Optimal Packet Scheduling in Output-Buffered Optical Switches with Limited-Range Wavelength Conversion

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Outline

- Introduction
- The WDM optical packet switch model
- Finding an optimal scheduling
  - Network flow approach
  - A new algorithm
- Simulation results
- Conclusions

Introduction

- The recent introduction and rapid growth of the wavelength-division-multiplexing (WDM) technology provides a platform to exploit the huge capacity of optical fiber.
- Optical switches that combine the advantages of WDM with packet switching capability are strong candidates for future ultra high speed switches.

Introduction

- In a WDM switch, the multiplexing of multiple optical signals on a single fiber is achieved by carrying each signal on a separate wavelength.
- Contention of wavelength channels arises when more than one packets are destined for the same wavelength channel of an output fiber.

Introduction - Buffering in optics

- No optical RAM
- Fiber delay lines (FDLs)
  - Buffers by letting the signal go through extra fibers.
  - Discrete buffering time.
- Slow light
  - Provides continuous buffering time by slowing down the signal.
  - Constrained by some fundamental physical limitations.

Introduction – Wavelength conversion

- A unique dimension to resolve contentions in WDM optical switches.
- Can be divided into full-range conversion and limited-range conversion.
- A well-designed switch needs to function in both time domain and wavelength domain.

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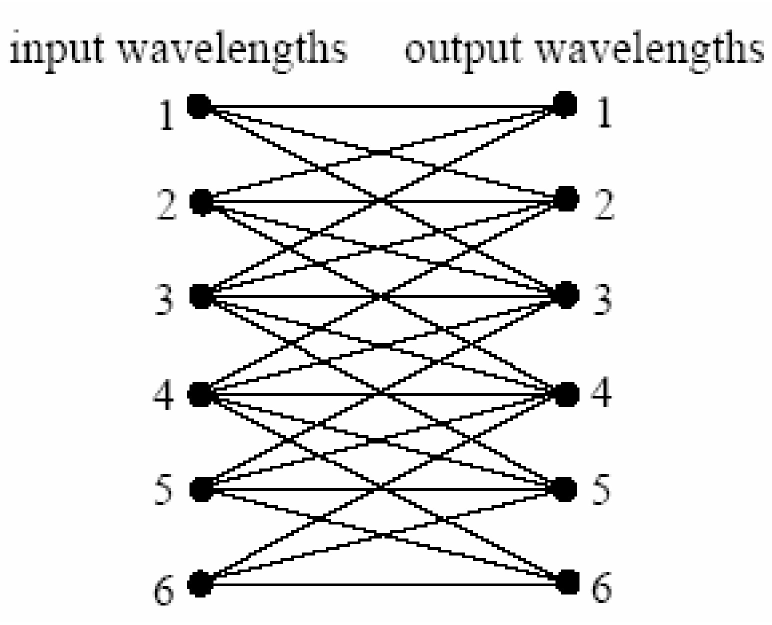
Wavelength conversion model

- Limited-range conversion.
- Convertible range of a wavelength is symmetric.
  - *d:* Conversion degree



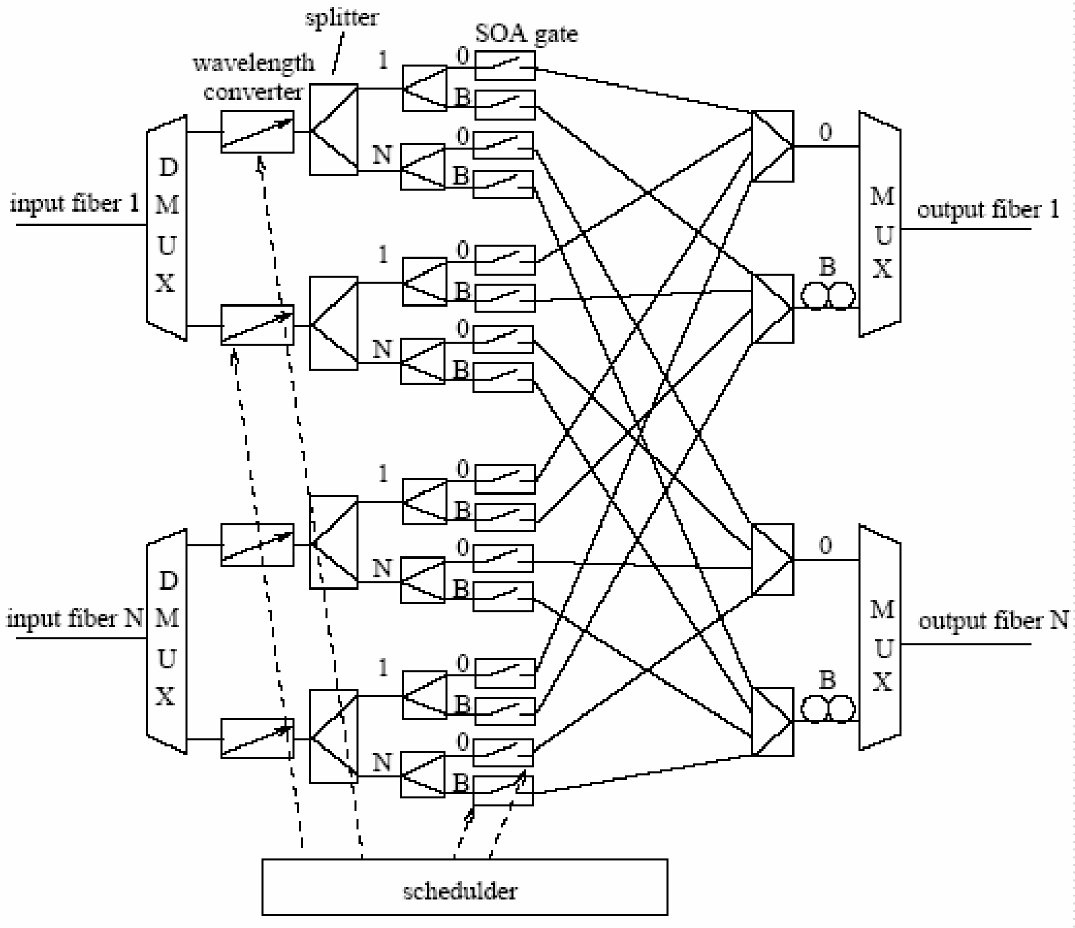
6 wavelengths; d = 2

The WDM optical packet switch model

- Free-space based *V.S.* guided-wave based
  - Guided-wave based switches require wavelength converters to function over a large spectrum.
- Output-buffered *V.S.* input-buffered
  - Input-buffered switches require VOQs which are difficult to implement in optics.

We consider a free-space based, output-buffered, WDM optical packet switch with limited wavelength conversion capability. The switch works in time slots, and all packets at the input are of the same size.

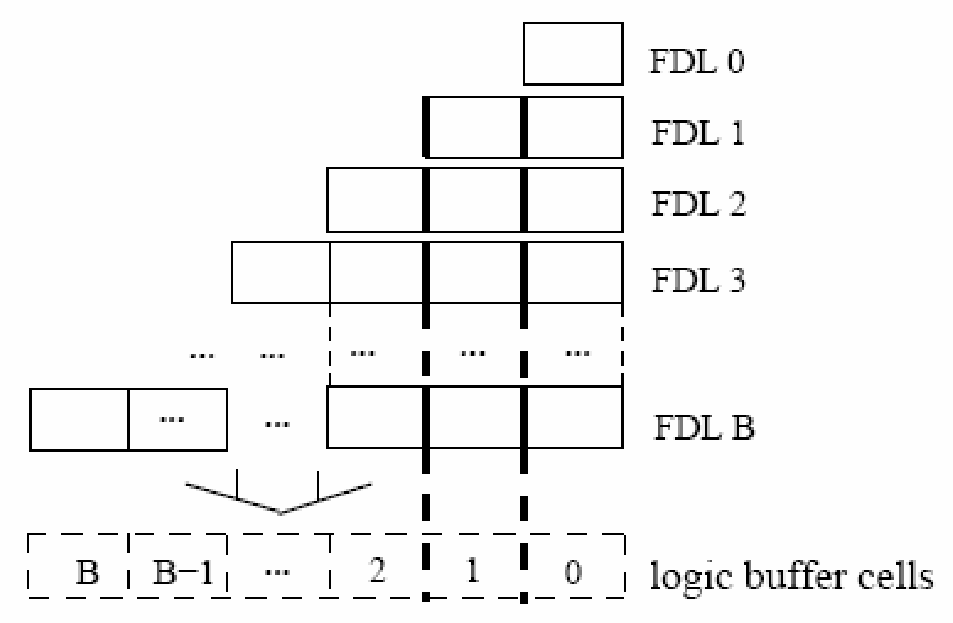
The WDM optical packet switch model



- Packets on the same wavelength and destined for the same output fiber can be sent to different delay lines of that fiber in the same time slot

  -- No speedup required if B >= N.

Physical and logic buffer on an output wavelength channel



- The *B+1* FDLs on each wavelength can store at most *B+1* packets.
- Can be considered as *B+1* **logic buffer cells**, each labeled by the buffer delay it introduces.

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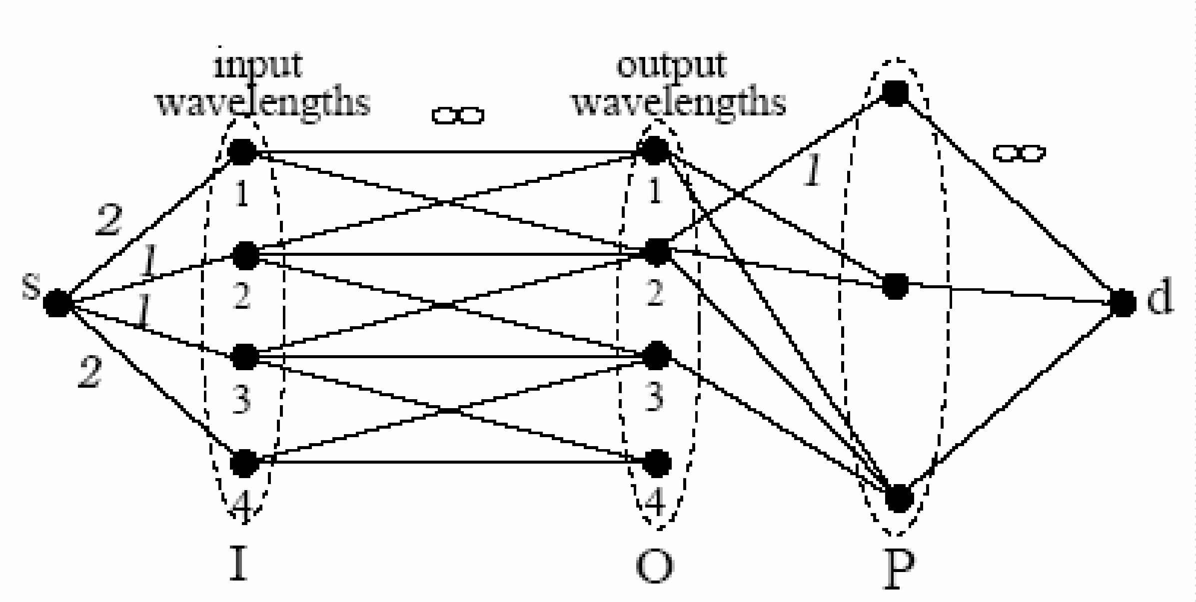
Optimal packet scheduling

- In each time slot, find a scheduling such that
  - the maximum number of packets can be transmitted to the output buffer, while
  - the minimum average buffering delay is introduced.

Network Flow Approach for Finding Optimal Scheduling



- An optimal scheduling corresponds to a *maximum flow with minimum cost* in the flow graph.
- Known network flow algorithms have high complexity.

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Properties of output FDL buffer

- An optimal scheduling uses buffer cells that introduce as small buffering delays as possible.
- If a buffer cell on a wavelength is not used in an optimal scheduling, then any buffer cells on the same wavelength with a larger label cannot be used by this scheduling.
- Available buffer cells on each output wavelength are consecutive at the beginning of any time slot.
- The output FDL buffer on each wavelength can be considered as a FIFO queuing buffer with capacity B+1.

The new scheduling algorithm

- Two-step
- Step 1: Augment to Full Algorithm
  - Determines the number of packets on each input wavelength to be transmitted (I) in current time slot, and the number of buffer cells on each output wavelength to be used (O), of an optimal scheduling.
- Step 2: Scheduling construction algorithm
  - Construct an optimal scheduling from I and O.

Augment to Full Algorithm

- *The filling process*
  - Starting from output wavelength 1, schedule as many as possible packets from input wavelength 1 to the available buffer cells on output wavelength 1.
  - If all packets from input 1 have been scheduled, we say input wavelength 1 is ``filled'' by output wavelength 1, then continue to send as many packets as possible from input wavelength 2 to output wavelength 1.
  - Either input wavelength 2 will be filled by some output wavelength, or the largest wavelength that wavelength 2 can be converted to will be reached. Then input wavelength 3 is to be filled.
  - The process continues until there are no more available packets or buffer cells.

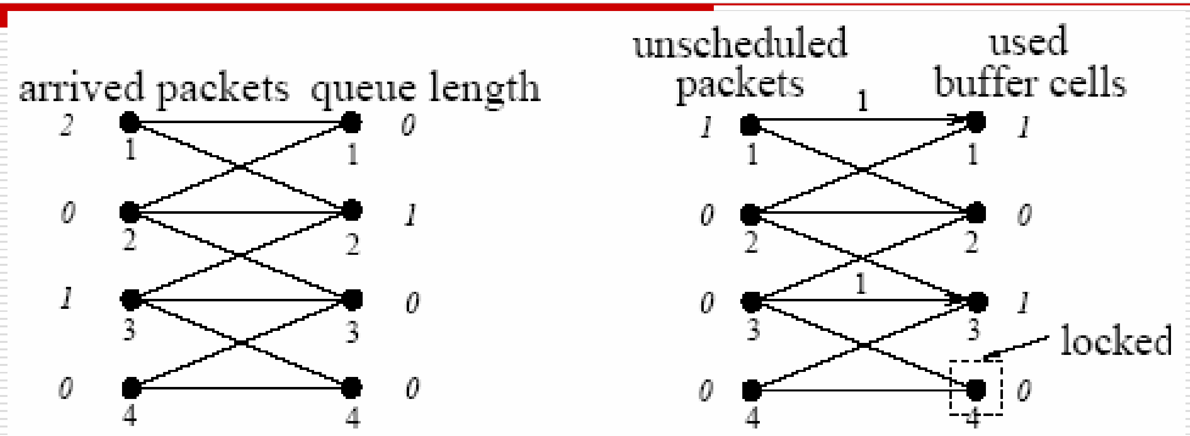
Augment to Full Algorithm

- Buffer cells that introduce shorter queuing delay should have a higher priority to be used.
- The priority is guaranteed in the algorithm by splitting the filling process into $B+1$ steps. In step i, only cells labeled smaller or equal to i will be used to fill the inputs.

Augment to Full Algorithm

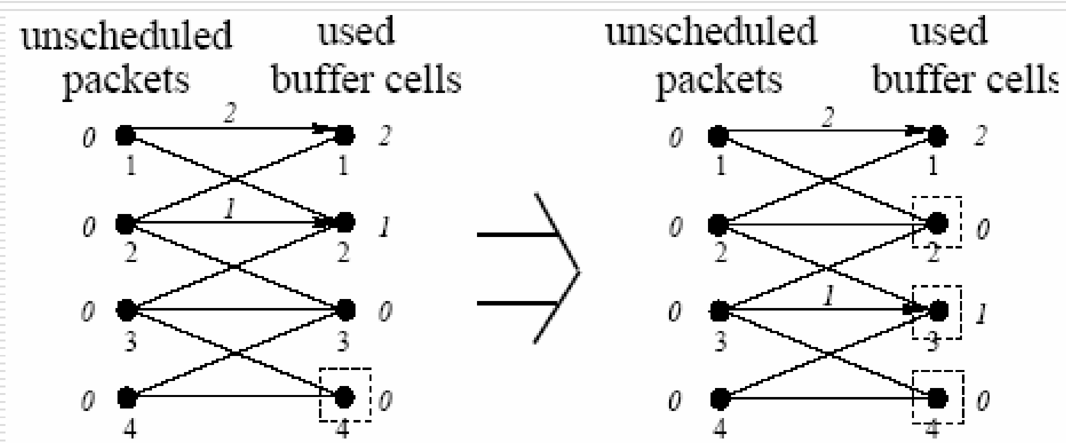
- It is possible that due to the participation of buffer cell *i* of each wavelength, some of the buffer cells labeled *i-1* or smaller that were used in step *i-1* now cannot be used – output wavelength locking takes place.
- Locking an output wavelength in step *i* means that buffer cells labeled greater or equal to *i* on this wavelength will not be considered in the following steps.

Augment to Full Algorithm – An example



(a) Request graph

(b) Step 0



(c) Step 1

Correctness of Augment to Full

- c_i^S - the number of buffer cells with label *i* to be used in scheduling *S.*
- *Saf* - the scheduling with minimum total queuing delay among all schedulings whose I and O are equal to the output of the Augment to Full Algorithm in a certain time slot.
- **Lemma 1.** c_i^{Saf} satisfies the following recursive property:

  c_i^{Saf} is the maximum number of buffer cells with label *i* that can be used under the precondition that c_j^{Saf} buffer cells with label *j* were used for $0 <= j < i$.
- **Theorem 1.** Scheduling *Saf* is an optimal scheduling.

Scheduling construction algorithm

- Input: I and O
- Output: an optimal scheduling
- Basic idea: similar to ``filling process''

Algorithm:

$in \leftarrow 1, out \leftarrow 1$
$p_{in} \leftarrow x_{in}, c_{out} \leftarrow y_{out}$
while $in \leq W$ and $out \leq W$
  if $c_{out} \leq p_{in}$
    schedule c_{out} packets from in to buffer cells on out with the smallest labels
    $p_{in} \leftarrow p_{in} - c_{out}, out \leftarrow out + 1$
    if $out \leq W$
      $c_{out} \leftarrow y_{out}$
    end if
  else
    schedule p_{in} packets from in to buffer cells on out with the smallest labels
    $c_{out} \leftarrow c_{out} - p_{in}, in \leftarrow in + 1$
    if $in \leq W$
      $p_{in} \leftarrow x_{in}$
    end if
end while

Correctness of scheduling construction algorithm

(1) I and O of the constructed scheduling are exactly the ones given by the Augment to Full Algorithm.

- Proved by contradiction.

(2) The constructed scheduling has minimum total queuing delay among all schedulings that satisfy (1).

- Guaranteed by using buffer cells with labels as small as possible.

Time Complexity Analysis

- Augment to Full Algorithm
  - All ``filling'' operations - $O(W^2)$
  - All ``locking'' operations - $O(min\{W^2, BW\})$
- Scheduling construction algorithm
  - $O(W)$
- Overall time complexity
  - $O(min\{W^2, BW\})$

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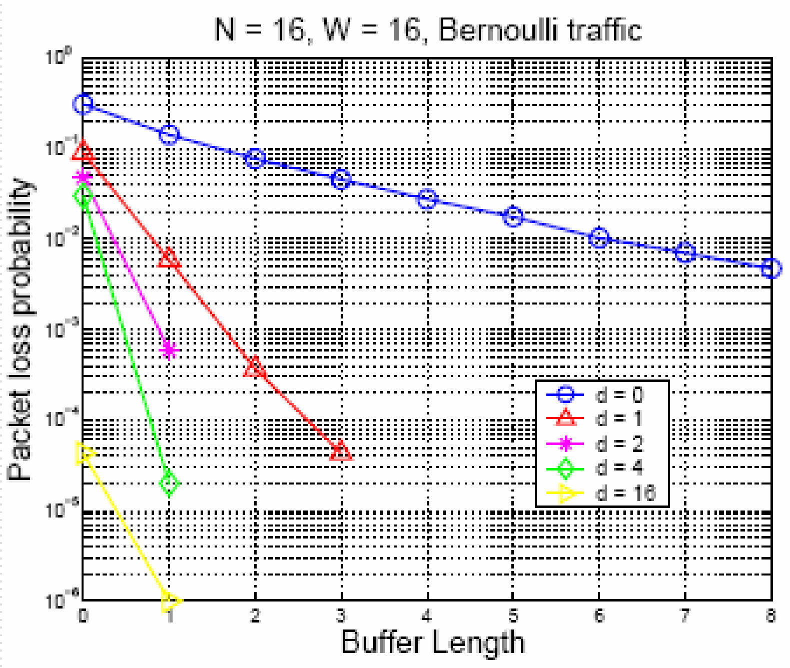
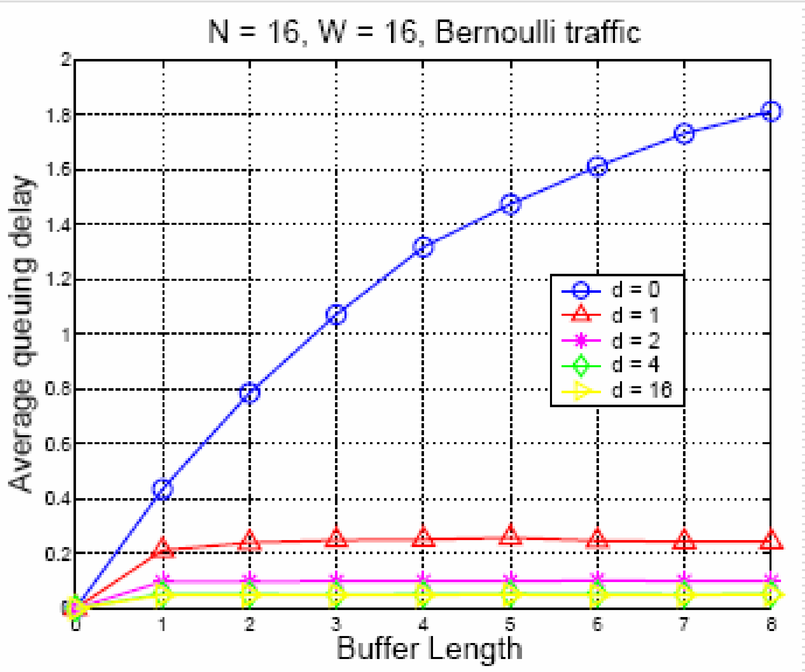
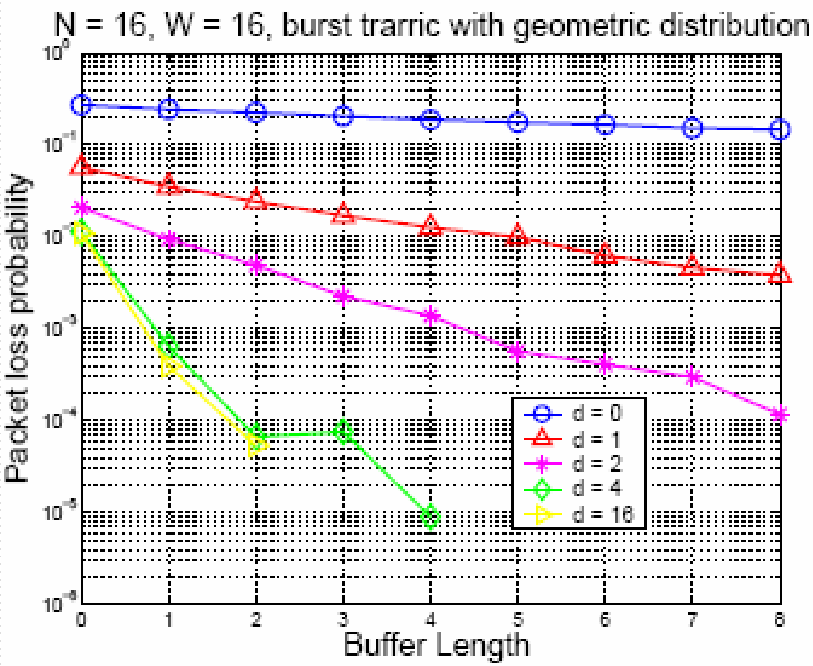
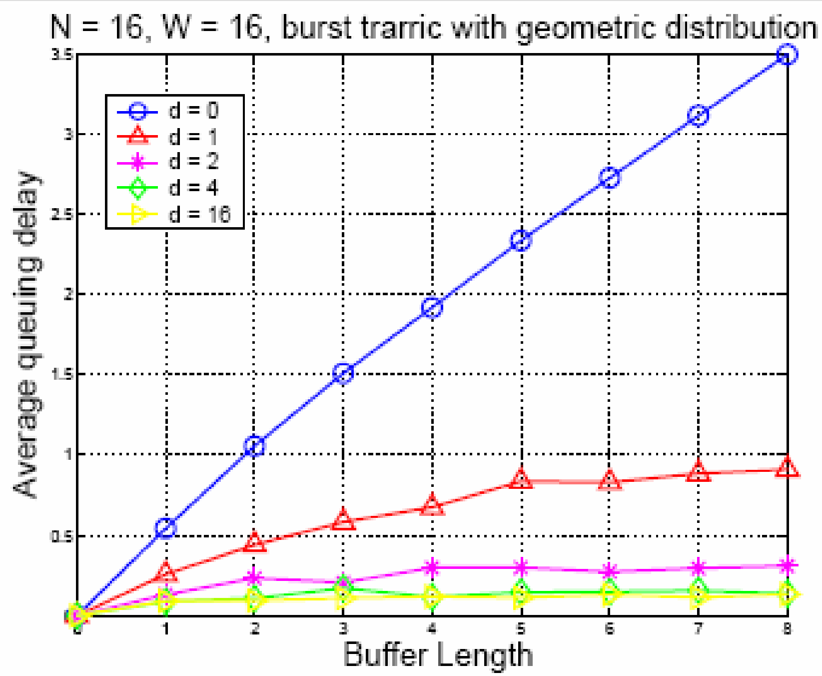
Simulation results – Bernoulli traffic



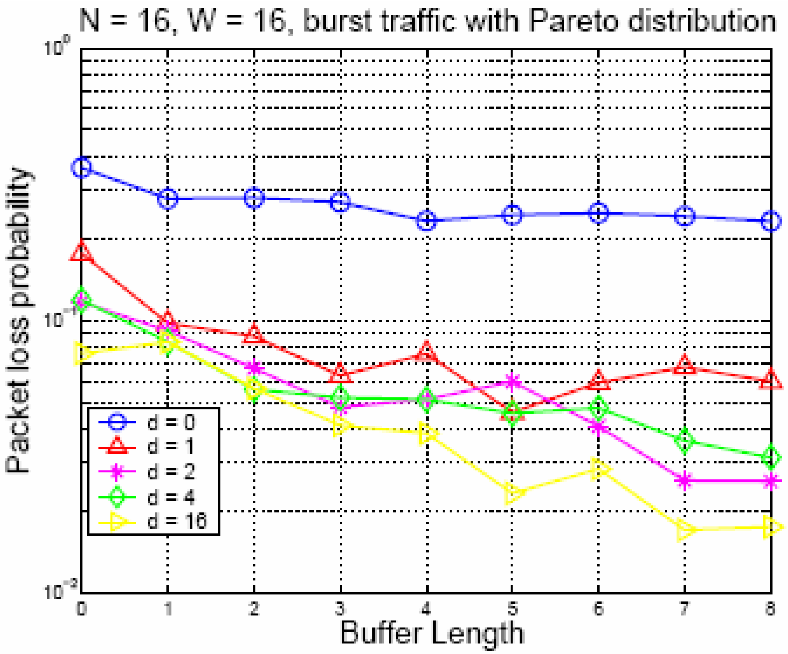


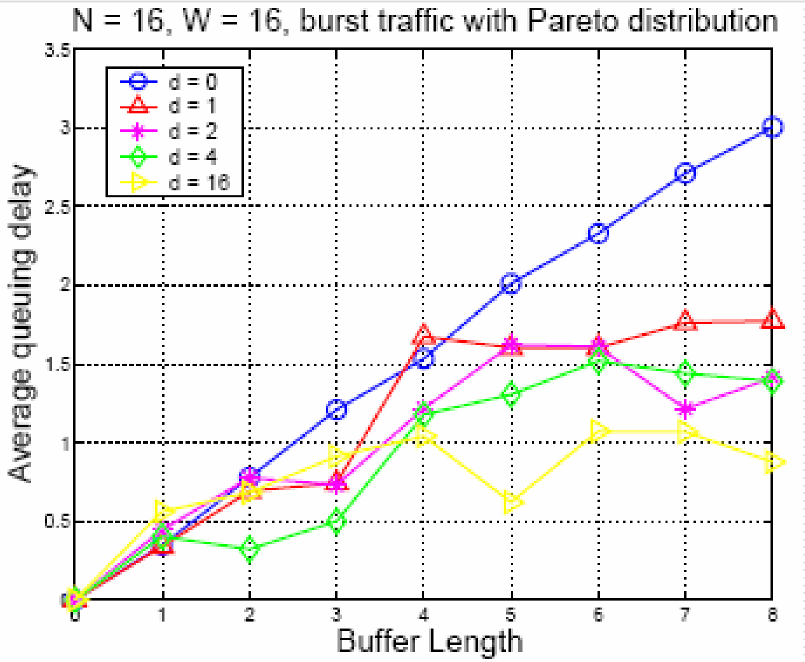
Simulation results – Burst traffic with geometric distribution





Simulation results – Burst traffic with Pareto distribution





Simulation results - Observations

- Under bursty traffic, packet loss probability drops rather slowly with the increase of the buffer length.
- The ability of wavelength conversion is critical, while it is not necessary to be full-range.
- System performance can greatly benefit from the reduction of traffic burstness.

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Conclusions

- We studied packet scheduling in WDM optical packet switches with output buffer and limited-range wavelength conversion
  - We showed that the output buffer can be viewed as a separate FIFO queuing buffer on each output wavelength channel.
  - We formalized the problem of finding an optimal scheduling in such a switch into a minimum cost maximum flow problem.

Conclusions

- We presented a new algorithm to find an optimal scheduling.
  - The Augment to Full Algorithm
  - The scheduling construction algorithm
  - Low time complexity – $O(\min(W^2, BW))$
- Can be applied to any output-buffered WDM optical packet switches whose output buffer on each wavelength can be modeled as an FIFO.

Thank you!

- Questions?