Energy-Efficient Networking

Rod Tucker, Kerry Hinton

Centre for Energy Efficient Telecommunications
University of Melbourne

Course description

- Introduction and overview of energy consumption and efficiency in communications networks.
- Trends (past and future), challenges and opportunities presented by the evolution to energy-efficient telecommunications.
- General overview of many areas
  - Not exhaustive coverage
- GreenTouch
  - www.greentouch.org
- Bibliography for further reading

Overview

1. Growth of ICT and its power consumption
2. Sustainability and ICT growth
3. Estimating ICT energy consumption
   - Sales and inventory based models
   - Network design based model
   - Transaction based model
4. Network design based estimates
   - Network segments
   - Access, Metro/Edge, Core, Data Centres
   - Data Centres
5. Power consumption of equipment
6. Equipment power consumption trends

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Overview

7. Models of equipment energy consumption
8. Quantifying equipment energy efficiency
9. Bringing it all together
   - Accounting for growth and improvement
   - Power consumption of the global Internet
10. Lower limits on energy consumption
11. Improving network energy efficiency
   - Technologies and circuits
   - Architectures
   - Protocols
   - The Cloud
   - GreenTouch

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

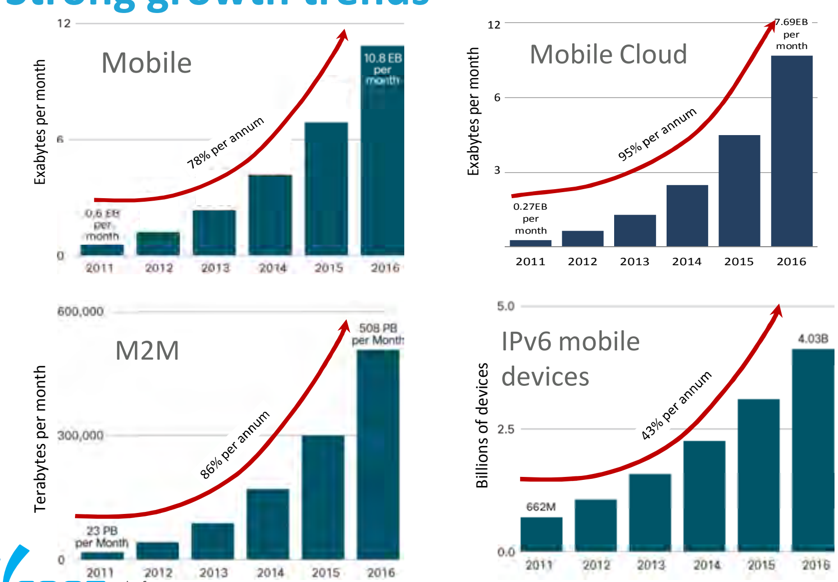
1. Growth of ICT & its power consumption

- ICT is now a fundamental resource for economic and social development
- Growth in number & speed of services plus number & geographical spread of users demands ever more infrastructure
- This infrastructure is consuming ever greater amounts of electrical power
- Carbon footprint of ICT is 1.9% of total human footprint
  - About same as air transport industry but growing faster
    - ICT 4% pa compared to air transport 1.4% pa (2012)
  - Expect to be 2.3% by 2020

(SMARTer 2020, 2012, IATA: Climate Change Fact Sheet)

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

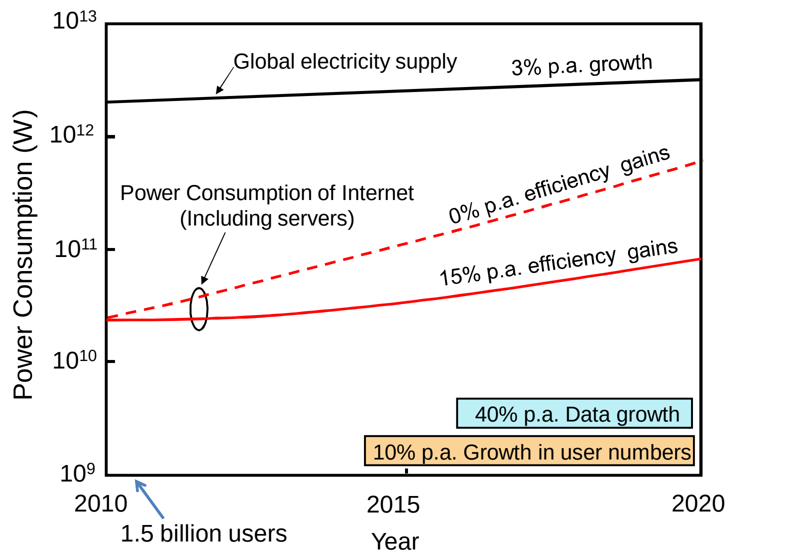
Strong growth trends



Source: Cisco VNI Global Mobile Data Traffic Forecast Update: 2011 - 2016

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

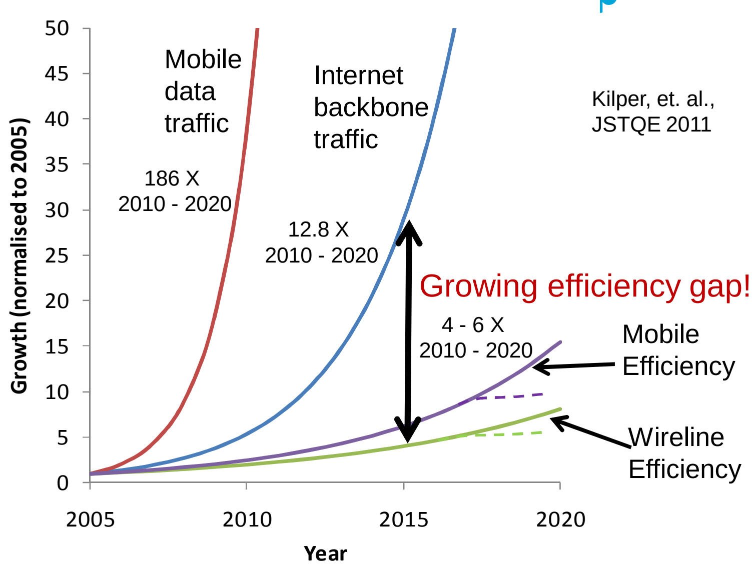
Power consumption of the global Internet



Source: Tucker, JSTQE 2011

7

The growing energy efficiency gap



8

2. Why energy matters

- If nothing is done to address the growing "efficiency gap":
  - ICT will consume ever larger proportion of global energy
  - Energy consumption could become a barrier to network growth
  - More power lost in power transmission network
    - Need more power generated
- Economic and engineering imperatives:
  - Energy is a growing component of OPEX
  - Increased energy consumption → increased equipment footprint
    - CAPEX & OPEX
  - Reaching thermal limits of equipment
  - Increasing difficulty in securing adequate power supply

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Motivation

GreenTouch

Global ICT Emissions:
2.3% of Global GHG in 2020; Growing at 4% YoY

Enabling Effect Leads to 16% reduction in Global GHG through Intelligent Use of ICT

Global aviation industry

50 million cars

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Motivation

GreenTouch

- Energy efficiency makes economic sense

NETWORK ENERGY USE
+27%
INCREASE
2012 to 2016

INTERNET
=5th
HIGHEST ENERGY
COSUMING "NATION"

NETWORK
~75%
ENERGY BILL
OF TELCO

ENERGY BILL
7-20%
OPERATORS OPEX

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

11

GreenTouch

GreenTouch

- Focused on energy efficiency for mobile communications, wire-line access and core networks
- Bell Labs initiated Global Research Consortium launched in May 2010
- New innovation and collaboration model for R&D
- Moving from fundamental research into the pre-competitive area through standardization

Deliver by 2015 Architectures, Specifications and Solutions and Demonstrate Key Technologies to Increase Network Energy Efficiency by a Factor 1000 Compared to 2010

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

12

3. Sustainability and ICT growth

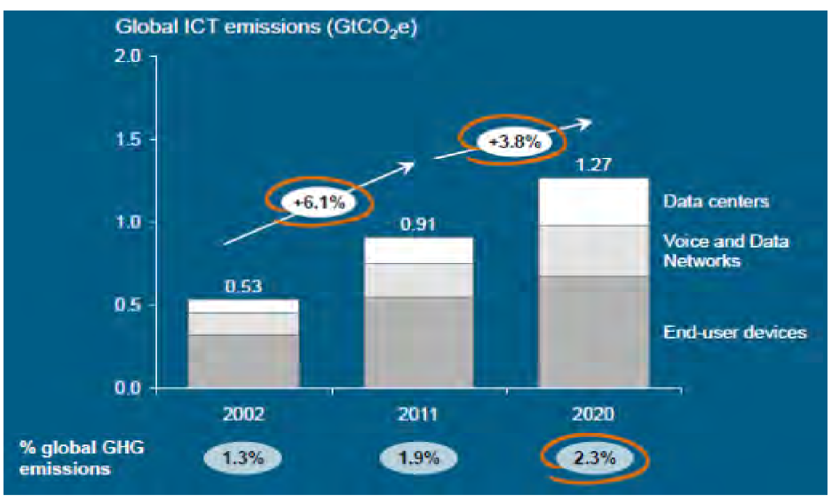
- To make the Internet & ICT sustainable we need to:
  a) Improve energy efficiency in ICT
  b) If possible, de-couple ICT power demand from its growth
  c) Replace CO_2 intensive energy production with renewable energy sources
- This short course focuses on a) and b)

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

13

GeSI: SMARTer 2020 Report

ICT emissions equal 2.3% of global emissions by 2020

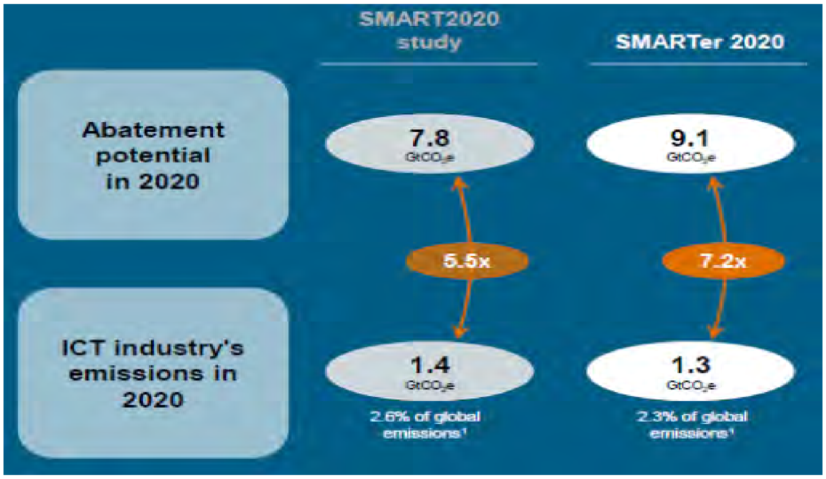


centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

14

GeSI: SMARTer 2020 Report

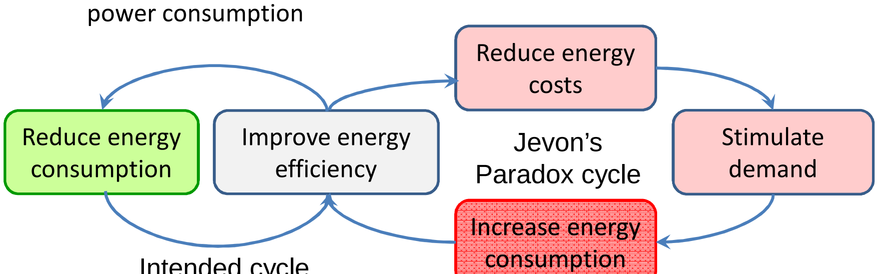
ICT can contribute to global abatement



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Why focus on energy efficiency?

- Reduce carbon footprint of ICT
  - Zero carbon power generation still some time away
  - Reduce power losses in supply grid
    - Save a Watt at plug means saving Watts at generator
- "Jevon's paradox"
  - Improving efficiency will stimulate economic activity & increase power consumption



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

4. Consumption & efficiency metrics

- Which metric(s) are appropriate?
  - Power consumption per "throughput"
  - Power consumption per "good put"
  - Energy per bit, power per bit rate
  - Energy per customer bit
  - Energy/bit/km^2 (mobile networks)
  - etc.
- Different metrics provide different optimal solutions to energy efficiency
- We adopt Energy/bit (Joules/bit, Watts/(bit/s))
  - Same as bits/energy (bits/Joule, (bit/s)/Watt)
  - Widely used for energy efficiency

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

"Joules/bit" energy efficiency

- ITU L.1310, "Energy efficiency metrics & measurement methods for telecommunications equipment"

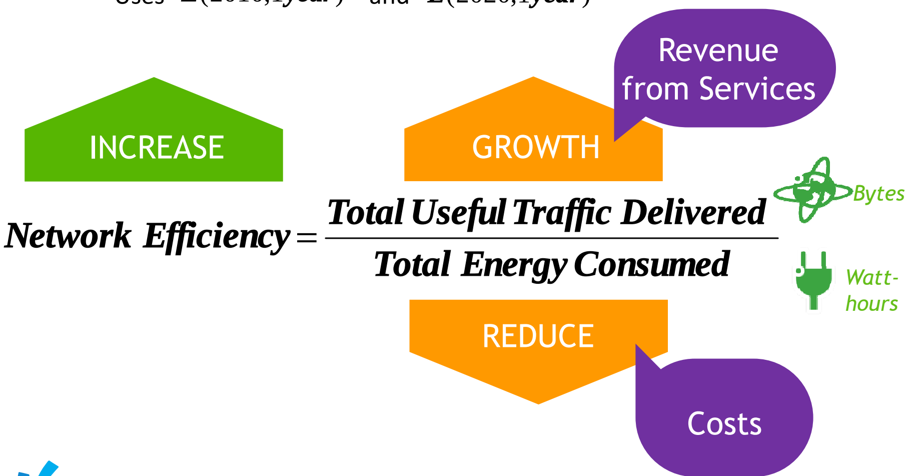
$$\textit{Energy efficiency} = \frac{\textit{functional unit}}{\textit{energy needed to deliver that functional unit}}$$

- Functional unit is "bits"
- Possibilities for "joules per bit"
  - Instantaneous $E(t) = \dfrac{P(t)}{C(t)}$
  - Average instantaneous $\langle E(t;T)\rangle = \dfrac{1}{T}\displaystyle\int_t^{t+T} \frac{P(t')}{C(t')}dt'$
  - Total energy/total bits $\bar{E}(t;T) = \displaystyle\int_t^{t+T} P(t')dt' \Big/ \int_t^{t+T} C(t')dt'$

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

GreenTouch energy efficiency

- Used to quantify GreenTouch goals
  - Uses $\bar{E}(2010;1\textbf{year})$ and $\bar{E}(2020;1\textbf{year})$



$$\textit{Network Efficiency} = \frac{\textit{Total Useful Traffic Delivered}}{\textit{Total Energy Consumed}}$$

19

5. Estimating ICT energy consumption

- Inventory-based estimates
  - Estimate power consumption by looking at what is out there
    - Use sales and deployment data from vendors and equipment surveys
    - Accessing accurate data is problematic
- Network design based estimates
  - Look at current access demand and design a network that will satisfy that demand
    - Use typical network design rules
    - Difficult to include network inefficiencies, overlays & legacies
- Transaction based estimates
  - Look at services provided and design a network to provide them
    - Similar to Network design approach

20

Network design based estimates

1. Network segmentation
   - Access
   - Metro/Edge
   - Core
   - Data centres, content storage
2. Model each part with representative architecture and equipment
3. Set access rate per customer
4. Dimension network to accommodate that access rate per customer
5. Calculate power consumption per customer for network

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Transaction/service based estimates

- Internet provides services to customers
  - Service centric focus for energy consumption
- Sum power of resources required to deliver services
  - Network equipment depends on service type
- Include network design rules

Service	Network path
General Web	Fixed access + Metro/Edge (x2) + Long haul + Enterprise
Video	Fixed access + Metro/Edge + Long haul + Enterprise
Peer to Peer	Fixed access (x2) + Metro/Edge (x2) + Long haul
Mobile data	Mobile + Metro/Edge (x2) + Long haul + Enterprise
Mobile voice	Mobile (x2) + Metro/Edge + Long haul

Source: Kilper et al. JSTQE 2011

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Examples of estimates

Author	Year	% national electricity use	Country	PC's, office equip. & servers	Wireless access	Notes
Huber	1999	13%	USA	Yes	No	Severe over estimate
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	2007	0.5%	OECD	No	No	Network design & dimensioning
Vereecken	2010	Not given	Not given	No	No	Network design & dimensioning
Lange	2010	Not given	Not given	No	Yes	Network design & dimensioning
Kilper	2011	Not given	USA	No	Yes	Transaction
Pickavet	2007 2012		Global	Yes	Yes	Users and equipment estimate

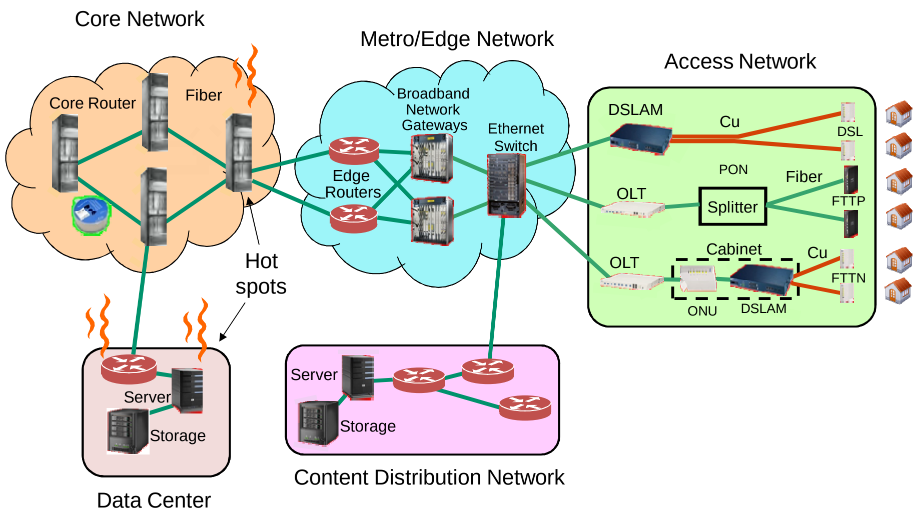
6. Network design based estimates

1. Network Segmentation
   - Access
   - Metro/Edge
   - Core
   - Data centres, content storage
2. Model with representative architecture and equipment
3. Dimension network to accommodate expected traffic
4. Calculate power consumption per customer for network

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

24

Network segmentation



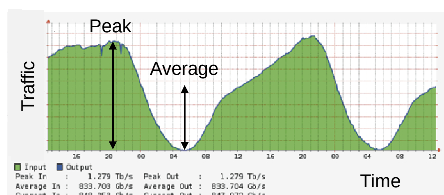
Baliga et al., 2007

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

25

Model parameters

- Equipment power models
- Peak vs average access speed
  - Contention & aggregation
- Network dimensioning
  - Traffic growth
    - Deployed capacity > demanded capacity
  - Equipment redundancy
    - Multi-homing , back-up storage
  - Service protection
    - 1 + 1, 1:1, 1:N protection
- Router hops between source and destination
- Data centre Power Usage Effectiveness (PUE)

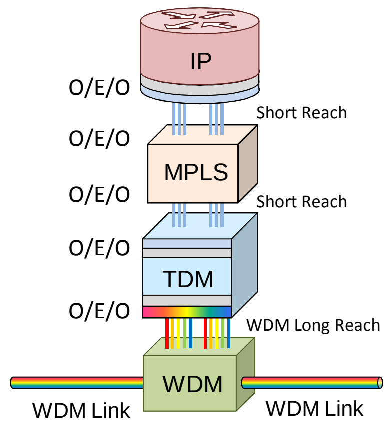


centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

26

7. Power consumption of equipment

- Dependent on throughput
  - Router, switch, server, mobile
- Constant power consumption
  - SDH, OTN equipment
- Dependent on signal power or WDM channel count
  - Optical amplifiers
- Dependent upon location
  - Mobile, WDM systems
- Dependent upon state
  - Sleep, rate adaptation



Optical line equipment power

Many Configurations

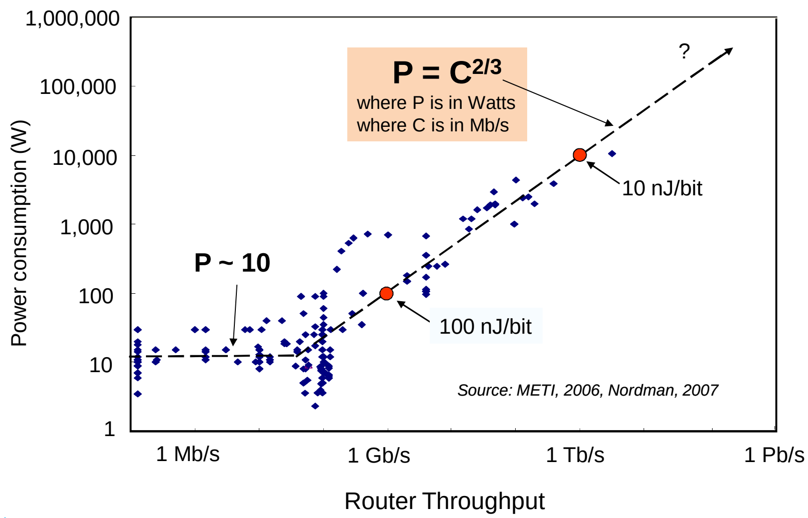
- Line cards: ~ 50 W
- Incl. OAs, ~10G OOK
- Fans: ~ 200 W
- Controller Boards: ~ 100 W

- 16 slot shelf: 50x15+100+200= 1 kW
  Telcordia CO (NEBS) standard:
  995 W/m^2/m (forced air cooling)
- Line system energy already constrained by thermal limits

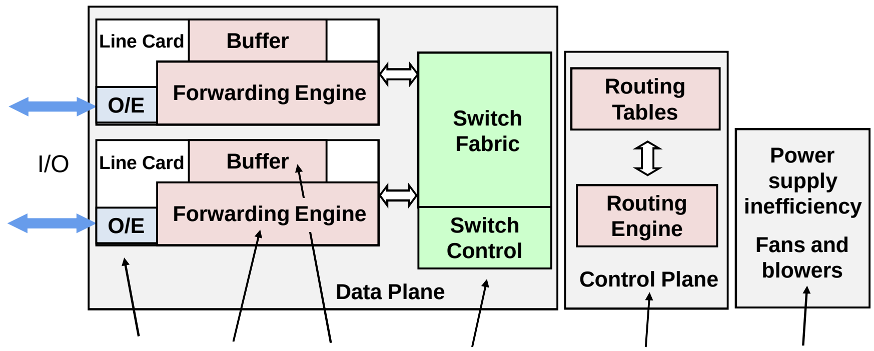
Router & switch power

- Cisco CRS-1 (core IP router)
  - 16 slot configuration: 640 Gbit/s, 2920 W
  - Maximum configuration: 92 Tbit/s
    - 72 x Line-card chassis + 8 Fabric chassis
    - Total power ~ 1 MW
- Cisco CRS-3 (core IP router)
  - 16 slot configuration: 2240 Gbit/s, 2668 W
- Juniper PTX 5000 (core packet switch)
  - Maximum configuration: 8 Tbit/s, 10.3 kW

Power consumption of router generations



Energy/bit in high-end core 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%

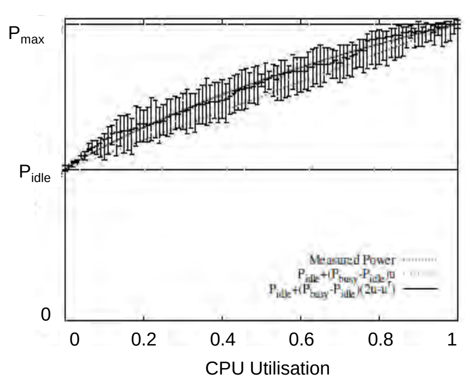
Source: R. Tucker et al. JLT, 2009

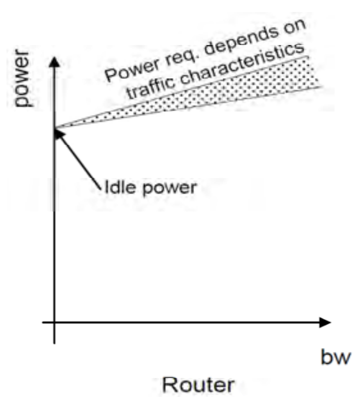
centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

31

Power consumption of routers & servers

Approximately linear dependence on throughput





Source: X. Fan et al., 2007

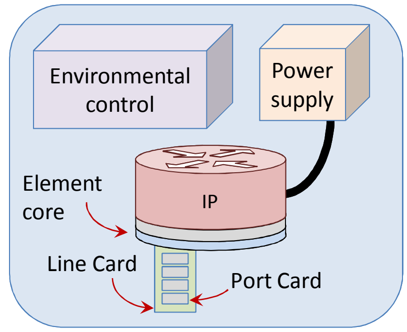
Source: B. Puype et al., 2011

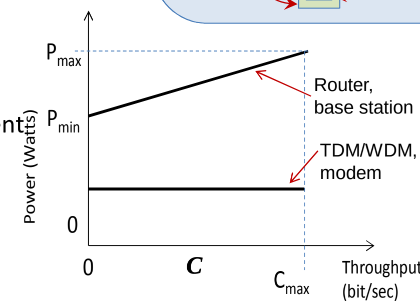
centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

32

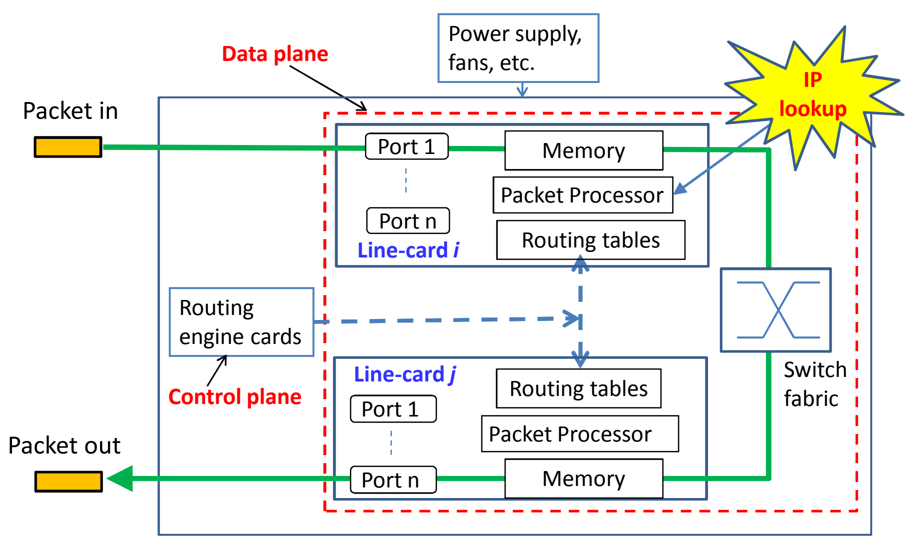
8. Models of equipment power consumption

- Power consumed by
  - Line card and its ports
  - Element core
  - Power supply
  - Environmental control
- Power consumption can be:
  - Shared across sub-systems
  - Specific to individual sub-systems
  - Fixed
  - Throughput dependent

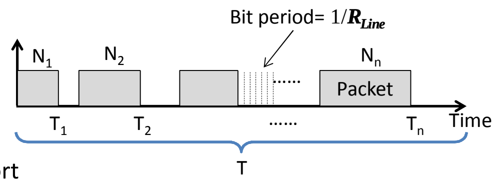




Router structure & function



Packet rate, data rate & line rate



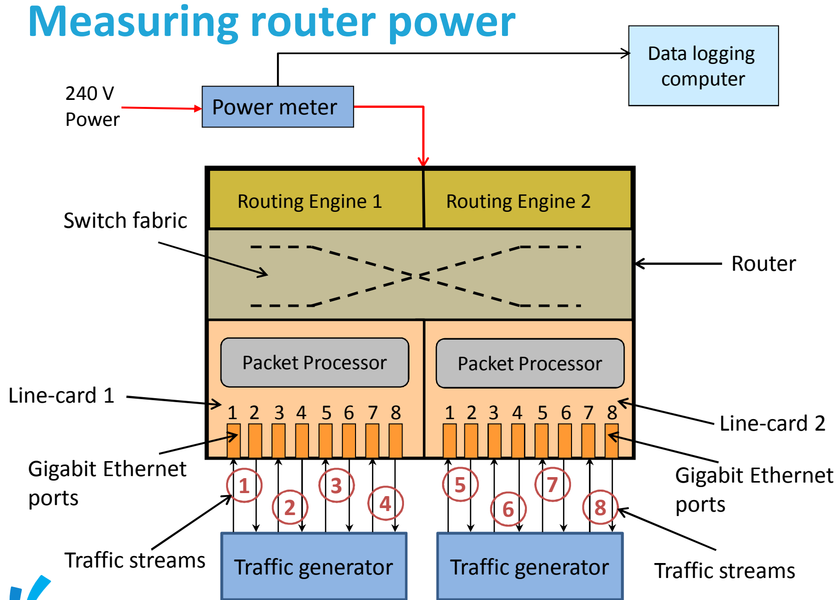
- *Line Rate*, R_{Line}
  - Bit/sec line rate of a port
- *Packet Rate*, R_{Pkt}
  - Packets per second into a port
- *Data Rate*, R_{Data}
  - The data rate (bit/sec) accounting for packet size and packet rate
  - May be much less than the line rate

$$R_{Data} = \frac{R_{Line}}{B} \qquad R_{Pkt} = \frac{R_{Line}}{B \cdot N_{Pkt}} = \frac{R_{Data}}{N_{Pkt}}$$

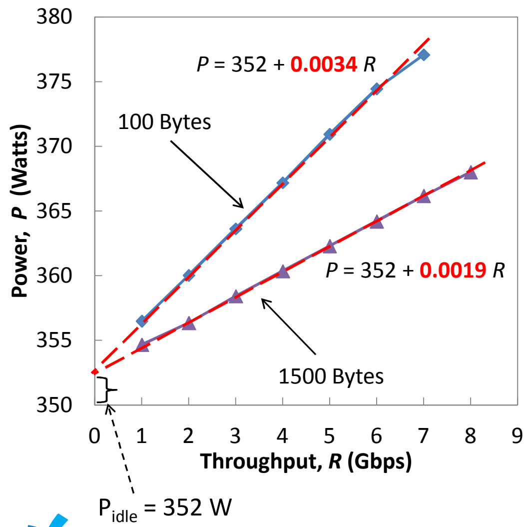
B is burstiness of packet flow ($B \geq 1$)

N_{Pkt} is average packet length

Measuring router power

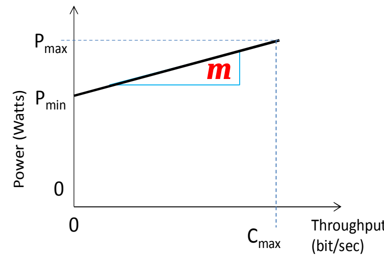


Power vs. Throughput



Source: Vishwanath et al. 2013

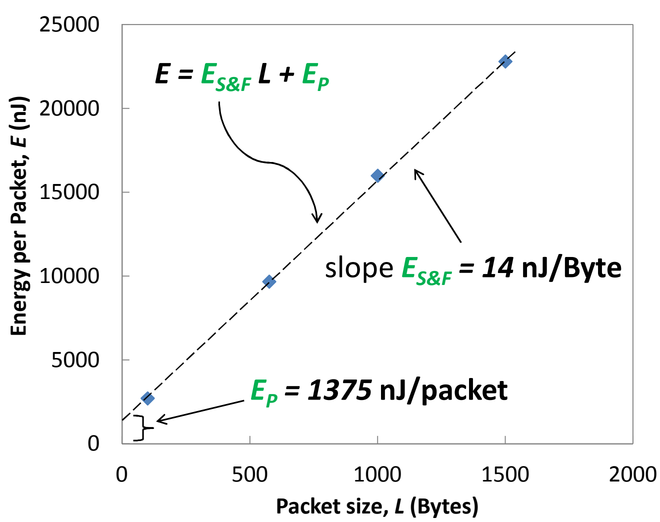
Remember



- Linear fit provides a good approximation
- Slopes represent the additional energy required to handle each packet
- Slope depends on packet size

37

Energy vs packet size



Source: Vishwanath et al. 2013

38

Linear power model

- Measurements show power equation is:

$$P = P_{min} + EC = P_{min} + R\,\underbrace{(E_{S\&F} + E_P/L)\,/8}_{\text{Incremental energy per bit } = m}$$

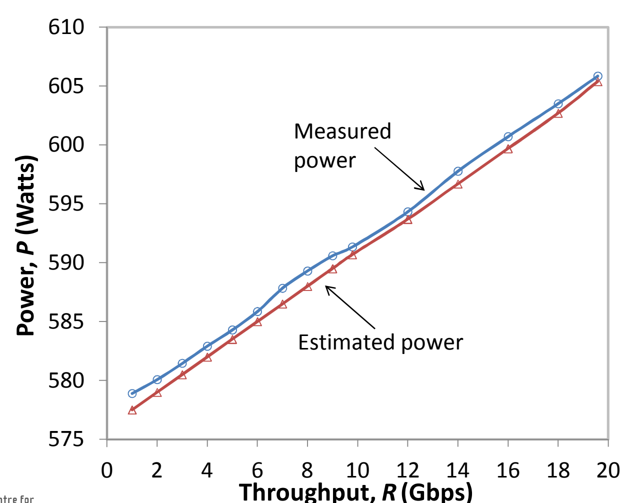
P_{min} Idle power of the router (W)
R Throughput (Gbps)
$E_{S\&F}$ Store and forward energy (J/byte)
E_P Processing energy (J/packet)
L Packet size (Bytes)

Incremental energy per bit = m

- Measurements determine equipment constants $E_{S\&F}$ and E_P

Validation of power model

Validated with random IP traffic



Experimental results

Device	P_{idle} (W)	E_P (nJ/byte)	$E_{S\&F}$ (nJ/byte)
Enterprise Ethernet Switch	36.2	40	0.28
Edge Ethernet Switch	631	1571	9.4
Metro IP Router	352	1375	14.4
Edge IP Router	576	1707	10.2

For multi-port network elements with multiple flows

$$P\left(\sum_{j}^{flows} R_{Pkt,j}\right) = \sum_{k}^{parts} P_{min,k} + \sum_{j}^{flows}\sum_{k}^{parts}\left(E_{Proc,k} + N_{Pkt,j}E_{S\&F,k}\right)R_{Pkt,j}$$

$P_{min,k}$ = *k*-th part idle power , $E_{proc,k}$ = packet processing energy,
$E_{S\&F,k}$ = *k*-th part per-bit store & forward energy,
$R_{Pkt,j}$ = *j*-th flow packet rate, $N_{Pkt,j}$= *j*-th flow mean packet length

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Configuration, protocol & traffic type

Power depends on router configuration and traffic details

$$P = P_{min} + \left(E_{Proc} + E_{S\&F}N_{Pkt}\right)R_{Pkt}(t)$$

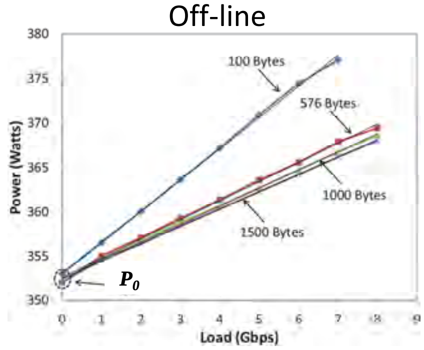
- P_{min} depends on router/switch configuration
  - Number line cards, ports, chassis
  - Switching & buffering technology
- E_{Proc} depends on router/switch & protocol
  - IPv4, IPv6, MPLS, Ethernet
- $E_{S\&F}$ depends on router/switch & buffering technology
- N_{Pkt} & R_{Pkt} depend on traffic type
  - Video, VOIP, M2M, Web, etc

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

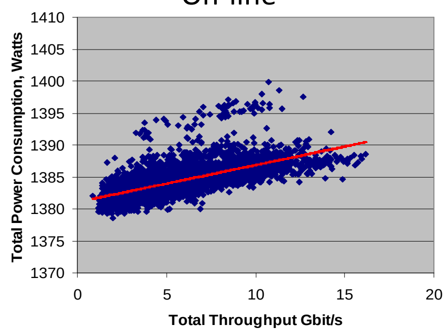
Traffic dependence

- Different traffic types have different values of N_{Pkt} & R_{Pkt}
  - Off-line measurement will give explicit slopes
    - Control over N_{Pkt} and R_{Pkt}
  - On-line measurement will give a "blob"

Off-line



On-line



Source: Vishwanath et al. 2013

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

43

9. Equipment "energy/bit" metrics

- Differential: dP/dC

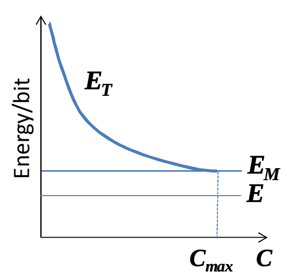
$$dP/dC = d\left(P_{min} + EC\right)/dC = E$$

E is the incremental energy per bit
  - Misses P_{min} as energy efficiency metric

- Energy per bit at max load:

$$E_M = P_{max}/C_{max}$$

  - Easier to extract from equipment data sheets
  - Inaccurate below maximum capacity



- Energy per bit at actual load:

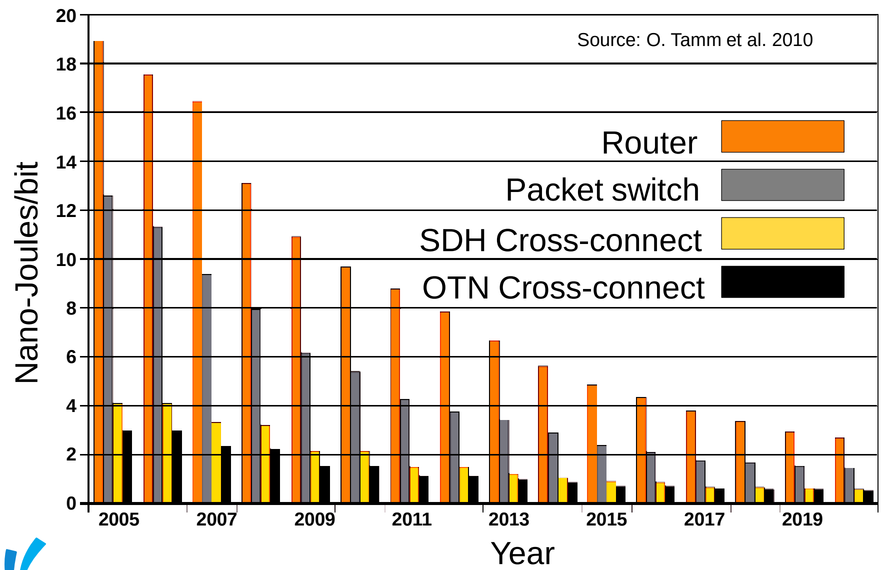
$$E_T = \frac{P(C)}{C} = \frac{P_{min}}{C} + E$$

Larger at low throughput

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

44

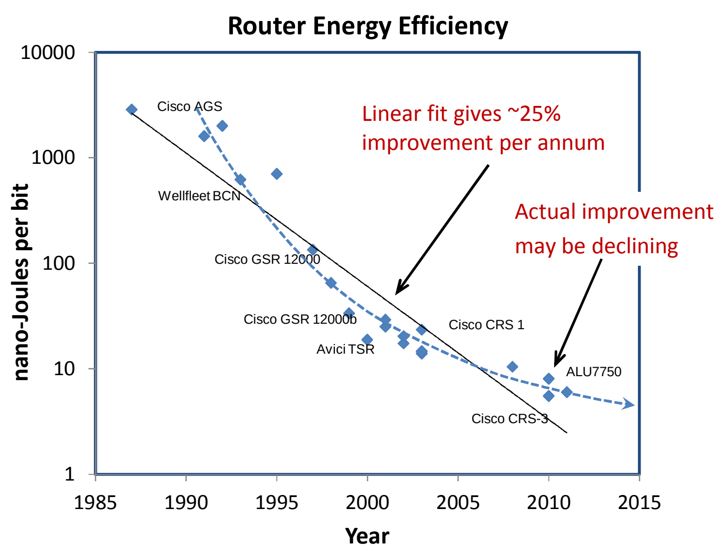
10. Power consumption trends



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

45

Router energy consumption trends

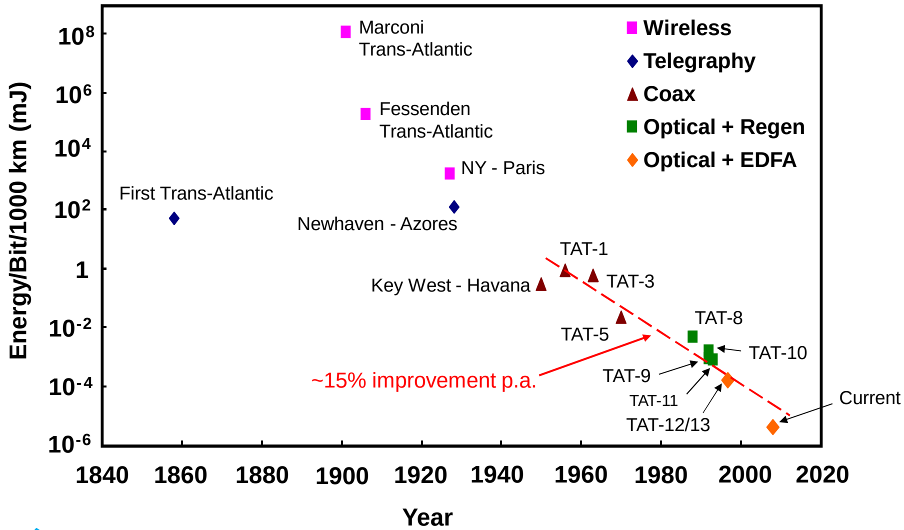


Nielsen, ECOC 2011

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

46

Transport energy consumption trends

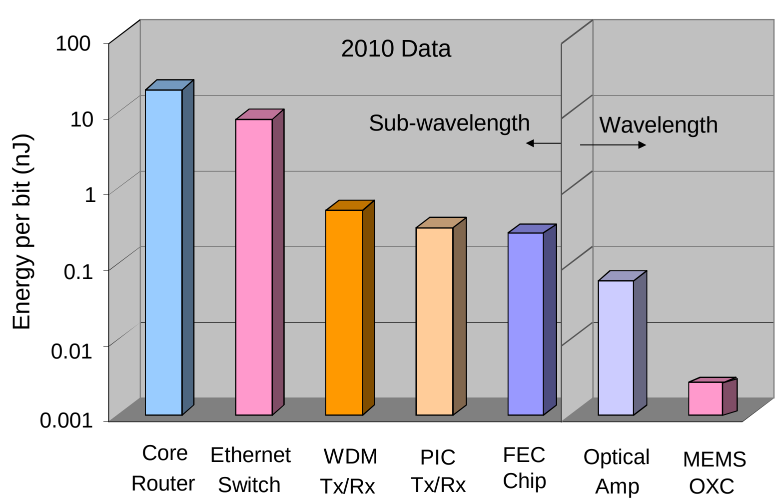


Tucker, JSTQE 2011

CEET centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

47

Electronic & optical network elements

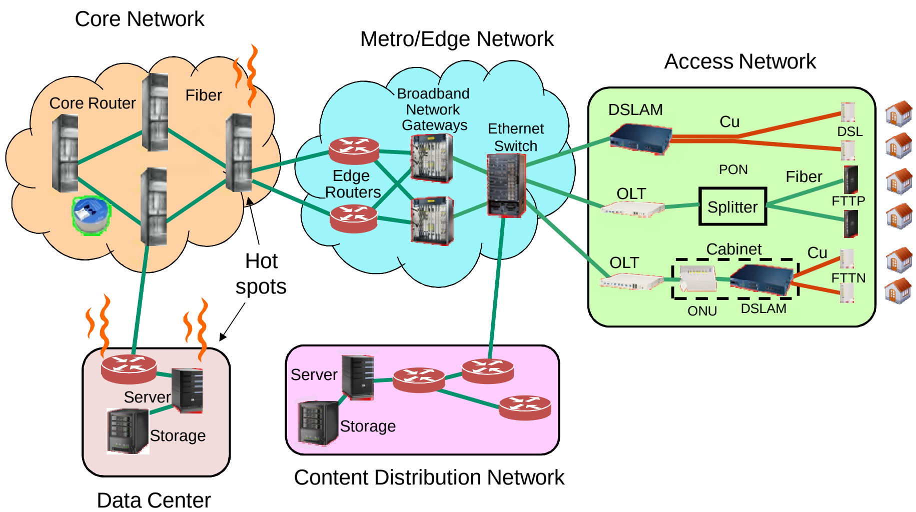


Tucker et al., 2010

CEET centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

48

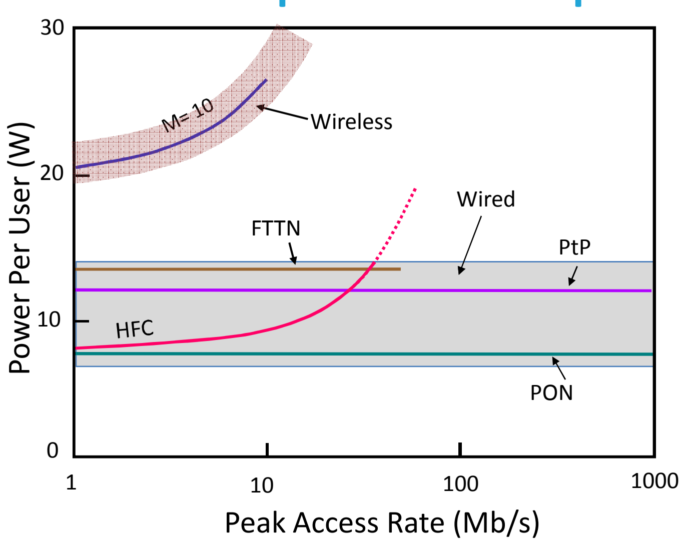
11. Network power consumption



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

49

Access network power consumption



Source: Baliga et al: OFC 2008

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

50

Power consumption in access networks

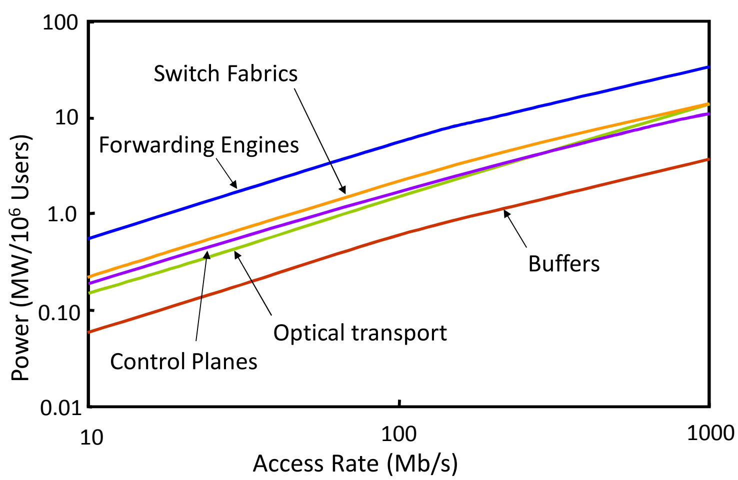
- Mobile access requires most power as access rates increase
  - Dominated by base station power
- Copper & fibre consume similar power per user
  - Copper has limited access speed compared to fibre
- Fibre provides most energy efficient access at higher data rates
- Technology improvements are unlikely to change these outcomes

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

51

Core network power consumption

Dominated by router forwarding engines

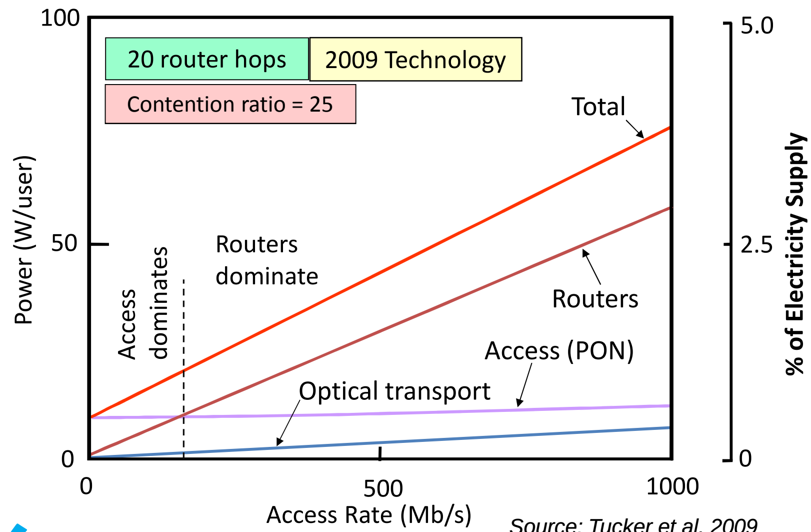


Source: Baliga et al. 2007

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

52

Internet power per user



Source: Tucker et al. 2009

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

53

Core network power consumption

- Today, Internet power consumption is dominated by the access network
  - Home DSL modem, ONU, cable modem
  - Access power consumption is not shared by many users

If we don't migrate to wireless access

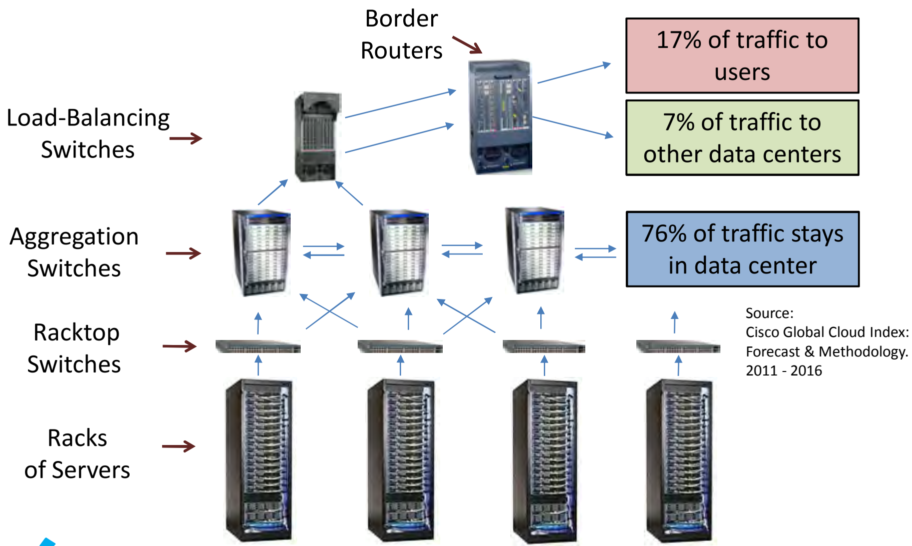
- As access speeds increase the core will come to dominate Internet power consumption
  - Aggregation of growing local traffic will produce an avalanche of traffic in the core
- As access speeds increase IP routers will dominate Internet core power consumption

If we do migrate to wireless access it will dominate network power consumption

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

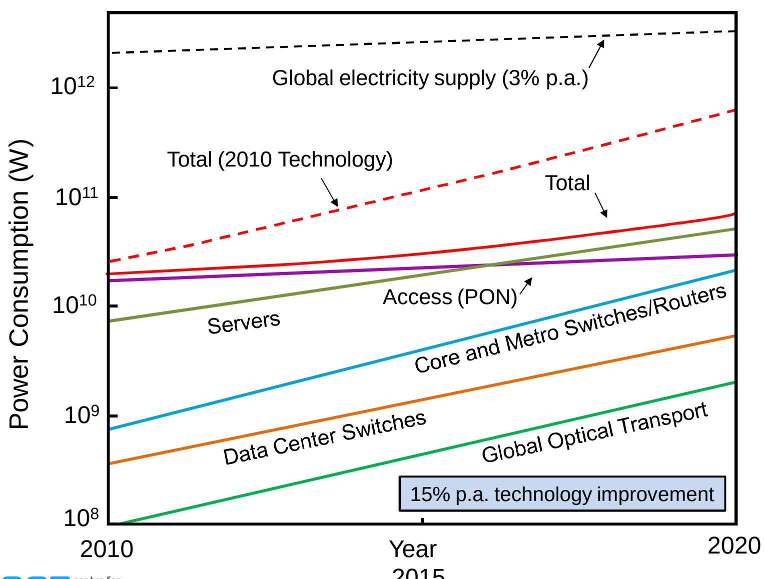
54

Data centers and content servers



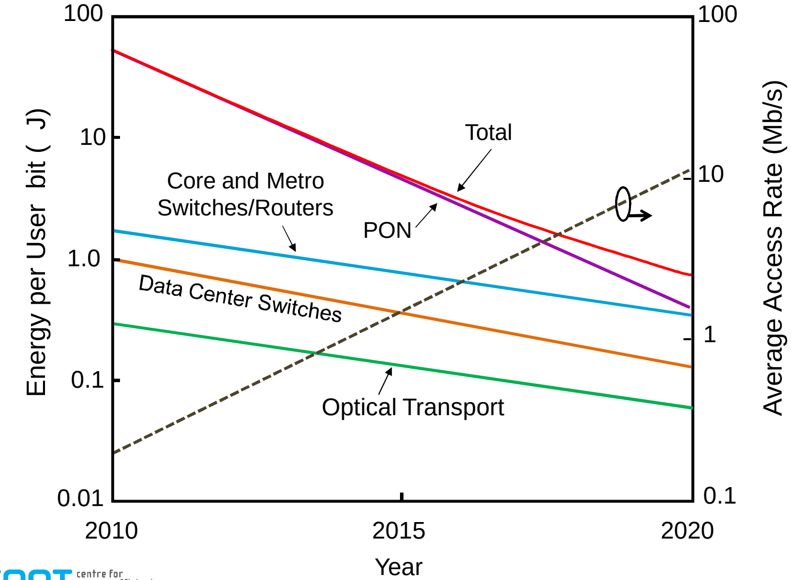
55

Power consumption of the global Internet



56

Network energy per user bit



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

57

12. Improving energy efficiency

GreenTouch

Case study: GreenTouch 1000x efficiency improvement

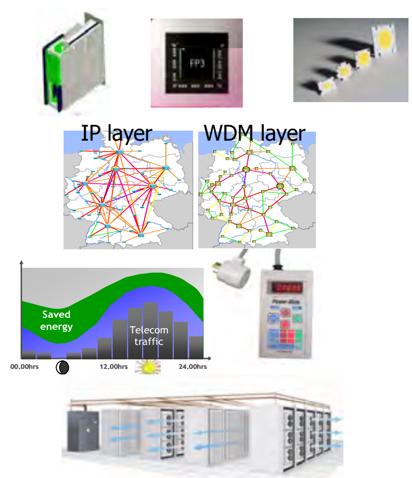
Multi-disciplinary approach

Components and Hardware

Network Architecture & Protocols

Equipment Management and Control

Thermal Management



Source: www.greentouch.org, 2013

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

58

GreenTouch GreenMeter

- Compares network energy efficiency
  - 2020 relative to 2010 using
    - Total Group 1 nation traffic
    - Best deployed technology in 2010
    - GreenTouch technologies in 2020
  - Network segments
    - Wireless access
    - Wireline access
    - Metro/Core

$$\textbf{\textit{Efficiency improvement}}_{Segment} = \frac{\bar{E}(2020, 1\,\textbf{\textit{year}})_{Segment}}{\bar{E}(2010, 1\,\textbf{\textit{year}})_{Segment}}$$

Source: www.greentouch.org, 2013

Traffic 2010 & 2020

- Cisco data & GreenTouch projections
  - Focus on "mature market" in developed nations
    - Slower growth than developing markets

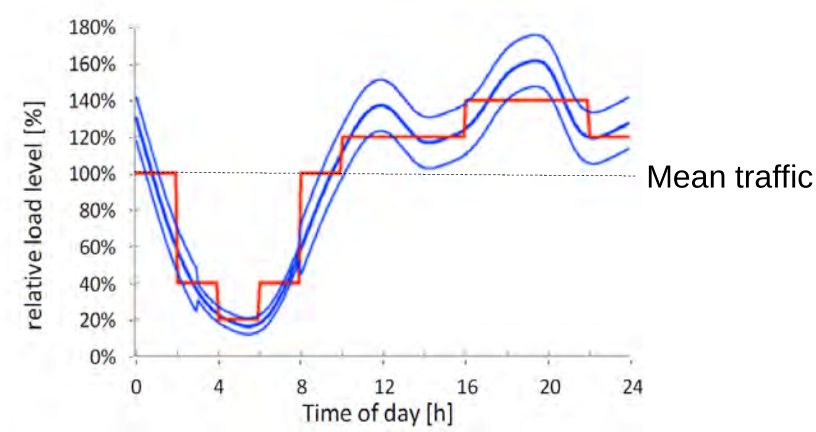
Mature Market Traffic Projections (PB/month)			
YEAR	Mobile Access	Wireline Access	Core Network
2010	161	7,727	10,707
2015	3,858	33,879	45,402
2020	14,266	74,462	103,085
2020/2010	89x	9.6x	9.6x

Source: www.greentouch.org, 2013

Traffic diurnal cycle

GreenTouch

- Daily variation in traffic offers energy savings opportunities



Source: *www.greentouch.org, 2013*

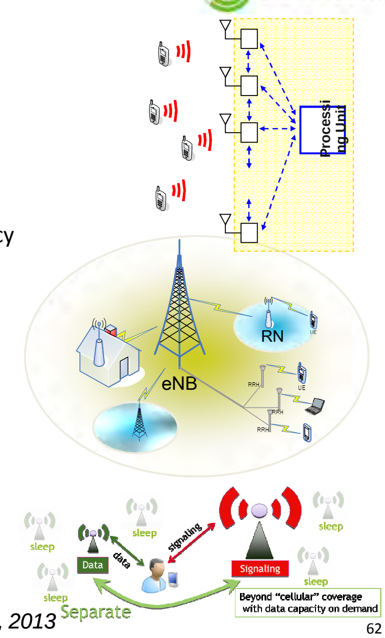
centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

61

Mobile access segment

GreenTouch

- Green Air Interface
  - Large Scale Antenna Systems (LSAS)
  - Very High Bandwidth
  - Bandwidth and Capacity Adaptation
- Network Architecture & Mgmt
  - Dynamic Management for Energy Efficiency
  - Small Cells
  - Beyond Cellular Green Generation (BCG)
  - Energy efficient C-RAN
  - Energy Efficiency Evaluation Framework
- Base Station Hardware
  - Ultra Low-Power Base-Station on a Chip
  - Load Adaptive Transceivers
  - High Efficiency RF-Power Amplifiers
  - Green Transmission Technologies



centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Source: *www.greentouch.org, 2013*

62

Mobile access gains

- Energy efficiency improvements for different topography & time of day

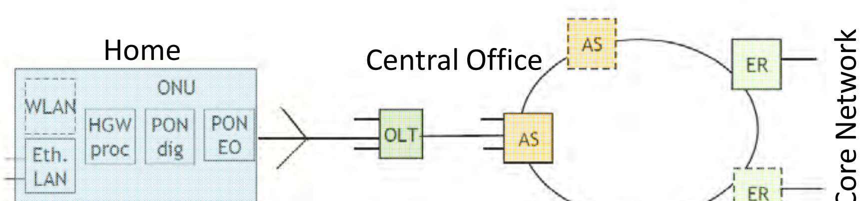
$E_{A,L}/T_{A,L}$	Night	Morning	Average	High	Busy Hour
[J/kbit]			2010		
DU	11.8	5.9	2.4	2.0	1.7
U	32.7	16.4	6.5	5.4	4.6
SU	35.2	18.2	7.3	6.0	5.1
RU	62.7	32.1	12.6	10.4	9.0
[J/Mbit]			2020		
DU	9.0	4.9	2.4	2.2	1.9
U	20.9	12.1	7.2	6.6	6.3
SU	23.9	13.5	7.7	7.5	7.0
RU	36.2	20.1	10.1	9.1	8.4

0.001 x

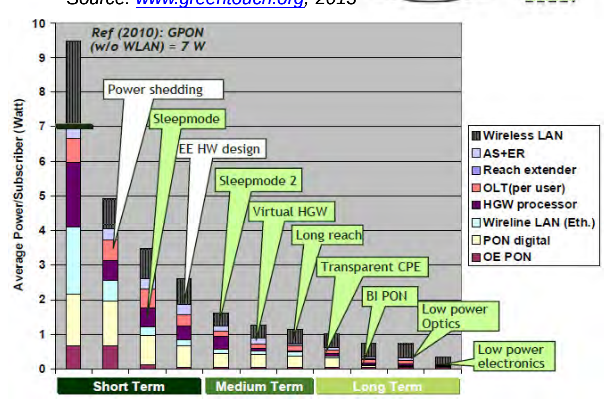
Source: www.greentouch.org, 2013

63

Wire-line access segment



Source: www.greentouch.org, 2013



64

Wire-line access gains

GreenTouch

Energy-saving approach	Gain factor	Subsystems affected
Power shedding	2.4x	Home gateway (HGW) processor, Ethernet LAN
Sleep mode (1 and 2)	2x	Electro-optics PON, PON digital, Ethernet LAN, OLT
Energy-efficient hardware (HW) design	1.2x	All hardware
Virtual HGW	5x	HGW processor
Long reach	2x	Edge router (ER), aggregation switch (AS) and OLT
Transparent CPE	2x	Ethernet LAN
Bi-PON protocol	10x	PON digital
Low-power optics	1.5x	EO PON, Reach extender
Low-power electronics	3x	All digital electronics
Moore's law for CMOS 2010-2020	2.6x	All digital electronics

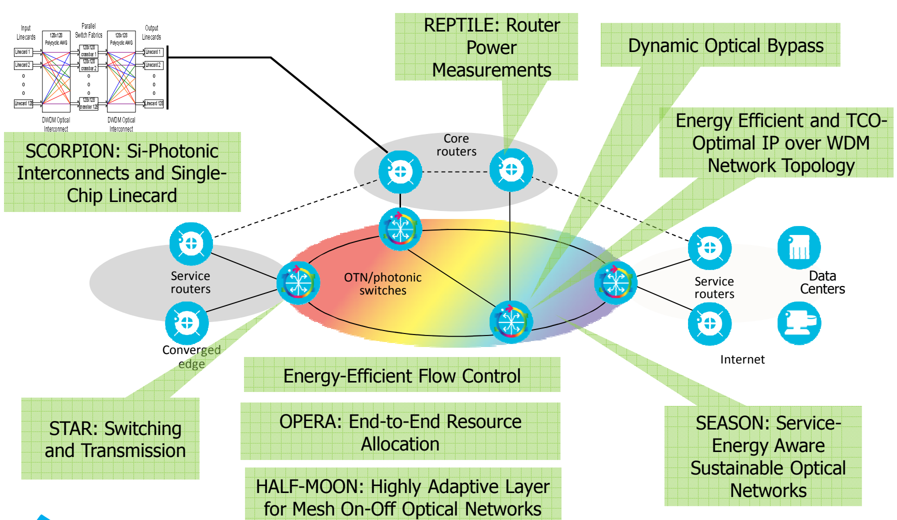
ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Source: www.greentouch.org, 2013

Core network segment

GreenTouch

- Based on NSFNet architecture



ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Source: www.greentouch.org, 2013

Core network gains

Source: www.greentouch.org, 2013

GreenTouch

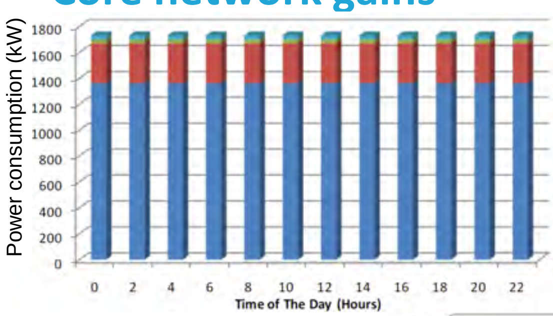
Device	Power Consumption 2010	Power Consumption 2020
Router Port	440 W	16 W
Transponder 40Gb/s	148 W, 2500 km reach	5.5 W, 2500 km reach
Transponder 100 Gb/s	Not widely deployed in field	6.4 W, 2000 km reach
Transponder 400 Gb/s	Not deployed In field	7.2 W, 150 km reach
Regenerator 40 Gb/s	22.2 W	8.25 W
Regenerator 100 Gb/s	Not widely deployed in field	9.6 W
Regenerator 400 Gb/s	Not deployed in field	10.8 W
EDFA	52 W	12.5 W
Optical switch	85 W	8.5 W

Technology	Energy Efficiency Improvement Factor
Improved components with lower power consumption	27
Mixed line rates (MLR)	1.2
Optical bypass, sleep and low-energy state modes	1.8
Physical topology optimization	1.1
Overall efficiency improvement	64

67

Core network gains

GreenTouch



2010 technologies

Regenerators

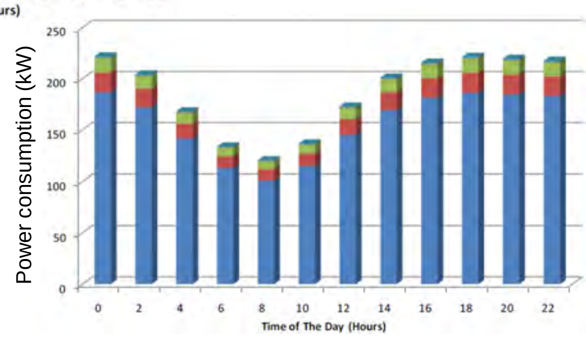
Optical switches

EDFAs

Transponders

Routers

2020 GreenTouch



Source: www.greentouch.org, 2013

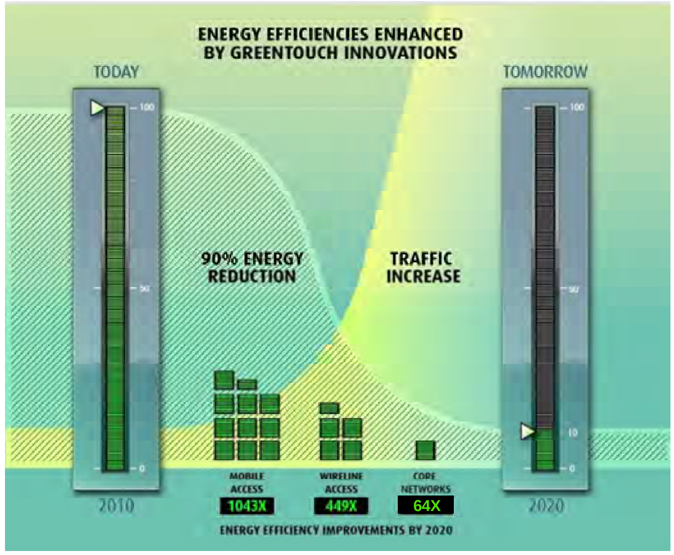
ceet centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

GreenMeter results

2020 relative to 2010

Traffic growth:
- 100 x in mobile
- 10 x in wireline
- 10 x in core

Energy:
- 0.1 x energy
- 90% reduction in network power

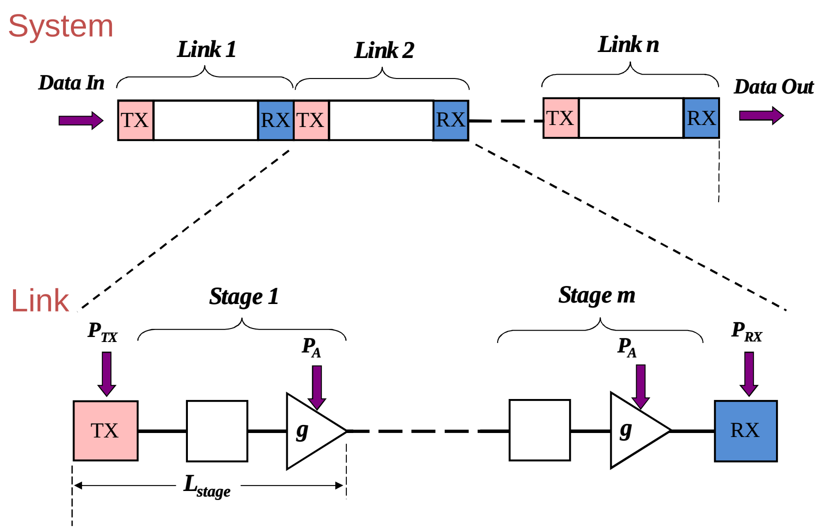


Source: www.greentouch.org, 2013

13. Network energy: how low can we go?

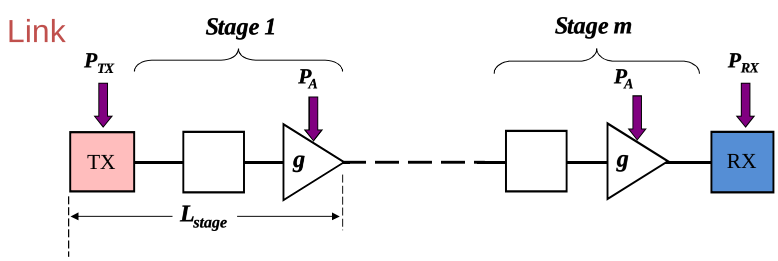
- Energy efficiency is ultimately constrained by the technologies available:
  - Laser diodes, modulators, fibre, EDFAs, CMOS, etc
- And by universal laws:
  - Shannon limit, quantum mechanics, thermodynamics, etc
- Each presents a lower limit to energy consumption
- Need to understand these lower limits
  - What are the key contributor to these limits?
  - How far are we from them?
  - What prevents us from attaining them?

Fundamental limits on transport energy



71

Lower bound on energy per bit

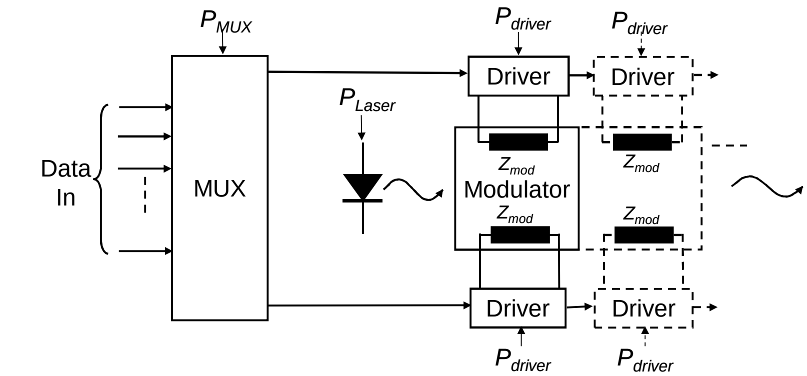


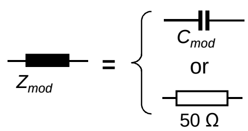
$$E_{AMP-min} = \sum \frac{P_A}{B_r} \simeq \frac{SNR_{bit}\, m^2 e^{L_{stage}} h}{B_r}$$

Bit Rate

72

Optical transmitter



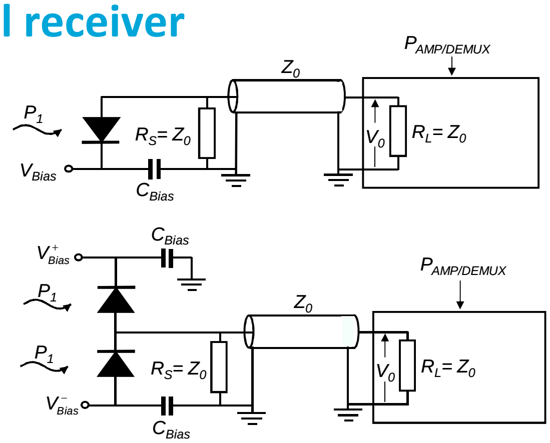


Lumped modulator $E = \frac{1}{2} C_{mod} V_{mod}^2$

Distributed modulator $E = \frac{V_{mod}^2}{50 B_r}$

~ 1 pJ

Optical receiver



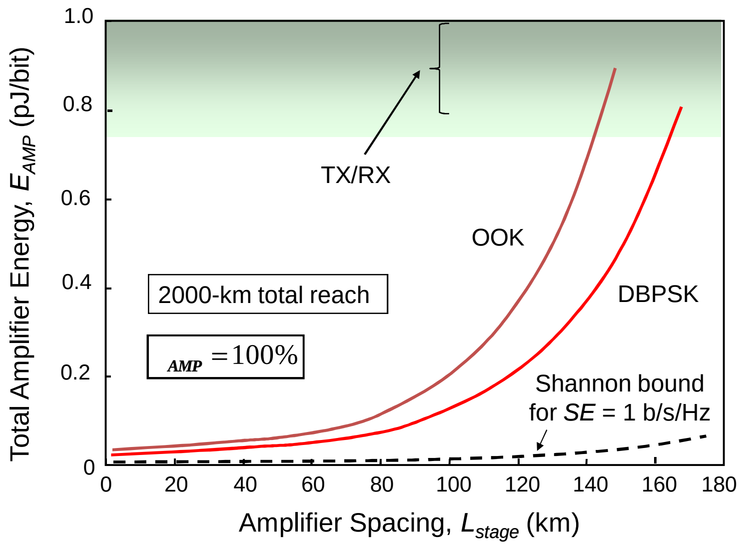
$$P_{total} = P_{Bias} + P_{preamp} = \frac{V_0^{p-p}}{Z_0}\left[V_{Bias} + \frac{1}{\Re_{preamp}} \right]$$

E ~ 500 fJ @ 100 Gb/s

Quantum efficiency

Responsivity

Lower bound on energy per bit

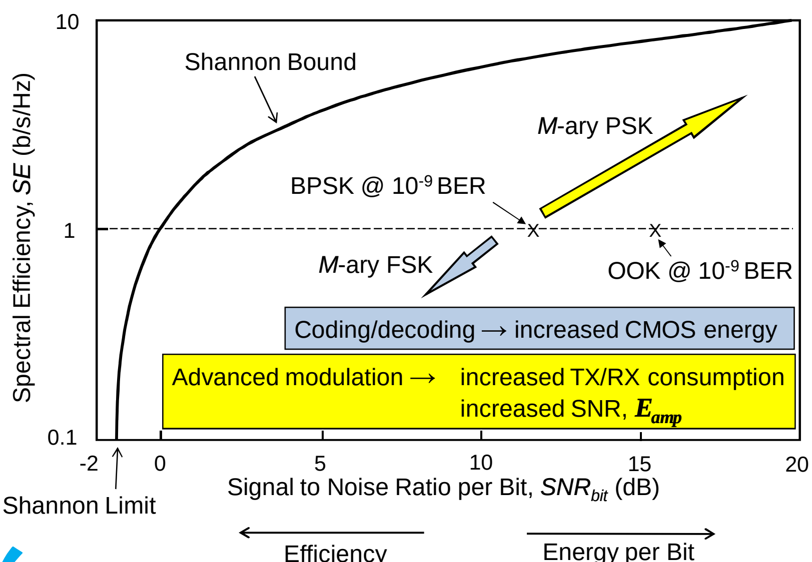


centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Tucker, JSTQE 2011

75

Shannon bound

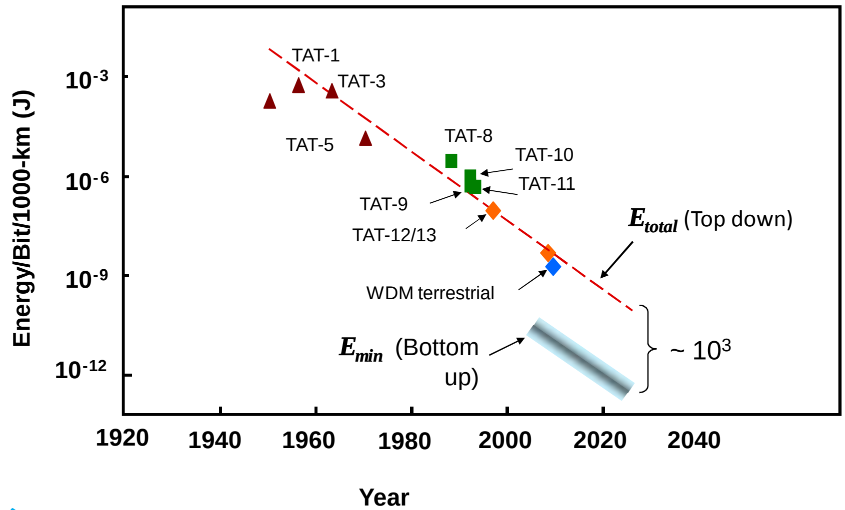


centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Tucker, JSTQE 2011

76

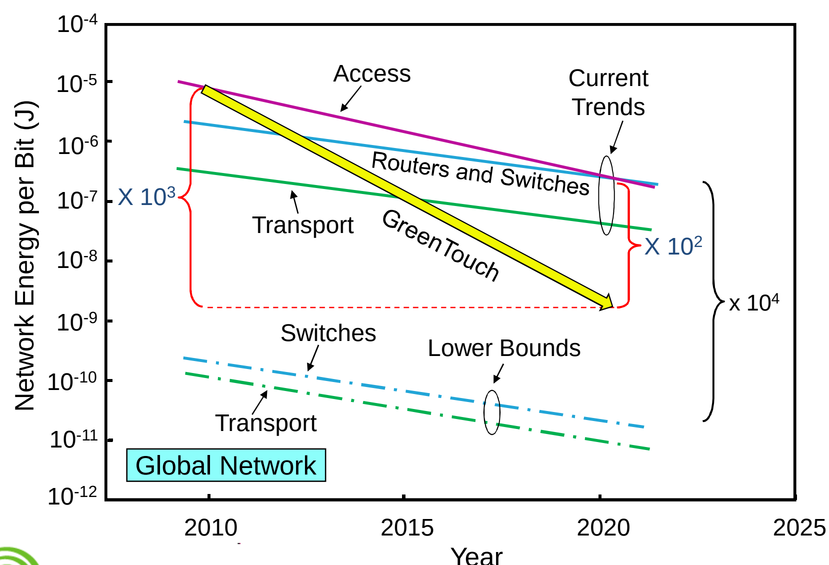
Energy per bit per 1000 km



Tucker, JSTQE 2011

77

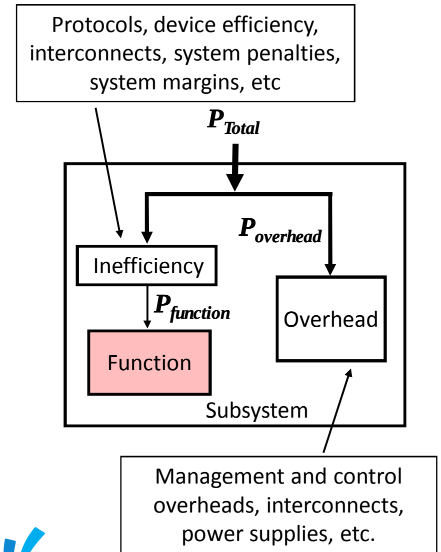
Gap between theory and practice

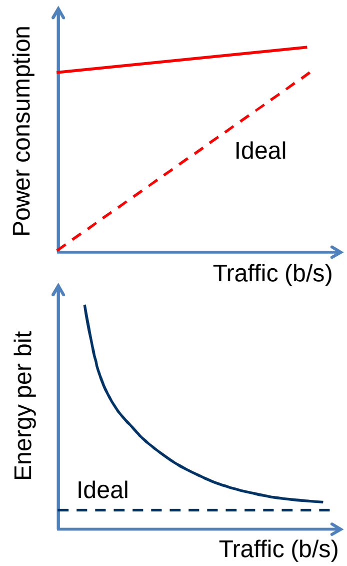


Tucker, JSTQE 2011

78

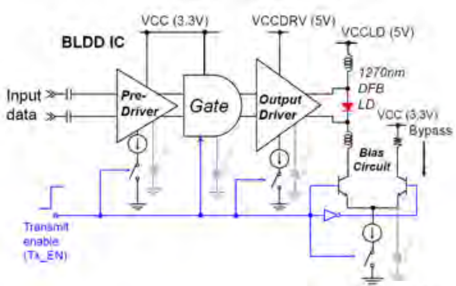
Gap between theory and practice





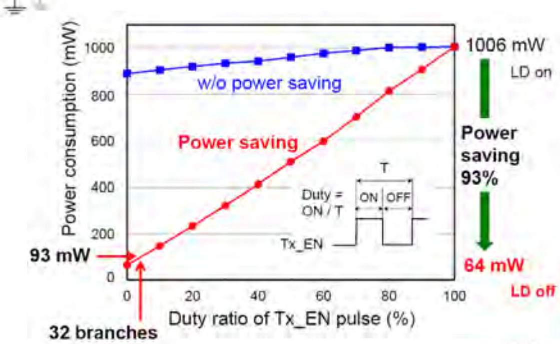
79

B. Low-energy circuit design



Koizumi et al., ECOC 2012 :
Low-power PON burst-mode laser driver

- Driver turned off between bursts
- Power reduced by 93%



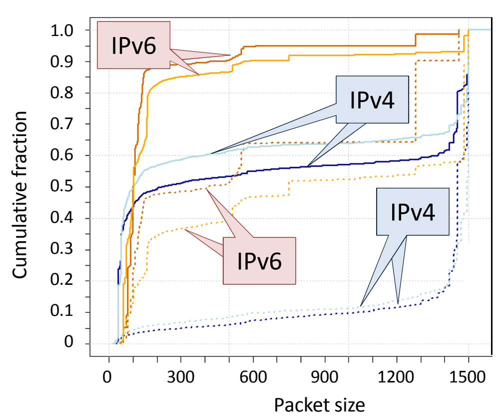
C. Protocols

- Service transactions and protocols
- Efficiency of multi-layer protocol suite
- XGPON framing
- Sleep and standby states
- Energy-efficient Ethernet
- Dynamic rate adaption

Packet size: IPv4 & IPv6

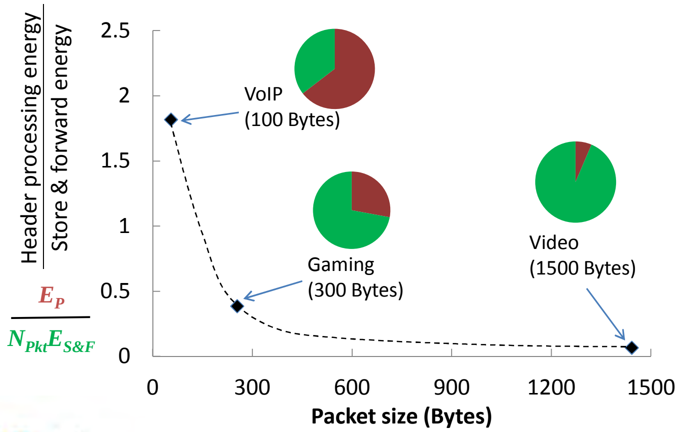
Packet size cumulative fraction for several IP routers:

- High occurrence of small packets reduces energy efficiency
  - Low efficiency for M2M, VOIP



Packet sizes & services

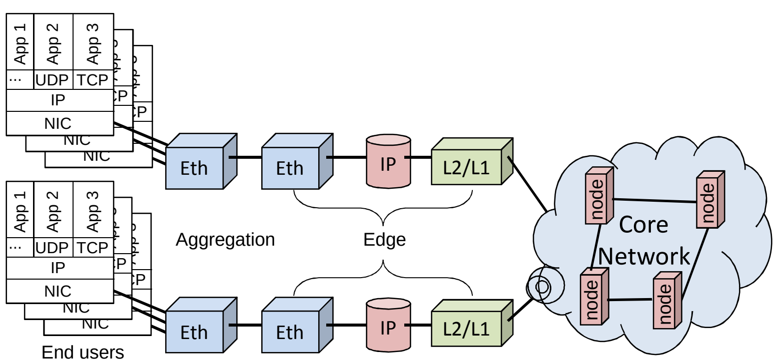
Per byte store and forward energy $E_{S\&F}$	14 nJ
Per packet processing energy E_p	1375 nJ



95

Transport & protocols

Protocols are used to transport service traffic through the network



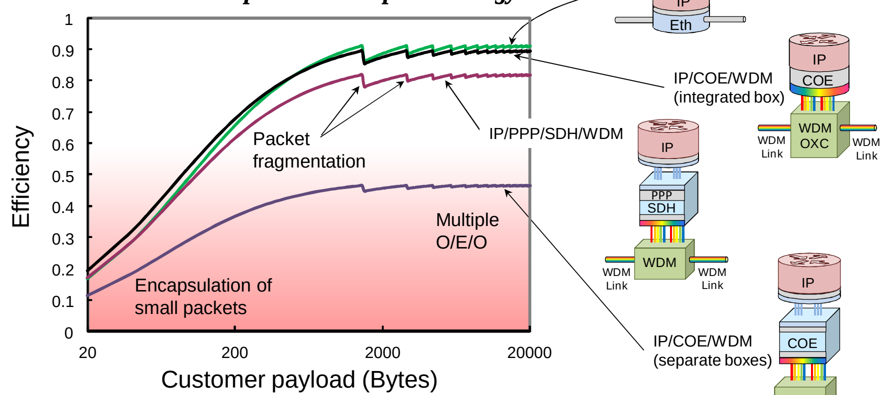
Source: Zhong et al., OFC 2012

96

Efficiency of multi-layer protocol suite

Combining boxes for multi-layer protocol suites can improve efficiency

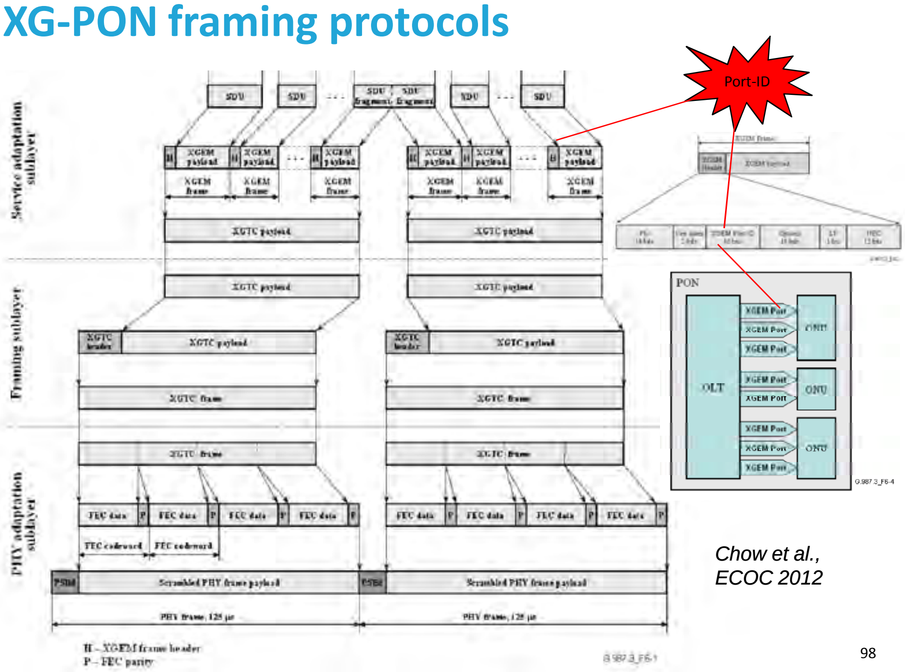
$$\textit{Efficiency} = \frac{\textit{Customer payload} \quad \textit{IP layer energy}}{\textit{Total multi-protocol suite packet energy}}$$



Source: Zhong et al., OFC 2012

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

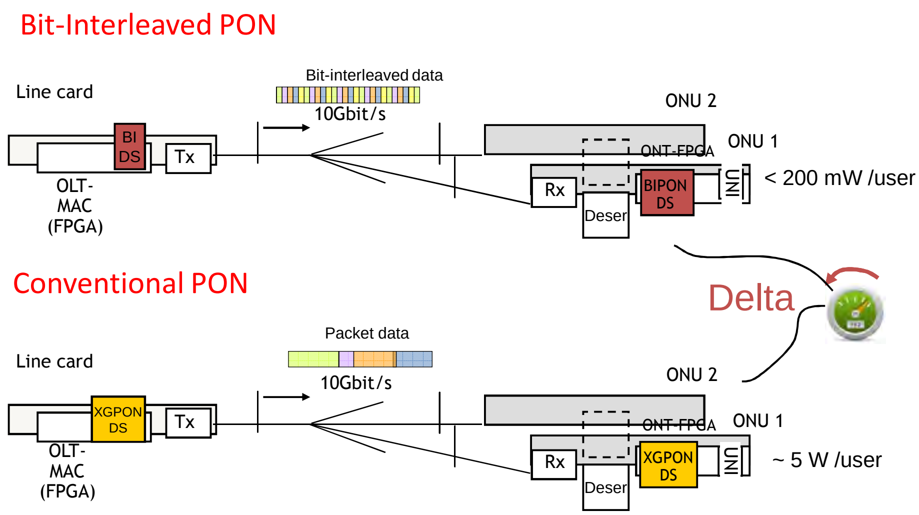
XG-PON framing protocols



Chow et al., ECOC 2012

Solution: BiPON

GreenTouch



Bell Labs

INTEC design

orange

Chow et al., ECOC 2012

Energy-efficient protocols

- Sleep & standby states
  - Network devices enter low power state when not in use
  - Can apply to systems and sub-systems
  - Need to ensure network presence is retained
    - Use Network Connection Proxy with sleep protocol
  - Need to account for state transition energy and time
  - May have multiple lower energy states
- IEEE Energy Efficient Ethernet (802.3az)
  - Low power idle mode when no packets are being sent
  - Approved Sept. 2010
  - Currently applies to copper interface only; not optical

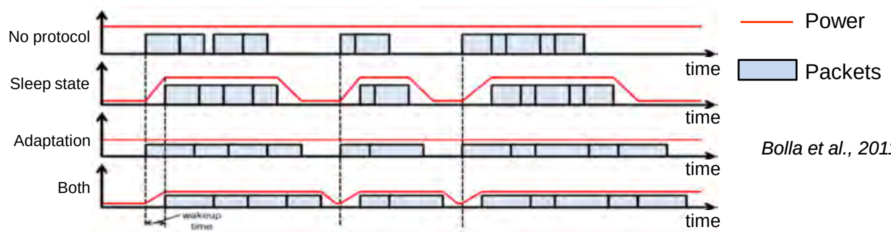
ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Energy-efficient protocols

- Dynamic rate adaptation
  - Modify capacity of network devices in response to traffic demands
  - Change clock frequency, processor voltage

$$Power = C \times Voltage^2 \times Frequency$$

  - Slower speed to reduce power consumption
  - Need to allow transition time between rates
- Dynamic rate adaptation and standby states can be combined



Bolla et al., 2011

101

Case study 1. The cloud

- Cloud services widely promoted as greener than on-site facilities:
  - Cloud Computing – The IT Solution for the 21st Century
    - *Carbon Disclosure Project Study 2011*
  - Salesforce.com & the Environment
    - *WSP Environment & Energy 2011*
- Strong case for enterprise private cloud
- What about the public cloud?
  - Apple iCloud
  - Google drive
  - Microsoft sky drive

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

115

Promoting the Cloud

iCloud

- "automatically and wirelessly store your content"
- "your devices are wirelessly updated almost instantly"

Google

- "everywhere you are"
- "wherever you are, your stuff is just...there."
- "Ready to go, ready to share"

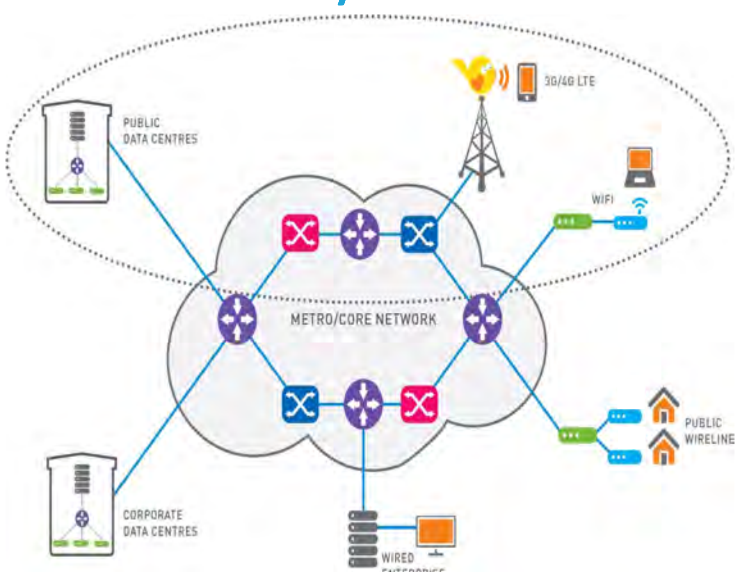
SkyDrive

- "Store anything"
- "it's automatically available"
- "no syncing or cables needed"

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

116

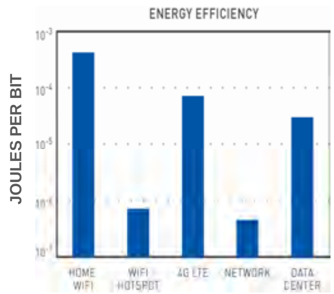
Cloud services eco-system

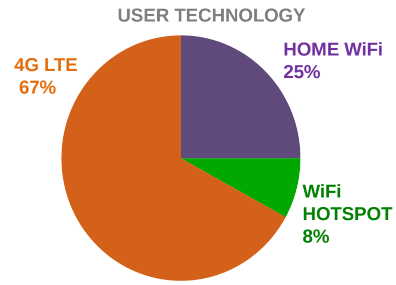


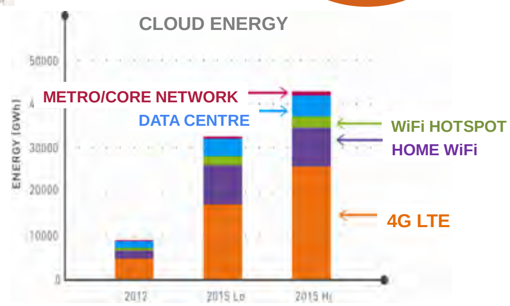
ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

117

1.a) Wireless cloud energy trends





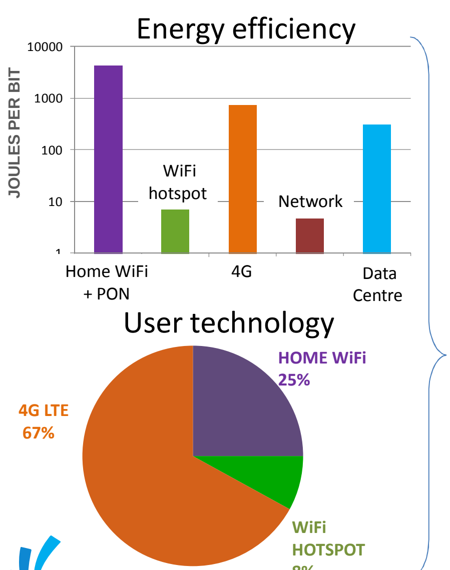


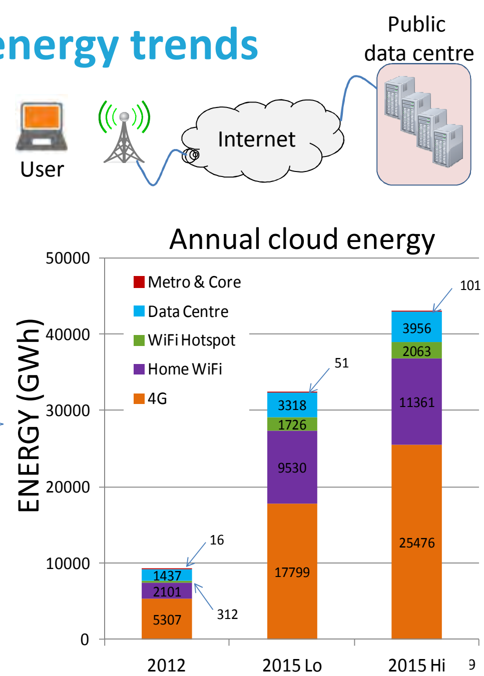
Source: www.ceet.unimelb.edu.au 2013

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

118

1.a) Wireless cloud energy trends



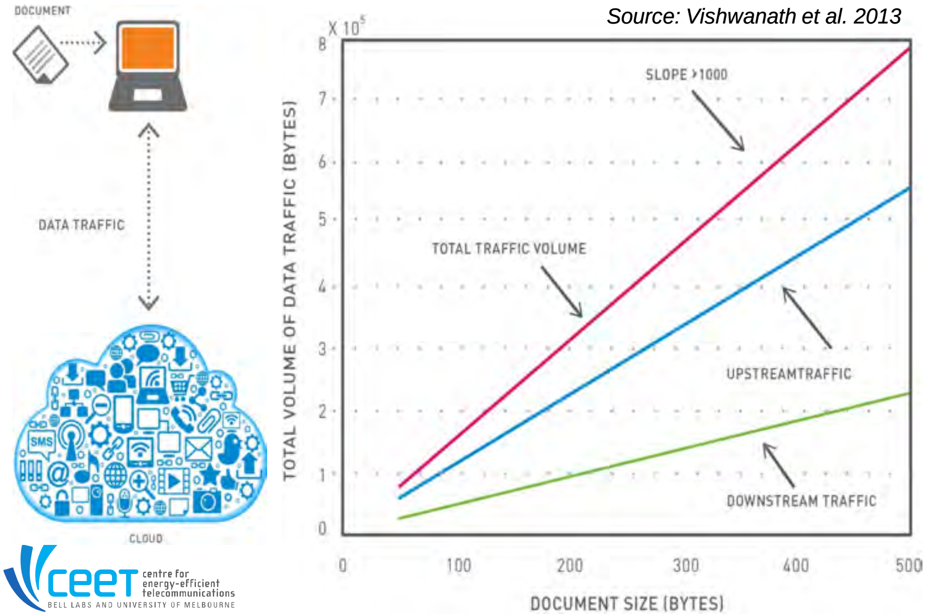


centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

9

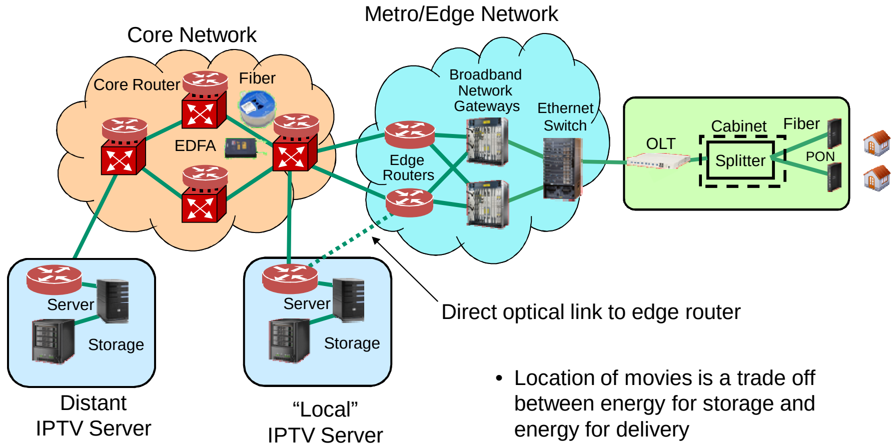
1.b) Interactive cloud services

Source: Vishwanath et al. 2013



ceet centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

Case study 2. Content distribution: IPTV

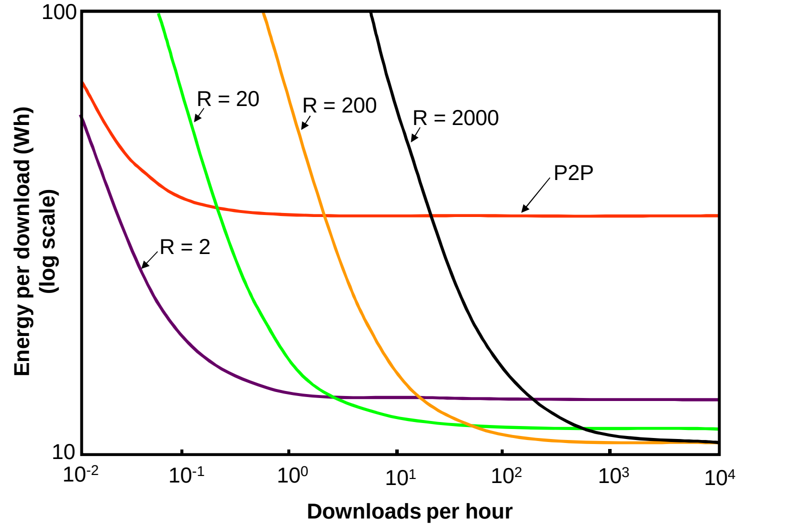


- Location of movies is a trade off between energy for storage and energy for delivery
- Each movie is replicated on R servers throughout the network

ceet centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

121

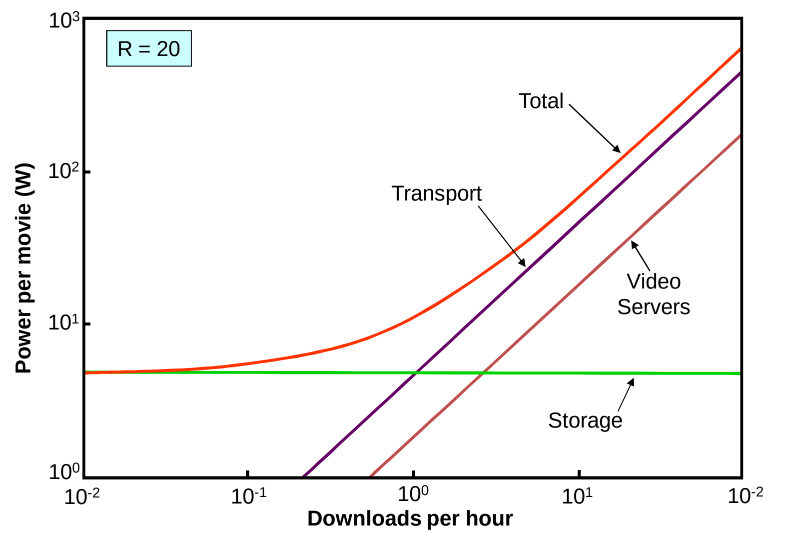
IPTV over the public Internet



Baliga et al., OFC, 2009

122

IPTV over the public Internet



Baliga et al., OFC, 2009

123

Case study 3. The Internet of Things

- Forecasts:
  - Infonetics: 428 million embedded M2M connections by 2014
  - Analysys Mason: 2.1 billion M2M connections by 2020
  - Ericsson: 50 billion M2M connections by 2020
  - Wireless World Research Forum: 7 trillion wireless devices by 2020
- Billions of gateways
  - Always on, wireless connection Things
- IPv6 with small packets (<80 bytes)
  - Energy inefficient
- Initially a low data rate but expected to increase
- Things expected to become increasingly intelligent
  - Most processing in the gateways

15. Global activities in green networking

- GreenTouch
  - A consortium of leading Information and Communications Technology (ICT) industry, academic and non-governmental research experts dedicated to fundamentally transforming communications and data networks, including the Internet, and significantly reducing the carbon footprint of ICT devices, platforms and networks.
  - www.greentouch.org
- GreenGrid
  - Non-profit, open industry consortium of end-users, policy-makers, technology providers, facility architects, and utility companies collaborating to improve the resource efficiency of data centers and business computing ecosystems.
  - www.thegreengrid.org

Global activities in green networking

- Climate Savers Computing
  - By improving energy efficiency of PCs and servers and encouraging the use of power management tools, Climate Savers Computing aims to reduce green house gas emissions by 54 million tons by 2010.
  - www.climatesaverscomputing.org
- GeSI
  - Create an open and global forum for the improvement and promotion of products, services and access to ICT for the benefit of human development and sustainable development
  - www.gesi.org

126

Global activities in green networking

- ITU
  - ITU-T & Climate Change
  - www.itu.int/ITU-T/climatechange/
  - **Dynamic Coalition on Internet and Climate Change (DCICC)** : an open body committed to moderating the environmental impact of the Internet, to seeking new ways to embrace the power of the Internet for reducing greenhouse gas emissions worldwide, and to enabling transformation in line with the objectives set and to be set under the United Nations Framework Convention on Climate Change (UNFCCC).
  - **Coalition on ICTs and Climate Change** is an initiative that aims at bringing together in an informal group a selection of the key actors working on the field of ICTs and climate change. Initiated by the International Telecommunication Union (**ITU**) and the Global e-Sustainability Initiative (**GeSI**) the coalition is a response to a call for a united ICT voice on the virtues of ICT in combating climate change.

127

Global activities in green networking

- Telecommunications Industry Association (TIA)
  - **Energy and environment policy program** runs a sustained advocacy campaign with key government officials asserting the role of the ICT industry in achieving national green goals through improving energy efficiency and decreasing carbon emissions.
  - www.tiaonline.org/environment/

Appendix

- The network power results calculated in this slide back are based on the typical network parameters given below.
- These values are indicative only
- As newer generations of equipment become available their values will change

Typical access network parameters

	P_{TU} (kW)	N_{TU}	P_{RN} (W)	N_{RN}	P_{CPE} (W)	Tech. Limit (Mb/s)	Capacity per user
ASDL	1.7	1008	N/A	N/A	5	15	2 Mb/s
HFC	0.62	480	571	120	6.5	100	0.3 Mb/s
PON	1.34	1024	0	32	5	2400	16 Mb/s
FTTN	0.47	1792	47	16	10	50	2 Mb/s
PtP	0.47	110	N/A	N/A	4	1000	55 Mb/s
WiMax	0.47	24400	1330	420	5	22	0.25 Mb/s
UMTS	0.47	15300	1500	264	2	20	0.25 Mb/s

$$P_{access} = PC\frac{P_{TU}}{N_{TU}} + \frac{P_{RN}}{N_{RN}} + P_{CPE}$$

Source: Baliga et al. IEEE Comms Mag. 2011

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Typical core network parameters

Device	Capacity (C_{max})	Power (W) (P_{max})	Efficiency (P_{max}/C_{max})	Equipment
Core IP router	640 Gb/s	10900	17 nJ/bit	Cisco CRS-1
IP router line card	10 Gb/s	150	15 nJ/bit	Cisco CRS-1, STM-256c POS, 4xSTM-64c POS,
IP router chassis (single shelf)	N/A	10920	N/A	Max. Power, fully configured
Edge router	160 Gb/s	4210	26.5 nJ/bit	Cisco 12816
Border Network Gateway	8 Gb/s	1100	137.5 nJ/bit	Cisco 10008
Ethernet switch (small)	64 Gb/s	474	7.4 nJ/bit	Cisco 4503
Ethernet switch	380 Gb/s	3200	8.4 nJ/bit	Cisco 6513
ROADM	N/A	8	0.025 nJ/bit (40G channels)	Transmode 1x8 ROADM
MPLS switch	15.5 Tb/s	20000*	1.3 nJ/bit	Juniper PTX-9000

*Power supply rating. Actual is less

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

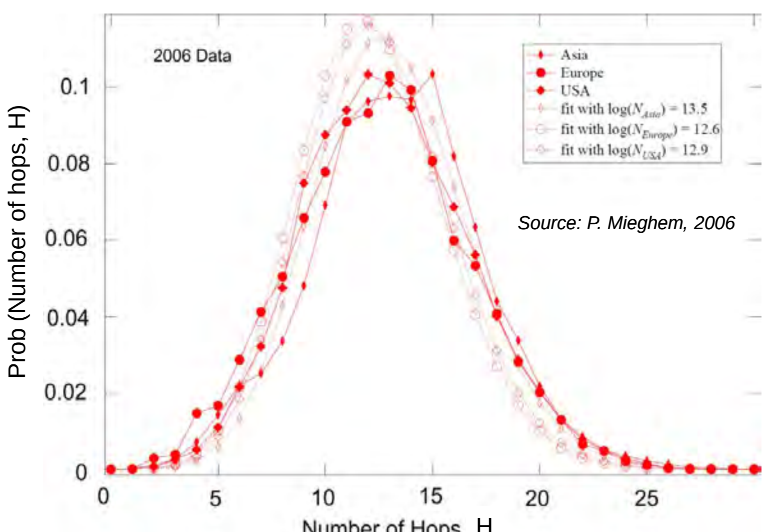
Typical core network parameters

Device	Capacity (C_{max})	Power (W) (P_{max})	Efficiency (P_{max}/C_{max})	Equipment
Regenerator	10 Gb/s	10.5	1 nJ/bit	JDSU Waveshifter 600ER
WDM terminal (800 km reach)	40 Gb/s	136 per channel	3.4 nJ/bit	Fujitsu 7700
Server	0.8 Gb/s	225	28.1 nJ/bit	HP DL380 G5
Storage	604.8 Tb	4900	0.008 nW/bit	HP 8100 EVA
LAN	320 Gb/s	3800	11.9 nJ/bit	Cisco 6509
Gateway router	660 Gb/s	5100	7.7 nJ/bit	Juniper MX-960
MEMS cross connect	19.2 Tbit/s max	< 85	<0.004 nJ/bit	Glimmerglass Intelligent Optical System 600
SDH transponder	10 Gb/s	18	1.8 nJ/bit	Transmode 10G Lite
SDH switch	100 Gb/s	250	2.5 nJ/bit	Alcatel-Lucent 1660
EDFA	32 channels	601	0.5 nJ/bit (40G channels)	Fujitsu Flashwave 7600

CEET centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

132

Pdf for number of router hops



CEET centre for energy-efficient telecommunications BELL LABS AND UNIVERSITY OF MELBOURNE

133

Bibliography

Authors	Article	Source	Year
Andre, L., Holzle, U.	The Case for Energy-Proportional Computing	IEEE Computer, Vol.40, No.12, p.33	2007
Baliga, J., et al	Energy Consumption in Optical IP Networks	JLT, vol. 27, p.2391	2009
Baliga, J., et al	Green Cloud Computing: Balancing Energy in Processing, Storage and Transport	Proc. IEEE, Vol.99, p.149	2011
Baliga, J., et al	Architectures for Energy-Efficient IPTV Networks	OFC/NFOEC 2009, paper: OThQ5	2009
Baliga, J., et al	Photonic Switching and the Energy Bottleneck	PS 2007, paper: WA3.5	2007
Baliga, J., et al	Carbon Footprint of the Internet	TJA, Vol.59, p.05.1	2009
Baliga, J., et al	Energy Consumption in Wired and Wireless Access Networks	IEEE Comm Mag. Vol.49, No.6, p70	2011
Barthel, C., et al.	GHG Emission Trends of the Internet in Germany	IGES & Wuppental Institute Joint Workshop on International Climate Policy and the IT Sector	2001
Berl, A., et al	Energy-Efficient Cloud Computing	The Computer Journal, Aug. 19	2009
Bianzino, A., et al.	A Survey of Green Networking Research	IEEE Communications Surveys and Tutorials, Vol.14, No.1, p.3,	2012

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Bolla, R., et al.	Energy Efficiency in Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures	IEEE Comm Surveys & Tutorials, Vol.13, p.223	2011
Bolla, R., et al.	The Potential Impact of Green Technologies in Next-Generation Wireline Networks – Is There Room for Energy Saving Optimization?	IEEE Comm Magazine, Vol.49, No. 8, p80	2011
Brookes, L.	Energy efficiency fallacies revisited	Energy Policy, Vol. 28, p.355	2000
Capone, A., Kilper, D., Niu, Z.	Special Issue on Green Communication Networks	Computer Networks, Vol. 56, No.10, pp.2317-2550	2012
Cremer, C., et al.	Energy Consumption of Information and Communication Technology in Germany up to 2010	Fraunhofer ISI and CEPE Project No. 28/01	2003
Despins, C, et al.	Leveraging green communications for carbon emission reductions: Techniques, testbeds, and emerging carbon footprint standards	IEEE Communications Magazine, Vol.49, No.8, p.101	2011
Devarajan, R., Jha, S., Phuyal, U., Bhargava, V.	Energy-Aware Resource Allocation for Cooperative Cellular Network Using Multi-Objective Optimization Approach	IEEE Transactions on Wireless Communications, Vol.11, No.5, p.1797	2012
Fan, X., et al.	Power Provisioning for a. Warehouse- sized Computer	ACM ISCA'07	2007
Fehratović, N., Aleksić, S.	Power Consumption and Scalability of Optically Switched Interconnects for High-Capacity Network Elements	OFC/NFOEC 2011, paper: JWA84	2011
Feldmann, A., et al.	Energy Trade-offs among Content Delivery Architectures	CTTE 2010,	2010

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Feng , M., Hinton, K., Ayre, R., Tucker, R.	Network Energy Efficiency Gains Through Coordinated Cross-Layer Aggregation and Bypass	Opt. Commun. Netw. Vol.4, No.11, p.895	2012
Francini, A., D. Stiliadis, D.	Rate Adaptation for Energy Efficiency in Packet Networks	Bell Labs Tech Jour. Vol.15, p.131	2010
Hilbert, M., Lopez, P.	The world's technological capacity to store, communicate, and compute information	Science, April	2011
Hinton, K., et al.	Power Consumption and Energy Efficiency in the Internet	IEEE Network, Vol. , p.6	2011
Hinton, K., et al.	Switching Energy and Device Size Limits on Digital Photonic Signal Processing Technologies	JSTQE, Vol.14, p.938	2008
Hinton, K., et al. (Editors)	Special Issue on Green Photonics	JSTQE, Vol.17	2011
Huber, P., Mills, M.	Dig More Coal -- the PC's are Coming	Forbes Magazine, 31 May, p.70	1999
ITRS	International Technology Roadmap for Semiconductors Roadmaps		1997-2009
ITU-T	NGNs and Energy Efficiency	Technology Watch Report 7, Aug	2008
Kalman, R., et al.	Space division switches based on semiconductor optical amplifiers	IEEE Photonics Tech. Lett., vol. 4, p. 1048	1992
Kani, J., et al.	Energy Efficient Optical Access Network Technologies	OFC/NFOEC, paper OThB1	2011
Kawatomo, K., et al.	Electricity Used by Office Equipment and Network Equipment in the US	LBNL-45917	2001

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

136

Bibliography

Authors	Article	Source	Year
Kilper, D. et al.	Power Trends in Communication Networks	JSTQE, Vol.17, p.275	2011
Kilper, D., Guan, K., Hinton, K., Ayre, R.	Energy Challenges in Current and Future Optical Transmission Networks	Proceedings of IEEE, Vol.100, No.5, p.1168	2012
Koomey, J., et al.	Initial Comments on "The Internet Begins with Coal"	LBNL 44698	1999
Lange, C., et al	Energy Consumption of Telecommunications Networks and Related Improvement Options	JSTQE, Vol.17, p.285	2011
Lange, C., et al.	Energy Consumption of Telecommunications Networks	ECOC 2009, paper 5.5.3	2009
Lee, B., et al.	Comparison of Ring Resonator and Mach-Zehnder Photonic Switches Integrated with Digital CMOS Drivers	23rd Annual meeting of IEEE Photonics Society, p.327	2010
Lee, K., Sedighi, B., Tucker, R. Chow, H. Vetter, P.	Energy efficiency of optical transceivers in fiber access networks	JOCN, Vol.4, No.9, A59	2012
Lee, U., et al.	Toward Energy-Efficient Content Dissemination	IEEE Network, Mar/April, p14	2011
Lei, B., Hofmann, H.	Energy Consumption and Low Power Design of Optical Equipment	Bell Labs Tech. Jour. Vol.15, p. 169	2010
Li, G., Xu, S., Swami, A., Himayat, M., Fettweis, G.	Special Issue on Energy-Efficient Wireless Communications	IEEE JSAC, Vol.29, No.8	2011.
Llorca, J., Guan, K., Atkinson, G., Kilper, D.	Energy efficient delivery of immersive video centric services	INFOCOM 2012, p1656	2012

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

137

Bibliography

Authors	Article	Source	Year
Mieghem, P.	Performance Analysis of Communications Networks and Systems	Cambridge Uni. Press	2006
Möller, M.	High-Speed Electronic Circuits for 100 Gb/s Transport Networks	OFC/NFOEC, paper: OThC6	2010
Nedevschi, S., et al.	Reducing Network Energy Consumption via Sleeping and Rate-Adaptation	NDSI' 08 Proceedings, p.323	2008
Neilson, D.	Photonics for Switching and Routing	IEEE JSTQE, Vol.12, p.669	2006
Neilson, D.	Power Dissipation Limitations to the Scalability of Network Elements	ECOC 2011, paper: Th12.A.2	2011
Neilson, J.	Mini-tutorial: The National Infrastructures for Voice and Data Communications	http://www.nerdylorrin.net/jerry/politics/Warrantless/WarrantlessBKGND.html	2007
Nordman, B.	Networks Energy and Energy Efficiency	70th IETF, Vancouver, BC	2007
Puype, B., et al.	Multilayer traffic engineering for energy efficiency	Photon Netw Comm. Vol.21, p.127	2011
Quittek, J., Christensen, K., Nordman, B.	Special Issue on Energy Efficient Networks	IEEE Network Magazine Vol.25, No.2	2011
Roth, K. et al.	Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings	US Dept. of Commerce NTIS PB2002-101438	2002
Shen, G., Tucker, R.	Energy-Minimized Design for IP Over WDM Networks	J. Opt. Commun. Netw. Vol. 1, p.176	2009

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

138

Bibliography

Authors	Article	Source	Year
Tamm, O. et al.	Eco-Sustainable System and Network Architectures for Future Transport Networks	Bell Labs Tech Jour. Vol.14, p.311	2010
Tanemura, T., Nakano, Y.	Design and scalability analysis of optical phased-array 1 × *N* switch on planar lightwave circuit	IEICE Electron. Express, Vol.5, p.603	2008
Tucker, R.	Green Optical Communications – Part 1: Energy Limitations in Transport	JSTQE, Vol.17, p.245	2011
Tucker, R.	Green Optical Communications – Part 2: Energy Limitations in Networks	JSTQE, Vol.17, p.261	2011
Tucker, R.	Optical packet switching: A reality check	Optical Switching & Networking, Vol.5, p.2	2008
Tucker, R., et al.	Energy consumption limits in high-speed optical and electronic signal processing	Electron. Lett. Vol.43, p.906	2007
Tucker, R., et al.	Evolution of WDM Optical IP Networks: A Cost and Energy Perspective	JLT, Vol.27, p.243	2009
Tucker, R., Hinton, K.	Energy Consumption and Energy Density in Optical and Electronic Signal Processing	IEEE Photonics Jour., Vol.3, p.821	2011
Turk, V.	Assessing the Resource Intensity of the Internet Infrastructure	Master's Thesis, Lund University	2001
Vereecken, W. et al. .	Optical Networks: How Much Power Do They Consume and How Can We Optimize This?	ECOC 2010, paper: Mo.1.D.1	2010
Vereecken, W., et al.	Energy Efficiency in Telecommunication Networks	NOC 2008	2008
Vereecken, W., et al.	Power Consumption in Telecommunication Networks: Overview and Reduction Strategies	IEEE Comm Magazine, Vol.49, No.6, p.62	2011

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

139

Bibliography

Authors	Article	Source	Year
Wu, J., Rangan, S., Zhang, H.	Green Communications: Theoretical Fundamentals, Algorithms and Applications	CRC Press	2012
Zhang, C., et al.	Energy Efficiency of optical IP protocol suites	OFCNFOEC, paper NTu1E.3	2012
Zhang, Y., et al.	Energy Efficiency in Telecom Optical Networks	IEEE Comm Surveys & Tutorials, Vol.12, p.441	2010
Vishwanath, A., Zhu, J., Hinton, K., Ayre, A., Tucker, R.	Estimating the Energy Consumption for Packet Processing, Storage and Switching in Optical-IP Routers	OFCNFOEC 2013, Paper OM3A.6	2013
Viswhanath, A, et al.	Energy Consumption of Interactive Cloud-Based Document Processing and Applications	IEEE ICC 2013	2013
Wu, J., Rangan, S., Zhang, H.	Green Communications: Theoretical Fundamentals, Algorithms and Applications	CRC Press	2012
Zhang, C., Ayre, R., Feng, M., Hinton, K., Vishwanath, A.	Energy Efficiency of optical IP protocol suites	OFCNFOEC, paper NTu1E.3	2012
Zhang, Y., et al.	Energy Efficiency in Telecom Optical Networks	IEEE Comm Surveys & Tutorials, Vol.12, p.441	2010
Grover, P. Woyach K., Sahai A.	Towards a Communication-Theoretic Understanding of System-Level Power Consumption,"	IEEE JSAC, Special Issue on Energy-Efficient Wireless Communications, Vol. 29, No. 8, pp. 1744, Sept.	2011

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Various	Special Issue on Energy Efficient Networks,	IEEE Network Magazine, , Vol. 25, No. 2	2011
Various	Special Issue on Green Communication Networks	Computer Networks, Vol. 56, No. 10, p.2317, July	2012
Various	Feature Topics Issue on Green Communications, "Energy Efficiency in Communications" Part 1	IEEE Communications Magazine, November	2010
Various	Feature Topics Issue on Green Communications, "Energy Efficiency in Communications" Part 2	IEEE Communications Magazine, June	2011
Various	Feature Topics Issue on Green Communications, "Energy Efficiency in Communications" Part 3	IEEE Communications Magazine, August	2011
Various	Special Issue on Green Information and Communications Technology (ICT) for Eco-Sustainability	Bell Labs Technical Journal, August	2010
Vereecken W. , Van Heddeghem W. , Deruyck M. , Puype B. , Lannoo B. , Joseph W. , Colle D. , Martens L. , Demeeste rP. ,	Power Consumption in Telecommunications Networks: Overview and Reduction Strategies"	IEEE Communications Magazine, June, p.62,	2011
Somavat P. , Namboodiri V.	Energy Consumption of Personal Computing Including Portable Communication Devices	Journal of Green Engineering, Vol.1, No.4, p.447	2011
Puype B. , Wereecken W. , Colle D. , Pickavet M. , Demeester P.	Multilayer traffic engineering for energy efficiency	Photonic Network Communications, DOI 10.1007/s11107-010-0287-6, Sept.	2010

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Phillips S. , et. al	A regression approach to infer electricity consumption of legacy telecom equipment,	ACM SIGMETRICS Performance Evaluation Review	2010
Matthews H., et. al	Planning Energy-Efficient and Eco-Sustainable Telecommunications Networks	Bell Labs Technical Journal, Vol.15, No.1, p.215	2010
Bianzino A. , Chaudet C. , Rossi D., Rougier J.	A Survey of Green Networking Research	IEEE Communications Surveys and Tutorials, Vol.14, No.1, p.3	2012
Zhang Y. , Chowdhury P., Torniatore M. , Mukerjee B.	Energy Efficiency in Telecom Optical Networks	IEEE Communications Surveys and Tutorials, Vol.12, No.4, p.441	2010
Roy S.N.	Energy logic: A road map to reducing energy consumption in telecommunications networks	IEEE International Telecommunications Energy Conference 2008, Sept.	2008
Chiaraviglio L. , Mellia M. , Neri F.	Reducing power consumption in backbone networks	Proc. IEEE ICC	2009
Bolla R. , Davoli F. , Bruschi R. , Christensen K. , Cucchietti F. , Singh S.	The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization?	IEEE Communications Magazine, vol. 49, p. 80, August	2011
Chen Y. , Zhang S. , Xu S.	Characterizing energy efficiency and deployment efficiency relations for green architecture design	Proc. IEEE ICC Workshops	2010
Aleksic S.	Analysis of Power Consumption in Future High-Capacity Network Nodes	IEEE/OSA Journal of Optical Communications and Networking, vol. 1, no. 3, p. 245, August	2009

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

142

Bibliography

Authors	Article	Source	Year
Miller D.	Device Requirements for Optical Interconnects to Silicon Chips	Proc IEEE, Vol.97, No.7, p.1166	2009
Lee U. , Rimac I. , Kilper D. , Hilt V.	Toward Energy-Efficient Content Dissemination	IEEE Network, March/April, p.14	2011
Wu Y . , Chiaraviglio L., Mellia M. , Neri F.	Power-Aware Routing and Wavelength Assignment in Optical Networks	Proc. ECOC	2009
Lee K.-L. , Sedighi B. , Tucker R. S. , Chow H. , Vetter P.	Energy efficiency of optical transceivers in fiber access networks	J. Opt. Comm. Networking	2012
Vereecken W. , et. al	Optical networks: How much power do they consume and how can we optimize this?	Proc. ECOC	2010
Suvakovic D. , et al.	Low energy bit-interleaving downstream protocol for passive optical networks	Proc. IEEE Online Green Communications Conference	2012
Karlsson M. , Agrell E.	Which is the Most Power-Efficient Modulation Formats in Optical Links?	Opt. Exp., vol. 17, p. 10814	2009
Krishnamoorty A. V. , et al.	Progress in Low-Power Switched Optical Interconnects	IEEE J. Spec. Top. Quantum Electron., vol. 17, no. 2, p. 357	2011
Chowdhury P. , Tornatore M. , Nag A. , Ip E. , Wang T. , Mukherjee B.	On the Design of Energy-Efficient Mixed Line Rate (MLR) Optical Networks	J. Lightwave Technol. Vol. 30, No. 1, p.130	2012

ceet centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

143

Bibliography

Authors	Article	Source	Year
Morea A. , et al.	Power management of optoelectronic interfaces for dynamic optical networks	Proc. ECOC 2011	
Guan K., Kilper D., Atkinson G.	Evaluating the energy benefit of dynamic optical bypass for content delivery	IEEE INFOCOM Green Communications Workshop	2011
Fan X. , Weber W. , Barroso L.	Power Provisioning for a Warehouse-sized Computer	Proc. ACM International Symposium on Computer Architecture,	2007
Berl A. , et. al	Energy-Efficient Cloud Computing	The Computer Journal, Vol.53, No.7, p1045	2010
Christensen K. , et. al	IEEE 802.3az: The Road to Energy Efficient Ethernet	IEEE Communications Magazine, Vol. 48, No. 11, p. 50, Nov.	2010
Despins, C., et. al	Leveraging green communications for carbon emission reductions: Techniques, testbeds, and emerging carbon footprint standards	IEEE Communications Magazine, vol.49, no.8, p.101, Aug	2011
Llorca J. , Guan K. , Atkinson G. , Kilper D.	Energy efficient delivery of immersive video centric services	INFOCOM 2012, p.1656	2012
Aleksic S.	Analysis of Power Consumption in Future High-Capacity Network Nodes	IEEE/OSA Journal of Optical Communications and Networking, vol. 1, no. 3, p. 245, August	2009
Andre, L., Holzle, U.	The Case for Energy-Proportional Computing	IEEE Computer, Vol.40, No.12, p.33	2007

Bibliography

Authors	Article	Source	Year
Baliga, J., et al	Energy Consumption in Optical IP Networks	JLT, vol. 27, p.2391	2009
Baliga, J., et al	Green Cloud Computing: Balancing Energy in Processing, Storage and Transport	Proc. IEEE, Vol.99, p.149	2011
Baliga, J., et al	Architectures for Energy-Efficient IPTV Networks	OFC/NFOEC 2009, paper: OThQ5	2009
Baliga, J., et al	Photonic Switching and the Energy Bottleneck	PS 2007, paper: WA3.5	2007
Baliga, J., et al	Carbon Footprint of the Internet	TJA, Vol.59, p.05.1	2009
Baliga, J., et al	Energy Consumption in Wired and Wireless Access Networks	IEEE Comm Mag. Vol.49, No.6, p70	2011
Barthel, C., et al.	GHG Emission Trends of the Internet in Germany	IGES & Wuppental Institute Joint Workshop on International Climate Policy and the IT Sector	2001
Berl A. , et. al	Energy-Efficient Cloud Computing	The Computer Journal, Vol.53, No.7, p1045	2010
Berl, A., et al	Energy-Efficient Cloud Computing	The Computer Journal, Aug. 19	2009

Bibliography

Authors	Article	Source	Year
Bianzino A. , Chaudet C. , Rossi D., Rougier J.	A Survey of Green Networking Research	IEEE Communications Surveys and Tutorials, Vol.14, No.1, p.3	2012
Bianzino, A., et al.	A Survey of Green Networking Research	IEEE Communications Surveys and Tutorials, Vol.14, No.1, p.3,	2012
Bolla R. , Davoli F. , Bruschi R. , Christensen K. , Cucchietti F. , Singh S.	The potential impact of green technologies in next-generation wireline networks: Is there room for energy saving optimization?	IEEE Communications Magazine, vol. 49, p. 80, August	2011
Bolla, R., et al.	Energy Efficiency in Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures	IEEE Comm Surveys & Tutorials, Vol.13, p.223	2011
Bolla, R., et al.	The Potential Impact of Green Technologies in Next-Generation Wireline Networks – Is There Room for Energy Saving Optimization?	IEEE Comm Magazine, Vol.49, No. 8, p80	2011
Brookes, L.	Energy efficiency fallacies revisited	Energy Policy, Vol. 28, p.355	2000
Capone, A., Kilper, D., Niu, Z.	Special Issue on Green Communication Networks	Computer Networks, Vol. 56, No.10, pp.2317-2550	2012
Chen Y. , Zhang S. , Xu S.	Characterizing energy efficiency and deployment efficiency relations for green architecture design	Proc. IEEE ICC Workshops	2010
Chiaraviglio L. , Mellia M. , Neri F.	Reducing power consumption in backbone networks	Proc. IEEE ICC	2009
Chowdhury P. , Tornatore M. , Nag A. , Ip E. , Wang T. , Mukherjee B.	On the Design of Energy-Efficient Mixed Line Rate (MLR) Optical Networks	J. Lightwave Technol. Vol. 30, No. 1, p.130	2012

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

146

Bibliography

Authors	Article	Source	Year
Christensen K. , et. al	IEEE 802.3az: The Road to Energy Efficient Ethernet	IEEE Communications Magazine, Vol. 48, No. 11, p. 50, Nov.	2010
Cremer, C., et al.	Energy Consumption of Information and Communication Technology in Germany up to 2010	Fraunhofer ISI and CEPE Project No. 28/01	2003
Despins, C, et al.	Leveraging green communications for carbon emission reductions: Techniques, testbeds, and emerging carbon footprint standards	IEEE Communications Magazine, Vol.49, No.8, p.101	2011
Despins, C., et. al	Leveraging green communications for carbon emission reductions: Techniques, testbeds, and emerging carbon footprint standards	IEEE Communications Magazine, vol.49, no.8, p.101, Aug	2011
Devarajan, R., Jha, S., Phuyal, U., Bhargava, V.	Energy-Aware Resource Allocation for Cooperative Cellular Network Using Multi-Objective Optimization Approach	IEEE Transactions on Wireless Communications, Vol.11, No.5, p.1797	2012
Fan X. , Weber W. , Barroso L.	Power Provisioning for a Warehouse-sized Computer	Proc. ACM International Symposium on Computer Architecture,	2007
Fan, X., et al.	Power Provisioning for a. Warehouse- sized Computer	ACM ISCA'07	2007
Fehratović, N., Aleksić, S.	Power Consumption and Scalability of Optically Switched Interconnects for High-Capacity Network Elements	OFC/NFOEC 2011, paper: JWA84	2011
Feldmann, A., et al.	Energy Trade-offs among Content Delivery Architectures	CTTE 2010,	2010

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

147

Bibliography

Authors	Article	Source	Year
Feng , M., Hinton, K., Ayre, R., Tucker, R.	Network Energy Efficiency Gains Through Coordinated Cross-Layer Aggregation and Bypass	Opt. Commun. Netw. Vol.4, No.11, p.895	2012
Francini, A., D. Stiliadis, D.	Rate Adaptation for Energy Efficiency in Packet Networks	Bell Labs Tech Jour. Vol.15, p.131	2010
Grover, P. Woyach K., Sahai A.	Towards a Communication-Theoretic Understanding of System-Level Power Consumption,"	IEEE JSAC, Special Issue on Energy-Efficient Wireless Communications, Vol. 29, No. 8, pp. 1744, Sept.	2011
Guan K., Kilper D., Atkinson G.	Evaluating the energy benefit of dynamic optical bypass for content delivery	IEEE INFOCOM Green Communications Workshop	2011
Hilbert, M., Lopez, P.	The world's technological capacity to store, communicate, and compute information	Science, April	2011
Hinton, K., et al.	Power Consumption and Energy Efficiency in the Internet	IEEE Network, Vol. , p.6	2011
Hinton, K., et al.	Switching Energy and Device Size Limits on Digital Photonic Signal Processing Technologies	JSTQE, Vol.14, p.938	2008
Hinton, K., et al. (Editors)	Special Issue on Green Photonics	JSTQE, Vol.17	2011
Huber, P., Mills, M.	Dig More Coal -- the PC's are Coming	Forbes Magazine, 31 May, p.70	1999
ITRS	International Technology Roadmap for Semiconductors Roadmaps		1997-2009
ITU-T	NGNs and Energy Efficiency	Technology Watch Report 7, Aug	2008

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

148

Bibliography

Authors	Article	Source	Year
Kalman, R., et al.	Space division switches based on semiconductor optical amplifiers	IEEE Photonics Tech. Lett., vol. 4, p. 1048	1992
Kani, J., et al.	Energy Efficient Optical Access Network Technologies	OFC/NFOEC, paper OThB1	2011
Karlsson M. , Agrell E.	Which is the Most Power-Efficient Modulation Formats in Optical Links?	Opt. Exp., vol. 17, p. 10814	2009
Kawatomo, K., et al.	Electricity Used by Office Equipment and Network Equipment in the US	LBNL-45917	2001
Kilper, D. et al.	Power Trends in Communication Networks	JSTQE, Vol.17, p.275	2011
Kilper, D., Guan, K., Hinton, K., Ayre, R.	Energy Challenges in Current and Future Optical Transmission Networks	Proceedings of IEEE, Vol.100, No.5, p.1168	2012
Koomey, J., et al.	Initial Comments on "The Internet Begins with Coal"	LBNL 44698	1999
Krishnamoorty A. V. , et al.	Progress in Low-Power Switched Optical Interconnects	IEEE J. Spec. Top. Quantum Electron., vol. 17, no. 2, p. 357	2011
Lange, C., et al	Energy Consumption of Telecommunications Networks and Related Improvement Options	JSTQE, Vol.17, p.285	2011
Koomey, J., et al.	Initial Comments on "The Internet Begins with Coal"	LBNL 44698	1999
Krishnamoorty A. V. , et al.	Progress in Low-Power Switched Optical Interconnects	IEEE J. Spec. Top. Quantum Electron., vol. 17, no. 2, p. 357	2011
Lange, C., et al	Energy Consumption of Telecommunications Networks and Related Improvement Options	JSTQE, Vol.17, p.285	2011

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

149

Bibliography

Authors	Article	Source	Year
Lange, C., et al.	Energy Consumption of Telecommunications Networks	ECOC 2009, paper 5.5.3	2009
Lee K.-L. , Sedighi B. , Tucker R. S., Chow H. , Vetter P.	Energy efficiency of optical transceivers in fiber access networks	J. Opt. Comm. Networking	2012
Lee U. , Rimac I. , Kilper D. , Hilt V.	Toward Energy-Efficient Content Dissemination	IEEE Network, March/April, p.14	2011
Lee, B., et al.	Comparison of Ring Resonator and Mach-Zehnder Photonic Switches Integrated with Digital CMOS Drivers	23rd Annual meeting of IEEE Photonics Society, p.327	2010
Lee, K., Sedighi, B., Tucker, R. Chow, H. Vetter, P.	Energy efficiency of optical transceivers in fiber access networks	JOCN, Vol.4, No.9, A59	2012
Lee, U., et al.	Toward Energy-Efficient Content Dissemination	IEEE Network, Mar/April, p14	2011
Lei, B., Hofmann, H.	Energy Consumption and Low Power Design of Optical Equipment	Bell Labs Tech. Jour. Vol.15, p. 169	2010
Li, G., Xu, S., Swami, A., Himayat, M., Fettweis, G.	Special Issue on Energy-Efficient Wireless Communications	IEEE JSAC, Vol.29, No.8	2011
Llorca J. , Guan K. , Atkinson G. , Kilper D.	Energy efficient delivery of immersive video centric services	INFOCOM 2012, p.1656	2012
Llorca, J., Guan, K., Atkinson, G., Kilper, D.	Energy efficient delivery of immersive video centric services	INFOCOM 2012, p1656	2012
Matthews H., et. al	Planning Energy-Efficient and Eco-Sustainable Telecommunications Networks	Bell Labs Technical Journal, Vol.15, No.1, p.215	2010

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Mieghem, P.	Performance Analysis of Communications Networks and Systems	Cambridge Uni. Press	2006
Miller D.	Device Requirements for Optical Interconnects to Silicon Chips	Proc IEEE, Vol.97, No.7, p.1166	2009
Möller, M.	High-Speed Electronic Circuits for 100 Gb/s Transport Networks	OFC/NFOEC, paper: OThC6	2010
Morea A. , et al.	Power management of optoelectronic interfaces for dynamic optical networks	Proc. ECOC 2011	
Nedevschi, S., et al.	Reducing Network Energy Consumption via Sleeping and Rate-Adaptation	NDSI' 08 Proceedings, p.323	2008
Neilson, D.	Photonics for Switching and Routing	IEEE JSTQE, Vol.12, p.669	2006
Neilson, D.	Power Dissipation Limitations to the Scalability of Network Elements	ECOC 2011, paper: Th12.A.2	2011
Neilson, J.	Mini-tutorial: The National Infrastructures for Voice and Data Communications	http://www.nerdylorrin.net/jerry/politics/WarrantlessBKGND.html	2007
Nordman, B.	Networks Energy and Energy Efficiency	70th IETF, Vancouver, BC	2007
Phillips S. , et. al	A regression approach to infer electricity consumption of legacy telecom equipment,	ACM SIGMETRICS Performance Evaluation Review	2010
Puype B. , Wereecken W. , Colle D. , Pickavet M. , Demeester P.	Multilayer traffic engineering for energy efficiency	Photonic Network Communications, DOI 10.1007/s11107-010-0287-6, Sept.	2010

centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Puype, B., et al.	Multilayer traffic engineering for energy efficiency	Photon Netw Comm. Vol.21, p.127	2011
Quittek, J., Christensen, K., Nordman, B.	Special Issue on Energy Efficient Networks	IEEE Network Magazine Vol.25, No.2	2011
Roth, K. et al.	Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings	US Dept. of Commerce NTIS PB2002-101438	2002
Roy S.N.	Energy logic: A road map to reducing energy consumption in telecommunications networks	IEEE International Telecommunications Energy Conference 2008, Sept.	2008
Shen, G., Tucker, R.	Energy-Minimized Design for IP Over WDM Networks	J. Opt. Commun. Netw. Vol. 1, p.176	2009
Somavat P. , Namboodiri V.	Energy Consumption of Personal Computing Including Portable Communication Devices	Journal of Green Engineering, Vol.1, No.4, p.447	2011
Suvakovic D. , et al.	Low energy bit-interleaving downstream protocol for passive optical networks	Proc. IEEE Online Green Communications Conference	2012
Tamm, O. et al.	Eco-Sustainable System and Network Architectures for Future Transport Networks	Bell Labs Tech Jour. Vol.14, p.311	2010
Tanemura, T., Nakano, Y.	Design and scalability analysis of optical phased-array 1 × *N* switch on planar lightwave circuit	IEICE Electron. Express, Vol.5, p.603	2008
Tucker, R.	Green Optical Communications – Part 1: Energy Limitations in Transport	JSTQE, Vol.17, p.245	2011

Bibliography

Authors	Article	Source	Year
Tucker, R.	Green Optical Communications – Part 2: Energy Limitations in Networks	JSTQE, Vol.17, p.261	2011
Tucker, R.	Optical packet switching: A reality check	Optical Switching & Networking, Vol.5, p.2	2008
Tucker, R., et al.	Energy consumption limits in high-speed optical and electronic signal processing	Electron. Lett. Vol.43, p.906	2007
Tucker, R., et al.	Evolution of WDM Optical IP Networks: A Cost and Energy Perspective	JLT, Vol.27, p.243	2009
Tucker, R., Hinton, K.	Energy Consumption and Energy Density in Optical and Electronic Signal Processing	IEEE Photonics Jour., Vol.3, p.821	2011
Turk, V.	Assessing the Resource Intensity of the Internet Infrastructure	Master's Thesis, Lund University	2001
Various	Special Issue on Energy Efficient Networks,	IEEE Network Magazine, , Vol. 25, No. 2	2011
Various	Special Issue on Green Communication Networks	Computer Networks, Vol. 56, No. 10, p.2317, July	2012
Various	Feature Topics Issue on Green Communications, “Energy Efficiency in Communications“ Part 1	IEEE Communications Magazine, November	2010
Various	Feature Topics Issue on Green Communications, “Energy Efficiency in Communications“ Part 2	IEEE Communications Magazine, June	2011
Various	Feature Topics Issue on Green Communications, “Energy Efficiency in Communications“ Part 3	IEEE Communications Magazine, August	2011
Various	Special Issue on Green Information and Communications Technology (ICT) for Eco-Sustainability	Bell Labs Technical Journal, August	2010

Bibliography

Authors	Article	Source	Year
Vereecken W. , et. al	Optical networks: How much power do they consume and how can we optimize this?	Proc. ECOC	2010
Vereecken W. , et. al	Power Consumption in Telecommunications Networks: Overview and Reduction Strategies"	IEEE Communications Magazine, June, p.62,	2011
Vereecken, W. et al. .	Optical Networks: How Much Power Do They Consume and How Can We Optimize This?	ECOC 2010, paper: Mo.1.D.1	2010
Vereecken, W., et al.	Energy Efficiency in Telecommunication Networks	NOC 2008	2008
Vereecken, W., et al.	Power Consumption in Telecommunication Networks: Overview and Reduction Strategies	IEEE Comm Magazine, Vol.49, No.6, p.62	2011
Vishwanath, A., Zhu, J., Hinton, K., Ayre, A., Tucker, R.	Estimating the Energy Consumption for Packet Processing, Storage and Switching in Optical-IP Routers	OFCNFOEC 2013, Paper OM3A.6	2013
Viswhanath, A, et al.	Energy Consumption of Interactive Cloud-Based Document Processing and Applications	IEEE ICC 2013	2013
Wu Y . , Chiaraviglio L., Mellia M. , Neri F.	Power-Aware Routing and Wavelength Assignment in Optical Networks	Proc. ECOC	2009
Wu, J., Rangan, S., Zhang, H.	Green Communications: Theoretical Fundamentals, Algorithms and Applications	CRC Press	2012
Wu, J., Rangan, S., Zhang, H.	Green Communications: Theoretical Fundamentals, Algorithms and Applications	CRC Press	2012
Zhang Y. , Chowdhury P., Torniatore M. , Mukerjee B.	Energy Efficiency in Telecom Optical Networks	IEEE Communications Surveys and Tutorials, Vol.12, No.4, p.441	2010

CEET centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE

Bibliography

Authors	Article	Source	Year
Zhang, C., Ayre, R., Feng, M., Hinton, K., Vishwanath, A.	Energy Efficiency of optical IP protocol suites	OFCNFOEC, paper NTu1E.3	2012
Zhang, C., et al.	Energy Efficiency of optical IP protocol suites	OFCNFOEC, paper NTu1E.3	2012
Zhang, Y., et al.	Energy Efficiency in Telecom Optical Networks	IEEE Comm Surveys & Tutorials, Vol.12, p.441	2010
Zhang, Y., et al.	Energy Efficiency in Telecom Optical Networks	IEEE Comm Surveys & Tutorials, Vol.12, p.441	2010

CEET centre for energy-efficient telecommunications
BELL LABS AND UNIVERSITY OF MELBOURNE