Multi-granular Waveband Switching in Optical Networks

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Outline

- Optical Networks
  - Why Optical Networks?
  - Wavelength Routed Network
  - Connection establishment
- Multi-granular Waveband Switching
  - Architectures
  - Traffic Grouping (or Wavebanding) Strategies
  - Wavebanding Approaches: Optimal (via ILP) and Heuristic
- Summary

Why Optical Network?

- Extraordinary transmission capacity
  - 25THz * 1bit/Hz = 25Tbps
    - Tbps = 10^{12}bps = 17million phone calls = 500, 000 compressed TV channels

- Most cost-effective
  - Cost/bit down by over 90% in last several years

- Traffic demand explosion
  - Internet growing at 100%/year (32x in 5 years)
    - "US Bancorp backs up 100 TB financial data every night – now."
      - David Grabski (VP Information Tech. US Bancorp), Qwest High Performance Networking Summit, Denver, CO. USA, June 2006.
    - "The Global Information Grid will need to store and access exabytes(10^{18}) of data on a realtime basis by 2010"
      - Dr. Henry Dardy, Optical Fiber Conference, Los Angeles, CA USA, Mar. 2006

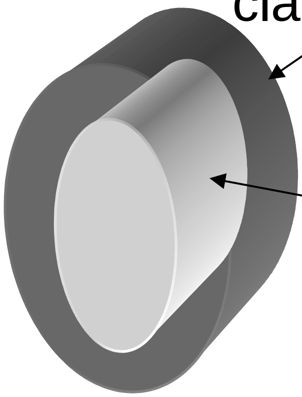
  - Electronic networks can hardly handle this traffic explosion

2006-7 BCS Championship Game Stadium

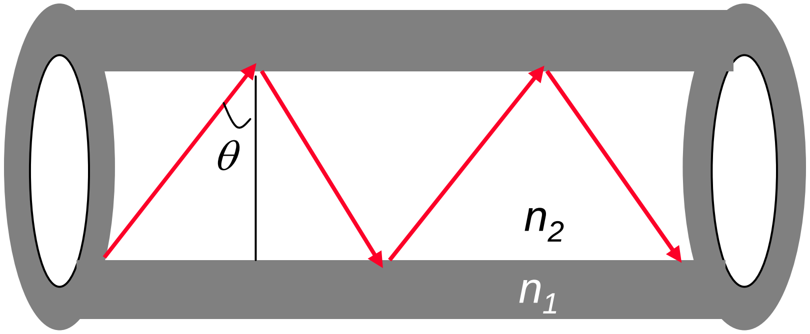
- Network comprising more than 100,000 feet of fiber

Optical fiber

- Fiber:a thin filament of glass that acts as a *waveguide*



Fiber

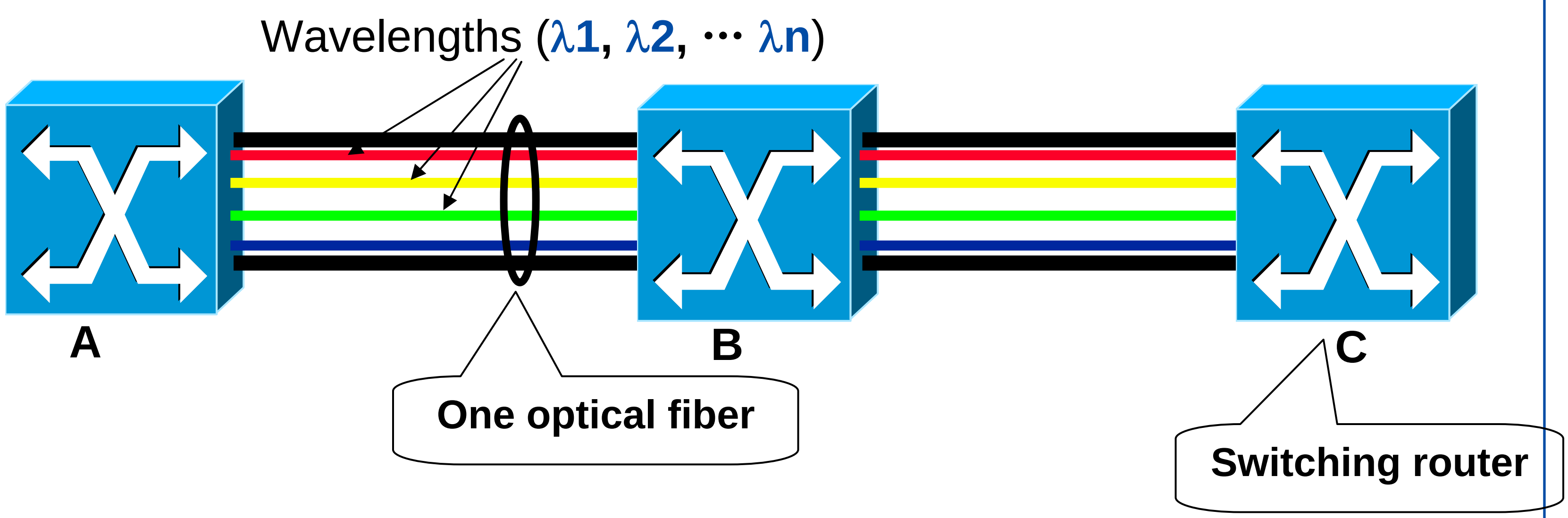


- Transmission via *total internal reflection*

1. $n_2 > n_1$
2. θ >critical angle
3. Critical angle=$\sin^{-1}(n_1/ n_2)$, **Snell's Law**

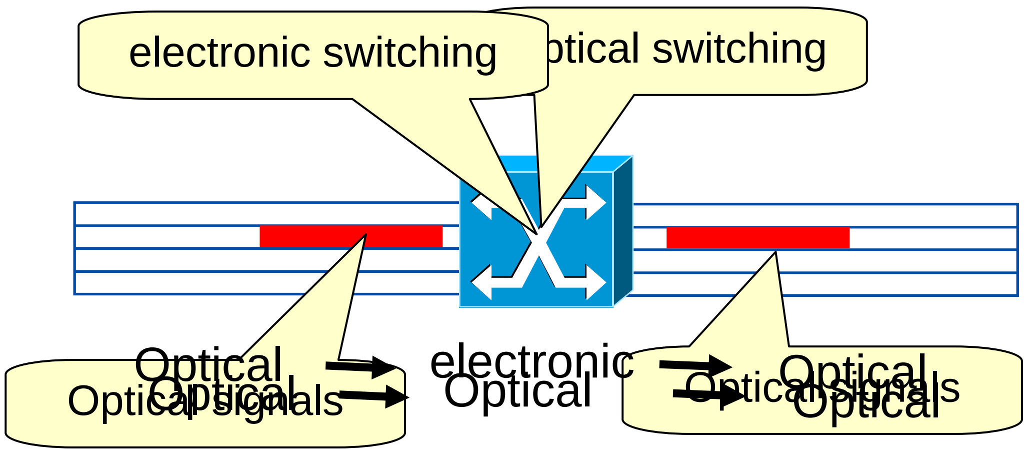
Current optical transmission technology

- Wavelength division multiplexing (WDM)
  - Each fiber carries multiple non-overlapping wavelengths (λ)
  - Each wavelength carrying huge data/traffic (e.g.,10Gbps)
  - Users transmit data at the *same* time on different wavelengths (colors)

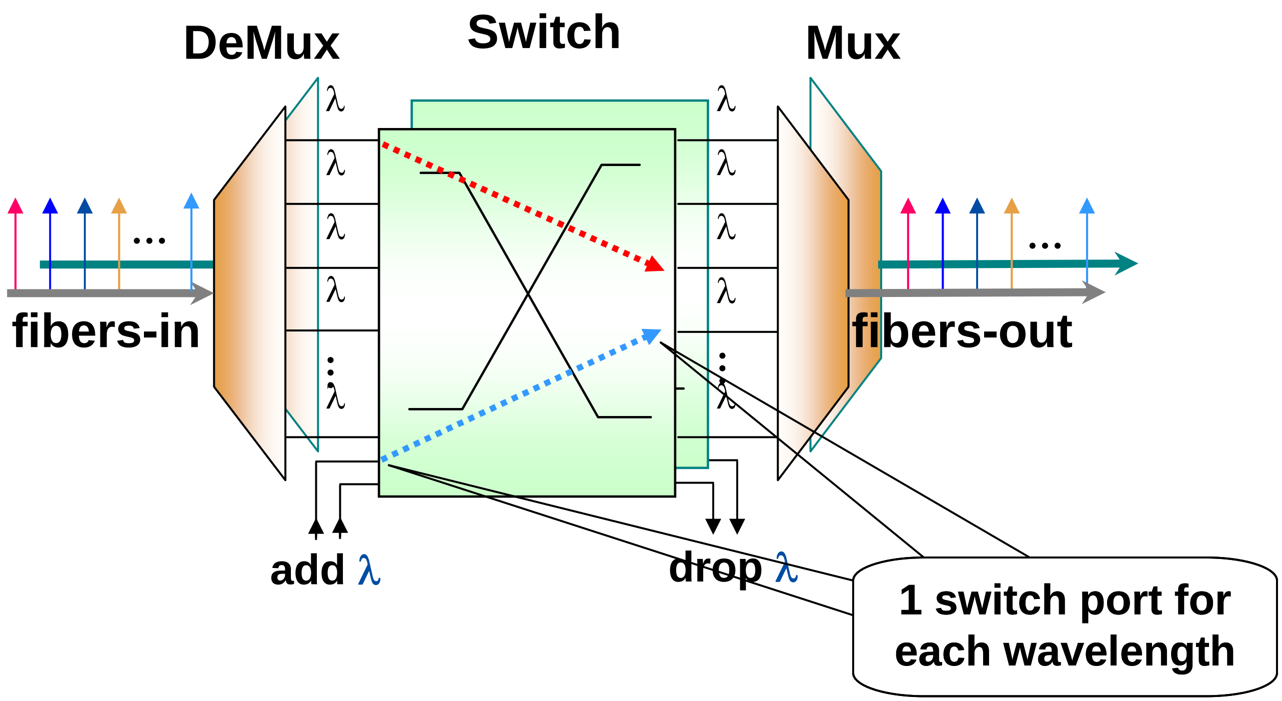


What is Optical Networking?

- Using optical fiber as medium for sending information
  - Optical Transmitter/ Receiver, Optical Amplifier
  - Transmission: **Optical Fiber**
  - Switching: could be optical, could be electronic
    could be circuit, could be packet, could be **burst**



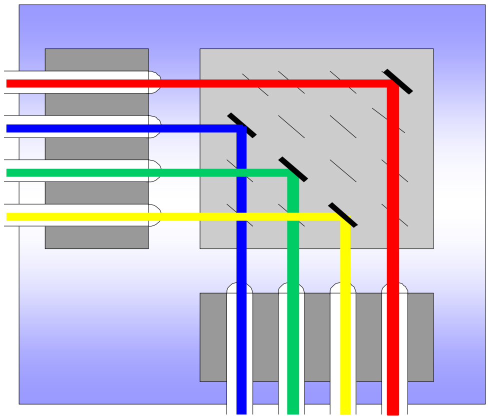
Optical Cross-connect (OXC): switching router

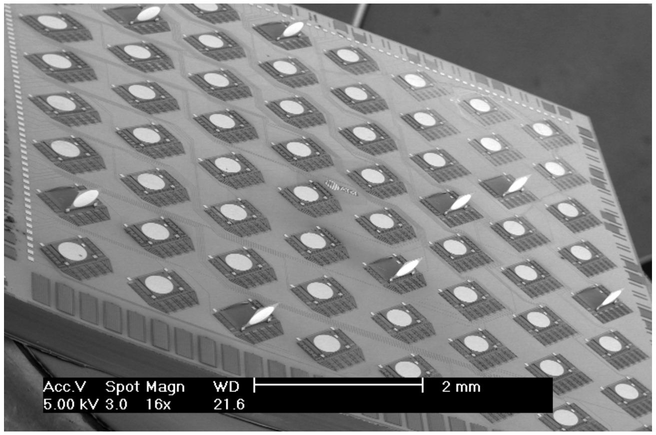


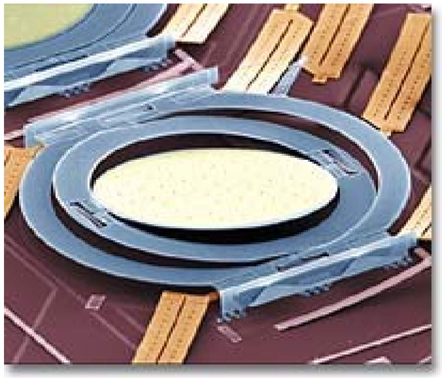
- OXC is a key component to manage/route traffic
- Components of an OXC node
  - DeMux/Mux - split/combine the wavelengths in fibers
  - Switch - connects the wavelengths to one another using ports
    - Requiring one port for each wavelength

OXC Switching Fabric Example

MicroElectroMechanical Systems (MEMS)







A MEMS Mirror

- NxN switch: N^2 mirrors
- ms switching speed

Major Optical Networking Issues

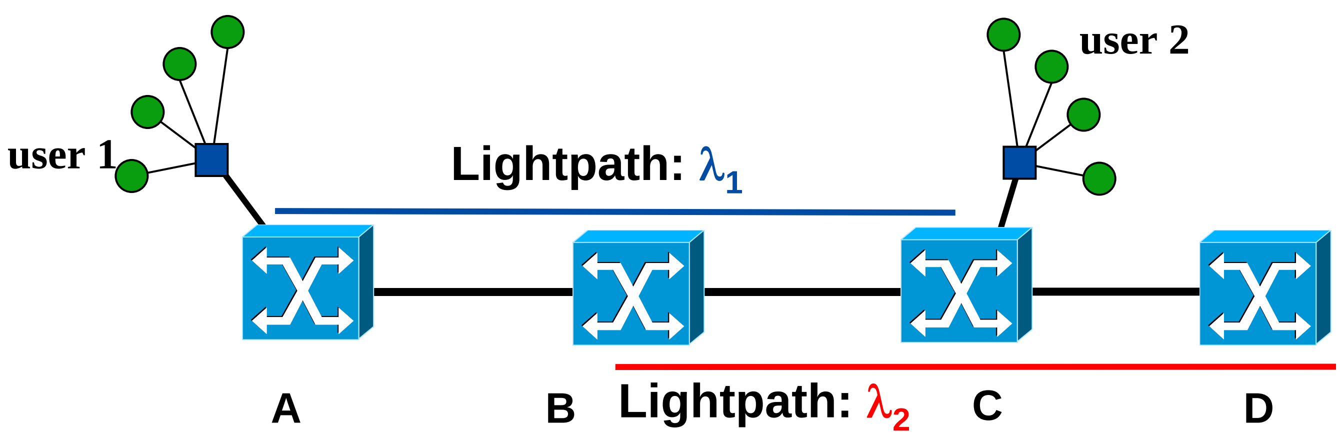
- No optical buffer memory (i.e. RAM)
- Difficult to process packet headers at high speed or optically
  - Electronic processing expensive
    - Scalability, power, latency
- Lack of precision optical synchronization
- Contention of traffic at the switching routers
- Survivability is extremely important

Paradigms of Optical Switching

- Switching technologies
  - Optical Packet Switching
    - optical buffer and logic not be available for a long time
  - Optical Burst Switching
    - fast, nanosecond optical switches
  - Optical Circuit Switching
    - Simpler, switch wavelengths rather than switching bits.
    - Wavelength Routed Networks (WRNs)
      - Waveband Switching (WBS)

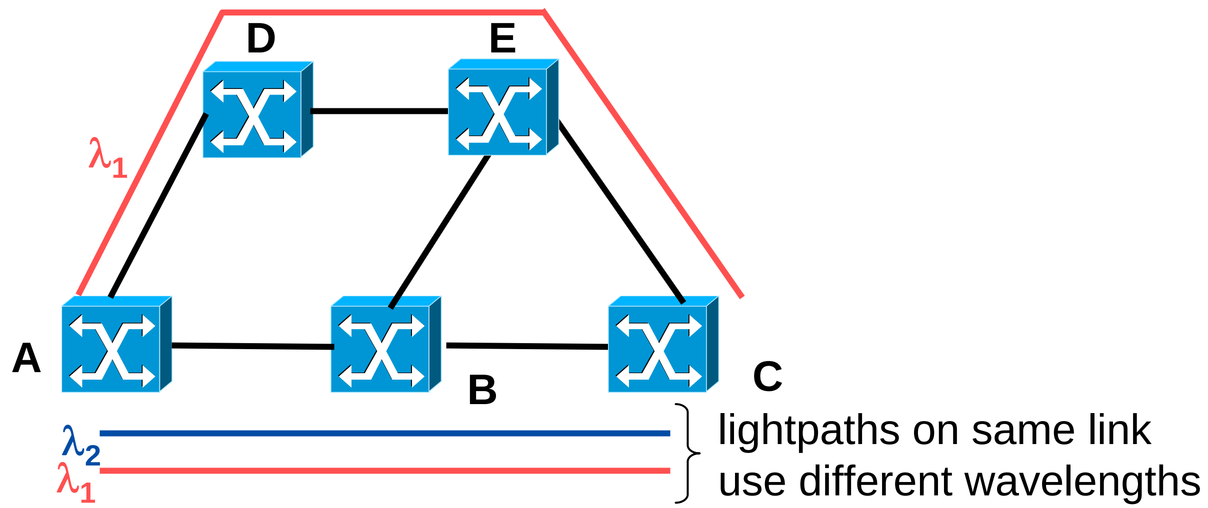
Wavelength Routed Networks (WRNs)

- Physical topology
  - Switching routers (i.e., cross-connects) connected by fiber links.
- Circuit Switching using Lightpaths
  - A lightpath has to be setup before data transmission
  - A lightpath is a connection between two nodes
  - Setup by using a dedicated wavelength (λ) on each fiber link.



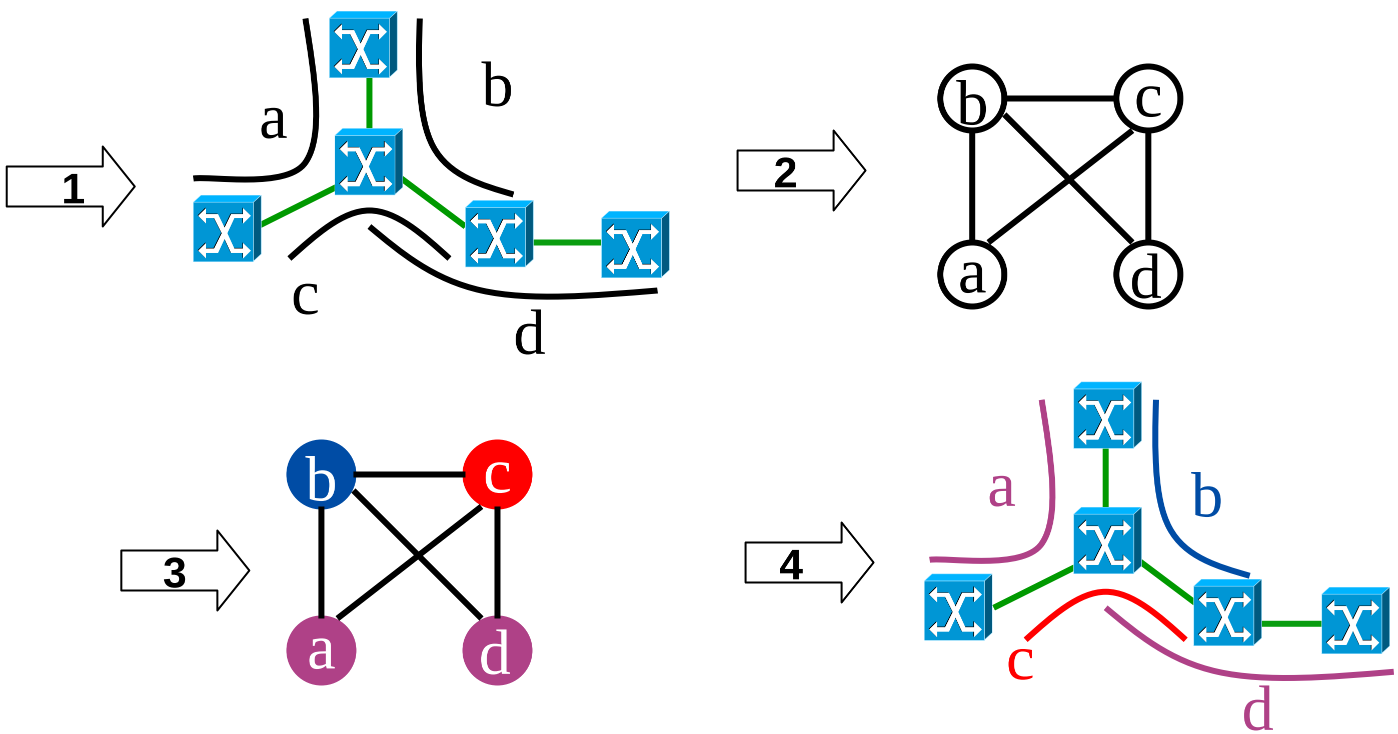
Routing and Wavelength Assignment (RWA)

- Definition
  - Given: network topology, a set of end-to-end lightpath (i.e. connection) requests
  - Problem: Determine routes and wavelengths for the requests
- Constraints
  - Wavelength capacity: lightpaths can't use the same wavelength (color) on the same link.
  - Wavelength continuity: a lightpath must use the ***same*** wavelength on all the links it spans (No wavelength conversion)



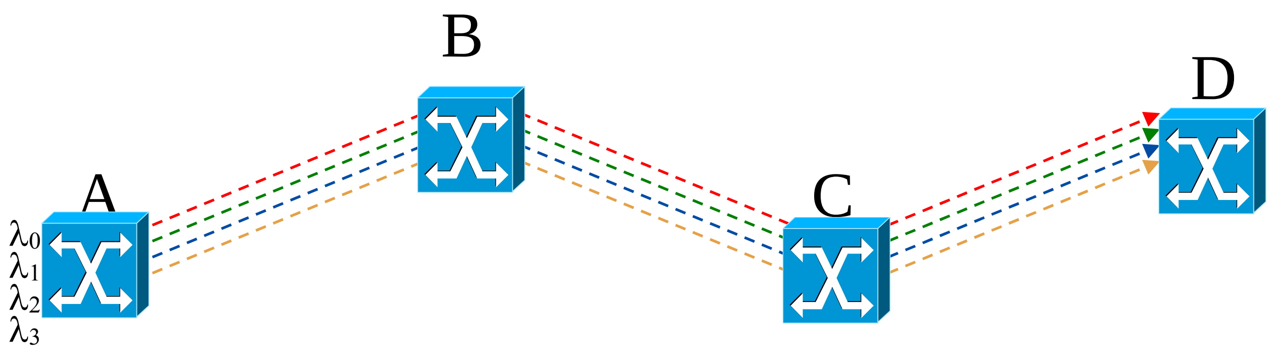
Optimal RWA is NP-Complete

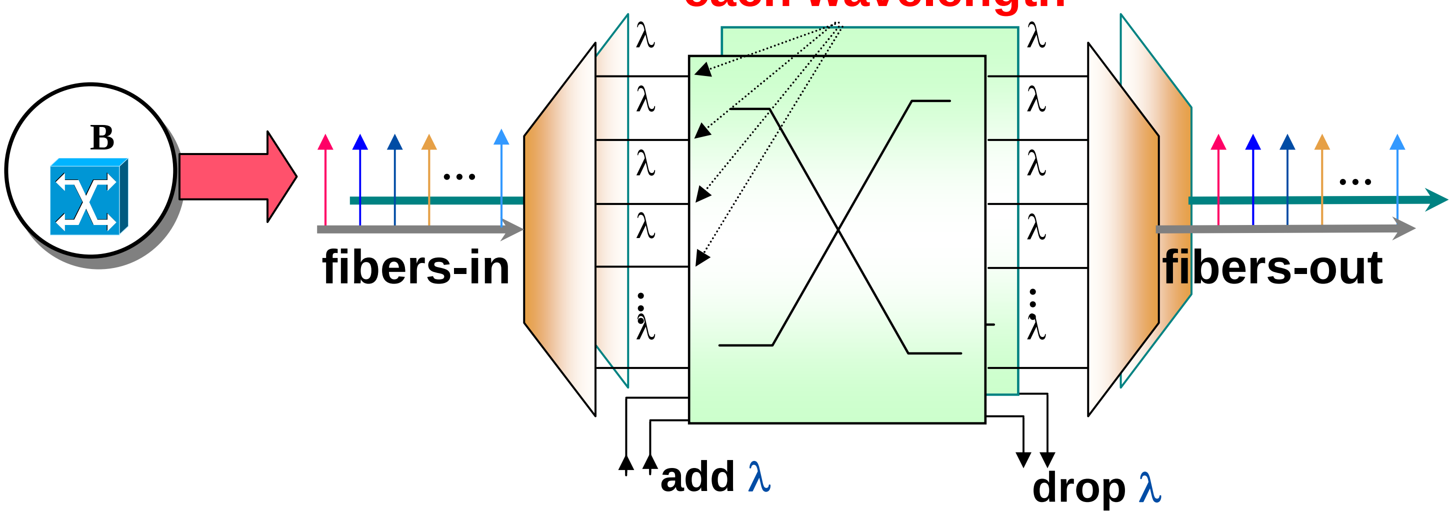
- Objective:
  - Establish ***all*** the connections using ***minimum*** number of wavelengths
- Two sub-problems
  - Routing
  - Wavelength Assignment (WA) - graph coloring



Multi-granular Waveband Switching

Wavelength Routed Networks (WRNs)– Revisited





Optical Cross-connect (Ordinary-OXC)

Why Waveband Switching?

- To satisfy the ever increasing traffic demand
  - Use a large number of fibers & more wavelengths per fiber
- Increases the size (i.e., port counts) of ordinary-OXC
  - Manufacturing & deploying large OXCs is expensive
    - Huge CApital EXpenditures (CAPEX)
  - Managing/controlling large OXCs is critical but difficult
    - Huge OPerating EXpenditures (OPEX)
  - The deployment and potential use of large OXC is limited
    - Unproven reliability (e.g.1000x1000 ports)
    - huge costs
    - (un) scalability
- Need a more cost-effective way to manage a large number of wavelengths

The Waveband Switching Solution

- 60-80% is bypass traffic
  - avoid demux every fiber
- A new flexible switching technique – Waveband Switching (WBS)
  - Waveband: a group of several wavelengths
  - All wavelengths in the band are switched as a ***single*** entity (using one port)
- A new OXC architecture – Multi-Granular OXC (MG-OXC) can switch traffic at multiple granularities
  - single-wavelength
  - wavelength-groups (bands)
  - entire fiber

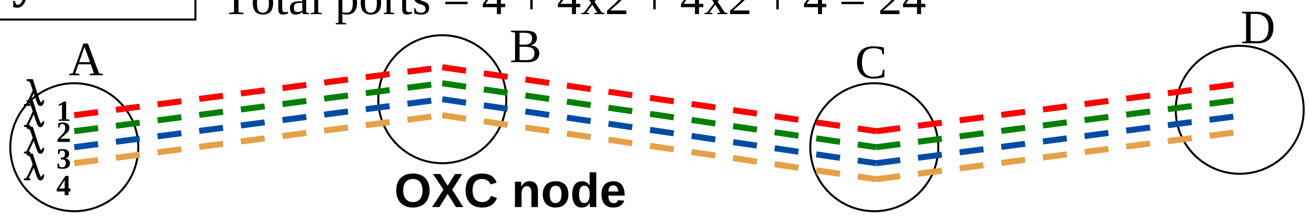
Port Saving

- All 4 lightpaths carry bypass traffic at B & C

Ordinary-OXC

Switch each wavelength ***individually*** at an OXC node

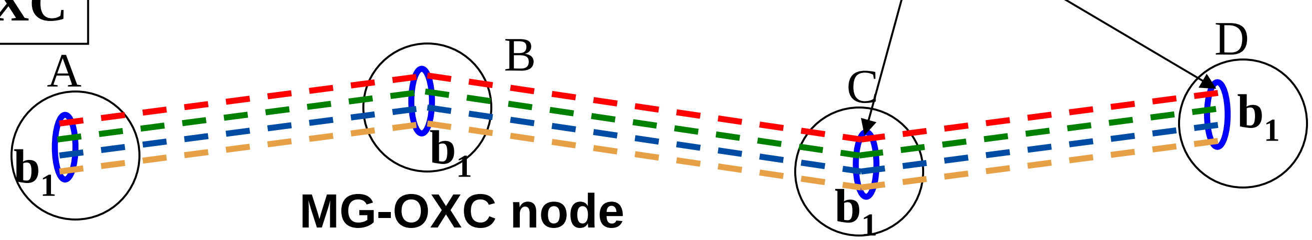
Total ports = 4 + 4x2 + 4x2 + 4 = 24



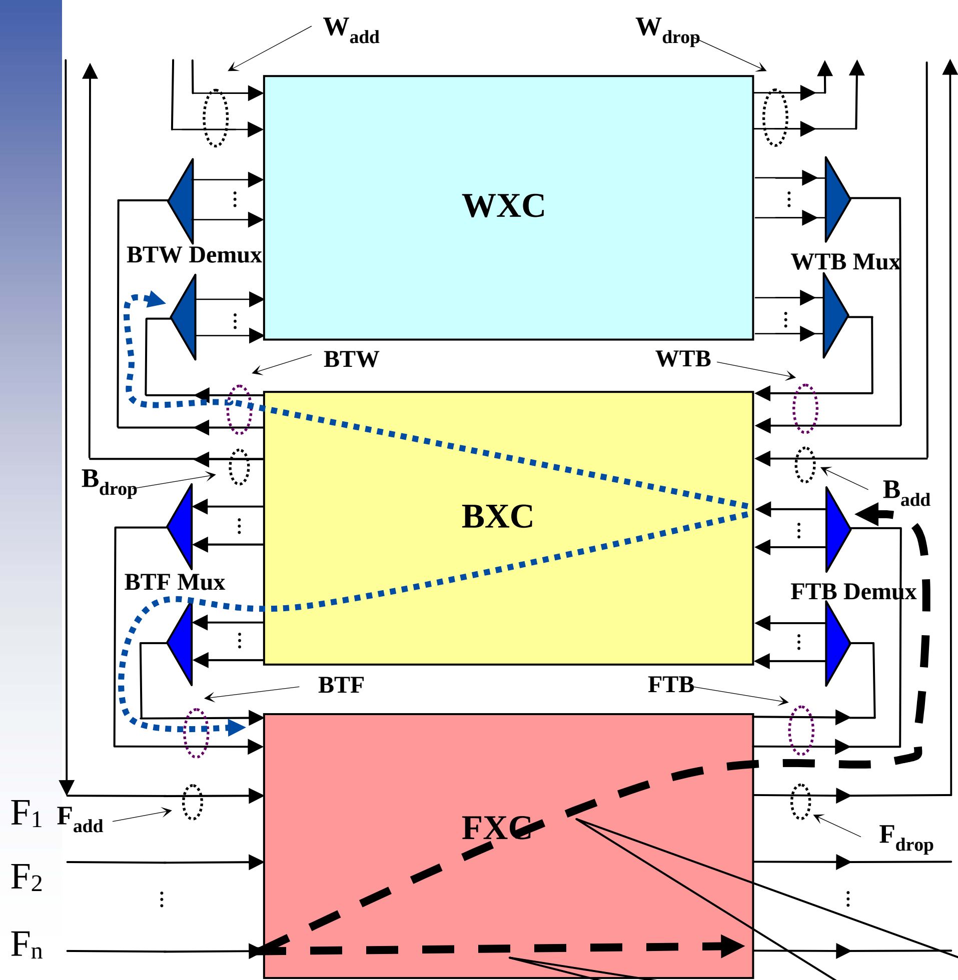
MG-OXC

Switch band of 4 wavelengths using ***1 port*** at an MG-OXC node

Total Ports = 1 + 1x2 + 1x2 + 1 = 6 **only!**



Three-layer Multi-Granular OXC (MG-OXC) for WBS



MG-OXC Architecture

If some traffic in some wavelengths needs to be dropped locally

If all traffic in *Fn* is bypass/through traffic

- FTB DeMux: fiber →bands
- BTW DeMux: band →wavelengths
- BTF Mux: bands→fiber
- WTB Mux: wavelengths →band
- Fibers/bands/wavelengths are switched at the FXC/BXC/WXC layers

WRNs Versus WBS

- Wavelength Routed Networks
  - Switch lightpaths only at wavelength level
  - Need one switch port for each wavelength
  - Using Ordinary-OXC
  - Need to solve RWA
- Waveband Switching Networks
  - Switch lightpaths at Fiber, band, wavelength level
  - May switch a group of wavelengths using one port
  - Using MG-OXC
  - Need to solve RWA + Grouping

- Major merits of WBS
  - reduce port count
  - reduce complexity
  - simplify network management
  - better scalability

Challenges Addressed in My Work

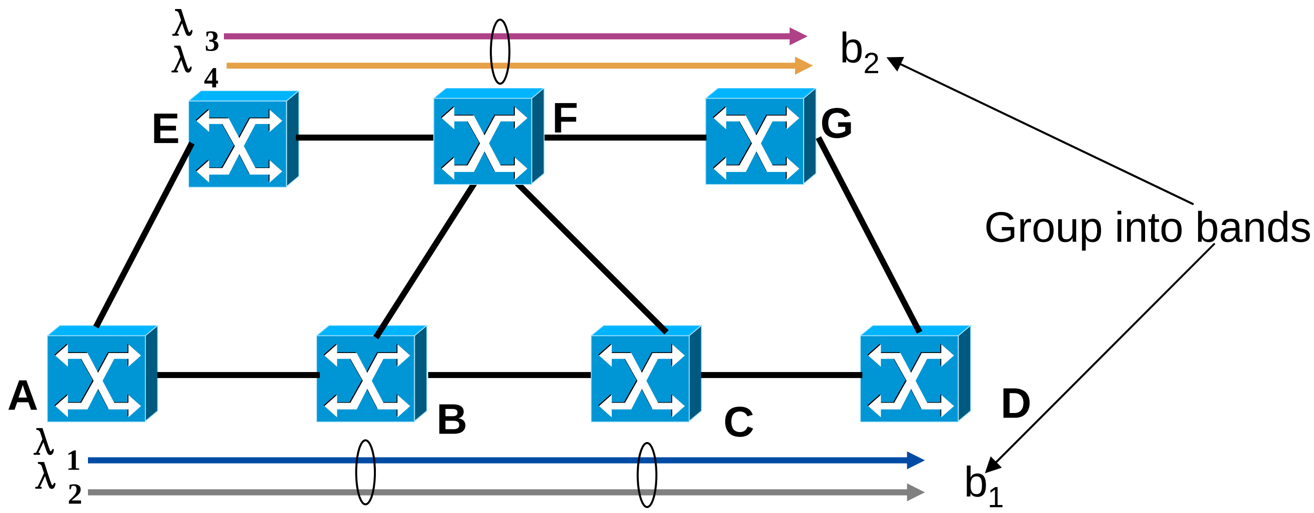
- MG-OXC architecture design
  - Compare different MG-OXC architectures
  - Reconfigurable MG-OXCs
- New algorithms and analytic models are needed
  - Static traffic (Off-line case)
    - Multi-Fiber vs. Single-Fiber
  - Dynamic traffic (On-line case)
    - Incremental traffic
    - Fully dynamic traffic
  - Wavelength/waveband conversion
  - Protection/restoration in WBS networks
- Has more constraints (i.e., grouping): optimization is still NP-complete
- Our methods:
  - Integer Linear Programming (ILP), Dynamic Programming, Markov Chain, Rational Approximation, Heuristic Algo., etc.

Static Waveband Switching (WBS) problem (Off-line Case)

- Given:
  - Network topology
  - Each fiber has a fixed number of bands (*B)*
  - Each band has a fixed number (*W)* as well as a fixed set of wavelengths
  - Static traffic demands
  - No wavelength conversion
- Goal:
  - Satisfy ***all*** traffic with a ***minimum*** number of ports

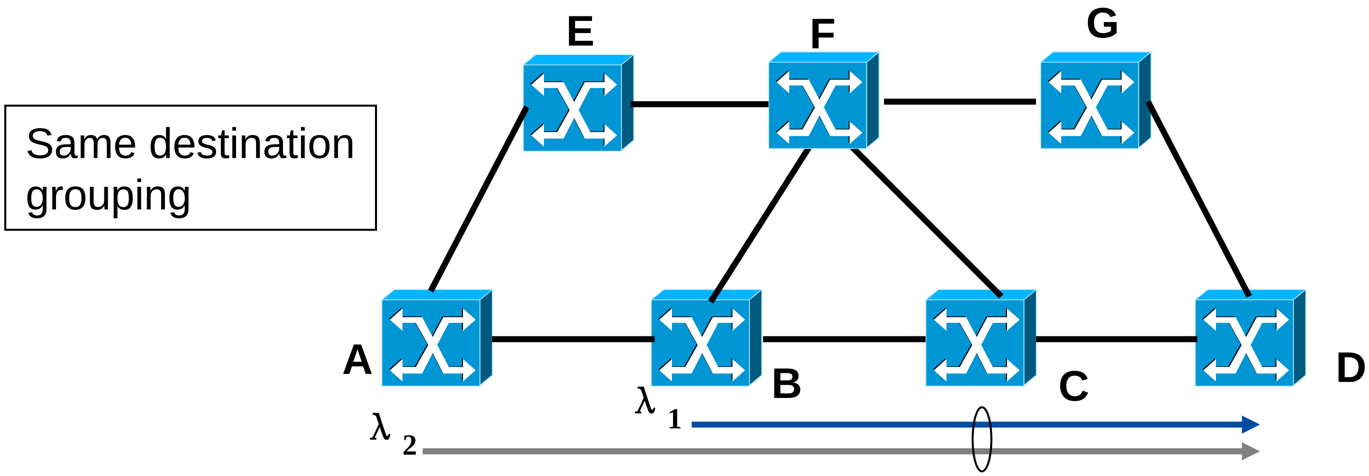
Group Strategies: End-to-end grouping

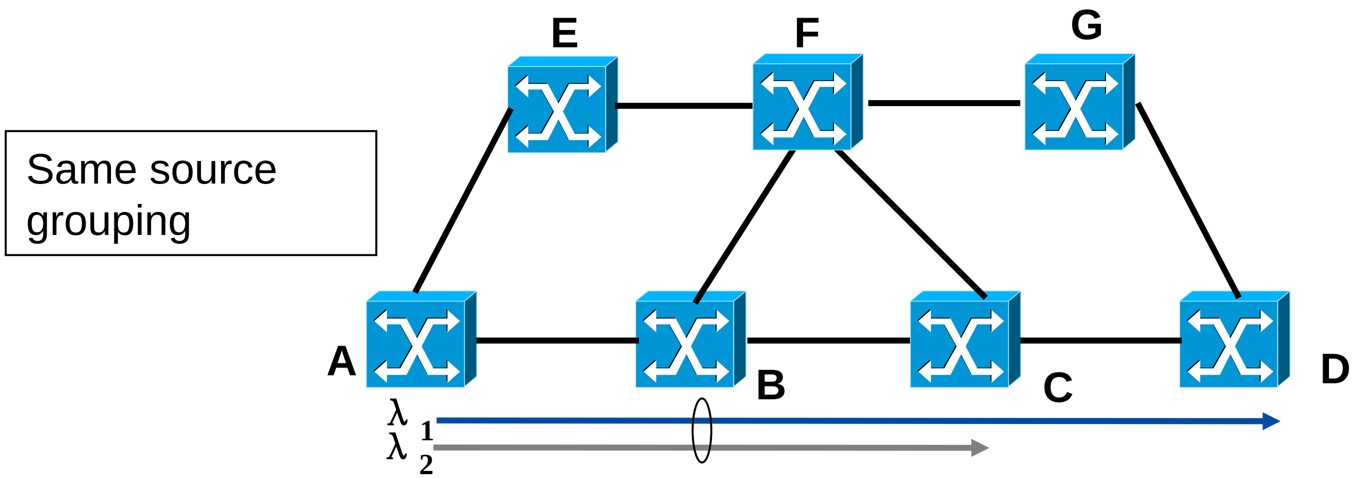
- Group lightpaths with the *same* source-destination pair only



Group Strategies: One-end grouping

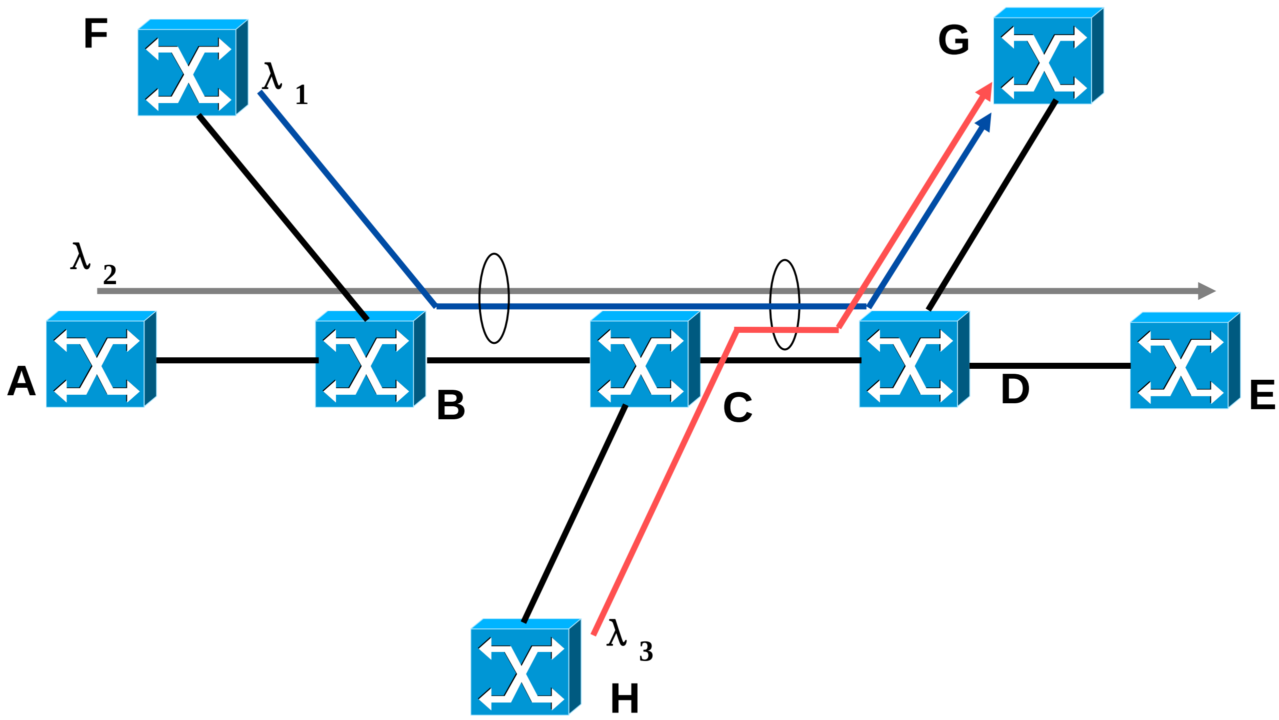
- Group lightpaths from the ***same source*** or lightpaths with ***same destination***





Group Strategies: Sub-path grouping

- Group lightpaths with common intermediate links (i.e. sub-paths), from *any* source to *any* destination



- Sub-path grouping is the most powerful, but also complex. We are the first to utilize this method.

Static WBS problem: Approach

1. Integer Linear Programming (ILP)
   - Optimize the routes, wavelength assignments/grouping
   - Not feasible for large problem sizes
     - Uses too much time and memory
   - Serves as a performance yardstick for other heuristics
     - Optimal, uses a minimum number of ports

2. Heuristic Algorithms
   - Waveband Oblivious (optimal) RWA (WBO-RWA)
   - Balanced Path with Heavy-Traffic first waveband assignment (BPHT)

3. Performance analysis of BPHT and establish lower and upper bounds on port count

ILP model for WBS

- Objective:

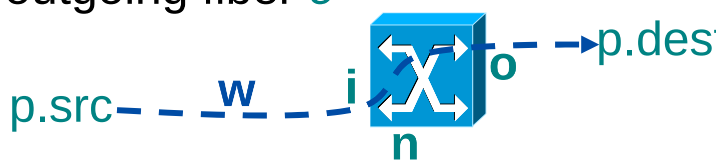
$$\min[\alpha \times \sum_n WXC_n + \beta \times \sum_n BXC_n + \gamma \times \sum_n FXC_n]$$

- Weight or coefficient of cost per port
  - α: WXC layer
  - β: BXC layer
  - γ: FXC layer
- $\alpha = \beta = \gamma = 1$, minimize the total number of MG-OXC ports in the network

ILP model for WBS: Constraints

- Traffic flow constraints
  - Satisfy all the traffic demands

$$V_{i,o,p}^{n,w} = \begin{cases} 1 & \text{if a lightpath for node pair } p \text{ passes node } n \text{ using wavelength } w \text{ from incoming fiber } i \text{ to outgoing fiber } o \\ 0 & \text{otherwise} \end{cases}$$



t_p: traffic demand of node pair *p*

If node n is the source node of p, then the number of lightpaths adding from node n has to be tp

$$\begin{cases} \sum_{w, i \in A_n, o \in O_n} V_{i,o,p}^{n,w} = t_p, \quad n = p.src \quad \forall p \\ \sum_{w, i \in I_n, o \in D_n} V_{i,o,p}^{n,w} = t_p, \quad n = p.dest \quad \forall p \end{cases}$$

If node n is the destination node of p, then the number of lightpaths dropping from node n has to be tp

ILP model for WBS: Constraints cont.

- Wavelength capacity-constraint

$$\begin{cases} \sum_{p,o \in O_n} V_{i,o,p}^{n,w} \le 1, & \forall n,w,i \in I_n \\ \sum_{p,i \in I_n} V_{i,o,p}^{n,w} \le 1, & \forall n,w,o \in O_n \end{cases}$$

- Wavelength continuity-constraint
- Waveband switching
  - Appropriately switch the lightpaths through the switch fabrics
- Mux/Demux
  - Appropriately Mux/Demux the lightpaths
- Detailed formulations in our papers
  - Use CPLEX solve all the formulations
  - Map variables (e.g., V) back to waveband assignment

Heuristic: Waveband Oblivious RWA (WBO-RWA)

- Based on an optimal RWA
  - Routing and wavelength assignment (RWA) is completely ***oblivious*** to the existence of wavebands
- Then group the assigned wavelengths into bands and calculate the number of required ports
  - The grouping is done as an ***afterthought***
- As to be shown, WBO-RWA is not efficient in WBS
  - Efficient in Wavelength Routed Networks (WRNs)
  - In general, existing techniques for WRNs cannot be directly applied to WBS

Heuristic: BPHT – basic ideas

- Balanced Path with Heavy-Traffic first waveband assignment (BPHT)

1. Load balanced routing of lightpaths
2. Wavelength assignments
   - based on *sub-path* grouping

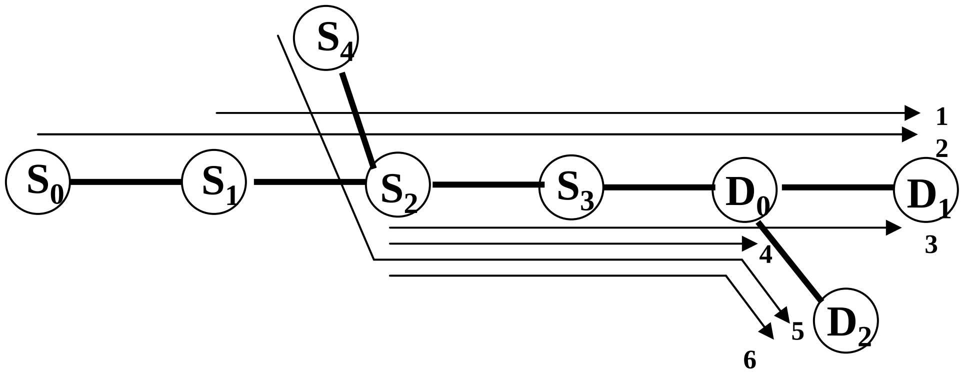
   a. Define a set Q_{sd} for every node pair (s,d), which includes all its subpaths. Calculate weight for each set

$$W_{sd} = \sum_{p \in Q_{sd}} h_p * T_p$$

   b. Starting with largest weight (or heaviest traffic) set,
   - assign wavelengths to lightpaths from s
   - assign wavelengths to lightpaths to d
   - Recursively assign wavelengths, until all sub-paths are assigned
3. Group and switch as many wavelengths into bands

Illustration of BPHT

After load balance



- Source S_0, destination D_1

$$LP_{S_0D_1} = \{1,2,3,4\}$$

$$W_{S_0D_1} = \sum_{p \in P_{D_1}^{S_0}} h_p \times t_p = 5\times1 + 4\times1 + 3\times1 + 2\times1 = 14$$

DONE

- Source S_4, destination D_2

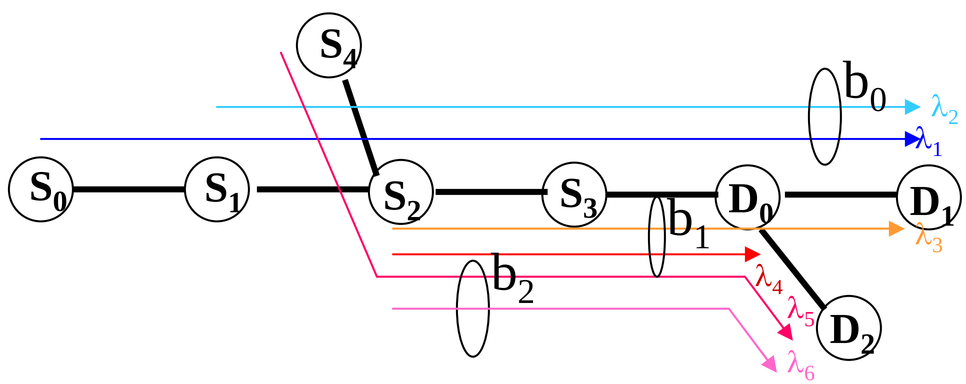
$$LP_{S_4D_2} = \{4,5,6\}$$

$$W_{S_4D_2} = \sum_{p \in P_{D_2}^{S_4}} h_p \times t_p = 9$$

X

RECOMPUTE

Start wavelength assignment



$$LPs_4D_2 = \{5,6\}$$

$$W_{S_4D_2} = \sum_{p \in P_{D_2}^{S_4}} h_p \times t_p = 7$$

DONE

Performance Analysis

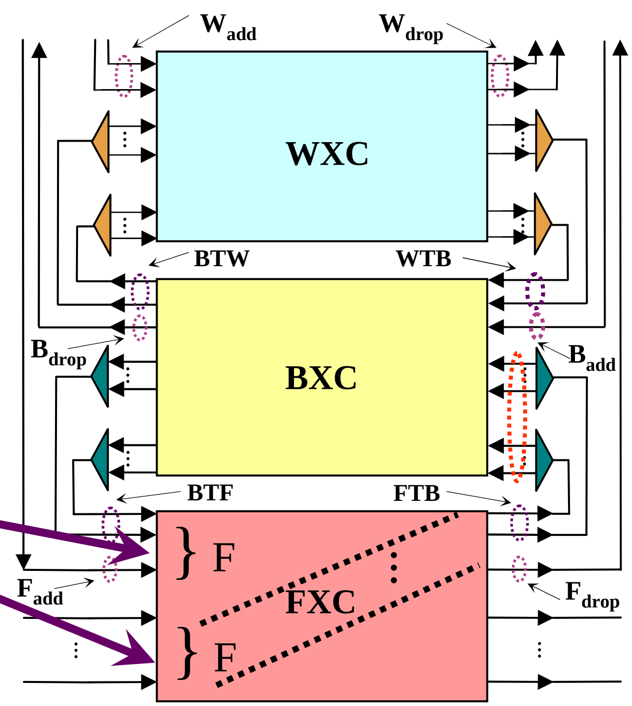
- Analyze the total number of ports in an MG-OXC network
  - Based on BPHT
  - Port count=P(mux/demux)+P(add/drop)+P(switching)
- Provide lower bound and upper bound on the total port count
  - G: lightpaths from incoming links
  - A: added lightpaths
  - K: number of wavelengths (λs) per fiber
  - N: node number, δ : average node degree
  - F: number of fibers,
  - B: number of bands per fiber

$$\text{LowerBound} = \left(\left\lceil \frac{G}{K} \right\rceil + \left\lceil \frac{A}{K} \right\rceil\right) \times \delta \times N$$

$$\text{UpperBound} = \{\min[(A+G), F\times 2] + \min[(A+G), F\times B\times 2] + (A+G)\}\times \delta \times N$$

Ports from BXC layer

Ports from WXC layer



Simulation Results I: random 6-nodes network

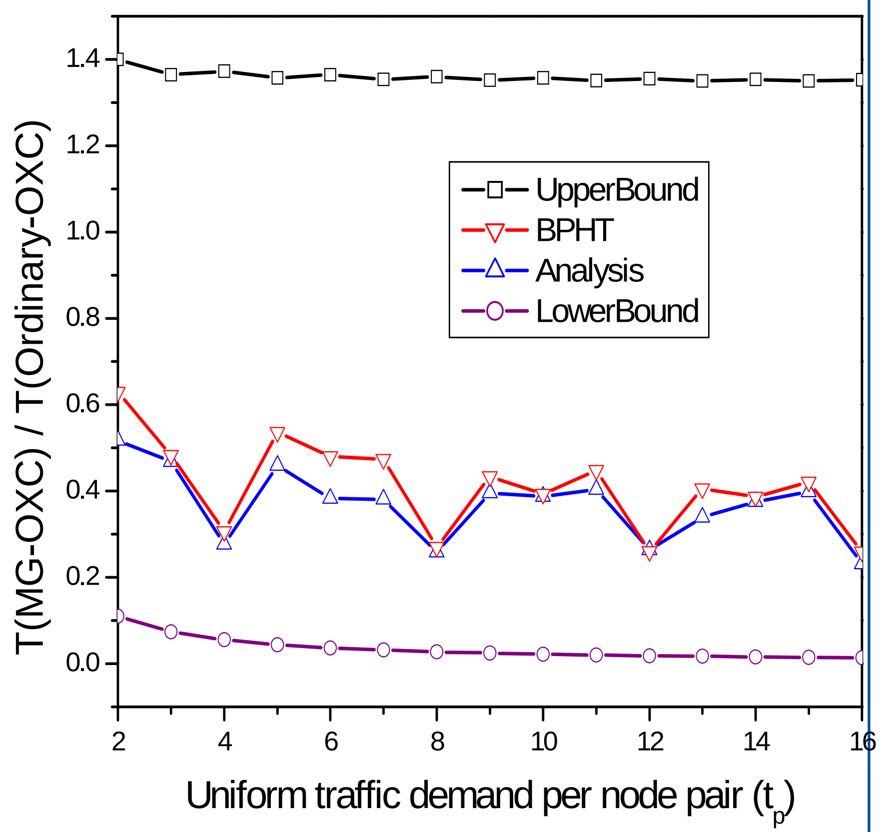
- Results of ILP model, Algorithm WBO-RWA and Algorithm BPHT

Metrics	**Optimal** WBS using ILP	WBS using WBO-RWA	WBS using BPHT
Total network ports	4500 ★★★	8300 ★	4900 ★★½
Max. node ports	480 ★★★	1160 ★	600 ★★½
Wavelength resources	10,400 ★	10,000 ★★★	10,200 ★★

- ILP: optimal results, *but* very time consuming
- Heuristic WBO-RWA: inefficient – too many ports
- Heuristic BPHT: sub-optimal, very ***fast***
- ILP and BPHT – in the process of **reducing** the ports use **more** wavelengths, ***a trade-off***

Simulation Results II-- large network, uniform traffic

- 14 nodes, 21 bidirectional links NSF Network, *W=4*
- ILP doesn't work due to its time/memory consuming
- X axis: *tp*, number of lightpaths between each node pair *p*
- Y axis: ratio of the total ports needed by MG-OXC and ordinary-OXC
- MG-OXC *reduce* ports (cost)
- When *tp* is multiple of band size (i.e,*W=4*)
  - Add/drop/bypass at the ***band*** granularity
  - No lightpaths switch through WXC layer



Other Simulations & Selected Studies

- Simulation scenarios
  - Different network topology
  - Different band size
  - Random traffic vs. Uniform traffic
- Other selected studies: efficient algorithms and theoretical models
  - Multi-fiber vs. Single-Fiber
  - Dynamic traffic (e.g., Incremental, fully dynamic)
  - Waveband conversion
  - Protection/Restoration
- Found a number of useful **insights**
  - E.g., effect of band size, effect of multi-fiber, trade-offs, effect of waveband conversions

Summary

- Internet traffic ***continues*** to grow
- Electronic networks ***incapable*** of satisfying the exponential growth
- Optical networks provide the solution: Waveband Switching (WBS)
  - Cheap and reliable service
  - *Reduce* the ***cost*** of building and managing optical networks
- Optical networking is a ***Promising*** field
  - Tremendous potential remains ***unexploited***
  - Much ***research*** needs to be done
  - Will be an ***exciting*** field of research for many many years to come

Questions?

Thank you!