

WDM Optical Interconnect Architectures Under Two Connection Models *

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*HOT Interconnects 10, Stanford University, August 2002

Overview

- Introduction
- Preliminaries
- Previous designs
- WDM optical interconnects under fiber-link-based model
- Extension to wavelength-based model
- Conclusions

Introduction

- Optical communication has become a promising networking choice to meet ever-increasing demands on bandwidth from emerging bandwidth-intensive computing/communication applications:
 - data browsing in the world wide web
 - multimedia conferencing
 - e-commerce
 - video-on-demand services
- As optics become a major networking media in all communications needs, optical interconnects will also play an important role in inter-connecting processors in parallel and distributed computing systems

Introduction

- Potential capabilities of optic technology
 - huge bandwidth
 - * a single optical fiber can provide a bandwidth of nearly 50 terabits per second
 - * four orders of magnitude higher than electronic data rate
 - low signal noise
 - low cost
 - * low material usage
 - * low power consumption
 - * small space requirement

Introduction

- Wavelength-division-multiplexing (WDM)
 - a promising technique to exploit the huge opto-electronic bandwidth mismatch
 - divide the bandwidth of an optical fiber into multiple wavelength channels
 - multiple devices can transmit on distinct wavelengths through the same fiber concurrently
 - next generation of the Internet is expected to employ WDM-based optical backbones

Introduction

- WDM optical interconnect
 - provides interconnections between a group of input/output fiber links with each fiber link carrying multiple wavelength channels
 - can provide much more connections than a traditional electronic interconnect
 - offers much richer communication patterns for various networking applications
 - can serve as a crossconnect (OXC) in a wide-area communication network
 - can provide high-speed interconnections among a group of processors in a parallel and distributed computing system

Introduction

- Challenges in designing WDM optical interconnects
 - how to design a high performance WDM optical interconnect with low hardware cost
 - * requires non-trivial extensions from the electronic counterpart
 - how to keep data in optical domain
 - * to eliminate the costly conversions between optical and electronic signals (O/E/O conversions)

Introduction

- Two approaches to meeting the challenges
 - use the same wavelength for a connection/lightpath throughout the network, known as wavelength continuity constraint.
 - use an all-optical wavelength converter to convert the wavelength of signals.
- Issues in designing cost-effective WDM optical interconnects
 - reduce network costs, including
 - * the number of crosspoints of switches
 - * the cost of wavelength converters
 - make trade-off between the connecting capability and the number of wavelength converters, along with other design factors

Preliminaries

- Connection models in WDM optical interconnects

Based on different applications, WDM optical interconnects can be categorized into different connection models:

- wavelength-based model

- * each device occupies a single wavelength on an input/output fiber link of a WDM optical interconnect

Example: an independent, simple device that needs only one communication channel.

- fiber-link-based model

- * each device occupies an entire input/output fiber link (with multiple wavelength channels)

Example: a processor with multiple input/output channels

Preliminaries

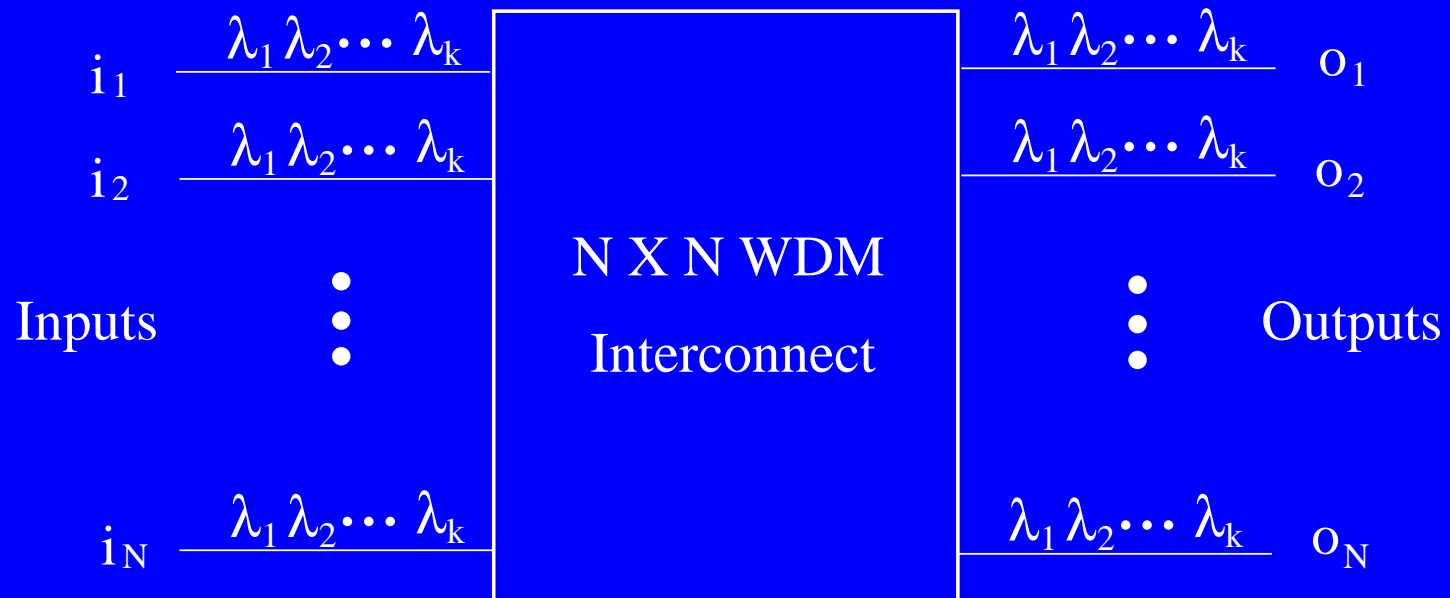
- hybrid models
 - * Example: use wavelength-based model on the network input side and fiber-link-based model on the network output side
- WDM optical interconnect offers much richer communication patterns than electronic interconnects

Example:

- permutation under wavelength-based model: a specific wavelength on the input side can be connected only to a specific wavelength on the output side.
- permutation under fiber-link-based model: a wavelength on a specific input fiber link can be connected to any one of the wavelengths on a specific output fiber link.

Preliminaries

- an $N \times N$ WDM optical interconnect with k wavelengths

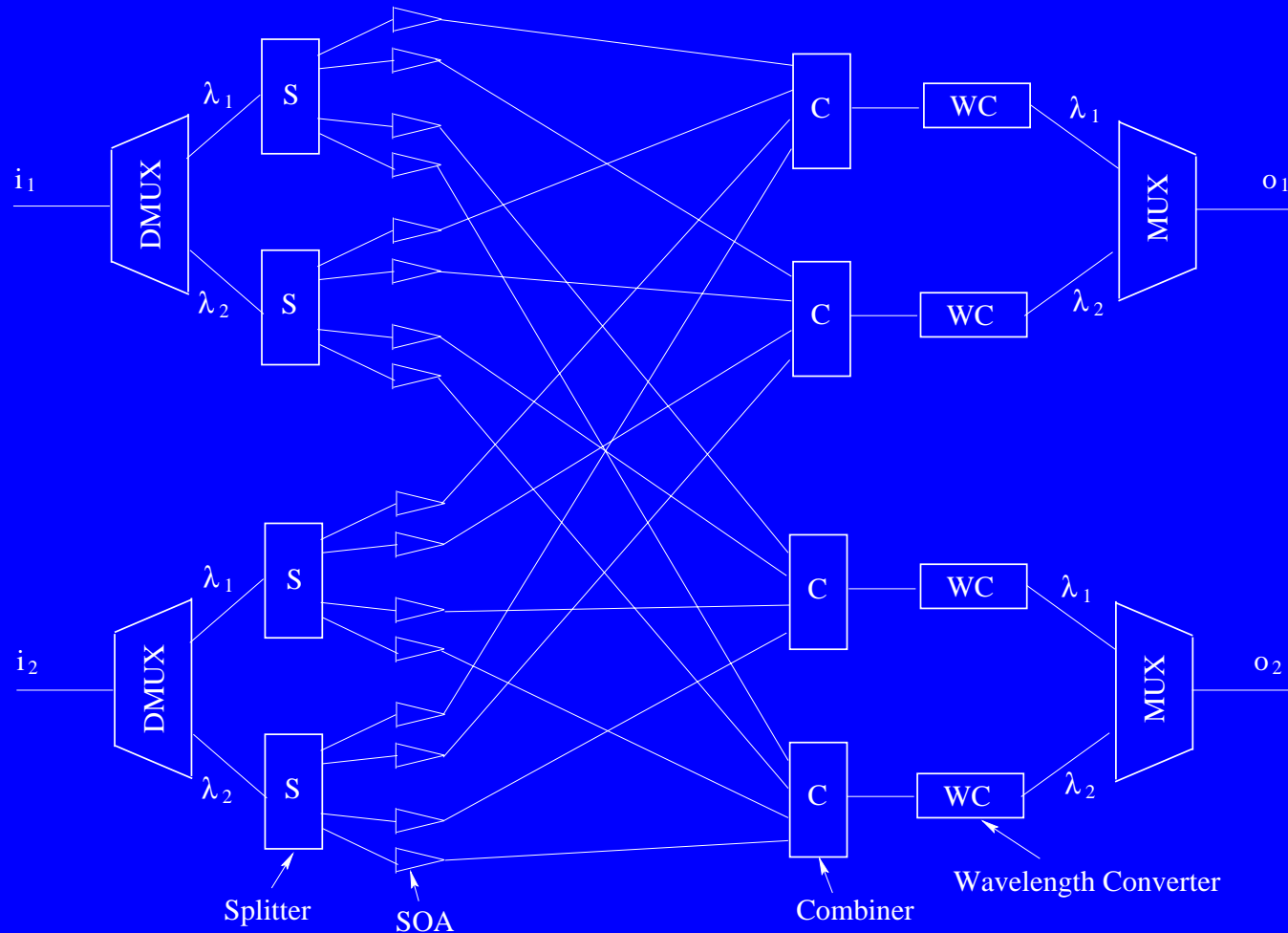


Preliminaries

- The interconnect consists of
 - the set of input fiber links
 $I = \{i_1, i_2, \dots, i_N\}$
 - the set of output fiber links
 $O = \{o_1, o_2, \dots, o_N\}$
 - each fiber link carries k wavelengths $\lambda_1, \lambda_2, \dots, \lambda_k$
 - (i_j, λ_{k_1}) : an input wavelength λ_{k_1} on link i_j
 - (o_p, λ_{k_2}) : an output wavelength λ_{k_2} on link o_p

Preliminaries

- The switch fabric of WDM optical interconnects

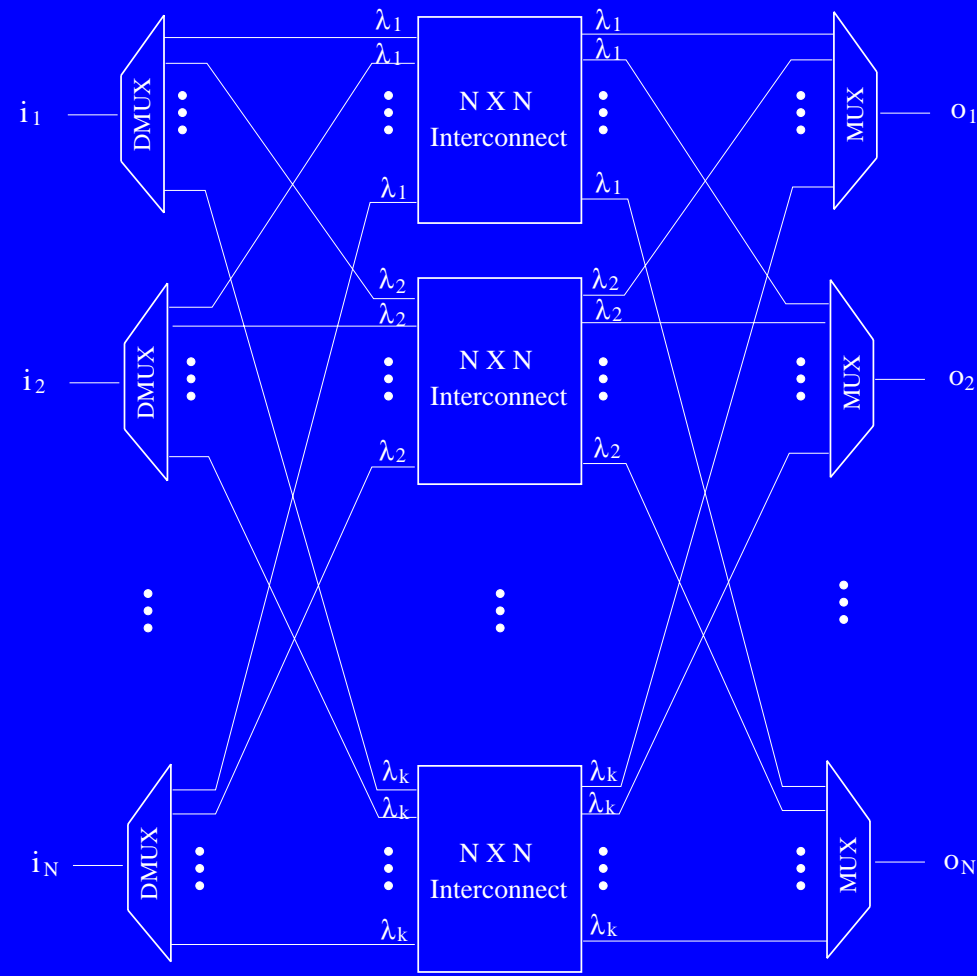


Preliminaries

- Major components
 - Demultiplexers:
decompose input fiber links to individual wavelength signals
 - Multiplexers:
combine individual wavelength signals to output fiber links
 - Splitters and combiners:
perform crossconnecting functions among wavelength signals
 - Wavelength converters:
change the wavelengths of signals
 - Semiconductor optical amplifiers (SOAs):
pass or block selected signals

Previous designs

- Previous design schemes [2, 5, 8]



Previous designs

- the network is decomposed into k $N \times N$ 1-wavelength interconnects
- with lowest number of crosspoints compared to other schemes
- only suitable for communication patterns in which the same wavelength is assigned for a connection

Example: It cannot realize one-to-one connections

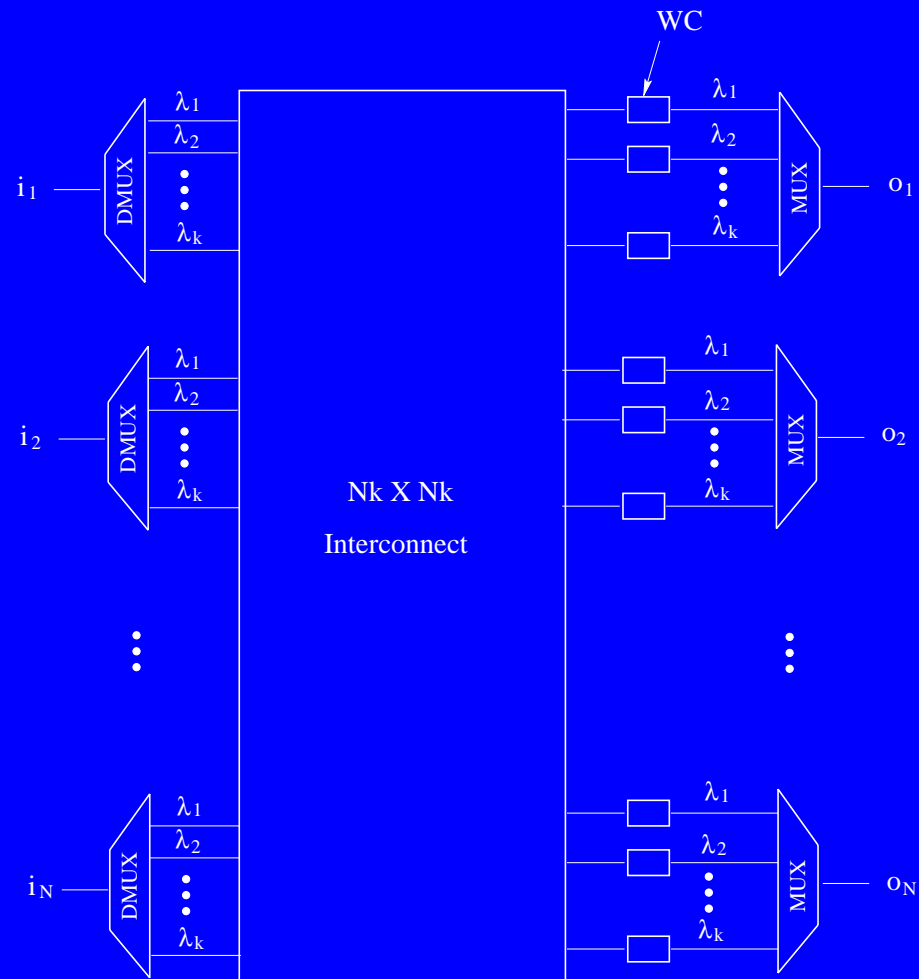
$$(i_1, \lambda_1) \rightarrow (o_1, \lambda_2)$$

$$(i_2, \lambda_2) \rightarrow (o_1, \lambda_1)$$

$$(i_2, \lambda_1) \rightarrow (o_1, \lambda_3)$$

Previous designs

- Design schemes in [5, 8]



Previous designs

- an $Nk \times Nk$ interconnect followed by Nk wavelength converters
- one stage implementation of the $Nk \times Nk$ interconnect is a full crossbar
- can realize any arbitrary permutation (or multicast)
- does not yield the minimum number of crosspoints for interconnects under different connection models

WDM optical interconnects with minimum cost under fiber-link-based model

- Design cost-effective $Nk \times Nk$ interconnect
 - consider an interconnect in which every k inputs on an input fiber link and every k outputs on an output fiber link are indistinguishable

Example: for a connection request from i_1 to o_3 , we can connect any idle wavelength (i_1, λ_{k_1}) to any idle wavelength (o_3, λ_{k_2}) .

WDM optical interconnects with minimum cost under fiber-link-based model

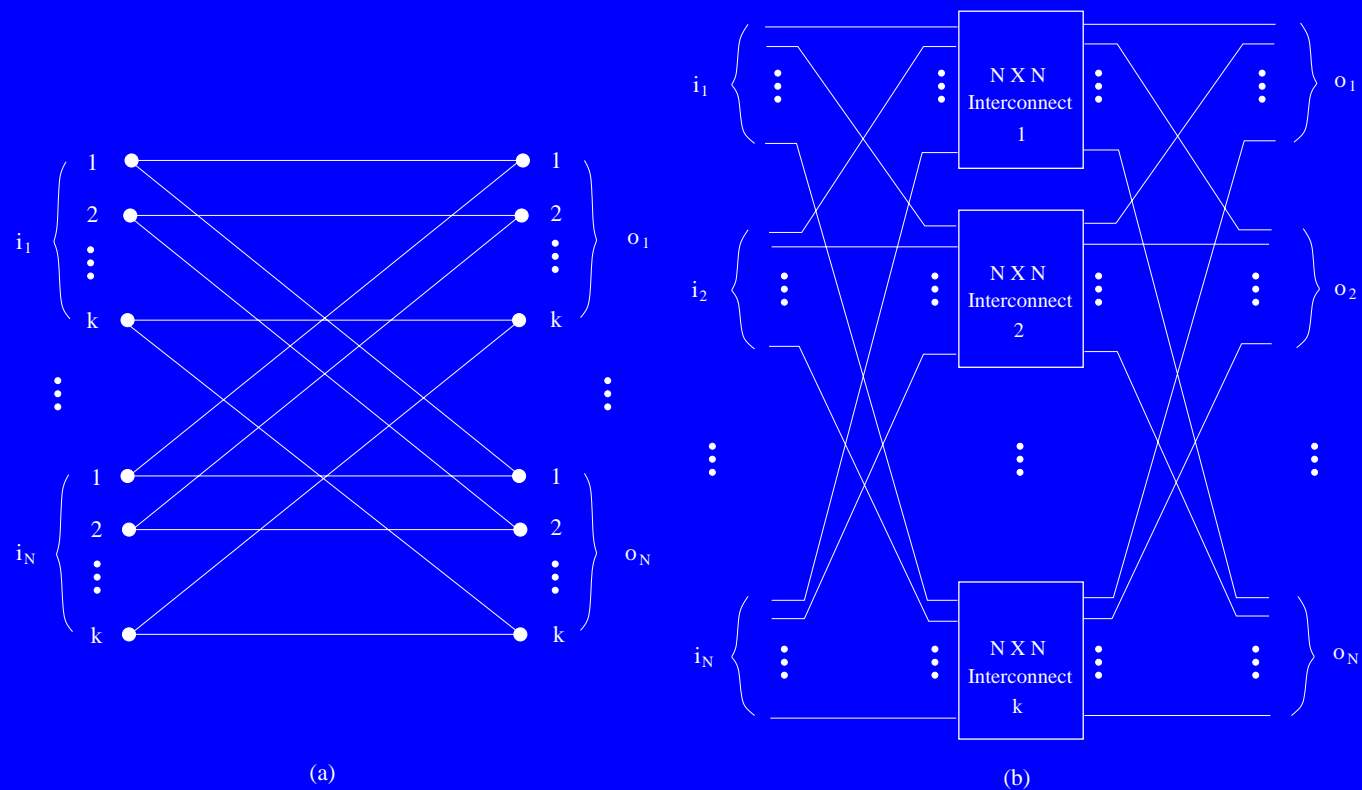
- Inter-group communication
 - Let every k inputs (outputs) corresponding to k wavelengths on an input (output) fiber link be an input (output) group
 - Consider the communication between input groups and output groups with inputs (outputs) within a group being indistinguishable
 - One-to-one inter-group connection
 - * realized by a connection from any idle input in the input group to any idle output in the output group

WDM optical interconnects with minimum cost under fiber-link-based model

- an inter-group permutation between N input groups and N output groups
 - * is N one-to-one inter-group connections such that no two connections are from the same input group and/or to the same output group
- an $Nk \times Nk$ interconnect under fiber-link-based model is suitable for supporting inter-group permutations
 - * can support k inter-group permutations simultaneously
- supporting k inter-group permutations does not necessarily mean it can support an arbitrary permutation between Nk inputs and Nk outputs

WDM optical interconnects with minimum cost under fiber-link-based model

- An $Nk \times Nk$ interconnect with minimum connections



(a) An $Nk \times Nk$ interconnect with minimum connections; (b) An equivalent design.

WDM optical interconnects with minimum cost under fiber-link-based model

- An $Nk \times Nk$ interconnect with minimum connections
 - is an interconnect in which each input (wavelength) can be connected to only one output (wavelength) of the k outputs on an output fiber link (a).
 - it can be proved that it is equivalent to (b).
 - it has the minimum number of crosspoints for a single stage implementation, kN^2 .

WDM optical interconnects with minimum cost under fiber-link-based model

Question:

Can any k inter-group permutations be realized in an $Nk \times Nk$ interconnect with minimum connections?

Theorem 1. *Any k inter-group permutations can be realized in an $Nk \times Nk$ interconnect with minimum connections shown in (b) with inputs (outputs) within a group being indistinguishable.*

WDM optical interconnects with minimum cost under fiber-link-based model

Proof (sketch). For realizing an inter-group permutation, only need to know the names of the groups, and the number of connections involved in each group.

Let M_j be a multiset of output groups that input group i_j has connections to in k inter-group permutations,

$$M_j = \{o_1^{k_{j,1}}, o_2^{k_{j,2}}, \dots, o_N^{k_{j,N}}\},$$

satisfying

$$k_{j,1} + k_{j,2} + \dots + k_{j,N} = k.$$

Then we can choose distinct $o_{p_1}, o_{p_2}, \dots, o_{p_N}$ such that $o_{p_j} \in M_j$ to realize an inter-group permutation. Other $k - 1$ inter-group permutations can be realized in a similar way.

WDM optical interconnects with minimum cost under fiber-link-based model

- The Overall WDM optical interconnect architecture

Construction: Use the $Nk \times Nk$ interconnect with minimum connections as the interconnect for the overall WDM optical interconnect architecture

Corollary 1. *Any k inter-group permutations among N input fiber links and N output fiber links can be realized in the overall $N \times N$ k -wavelength WDM optical interconnect architecture constructed above.*

Proof (sketch). By Theorem 1, any given k inter-group permutations can be realized in the $Nk \times Nk$ interconnect. Let a connection be from the s_{th} input in input group i_j to the t_{th} output in output group o_p , which is corresponding the lightpath connection $(i_j, \lambda_s) \rightarrow (o_p, \lambda_t)$. It can be realized by first starting from (i_j, λ_s) with wavelength λ_s , going through the path already set in the $Nk \times Nk$ interconnect, then converting the wavelength from λ_s to λ_t by the wavelength converter.

WDM optical interconnects with minimum cost under fiber-link-based model

- Hardware cost
 - number of crosspoints: kN^2
 - number of wavelength converters: Nk
 - minimum possible cost for a single stage $N \times N$ k -wavelength WDM optical interconnect under the fiber-link-based model
 - can be extended to multistage interconnects

Example: for a three stage interconnect, number of crosspoints can be reduced to $k(2N)^{\frac{3}{2}}$

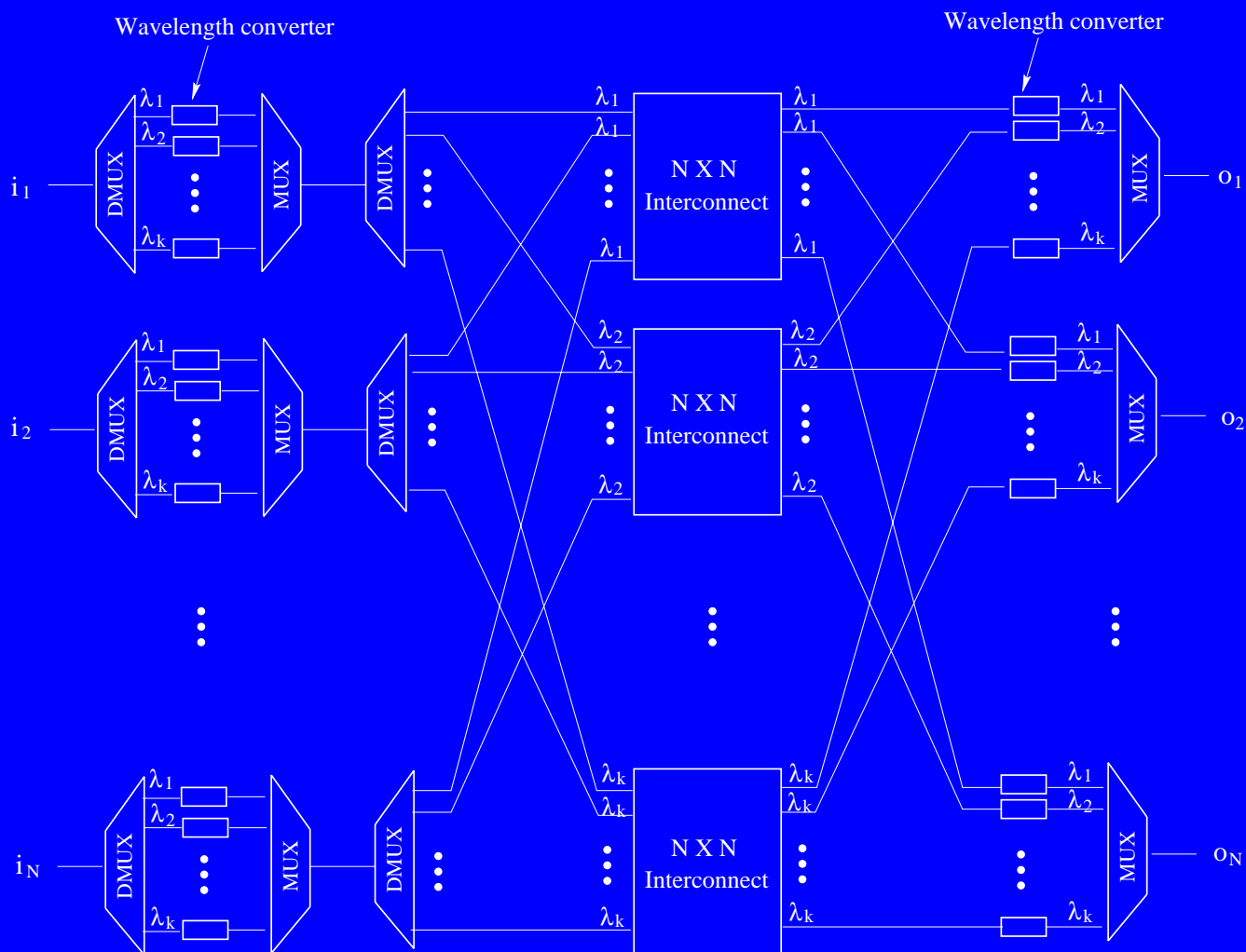
Extension to wavelength-based model

- In existing designs, a single stage WDM interconnect under wavelength-based model has
 - $(Nk)^2$ crosspoints
 - Nk wavelength converters
- Based on the technique we have developed, we can obtain a design for wavelength-based model with much less crosspoints by using more wavelength converters

Extension to wavelength-based model

- The new design
 - An $Nk \times Nk$ full permutation cannot be realized in an $Nk \times Nk$ interconnect with minimum connections in general
 - Let the original connection $(i_j, \lambda_s) \rightarrow (o_p, \lambda_t)$ be realized by the connection from input s' of input group i_j to output t' of output group o_p
 - Can we adopt a similar scheme on the network input side, i.e., placing a set of Nk wavelength converters right after demultiplexers?
 - The answer is “no,” because the wavelengths leaving a demultiplexer follow some order while wavelengths entering a multiplexer need not to be ordered.
 - it fails whenever $s \neq s'$.

Extension to wavelength-based model



Extension to wavelength-based model

Theorem 2. *Any permutation between Nk input wavelengths and Nk output wavelengths can be realized in the newly designed $N \times N$ k -wavelength interconnect.*

- Hardware cost trade-off
 - number of wavelength converters and multiplexers/demultiplexers doubled from the existing design
 - number of crosspoints is only $\frac{1}{k}$ of the existing design
 - when k is larger, the new design is better

Extension to wavelength-based model

– More comparisons:

Model	# Crosspoints	# WCs	# Mux's	# DeMux's
Prev/SS	$k^2 N^2$	kN	N	N
Prev/TS	$(2kN)^{\frac{3}{2}}$	kN	N	N
FLB/SS	kN^2	kN	N	N
FLB/TS	$k(2N)^{\frac{3}{2}}$	kN	N	N
WB/SS	kN^2	$2kN$	2N	2N
WB/TS	$k(2N)^{\frac{3}{2}}$	$2kN$	2N	2N

Conclusions

- categorized WDM optical interconnects into two different connection models based on target applications:
 - fiber-link-based model
 - wavelength-based model
- for WDM optical interconnects under fiber-link-based model, the network cost can be significantly reduced
- presented such a minimum cost architecture design for WDM optical interconnects under fiber-link-based model
- generalized the idea to wavelength-based model
- obtained a new architecture design which can trade-off the cost of different components of a WDM optical interconnect