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Tutorial:
Energy Efficient Networks

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Dan Kilper
Chair, Technical Committee
GreenTouch Consortium
Bell Labs, Alcatel-Lucent

OFC 2011

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Outline: Focus on Big Picture & Core Networks/Optical Networking

1. The Big Picture: Energy in ICT and the Internet
2. Viewpoints: Enabler vs. Culprit
3. Why We (Optikers) Should Care About Energy
4. Energy by Audit: the Accountant's Approach
5. Network Modeling Methods
   - The model network approach
   - The transaction-based approach
6. The Data Challenge
7. Going into detail: Optical Networking
8. Directions moving forward

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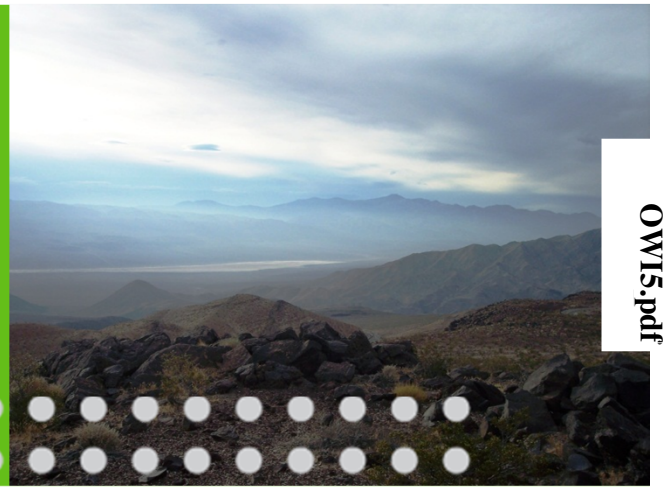
The Big Picture



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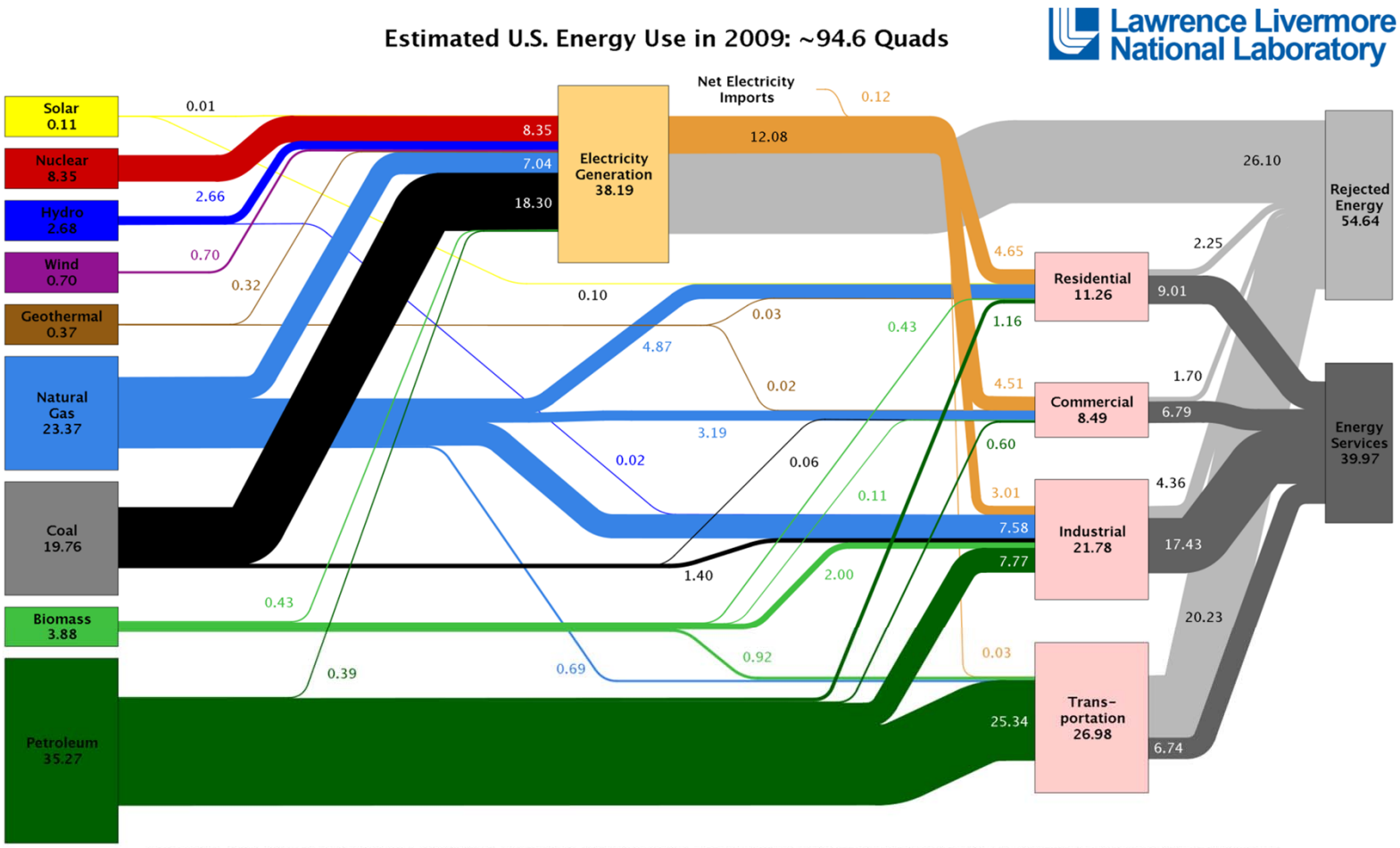
US Energy Supply and Consumption

Supply

Consumption



Source: LLNL 2010. Data is based on DOE/EIA-0384(2009), August 2010. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for non-thermal resources (i.e., hydro, wind and solar) in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Most Energy is Lost!

Quads (10^{15} BTUs)

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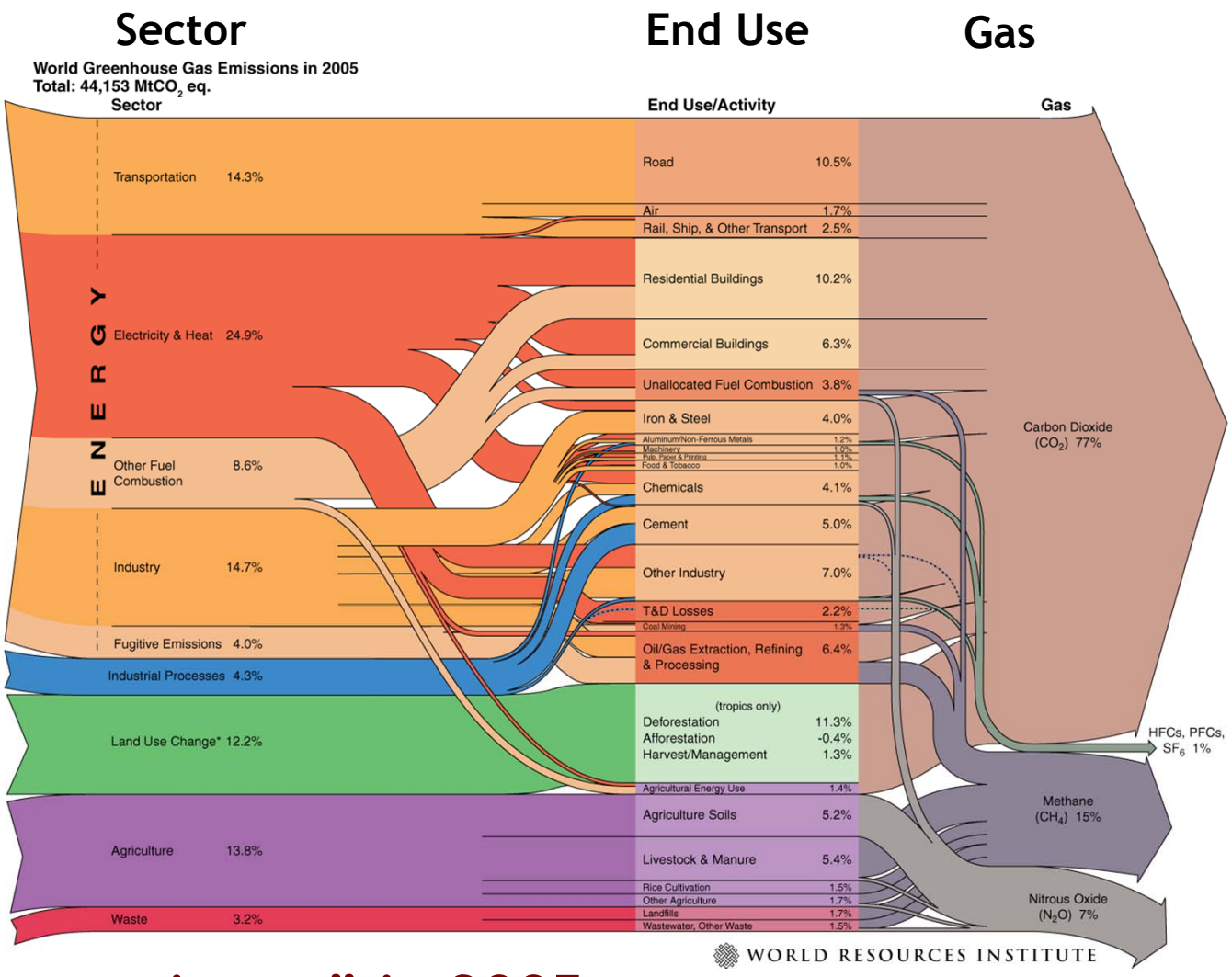
World Greenhouse Gas Emissions (yr 2005)



ICT "nonexistent" in 2005….

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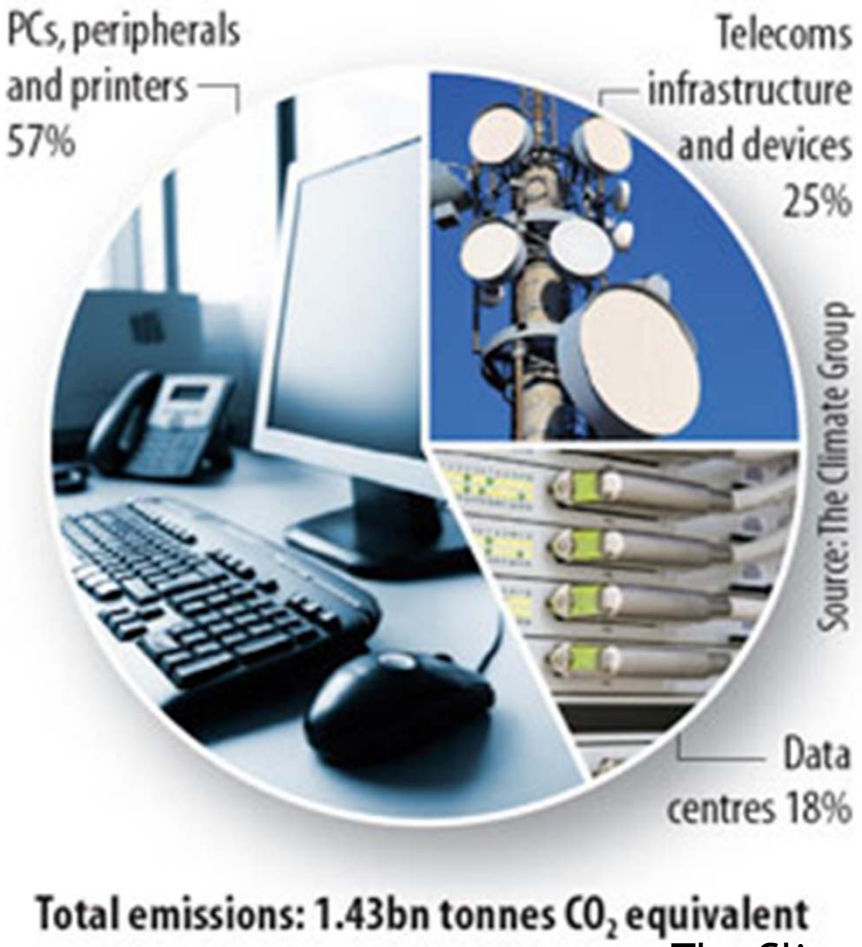
2020 ICT Carbon Footprint

820m tons CO_2

2007 Worldwide ICT carbon footprint:
2% = 830 m tons CO_2
Comparable to the global aviation industry

Expected to grow to 4% by 2020



360m tons CO_2

260m tons CO_2

The Climate Group, GeSI report “Smart 2020”, 2008

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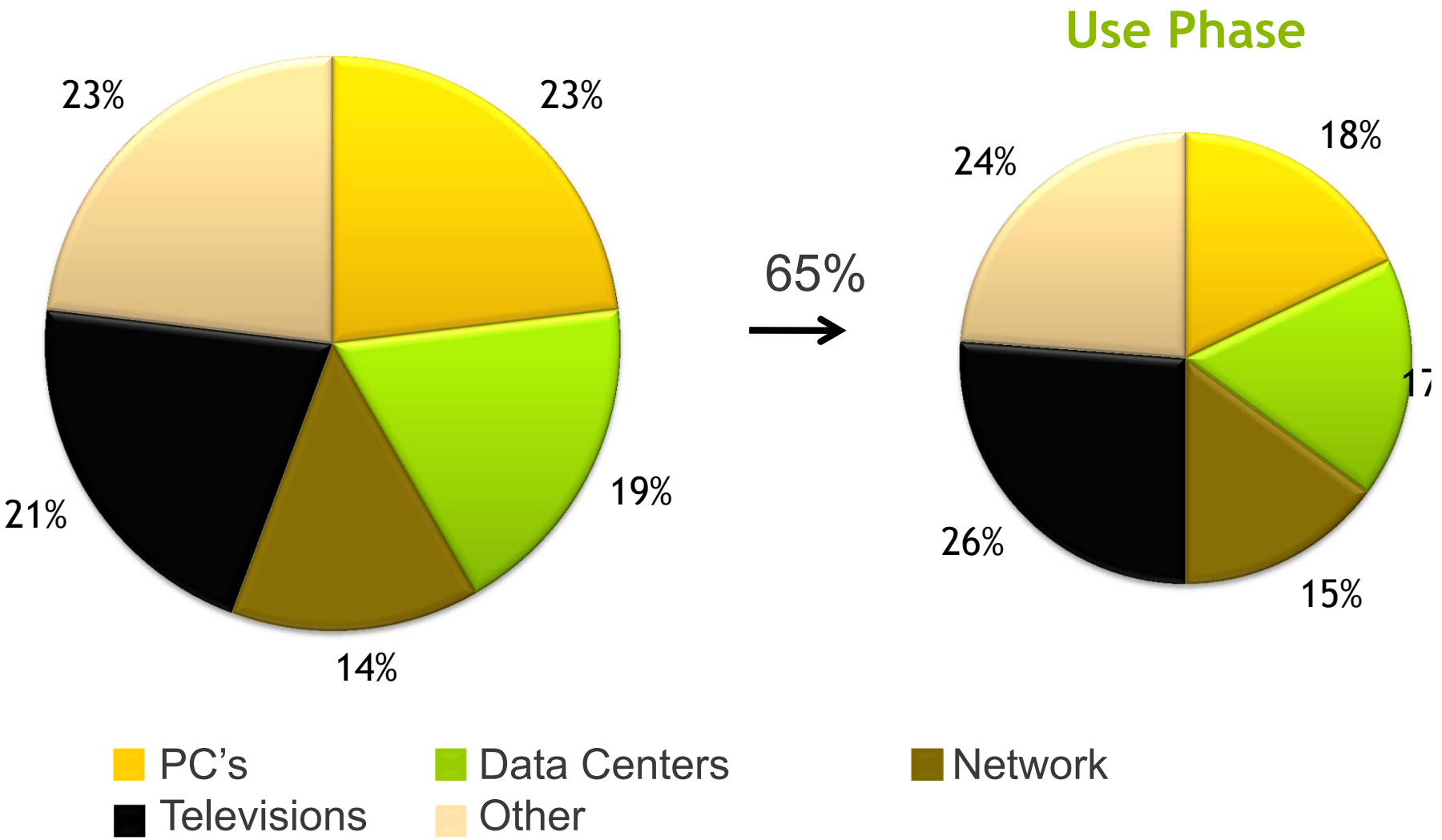
ICT Carbon Emissions



Courtesy of Mario Pickavet, IBBT

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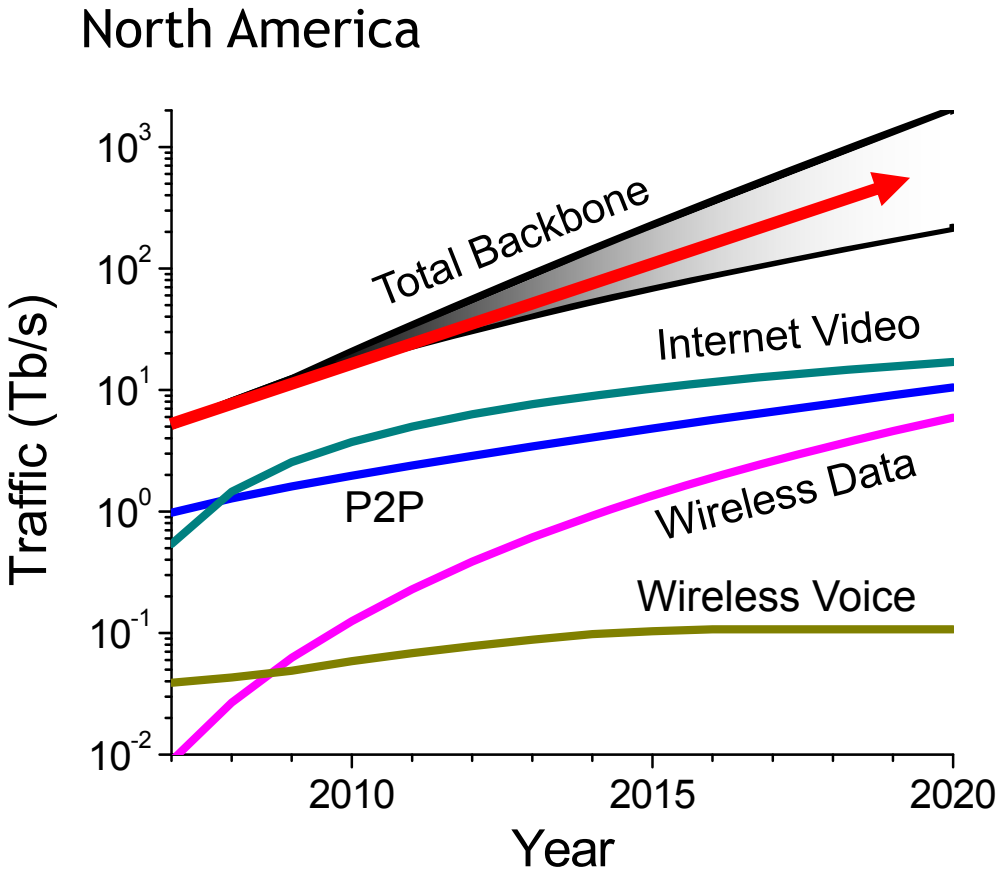
Continued Exponential Traffic Growth



Doubling every 2 years

- **40% per year**
- **30x in 10 years**
- **1000x in 20 years**

Mix of services is important from energy perspective:

- **Mobile less efficient than fiber optics**

Data from: RHK, McKinsey-JPMorgan, AT&T, MINTS, Arbor, ALU, and Bell Labs Analysis: Linear regression on log(traffic growth rate) versus log(time) with Bayesian learning to compute uncertainty

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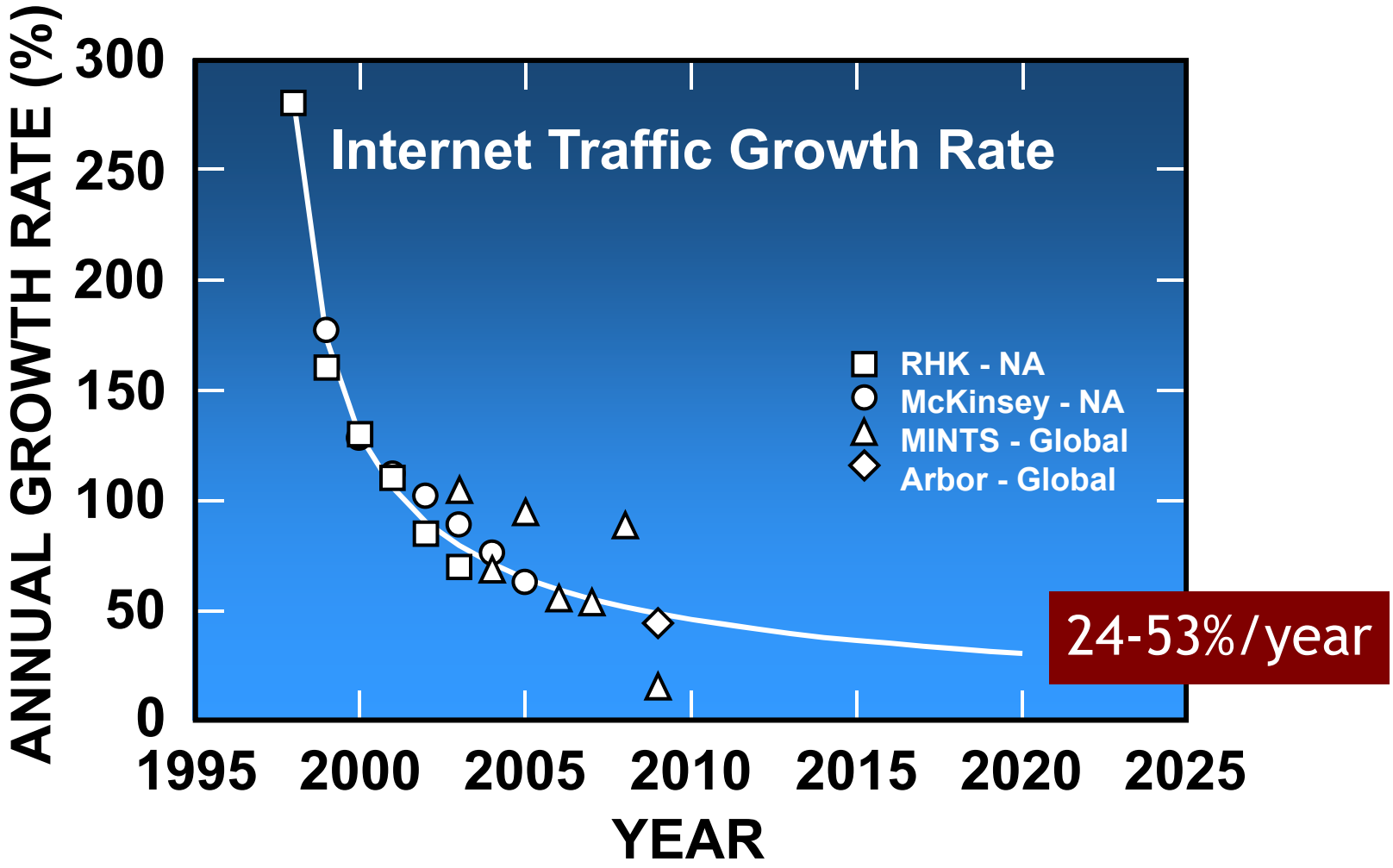
Past and Anticipated Internet Growth



SKK, 2010 (Sources: RHK, 2004; McKinsey, JPMorgan, AT&T, 2001; MINTS, 2009; Arbor, 2009).

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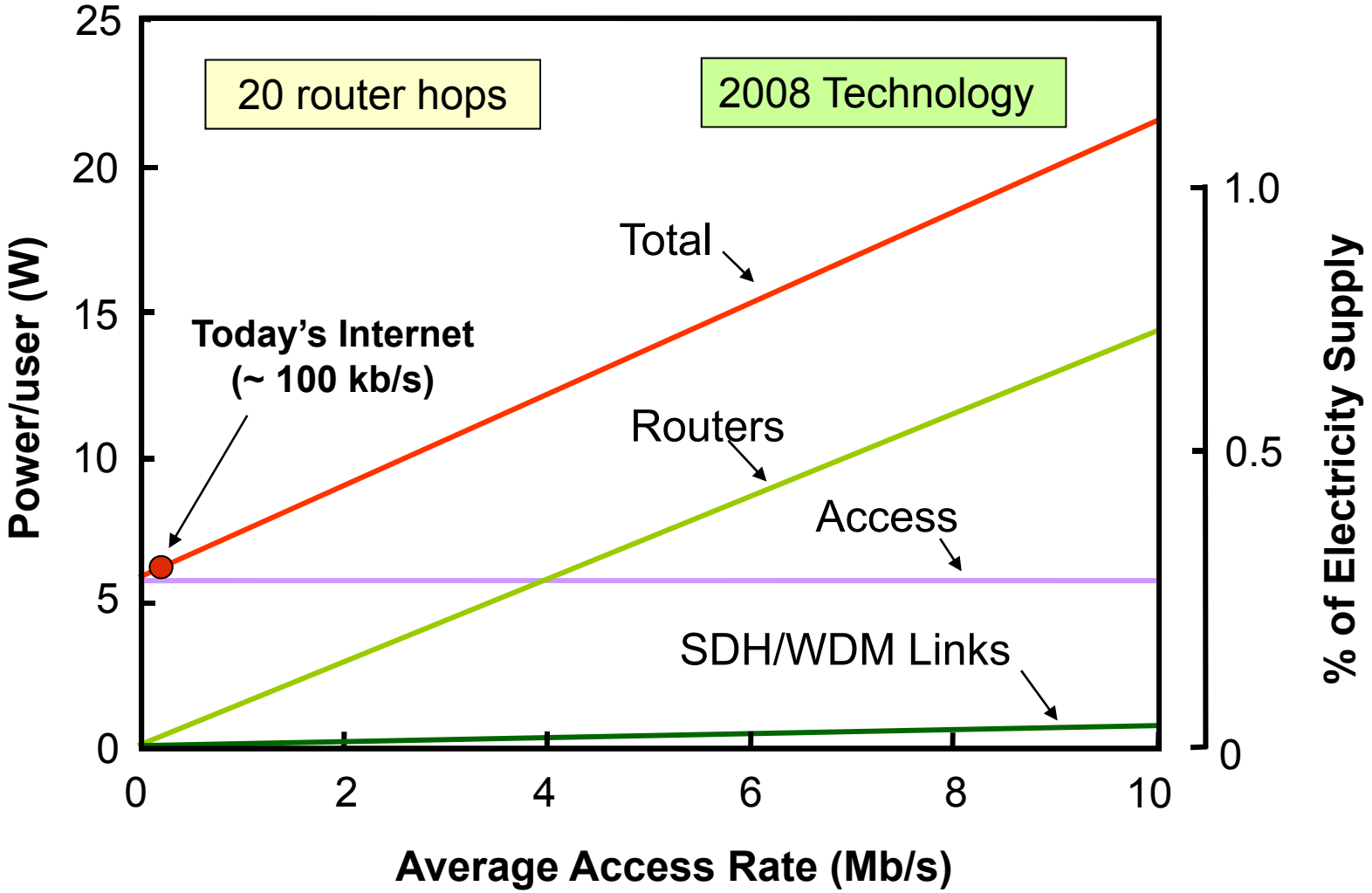
IP network power consumption today

Courtesy of Kerry Hinton, U. Melbourne

Home access gateway dominates today



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Viewpoints:
Enabler vs. Culprit

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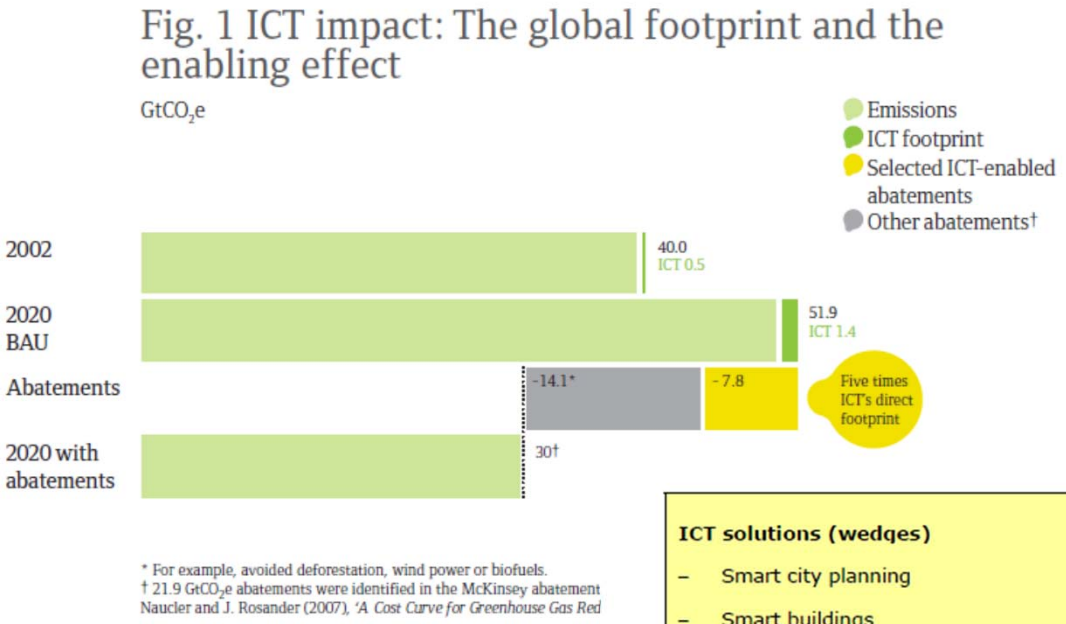
Prediction: ICT will save more energy than it will consume



The Climate Group, GeSI report "Smart 2020", 2008

WWF Report: "The potential global CO2 reductions from ICT use", 2008

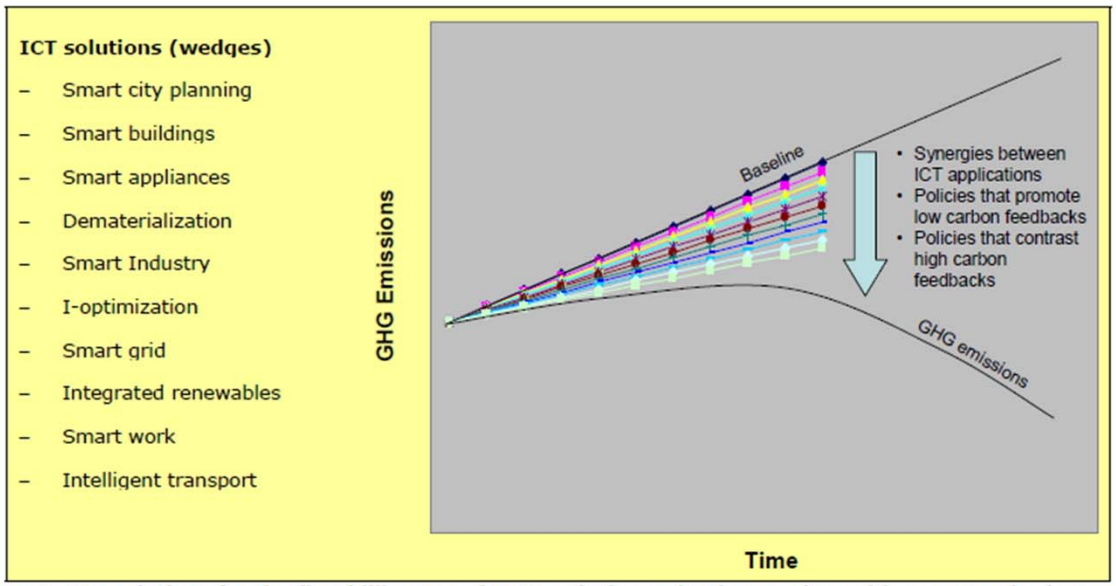


Figure 1: ICT solutions for the first billion ton of GHG emission reductions and to achieve systemic change

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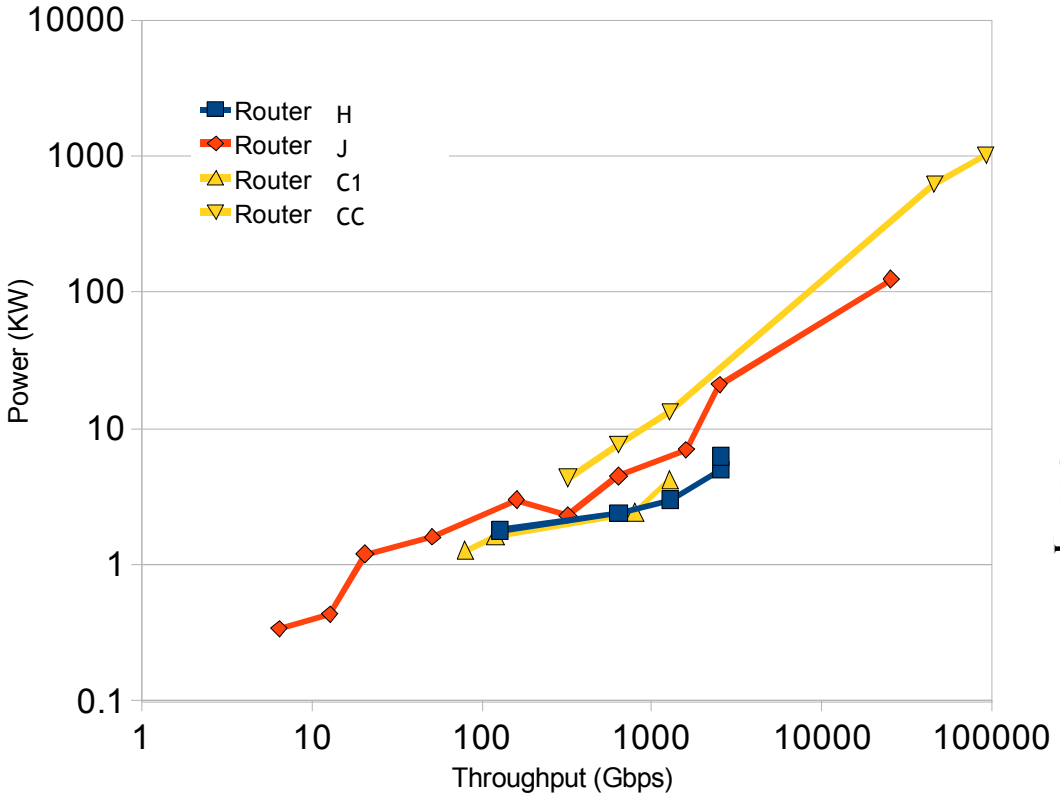
Power Scaling of Switching Devices (Routers)

- The power consumption of commercial routers is increasing too fast with traffic
- Top-level devices need 10s of KW today
- Energy efficiency metric (Capacity vs. Power increase): Energy scaling index (ESI)



$$\mathrm{ESI} = \frac{\Delta C}{\Delta P}$$

ESI ~ 0.09 Gbps/Watt → for complete routers today

- Lower power requirements are exhibited by circuit switches in general, and by optical cross-connects in particular

Courtesy of Fabio Neri, Politecnico di Torino

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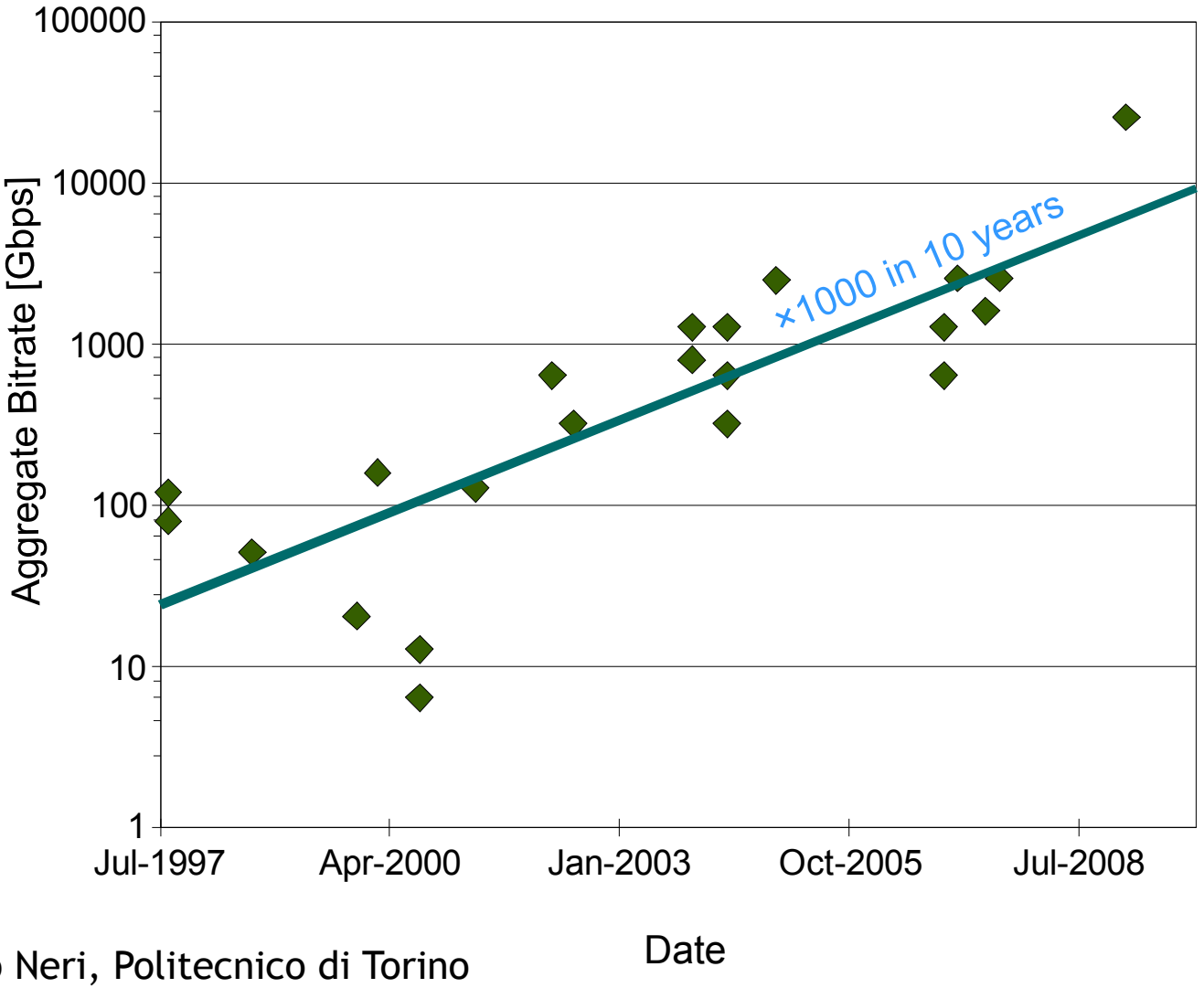
Router Aggregate Bit Rate Evolution

From data sheets of large routers

This can be read as the evolution of users' demands



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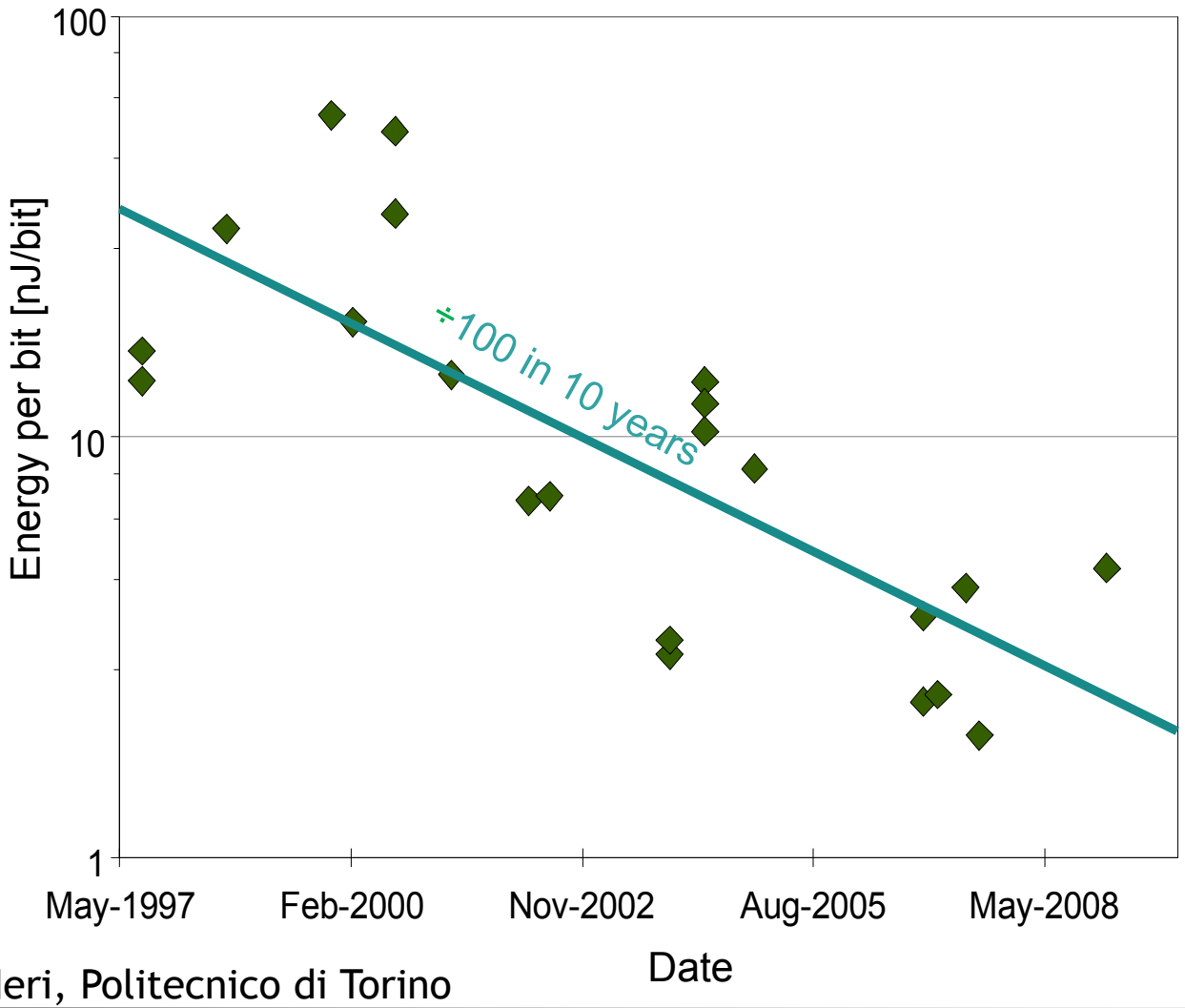
Router Energy per Bit Evolution

From data sheets of large routers

This can be read as the technology improvement



Courtesy of Fabio Neri, Politecnico di Torino

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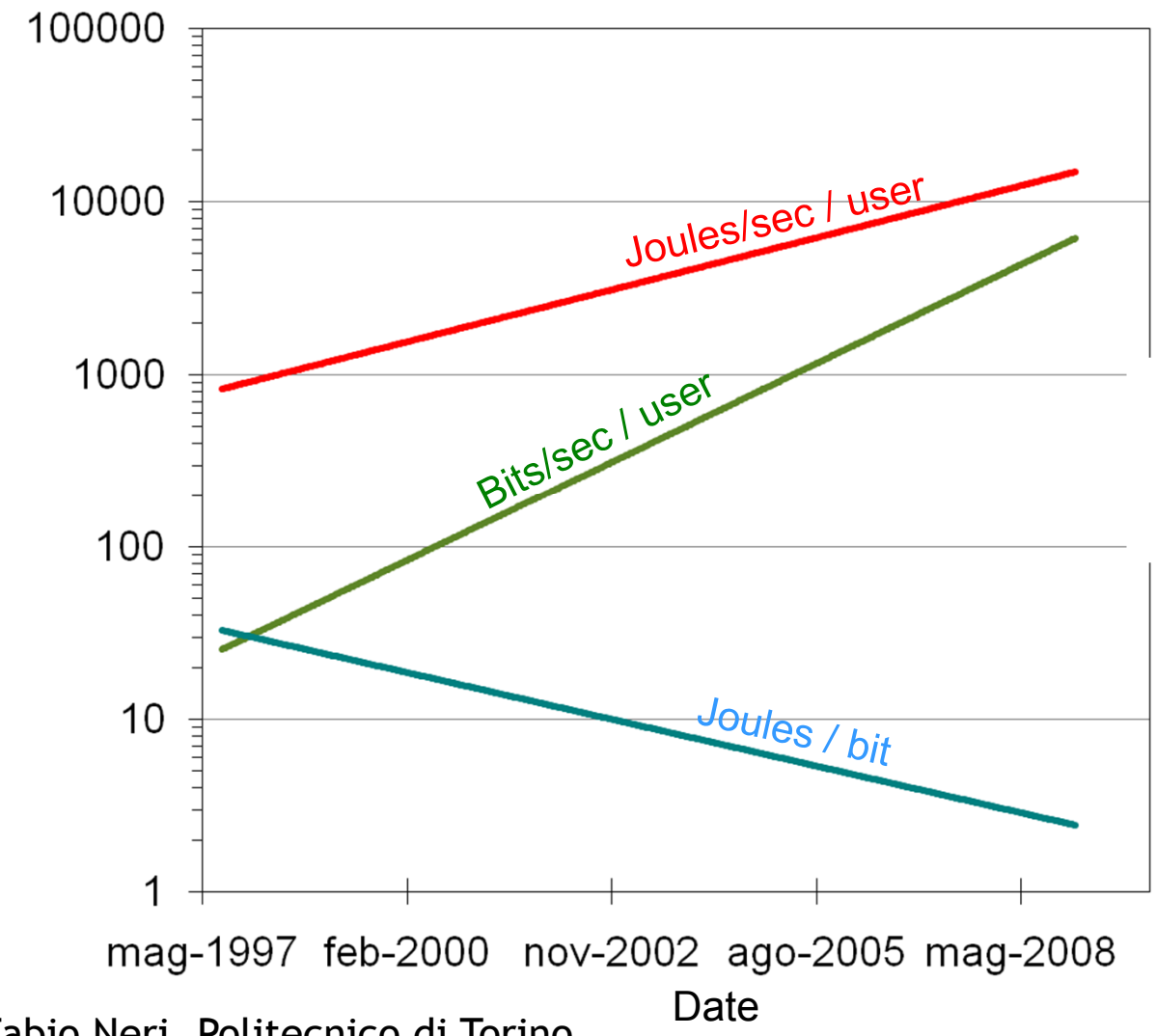
Router Based Power Consumption Trends

While the joule/bit is decreasing with time, the joule/sec/user keeps increasing, due to the faster traffic increase



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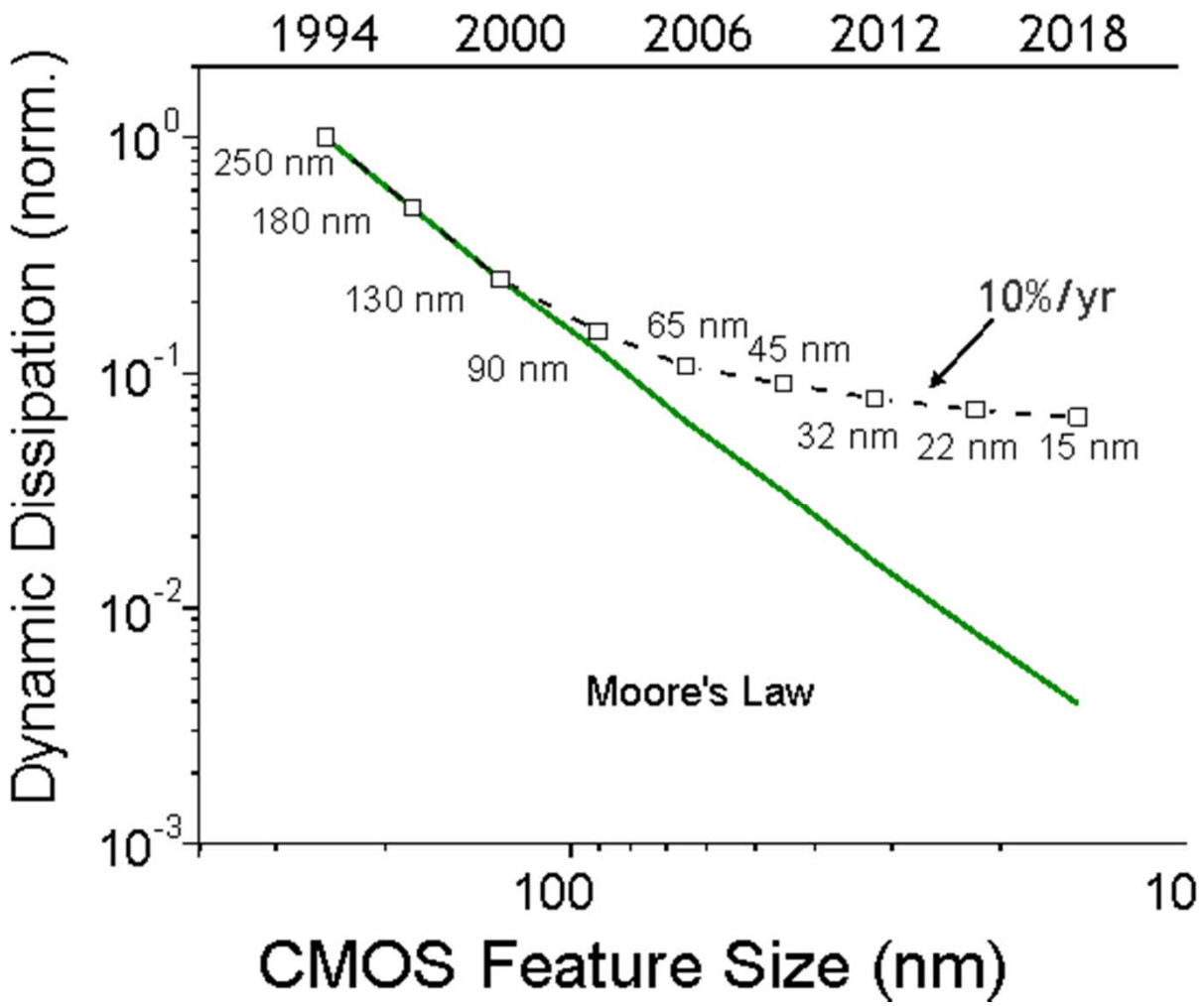
Slowdown in Electronics: Power is Not Scaling

- Reduction in dynamic dissipation with feature size is slowing



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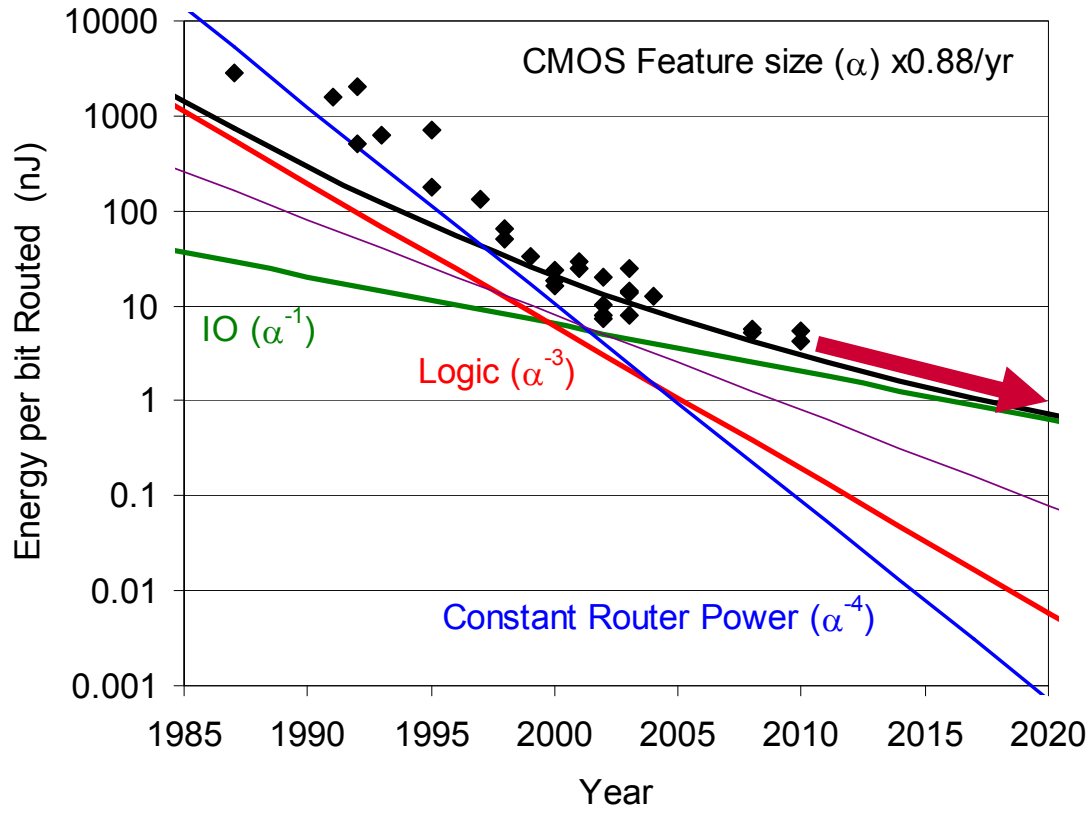
Routers Scalability : Power Consumption

Up to year 2000 energy per bit fell at 30-40% per year

Energy per bit for routing is now falling only at 10% per year

Traffic still growing 40% per year

Interconnect power will dominate future router system power dissipation.



Current trend

Scaling consistent with Interconnect-limited systems

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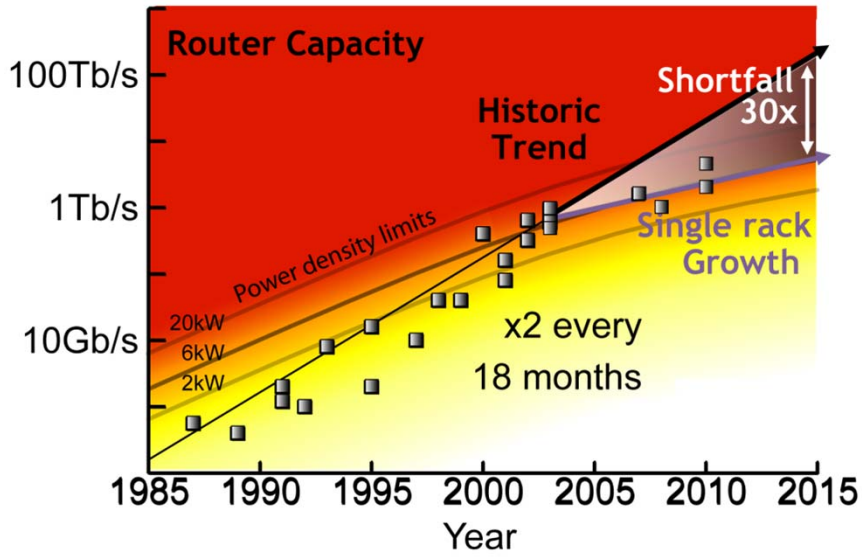
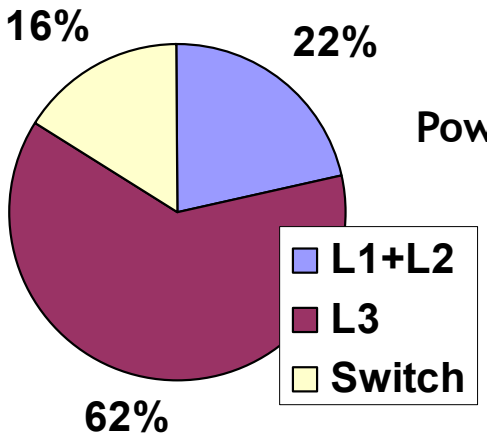
Electronic Router Scalability Issue : Power Density Limited Racks

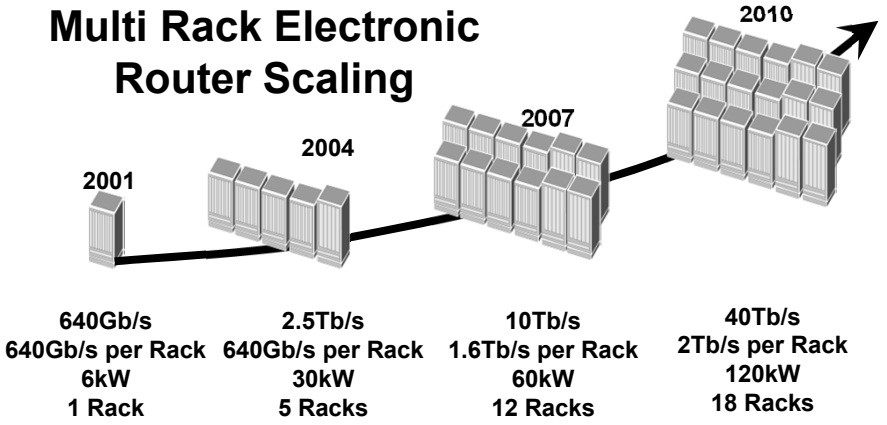
Historical trend of capacity x2 every 18 months

- Not sustainable because of thermal density
- Tb/s router today with 10kW is at the limit
- Current systems are multi rack
- Shortfall of 30 fold in capacity by 2015 compared to historical trend for single rack router





Core Router Power Consumption by Layer



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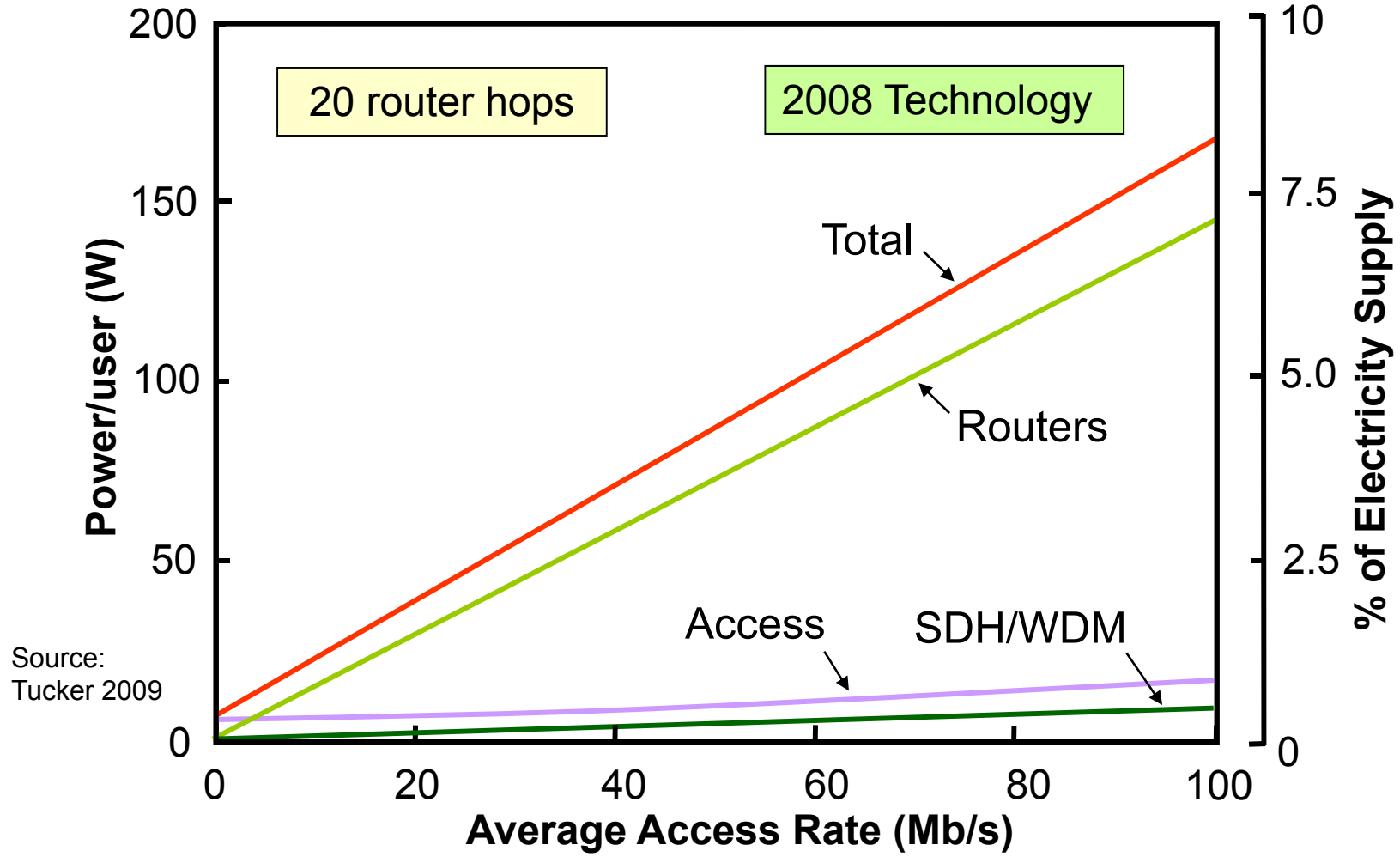
IP network power consumption tomorrow

Courtesy of Kerry Hinton, U. Melbourne

Routers will dominate in future



Source:
Tucker 2009

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Why we (Optikers) should care about energy

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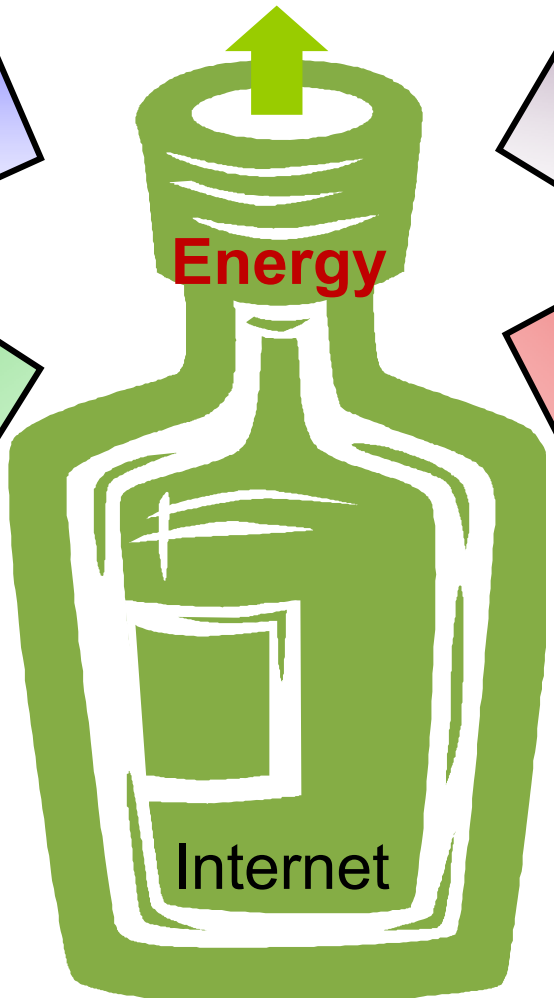
Tightening Energy Bottleneck



Bandwidth, Services, Applications

Technology Limits

- Capacity limits for existing technology and by power/thermal budgets

CAPEX

- Deploying new efficient equipment

Corporate Responsibility to Climate Change

- Publicly visible good-will provided by being "Green"
- Proactive stance in reducing greenhouse gas emissions
- Customers feel better about service provider . . . leading to revenue growth

OPEX $$$ Energy costs

- With energy costs sky-rocketing, increasing share of operations cost
- Cooling is high percentage of network power consumption (20% to 50%)

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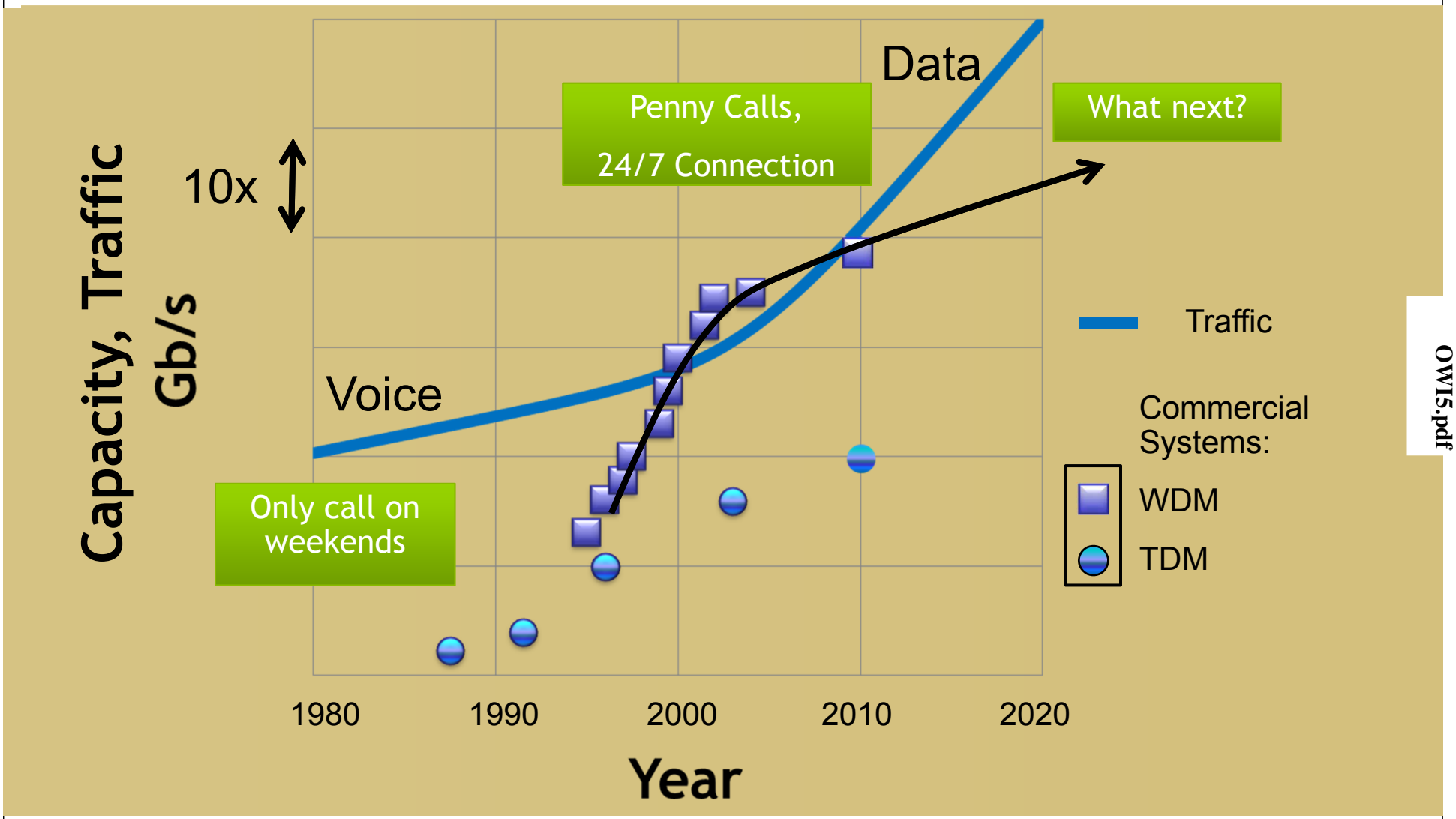
Capacity Deficit or “Crunch”



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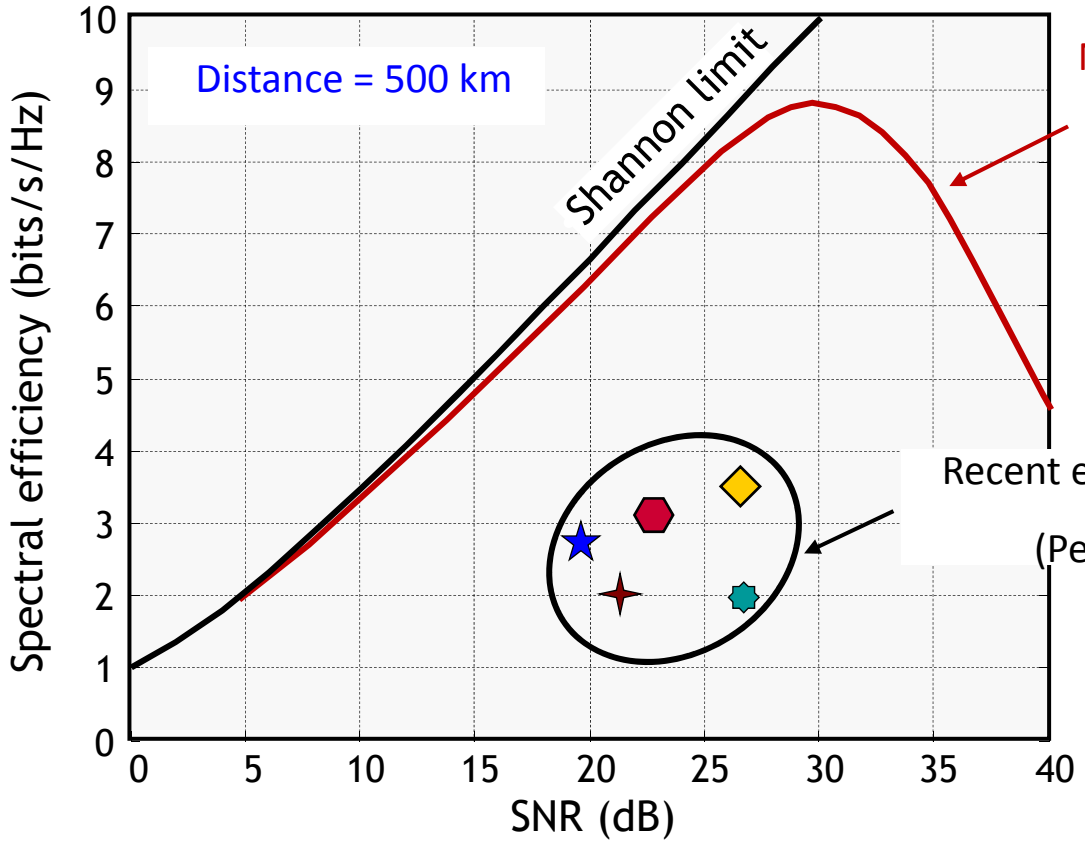
How much better can we do with a single channel?



- At&t, NEC, and Corning, ECOC 2008 (106-Gb/s PDM-RZ-8PSK, distance = 662 km)
- KDDI, ECOC 2008 (50.5-Gb/s PDM-OFDM-16QAM, distance = 640 km)
- Alcatel-Lucent, ECOC 2008 (104-Gb/s PDM-16QAM, distance = 315 km)
- KDDI, OFC 2009 (56-Gb/s PDM-OFDM-32QAM, distance = 240 km)
- Alcatel-Lucent, OFC 2009 (104-Gb/s PDM-16QAM, distance = 630 km)

Courtesy of R-J. Essiambre

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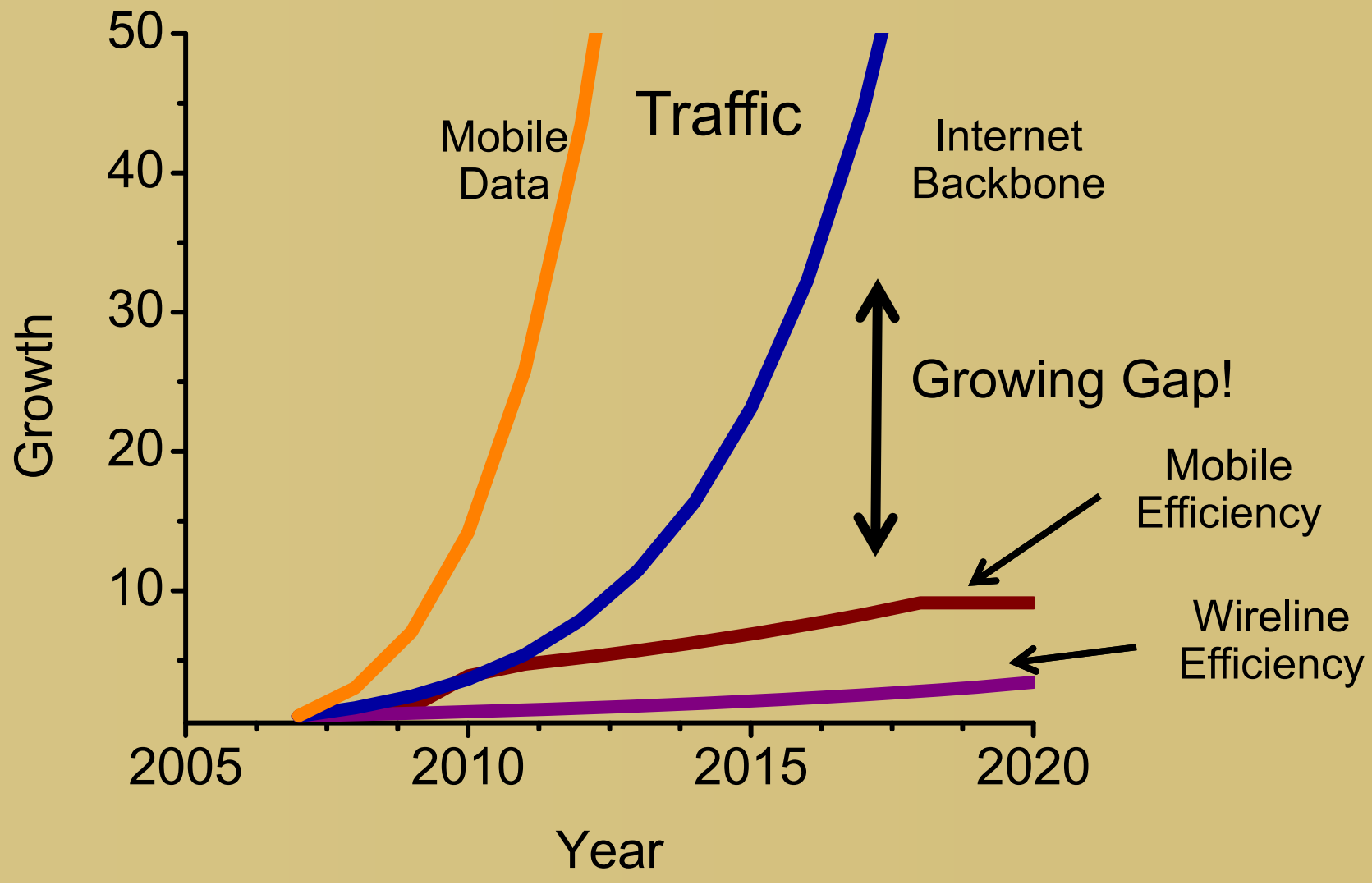
The Network Energy Gap



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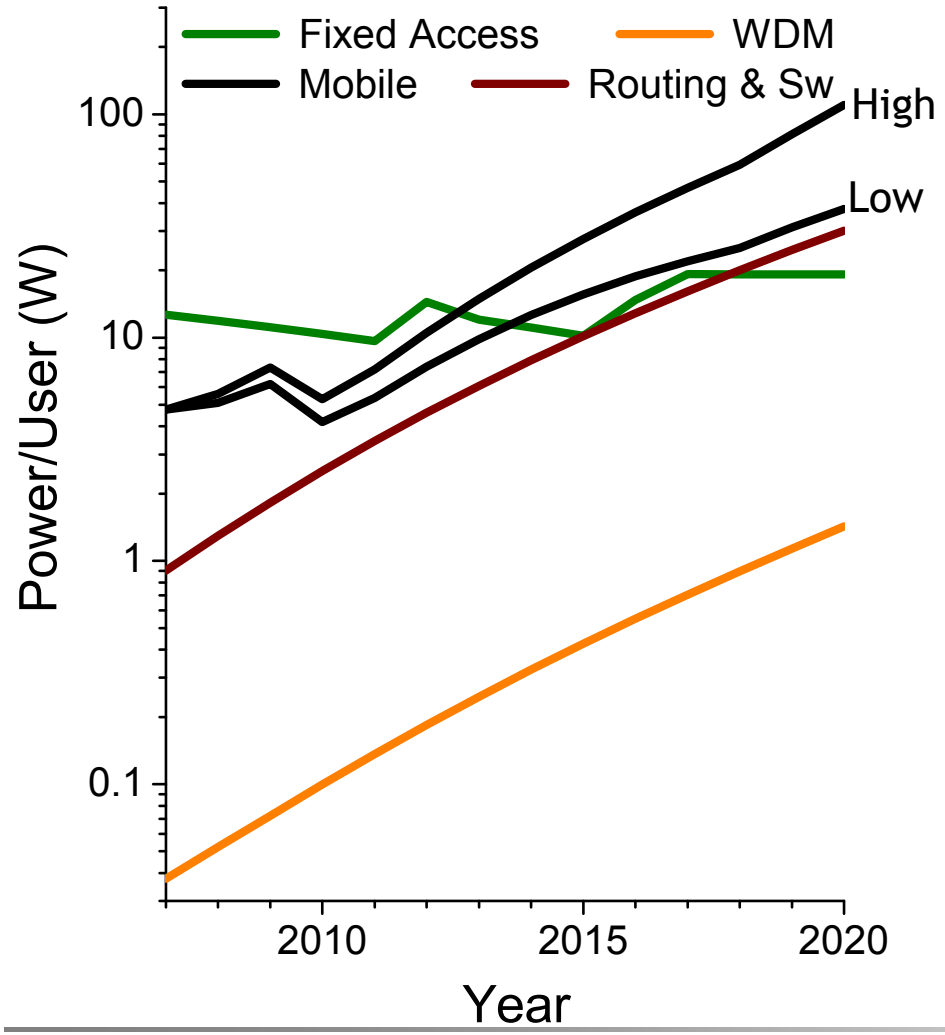
Business-As-Usual Trends



Model network using state-of-art commercial technology

Account for high and low traffic trends by service

Switching, routing & WDM is small, but growth is unsustainable

Traffic growth:
>30%/year

Equipment efficiency:
10%-20%/year

Kilper, et. al., IEEE JSTQE 2011

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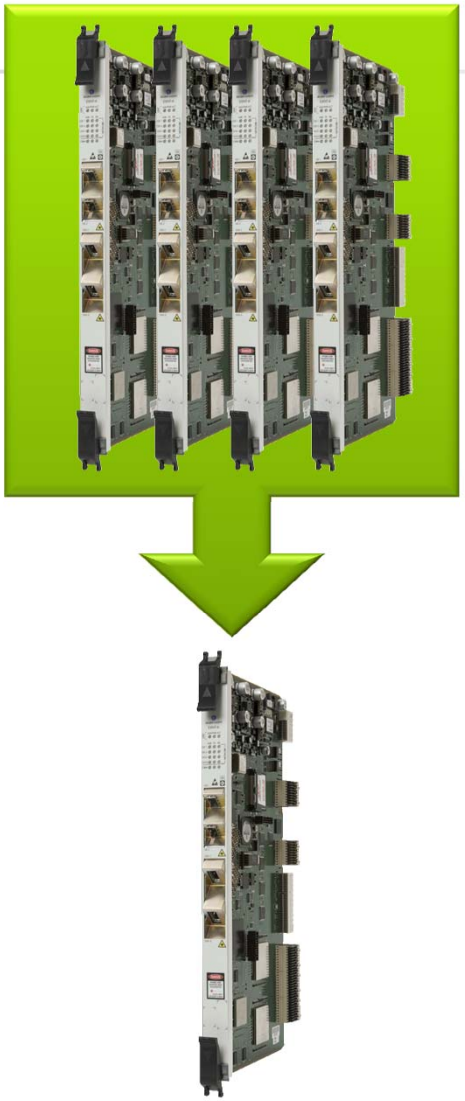
Simple Answer: Fit More in the Box

- Footprint becomes a problem
  - Power density
  - Need to reduce energy to realize savings



Integration central for optics

- Interconnects will be a driver
- Again, focus is on energy

Of course its all about cost

- Energy will be the bottleneck to:
  - Increase capacity
  - Increase functionality (latency, streaming, security,….)

Cost!

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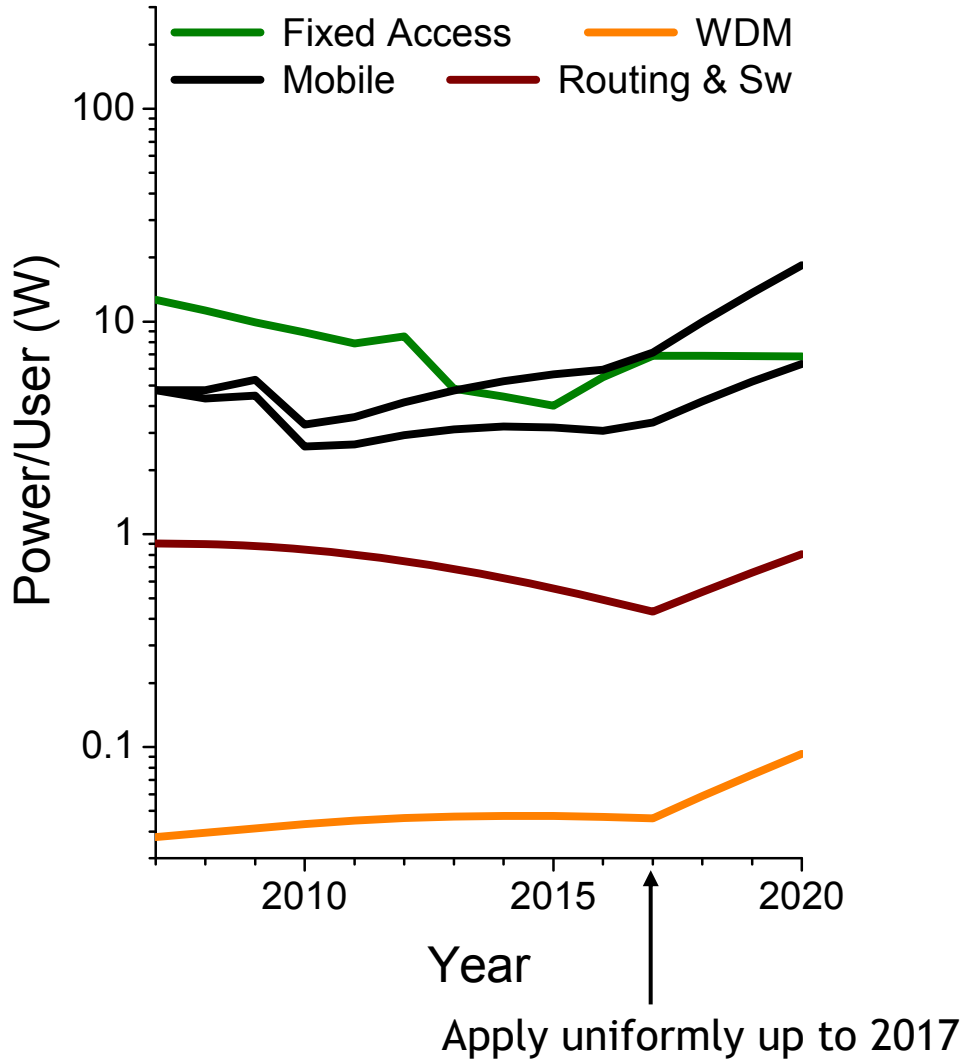
Best Case (Optimistic) Efficiency Improvements



Mobile Access:
- Ultra-efficient power amplifiers (70%)
- Active antennas
- Self organizing networks
- Network MIMO

Fixed Access:
- Cost-reduced FTTH/N
- Green PON (from ~16W/user to ~5W/user)

Metro/Core:
- Mesh protection / fast restoration
- Dynamic Optical Bypass

Other:
- Passive cooling everywhere
- Dynamic energy usage (proportional to load)
- Network Virtualization

Degree of Difficulty: Lower ↕ Higher

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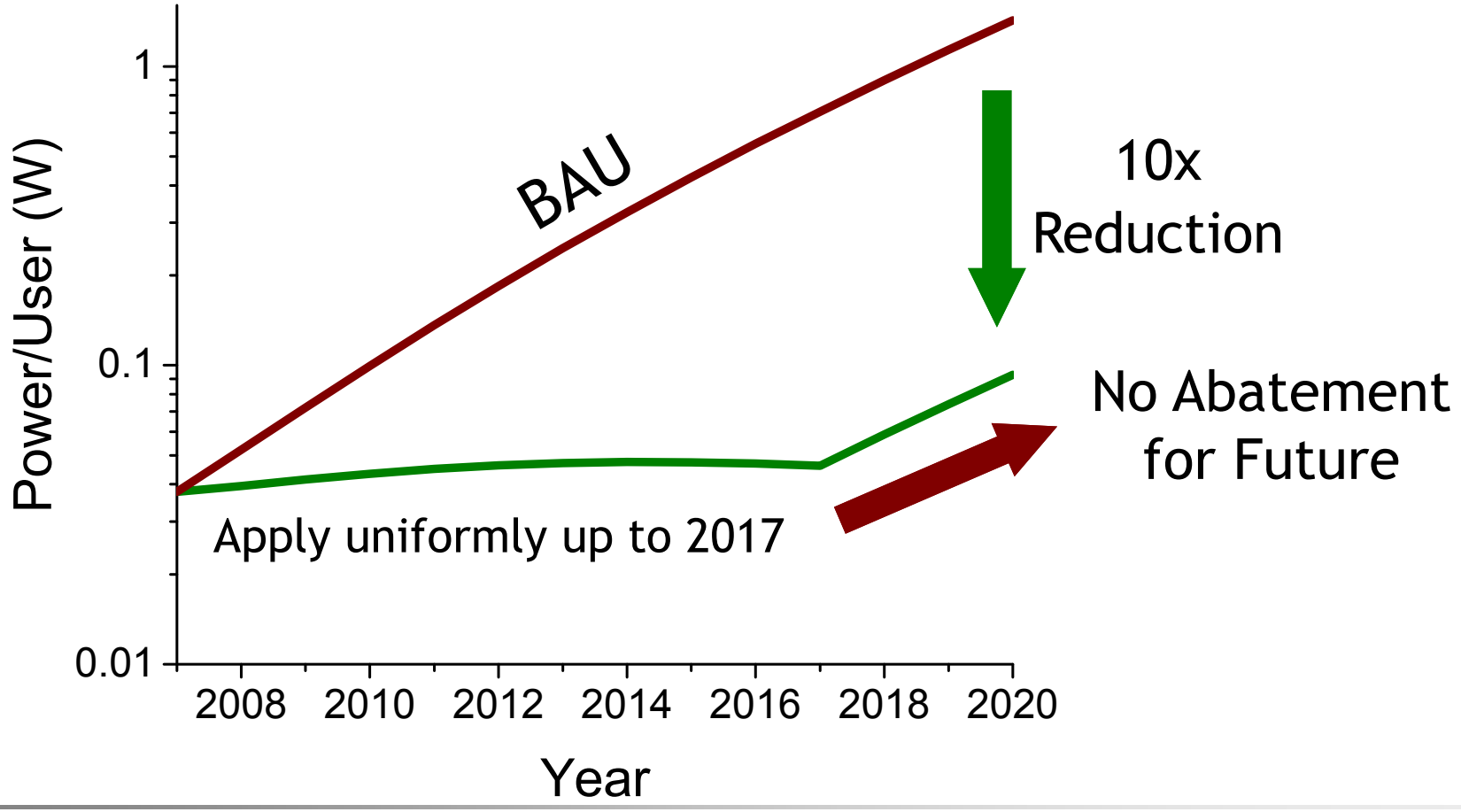
Eff. Improvement Scope for Optical Networking

- Reduce over-provisioning to 1 (energy proportional operation)
  - No protection: use wavelength switching
- Passive cooling (cooling factor becomes 1)



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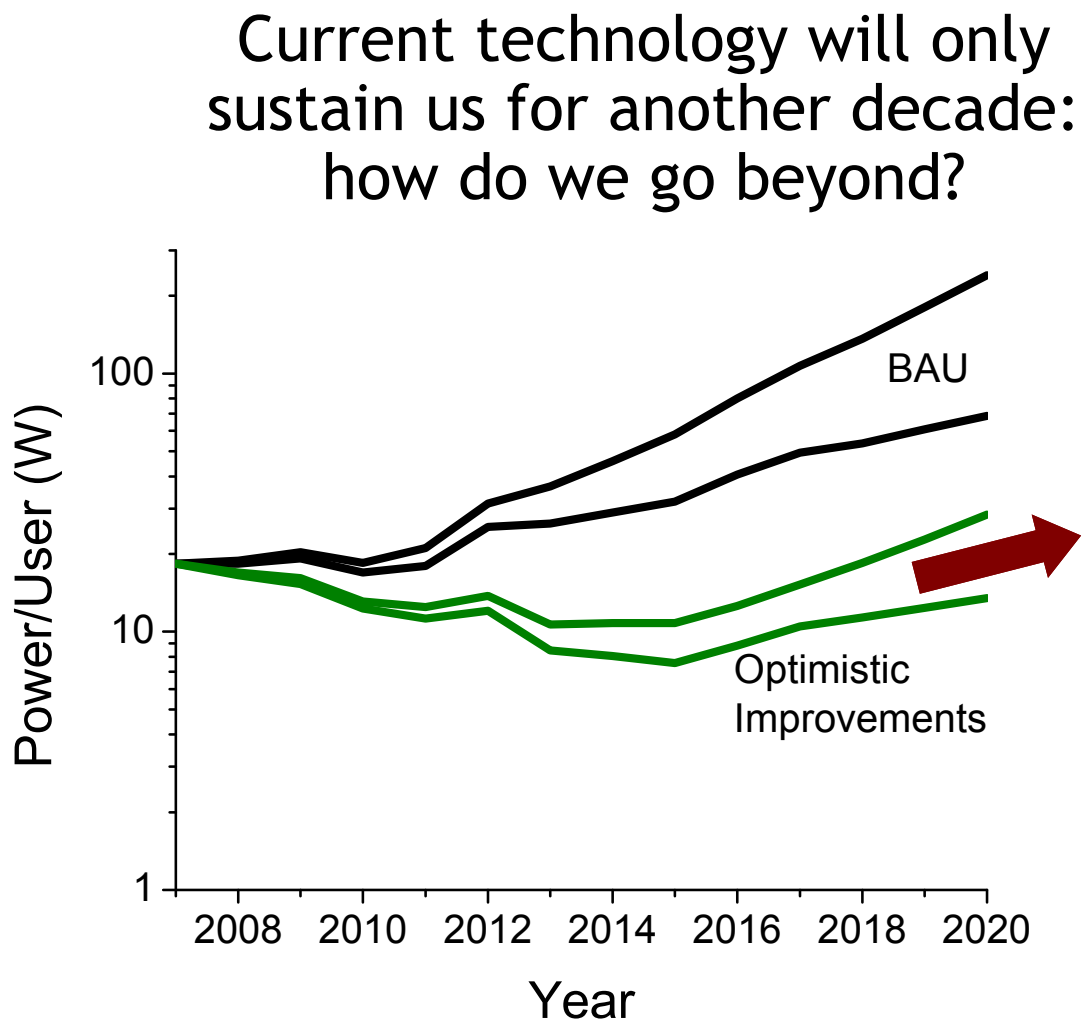
Ideal Efficiency Improvements on BAU: Flat in 2020



Improving network efficiency at best keeps power consumption flat over next decade

- What happens after 2020?
- Can only use 'sleep modes' once

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Energy by Audit

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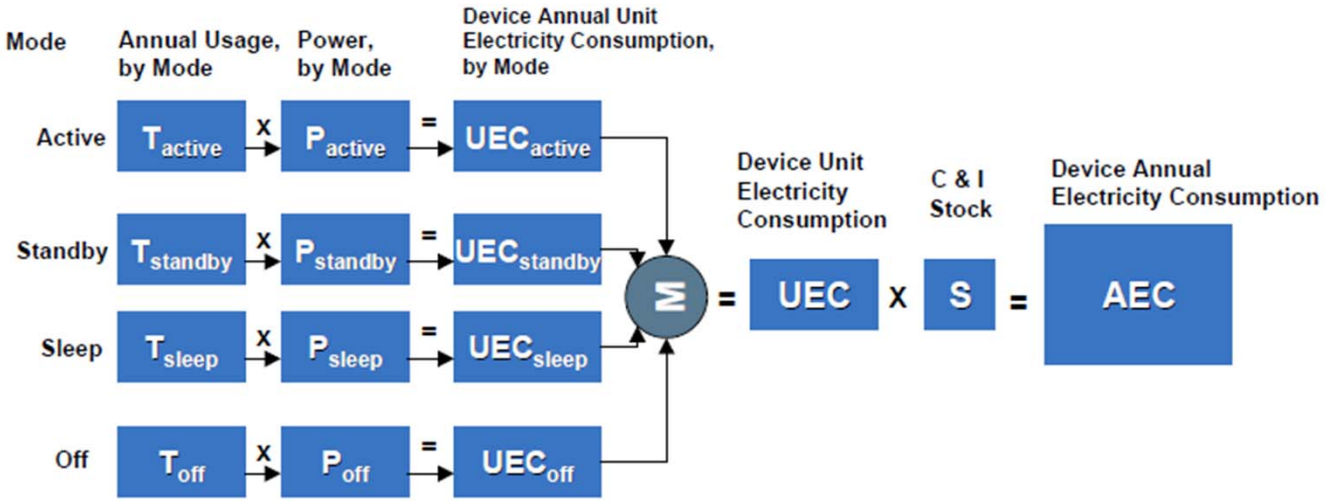
Energy by Association

Take public data from energy bills, unit sales, number of users,…

- Back out contributions of large classes of equipment

Examples:

- Koomey, J. G., et. al., LBNL report 44698, 1999
- Kawamoto, et. al., LBNL report 45917, 2001.
- Roth, K., et. al., US DOE report 2002



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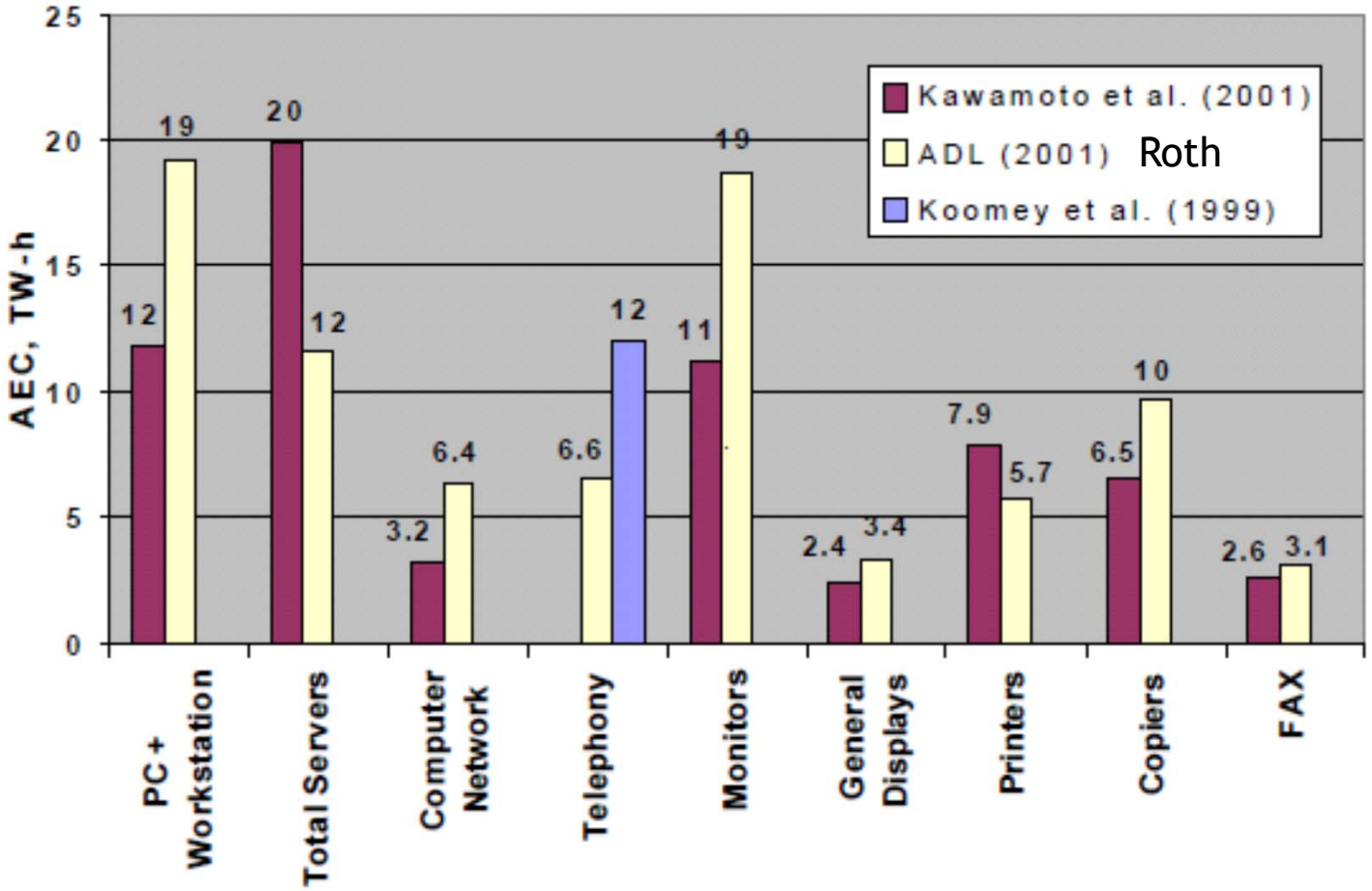
Comparison of some estimates

Courtesy of Kerry Hinton, U. Melbourne

AEC = Annual Energy Consumption



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Limitations on Accounting Methods

Recent Report: Legacy Class-5 telephone switches make up majority of power consumption in central offices today (~ 43%)

- Phillips, S., et. al., ACM SIGMETRICS Performance Evaluation Review 2010

Inferring actual equipment energy use from bulk numbers:

- Relying on unit numbers does not take into account actual use
- Wide range of equipment configurations and uses
- Hard to identify root cause from technology perspective
  - May not be clear why or how used
  - May say more about commercial strategy than technology challenges

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Summary of Global Estimates

Author	Year	% national electricity use	Nation	PC's, office equip. & servers	Wireless access	Notes
Huber & Mills	1999	13%	USA	Yes	No	Severe over estimate; Forbes Magazine Article
Koomey	1999	2%	USA	Yes	No	Users & equipment estimate
Kawatomo	2001	3%	USA	Yes	No	Users & equipment estimate
Turk	2001	0.5 - 1.7%	Germany	Yes	No	Users & equipment estimate
Barthel	2001	0.9 – 1.5%	Germany	Yes	Yes	Users & equipment estimate
Roth	2002	< 2.3%	USA	Yes	Yes	Users & equipment estimate
Cremer	2003	7.1%	Germany	Yes	Yes	Users & equipment estimate
Baliga	2008	0.4%	OECD	No	No	Network design model

Courtesy of Kerry Hinton, U. Melbourne

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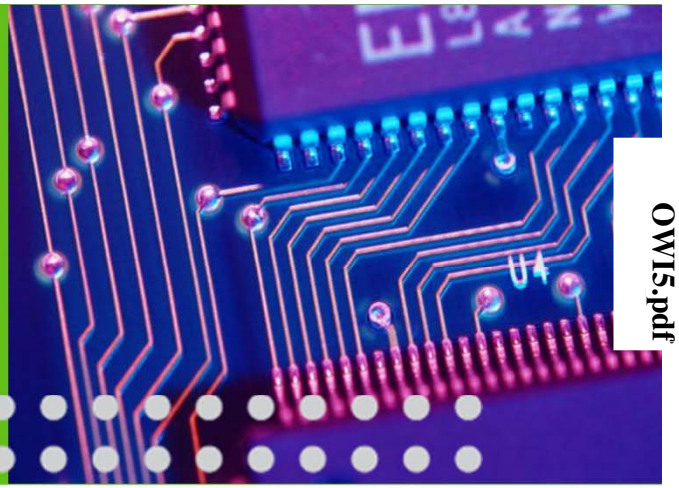
Network Modeling Methods



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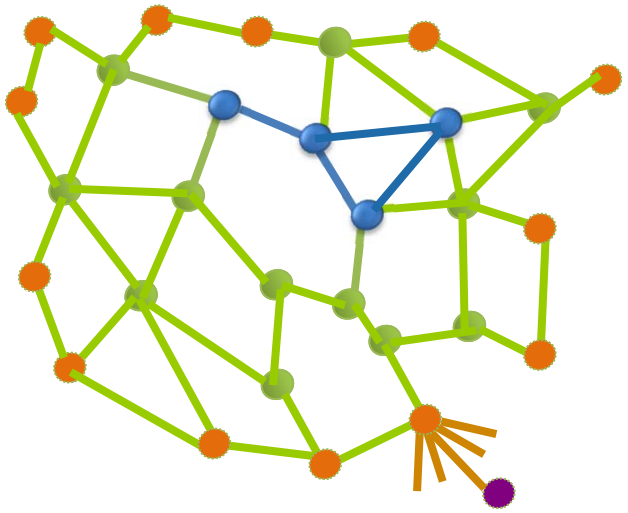
Transaction Model vs Network Model

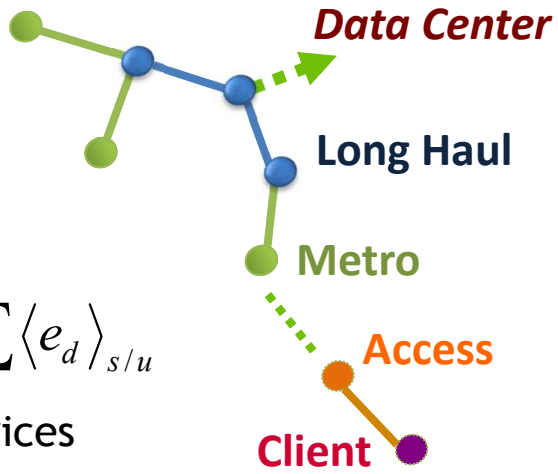


$$E_T = \sum_{l}^{L} e_l + \sum_{n}^{N} e_n = L\langle e_l \rangle + N\langle e_n \rangle$$

links nodes

Network Use Case:

- Most Accurate
- Tied to specific case



$$E_T = n_{users} \sum_{i}^{S} \langle e_d \rangle_{s/u}$$

services

$$E_T = \sum_{d}^{D} e_d = \sum_{d}^{D} \left[\langle H \rangle_d \langle e_l \rangle_d + \langle N \rangle_d \langle e_n \rangle_d \right]$$

demands links nodes

Transaction based approach*:

- Breakdown service contributions
- Represent many networks
- Evaluate limiting cases

*Baliga, et. al. JLT, 2009; S. K. Korotky JLT, 2004

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Network Path for Each Traffic Category

	Service Category	Network Path
1	General Internet	Fixed Access+Metro+Long Haul+Metro+Enterprise
2	Peer-to-peer	Fixed Access+Metro+Long Haul+Metro+Fixed Access
3	Video	Fixed Access+Metro+Long Haul+Enterprise
4	Wireless Data	Wireless Access+Metro+Long Haul+Metro+Enterprise
5	Wireless Voice	Wireless Access+Metro+Long Haul

$$\langle e_d \rangle_{s/u} = \langle H_{LH} \rangle_s \langle e_{lLH} \rangle_s + \langle N_{LH} \rangle_s \langle e_{nLH} \rangle_s + \langle H_M \rangle_s \langle e_{lM} \rangle_s + \langle N_M \rangle_s \langle e_{nM} \rangle_s + \langle e_{Acc} \rangle_s$$

Transaction based approach*:

- Determine total energy consumed each transaction, for example transmitting a video along the network path
- Add up energy consumed for all transactions on network gives total network energy consumption
- Use mean quantities and efficiencies throughout, e_d = energy/bit
  - Multiply be traffic per user per service to get energy or power

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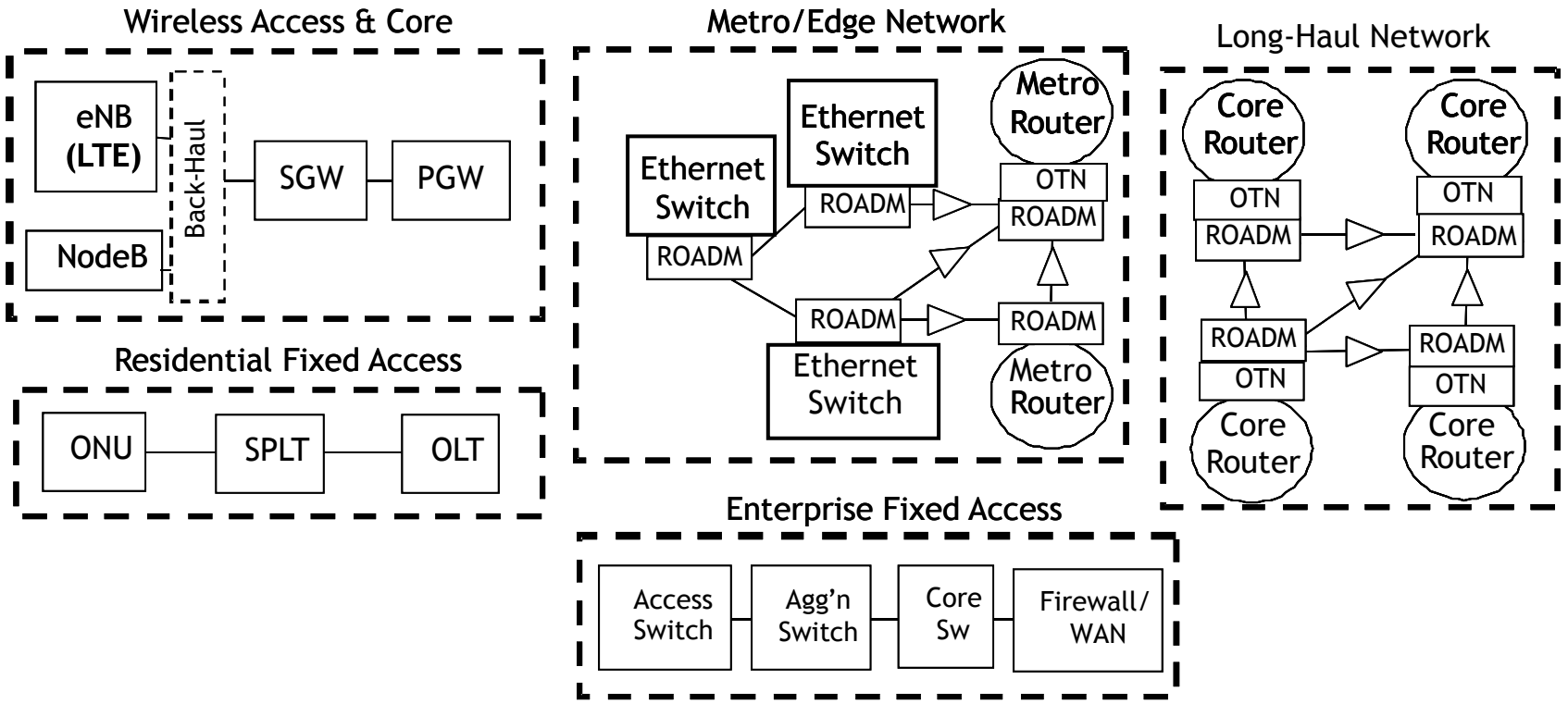
Sub-Networks



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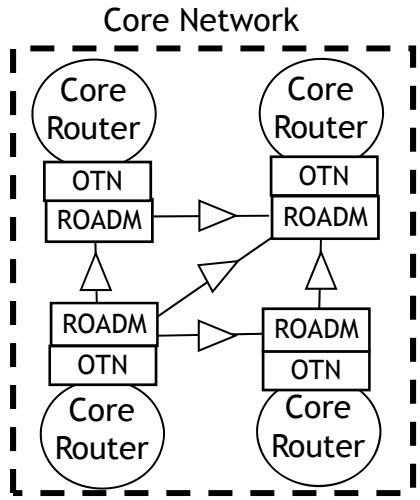
Transport+Routing+Switching

P/C = Power/bit/second (energy per bit)

η_c = cooling, η_{pr} = over-prov.

η_G = green energy factor

H_{LH} = # hops in core = 3 (4 hops in metro)



Transport: Terrestrial

P_{tr0} = node power, P_{tr1} = distance dep. power

C_{tr} = transport equip capacity

Use 'worst case' 1500 km transmission distance

Routing

P_{CR} = Core router power

C_{CR} = Core router capacity

OTN Switching

P_{OTN} = Core OTN power

C_{OTN} = Core OTN capacity

$$E_{bLH} = (H_{LH}+1)\eta_{pr}\eta_c\left(\frac{P_R}{C_R}+\frac{P_{OTN}}{C_{OTN}}\right)+H_{LH}\eta_{pr}\eta_c\left(\frac{P_{TR0}}{C_{TR0}}+\frac{P_{TR1}}{C_{TR1}}\right)$$

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Models for each Sub-Network

Network	Efficiency Model (energy/bit)	Notes & Exceptions
Fixed Access	$\frac{P_{TU}}{A \cdot N_{TU}} + \frac{P_{cpe}}{A}$	CPE does not include CATV, A is the access rate
Edge Aggr.	$\eta_{pr}\eta_c \frac{P_{Eth}}{C_{Eth}}$	
Metro	$(H_M + 2)\eta_{pr}\eta_c\left(\frac{P_R}{C_R} + \frac{P_{OTN}}{C_{OTN}}\right) + H_M\eta_{pr}\eta_c\left(\frac{P_{TR0}}{C_{TR0}} + \frac{1}{2}\frac{P_{TR1}}{C_{TR1}}\right)$	One metro hop is taken to be an inter-carrier exchange point with no transmission between routing equip.
Long Haul	$(H_{LH} + 1)\eta_{pr}\eta_c\left(\frac{P_R}{C_R} + \frac{P_{OTN}}{C_{OTN}}\right) + H_{LH}\eta_{pr}\eta_c\left(\frac{P_{TR0}}{C_{TR0}} + \frac{P_{TR1}}{C_{TR1}}\right)$	
Enterprise	$\eta_{pr}\eta_c\left(\frac{P_{AS}}{C_{AS}} + \frac{P_{AgS}}{C_{AgS}} + \frac{P_{CS}}{C_{CS}} + \frac{P_{FW}}{C_{FW}}\right)$	
Mobile	$\frac{P_{BTS}N_{BTS}}{N_U T_M} + \eta_{pr}\eta_c\left(\frac{P_{PGW}}{C_{PGW}} + \frac{P_{SGW}}{C_{SGW}}\right)$	LTE model with converged voice and data, T_W is a reference wireless access rate per user

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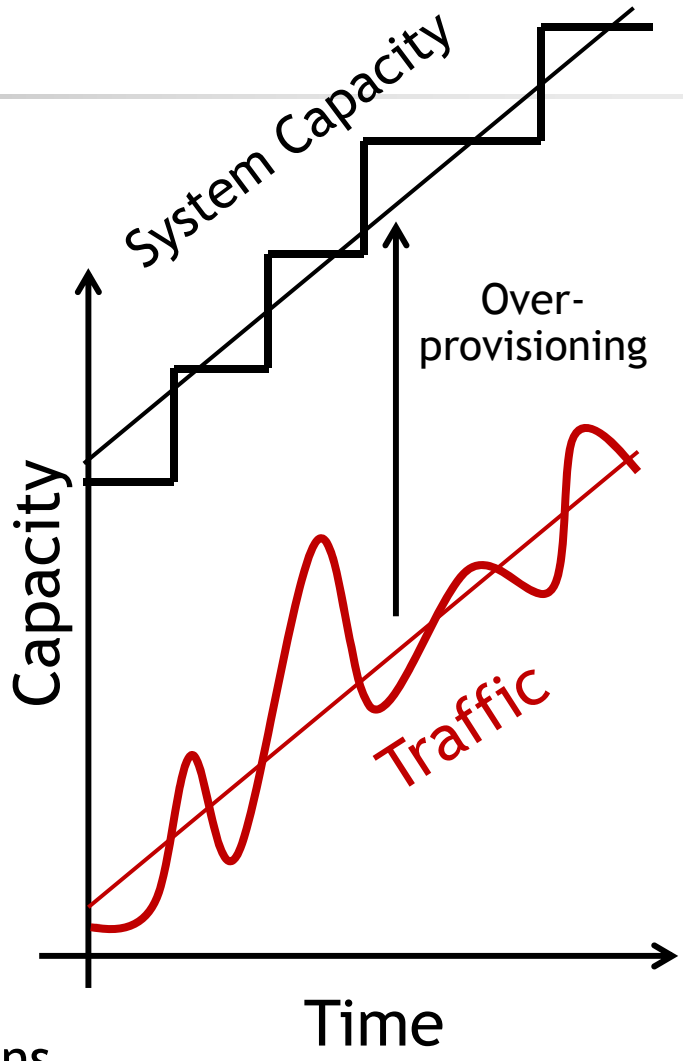
Provisioning factors: how many boxes/transaction

Network	Factor (x prot.)	Notes
Fixed Access	1	CPE is provisioned with one unit per household regardless of traffic
Edge Aggr.	10x2	
Metro	5x2	
Long Haul	2x2	
Enterprise	10x2	
Mobile	5x2	Routing & switching hardware only



'Over-provisioning' includes many contributions

- Protection, excess deployment to allow for traffic growth, over-subscription (peak to mean ratio)

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The Data Challenge

Data Challenge: Finding Reliable Sources of Data

Key Challenges:

- Much information about networks is confidential to network operator
  - Variations between operators and regions
- Some information about networks is protected by privacy laws

- Networks are built from commercial products
  - Information about equipment and systems is often proprietary
  - Variations between vendors

- Lack of measurement equipment, methods, and standards
  - Rapidly improving, but still catching up
  - Methods must adapt as network evolves

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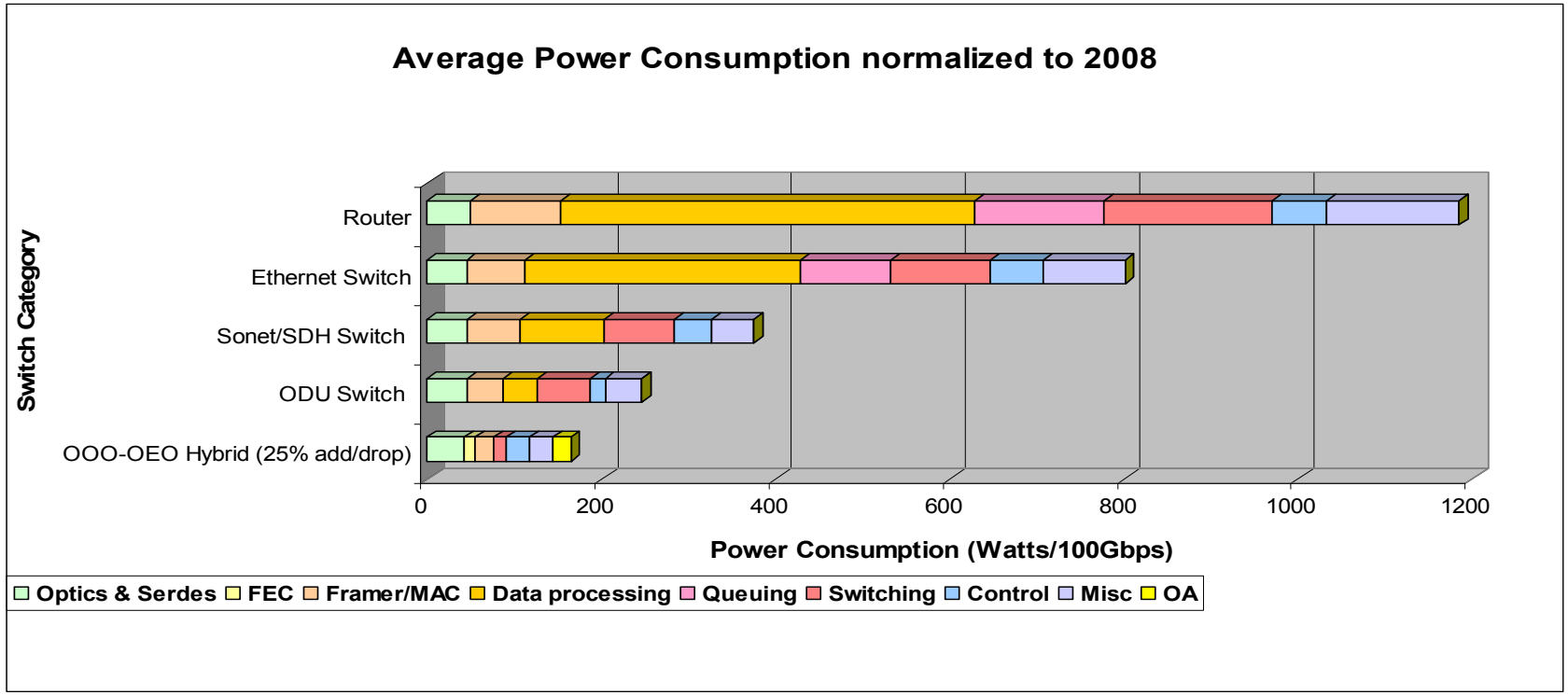
Equipment Models: Industry Averages Normalized to Ref. Year



Router: 12 mW/Mb/s, 12 nJ/bit

Switch: 2-8 mW/Mb/s

ROADM: < 2 mW/Mb/s

Good information, but not comprehensive

Oliver Tamm, et. al., BLTJ 2010

Includes time dependence

- Driven by electronics

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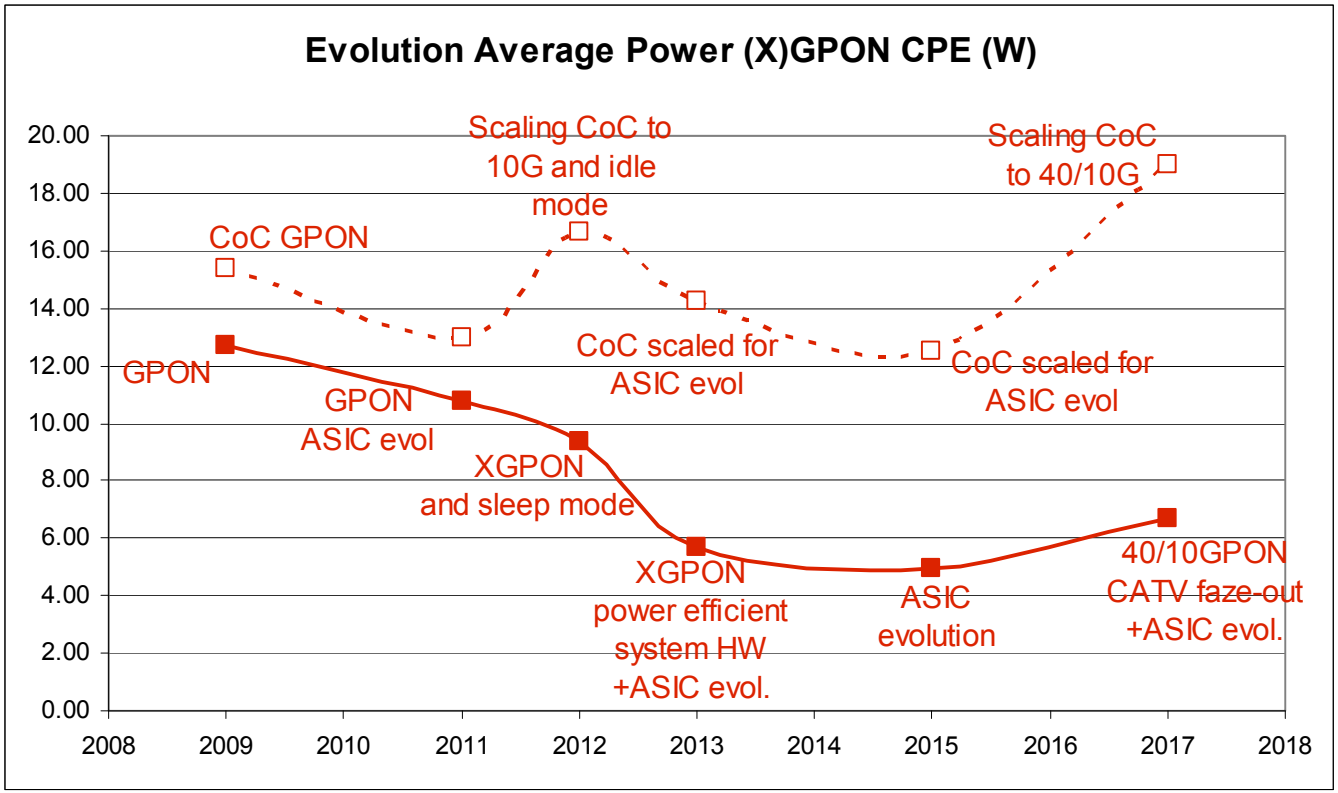
Technology Evolution Trends: Fixed Access, GPON only

Establish Baseline:
For EU Code of Conduct for 2006, project forward in time

Optimistic Trend:
Consider aggressive research-driven improvement timeline



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Going Into Detail: Optical Networking

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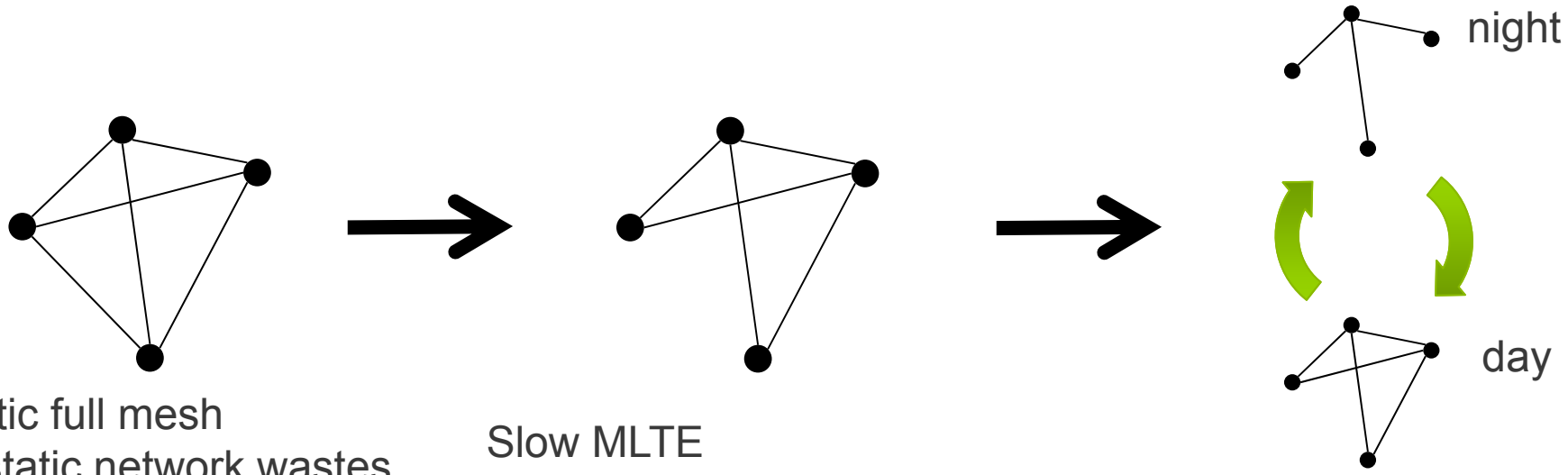
Multilayer Traffic Engineering

- Control IP/MPLS flow routing & logical topology
- Adapt these to changing traffic demand



Static full mesh
(a static network wastes power because of high idle power requirement)

Slow MLTE
(adapt network to traffic demand
less links = less power)

Fast MLTE
(link switch-off
during off-peak hours)

Source: Bart Puype et al., Power Reduction Techniques in Multilayer Traffic Engineering , IBCN

Courtesy of Mario Pickavet

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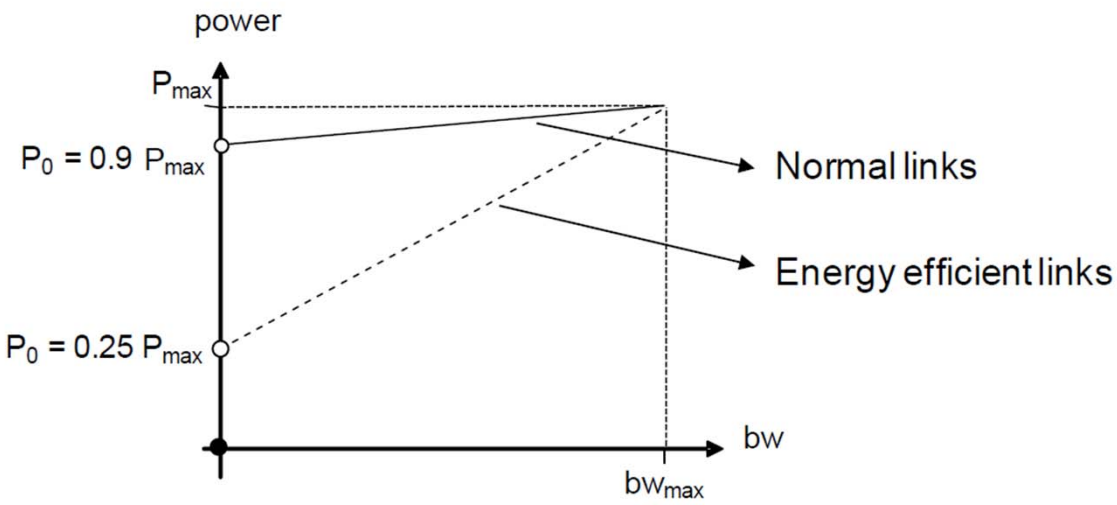
Power model



Network: 14 nodes

- 4 with energy efficient line cards (P0 = 0.25 Pmax)
- 10 with normal line cards (P0 = 0.9 Pmax)

Source: Bart Puype et al., Power Reduction Techniques in Multilayer Traffic Engineering , IBCN

Courtesy of Mario Pickavet

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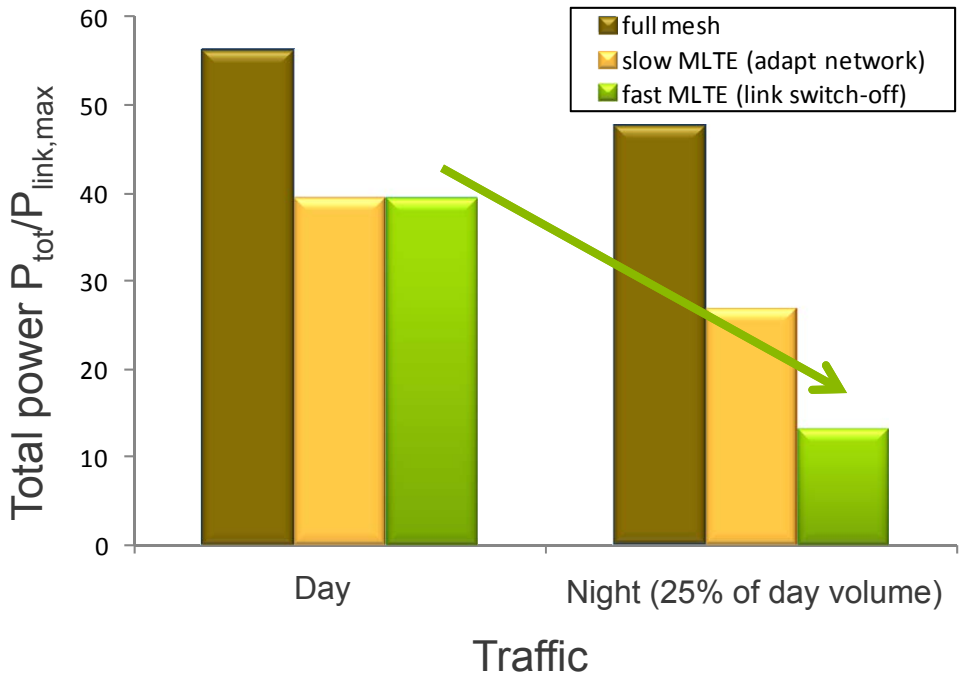
Multilayer Traffic Engineering

Two optimization modes

- Slow: days/weeks
- Fast: hours

Power scales better with traffic volume as MLTE acts faster.



Source: Bart Puype et al., Power Reduction Techniques in Multilayer Traffic Engineering , IBCN

Courtesy of Mario Pickavet

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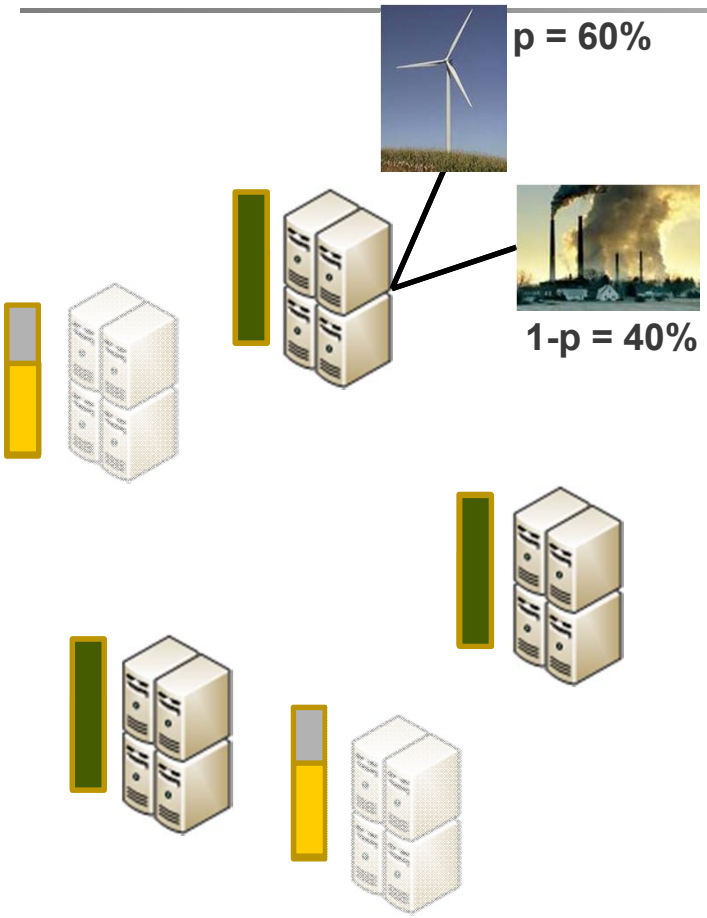
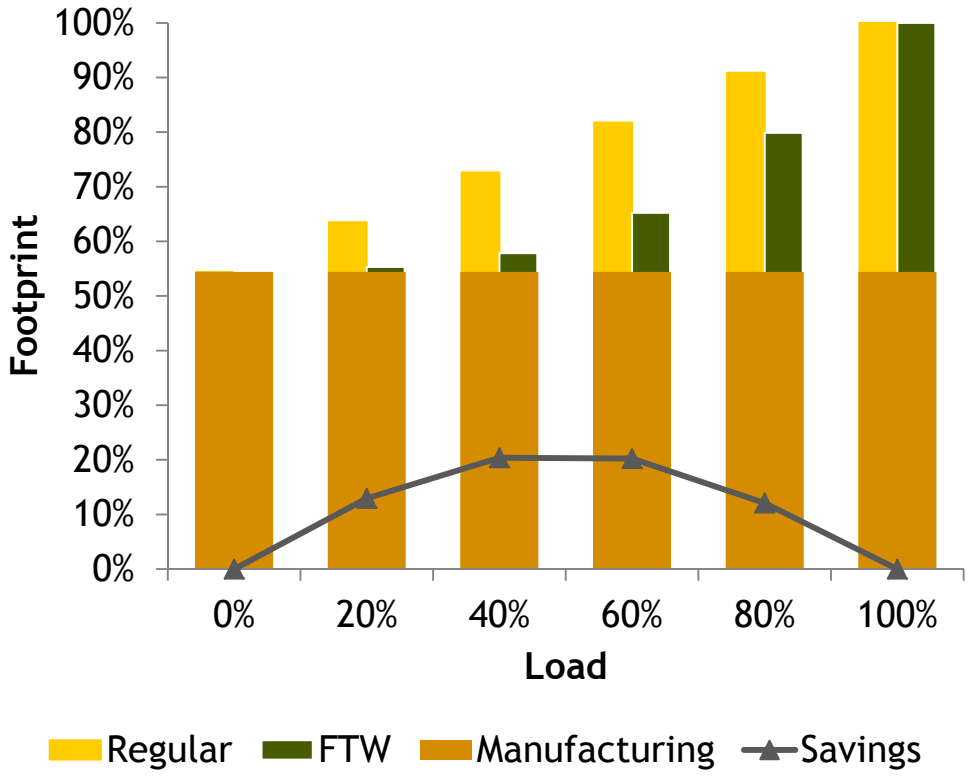
Follow the wind





3/5 load: regular

3/5 load: follow the wind (FTW)

Courtesy of Mario Pickavet, IBBT

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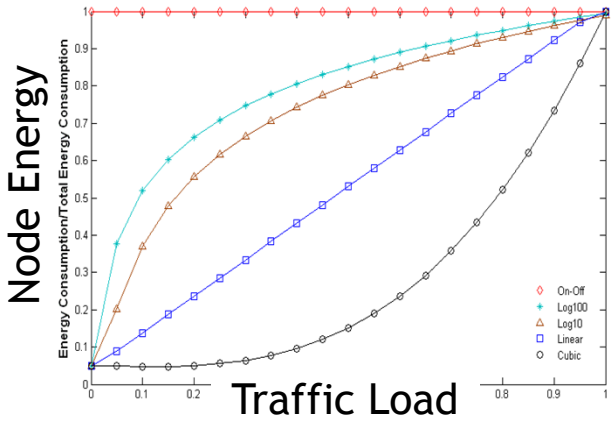
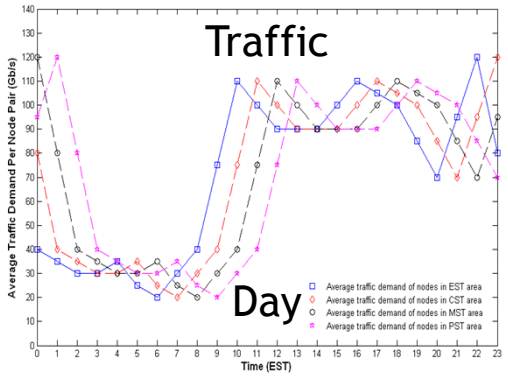
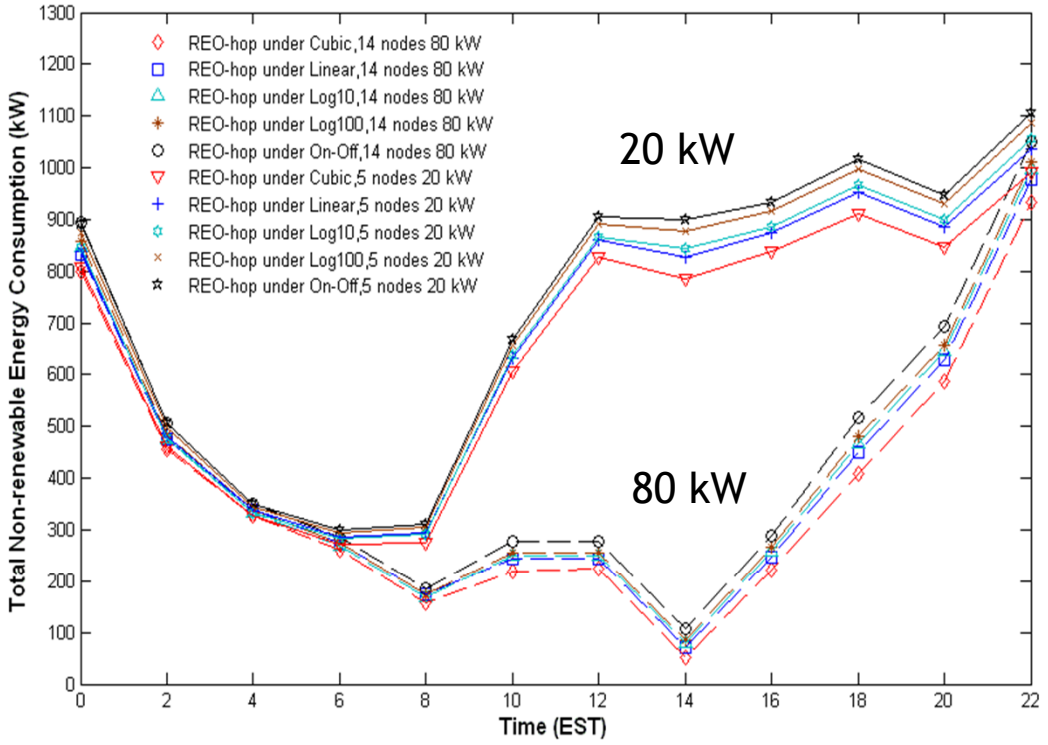
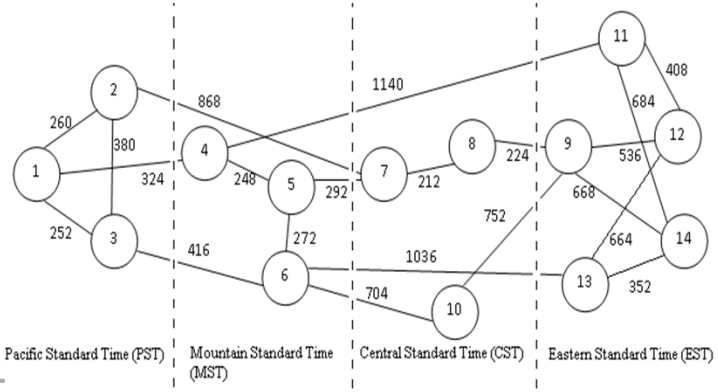
RWA Including Renewable Energy & Energy Proportional Routing

- Use solar energy during daylight hours
- Route for maximum renewable energy use









NSFNET

By time zone

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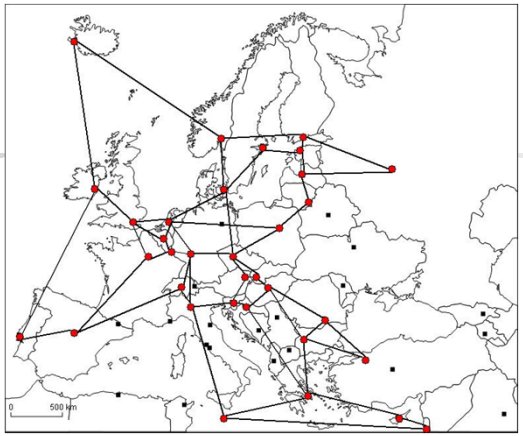
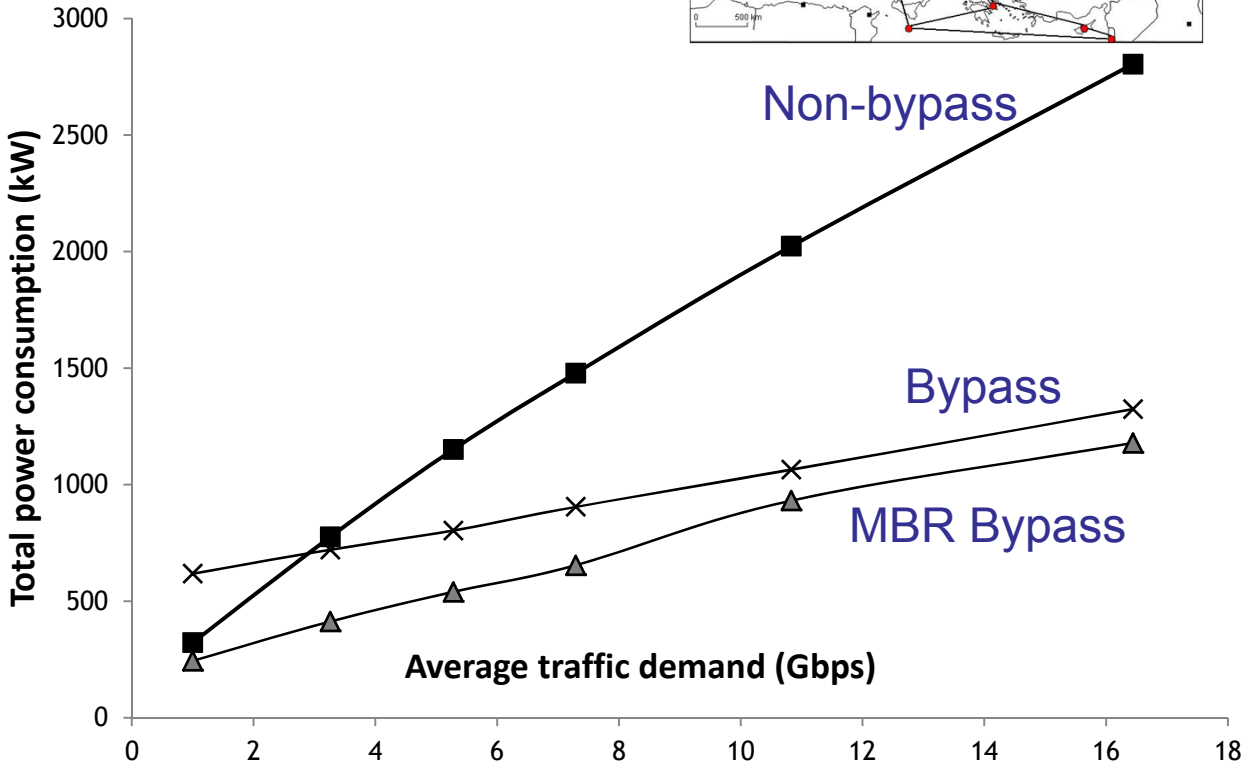
Optical Bypass For Efficient Wavelength Routing



- Link utilization is critical

For low demands
→ bypass not efficient
(10 Gbps ports !)

- Multi Bit Rate Bypass
→ always more efficient



Courtesy of Mario Pickavet, IBBT

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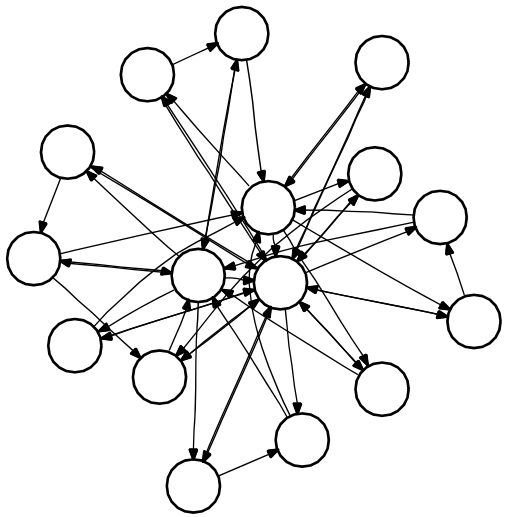
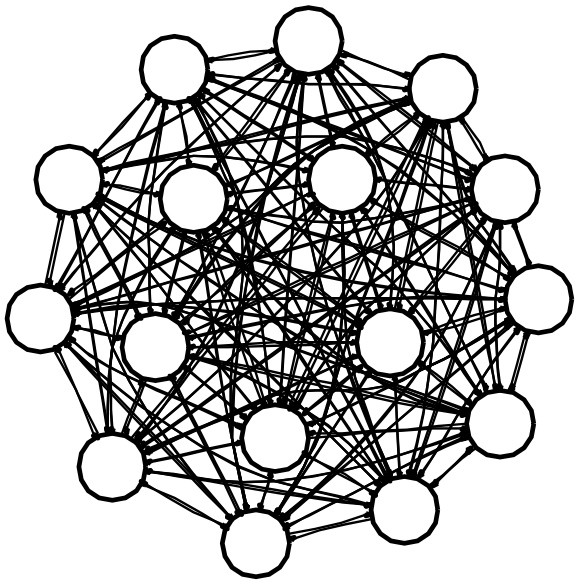
Transmission vs. switching

Depending on the power consumption of switching with respect to transmission, the logical topology can be partially connected to minimize the number of transceivers (equivalent to cost-optimized) …



Partial mesh:
forward traffic
on most of the nodes

But for less power-efficient switches, more links become convenient (cost- and power- optimized solutions differ)



Full mesh:
no ftraffic
forwarding

Courtesy of Fabio Neri, Politecnico di Torino

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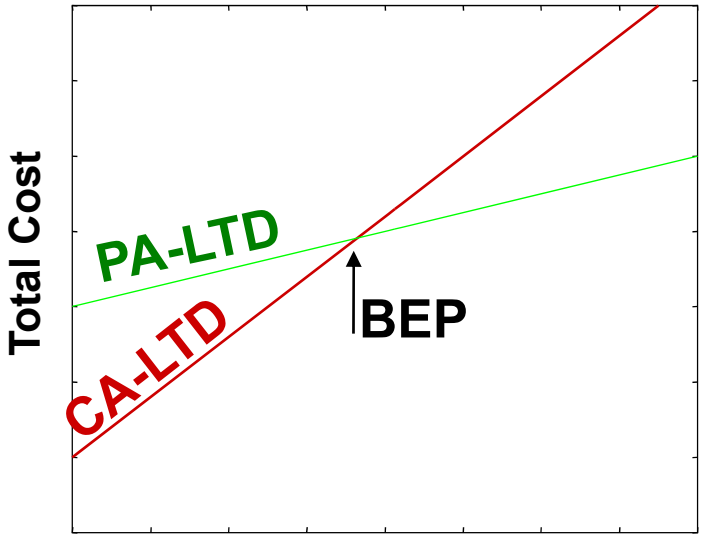
Economic analysis

Bianco, A., et. al., ECOC 2010

- For $P^{TX} < P^{SW}$, lower power consumption means higher costs (due to the larger number of transceivers), but also money savings by energy-efficiency
- PA-LTD finds results having usually larger CAPEXs than CA-LTD results
- It is possible to recover the difference due to a smaller OPEX
- Break-Even Point (BEP):
  - Time required to start getting an economical advantage for a PA-LTD solution respect to the CA-LTD one

PA-LTD = Power Aware Logical Topology Design

CA = Cost Aware



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Directions Moving Forward

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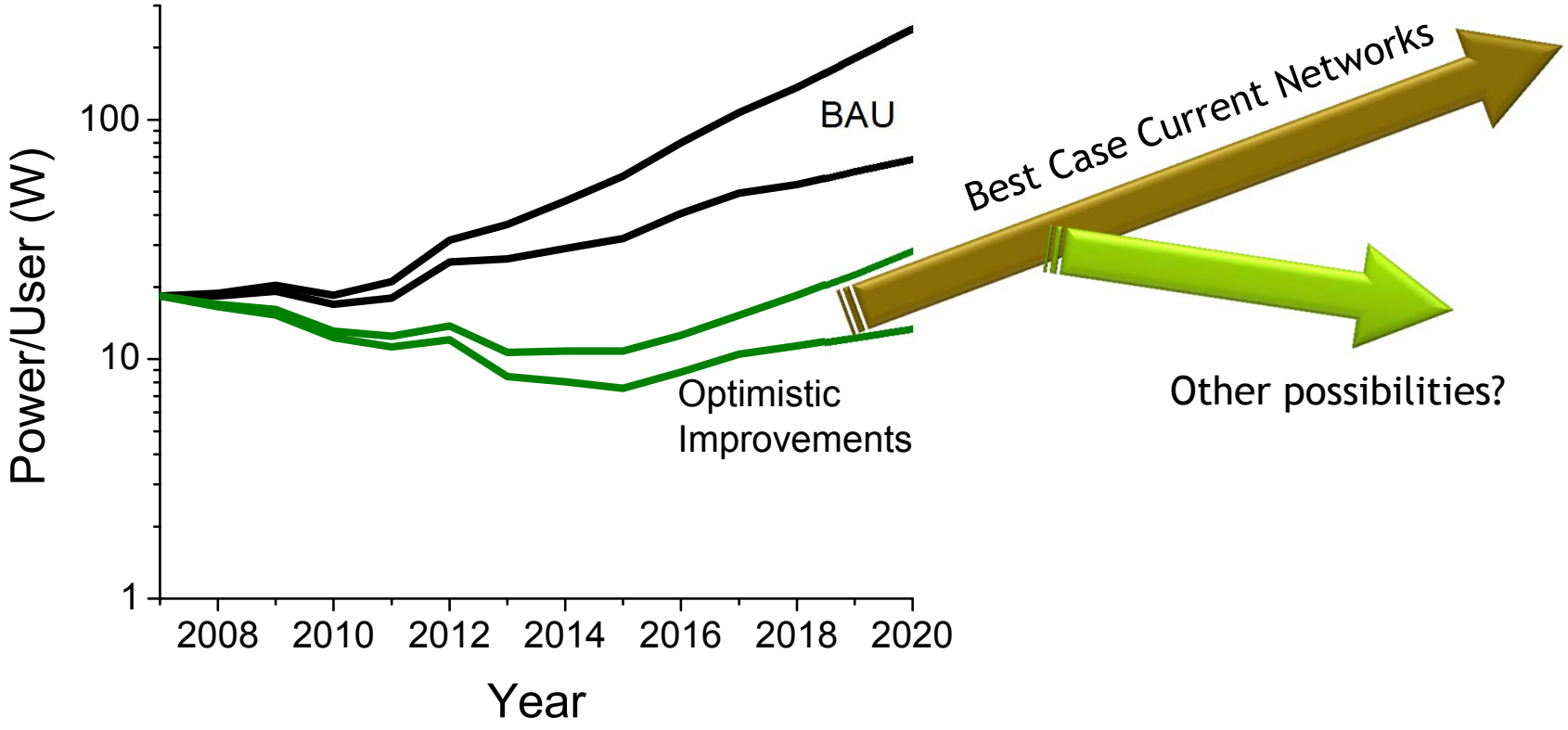
Staying Flat or Reducing Power Beyond 2020…

Need models to identify bottlenecks and unlock new network design and control capabilities



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Benefit Derived from Wavelength Dynamics

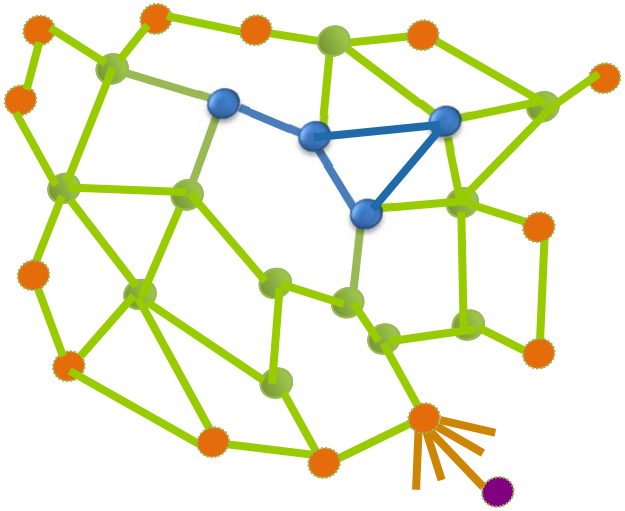
Two Traditional Factors:

- Energy proportional operation
  - Reduce over-provisioning
  - Resource sharing

<10x

- Utilization of low energy, green energy sources

~ P^{old} / P^{new}



Added dimension:

- End-to-end connectivity: simplified hardware
  - Reduced buffer sizes
  - TDM/circuit switching

Enable hardware changes

Service Coordination: match transport to service needs

e.g. Using a Netbook for web browsing

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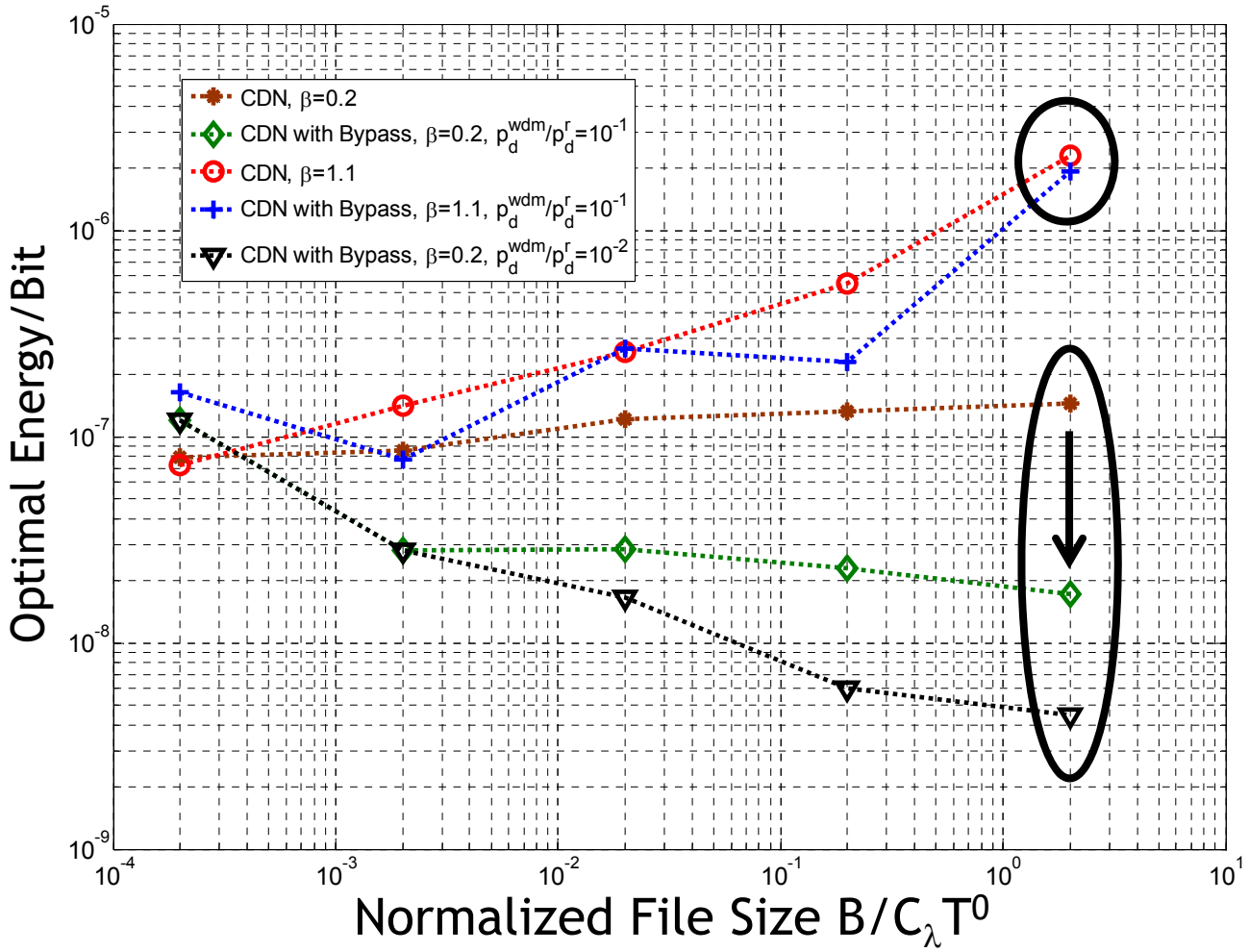
Optical bypass power reduction potential for content delivery

Efficient bypass for $B > C_\lambda T^0 p^{wdm}/p^r$



Few large files

Frequent download of large files

$p^{wdm}/p^r = 0.1$

$p^{wdm}/p^r = 0.01$

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How does cost of energy influence networks?

Energy consumption depends sensitively on the demand distribution

- High energy cost can drive low energy demand distributions
  - Remember the days of ‘long distance phone calls only on weekends’

Most network services today are provided by servers deep in the Metro/Core

- E-mail
- On-line shopping
- On-line banking
- Telephony
- Search

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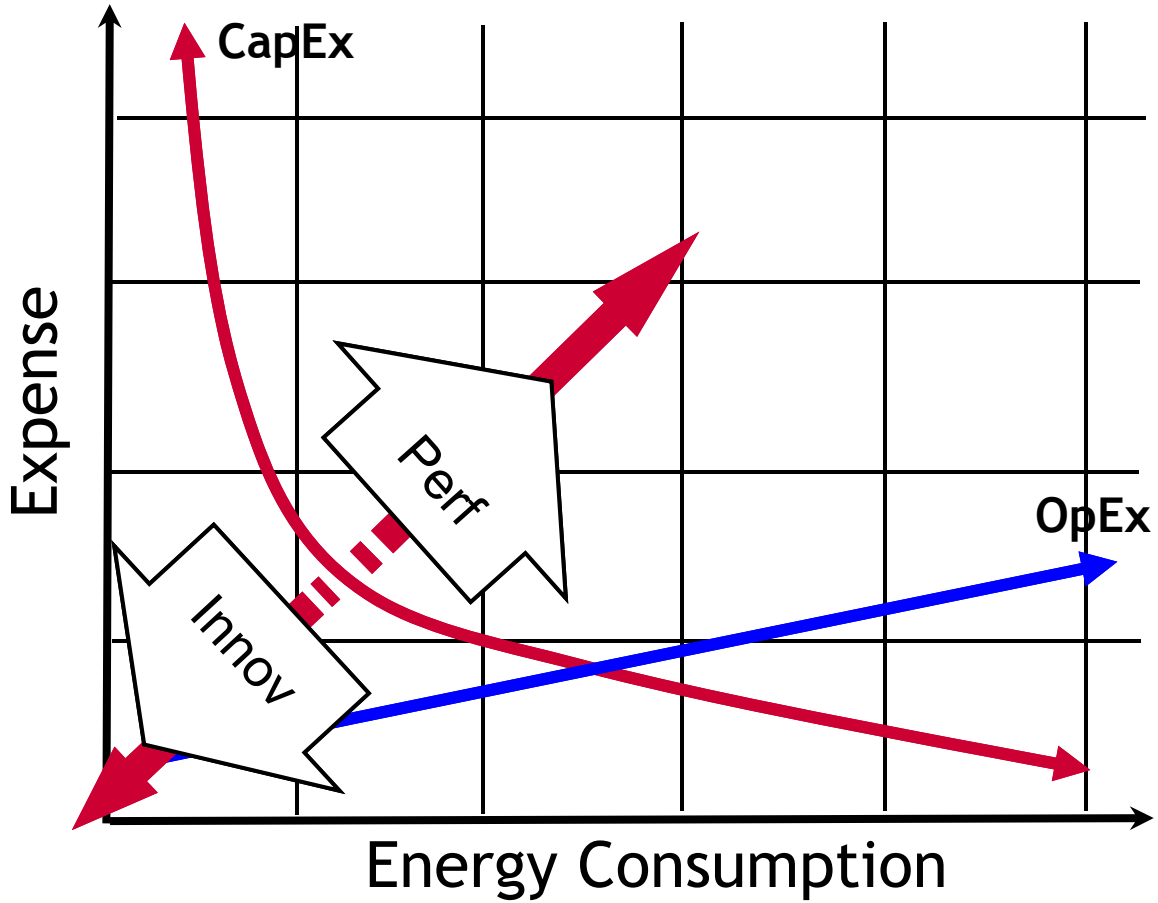
The price of efficiency



Lowest energy network is prohibitively expensive/impractical today:

- **Technology innovation can drive cost down**
- **Real cost of energy consumption will result in an optimum cost**

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ICT Industry Responds

First Step: metrics, awareness, standards, call to action

- Global e-Sustainability Initiative (GeSI)
- ITU-T
- GreenGrid

Next Step: alliance, action

- EARTH: LTE 2x
- Mobile VCE: Green Radio 100x
- Institute for Energy Efficiency: Wireless and optical 100x
- GreenTouch: ICT Networks 1000x

Semiconductor Industry Already Organized for the Long View:

ITRS 15 years out

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Conclusions

Networks are key part of overall social strategy to reduce carbon footprint

- Essential tool in realizing sustainable living
- Must be reconciled with network growth

Scaling networks is becoming harder

Understanding energy use in networks is a complex and important problem

- Access to data will be an on-going challenge
- Complimentary methods available: network model vs. energy accounting

Much recent activity looking at core network techniques

- EE-network design and traffic engineering
- Dynamic wavelength capabilities

Need to look beyond current network paradigm to address long term challenges

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Thank you!

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