The Optical Internet
Wavelength Division Multiplexing (WDM) and Lambda Switching

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WDM: Wavelength Division Multiplexing 波分多路复用

Transmission of multiple light signals (wavelengths) on the same strand of fiber

- **DWDM - Dense WDM** 密集波分复用
  - **More sophisticated → more expensive**
- **CWDM - Coarse WDM** 粗波分复用
  - **Lower number of wavelengths → cheaper**

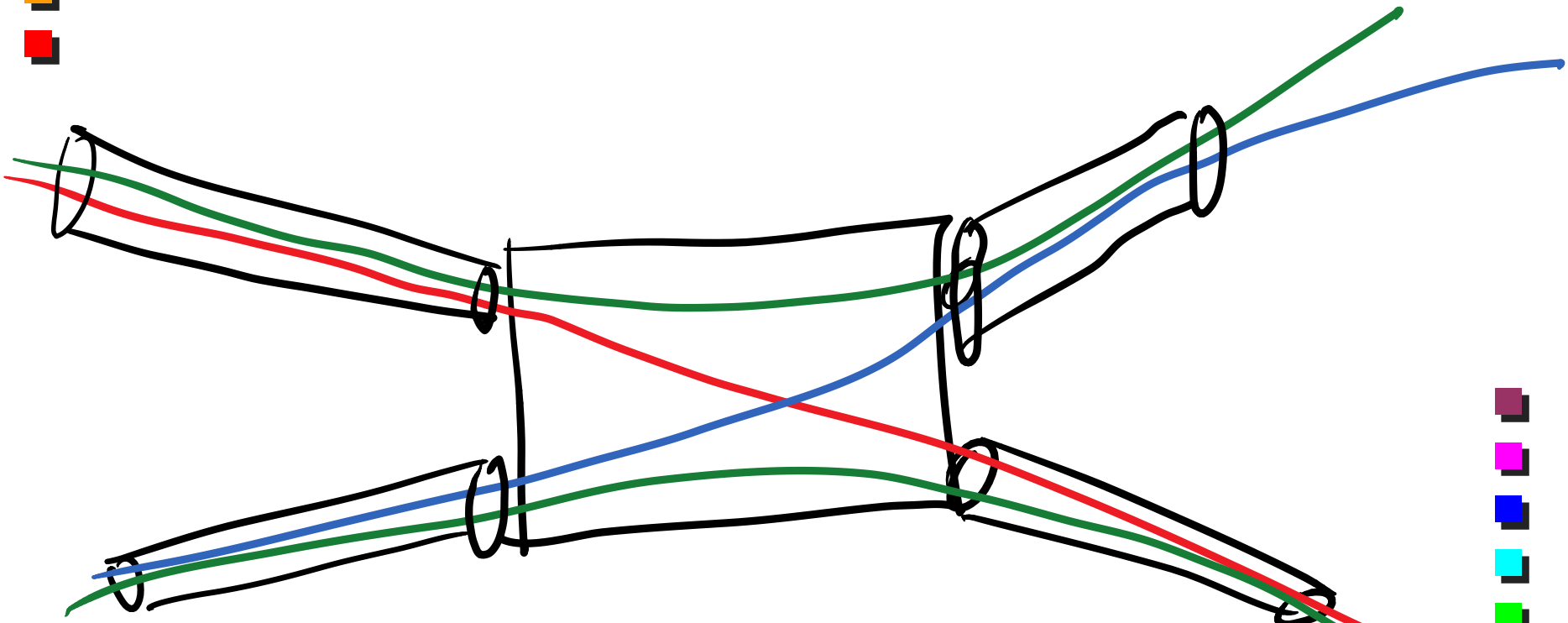
Initial WDM Application

Increase transmission capacity of fiber

增强了光纤的吞吐

- Trunk bandwidth
- Increase the utilization (ROI: return of investment) of [existing] fiber
- Point to point configurations

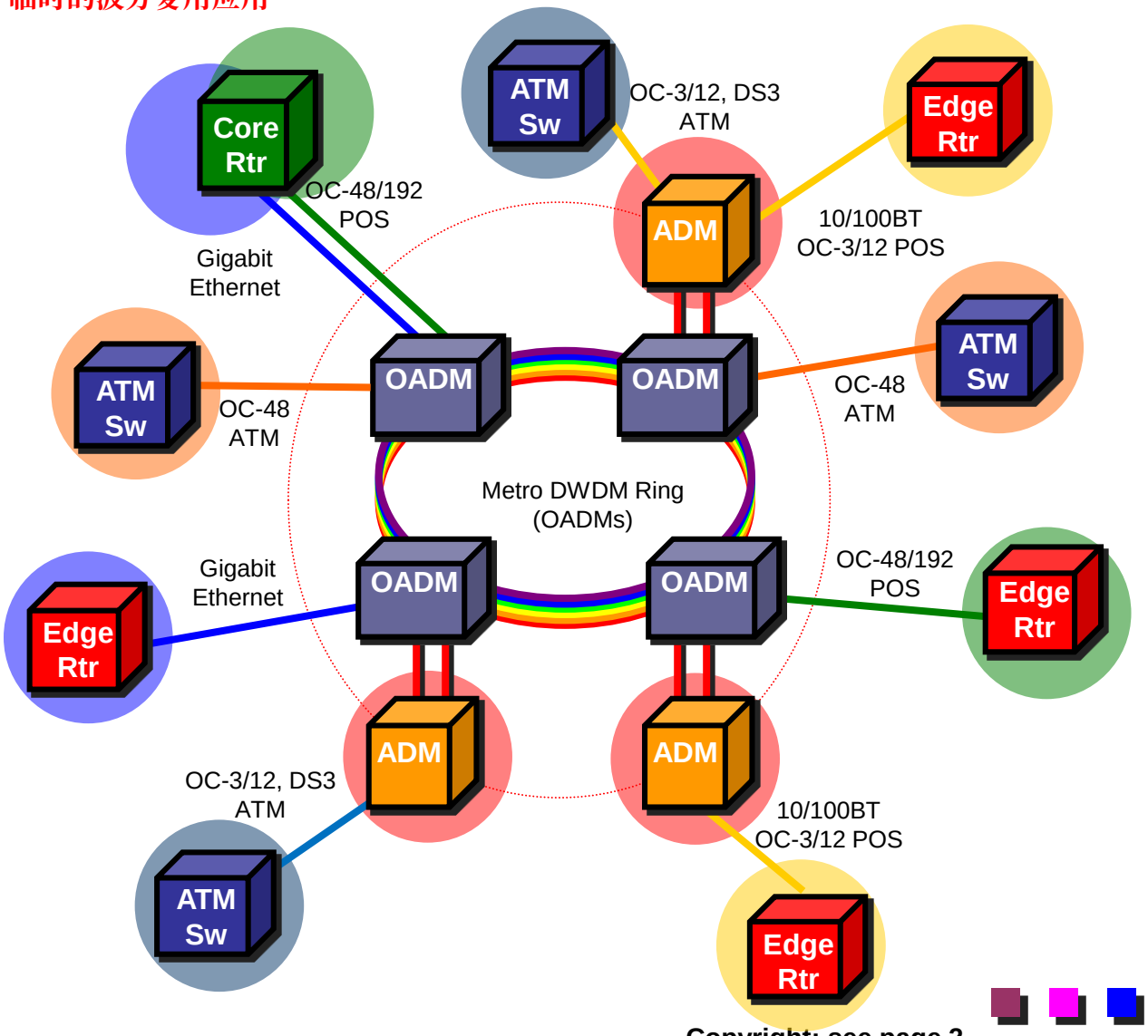
Taking it a step further: Wavelength Switching



“Interim” WDM Application

临时的波分复用应用

Add/drop multiplexing



“Interim” WDM Application

临时

Add/drop multiplexing

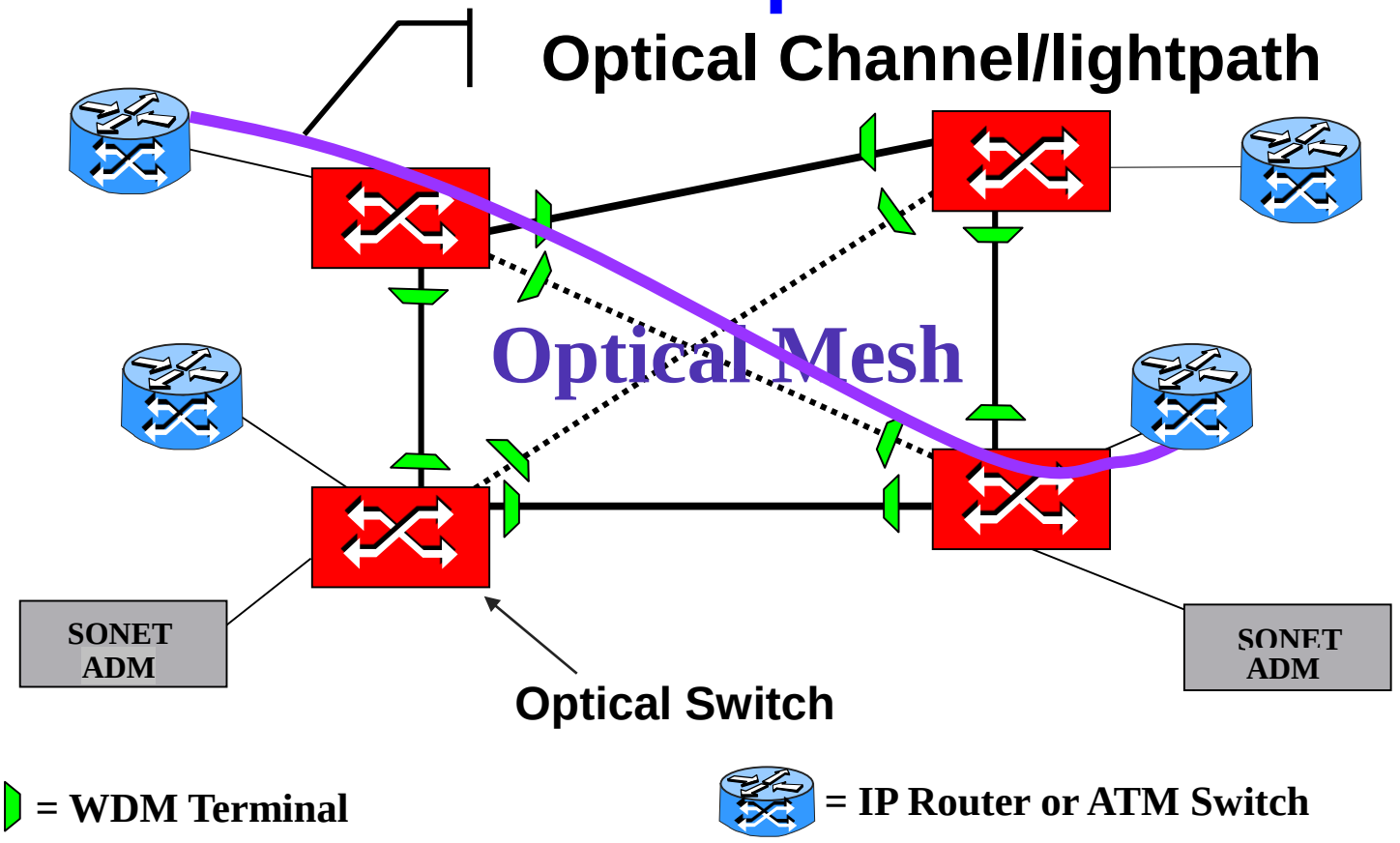
- Ring topologies with WDM add/drop multiplexers
  - Optical Add-Drop Multiplexer (OADM)
  - Inserting wavelengths on the ring
  - Extracting wavelengths from the ring
- Mostly static or semipermanent interconnection configurations
  - Reconfigurable OADM (ROADM)

Ultimate WDM Application

Wavelength switched networks

- Arbitrary mesh topologies of WDM links and wavelength switches
  - A.k.a. wavelength routers, lambda routers, lambda switches
  - Mostly (“only”) optical cross connects
- Optical Switching – Wavelength switching

What to do with Optical Switches?



Deployed in the network core because of its coarse bandwidth allocation

- **1 optical channel: 2.4Gb/s or more**

Why Optical Switching?

It has the potential of being simple, hence delivering a (very) low cost per switched bit

它有简单的潜力，因此提供一个(非常)低成本的每交换位

A bit of context

A look into the historical moment in which optical switching became extremely popular

[problems are still current, expectation on optical switching is lower]

RHK

Telecommunications Industry Analysis

Optical Technologies in Terabit Networks

Dr. John Ryan

Principal & Chief Analyst

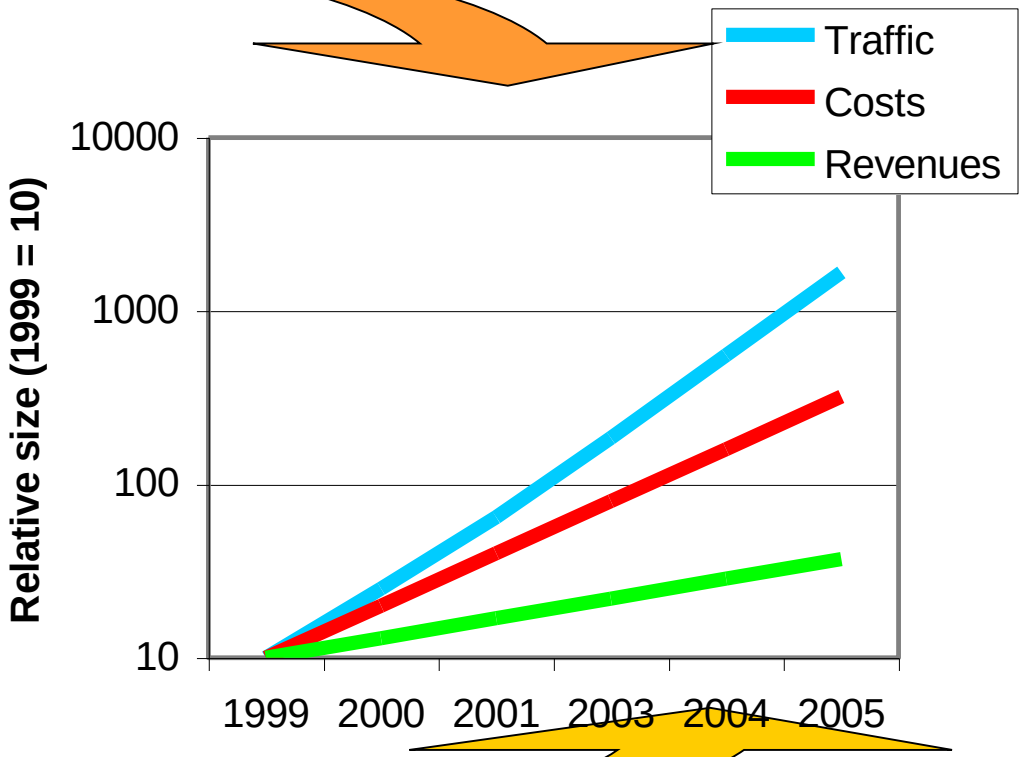
RHK

Optical Internetworking Forum, Atlanta, June 5th, 2000

The Resulting Traffic Dilemma...

Traffic is growing at explosive rates

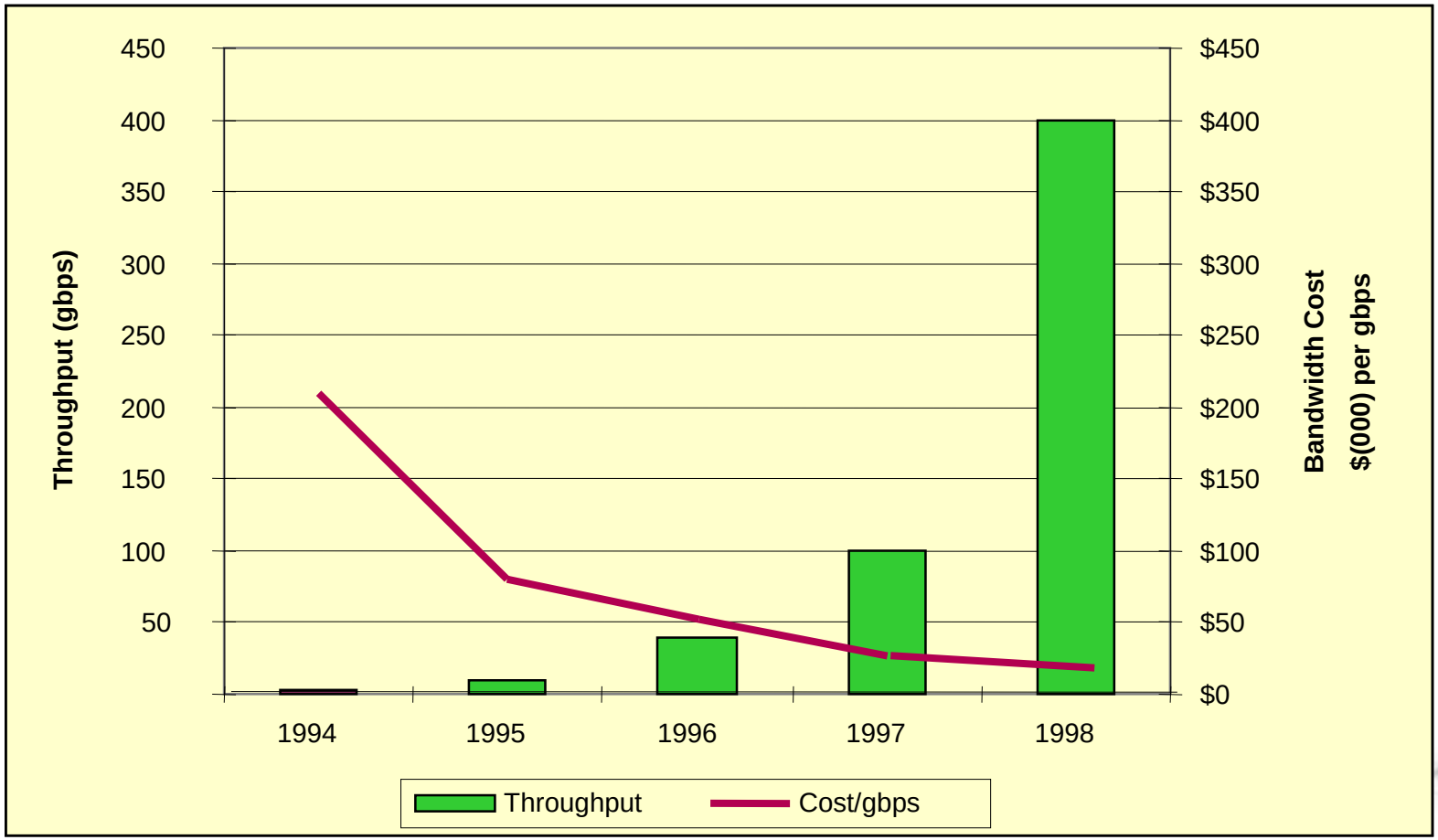
...And network costs are growing faster than revenues



- **Optical networks help solve this dilemma -- on a large scale.**

Optics Reshape the Cost Curve

- **DWDM driving down the cost of trunk bandwidth**



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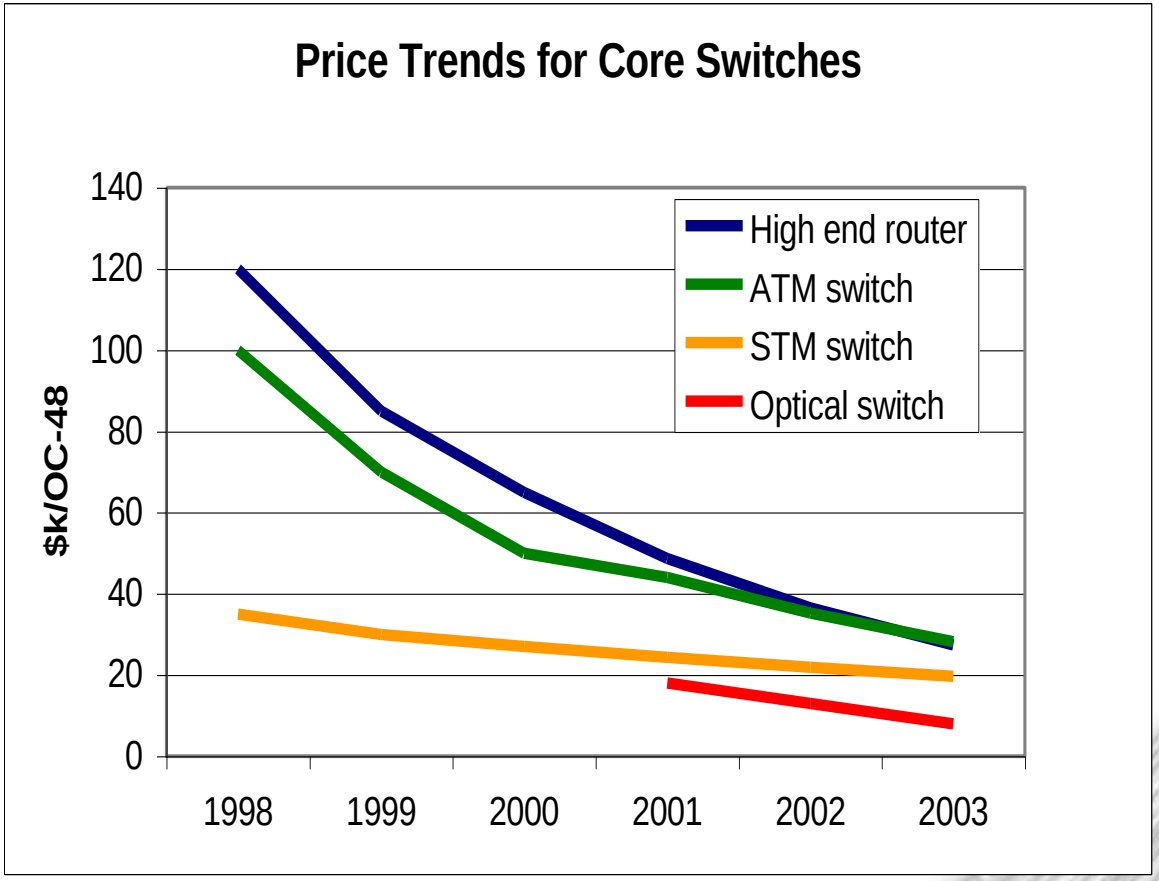
Pricing & The Technologies

- **Prices/OC-48 (2.5Gbps) dropping rapidly – in favor of 10Gbps+ systems**
- **By 2002, optical switches could offer the most bandwidth per dollar**



RHK

Back to the future

And to technology, leaving hype behind

Many Flavors of Optical Switches

- Optical vs Electronic core
- Cross Connect vs Switch
- Wavelength Conversion

Different levels of *complexity*

不同等级的复杂度

不同等级的弹性

Different levels of *flexibility*

Switching Core

Optical Core 光核心

Deploy physical properties of materials to deflect light from incoming fiber to outgoing fiber

- **Tilting mirrors** 倾斜的镜子
  - **Micro-electro-mechanical systems (MEMS)**
  - **Voltage operated**
- **Holographic reflecting surfaces** 全息反射表面
  - **Voltage operated**
- **Materials changing properties with**
  - **Heat**
  - **Pressure**
  - **Voltage/current**

Optical Core Properties

- [Potentially] inexpensive (low CAPEX) 便宜
  - Low cost material
  - Low cost process [once technology is mature]
- Bit rate and signal independent 比特率和信号无关
  - Unlimited scalability
  - Multi standard
- Low power consumption 更少的能量消耗
  - Low operation costs (OPEX)

- High production costs 高昂的造价
  - Immature technology
- High attenuation (and no regeneration)

高衰减

Electrical Core

Convert optical signal into an electric one and use a circuit interconnection network

- **Optical-electrical conversion** 光电转换
- **Receive the bits and switch them**
- **It loses all the nice properties of an optical core**
  - **Bit rate independence**
  - **Low power consumption**
  - **Low cost**

便宜
更低的复杂度

However

- **At current state of technology, cheaper**
- **Less complex/costly than packet switching**

Switching Dynamics

交叉连接

Cross Connect

- Fixed/static configuration
  - Changed seldom
  - Through a management system/interface
- Usually optical core

静态配置

很少改变

通过一个管理系统

通常是光学核心

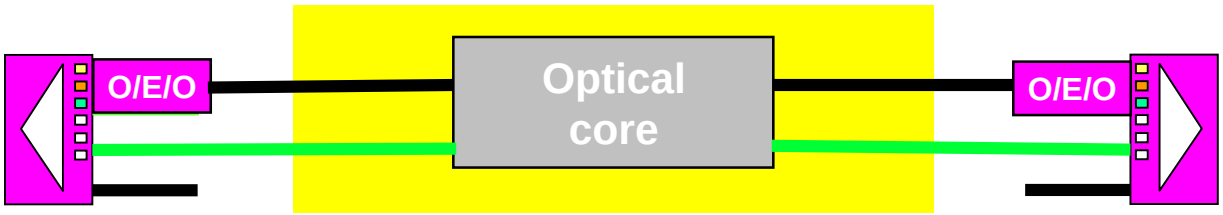
光纤交叉连接

Fiber Cross Connect

- The whole signal from an input fiber switched to an output fiber
  整个信号从输入光纤口转换到输出光纤口
- Micro-electro-mechanical systems (MEMS)
  - Long re-configuration time
    微电子系统
- Optical amplification might be used before and after switching
  可在交换前后使用光放大

Wavelength Cross Connects

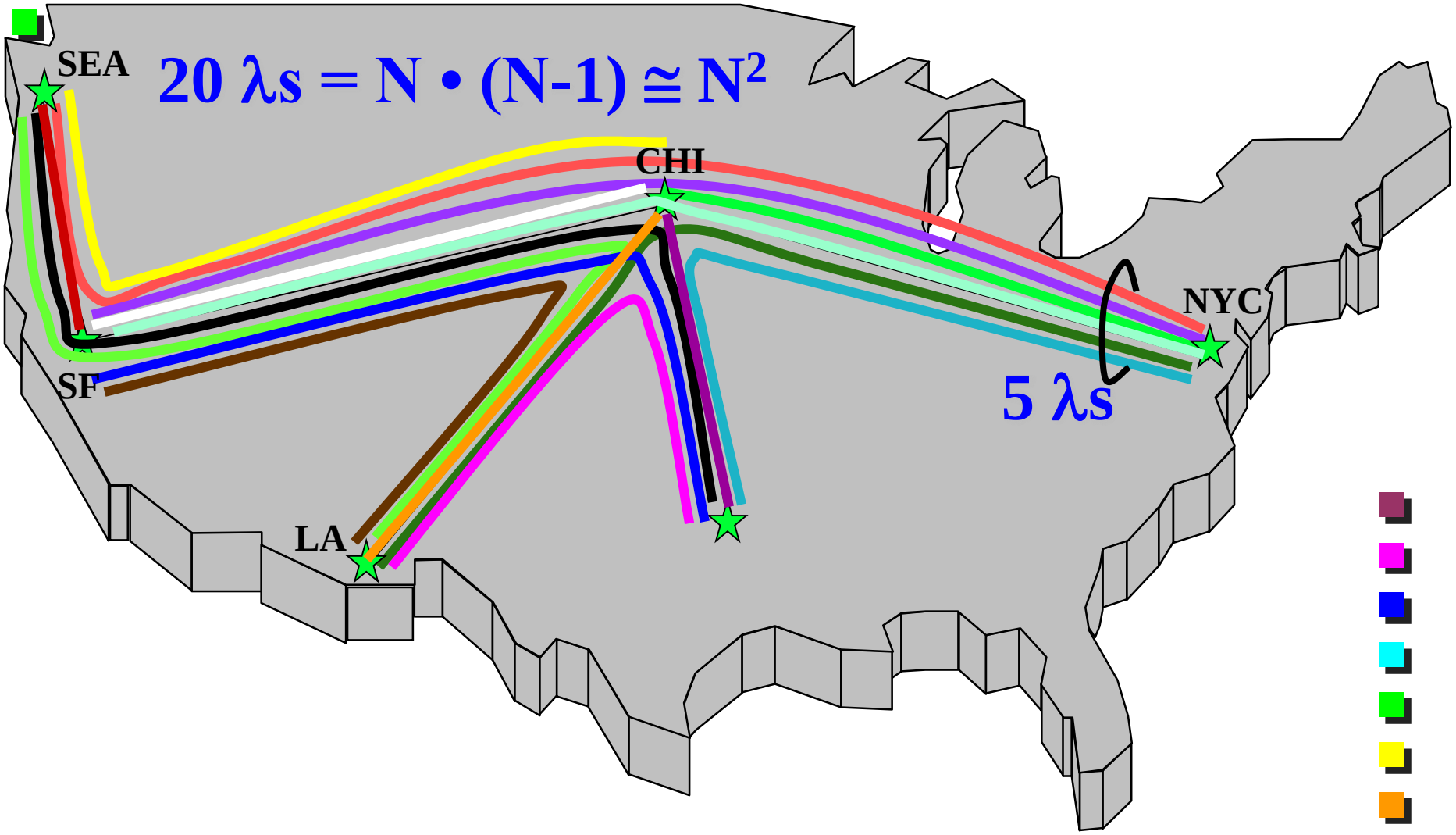
- One (or more) wavelengths from an input fiber to an output fiber 从输入光纤到输出光纤的一个或多个波长
- WDM de-multiplexer+MEMS
  - Separates different wavelengths in space
    - "Prism"
- Regeneration may be used before or/and after switching
  - OEO (optical-electrical-optical) conversion with electrical regeneration
    - Requires "receiving" the bits -> bit rate dependent



Wavelength Conversion

波长转换

λ Switching: the N^2 Problem



Wavelength Conversion

- Complex 复杂
  - OEO conversion OEO 昂贵且扩展性不好
    - Expensive
    - Non data transparent → does not scale
  - Physical properties
    - E.g., resonance chamber
    - Immature technology -> expensive
- Does not require the same wavelength end-to-end 并不要求相同的波长在端对端传输过程中
- No wavelength assignment problem
  - N^2 problem 没有波长分配的问题

Common Combinations

组合

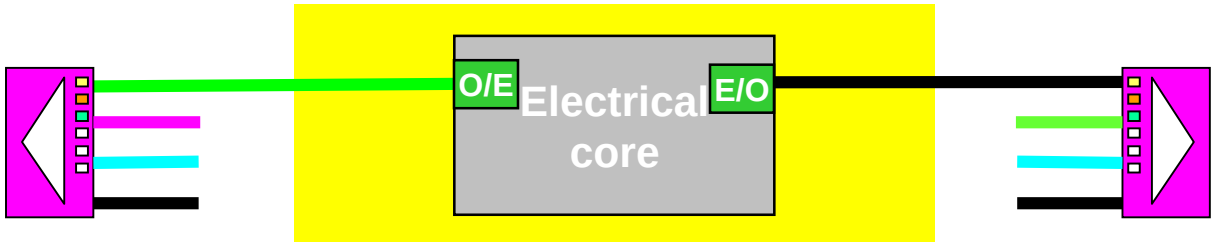
波长交叉连接+波长转换

Wavelength cross-connect with Wavelength Conversion

One (or more) wavelengths from an input fiber to other one (or others) on an output fiber

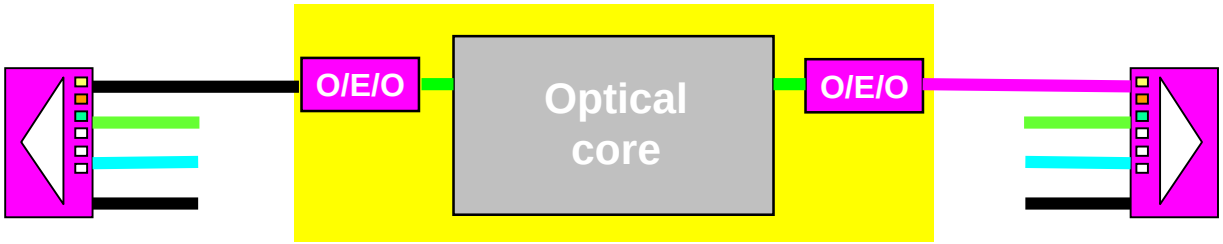
- Electrical core might be used
  - Easier signal monitoring
  - Forward error correction (FEC) possible to reduce Bit Error Ratio (BER)

电子核心可以用来，信号监管，识别纠正错误



Wavelength cross-connect with Wavelength Conversion

- Optical core with OEO (optical-electrical-optical) conversion
  - Also providing signal regeneration



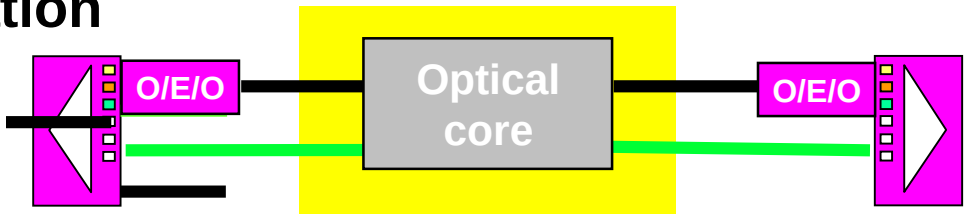
Dynamic Optical Switching

- Wavelength switch with or without wavelength conversion 波长交换和波长转换 波长交换
- Switch configuration is changed dynamically
  - By management
  - By time of day
  - By end system signaling
  - Every packet!?! …
    - Optical packet switching
    - Optical burst switching

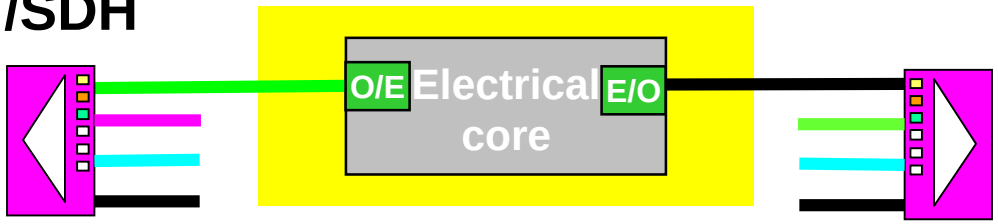
Dynamic Optical Switching

- Optical core
  - Electroholography, bubbles
  - OEO for regeneration and wavelength conversion

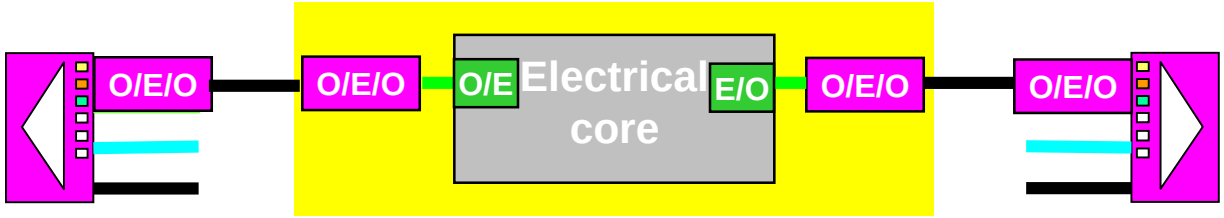
用于再生和波长转换



- Electrical core
  - Possibly SONET/SDH



  - Possibly multiple OEO for regeneration



Deployment

What is Expected from the Optical Network?

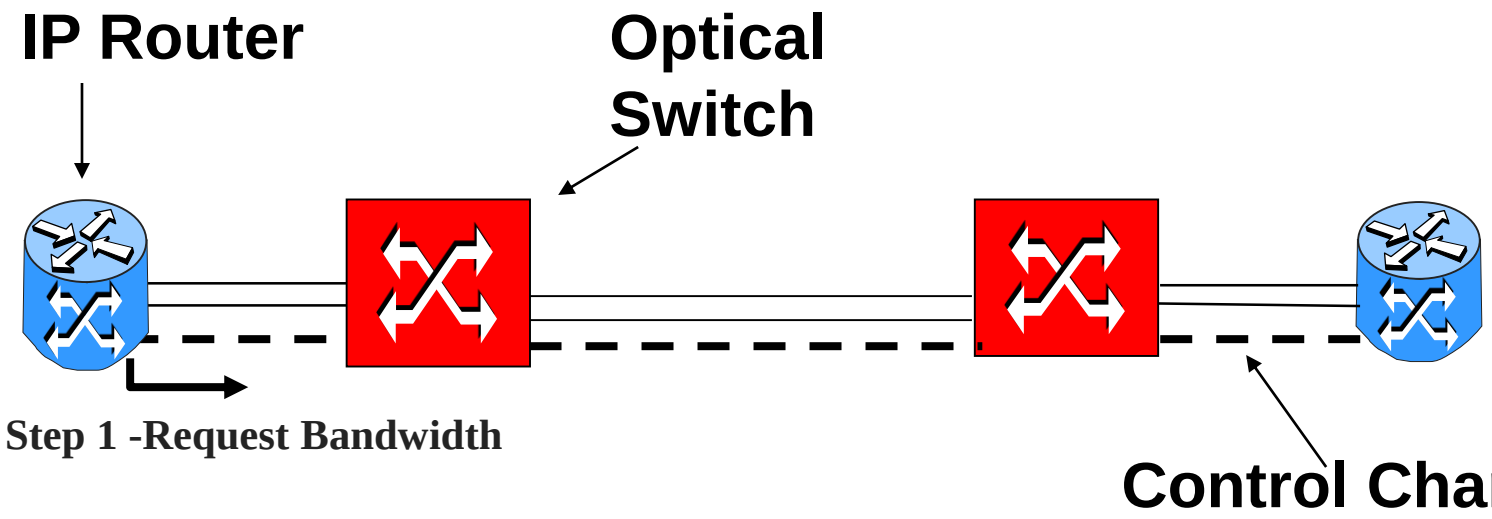
端到端的光路供应和保护

- ***Provisioning*** **and** ***protection*** **of lightpaths *end-to-end***
- **Client equipment (e.g. routers) to control provisioning of optical layer *lightpaths***
  - **Signaling**

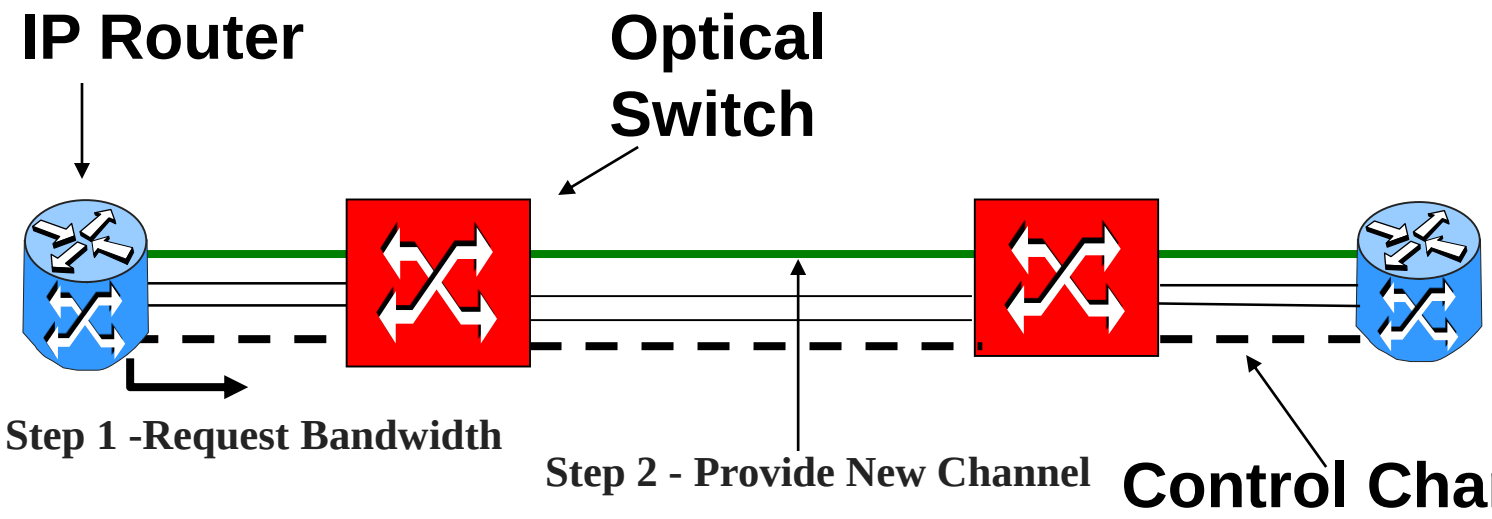
控制光层光路供应的客户端设备(例如路由器)

- **Cost-effective deployment of flexible networks**

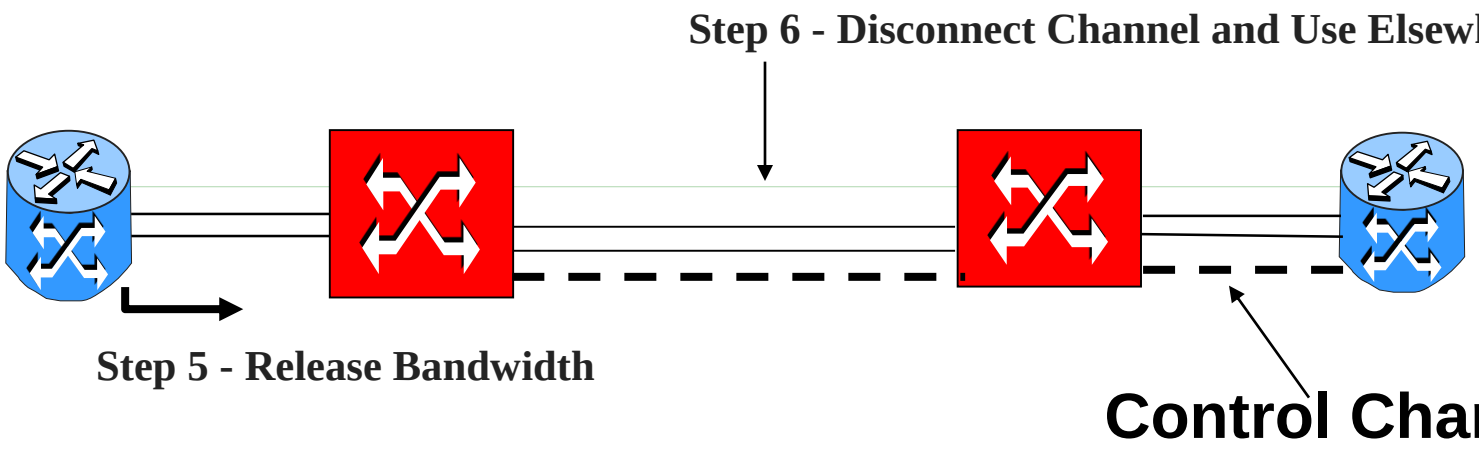
Provisioning



Provisioning

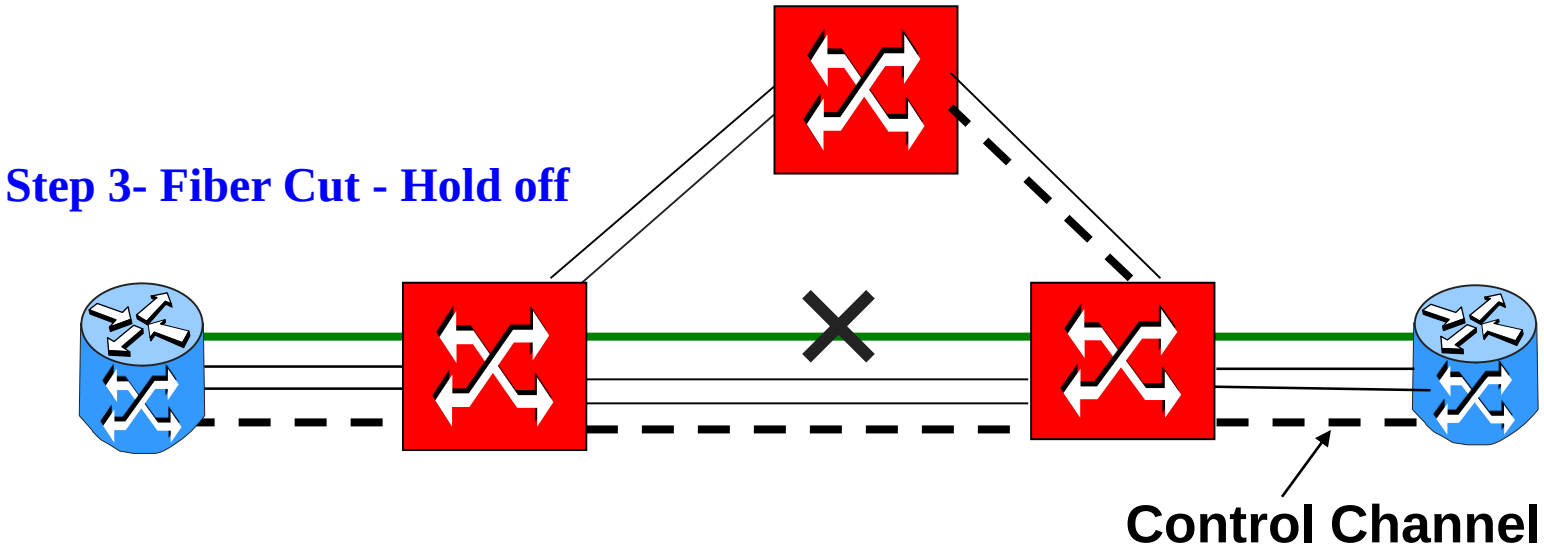


Provisioning



Protection/Restoration

- Protection: pre-determined action
  - non-optimal resource utilization
- Restoration: dynamically determined action
  - optimization of resource utilization



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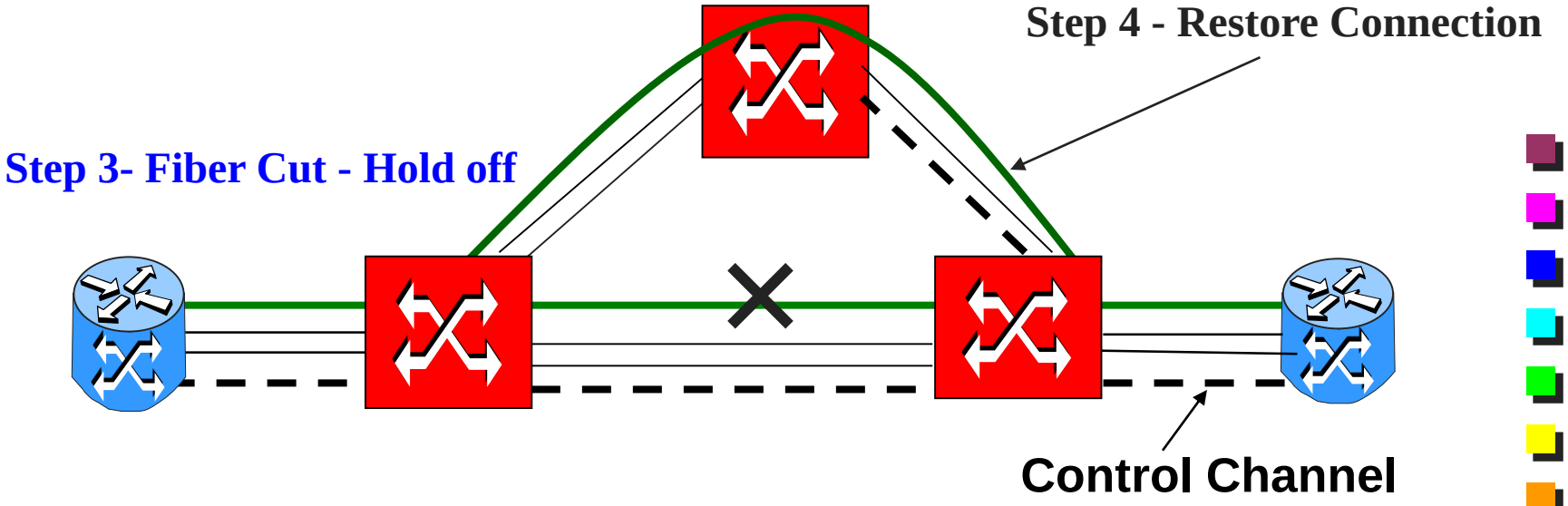


Protection/Restoration

- Multiple levels of protection:
  - Layer 1 optical, e.g. SONET-like
  - Layer 2 data link bundle
  - Layer 2.5 protected MPLS LSPs
  - Layer 3 routing
- Multiple layers of restoration can be triggered
  - Each different timescales for detection and repair
- Must avoid:
  - Unnecessary traffic shifting
    - Packet loss, reordering, control plane churn
  - Pathological feedback
    - Non self-stabilizing

Control Plane

What Optical Switches Need

- Resource discovery
  - Topology
  - Access points and node identification
  - Resource usage
- Connection management/signaling
  - Lightpath setup
  - Lightpath take down
  - Lightpath modification
- Distributed routing
- Mesh/ring network protection and recovery
- Establishment of protection service classes

What Optical Network Users Need

- Resource discovery
  - Address of users reachable through the optical network
- Manage lightpaths
  - Lightpath setup
  - Lightpath take down
  - Lightpath modification
- Negotiate protection service classes
  - Protected, unprotected, best effort lightpaths

Does all this sound familiar? **ATM**

Routing

In the Optical Internet network users are routers

- Overlay Model
  - The optical network provides connectivity between routers
  - Routers see the optical network as a black box
  - Routers might be provided with reachability information
- Peer Model
  - Routers and switches participate to the same routing protocols
  - Routers know the topology of the optical network
  - Routers can choose the preferred path for lightpaths between them
    - To reach specific destinations

How to Do It

- How is the optical network controlled?
  - Layer 3 control plane?
  - MPLS/LDP?
    - LSPs mapped over wavelengths
  - OSPF, BGP4?
  - New signaling and routing standards?
  - Proprietary vendor specific?
- Out of band or in-band
  - Ethernet control channel

MPLS the only sensible choice for the Optical Network Control Plane

MPλS - Multi-Protocol Lambda Switching

- OSPF, IS-IS, BGP for resource discovery
- RSVP/LDP for signaling

Players in the Optical Arena

Standardization

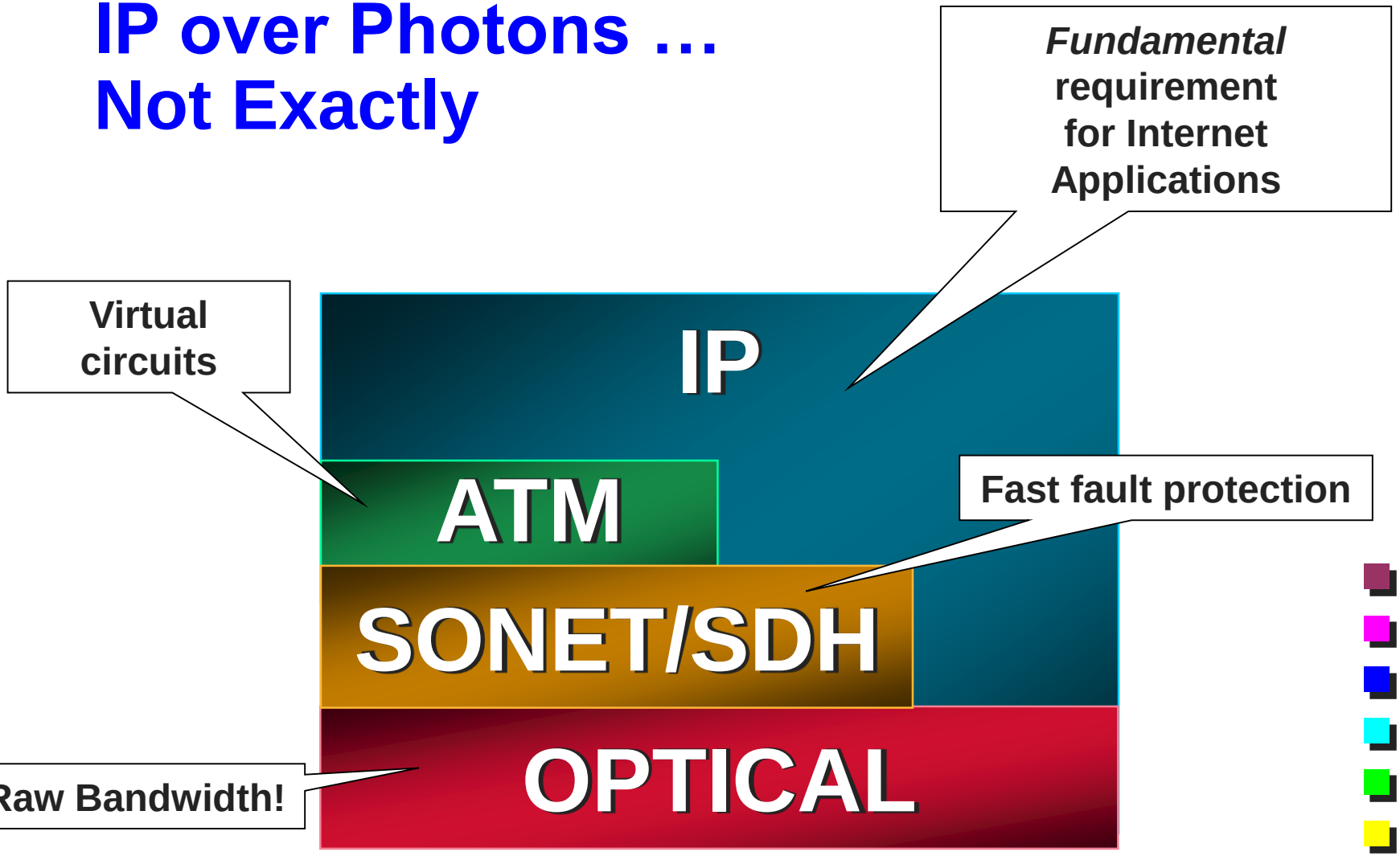
- ITU-T - International Telecommunication Union - Telecommunication Sector
  - OTN - Optical Transport Network
  - Recommendation G.872
  - ASON - Automatic Switched Optical Channel Networks
- IETF - Internet Engineering Task Force
  - MPLambdaS - Multi-Protocol Lambda Switching
    - MPLS signaling

Fora - Consortia

- OIF - Optical Internetworking Forum
  - Focus on SONET
  - Adopting MPLS signaling
- ODSI - Optical Domain Service Initiative
  - Service inteface
  - No NNI

Data Transport and Protocol Stack

IP over Glass …
IP over Photons …
Not Exactly

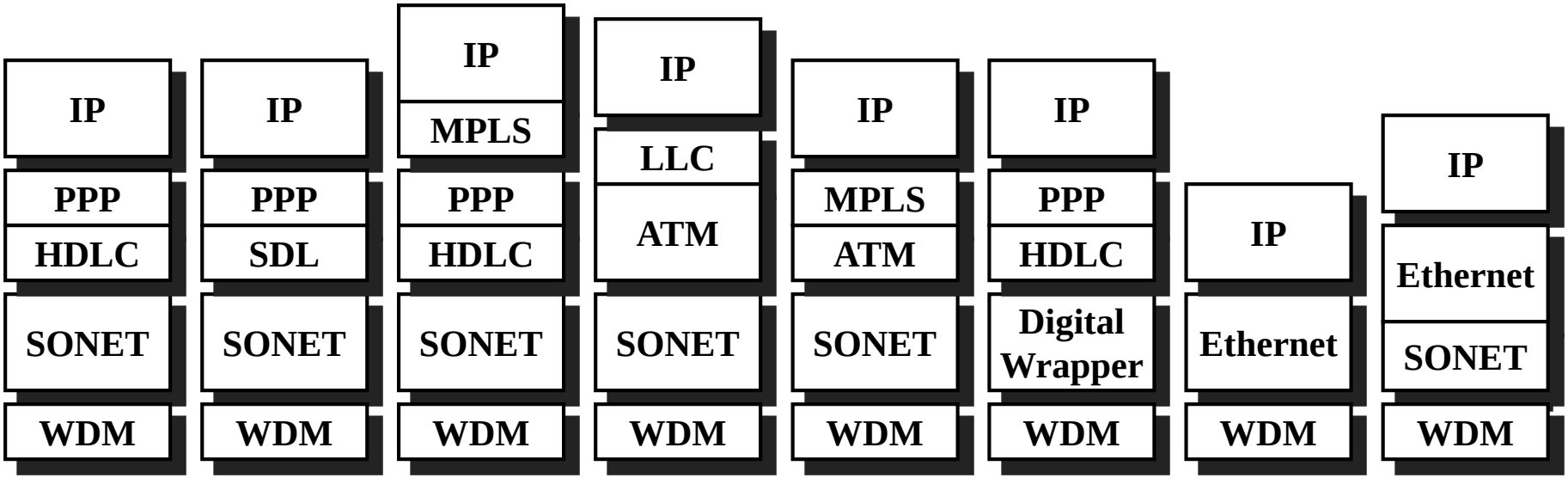


Data Transport

- Physical Layer -> transfer of bits
  - SONET/SDH
  - Ethernet
  - Digital Wrapper
- Data link layer -> framing
  - PPP with HDLC framing
  - PPP with SDL framing
  - Ethernet
  - ATM
- MPLS?
- Network layer: IP

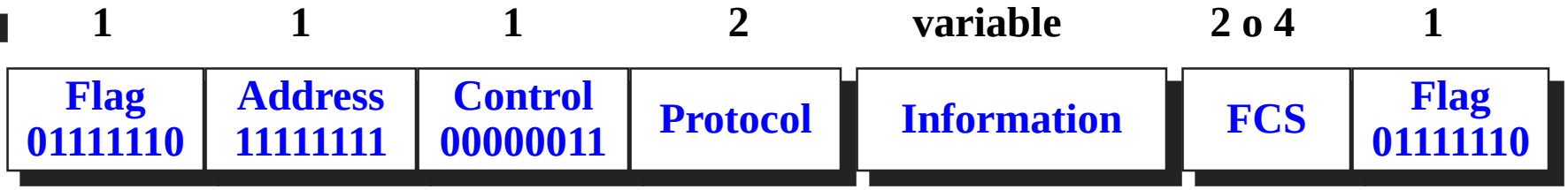
PPP - Point-to-Point Protocol
HDLC - High-level Data Link Control
SDL - Simple Data Link
ATM - Asynchronous Transfer Mode

Some Encapsulation Options

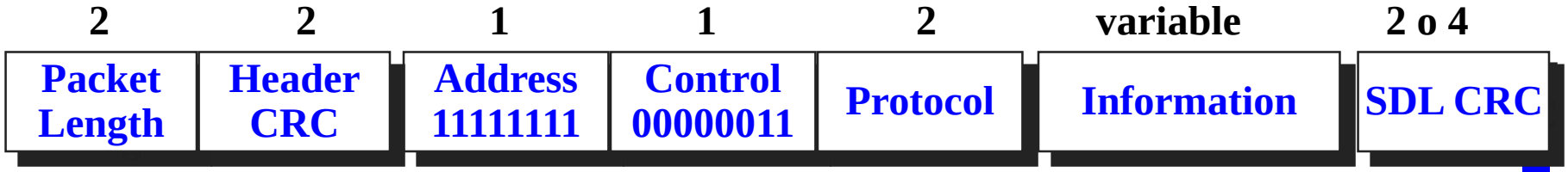


Point-to-Point Protocol (PPP)

- High-Level Data Link Control (HDLC) framing



- Simple Data Link (SDL) framing



- CRC hunting

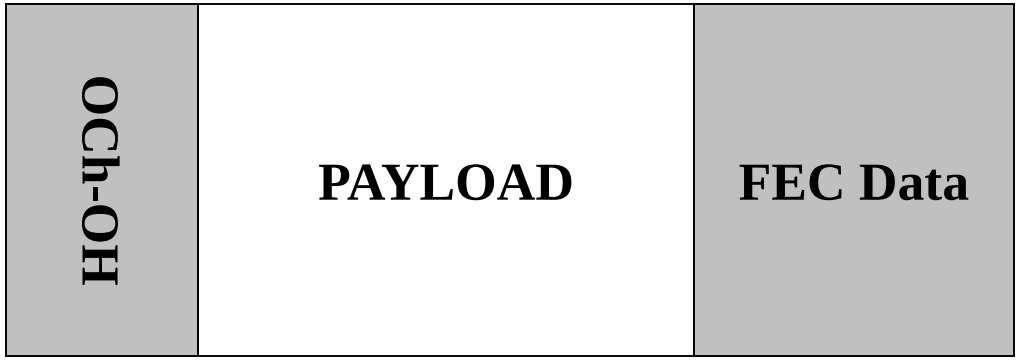
同步光线网络

PoS: Packet Over SONET

- Use SONET/SDH physical layer for transmission of bits
  - No SONET switching
  - No SONET (de)grooming
  - No SONET (de)multiplexint
    - Channels
- Way to encapsulate IP packets in SONET frames
  - One SONET channel per link/optical channel
  - PPP deployed

Digital Wrapper

- Improve Bit Error Ratio (BER)
- Provide transparent transport



OCh - Optical Channel
OH - Overhead
FEC - Forward Error Correction