Optical Burst Switching

A tutorial from E-photon/ONe

The VD1 OBS taskforce
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- Burst switch architectures
- Evolution of existing backbones to OBS - Routing
- Performance evaluation of contention resolution schemes
- Traffic models

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- Analytical techniques for OBS
- OBS testbeds
- Resilience

Introduction to OBS

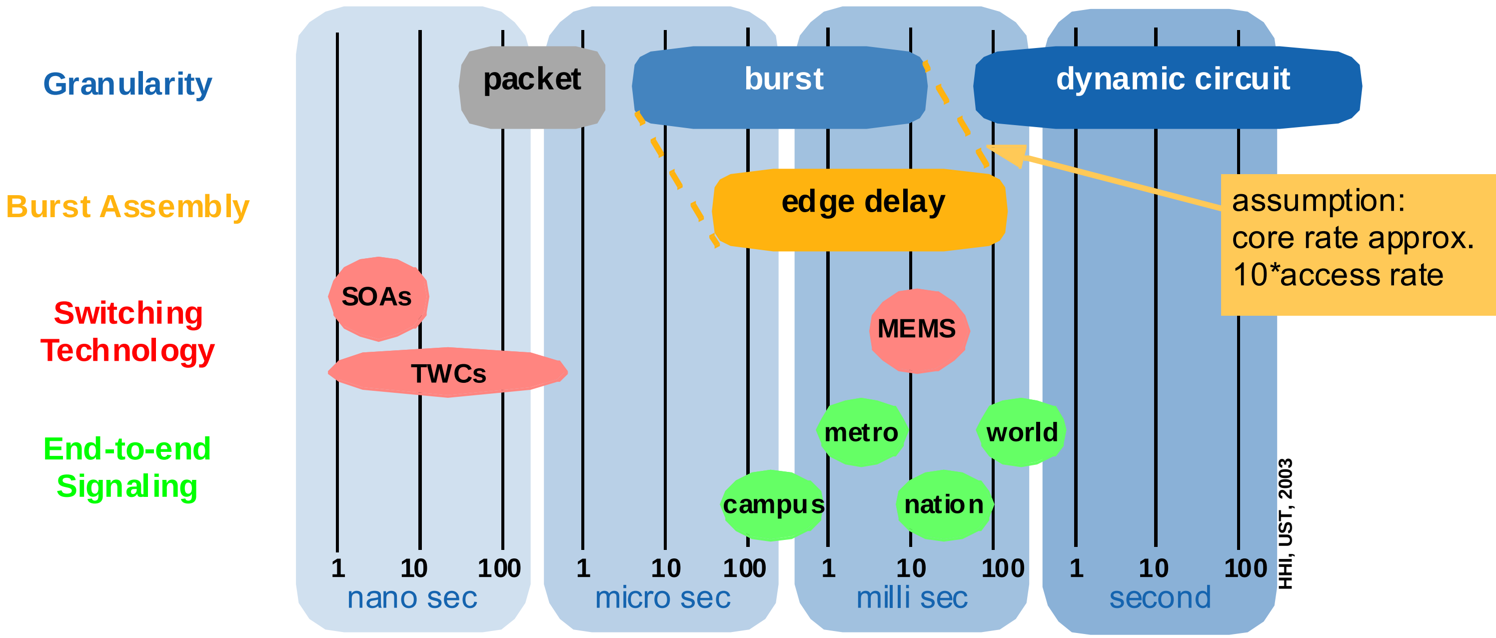
Motivations

- Changes in traffic profile
  - P2P file downloading vs. multimedia streaming
  - grid networking
- Wavelength-Switched Networks
  - low network utilization and flexibility
- Problems in Optical Packet-Switched Networks
  - lack of optical buffering
  - need for fast packet switching and header processing

OBS approach

- Main design objectives
  - decreasing complexity of OPS with still employed statistical multiplexing in optical domain
  - building a buffer-less network
  - user data travels transparently as an optical signal and cuts through the switches at very high rates
- Solution
  - sending a header in order to temporary reserve a wavelength path
  - after that, sending an optical burst (a block of IP packets) through the network
- Thanks to the great variability in the duration of bursts, the OBS can be view as lying between OPS (one-way reservation) and WS networks (two-way reservation)

OBS Timing Overview



- Granularity determines switching technology and vice versa
  → switching time << mean burst duration
- Tell-and-Wait: Granularity determines end-to-end signaling distance
  →end-to-end propagation < mean burst duration
- Access rate (assembly delay) determines granularity

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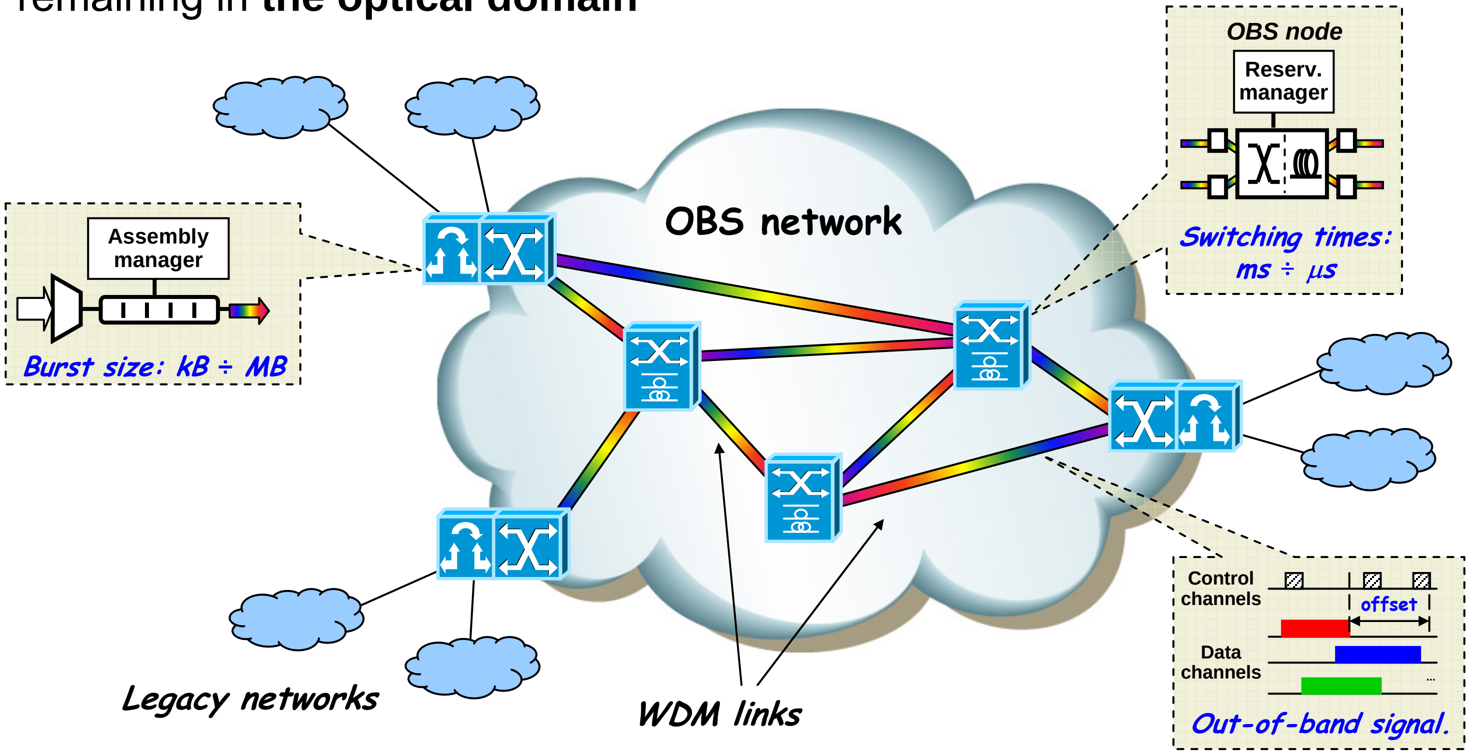
OBS network

- Control and data information travel **separately** on different channels
- Data coming from legacy networks are aggregated into **a burst unit** in edge node
- **The control packet** is sent first in order to reserve the resources in intermediate nodes
- The burst follows the control packet with some **offset time**, and it crosses the nodes remaining in **the optical domain**



OBS principles

- Variable-length packets, named bursts
- Asynchronous node operation
- A strong separation between the control and data planes
  - Control burst (with control information) transmitted on dedicated control channel and processed electronically
  - Data burst transmitted and switched all-optical way

Burst Signaling Protocols

- **Burst transmission is preceded by a setup message to reserve resources**
- **Signaling packets undergo E/O conversion at every hop while burst data travel transparently**
- **Two different types of protocols**
  - Tell-and-Wait (TAW): two-way reservation schemes
  - Tell-and-Go (TAG): one-way reservation schemes

TAW-two way reservation schemes

- **The data bursts is transmitted after an end-to-end connections is established**
  - SETUP is send to hard reserve resources
  - ACK packet acknowledges the reservation
  - In case of failure – setup phase can be repeated
- **Main drawbacks: Long round trip time**
- **Solutions:**
  - burst size estimation -> earlier transmission of SETUP
  - “timed” and “in advance” mechanism ->

    increase burst acceptance probability

    decrease the number of setup retransmissions

TAG-one way reservation schemes

- **Signaling messages travel ahead of the data-burst**
- **Burst is transmitted after a time offset that prevents a burst from entering the switch before the configuration is finished**
- **Classification of TAG Variants determined by the start/release policy:**
  - Start of Reservation:
    - Immediate-explicit: reservation starts immediately after the reception of the SETUP.
    - Delayed-implicit: reservation start by the beginning of the data
  - Release mechanism (tearing down)
    - Implicit: based on burst length information.
    - Explicit: use a release control packet.
- **Implicit (start/release) has two options for getting the information about the bust length based on :**
    - the SETUP packet or
    - the arriving burst itself.

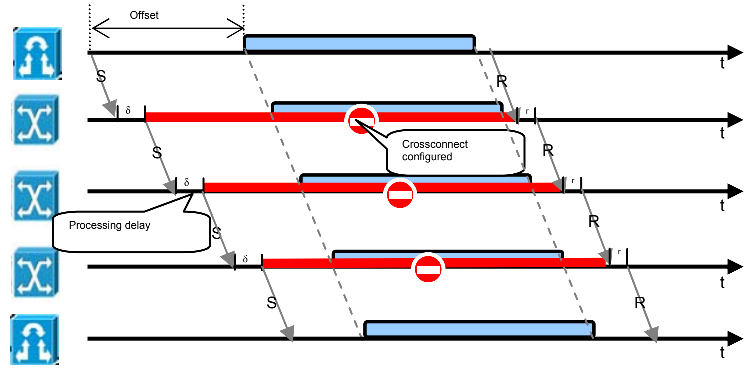
State-of-art in OBS signaling

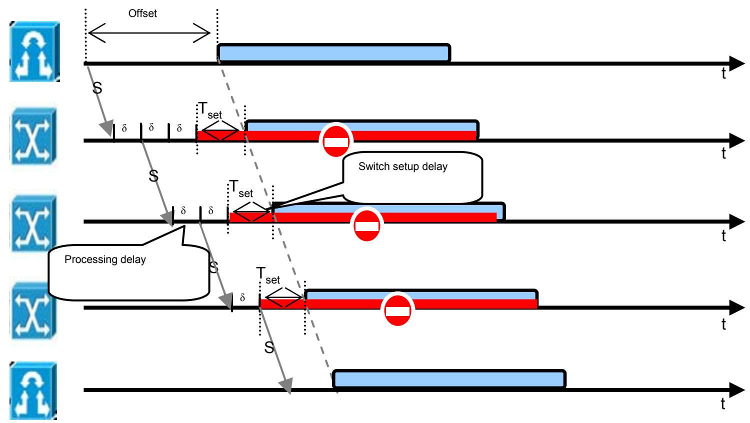
- JIT protocol :

  explicit setup and explicit or implicit release

- Horizon and JET protocols

  employ estimated setup and estimated release
  - Horizon doesn't support void filling
  - JET supports void filling





Edge Node

- Consist of electronic router and OBS interface
- Functions
  - Electronic data buffering and processing
  - Burst Aggregation (BA), responsible for collecting data from legacy networks and building the burst unit
    - impact on the overall network operation by the control of the burst characteristics
    - in order to reduce the burst loss probabilities in the network the aggregation function can segmentate data bursts for the purpose of their partially dropping in core nodes when contention occures
  - Setting up the pre-transmission offset time
    - in simple fixed offset scheme, the offset time is calculated as a sum of the total processing time at all the intermediate hops
    - offset time is one of the crucial OBS network parameter, since his incorrect estimation has impact on data lost
  - Sending the control packet
  - Sending the burst

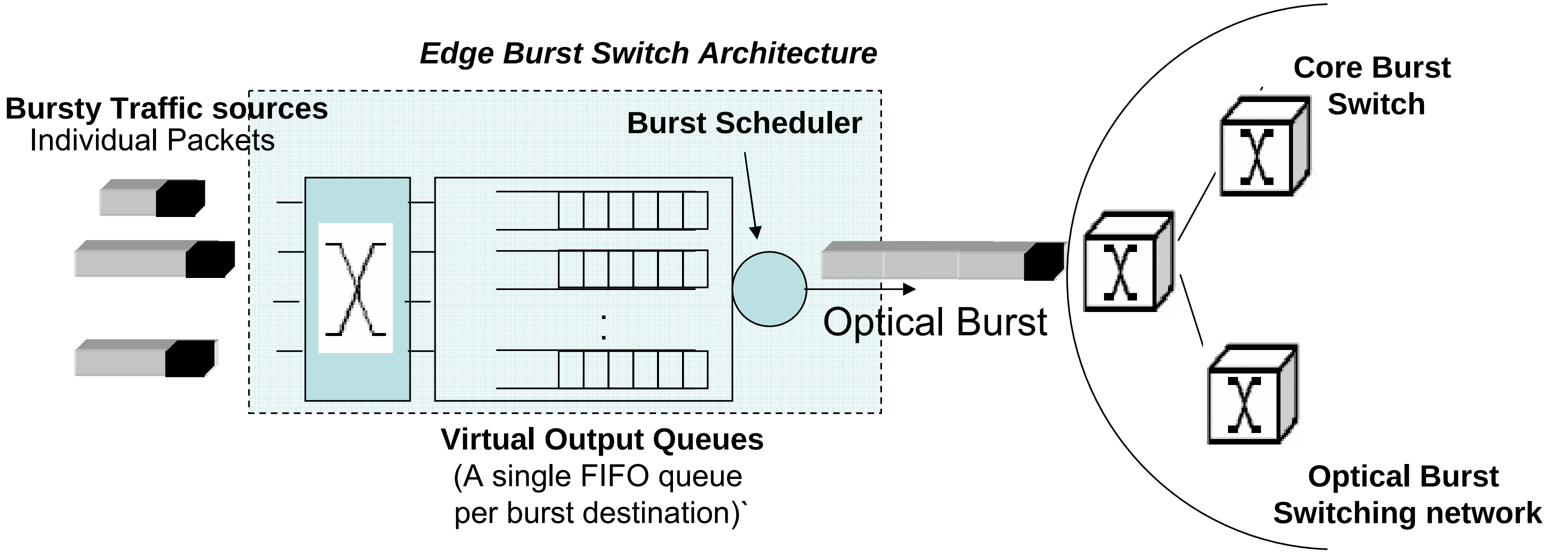
Core Node

- Hardware requirements
  - O/E/O conversion for header processing
  - λ-conversion
  - switching speeds fast enough
  - eventually optical buffering (FDLs)
- Operation
  - Processing of incoming control packets (electronically) and sending it to the next node that lays on the routing path
  - Reservation of optical resources for transferring the burst
    - Just-In-Time (JIT)
    - Horizon Reservation Mechanism (HRM)
    - Just-Enough-Time (JET) – the most efficient but of high complexity
  - Fast optical switching with wavelength conversion and optical buffering (when available and necessary)
  - Dealing with contention resolution (by a proper scheduling algorithm)

Burst switch architectures

Edge Burst Switch Architectures

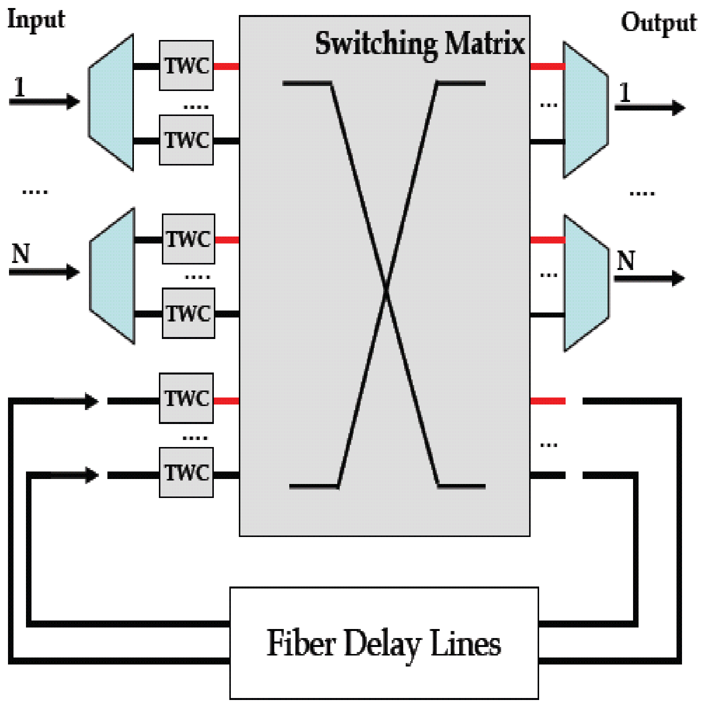
Architecture of a typical OBS ingress node



- **Burst assembly algorithms can be classified as**
  - Timer-based, where the burst is sent out after a Time-out signals expires.
  - Burst-length-based where the burst is sent out when it reaches a certain size
  - Mixed timer / burst-length-based ones, where burst transmission time is constrained on both Time-out and Burst size criteria.

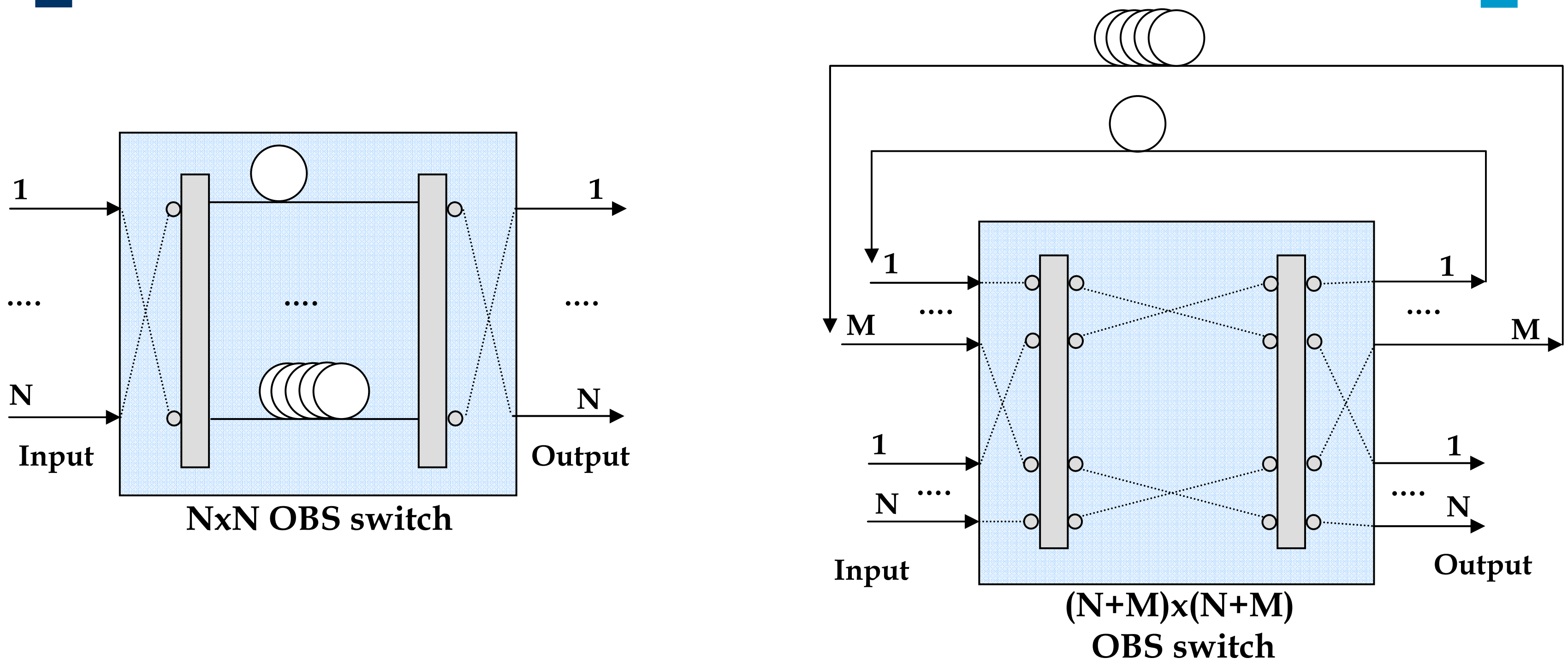
Core Burst Switch Architectures

- Different nodes design: according to contention resolution mechanism
  - time domain: using Fiber-Delay-Lines (Feed-forward and/or Feedback)
  - wavelength domain via wavelength conversion
  - space domain via deflection to another fiber output



Example of OBS node using feedback FDLs and tunable wavelength converters.

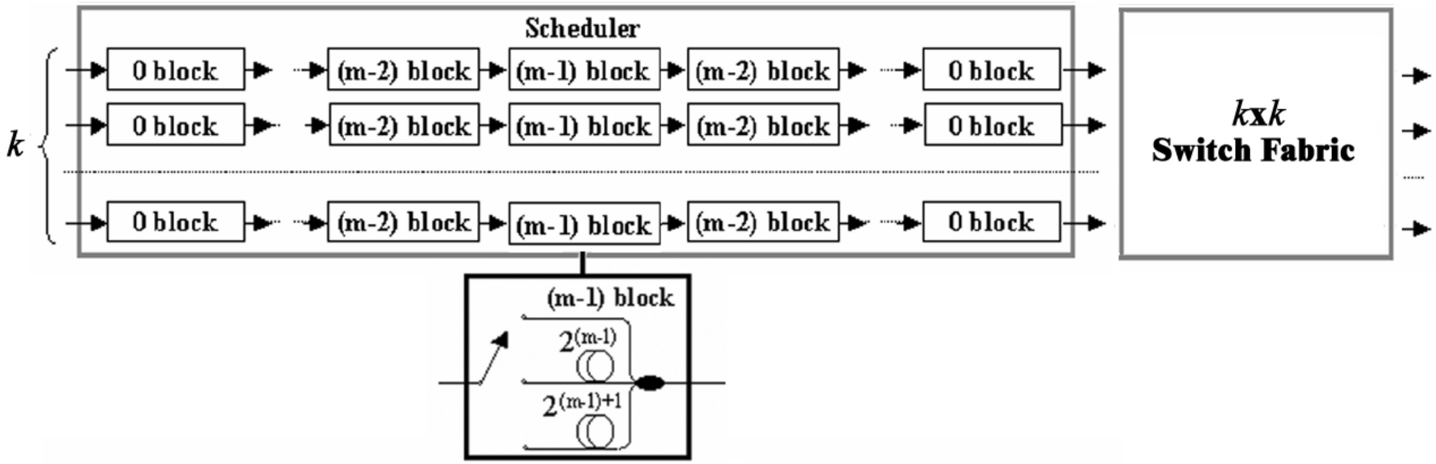
FDL Architectures



- In the feed-forward method, bursts are fed into fiber delay lines of different lengths and when they come out, they have to be switched out.
- In the feedback scheme, a burst may re-circulate as long as there is a bandwidth shortage at the output ports.

Implementation example of a feed forward FDLs Burst Switch architecture

The Burst Scheduler Architecture



Concept: Use a branch of delays per input port to scheduler packets/burst to resolve contention at the switch fabric input. Each delay branch consist of $2m$-1 delay blocks, where $m = logT$. (For convenience T is a power of m).

The *i*th block consists of a three-state (or two 2x2) optical switch and three fiber delay paths, corresponding to delays equal to 0, 2^i and 2^{i+1} slots.

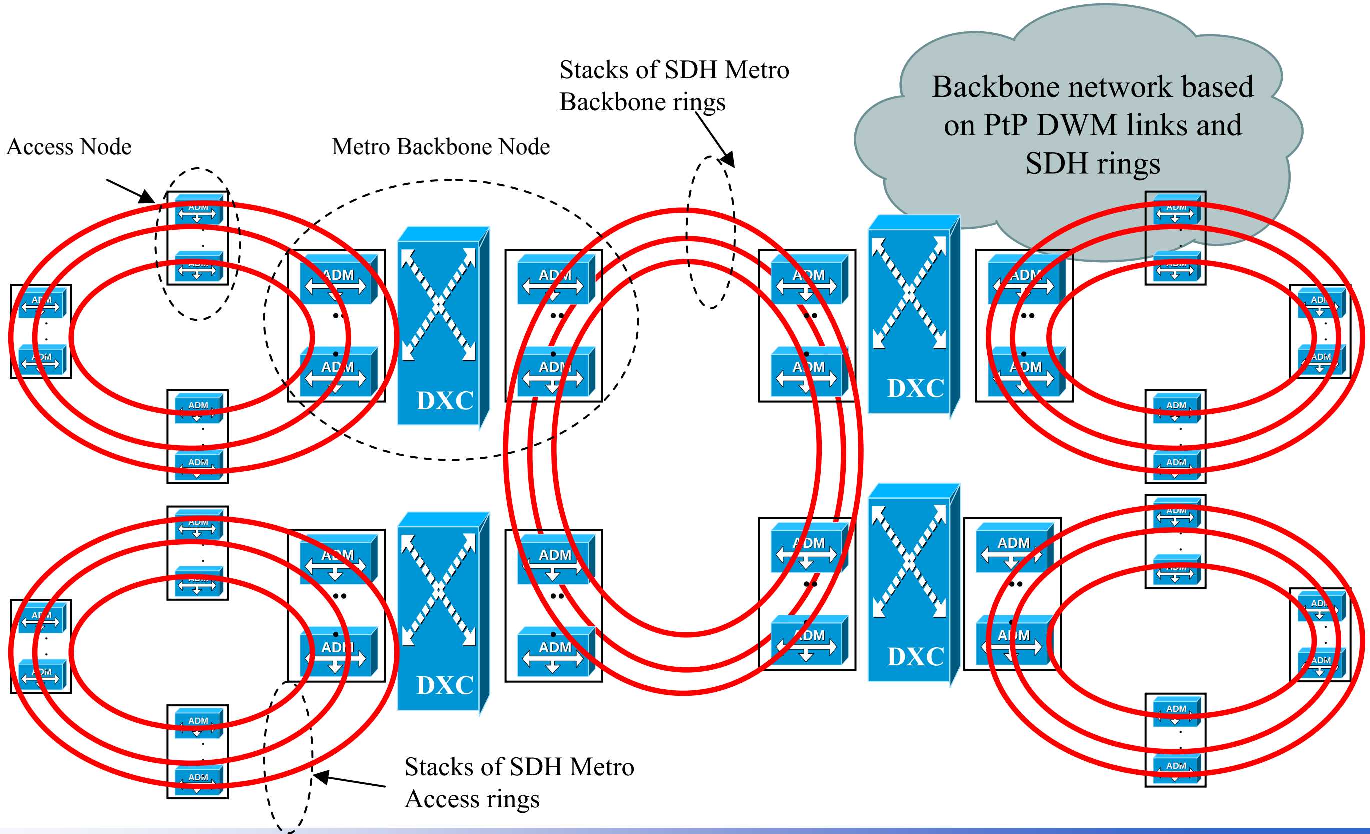
OBS tutorial

Evolution of existing backbones to OBS
Routing in OBS

Network Topology:
Previous steps before OBS deployment

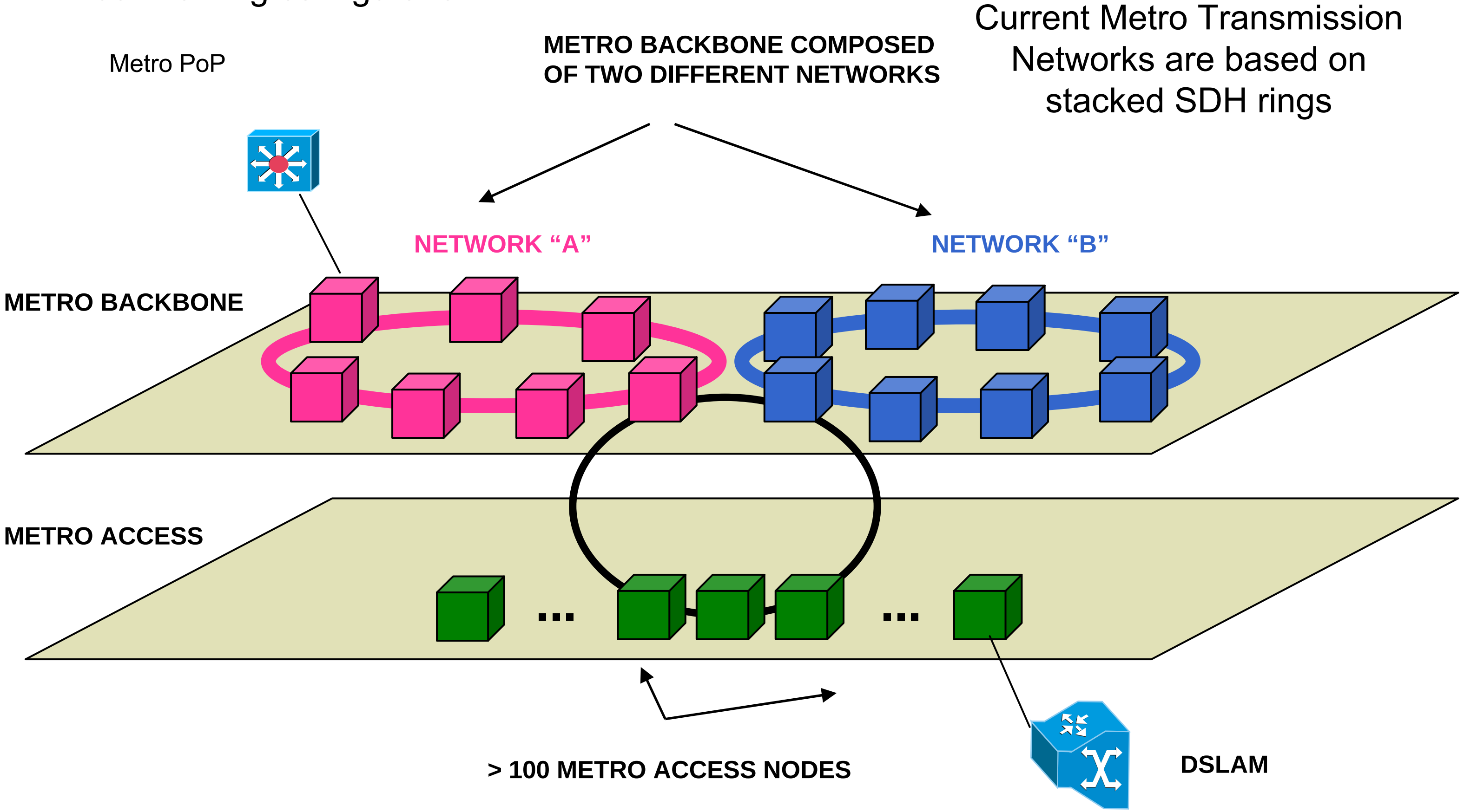
Scenario 0: Opaque network

- Layer 1 networks are mainly based on SDH technology
- Ethernet is replacing ATM as main Layer 2 technology



Network Topology: Previous steps before OBS deployment

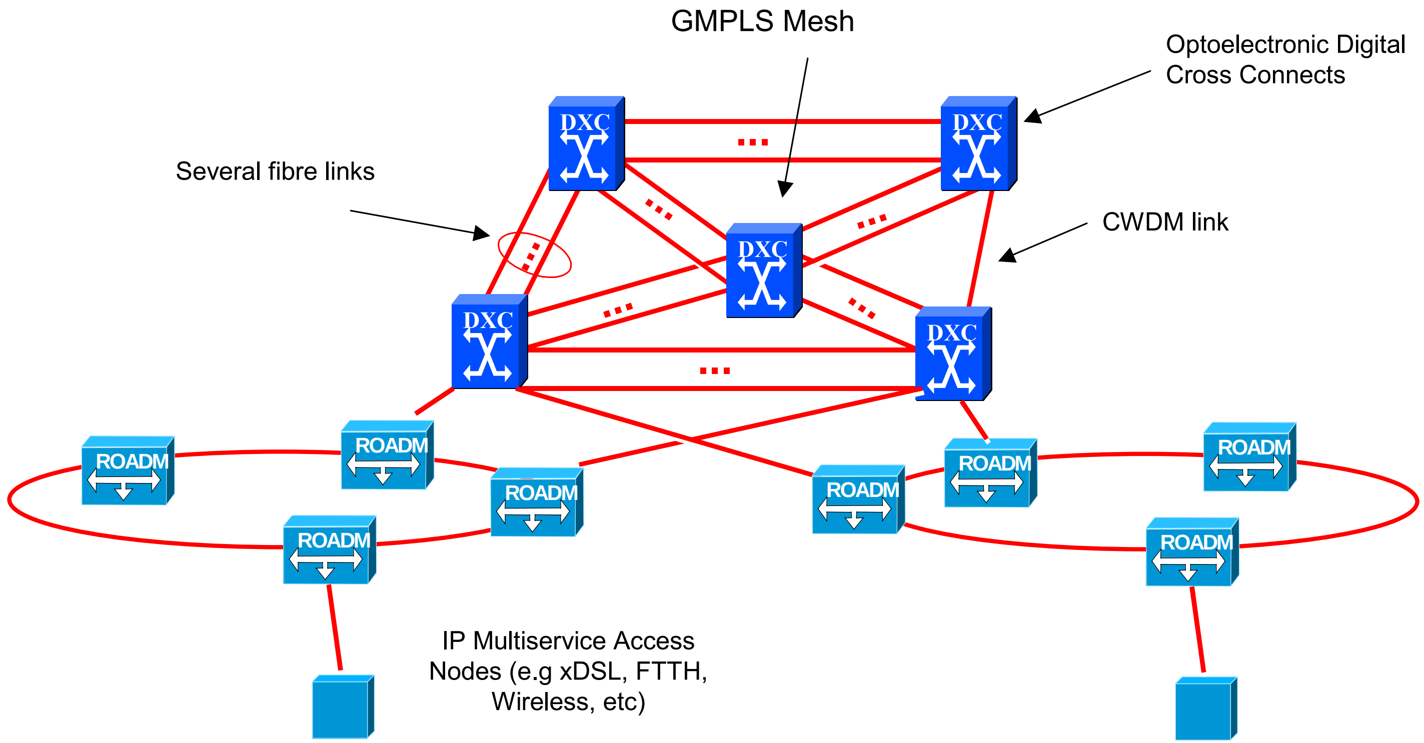
- **Scenario 0: Opaque network**
  - Dual Homing configuration



Network Topology:
Previous steps before OBS deployment

Scenario 1: Hybrid Network

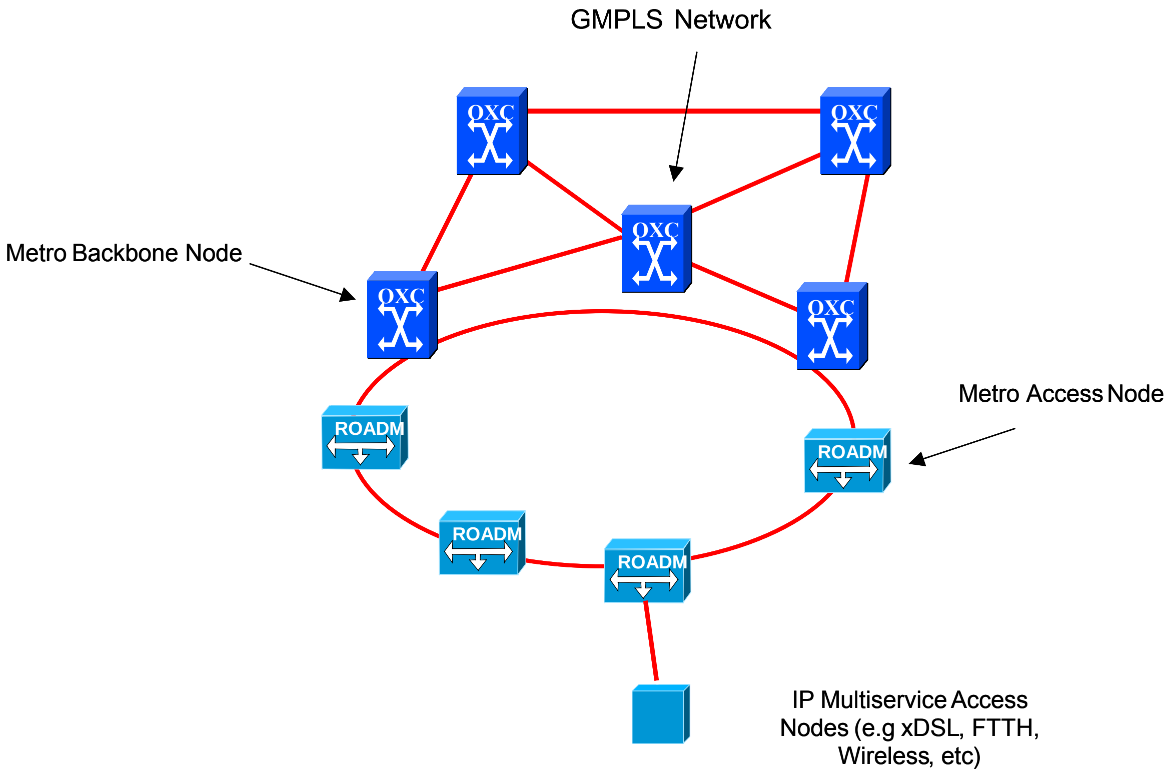
- Core and metro backbone networks are based on a GMPLS mesh composed of OEO DXCs
- Metro Access rings are based on DWDM rings composed of ROADMs



Network Topology:
Previous steps before OBS deployment

■Scenario 2: WS Network

- ■Evolution towards an all optical Layer 1 network composed of OXC and ROADMs with GMPLS capabilities



Network Topology: First OBS deployments

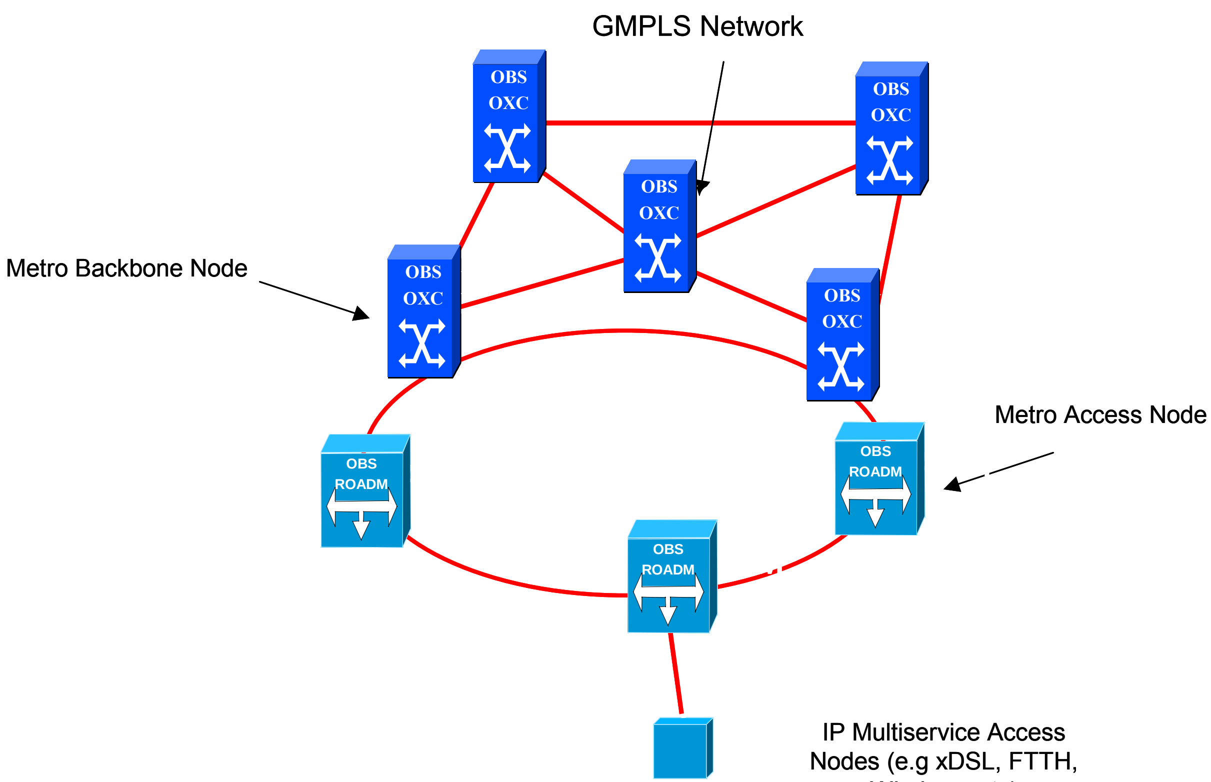
- **OBS networks are expected to be deployed in long term scenarios with dramatically increased traffic demands and higher flexibility and granularity requirements**
- **A natural, simple and low cost evolution from WS to OBS scenarios may be achieved by gradually updating the ROADMs and OXCs previously used in the WS scenario in order to support optical burst transmission.**
- **Therefore, in a first step, OBS networks may have similar topologies than WS (i.e metro access rings and core meshes).**

Network Topology: Previous steps before OBS deployment

- **OBS network topologies will be strongly affected by the previous network evolution**
- **Currently, European transmission networks are mainly based on traditional SDH topologies (i.e SDH rings interconnected by DXCs).**
- **The appearance of GMPLS is favoring the migration from static SDH ring architectures with protection mechanisms towards more flexible SDH meshed backbone network architectures including GMPLS restoration**
- **In the short term, SDH technology is expected to be gradually migrated to Wavelength Switching (WS) due to the following drivers:**
  - **Technological availability (appearance of the first ROADMs and OXCs)**
  - **CAPEX and OPEX reduction, mainly due to automation and transparency, and increase of revenue coming from new services (Optical VPNs)**
- **A feasible trend could be the evolution towards metro aggregation rings based on ROADMs and connected through a core mesh composed by OXCs with full GMPLS support.**

Network Topology: First OBS deployments

- **Scenario 3: Optical Burst Switching (OBS) network**
  - –Optical equipment is updated in order to support optical burst transmission



Routing: OBS features

- Some OBS features need to be taken into account in the routing strategy:
  - Calculation of the optimal value of the offset time (time between the arrival of the control packet and the arrival of the burst)
  - Contention in nodes. Buffering is still very limited.
- Goals of routing in OBS
  - Reduce contention in nodes
  - Improve performance

Source routing

- Where is routing performed?
  - Source and hop-by-hop routing
- Source Routing
  - The routing decision is performed in the ingress router. The path is not changed in the intermediate nodes.
  - The control packet contains the information of all the hops of the path
  - The optimal value of the offset time can be calculated accurately, because the number of hops is known
  - In order to consider network state, flooding the network with congestion information is needed
  - Traffic engineering techniques can be used (GMPLS approach)

Hop-by-hop Routing

- Hop-by-hop routing
  - Routing decision in performed in every node
  - The whole path and the number of hops is unknown
  - The value of the offset time must be estimated (the number of hops is not known).
  - Possibility to use routing algorithms of IP networks
    - Need to adapt metrics to OBS
  - It is possible to use local congestion information (there is no need to flood the network)

Contention Resolution

Performance evaluation of contention resolution schemes

Contention resolution

- Burst loss possible due to statistical multiplexing
- Application of OBS in high-speed metro/core networks
  - lost data has to be retransmitted on end-to-end basis (e.g. TCP)
  - very low burst loss probability required

  → need for highly effective contention resolution

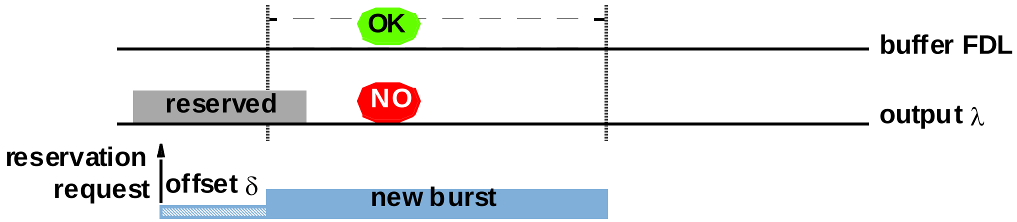
Domains of contention resolution

- Wavelength domain — wavelength conversion
  - very effective as all WDM channels shared among all bursts
  - but: low burst loss probabilities only for many λs

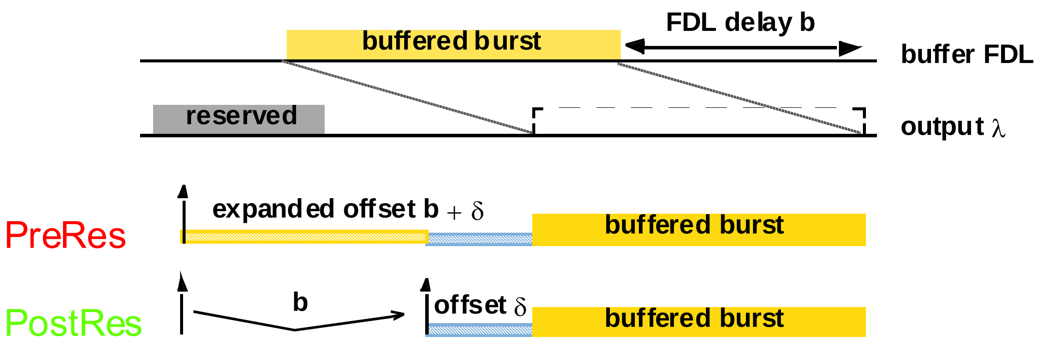
  → additional schemes necessary, combinations beneficial
- Time domain — fiber delay lines (FDLs)
- Space domain — deflection/alternative routing
- Segmentation — only conflicting part of burst dropped

Contention resolution

- **Use of FDL buffer in case of blocked output wavelength**



- **Reservation of buffer FDL and output wavelength**
  – PreRes: early reservation of output together with buffer, no reloop
  – PostRes: reservation of output only after buffering time b



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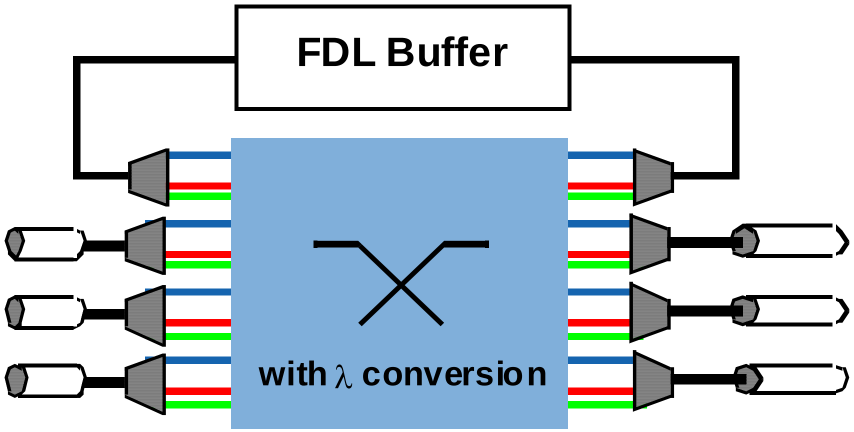
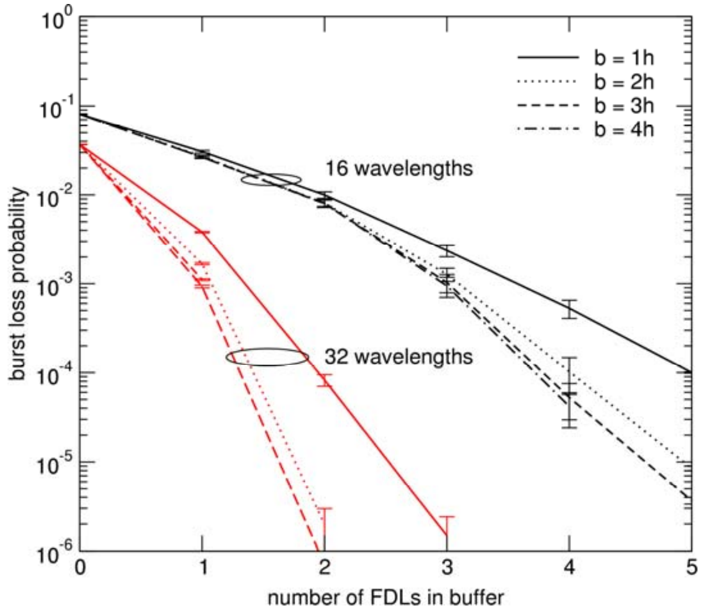
FDL buffer dimensioning

Shared FDL buffer, PreRes

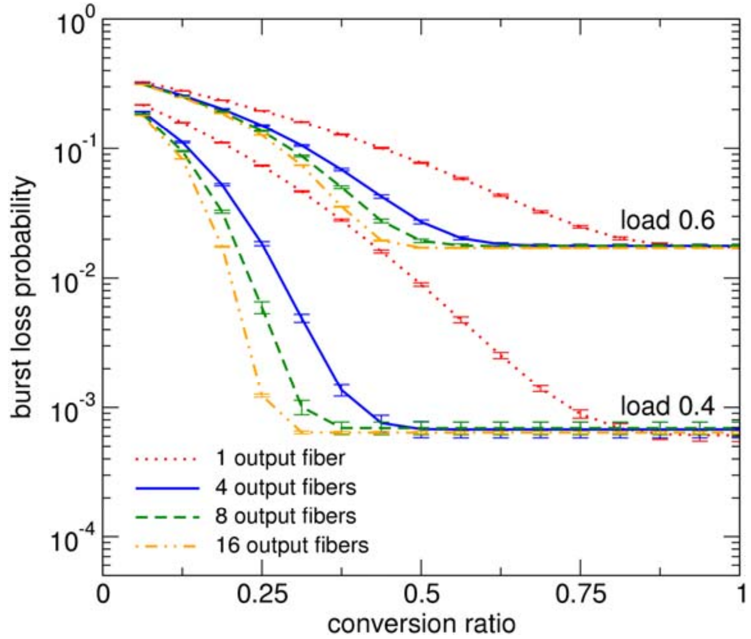
- **Delay of FDL 1: b**
- **Delay of FDL *i*: i*b**





- Combination of FDL and converters: Conv first
- Delay b of FDL 1 should be a few mean burst lengths h
- Increasing FDL count improves performance
- Lower load or more wavelengths per output make FDL more efficient

Case Study: Shared Conv Pool



- Share-per-node converter pool
- M = 16 wavelengths per fiber
- N output fibers
- C converters
- Conversion ratio = C / (M*N)

- Significant converter savings possible
  - → For realistic load values up to 50-75% savings possible
- N=1 is case of share-per-output pool

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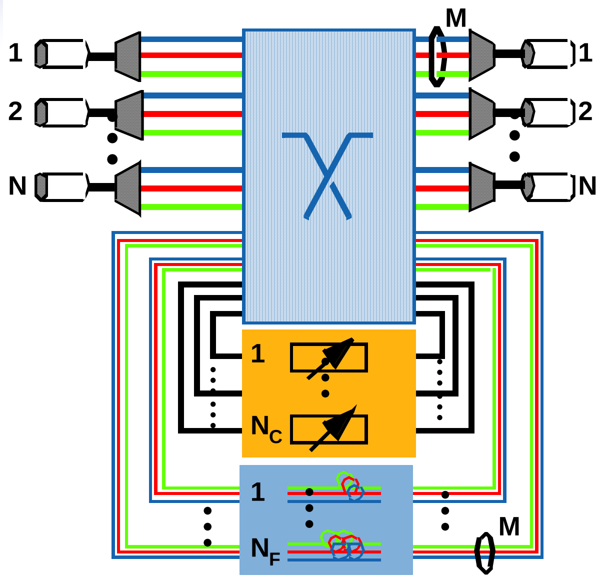
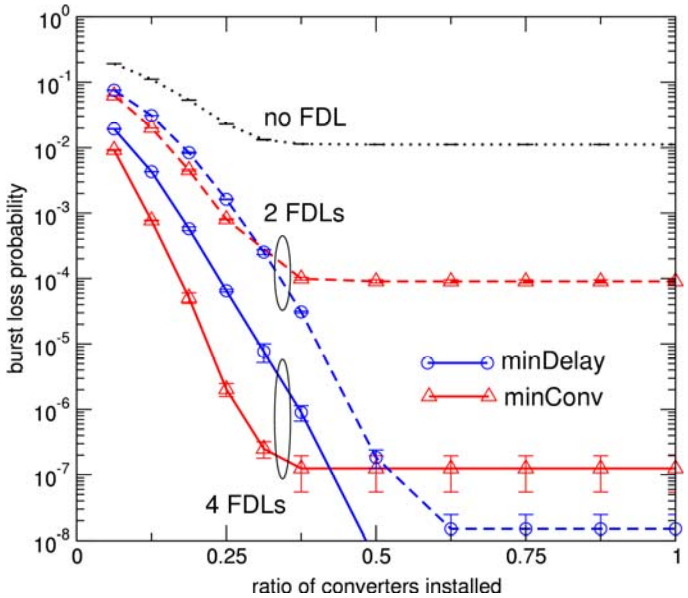
Case study: Optimized CR





- Share-per-node
- M = 8 wavelengths
- N = 8 output fibers
- N_C tun. converters
- N_F FDLs
- $r_C=N_C/(MN)$

- Combination of FDL buffers and shared converter pools
- Strategy for selecting resources has significant impact
  - Red: strategy that minimizes converters (minConv)
  - Blue: strategy that minimizes FDL usage (minDelay)

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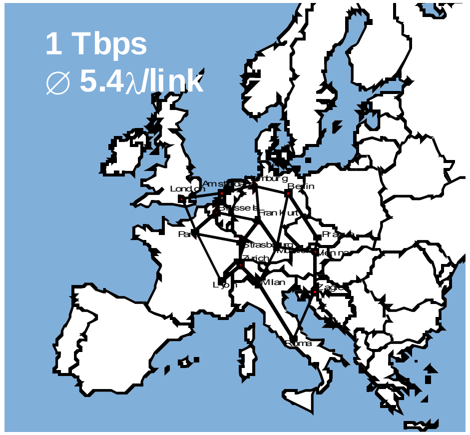
Case study: CR in networks



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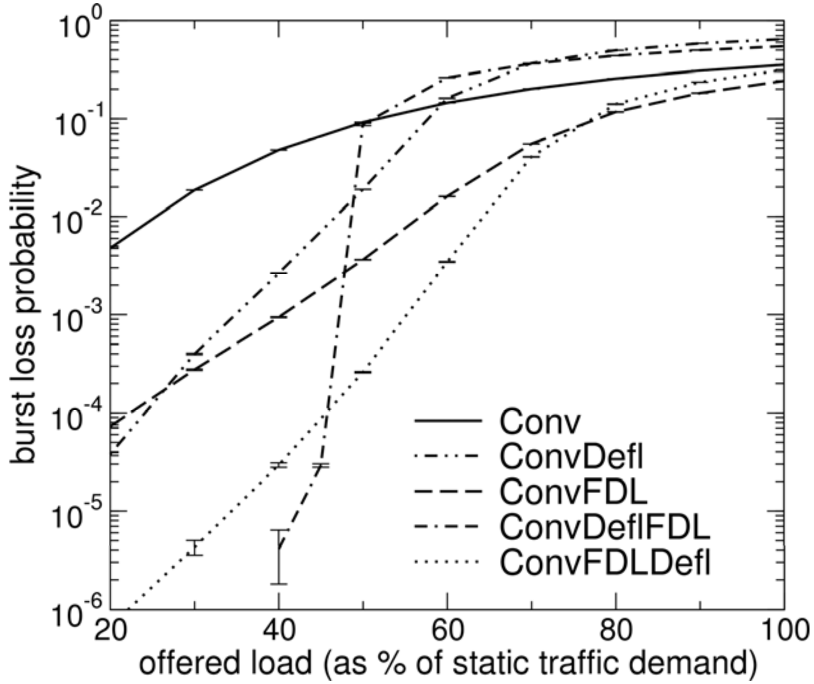


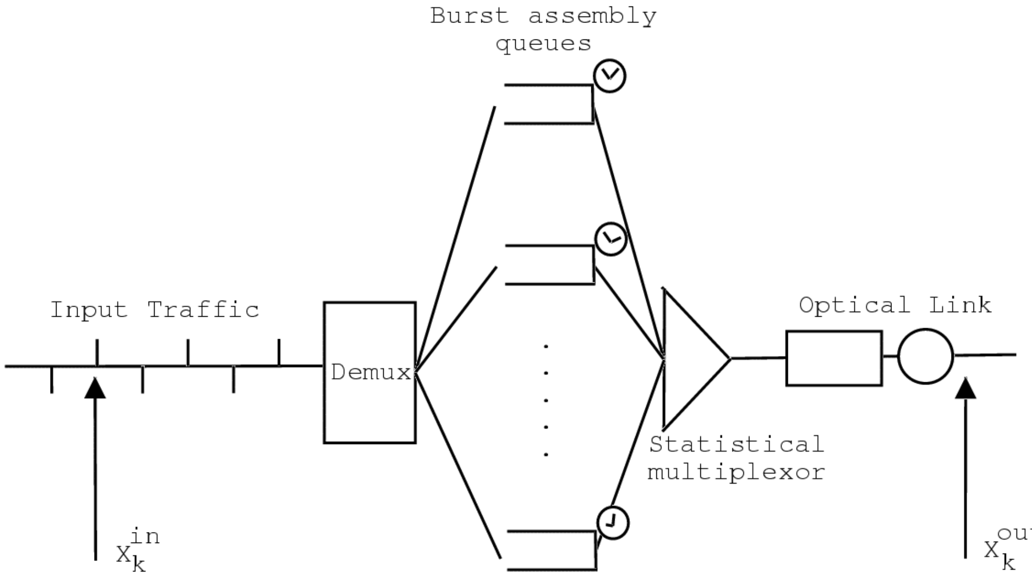
- Combinations of conversion (Conv), FDL buffer (FDL) and, deflection routing (Defl)
- Clear improvements for combined schemes

Traffic models

Traffic models for OBS

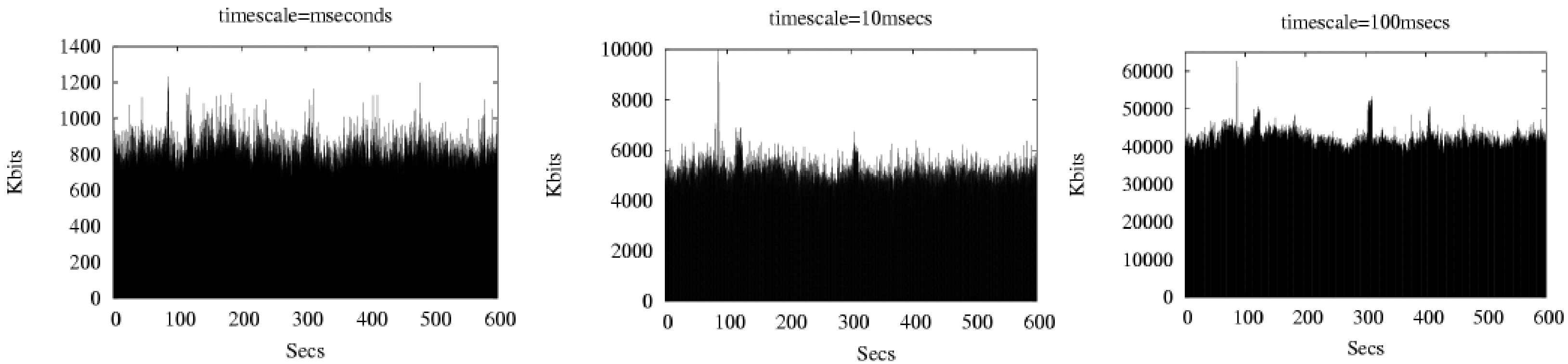
- The generated OBS traffic depends on
  - Burstification algorithm
  - Input traffic features:
    - Long-range dependence
    - Instantaneous burstiness
- No single traffic model can portray all possible scenarios!

Bustification algorithms



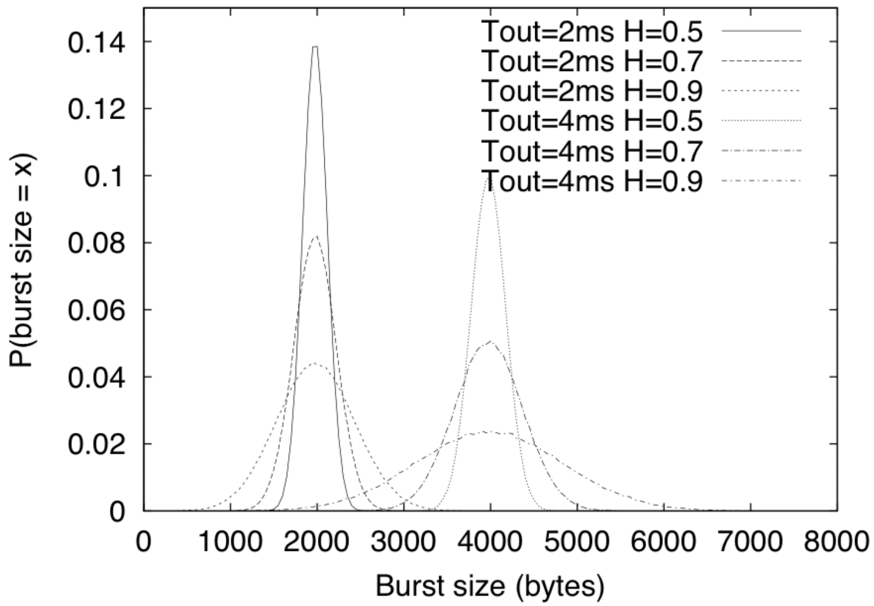
- Time-based, burst-size based or mixed-time-size based
- In all cases input traffic goes through demultiplex and then burst formation queues

Traffic models



- Long-range dependence happens from a cutoff timescale, beyond which traffic may show independent increments
- For time-based burstifiers only the number of bytes per interval matters
- For burst-size-based burstifiers the packet arrival dynamics matter

Burst size



- For time-based burstifiers: Gaussian (or Gamma)
- For burst-based burstifiers: Constant

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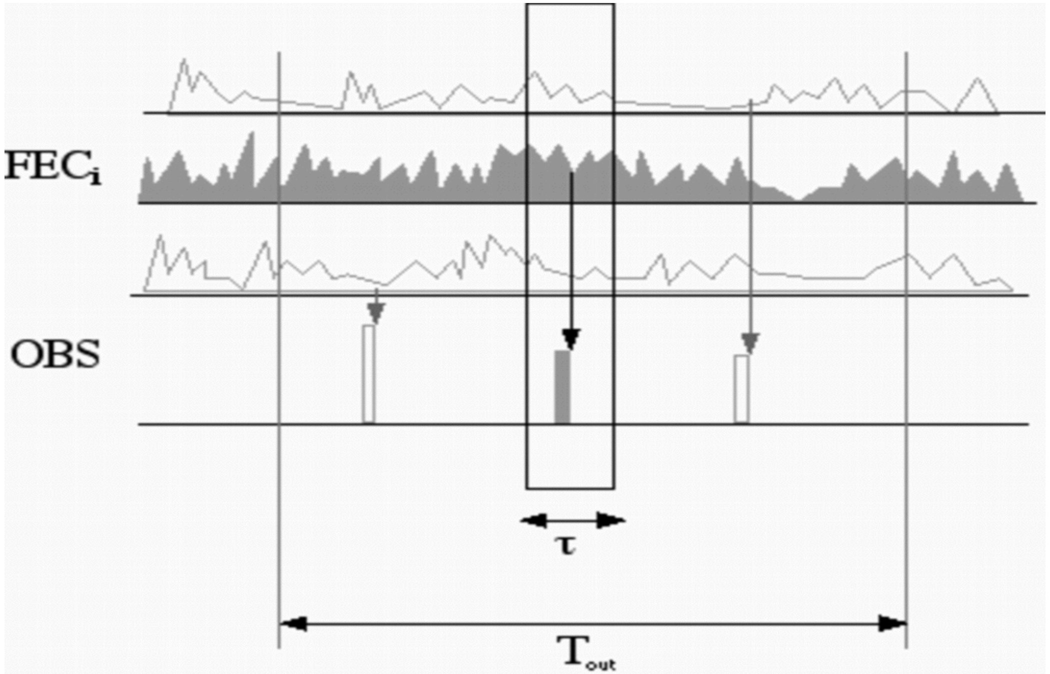
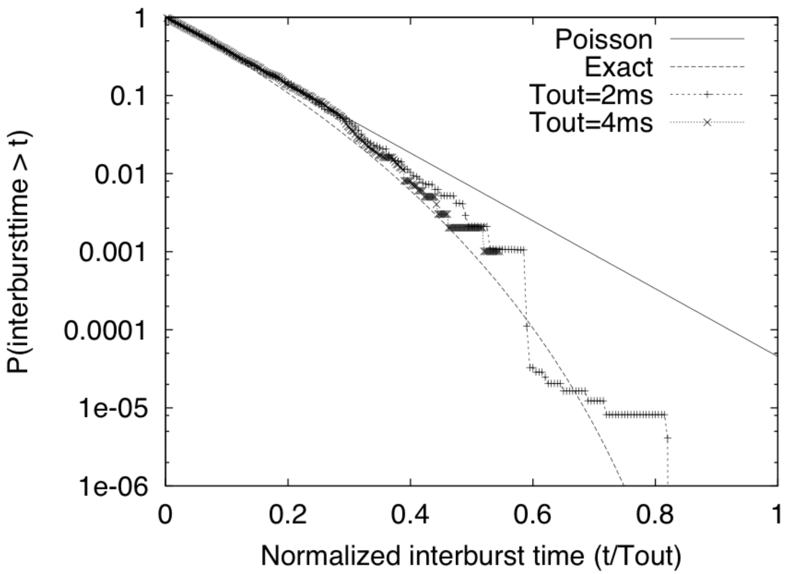
Long-range dependence



- Long-range dependence is inherited at large timescales only but at short timescales the statistical interleaving of bursts produces independent traffic

Burst interarrival time



- If many burstifier queues are statistically multiplexed to the same wavelength: Poisson at the burstifier output!

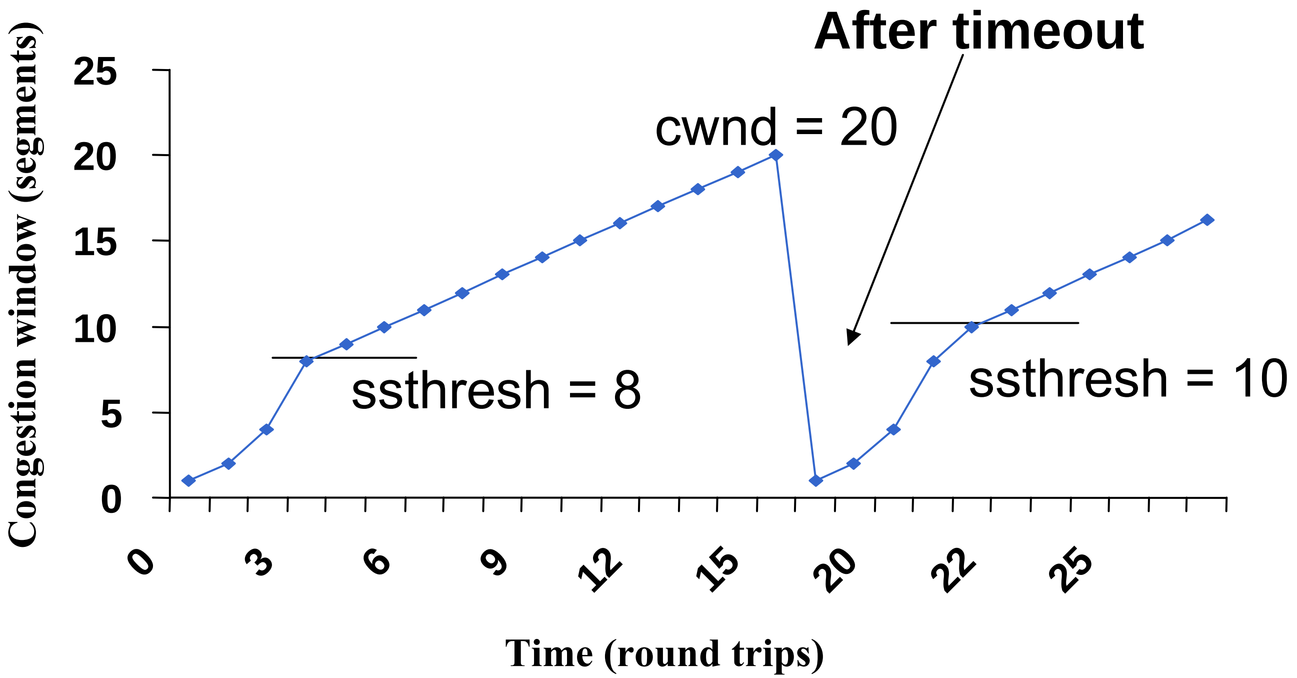
TCP over OBS

Basic TCP control functions

- Flow control
  - – the TCP window size is used to prevent the sender from flooding the receiver
- Congestion control
  - – TCP window is dynamically updated in relation to the network state as perceived by the sender

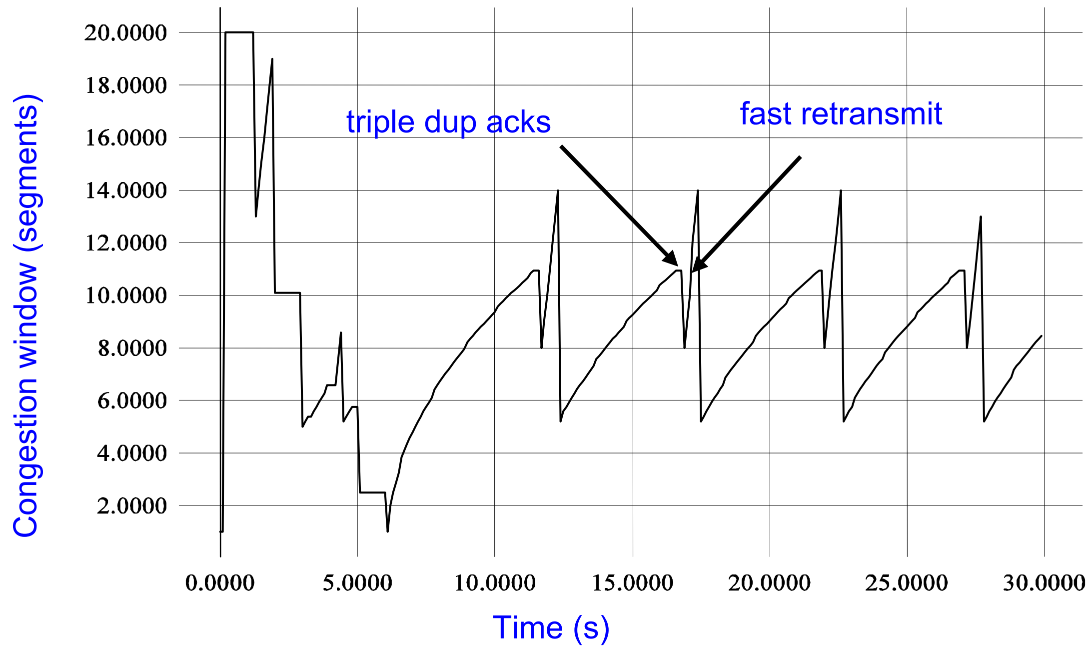
TCP Congestion Control

- Congestion window adaptation
  - Additive increase/multiplicative decrease



TCP loss detection

- Retransmission Time Out (RTO)
- Triple duplicate ACKs (TCP Reno)
  – Fast retransmit/Fast recovery



Impact of OBS network on TCP

- Edge node
  - Assembly algorithms
    - Mixed flow/ per flow
    - Time out, threshold-based
- Core node
  - Scheduling algorithms
  - Contention resolution schemes
    - Wavelength domain
    - Time domain
- Network
  - Routing algorithms
    - Deflection routing
    - QoS routing

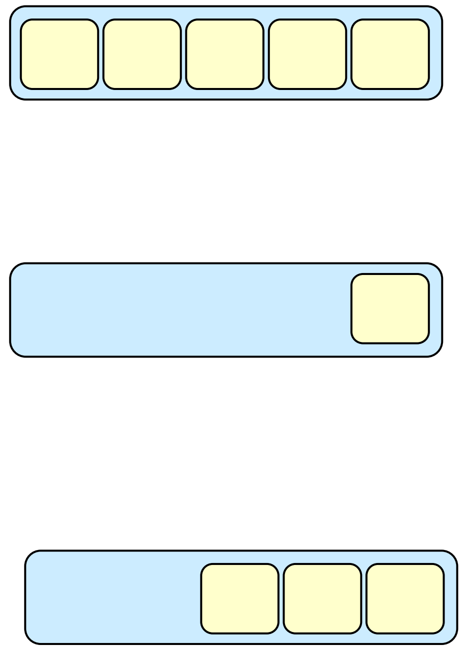
TCP performance
(throughput, fairness)
is influenced
by OBS networks

cr1

Classes of TCP sources

B_a (bit/s) access network rate, L (bit) segment length, W_m (bit) maximum window size, T_b (s) burstification time out

Optical bursts



- Fast source

$$\frac{W_m L}{B_a} \leq T_b$$

  – All segments of the maximum window are emitted in T_b

- Slow sources

$$\frac{L}{B_a} \geq T_b$$

  – At most one segment emitted in T_b

- Medium source

$$\frac{L}{B_a} < T_b < \frac{W_m L}{B_a}$$

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cr1 TCP performance depends on the number of segments collected in a single burst. This in its turn depends on access speed. Iit is convenient to classify sources in relation to speed into three main classes: fast, slow, intermediate.
carla, 7/21/2005

cr2

Burst loss

Burst loss is a consequence of contention in core nodes

- Multiple segment losses
  – Depend on the level of aggregation of segments in a burst
- Retransmission time out is the main indication of loss for fast sources
  – Congestion window shrinks to 1 MSS when a burst is lost
- Slow sources recover mainly by means of fast recovery/fast restransmit

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cr2 TCP performance are mainly determined by reaction of the TCP sources to burst loss. Burst losses are caused by contention in core nodes and cause correlated multiple segment losses in the general intermediate case. As a consequence the main reaction is retransmission time out. On the other hand slow sources recover mainly by means of fast recovery/fast restrasmit because of absence of correlation in segment losses.

carla, 7/21/2005

cr3

Correlation benefit

- Effect related to correlated segment delivery
  - Fast/medium source
- Fast window reopening is due to concentrated acks
- Congestion window quickly reaches its maximum value

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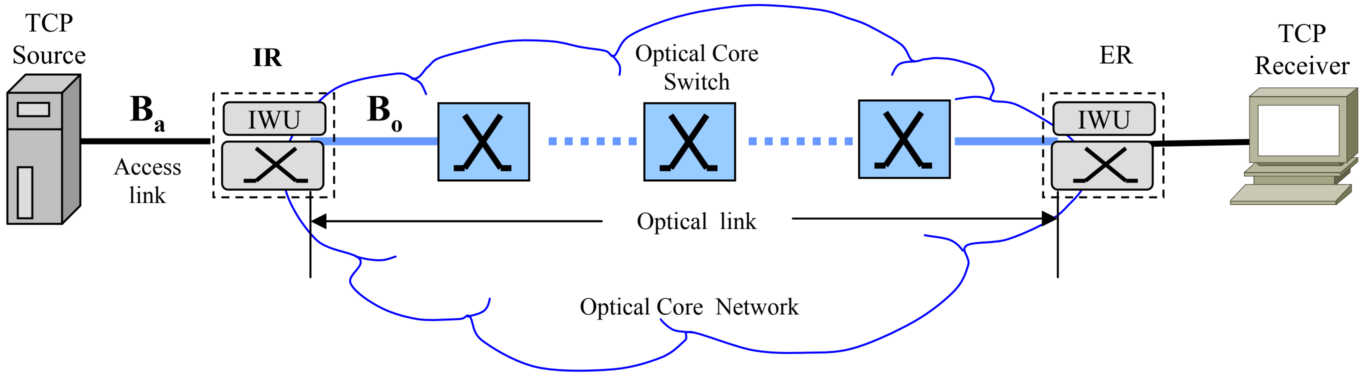
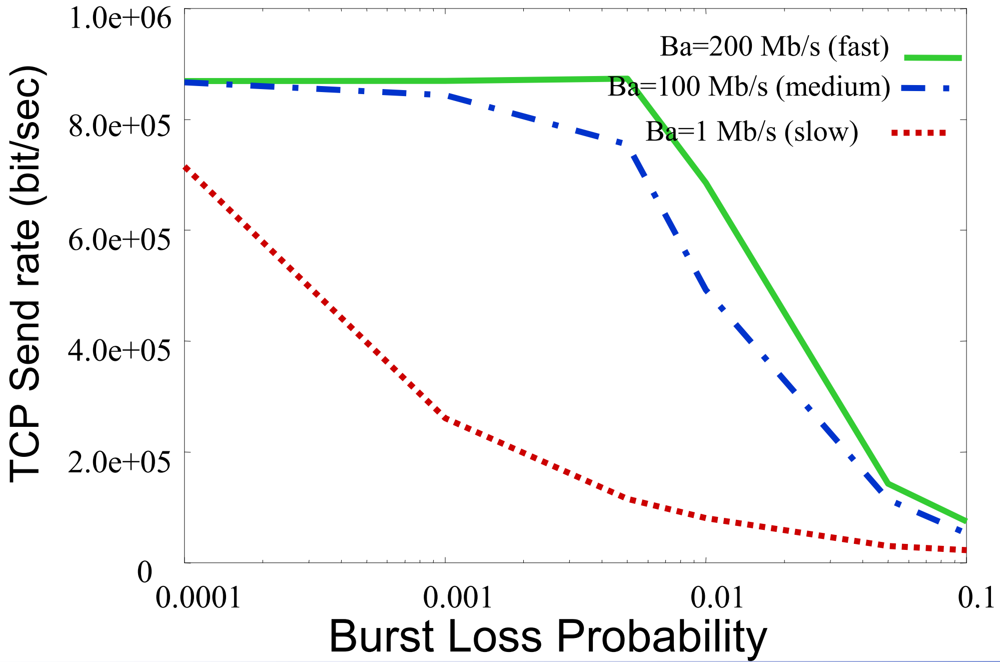
cr3 The correlation benefits arise as a consequence of correlated delivery of the segments in the same burst. This delivery causes fast reopening of the congestion window for fast and intermediate sources

carla, 7/21/2005

TCP send rate for different sources





- B_o = 2.5 Gb/sec
- RTT =600 ms
- Max window size W_{max}=128 MSS
- MSS = 512 bytes
- T_b= 3 ms

More segments are in a burst, the higher the TCP performance

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Variable delay

- Delay due to burst assembly task
  - Edge architecture
  - Algorithm employed (Time out, threshold-based,…)
- Delay due to the presence of FDLs
  - Core architecture
- Delay due to the scheduling algorithm

Modeling TCP throughput

- A simple model is able to calculate throughput as a function of burst loss probability p
  - p is a Bernoulli r.v.
  - Aggregation is accounted through the average number of segment in a burst E[N]
- The average TCP throuhput is calculated starting from the formula

$$B_{TCP} = \frac{E[Y] + E[R]}{E[I] + E[Z^{TO}]}$$

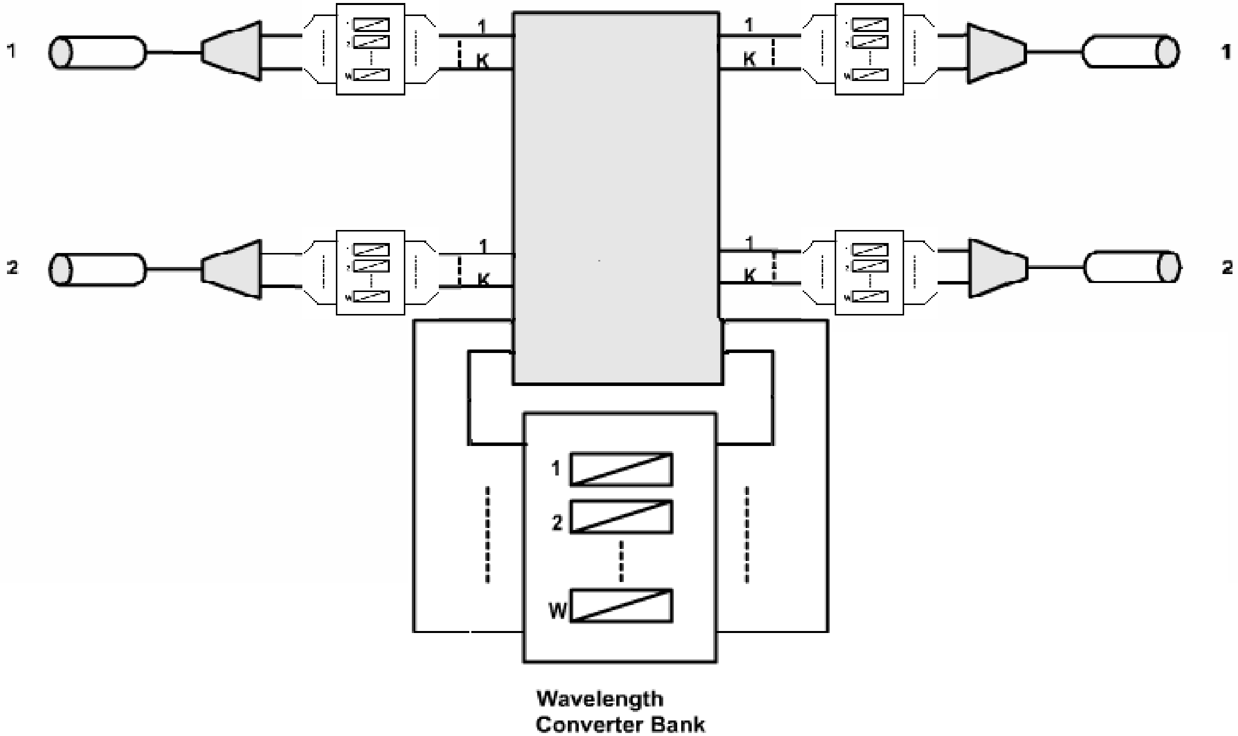
  - where E[Y] is the average number of segments transmitted in bursts during the interval I between two time out periods and E[R] is the average number of segments transmitted during the time out period Z^{TO}
- The result is

$$B_{TCP} = F(p)$$

p is due to losses arising in the network and in the core nodes

Analytical techniques for OBS

OBS Node - Architectures



- Trade-off between burst blocking performance & switching matrix complexity
- Share Per Node (SPN)
- Share Per Input Link (SPIL)
- Share Per Output Link (SPL)

OBS Node Model – SPL

- K wavelength channels per fiber.
- A Wavelength Converter (WC) bank of size $0 < W < K$ per output fiber; (Share Per output Line).
- Burst arrival process is Poisson with rate λ.
- The wavelength channel they arrive on is uniformly distributed on (1,K).
- Burst durations are exponentially distributed with mean $1/\mu$.
- A new burst arriving at the switch on wavelength w and destined to output line k
  - is forwarded to output line k without using a converter if channel w is available, else
  - is forwarded to output line k using one of the free WCs in the converter bank and using one of the free wavelength channels selected at random, else
  - is blocked

OBS Node Analysis

- W = K, Full Wavelength Conversion (FWC)
  - M/M/K/K loss system with offered load $r=\lambda/\mu$
  - Erlang-B loss formula
- W=0, No Wavelength Conversion
  - K independent M/M/1/1 loss systems each with offered load $r=\lambda/\mu K$
- 0 < W < K, Partial Wavelength Conversion (PWC)
  - Can one have an exact analysis?
  - Seek numerically stable and efficient computational schemes

OBS Node Analysis

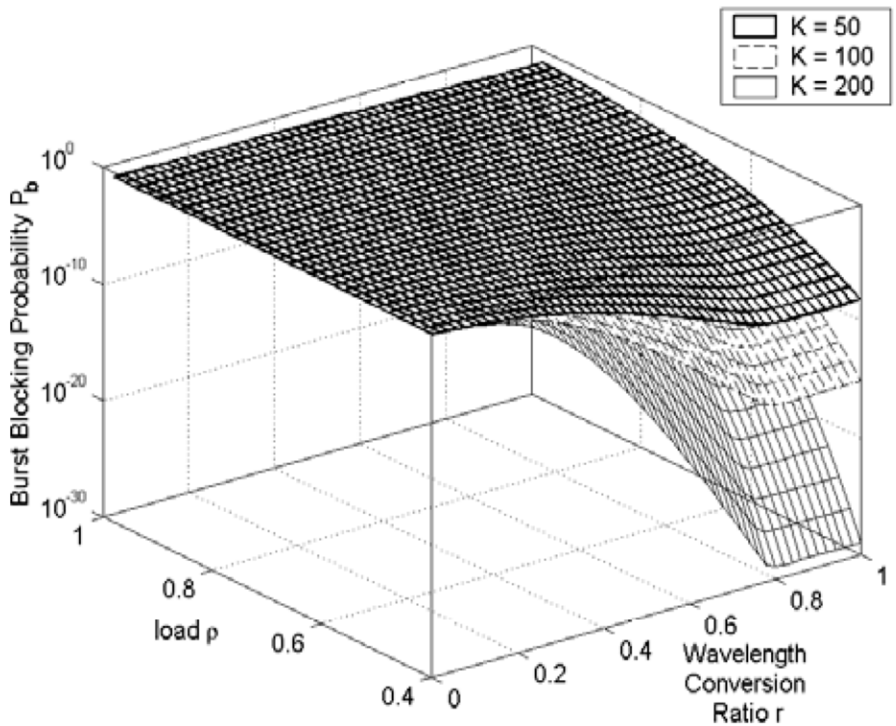
$$Q = \begin{bmatrix} A_0 & U_1 & & & \\ D_0 & A_1 & U_2 & & \\ & D_1 & A_2 & \ddots & \\ & & \ddots & \ddots & U_K \\ & & & D_{K-1} & A_K \end{bmatrix}$$

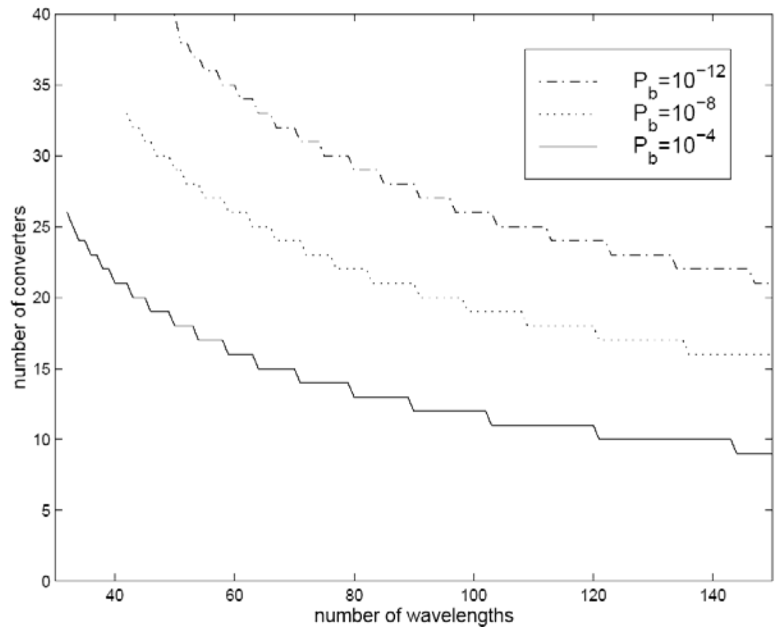
$$xQ = 0, xe = 1$$

$$P_b = x_K e + \sum_{i=W}^{K-1} x_{i,w} \frac{i}{K}$$

- Formulated as the steady-state solution of a structured Markov chain
- Known as nonhomogeneous QBD (Quasi-Birth-Death-Process) in the applied probability literature
- Stable and efficient way to solve based on block LU factorizations
- Computational complexity less than $O(K\,W^3)$ compared the brute force approach $O(K^3\,W^3)$

SPL - PWC Results





- Model can be used for
  - Rapid production of burst loss curves
  - Iterative methods for finding cost-optimal choices for the pair (K,W) so as to satisfy a QoS requirement in terms of burst loss

Network-wide Study – Reduced Load Fixed Point Approximations

- Reduced offered loads are obtained by

$$\rho_j = \mu_j^{-1} \sum_{r \in R_j} \lambda_r \prod_{i=1}^{J} \left(1 - I(i, j, r) \times B_i\right), \quad \text{where}$$

  - *I(i,j,r)* → 1 or 0 whether or not $i \in \boldsymbol{r}$ and link *i* strictly precedes link *j* along route ***r***
  - B → vector of blocking probabilities
- Evaluate B_j's by using ρ_j's on each link by using the PWC model described before, denoted as PWC(ρ_j,W_j,K)

$$B_j = PWC\left(\rho_j, W_j, K\right)$$

- By successive iterations, approximate blocking probabilities could be obtained.

OBS tutorials

OBS testbeds

Core OBS Node Technology

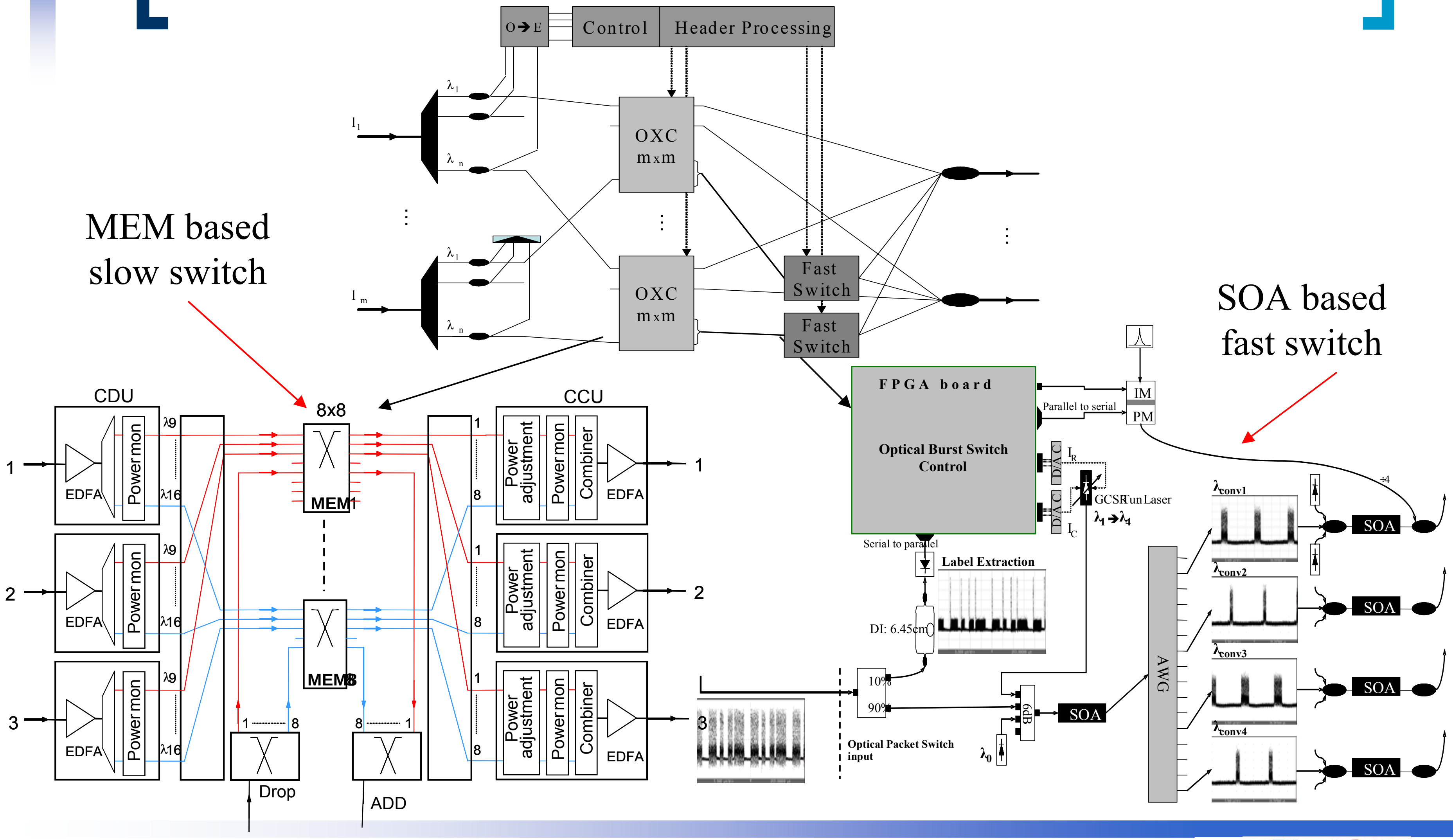
- Traditionally OBS switches are based on slow switching technology (e.g. MEM)
  - Suitable for long bursts with large offset time
  - Not suitable for networks with large number of users transmitting small data bursts
    - Not efficient for short bursts with short offset time

- Combination of fast and slow optical switching technology is emerging for future OBS networks
  - SOA based switch technology for fast switching
  - MEM based switch technology for slow switching

Core OBS Node Architecture

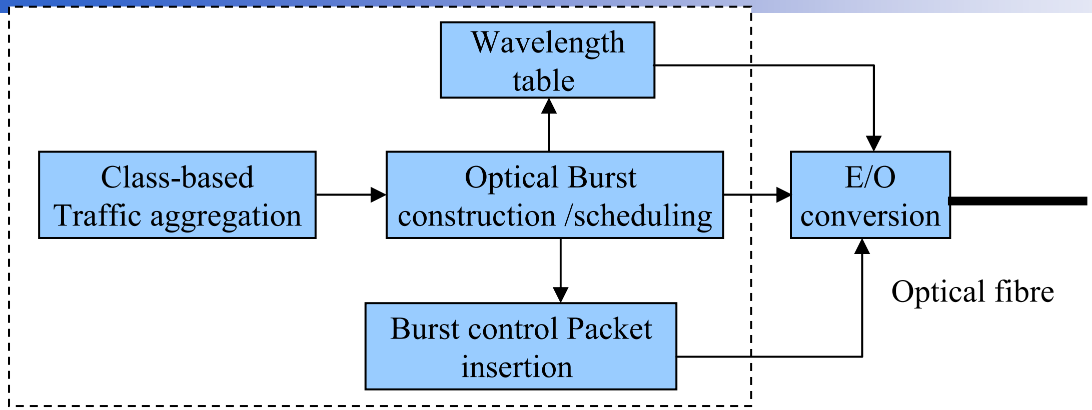
MEM based slow switch

SOA based fast switch



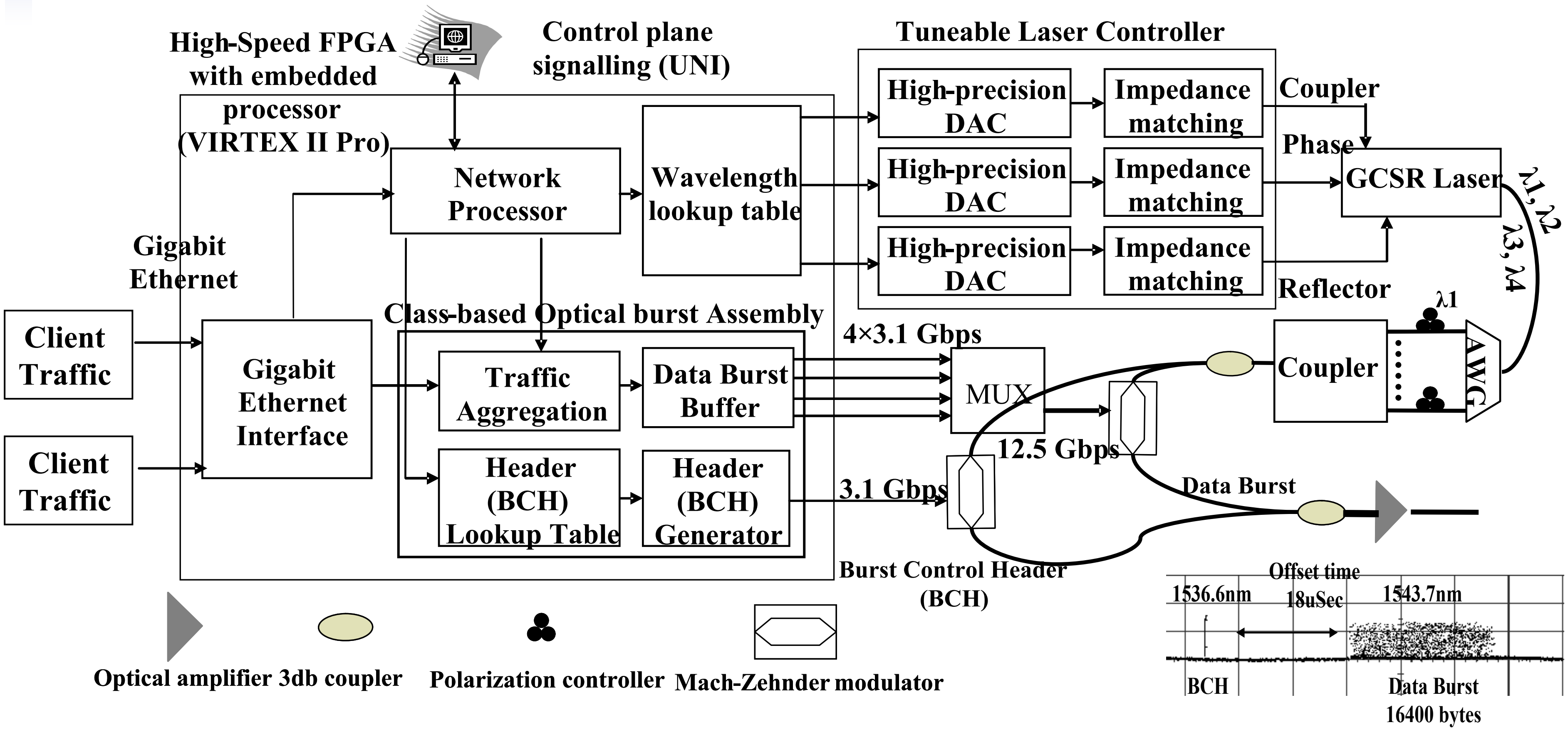
e-Photon ONe

Edge OBS Node Functionality



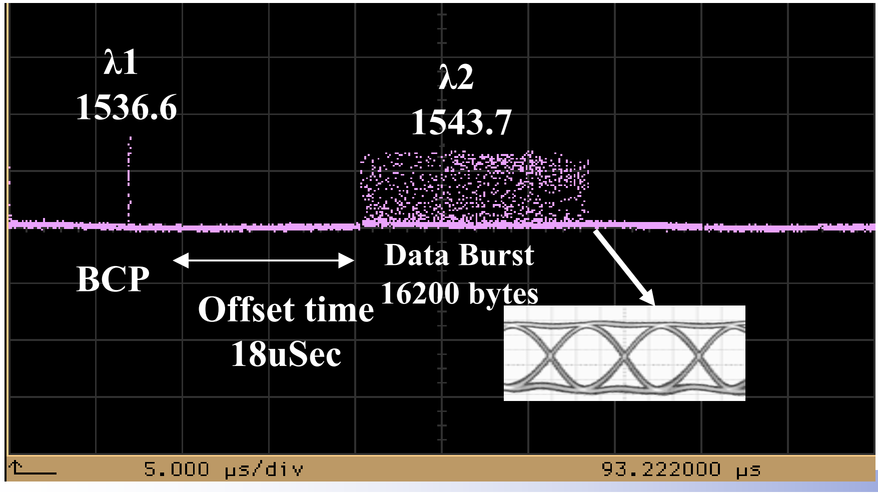
- User data (electronic packets) are aggregated in optical bursts based on:
  - Destination address
  - Class of service
- Optical bursts are scheduled for transmission based on :
  - Number of bytes per optical burst
  - Maximum experienced delay
- Optical control packet and wavelength are assigned based on:
  - Destination address and class of service
  - Information from control plane (lookup table)

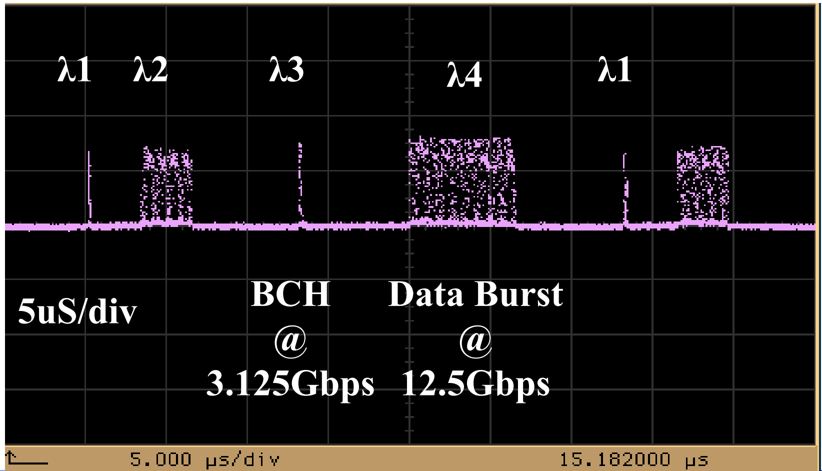
Edge OBS Node Architecture



Optical Burst Construction (Results)

- The length of payload is variable : 3KBytes, 16KBytes
- Optical Burst size are multiple integral of 100 bytes
- Optical Bursts modulate in four different wavelengths (1536.6, 1543.7, 1546.1, 1548.5 nm)
- Programmable BCP (length here =80 bytes=preamble+label+burst length+offsettime+wavelength)
- Offset time variable
- Guard band between two adjacent bursts is variable based on the traffic load



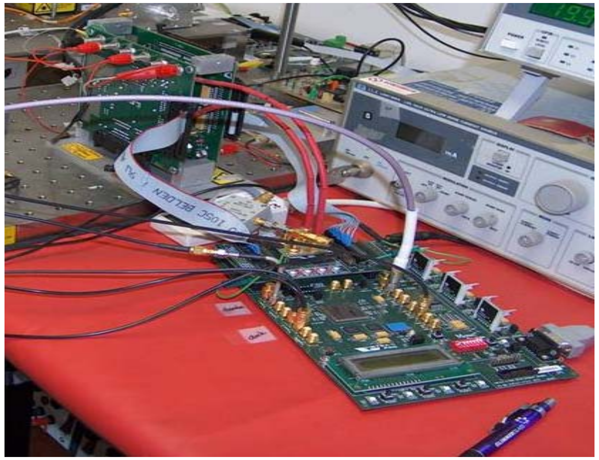


e-Photon ONe

Edge & Core Routers

Fast SOA-Based Switch

Slow Mem-based Switch



Burst Generator + Tuneable laser

Resilience

Resilience – OBS challenges (1)

- Main rationale for an OBS network:
  - – Use of packet based information transport is increasing.
  - – Resilience functionality comparable to SDH/SONET must be present in packet based optical networks.
- Disruption of service delivery due to:
  - – Fibre cuts.
  - – Component/node failure.

Resilience – OBS challenges (2)

- Specific Resilience challenges for OBS:
  – Use of offset time reservation protocol
  => vulnerability to loss of both control packet and data bursts.
  – Detecting failures by detecting loss of control messages
  => increased overhead and congestion due to need of frequent control message transmission.
  – No optical RAM for buffering during restoration.

Resilience - Main approaches

- Two main approaches:
  - **Fault avoidance:** minimize the probability of faults in the network.
  - **Fault tolerance:** continue to provide the intended service even when faults occur.
- Faults can never be completely avoided =>
  Goal: We should aim at building a fault-tolerant (survivable) OBS network.

Resilience - Fault-tolerance (1)

- Building fault-tolerance into a network by adding redundancy at different levels:

Redundancy

Component redundancy

- Active or passive spare components used in a node.
- Duplicated links between two nodes.

Node redundancy

- Duplication of a full switching node; active or passive operation.

Network redundancy

- End-to-end redundant paths used in the network; back-up may be pre-planned.

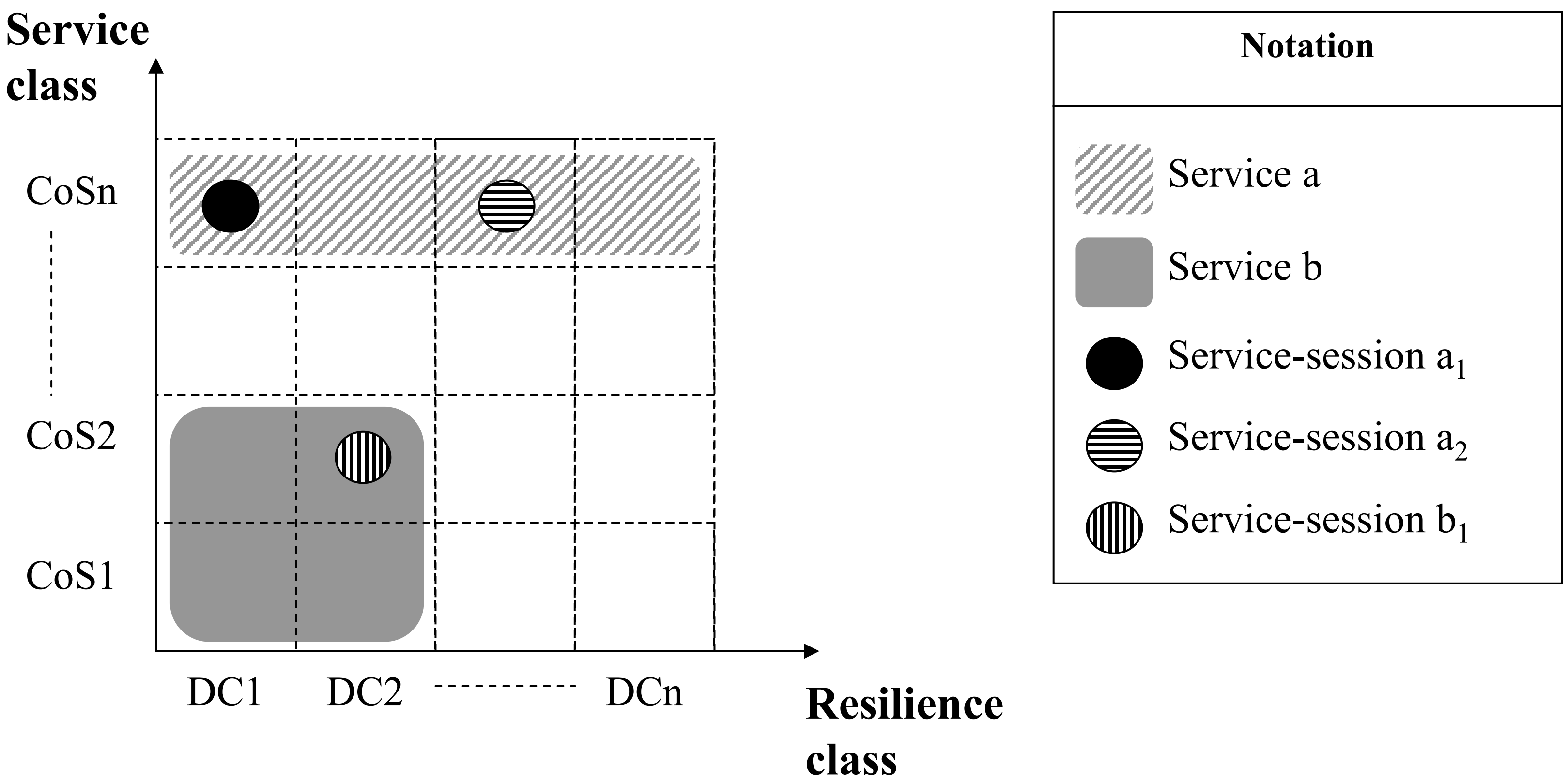
Resilience - Fault-tolerance (2)

- Mechanisms to achieve network redundancy involves control signalling and have slower response times than (local) mechanisms to achieve component or node redundancy.
- Coordination between mechanisms at different levels is important (e.g. avoid rerouting of traffic end-to-end if a local mechanism may be sufficient to handle the problem).
- Any fault must be reported to the control level for follow-up (e.g. change of spare part).

Resilience - Differentiation (1)

- We should aim at differentiated Resilience:
  - To optimize resource utilization.
  - To enable price discrimination.
- The Resilience level and performance level should be independently chosen:
  - A service with high performance (e.g. real-time) demands may have low Resilience demands.
  - A given service may have different Resilience demands in different situations or contexts.

Resilience – Differentiation (2)



- A ”service-session” is a given service used in a given situation or context.

Resilience - Differentiation (3)

Examples:

- High picture-quality video-telephony:
  - High performance demands (wrt. real-time and packet loss)
  - Moderate to low Resilience demands depending on context.
- Messaging services:
  - Have in general very low performance demands.
  - May have very high Resilience demands if used in a business context.
- Regular phone call vs. Emergency phone call:
  - Both have the same performance demands (high real-time demands but moderate packet loss demands)
  - Regular phone call has moderate Resilience demands; Emergency phone call has very high Resilience demands.

i.e. even the same service may have very different Resilience demands in different contexts.

Optical Burst Switching

A tutorial from E-photon/ONe

The VD1 OBS taskforce