Optical Packet Switching

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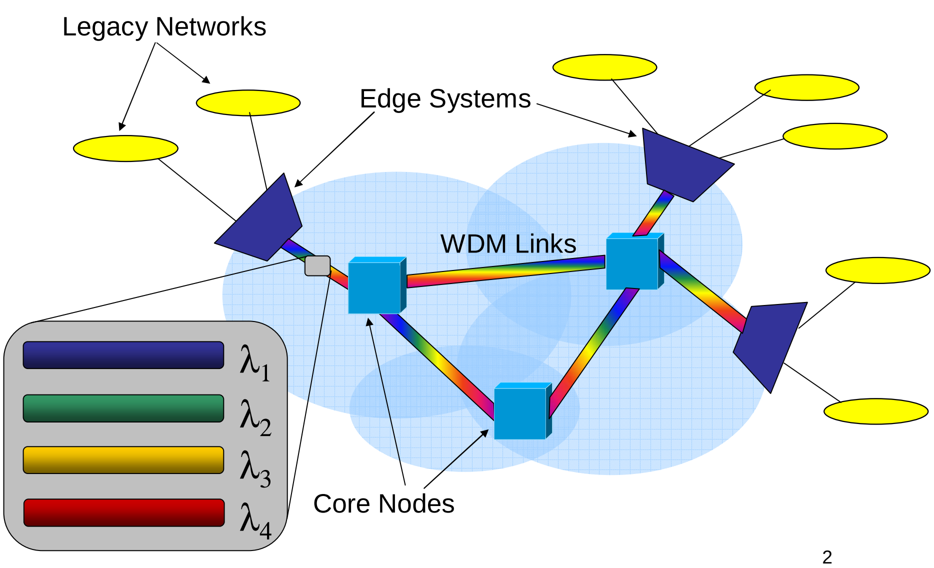
WDM Optical Network



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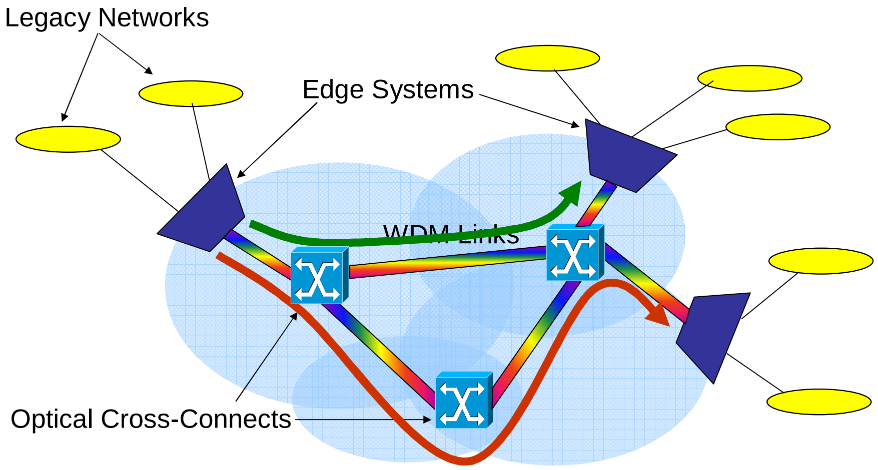
Wavelength Routing Network



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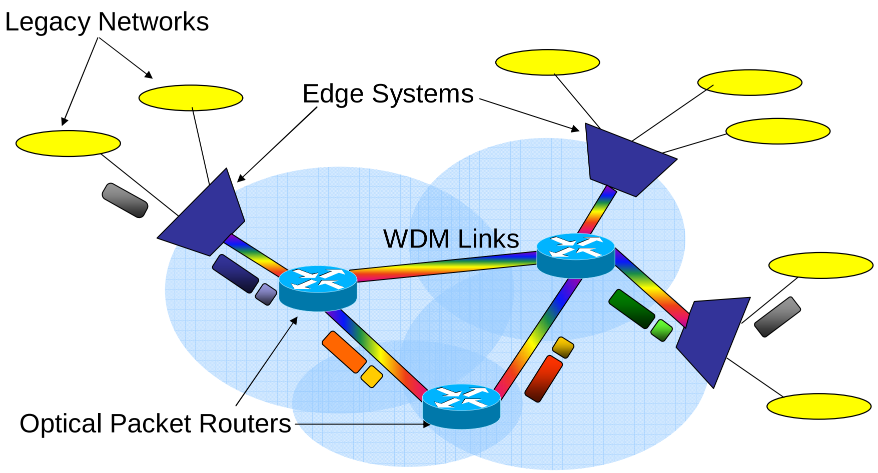
Optical Packet-Switched Network



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Optical Packet Switching

- Long-term alternative to the optical circuit switching techniques currently under development (e.g. Wavelength Routing, MPλS)
- Availability of the optical resource at packet level ➡ efficient use of the bandwidth
- Optical Packet Format:

- No O/E/O payload conversion needed at the core nodes, only header conversion may be performed

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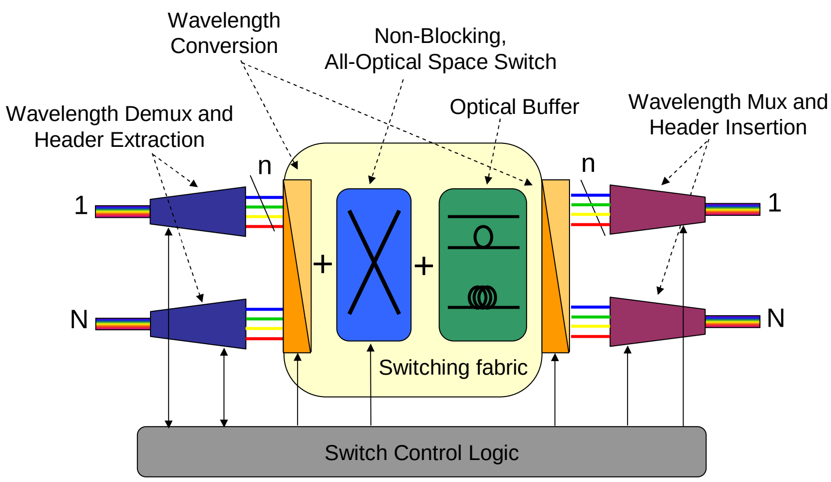
Optical Packet Router Architecture



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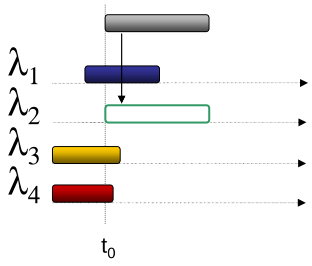
Contention resolution in OPS networks

- Typical problem of packet-level switching
- Resolution techniques available in OPS networks:
  - **wavelength domain**: contending packets transmitted on separate wavelengths of the same WDM link



Contention resolution in OPS networks

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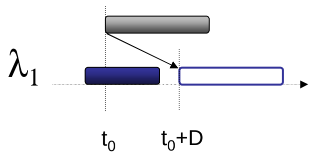
  - **time domain**: contending packets delayed by optical buffers



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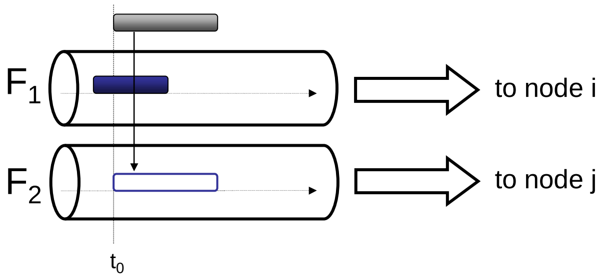

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  - **wavelength domain**: contending packets transmitted on separate wavelengths of the same WDM link
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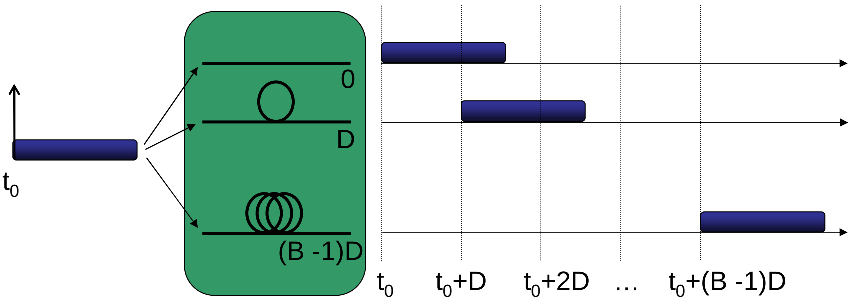
- Performance of OPS contention resolution schemes traditionally evaluated in terms of
  - **packet loss rate**
  - **packet latency**
- Effects on the packet stream are also important
  - **packet sequence**
  - **delay jitter**

Optical Buffer



- Realized with B **Fiber Delay Lines** (FDL):
  - the delay must be chosen at packet arrival
  - packets are delayed until the output wavelength is available
  - available delays are consecutive multiples of the **delay unit** D (different choices are also possible)
  - packets are lost when the buffer is full, i.e. the required delay is larger than the maximum delay achievable D_M = (B -1)D

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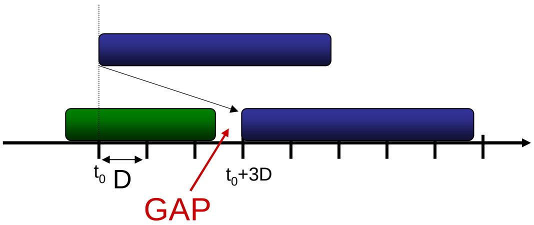
The FDL-gap problem

- Using asynchronous, variable-length optical packets is efficient to carry one or more IP datagrams or packets from heterogeneous legacy networks
- Assumption: FIFO queuing, i.e. packets cannot overtake one another
- Due to the packets variable length and the finite delay granularity, when packets are queued a **time gap** between the end of a packet and the beginning of the following one is present (**0 < gap size < D**)



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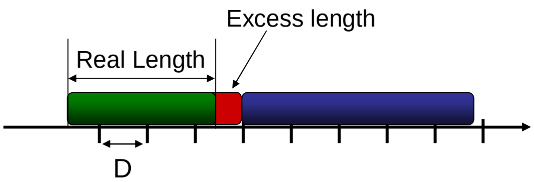
The Excess Load

- During the gap:
  - the server is idle
  - the queued packet must wait for the delay to expire
  - the result is some waste of the available output bandwidth

The gap can be seen as an artificial increase of the length of the previous packet ➡ it results in an **excess load** at the output



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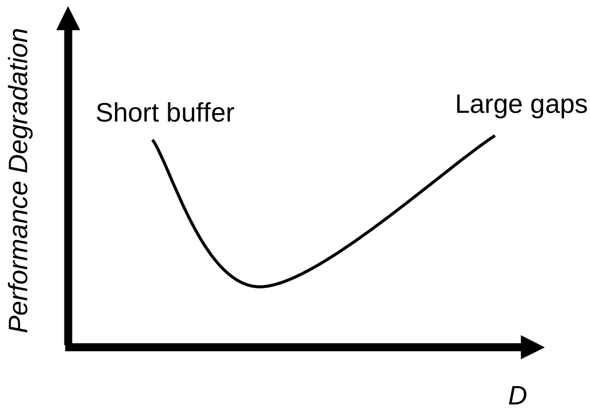
Choosing the Buffer Delay Unit

- D is directly related to
  - time resolution of the FDL buffer
  - maximum delay achievable (buffer size)



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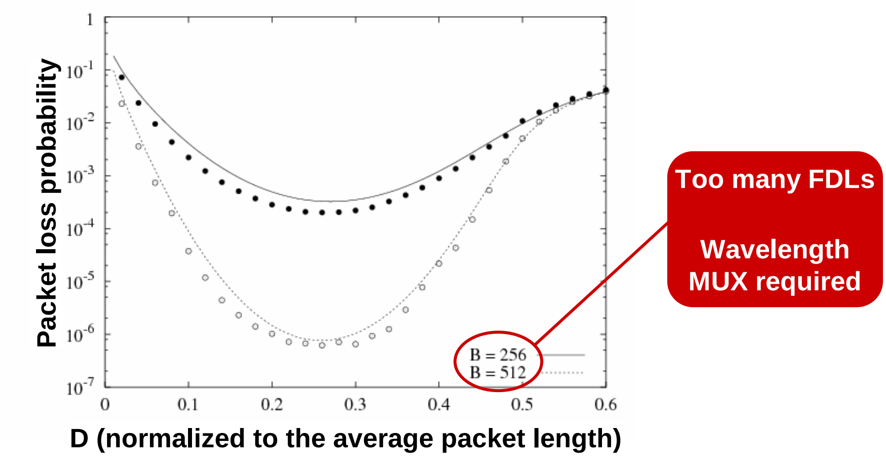
Single wavelength case

- Simulation VS. approximate Markov model assuming a finite queue



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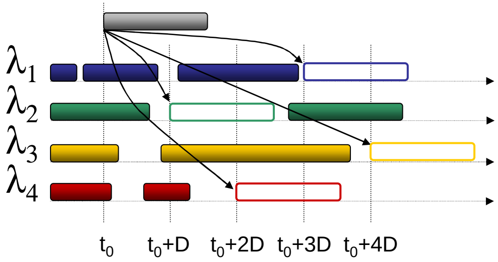
Wavelength and Delay Selection (WDS)

- At packet arrival
  - Given the output fiber (from routing table lookup)
  - Forwarding algorithm must determine
    - the output wavelength
    - the required delay

Example:
- 4 delays
- 4 wavelengths



- WDS problem:
  how to assign the best wavelength to the packet ?

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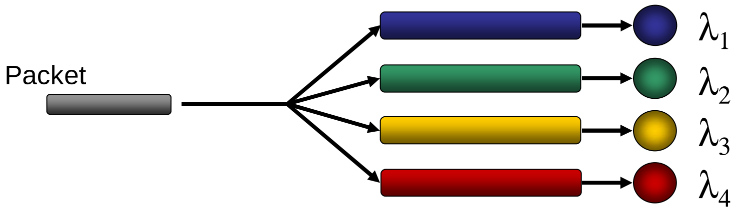
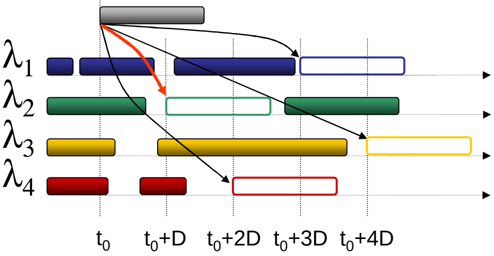
Queuing Model of a WDM Optical Buffer

- For each output fiber:
  - n identical servers represented by the *n* wavelengths
  - n logical FDL buffer in parallel, one for each wavelength (realized with a single set of FDLs operated in WDM)



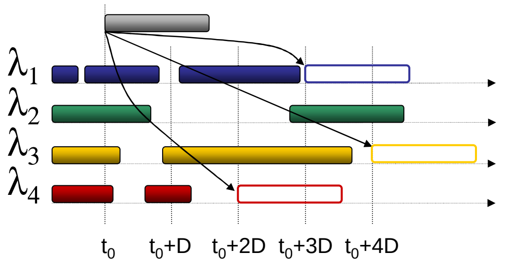
WDS policies

- Gap-filling techniques may be too complex for the optical packet switching time-scale



WDS policies

- Gap-filling techniques may be too complex for the optical packet switching time-scale
- Simpler policies based on wavelength availability, with increasing intelligence
- Pursuing an analytical approach seems very complex ➡ simulation study



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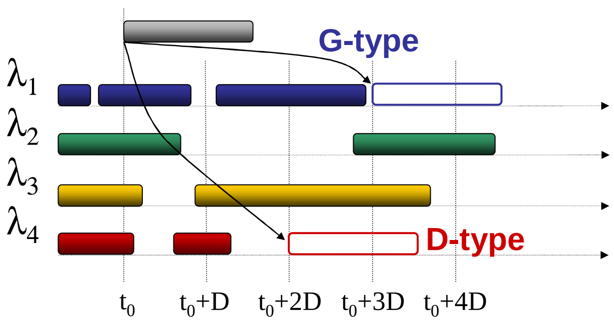
WDS policies

- **D-type**: delay oriented, aiming at minimizing the queuing time
  - choice of the first available wavelength
- **G-type**: gap oriented, aiming at minimizing the gaps between queued packets
  - choice of the wavelength with the closest queued packet



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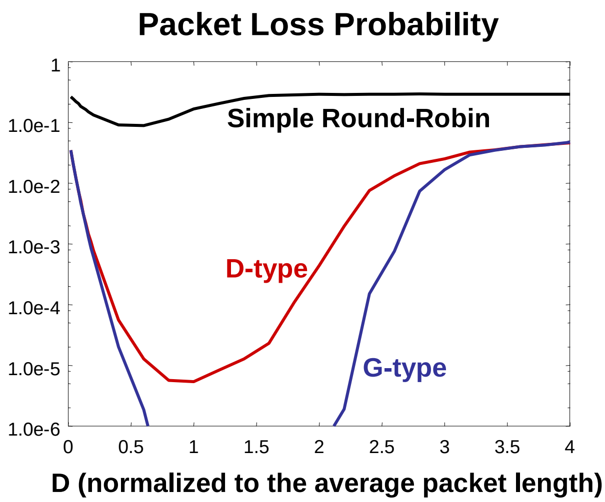
Single-node WDS performance



Input Load per wavelength = 0.8
Uniform random traffic
4 I/O fibers
16 wavelengths/fiber
8 FDLs

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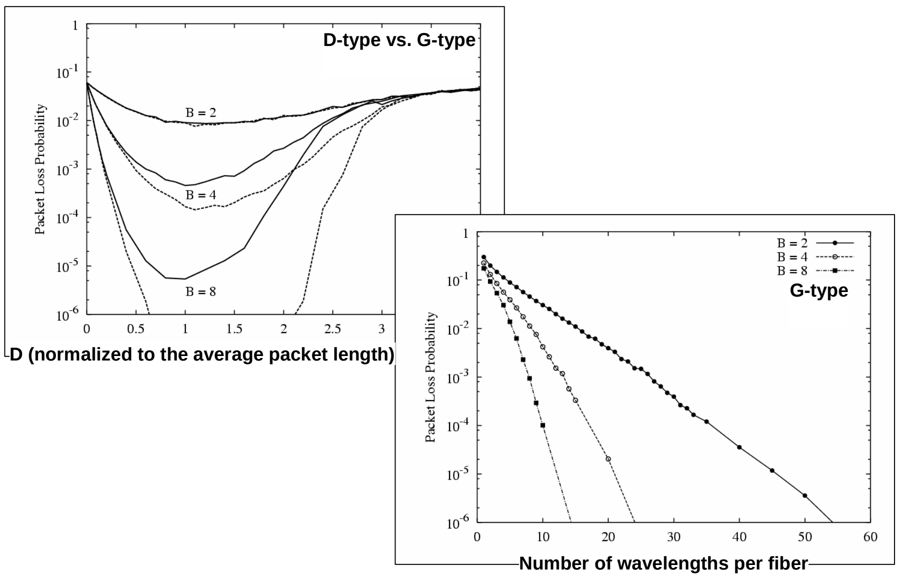
Role of time and wavelength domains



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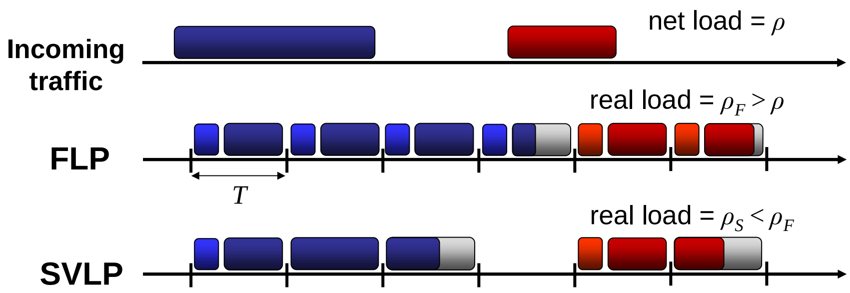
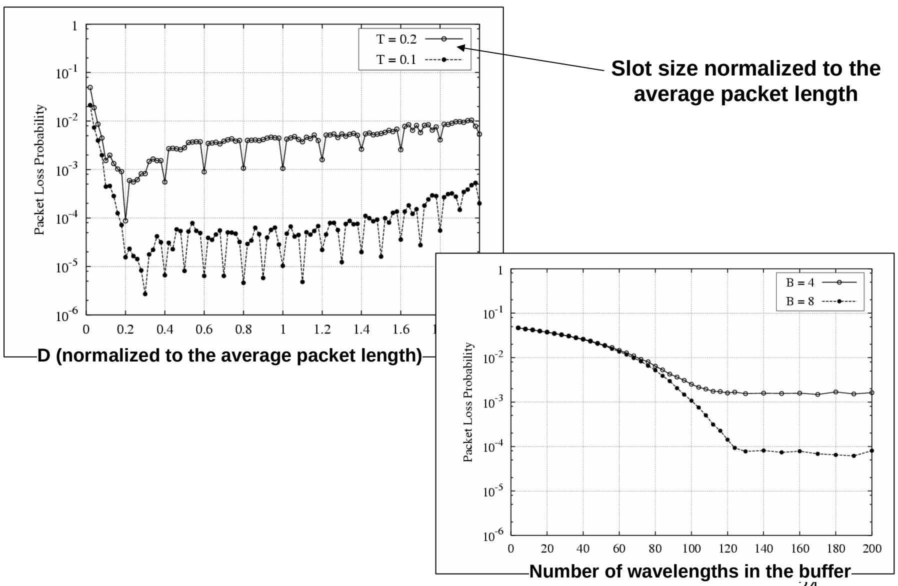
Synchronous network, slotted operation

- Asynchronous, variable-length legacy packets are split and inserted into a number of slots (slot size = T)
- Alternatives for the optical packet format:
  - *Fixed-Length Packet* (**FLP**): each slot is routed independently
  - *Slotted Variable-Length Packet* (**SVLP**): each train of slots is routed altogether

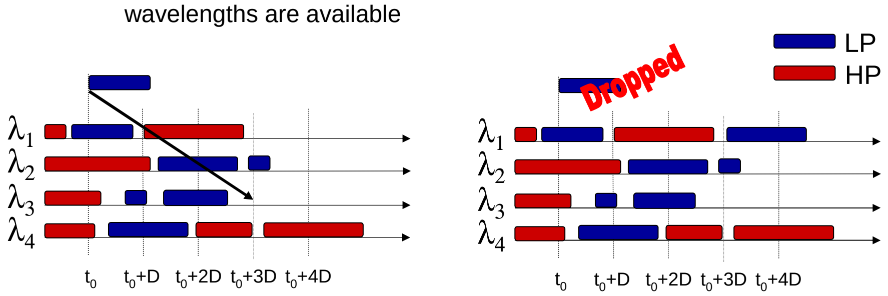


SVLP – performance



QoS differentiation in the OPS node

- Due to FDL buffering constraints, traditional priority queuing and scheduling techniques are not feasible
- QoS differentiation at the OPS node level possible through **resource partitioning**
  - any K wavelengths are reserved to HP traffic based on the actual occupancy
    - e.g. K=2 → LP packets are allowed as long as more than 2 wavelengths are available



Routing strategies in OPS networks

- Path computation algorithms provide:
  - a **default path**, i.e. the shortest path (e.g. in terms of number of hops)
  - a number of **alternative paths**, with equal or higher hop count than the default one
- The routing strategy may use:
  - **Shortest-Path Routing** (**SPR**) only
    - static routing tables
    - not using any alternative path
  - **Multi-Path Routing** (**MPR**)
    - dynamic routing tables
    - alternative paths used to relieve congestion on the default one
- Decisions to be taken by MPR strategy
  - how many alternative paths should be considered
  - how they should be dealt with by WDS policies

Dynamic MPR strategies (1)

- Strategies applying WDS on one of the alternative paths only when the default path is congested:
  - a path is considered **congested** when, on the corresponding output link, all the wavelengths are busy and there are no places left in the optical buffer
- **SAP** (**Shortest Alternative Paths**)
  - beside the default link, an alternative set of routes is considered, including any other shortest path different from the default one
- **n-SAP** (**n-Shortest Alternative Paths**)
  - besides the default link, n alternative sets of routes are considered, corresponding to paths with up to n–1 hops more than the shortest one

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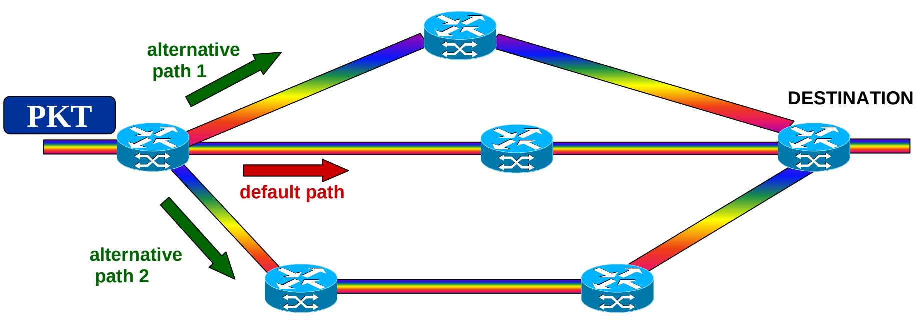
Dynamic MPR: 2-SAP

Alternative paths available toward the packet destination



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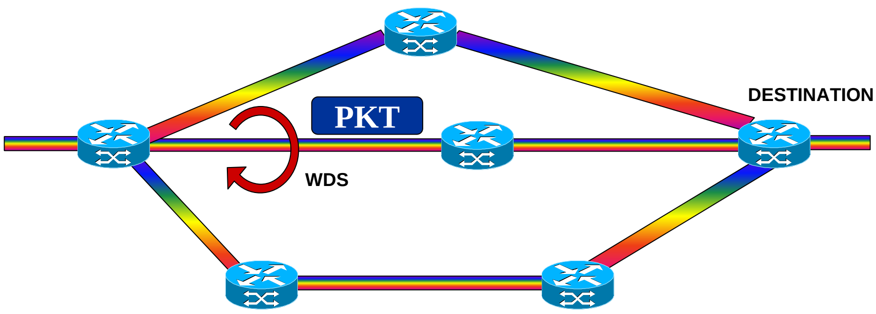
Dynamic MPR: 2-SAP

Packets are sent through the default path, as long as this one is not congested



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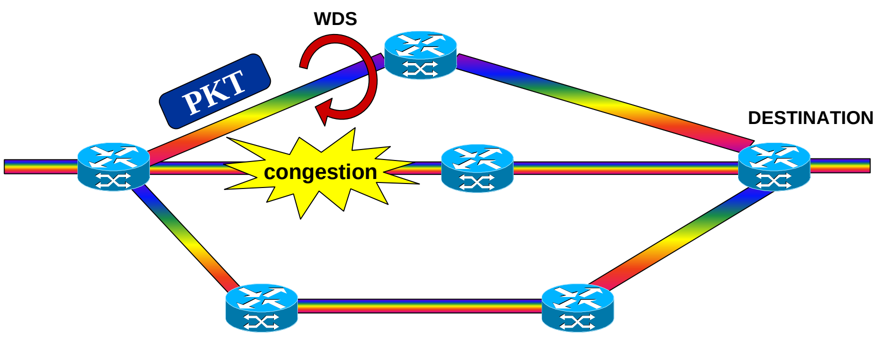
Dynamic MPR: 2-SAP

In case the default path is congested, the best wavelength is chosen by the WDS policy on one of the alternative paths



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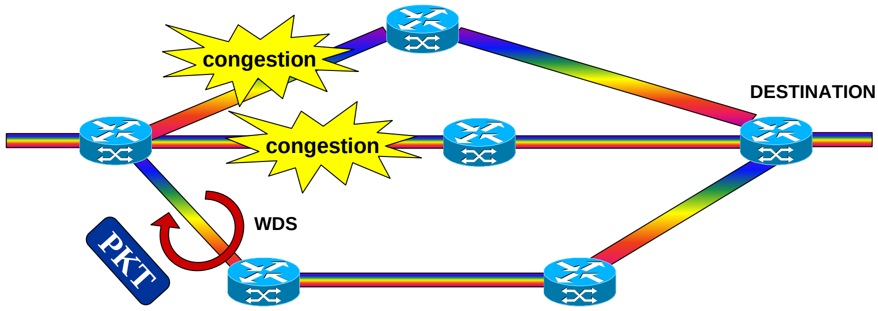

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Dynamic MPR strategies (2)

- Strategies applying WDS not on a single link, but on an entire set of links
  - sharing the wavelengths belonging to different paths
- **SSP** (**Shared Shortest Paths**)
  - WDS is performed over all the wavelengths on any shortest path link, including the default one
- **n-SSP** (**n-Shared Shortest Paths**)
  - WDS is performed over all the wavelengths on any link corresponding to paths with up to n–1 hops more than the shortest one

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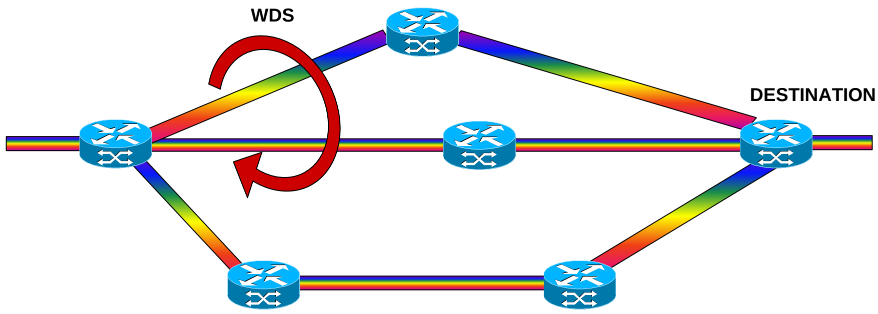
Dynamic MPR: SSP

WDS performed on any shortest path link



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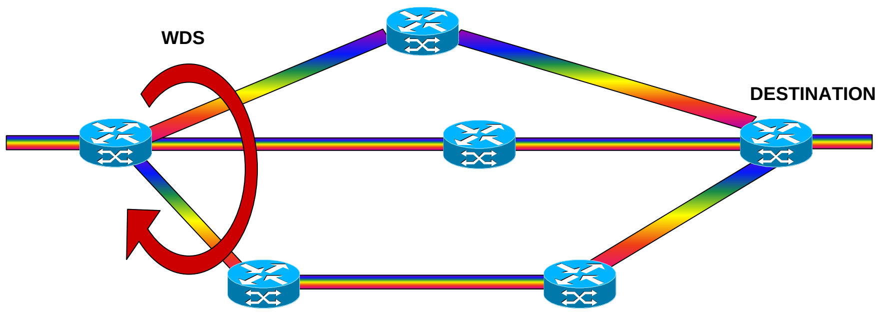
Dynamic MPR: 2-SSP

WDS performed on any shortest and 2nd-shortest path link



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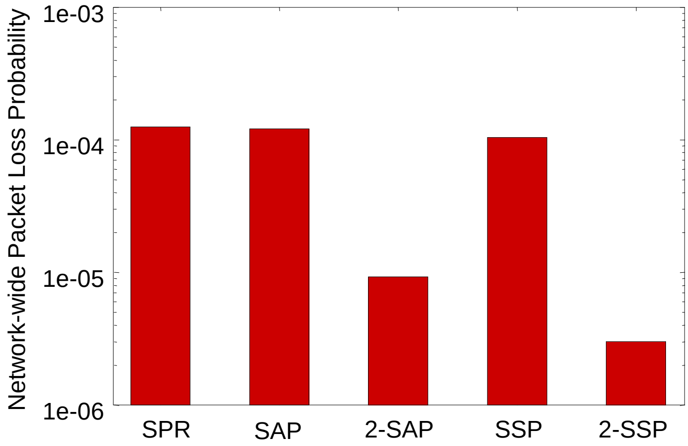
Dynamic MPR strategies performance

Simulation of European network (15 nodes, 24 links)

Dynamic MPR effective when non-shortest paths are used



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QoS differentiation at the routing level

- Integration of QoS management into dynamic MPR strategies
  - aggregate QoS classes (sort of DiffServ approach)
  - simple set-up: 2 priority classes
- **High-Priority** (**HP**) traffic: always routed along the shortest path (SPR) using node-level resource partitioning
  - limited packet loss
  - limited delay and packet jitter
- **Low-Priority** (**LP**) traffic: two options
  - always routed along the shortest path (SPR) using spare resources
  - overflow traffic re-routed to alternative paths (MPR)

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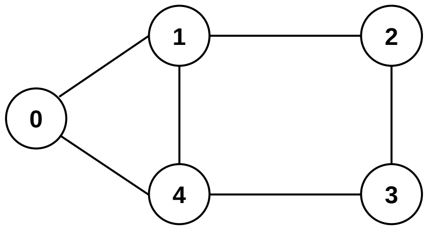
Simple test topology



Average node degree: E = 2.4

16 wavelengths per link, each loaded with 0.8
→ traffic matrix generated accordingly

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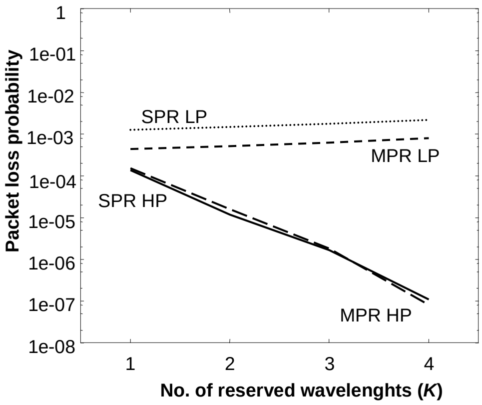
QoS performance

- **SPR**/**MPR** is the routing policy adopted for LP traffic
  - HP traffic (20%) always uses SPR
- Accurate dimensioning gives a good degree of traffic differentiation
  - LP routing policy does not affect HP
  - LP performance is slightly affected by HP resource dimensioning (within the range considered)



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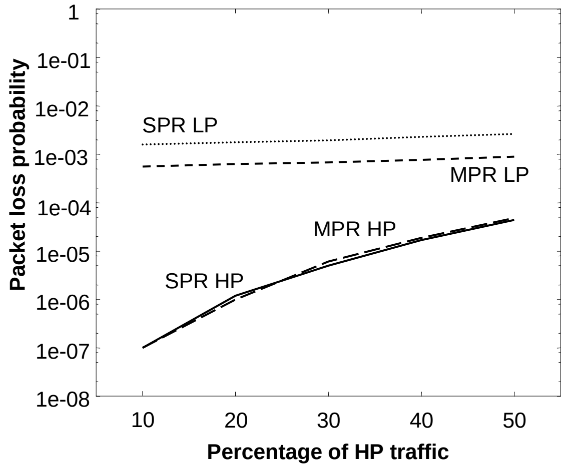
QoS performance

- **SPR**/**MPR** is the routing policy adopted for LP traffic
  - HP traffic always uses SPR
  - K = 3



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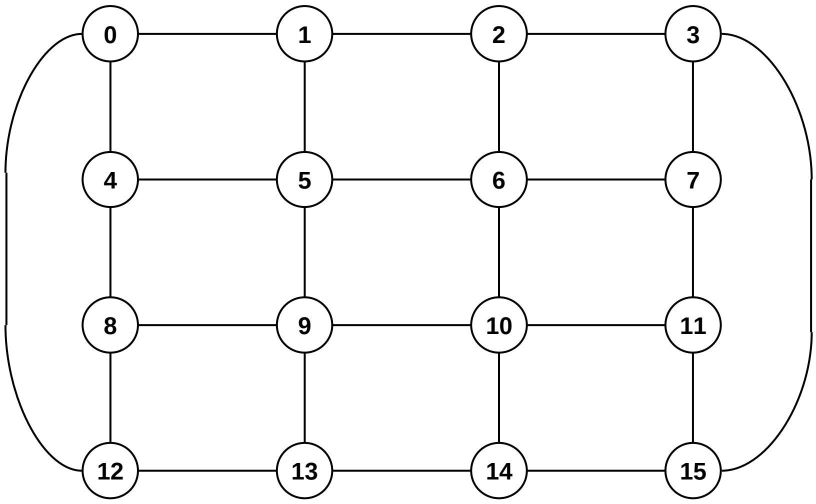
Reference topology 1



Average node degree: E = 3.25

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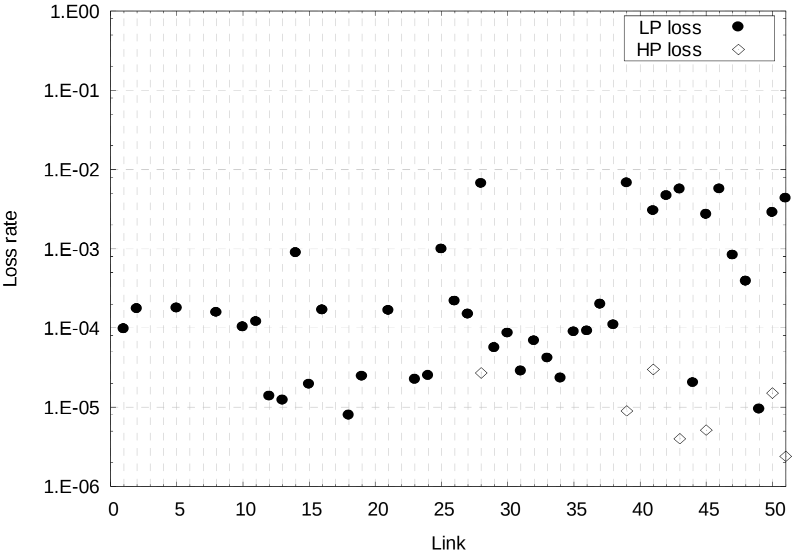
Topology 1: uniform matrix, balanced load



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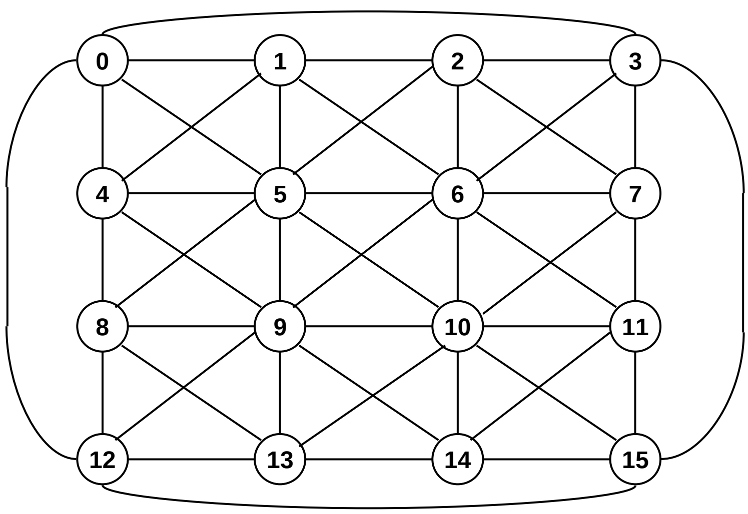
Reference topology 2



Average node degree: E = 5.75

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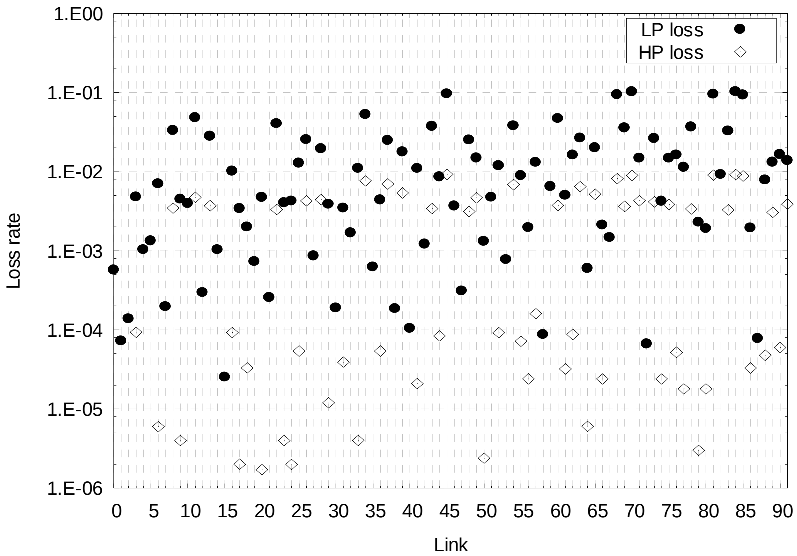
Topology 2: uniform matrix, balanced load



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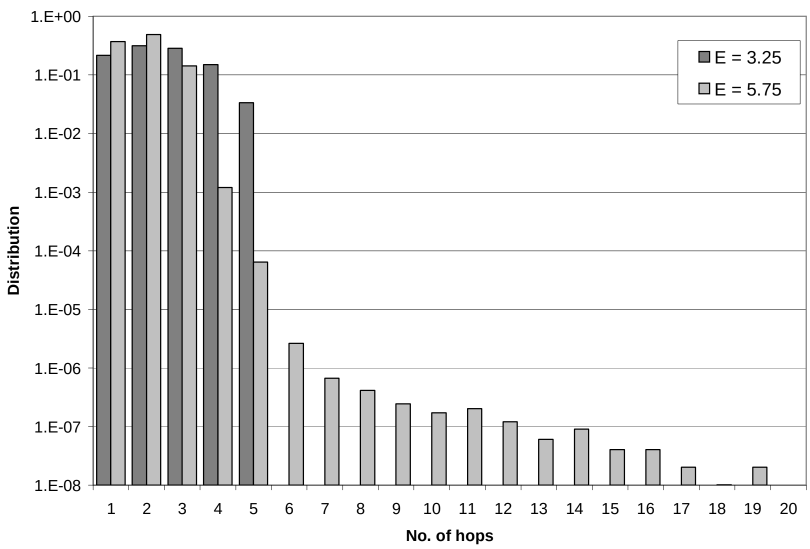
Topologies 1 & 2: no. of hops distribution



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Link failure recovery in OPS networks

- Connectionless approach
- Single link failure
- Link failure detection technique
  - notified by physical layer
  - time-based
  - signaling-based
- During failure detection, loss of optical packets supposed to be transmitted on the failed link
- After failure detection, the recovery procedure is called and a MPR alternative path is used

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Packet loss during failure detection

- Analytical model for the packet loss probability as a function of detection time
  - p is the loss probability in a failure free scenario
  - t_f is the failure time
  - d is the failure detection delay

$$P_L(t) = \begin{cases} p & t \le t_f \\ 1-(1-p)\dfrac{t_f}{t} & t_f < t < t_f + d \\ 1-(1-p)\dfrac{t_f}{t_f + d} & t \ge t_f + d \end{cases}$$

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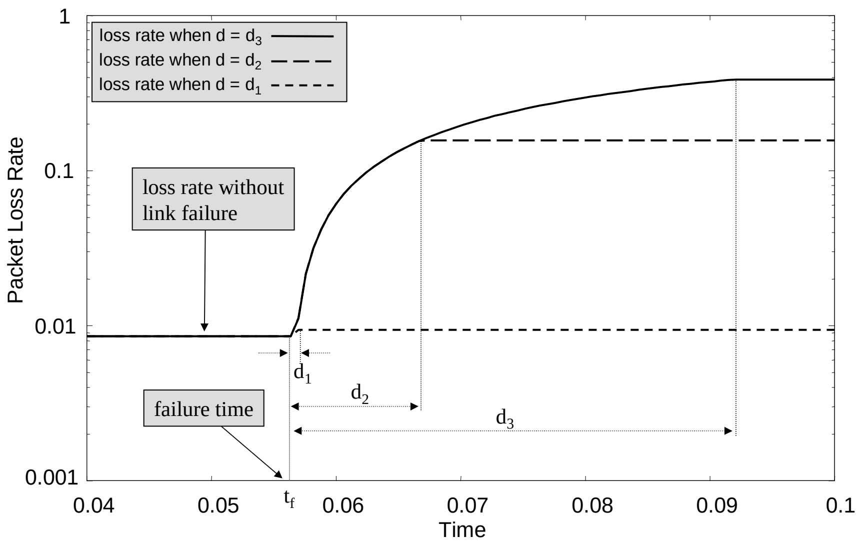
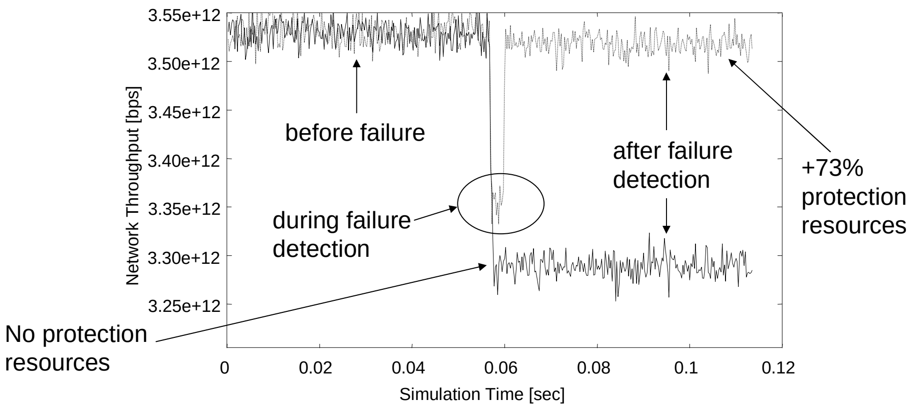
Packet loss during failure detection



Adding resources for protection

- The MPR-based protection scheme needs additional resources to be effective
- First, the network is dimensioned to have a given average load per wavelength (e.g. 0.7) with relation to the input traffic matrix
- Then, further wavelengths are added to each fiber so that each node sees all its output fibers with the same capacity
- Additional cost due to protection is 73% of the initial cost in terms of number of wavelengths

Impact on throughput



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Out-of-sequence packet delivery

- A consequence of dynamic resource allocation techniques deployed to reduce congestion
- Implications:
  - complex reordering operations at the optical network edges
    - due to the huge bit rate of the optical channels
  - throughput degradation at the transport/application level
    - TCP congestion control highly affected by unordered segments
    - real-time, UDP-based traffic requirements impaired by excessive delay due to unordered packets and/or reordering process
- Possible solutions:
  - WDS policy with some time constraints in order to keep the correct packet sequence
  - dynamic multi-path routing limited to delay-equivalent paths

- But what do we intend with **correct packet sequence**?

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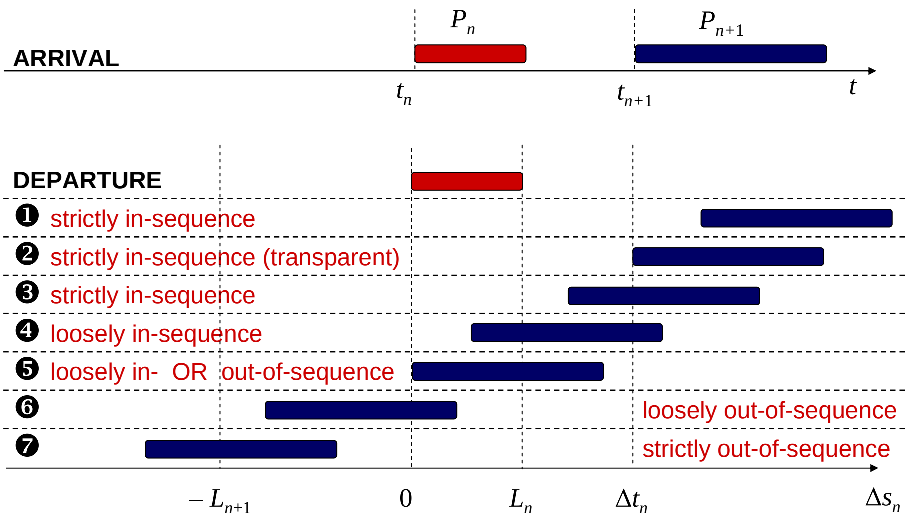
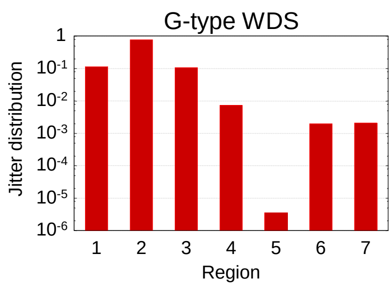
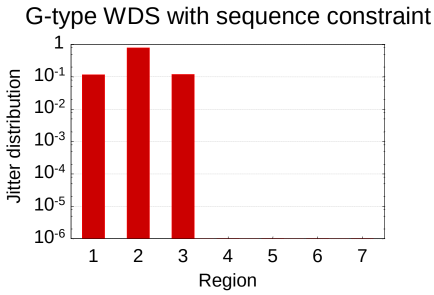
Alternatives for packet sequence

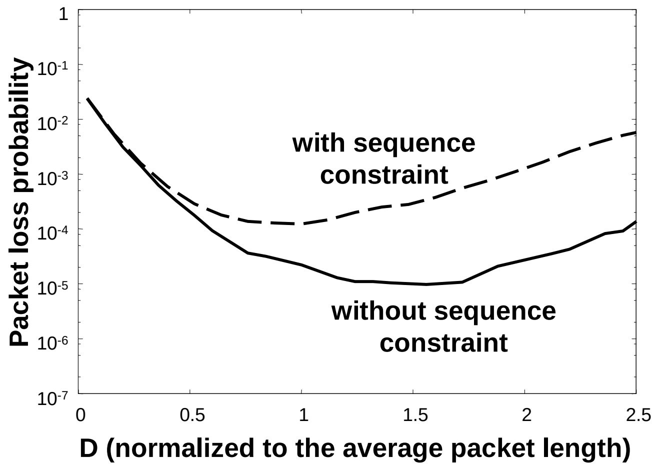


Jitter distribution





Impact on loss



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Conclusions

- OPS from the network perspective: issues
  - dynamic multi-path routing for contention resolution
  - QoS differentiation through resource partitioning and differentiated routing strategy
  - link failure protection strategy through multi-path routing and additional resources provisioning
  - packet sequence issues
- Further ongoing activities:
  - effective low-complexity implementation of void filling WDS
  - study of dynamic routing through ant colony optimization
  - study of the impact of packet sequence break on higher layer protocols
  - study of the impact of limited wavelength conversion on node and network performance

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