Optical Packet-Switched WDM Networks: a Cost and Energy Perspective

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Acknowledgements: Jayant Baliga, Kerry Hinton, Rob Ayre, Gangxiang Shen, Wayne Sorin

Australian Research Council, Cisco

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Summary

- Optical packet-switched networks
- Network architectures
  - Point-to-point WDM IP networks
  - IP networks with optical grooming
  - Optical burst switching
  - Optical packet switching
- CAPEX and network architectures
  - Scaling
- Energy consumption and network architectures
  - Core and access networks

Impact on network growth

- Disclaimers:
  - Numbers given here are approximate - YMMV
  - OPEX not included
- E-mail me for copies of these slides

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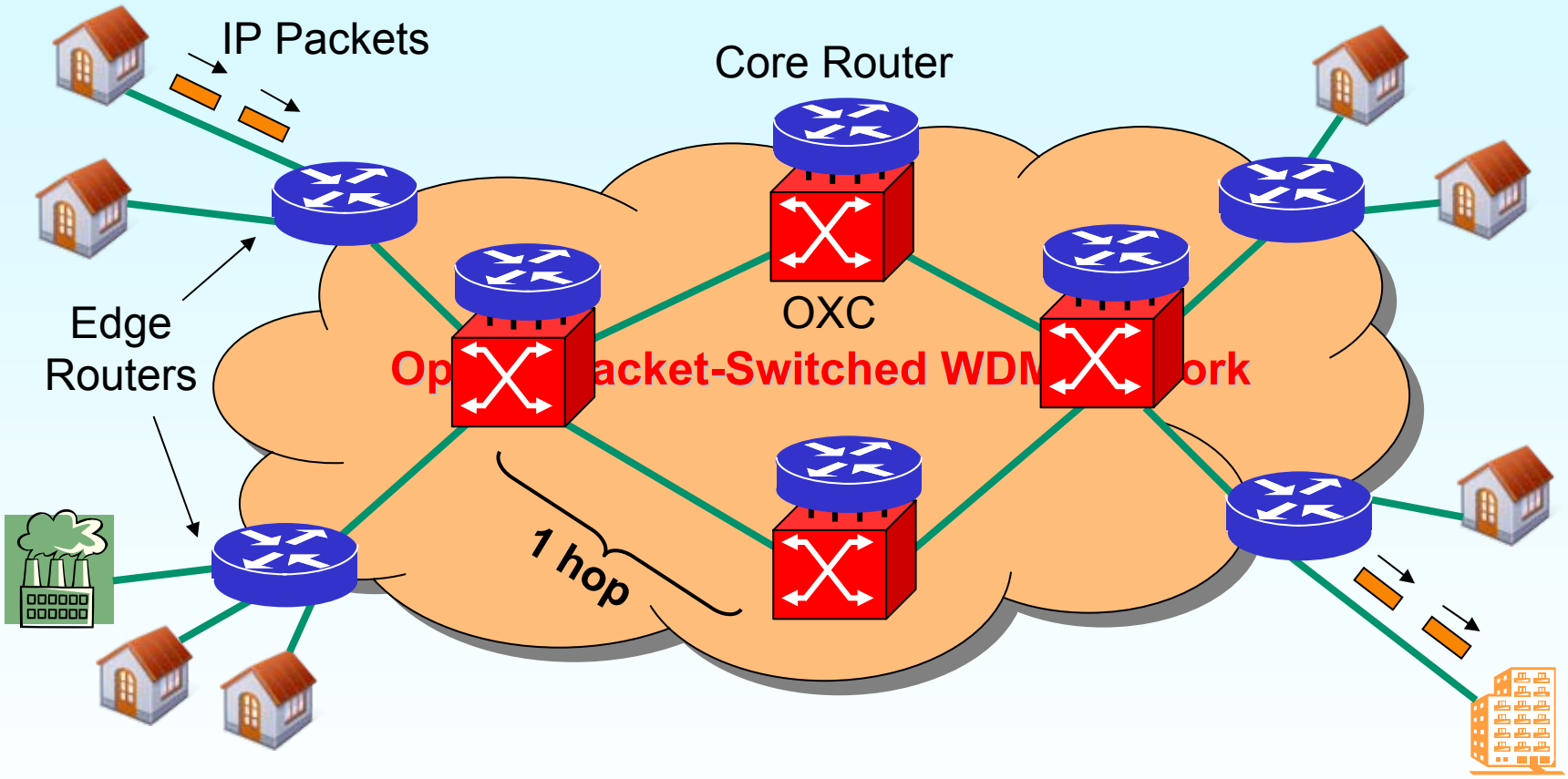
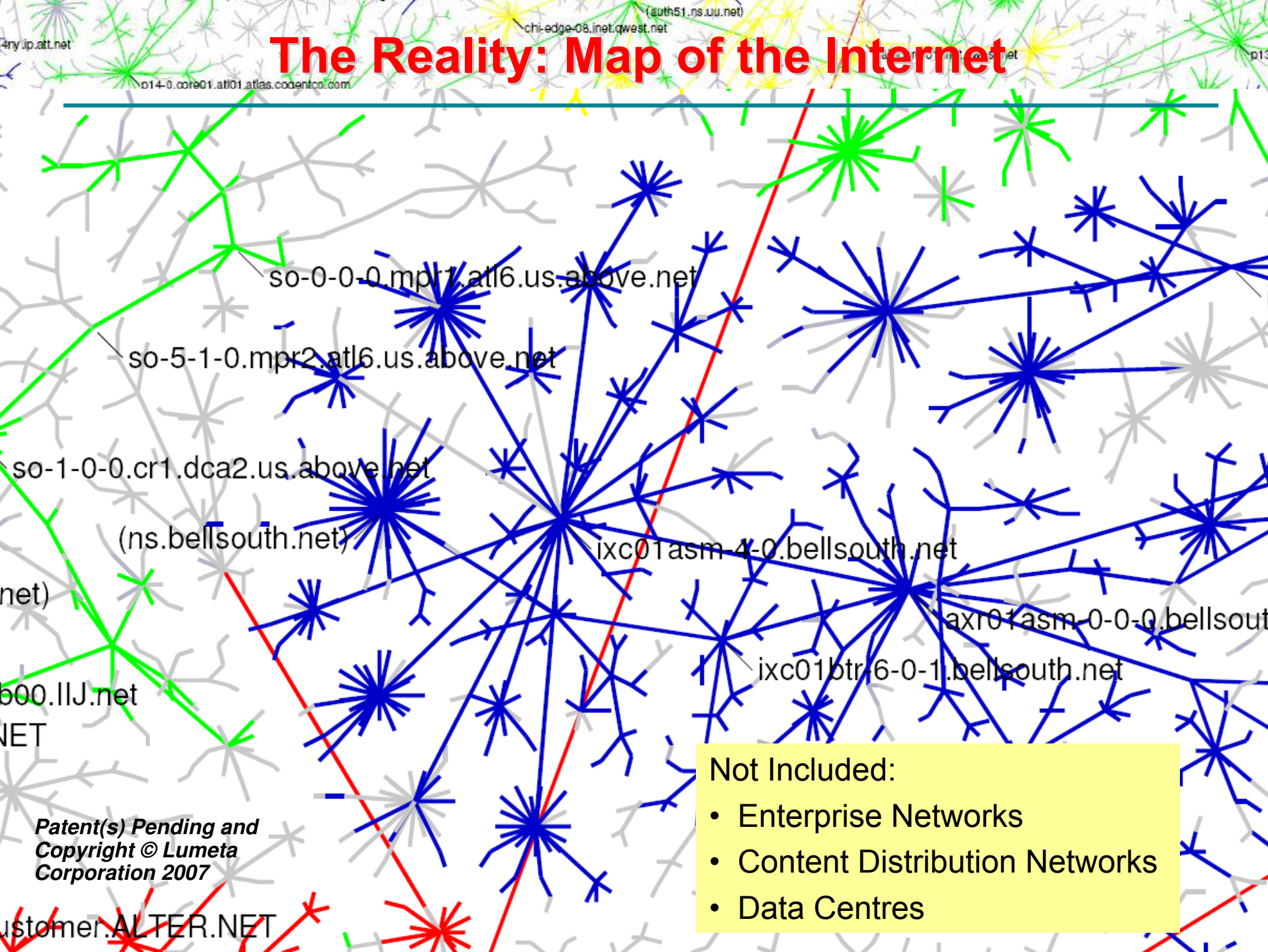
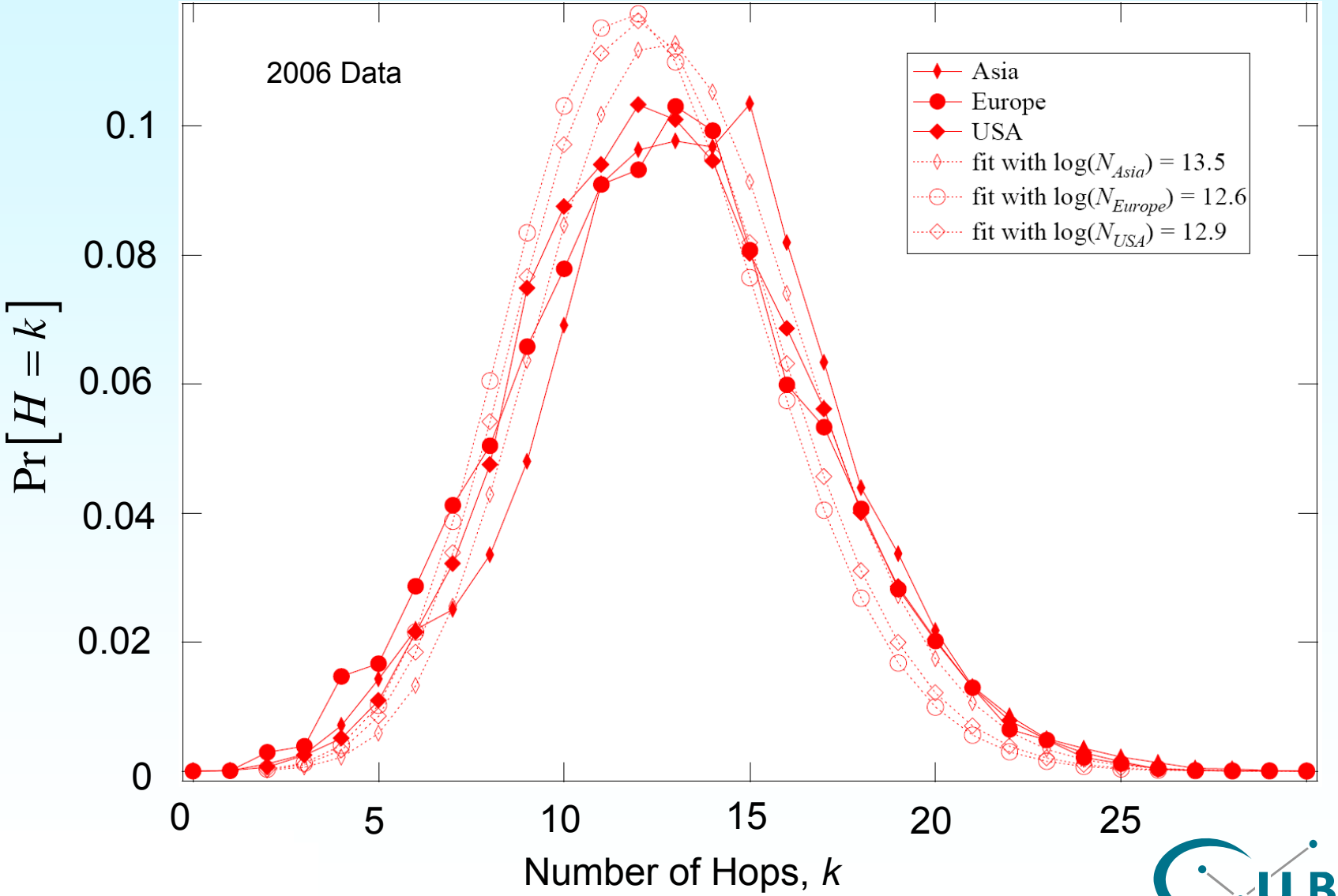


Is this simple model realistic?

The Reality: Map of the Internet



Number of Hops in the Internet



Source: P. Van Mieghem,
"Performance Analysis of Computer Systems and Networks", Cambridge (2006)

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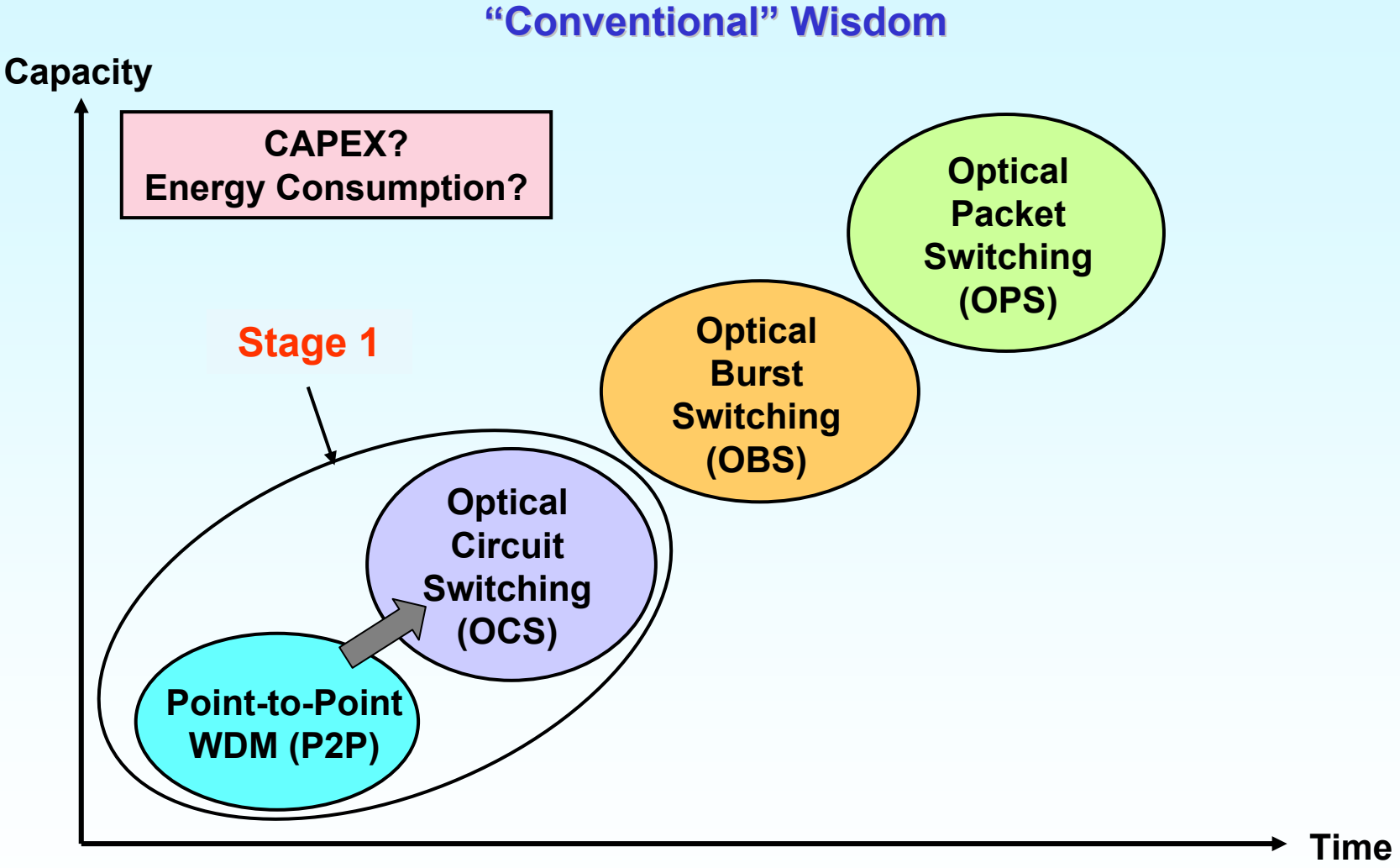
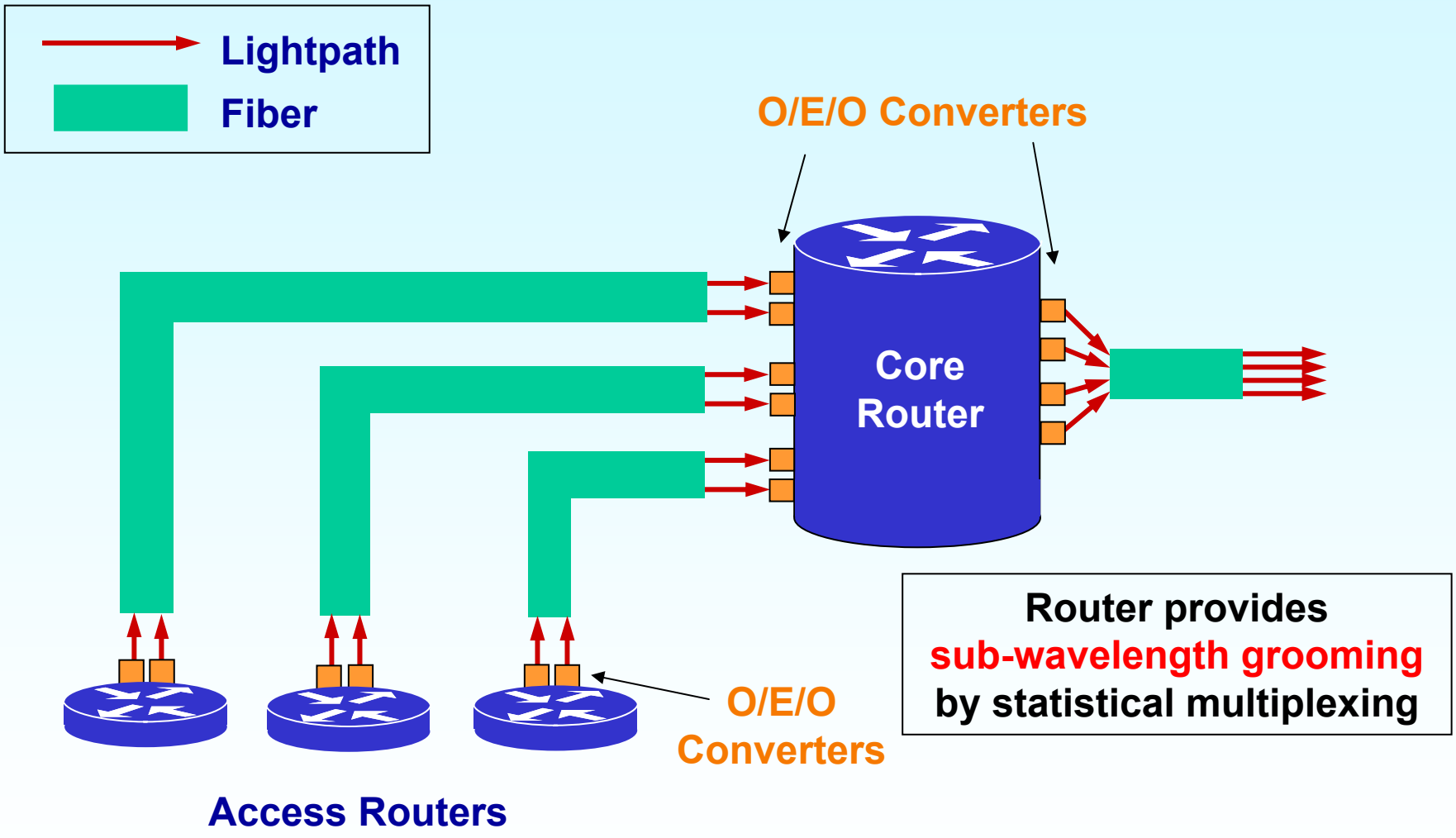
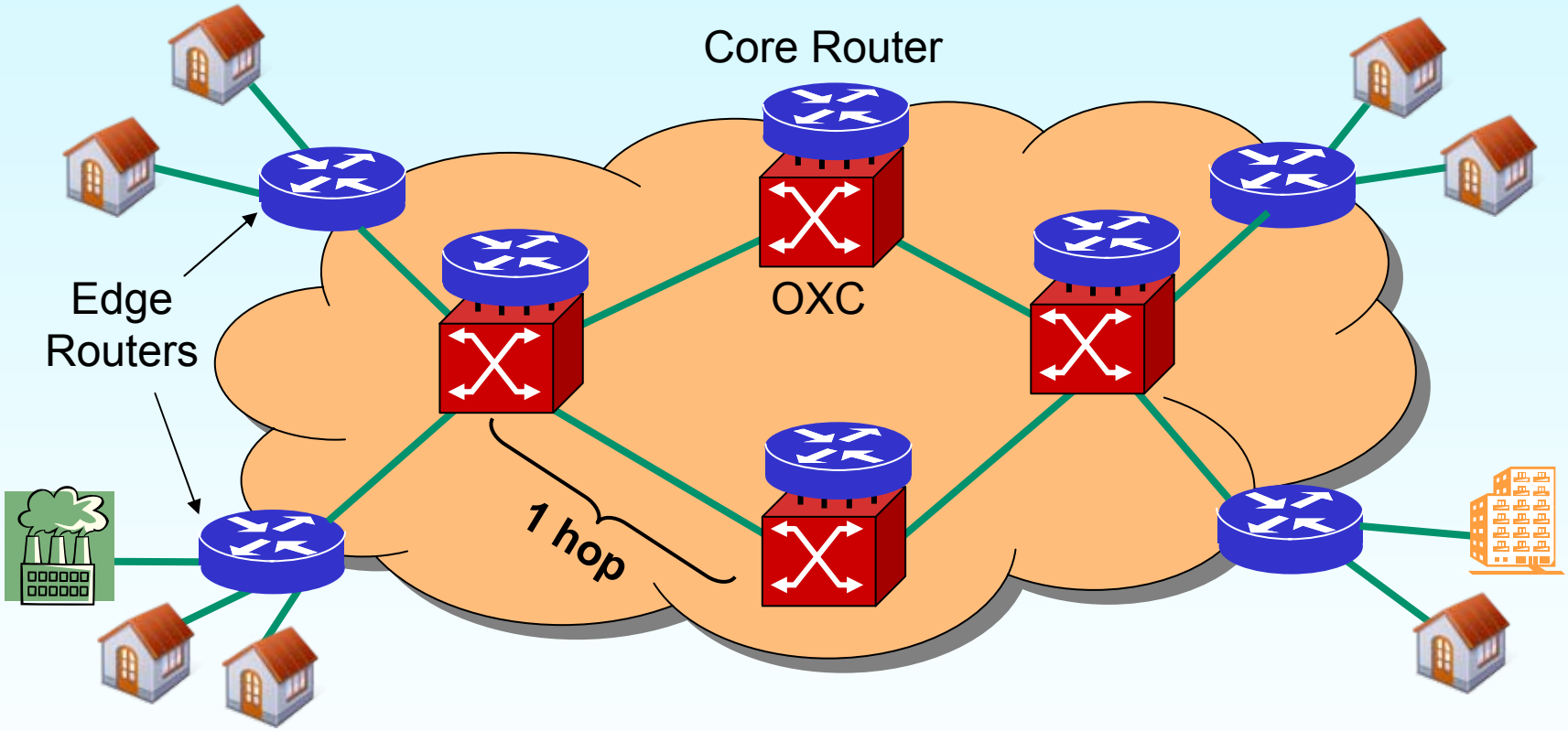
Evolution of Optical Packet-Switched Networks



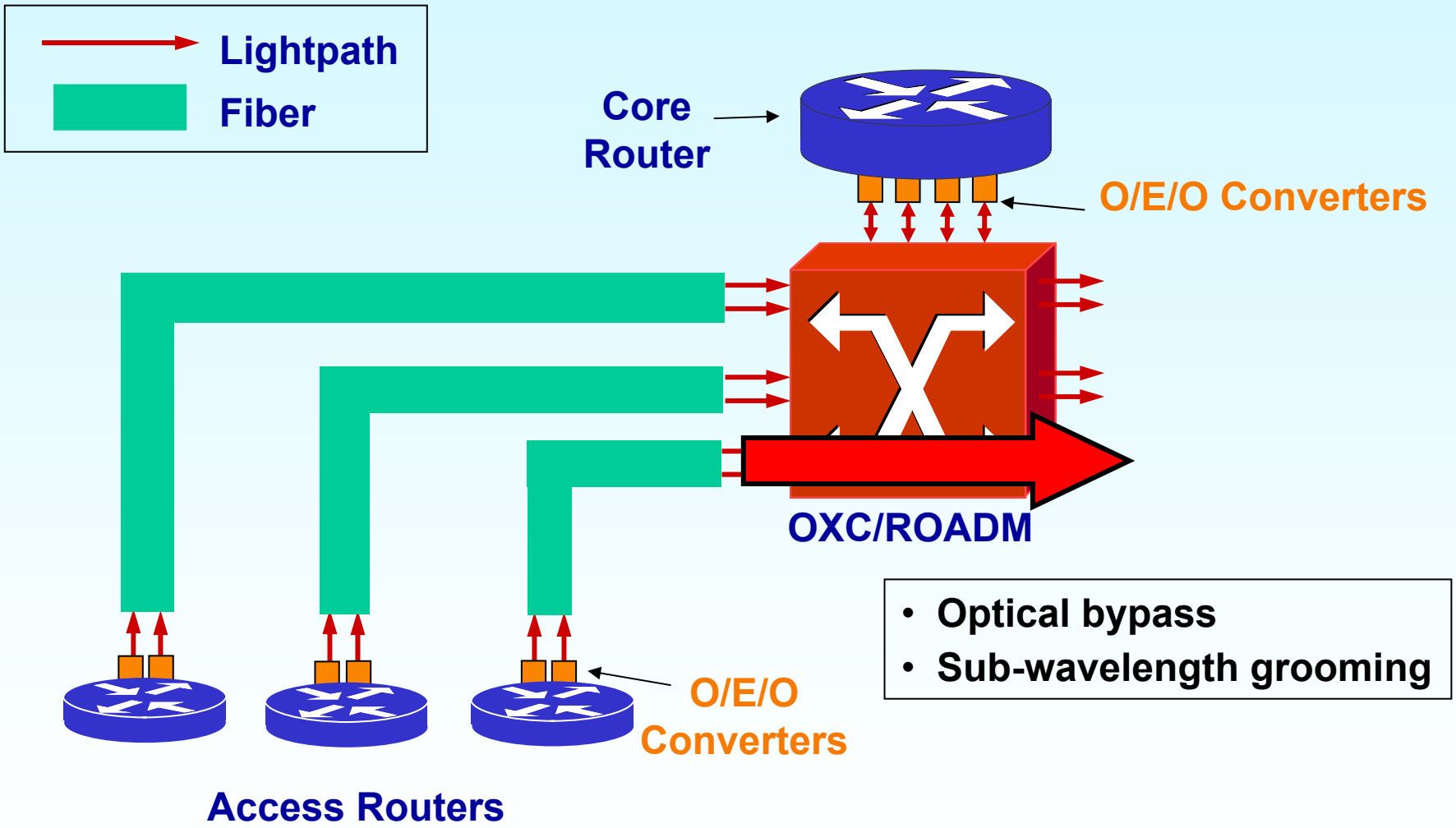
1. Point-to-Point WDM Network



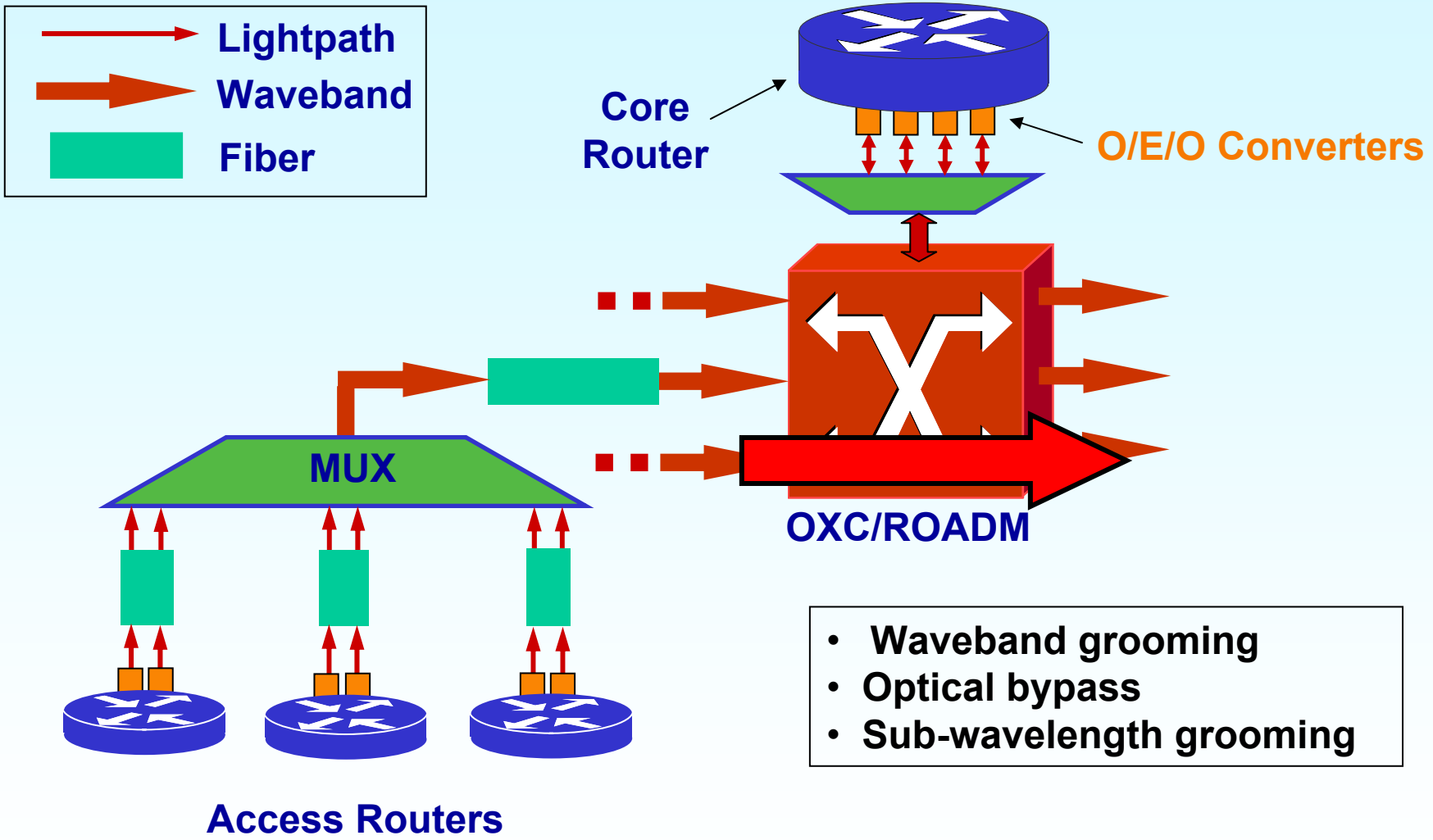
2. Optical IP Network



2. Optical IP Network



3. Waveband IP Network

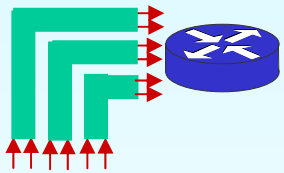


- Waveband grooming
- Optical bypass
- Sub-wavelength grooming

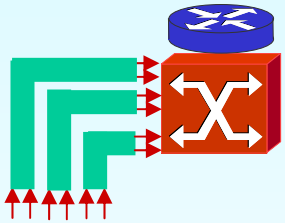
Cost and Scalability of Optical Networks

Consider three network architectures:

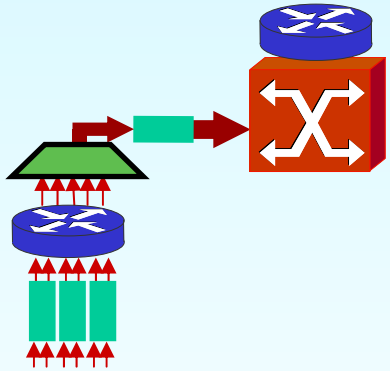
P2P WDM



Optical IP



Waveband IP



Number of users: 10 million

Compare CAPEX

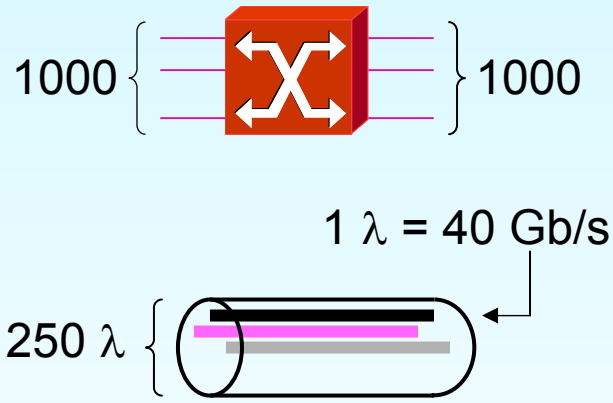
Parthiban et al., 2003

Input Parameters

- Average Access rate per user: 1 - 100 Mb/s
- 10 million users

Capacities:

- Router: 5 – 90 Tb/s
- OXC: 1000 ports
- Lightpath: 40 Gb/s
- Fiber: 250 lightpaths



Component costs [Ferreira 02, Sengupta 03]

- OXC, router – chassis, port
- Fiber, amplifiers, lightpath terminations

Ignore

- Access network, search engines, data centers, etc.
- Optical impairment cost – e.g. regenerators
- Protection & restoration
- Multiple domains
- Cost reductions as technology matures
- OPEX

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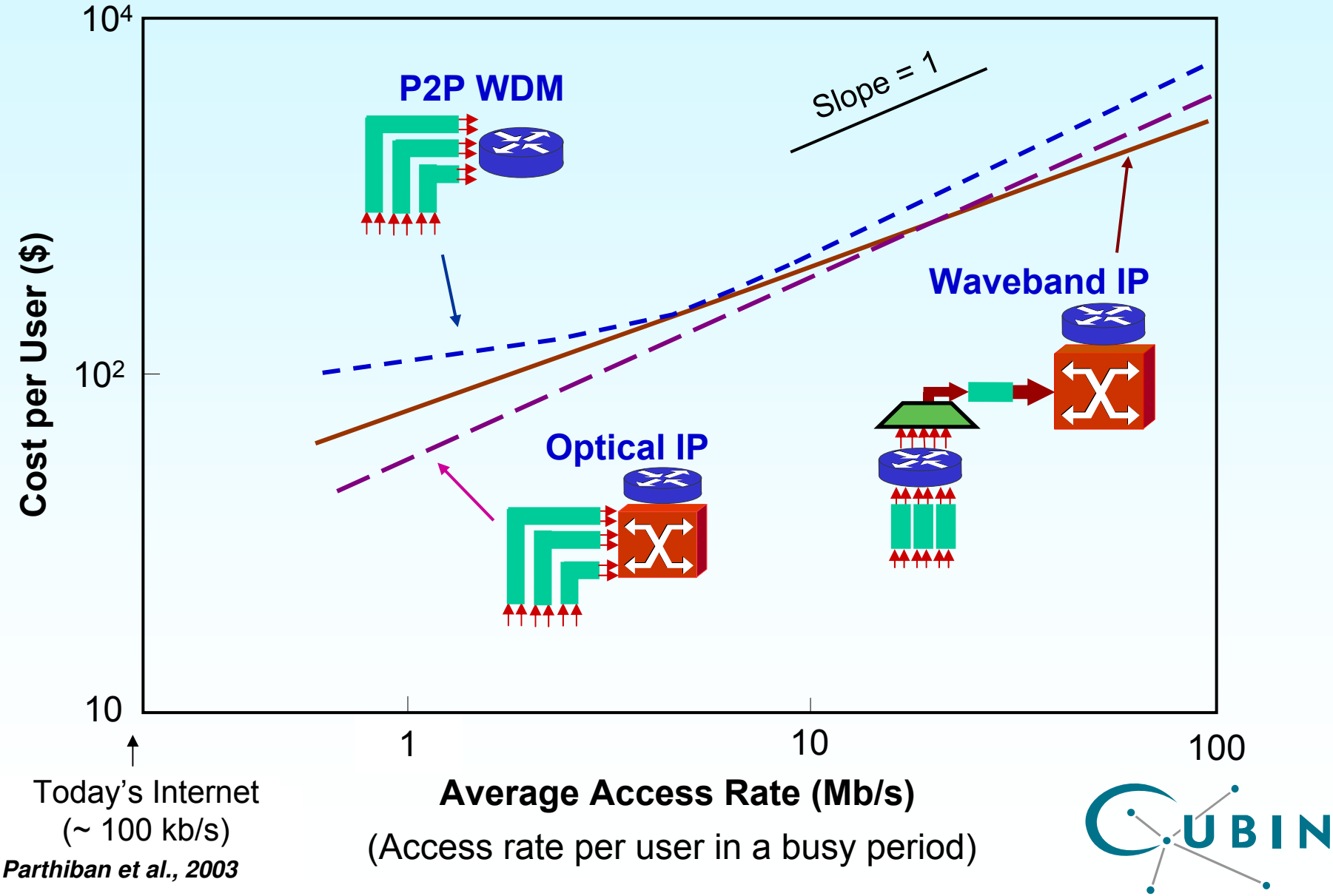
Results – Network Cost



Parthiban et al., 2003

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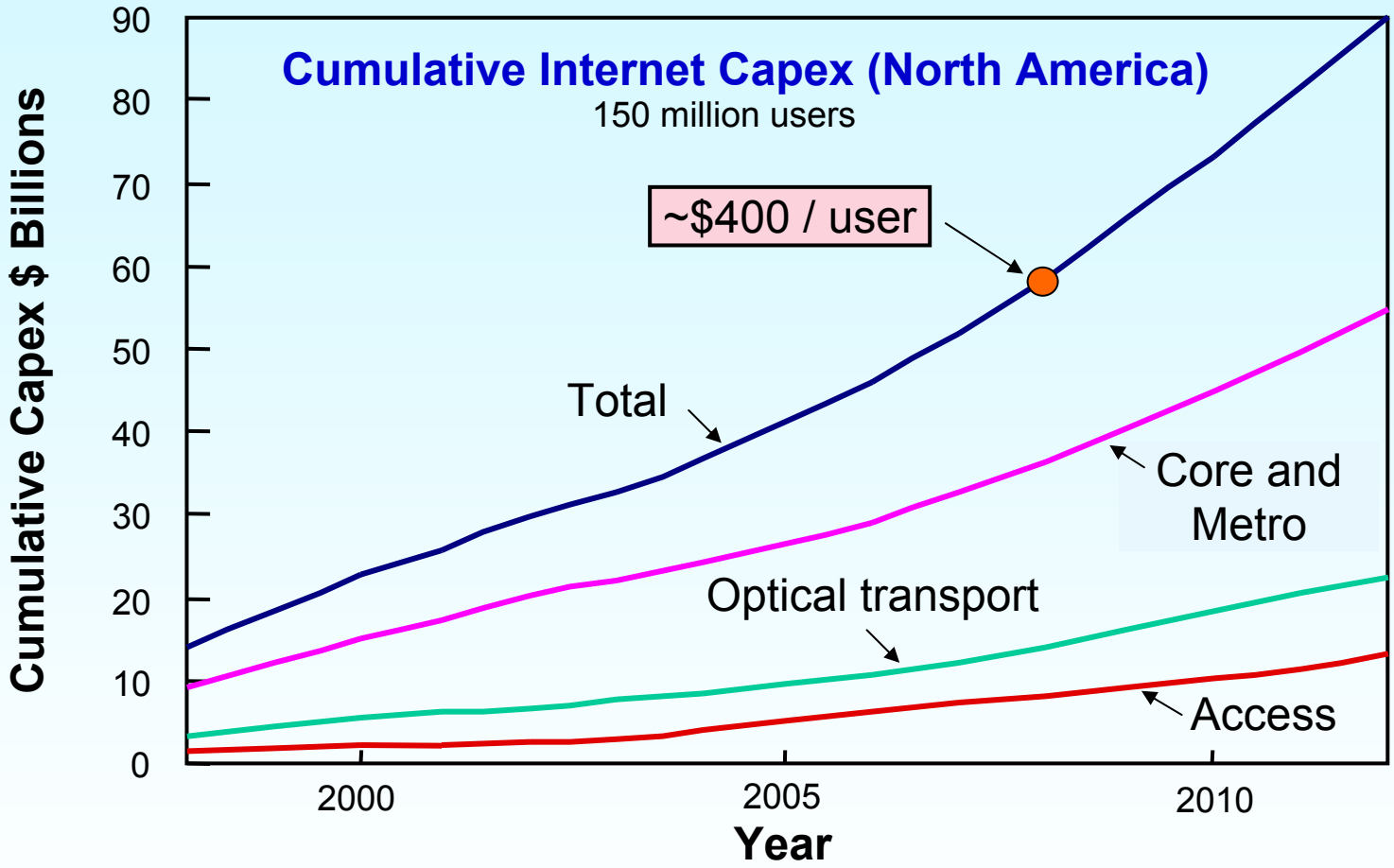
Sanity Check



Nemertes, November 19, 2007:

"User demand could outpace network capacity by 2010
$137 billion global infrastructure investment needed"

Based on data from Nemertes Research, 2007

Observations

- Optical IP network
  - Can save costs in today's network
  - Optical bypass reduces router ports
- Waveband IP network
  - Eliminates the bottleneck in number of ports and lightpaths
  - Least costly for high access rates
- There is no such thing as a free lunch
  - If you want more bandwidth, you will have to pay for it

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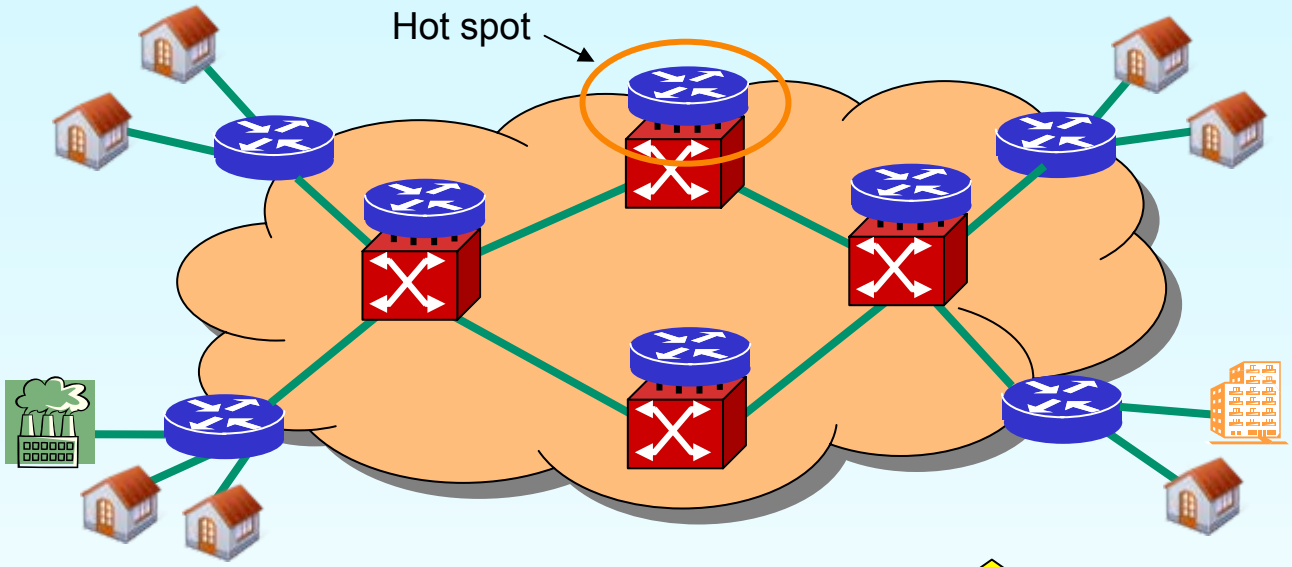
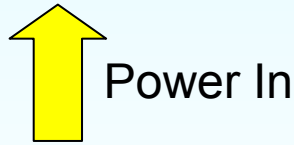
Energy Consumption of the Network



Why worry about energy consumption?

- OPEX
- Greenhouse Impact
- Managing “Hot Spots”
  - Getting the energy in
  - Getting the heat out
- Energy-limited capacity bottlenecks



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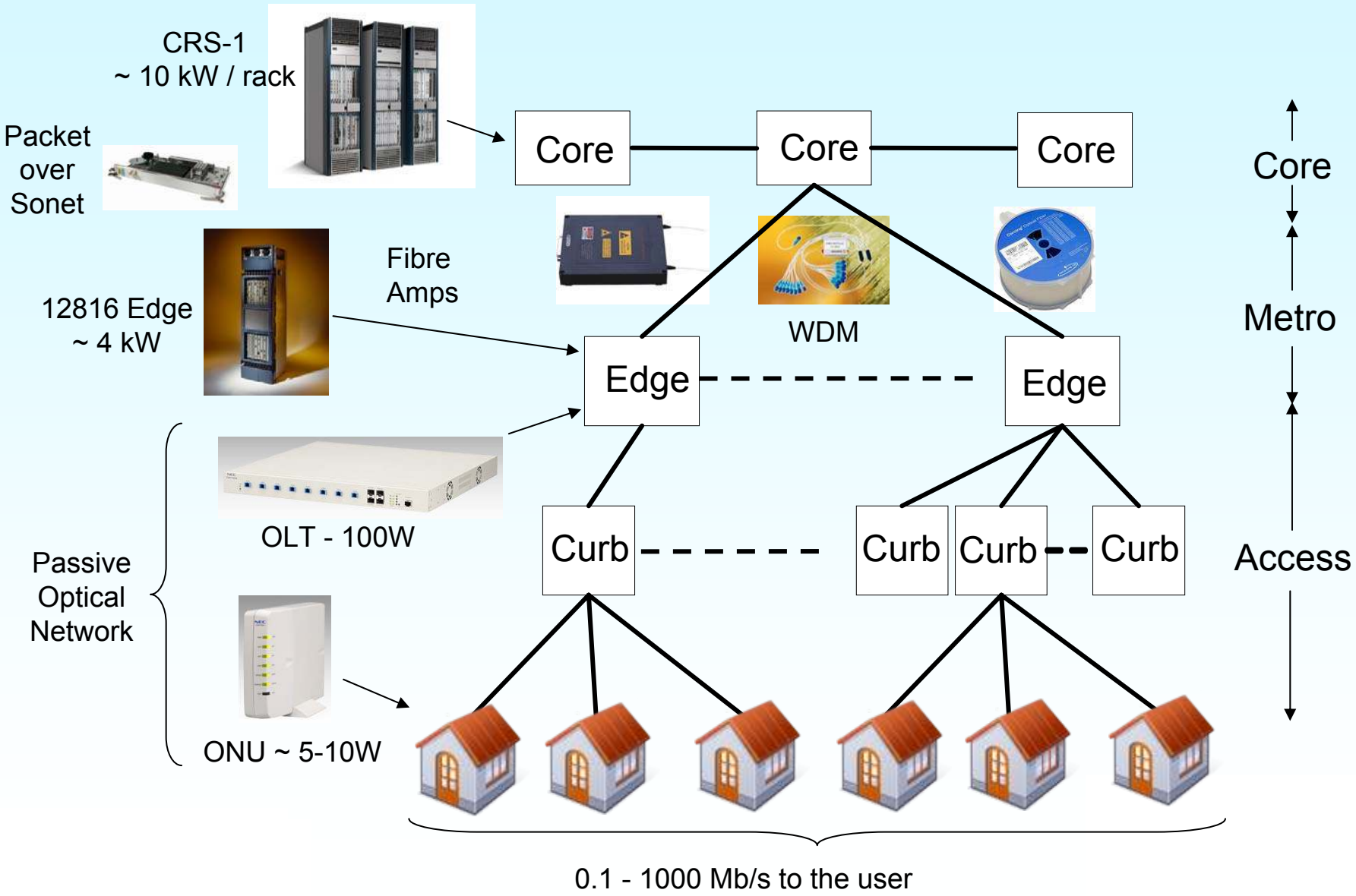
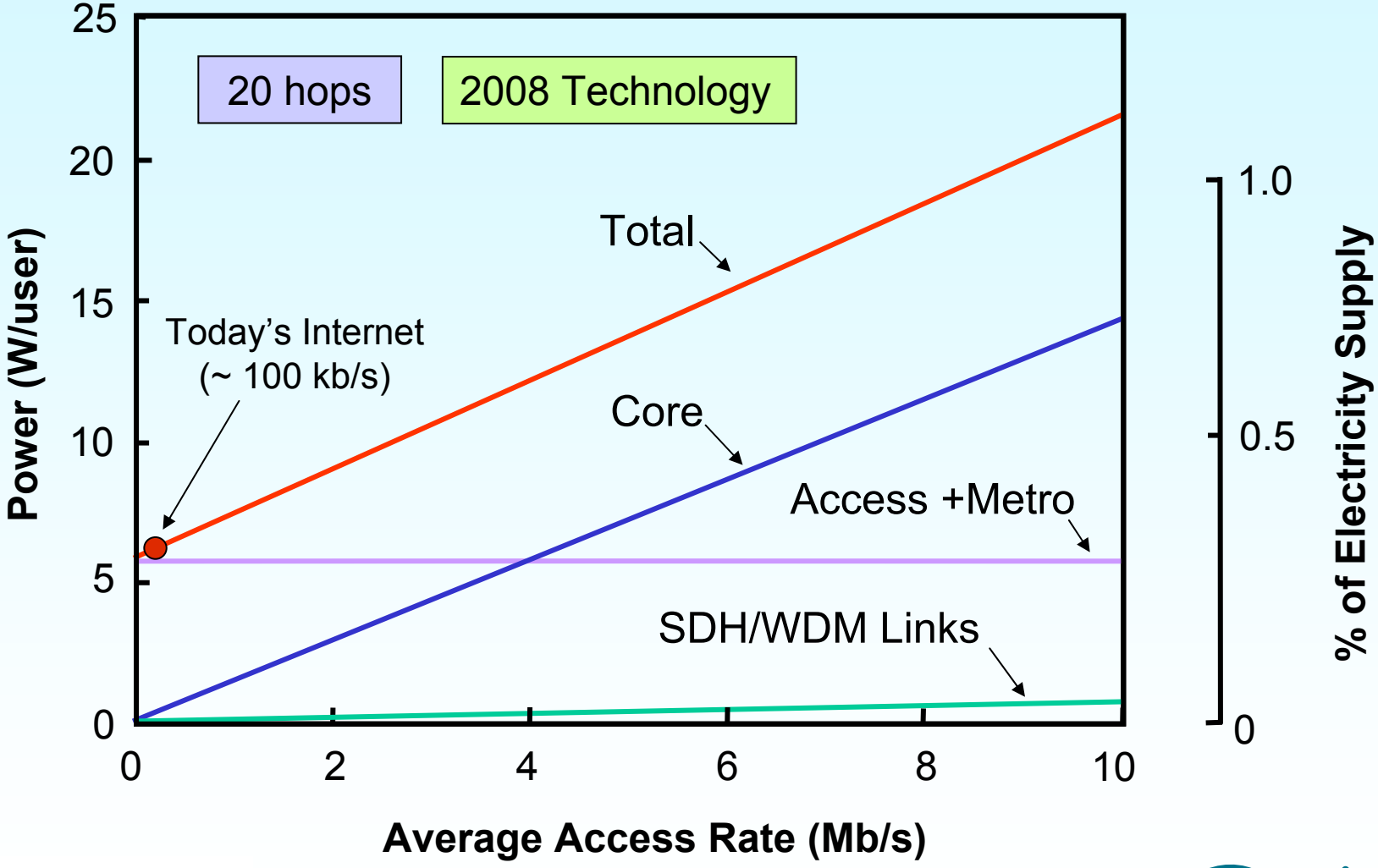
Energy Model of Simple IP Network



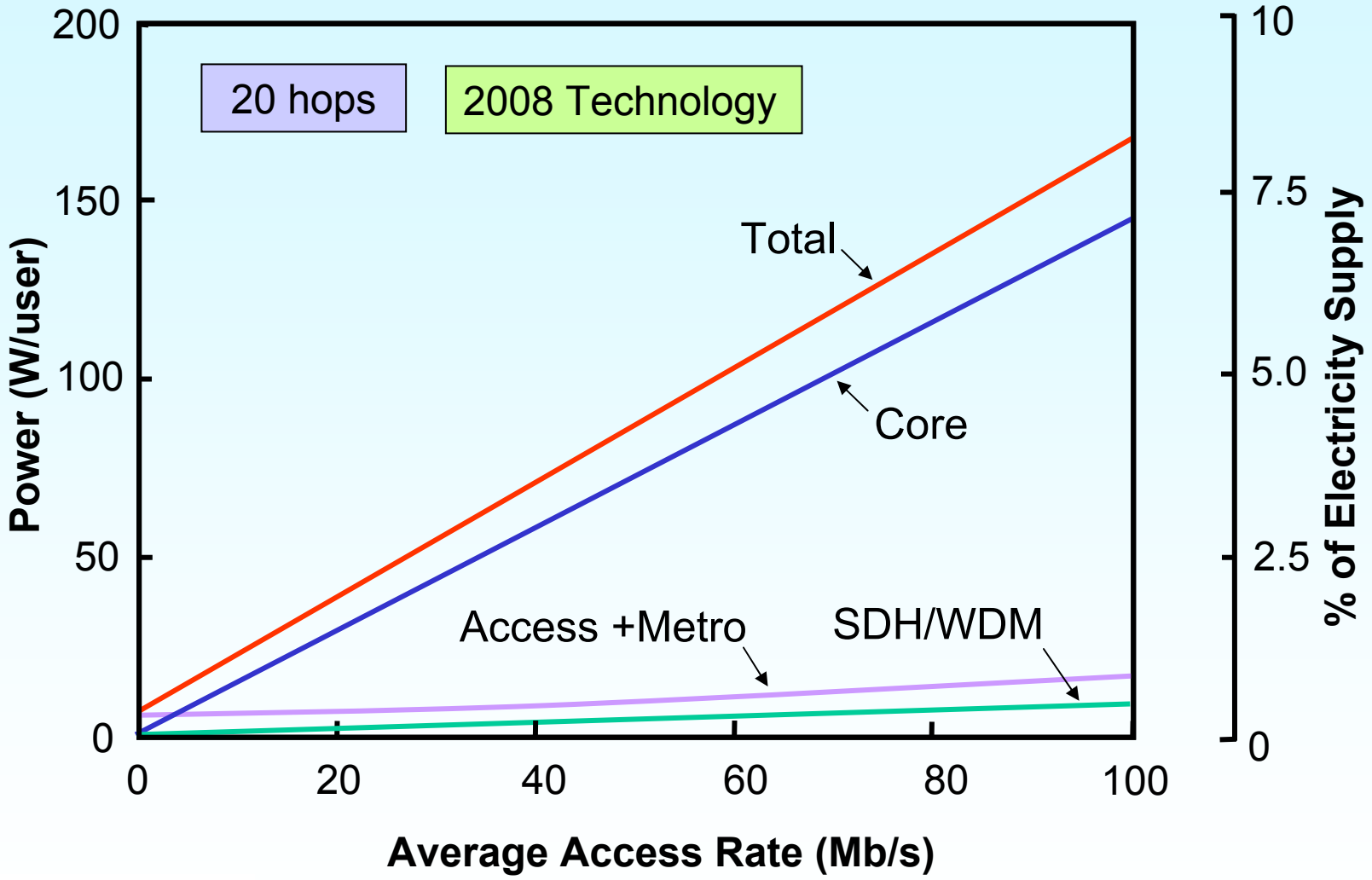
Baliga et al., 2007

Power Consumption of IP Network



Baliga et al., 2007

Power Consumption of IP Network



Baliga et al., 2007

Observations / Questions

- Access network dominates energy consumption at low rates ← 2
  - Standby mode?
- Core network dominates at higher rates
  - Reduce hop count?
- What is the bottleneck in the core? Speed or energy? ← 1
  - Optical packet switching ← 3
- Optical transport (WDM) consumes relatively little energy
  < 5% of energy
  > 25% of CAPEX
- Annual CAPEX / Annual energy OPEX > 2

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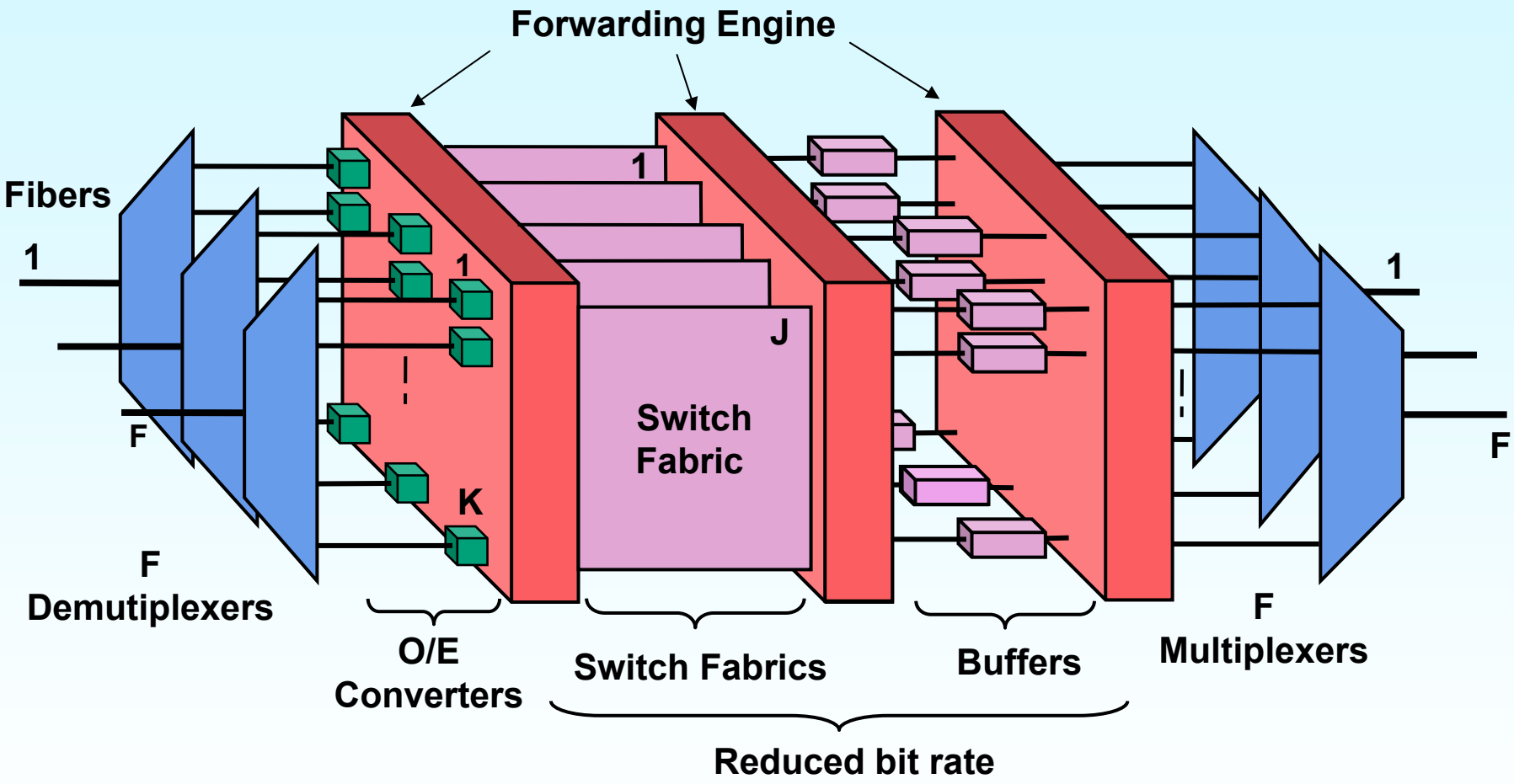
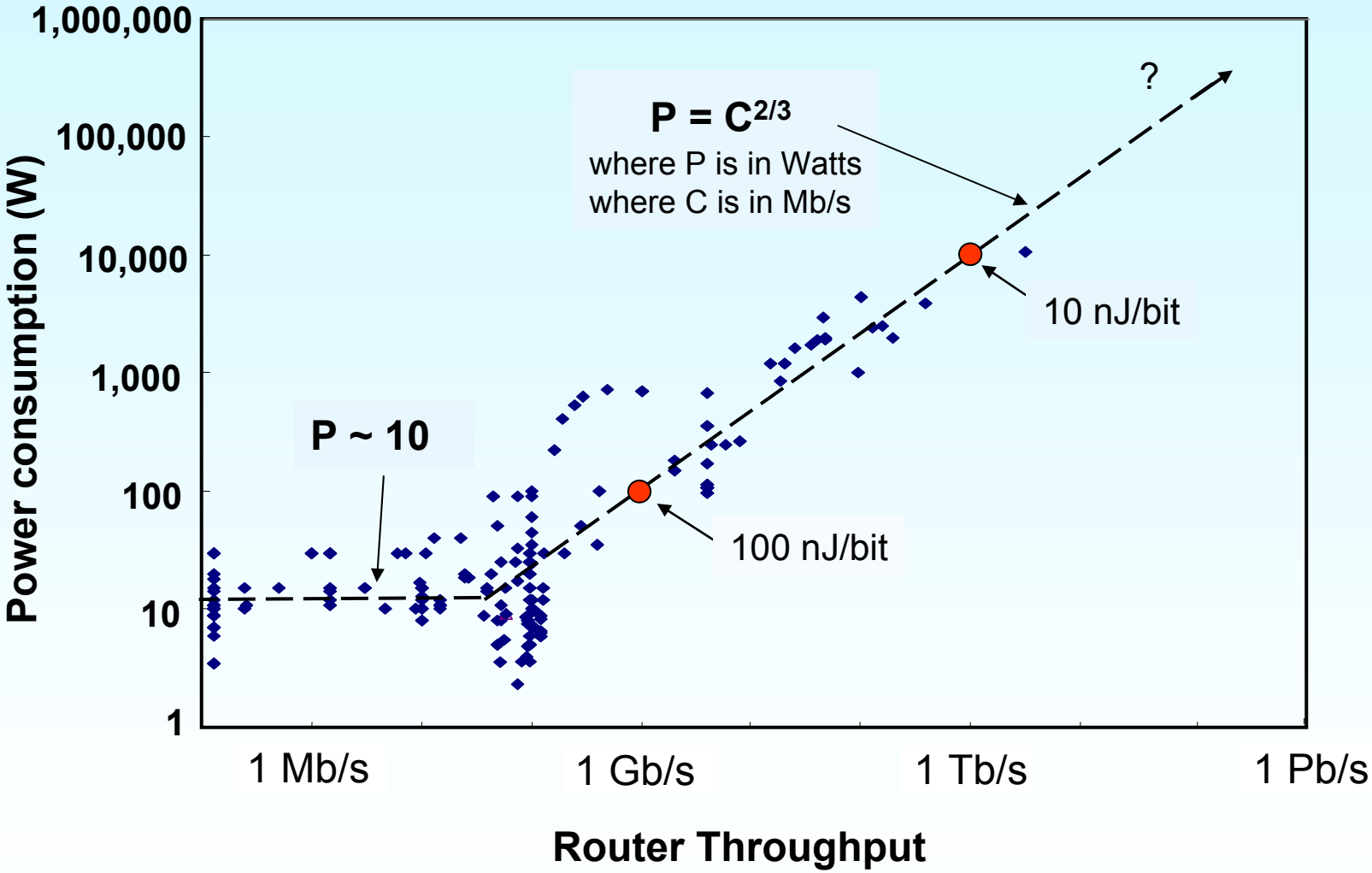
Electronic Router

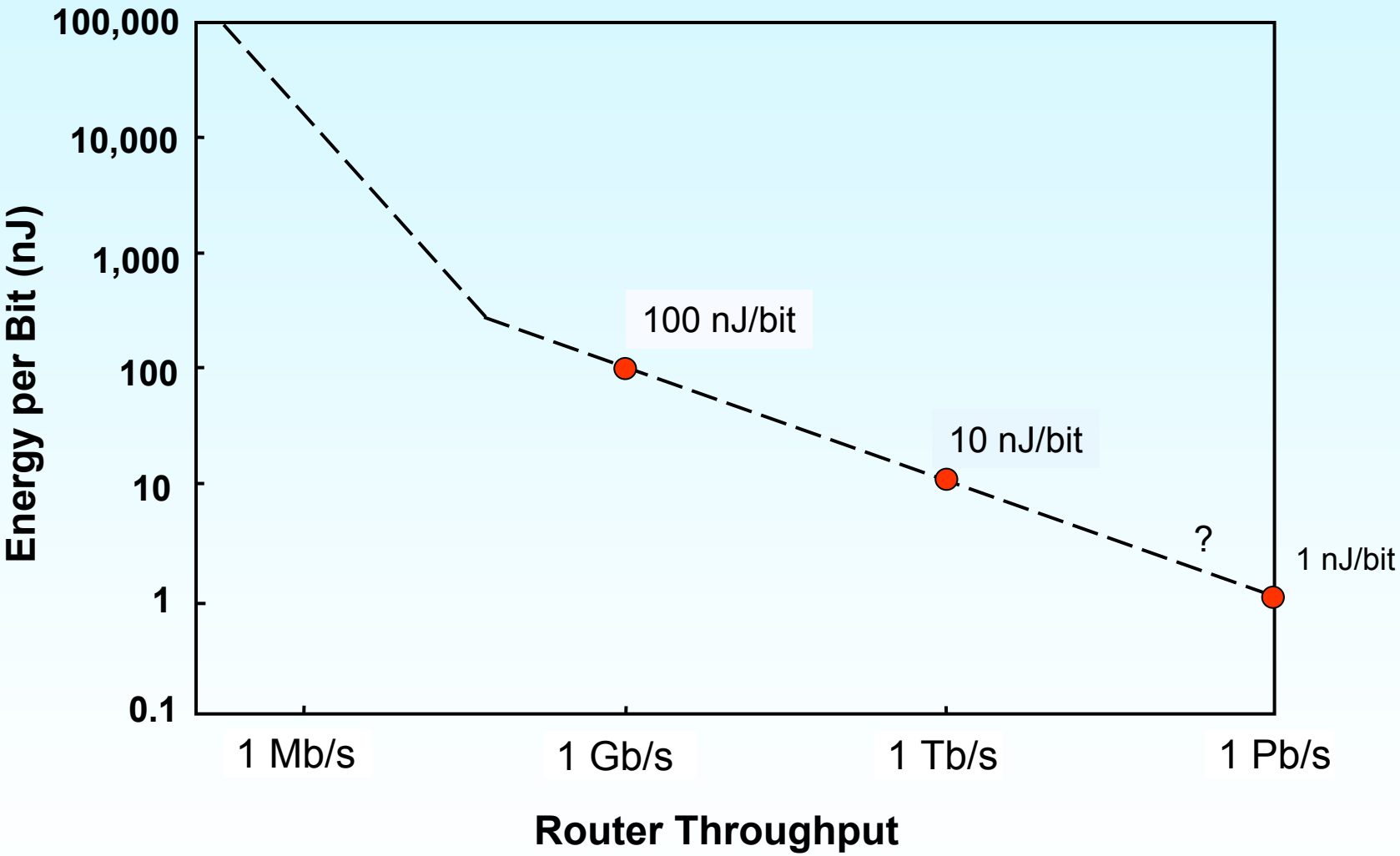


Power Consumption in Routers



Source: METI, 2006, Nordman, 2007

Energy per Bit in Routers



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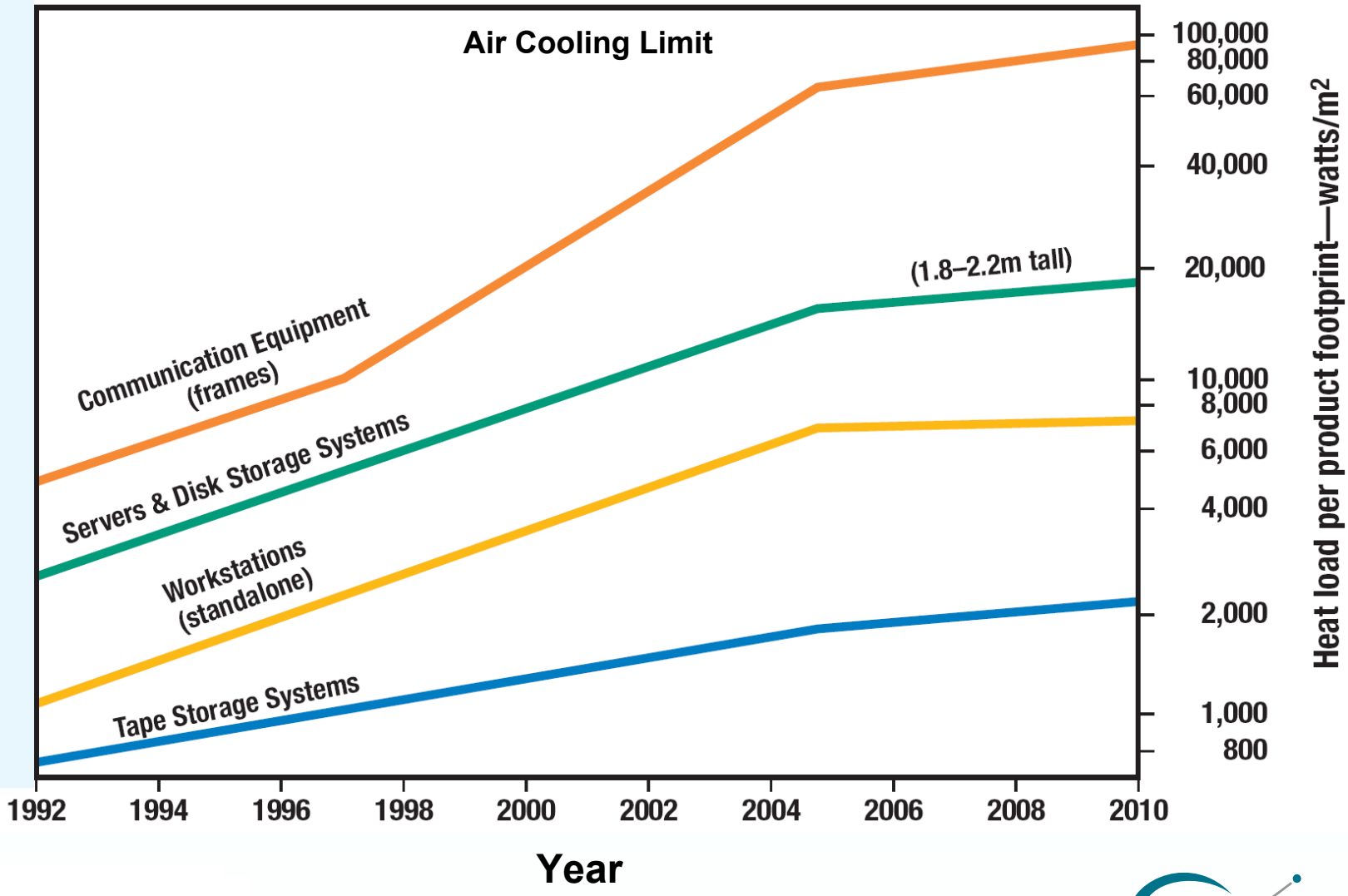
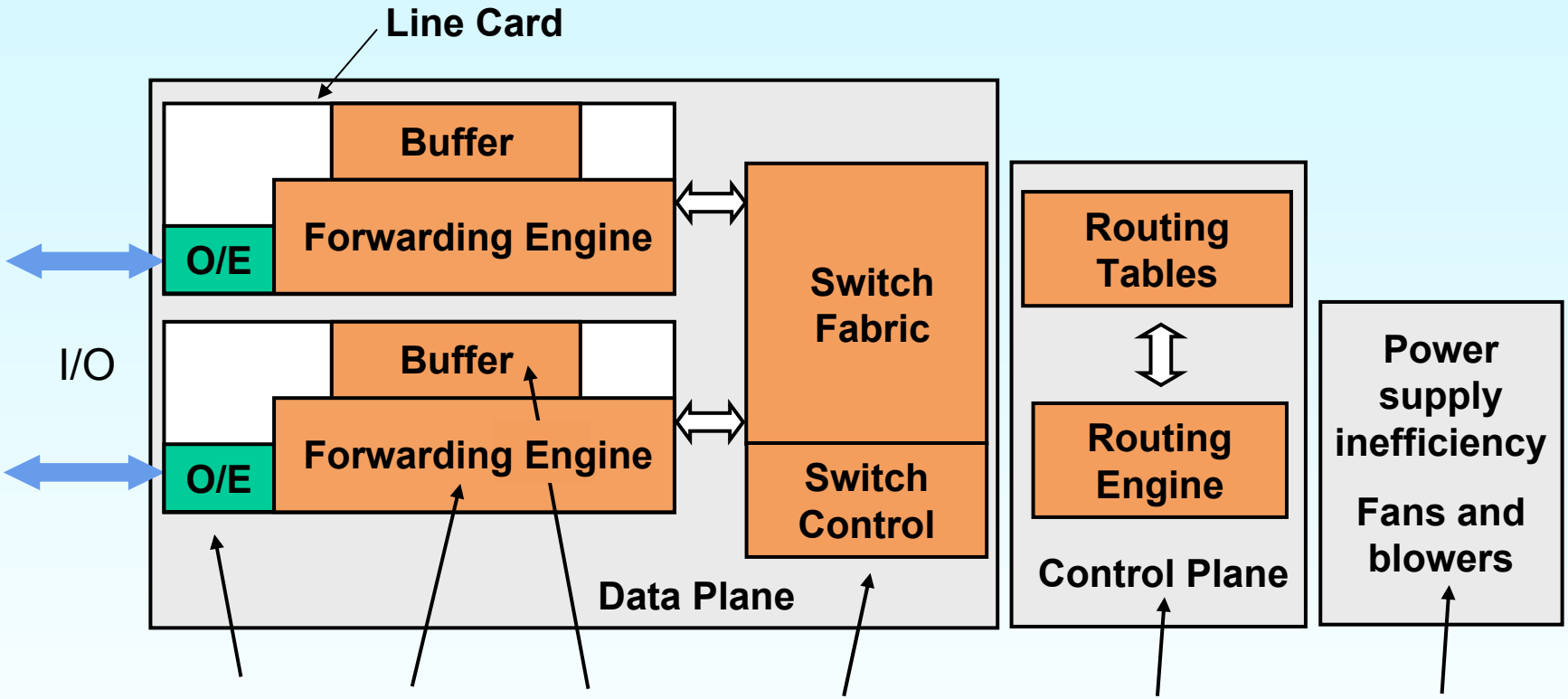
Heat Load



Source: K. Brill, The Uptime Institute

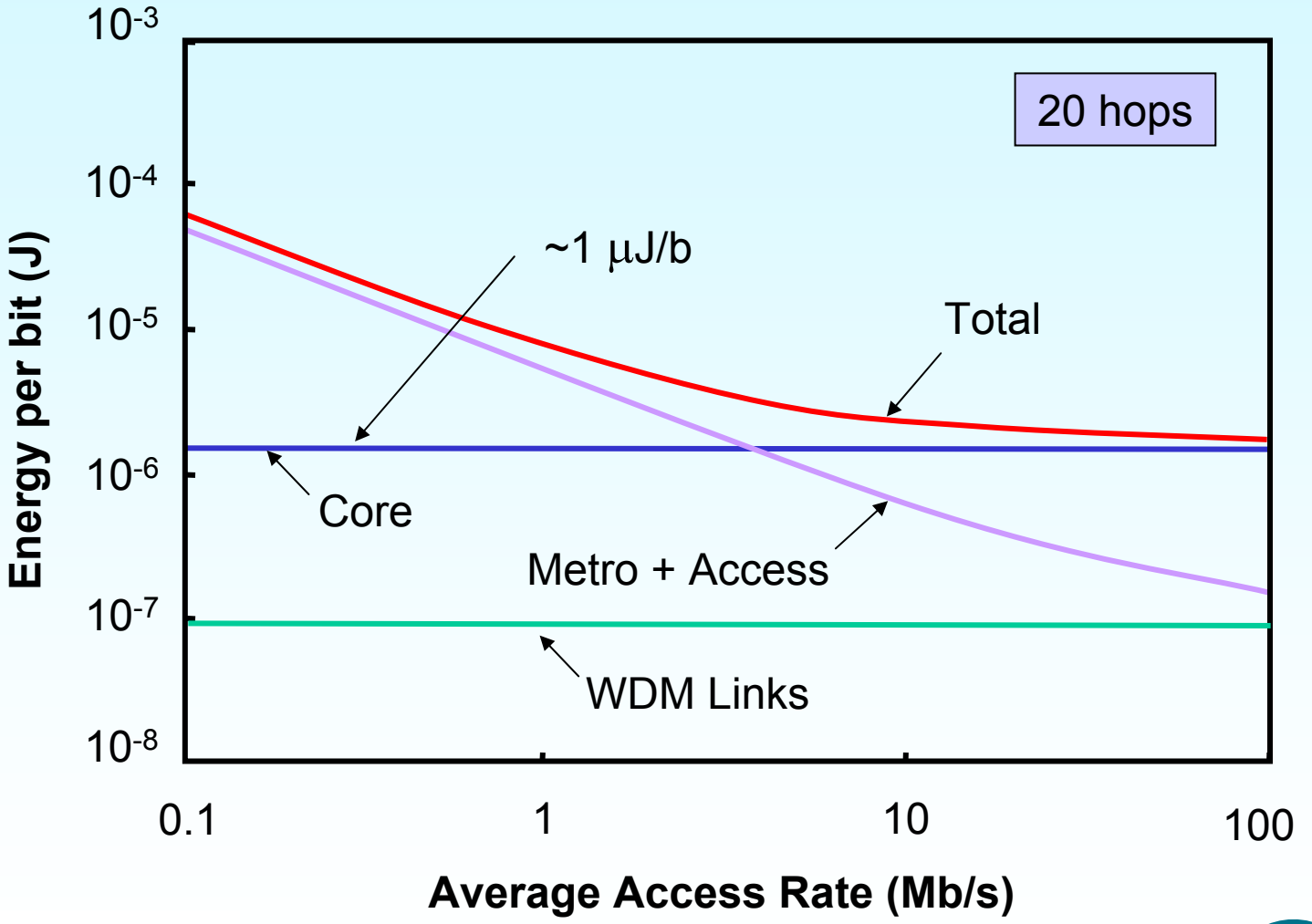
Energy in High-End Electronic Router



Energy/bit	0.7 nJ	3.2 nJ	0.5 nJ	1.0 nJ	1.1 nJ	3.5 nJ
Fraction of Total	7%	32%	5%	10%	11%	35%

Source: G. Epps, Cisco, 2007

Network *Energy* Consumption per Bit



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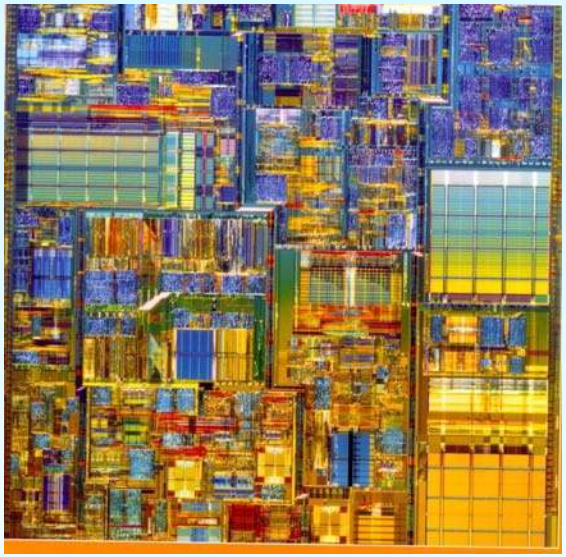
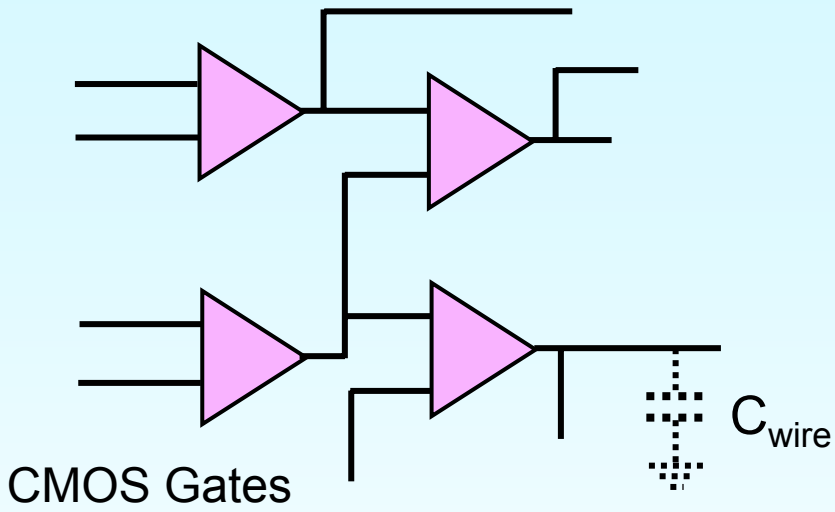
Energy in Electronic Integrated Circuits



CMOS IC



$$\text{Energy} = \sum E_{gate} + \frac{1}{2}\left[\sum C_{wire}\right]V^2$$

$$\text{Power} = \text{Energy x Bit Rate}$$

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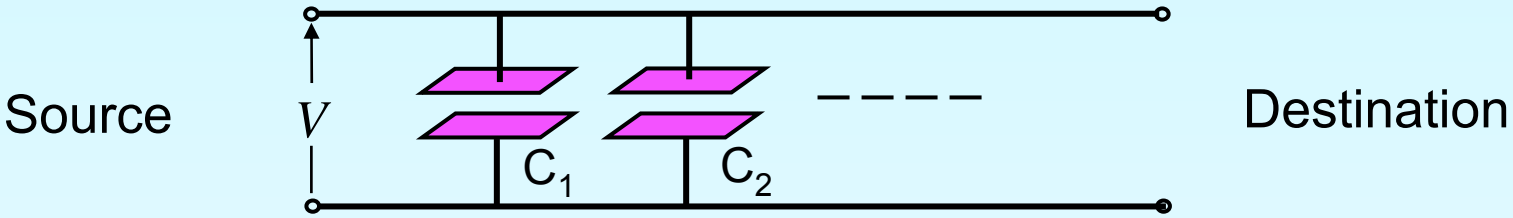
Diversion: *Capacitance* of the Core Network



Energy per bit per user: $E = \frac{1}{2}\left[\sum C\right]V^2$

$$V = 2,\quad E = \frac{1\ \mu J}{2} \rightarrow \sum C \approx 200\ \text{nF}$$

← Capacitance per user

← 50% efficiency

~ 150 million users $\rightarrow C_{Network} = 200\ \text{nF}\ x1.5 \times 10^8$

$C_{Network} \approx 30\ \text{F}$ (North America)

$C_{Network} \approx 300\ \text{F}$ (Global)

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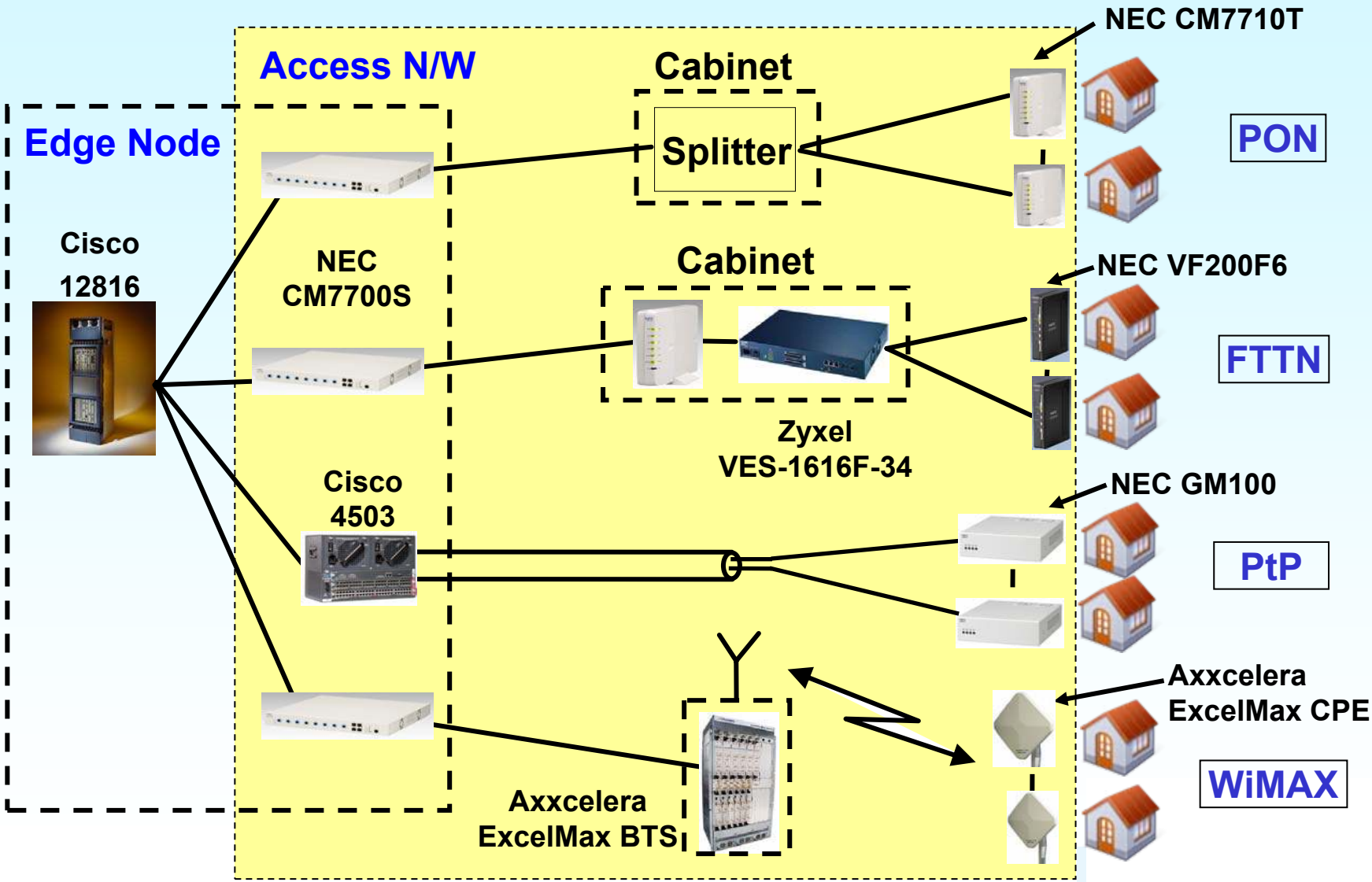
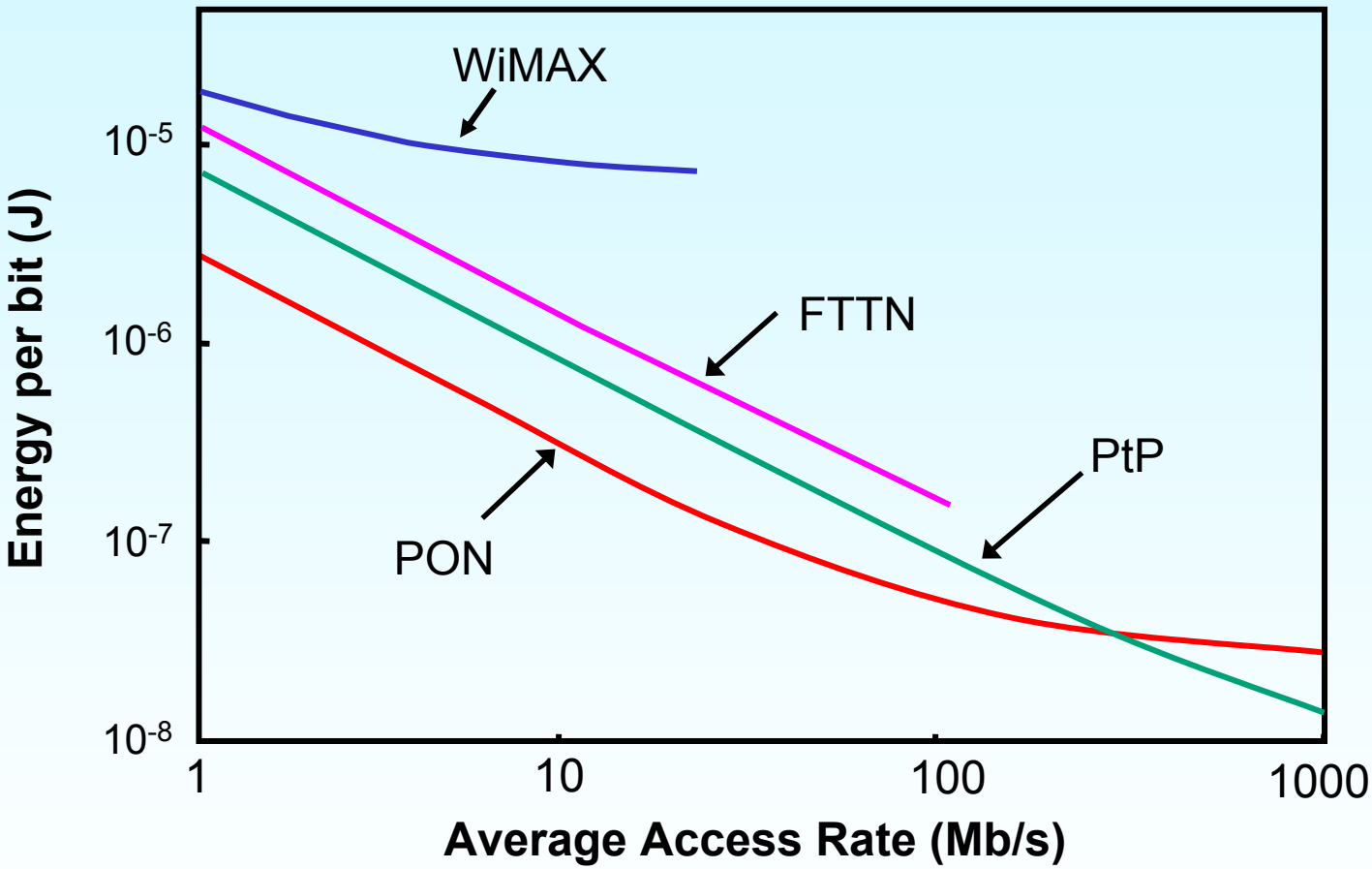
Energy Consumption in Access Networks



Baliga et al., OThT6

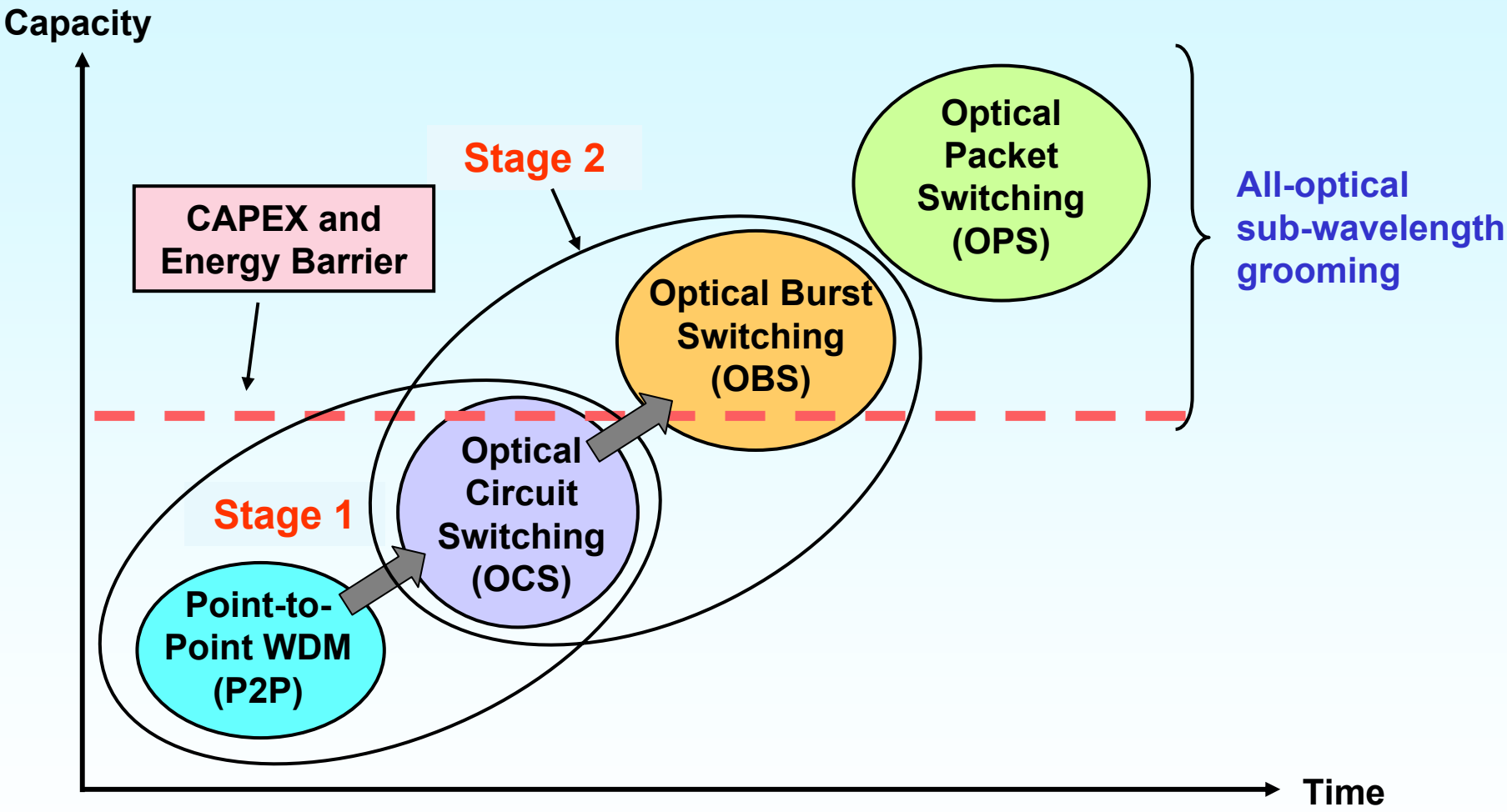
Energy Consumption in Access Networks



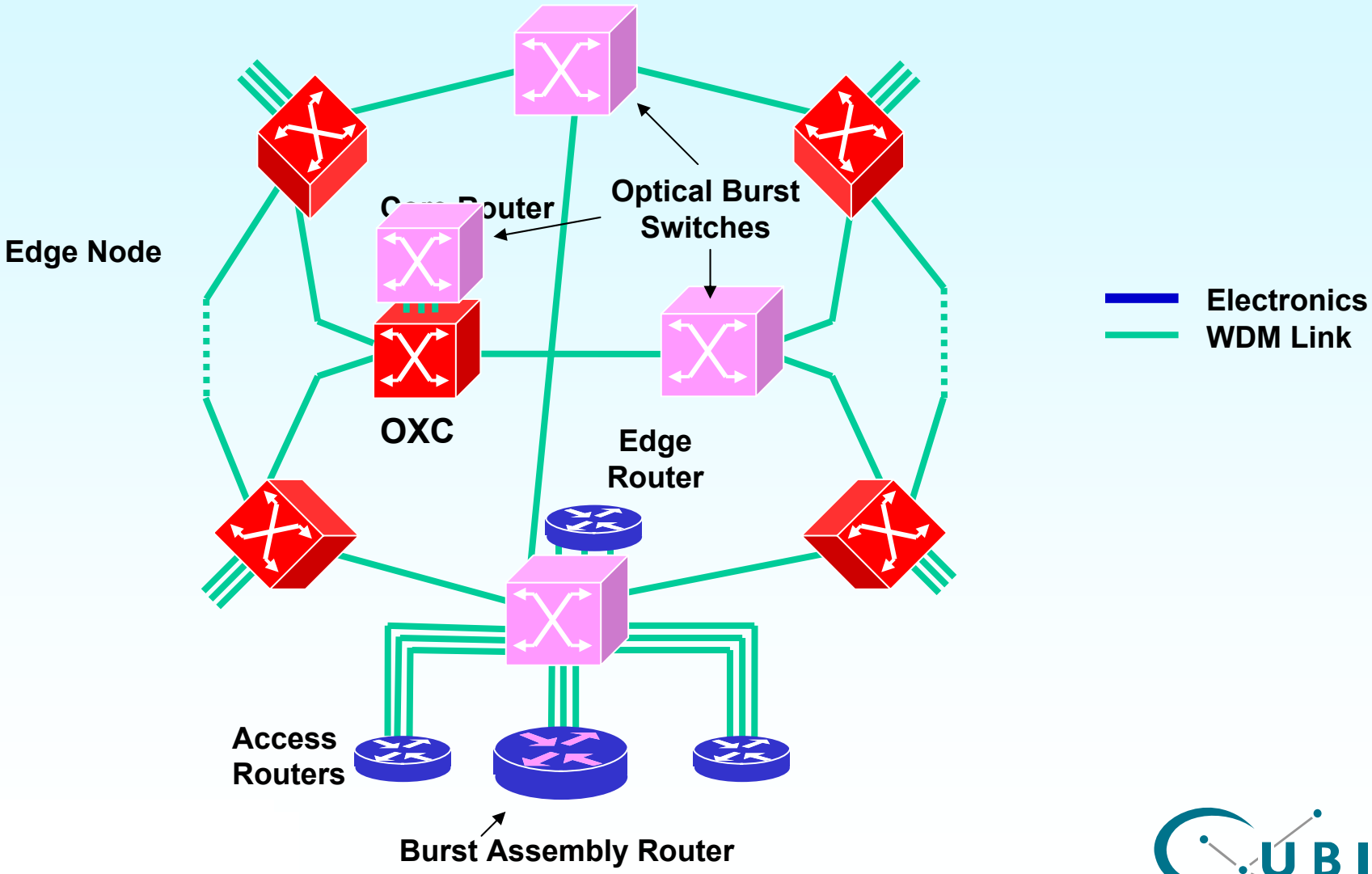
- Wireless access consumes more energy than optical access
- PON FTTH is “greener” than FTTN
- “Standby mode” shows significant potential (OThT6)

Baliga et al., OThT6

Evolution of Optical Packet-Switched Networks

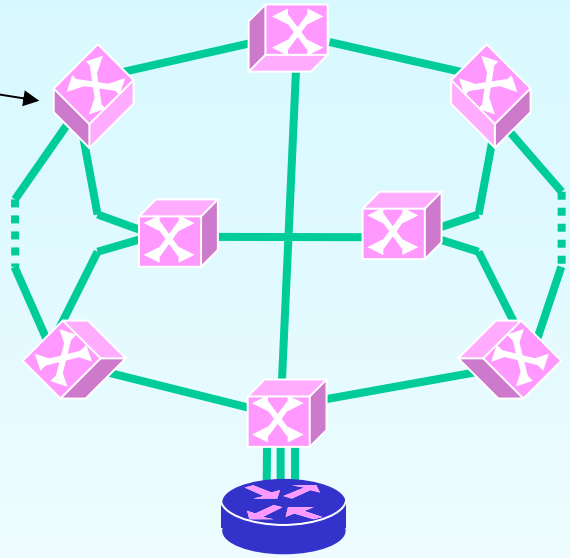


Stage 2 Evolution – OCS to OBS

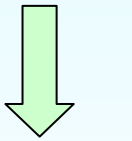


Optical Burst Switched Network

Optical Burst Switch
No Buffering

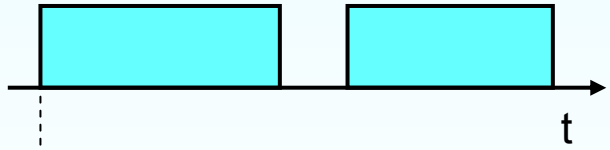


IP Packets (duration < μs)

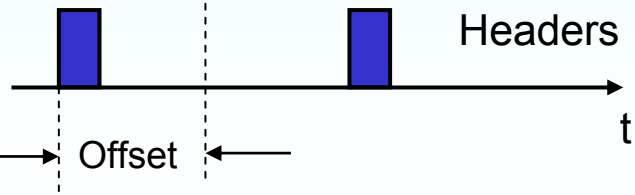


Burst Assembly Router

Data Bursts (duration < ms)



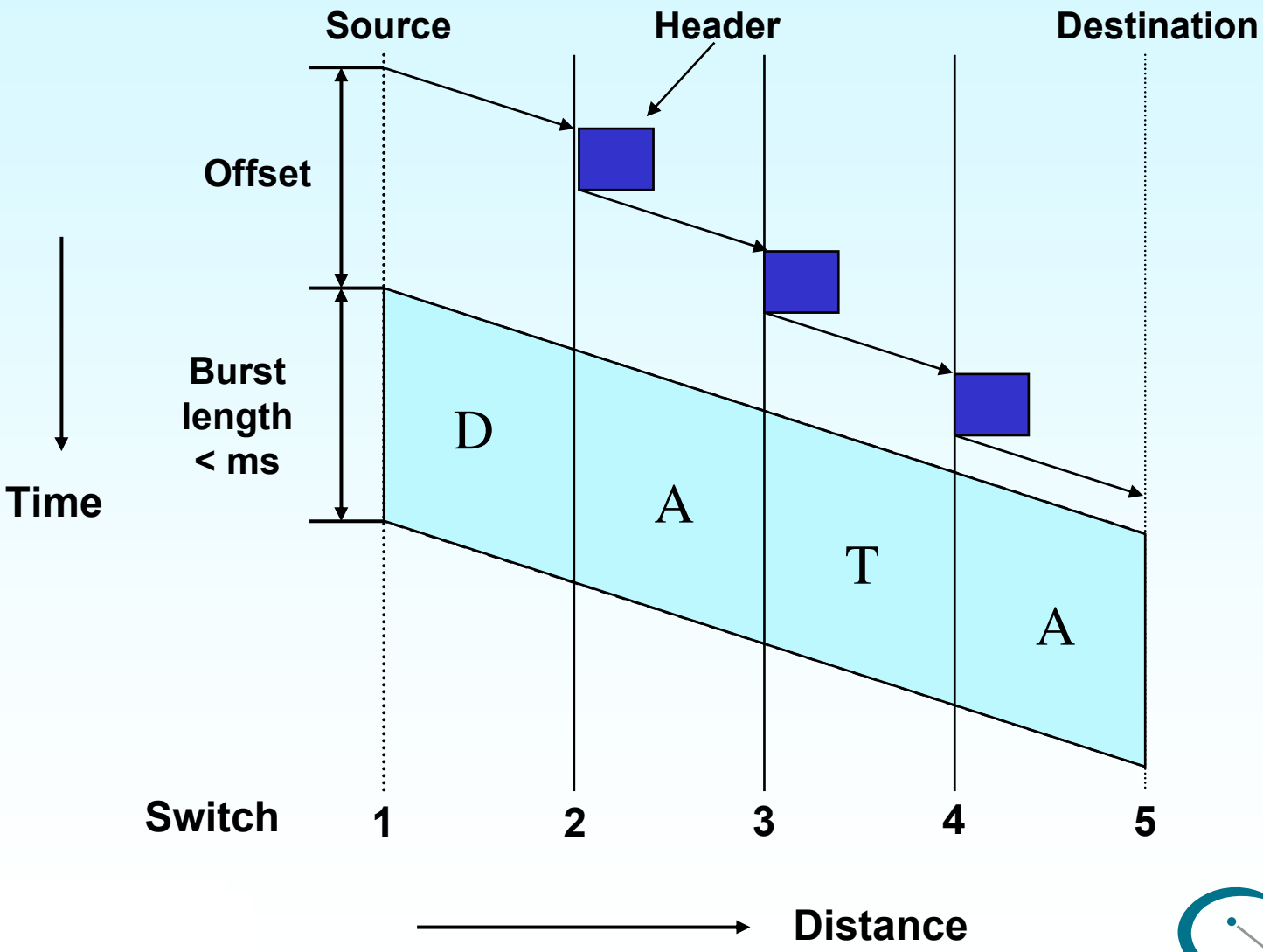
Headers



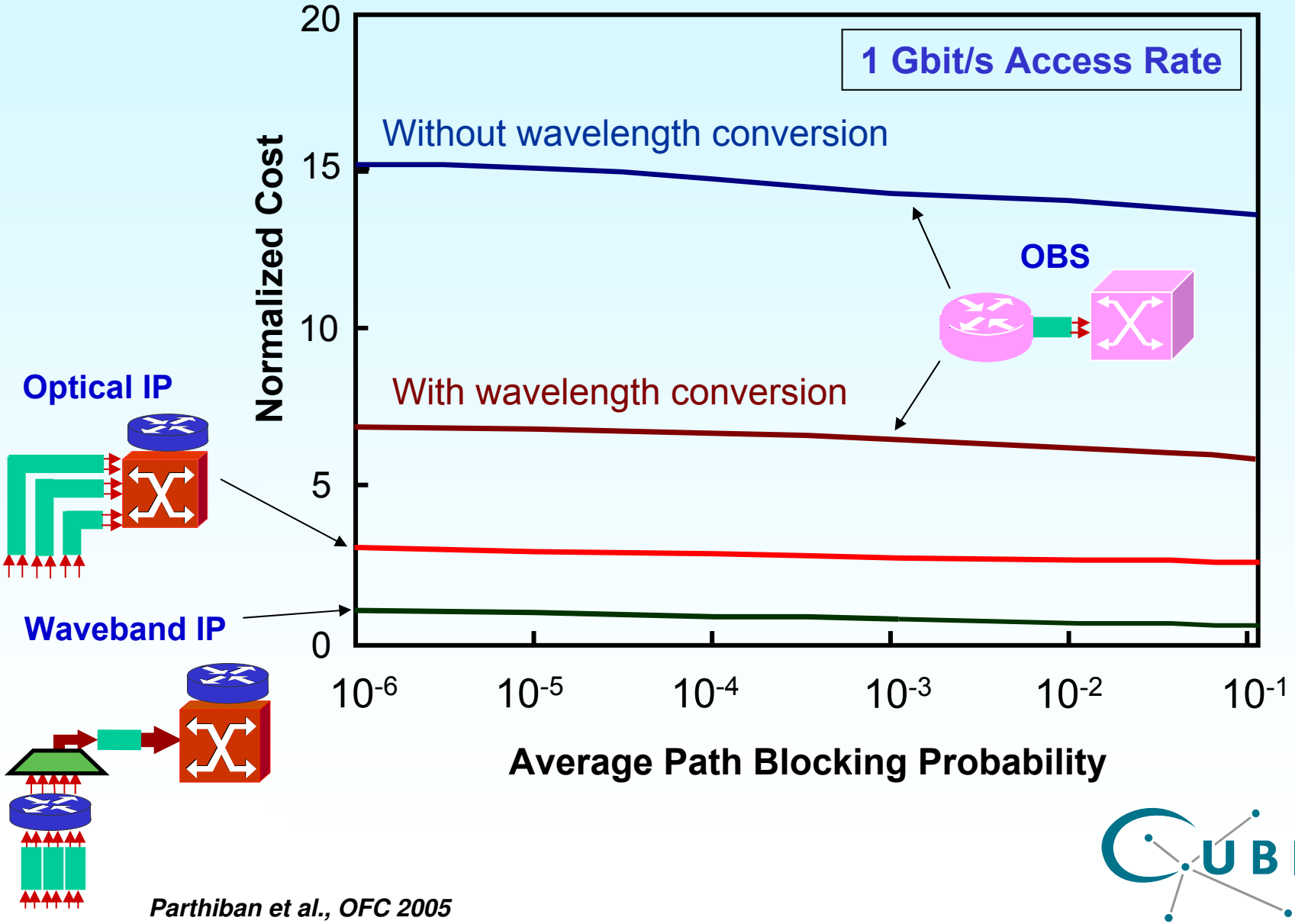
IP Packets

C. Qiao and M. Yoo, JHSN, 1999

Optical Burst Switching

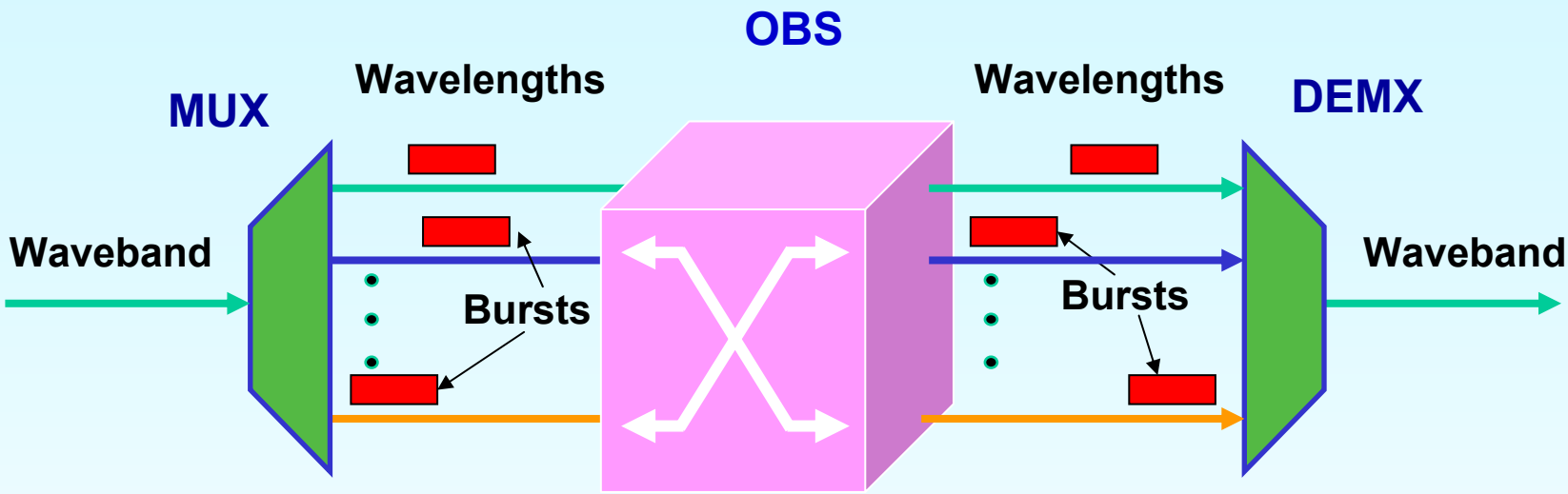


Normalized Cost: OBS vs. IP



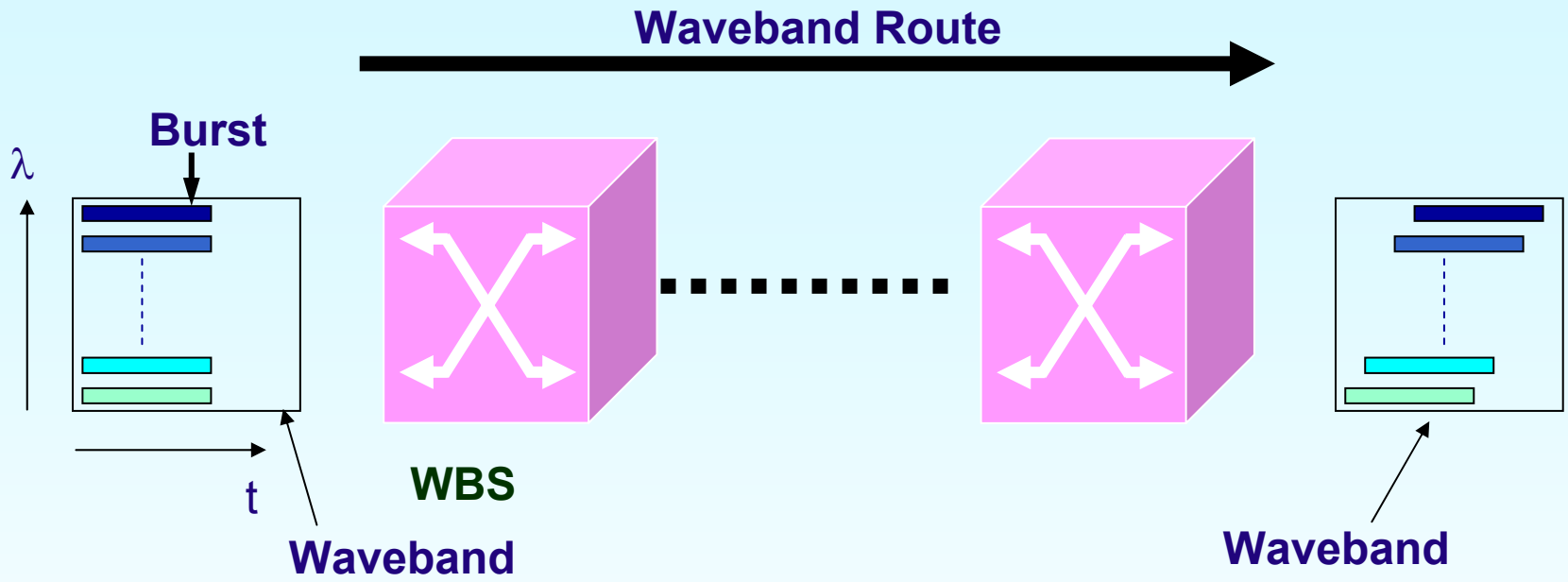
Parthiban et al., OFC 2005

Why is OBS more Costly?



- Requires increased number of lightpaths for a given blocking probability
- Switch technology requires fast reconfiguration time: More costly per port than “slow” OXC’s (MEMS etc.)

Solution: Waveband Burst Switching (WBS)



Pro's:

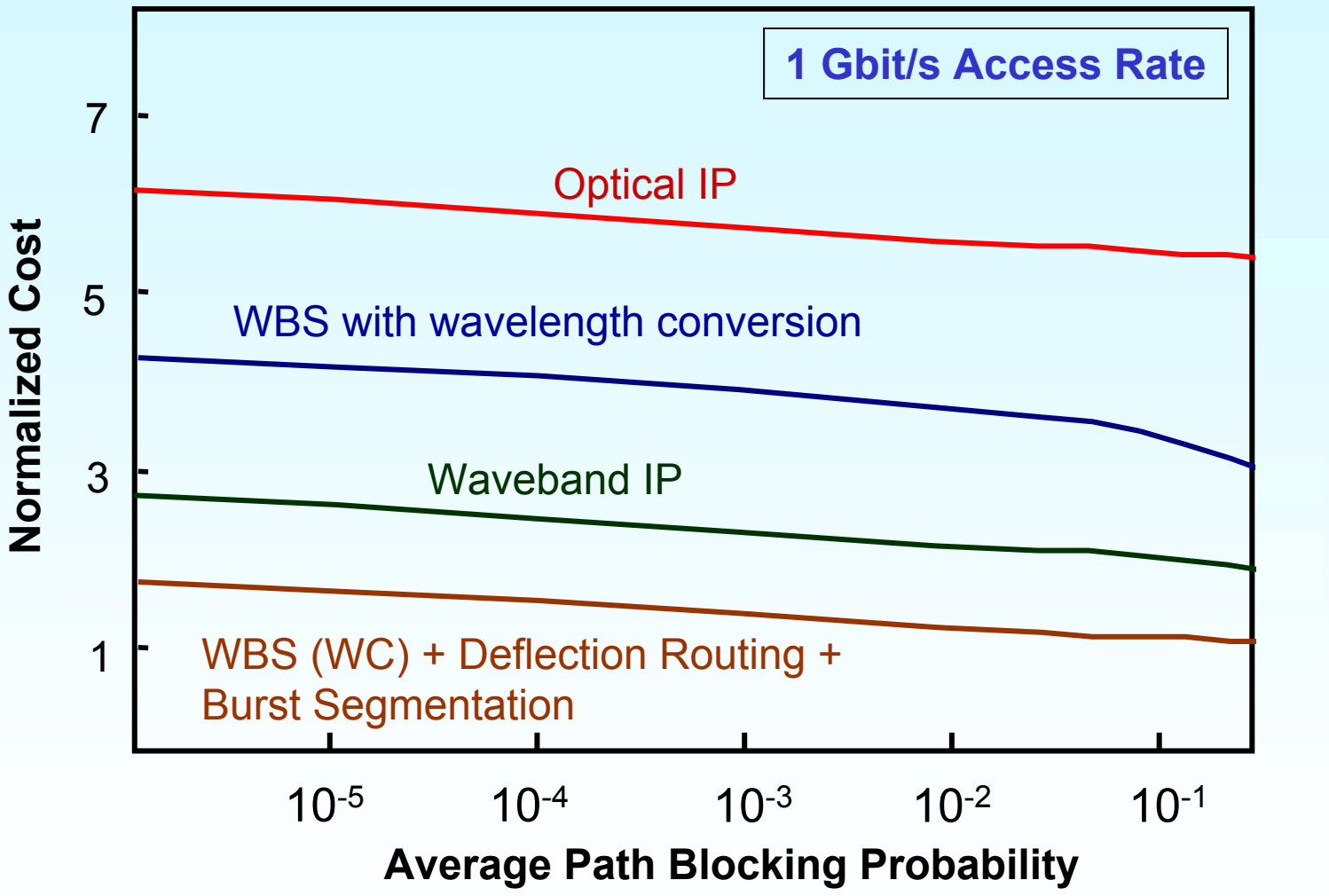
- Requires fewer OXC ports

Con's:

- OXC ports must be wideband
- Requires waveband (i.e. multi-channel) wavelength conversion
- Dispersion issues

Y. Huang et al., OFC 2004, Pathiban et al., OFC 2006

Waveband Burst Switching (WBS)



Parthiban et al., OFC 2006

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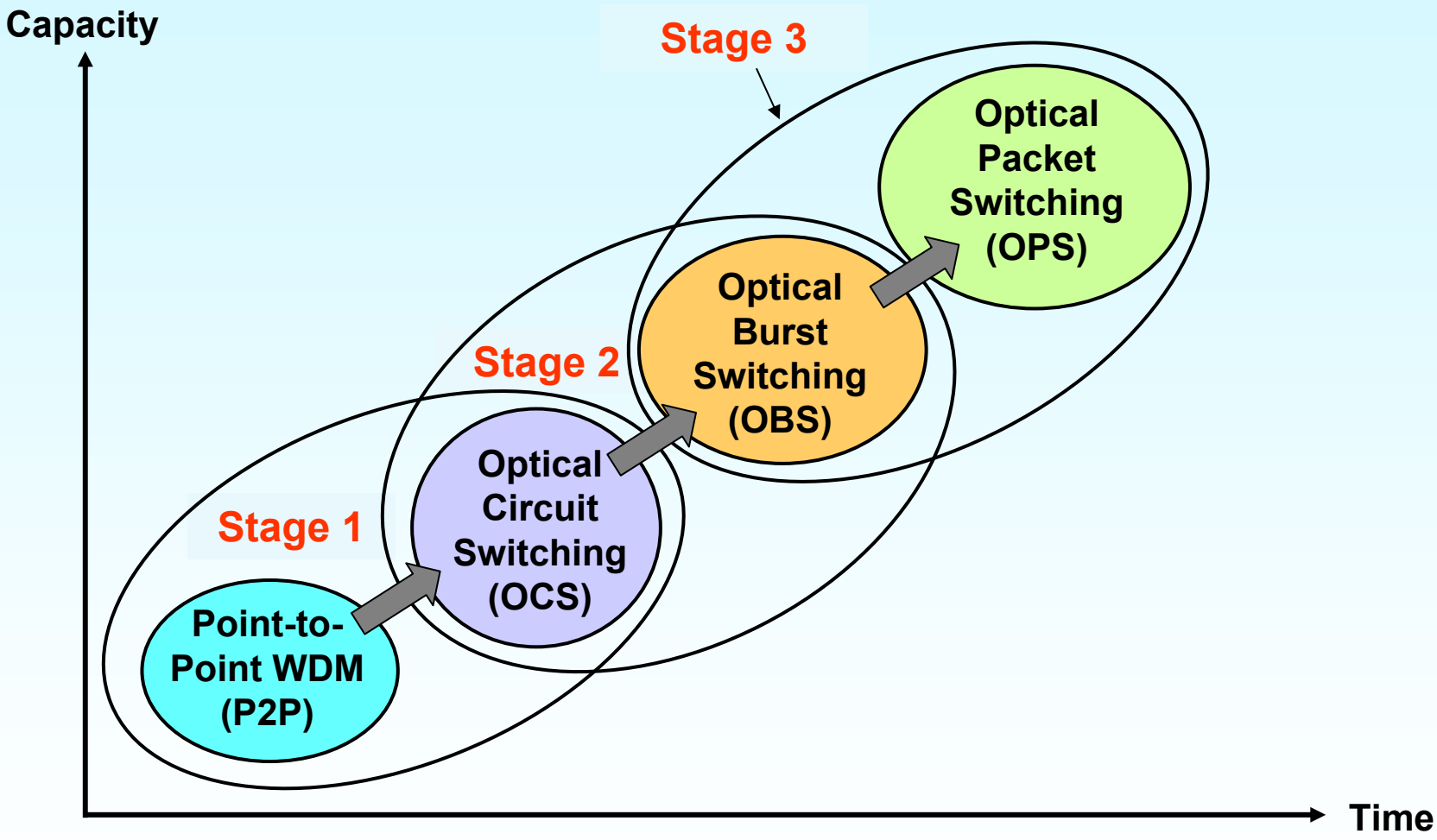

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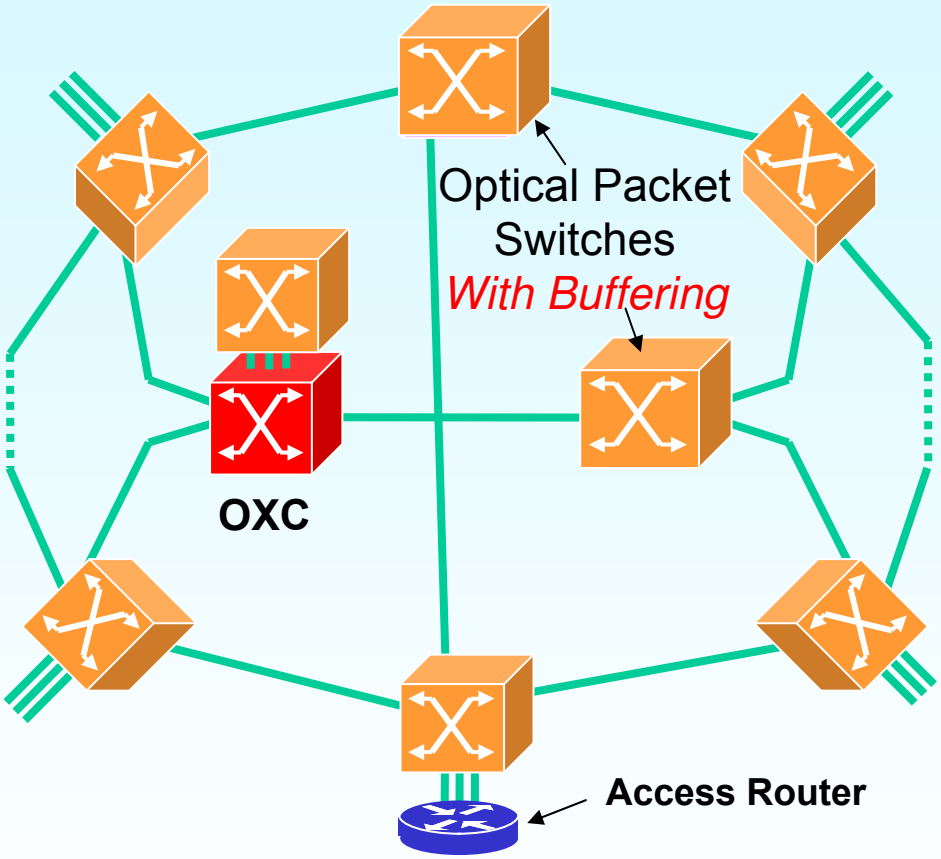
Optical Packet-Switched Network

The "Holy Grail" of Optical Networking



- Will a viable optical buffering technology emerge?
- Can OPS reduce energy consumption?

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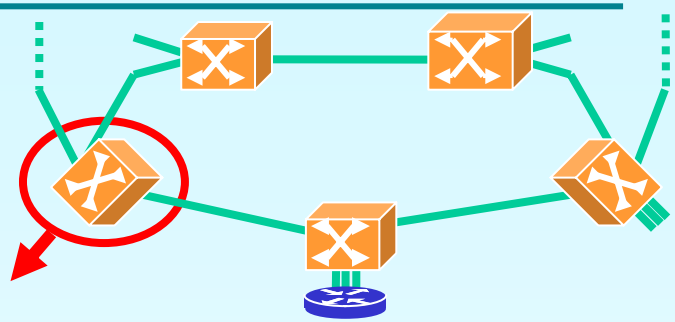
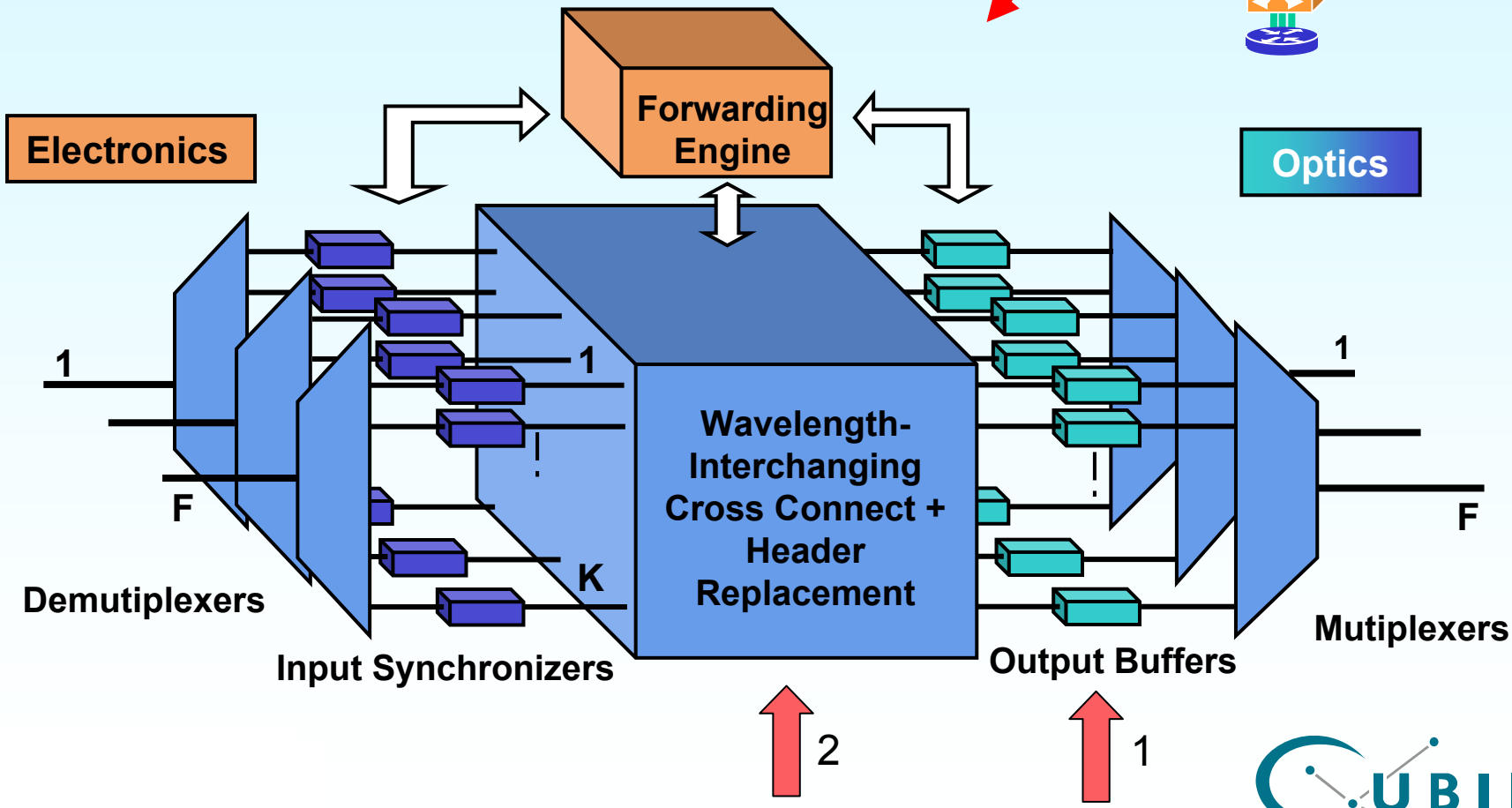
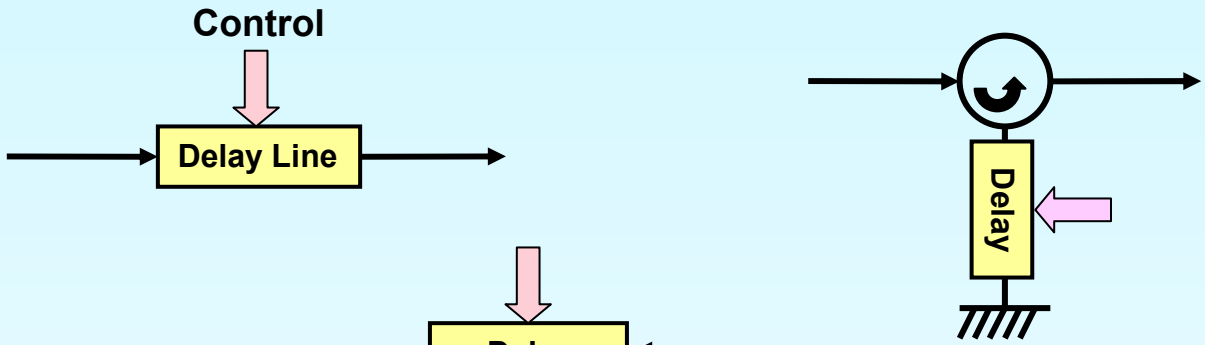
Optical Packet Switch (OPS)



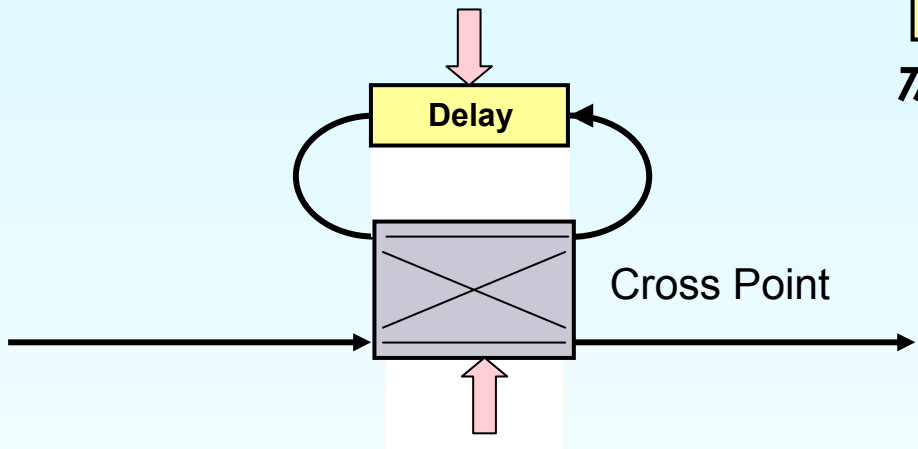


Optical Buffer Structures

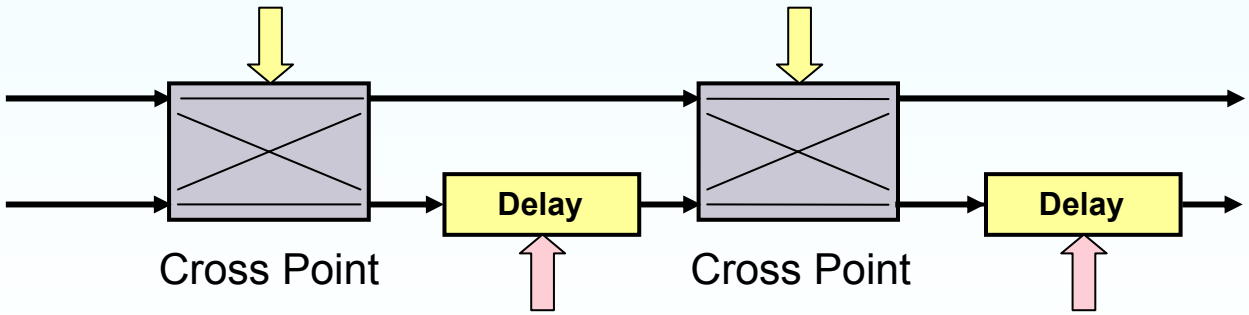
Variable Delay Line



Recirculating Loop



Staggered Delay Line



Optical Fiber Buffers

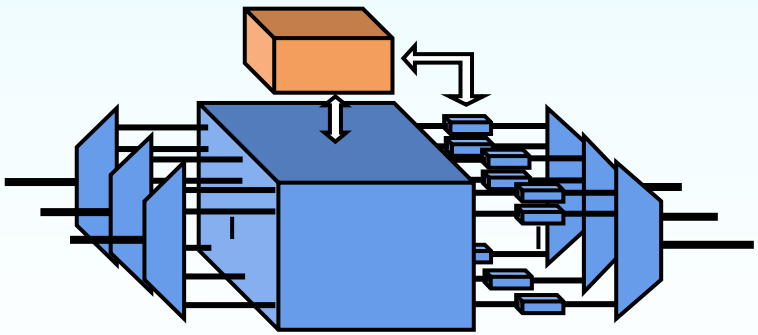
Cisco CRS-1 with 1000 ports,
250 ms buffering per port

Total buffer capacity of 10^4 Gigabits

~ 10^3 RAM chips

Cost < US$ 50k

Buffer power dissipation < 1 kW



OPS with 1000 ports,
250 ms buffering per port
optical fiber delay lines

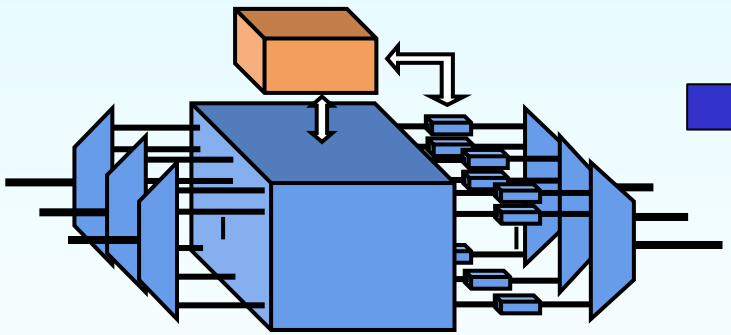
Total fibre length = 40 Gm

150 times distance from Earth to Moon!

Reduced Buffer Size

Minimum feasible buffer size?

~5 μs (~20 packets) buffering per port

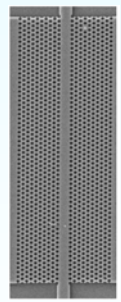


Optical fiber delay lines

Total fibre length = 1000 km

Loss per port = 0.2 dB

Planar waveguide or slow light delay lines (0.1 dB/cm)



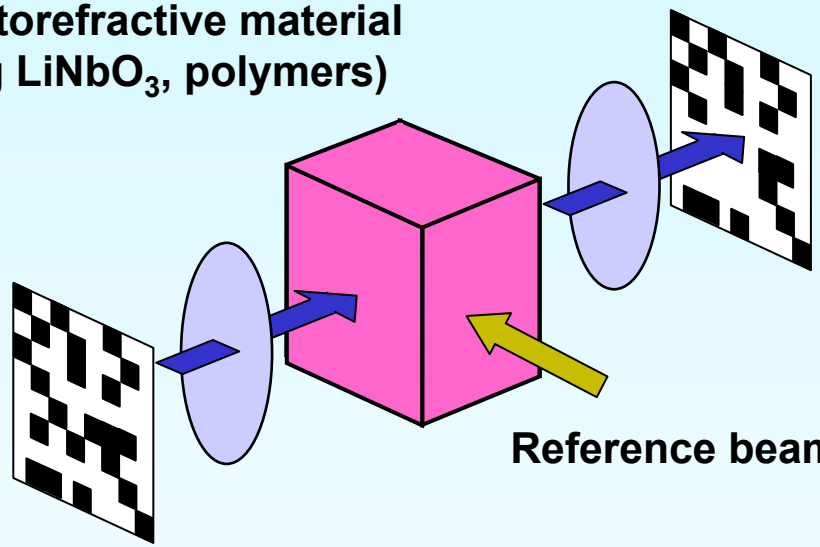
Loss per port = 33,000 dB

Loss ➡ Energy

Tucker, PS 2007

Holographic Buffers

Holographic Medium:
Photorefractive material
(e.g $LiNbO_3$, polymers)



Write speeds up to 1 Gb/s

Read speeds up to 10 Gb/s

Storage density	Retention time	Access Time	Write Time
→ $1/\lambda^3$	→ ∞	~ 50 µs	> 500 µs

Orlov et al., Proc IEEE, 2004
Psaltis, CLEO 2002
Ashley et al. IBM J. Res. Dev., May 2000

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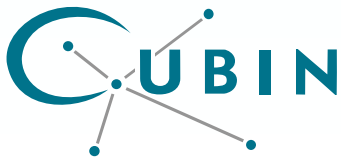
Comparison of Optical Buffer Technologies

Technology	Fiber	Planar WG, Slow Light	Optical Resonator	Holographic	CMOS
Access Time	Structure-dependent	Structure-dependent	Small	~ 50 μs	200 ps
Retention Time	> 500 μs	< 5 μs	1-100 ns	→ ∞	64 ms
Capacity (Packets)	> 2,000	< 20	<< 1	→ ∞	→ ∞
Energy/bit	~ 1 fJ	~ 1 pJ	~ 1 pJ	~ 1 pJ	~ 1 fJ
Physical Size	Very Large	Medium	Medium	Small	Very Small
Chirp Sensitivity	No	Small	Large	Large	No

Show stopper

Challenge

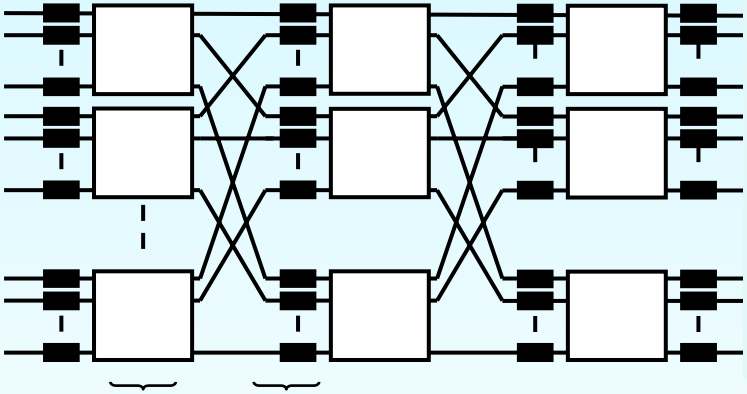
Tucker, PS 2007



Packet Switch Cross-Connect Technologies

Projected Energy Consumption

AWG-Based ~5 pJ/bit

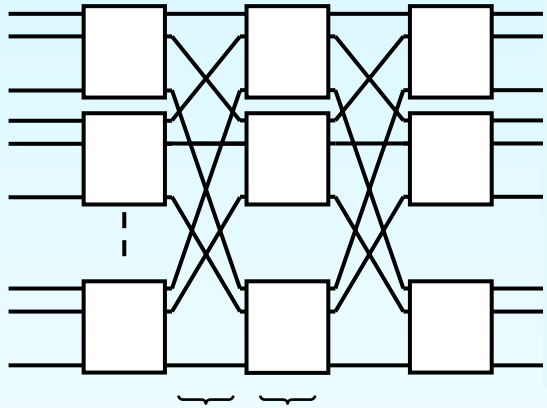


AWG's

Wavelength Converters (1.5 pJ/bit)

3-stage Clos

CMOS ~10 pJ/bit

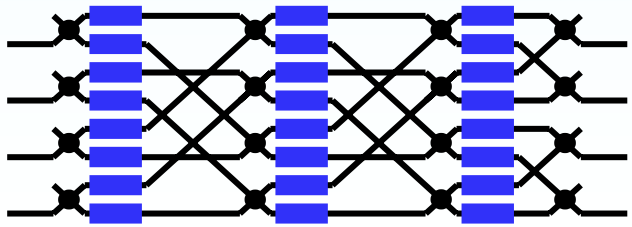


Optical Interconnects (1 pJ/bit)

Chips (2 pJ/bit)

SOA-Based >100 pJ/bit

Benes Array



Benes

(10 pJ/bit per gate)

Tucker, JLT 2005, OSN 2008

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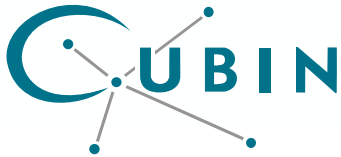
Observations on Optical Packet Switching

- No viable optical buffering technology in sight
- Optical switch fabrics may become competitive with CMOS
- Not clear whether optical packet switching will solve the energy bottleneck problem



Summary

- Optical bypass reduces CAPEX and energy consumption
  - Promising future for optical cross-connects and ROADMs
- Energy bottleneck in routers is looming
  - More significant than the so-called “electronic speed bottleneck”
- Can optical packet switching overcome the energy bottleneck?
  - Optical buffering is currently a show-stopper
- Think “Energy per Bit”

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