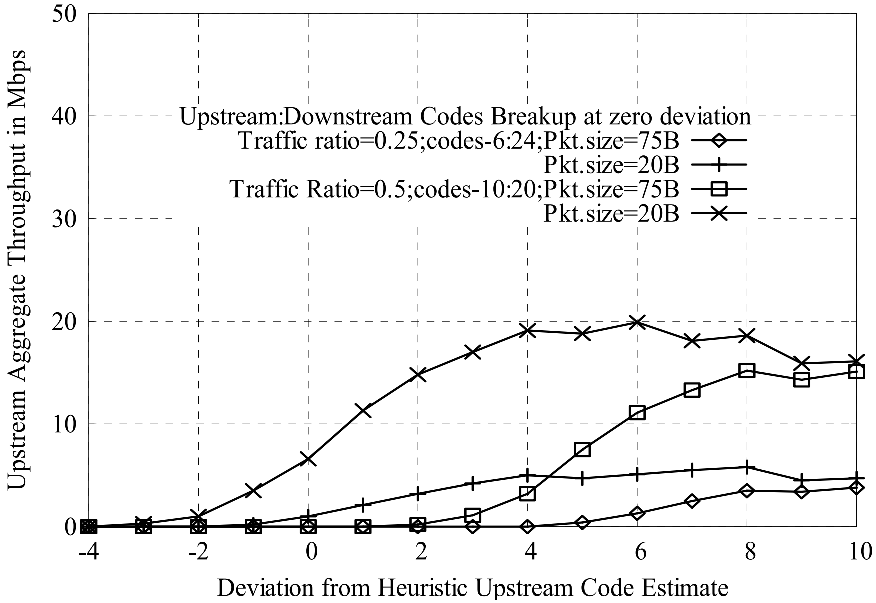
Upstream throughput versus Δ with code contention; OOC = (364,4,1); Users = 30; Packet Size = 75B



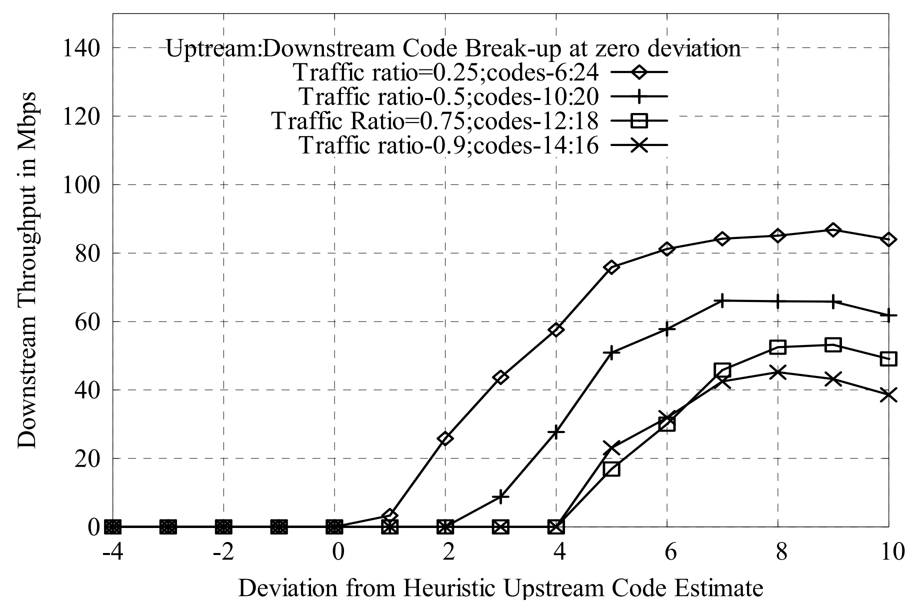
Effect of packet length on upstream throughput with code contention; OOC = (364,4,1); Users = 30; Packet size = 150B

Numerical Results

Upstream data rate throughput (2.4 Gbps symmetric)



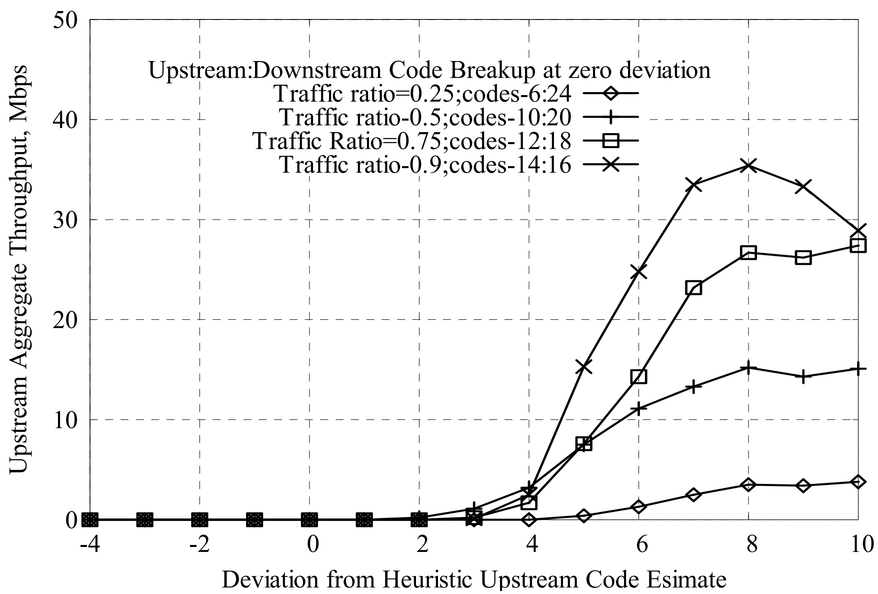
Effect of packet length at low to medium β on upstream throughput with contention avoidance; OOC = (364,4,1); Users = 30



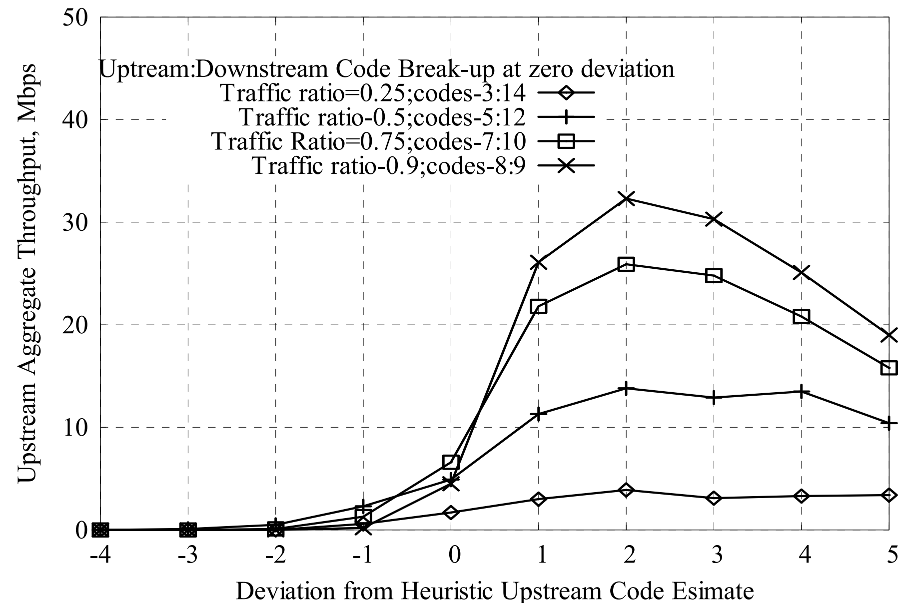
Downstream aggregate throughput versus Δ; OOC = (364,4,1); Users = 30; Packet size = 75B

Numerical Results

Upstream data rate throughput (2.4 Gbps symmetric)



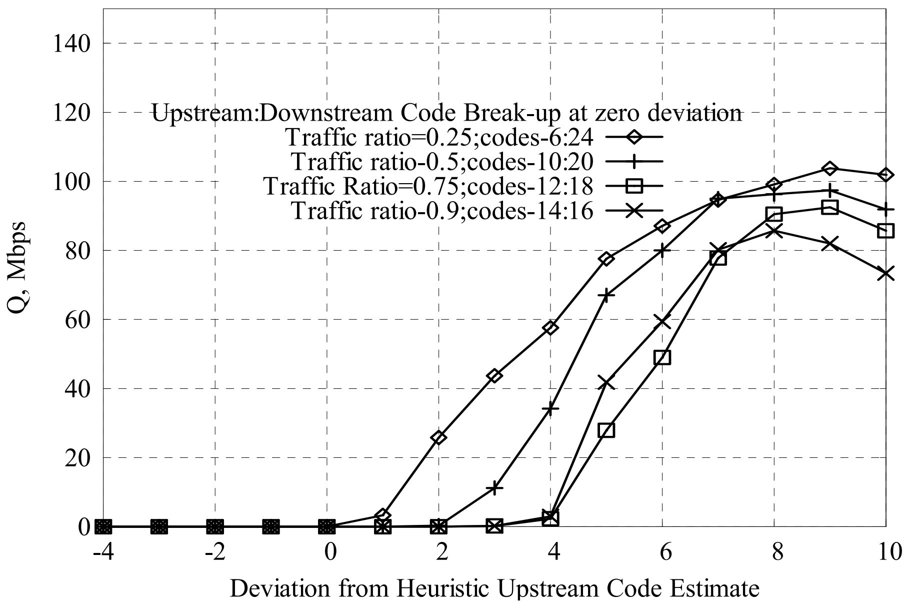
Effect of packet length on upstream throughput with code contention; OOC = (364,4,1); Users = 30; Packet size = 150B



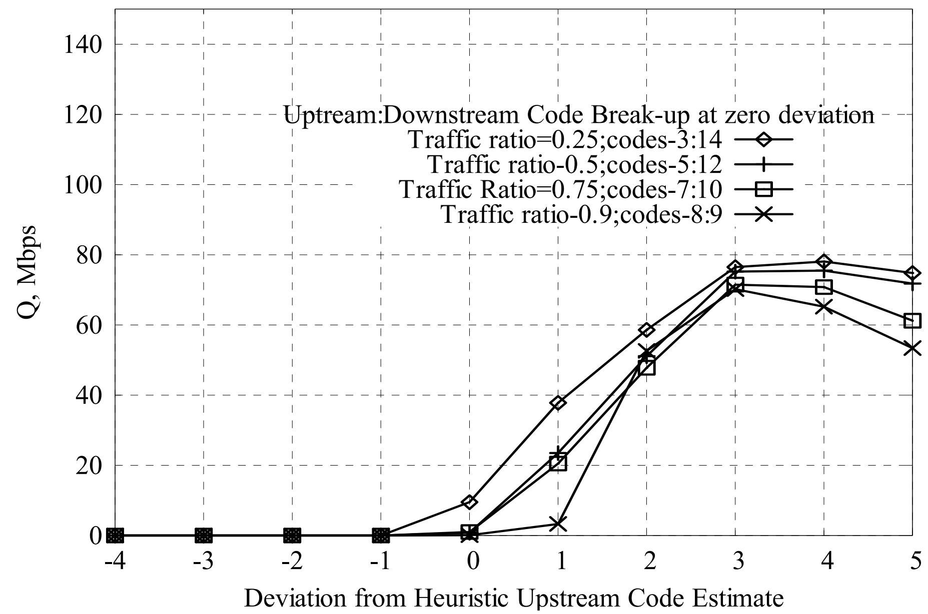
Upstream throughput versus Δ; OOC = (341,5,1); Users = 17; Packet size = 1500B

Numerical Results

Upstream data rate throughput (2.4 Gbps symmetric)



User- total throughput product *Q* versus Δ; OOC = (364,4,1); Users = 30; Packet size = 75B



User- total throughput product *Q* versus Δ; OOC = (341,5,1); 17 users; Packet size = 1500B

Conclusions

Resource provisioning aspects of a W-OCDM PON using Heuristic optical code allocation approach

- **Hybrid WDM PONs offer resource provisioning with finer granularity in bandwidth utilization**
- **Bidirectional traffic performance in a code-cluster is affected both by MUI and code contention, depending upon the traffic ratio in a PON**
- **Medium to high β PONs are capable of network expansion through the use of contention avoidance schemes**
- **For a given OOC, a trade-off exists between data packet length and user-cluster size due to MUI constraint**
- **Low β PONs benefit from over-provisioning by improving per-ONU data rate**
- **Medium to high β (>0.5) PONs support n/w scaling under a contention avoidance scheme provided packets are short**
- **OOCs with high n/w ratio are crucial for MUI-constrained PONs albeit with a trade-off between system throughput and per-ONU data rate**

Final Remarks

- FTTP technology created an unchallenged niche in telecom access segment through passive, point-to-multipoint PON technology

- WDM in combination with TDM and OCDM can be significantly improve the scalability and provisioning aspects of PONs

- NexGen PONs are expected to deliver: new and legacy services, both analog and digital in a single converged conduit

- NGPONs should gear up for serving as mobile backhaul networks with high accuracy of the clock timing for mobile services

- Burst-mode transceivers, Colorless ONUs hold the key to massive deployment of NGPONs

- Scheduling policies accounting for traffic and multi-service characterization can deliver bandwidth efficient and fair bidirectional transmissions

- A synergy between fiber –based PONs and advanced wireless technologies alone assures future-proof access network infrastructure

- FTTP being a “GREEN“ technology (low energy with lifetime emissions reduced by 50%) is bound to receive attractive incentives from many nations world over

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Thank You!