A Survey of Energy Efficiency Metrics

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Agenda

- Centre for Energy Efficient Telecommunications
- Equipment and network power
- Service power: Photo sharing
  – Constructing use phase energy models
  – Unshared and shared equipment models
  – Single user and total service energy
  – Consequential & attributional energy
- Metrics
  – What is the purpose of a metric?
  – Standardised metrics
- Energy efficiency of a service
  – Network synchronisation and energy efficiency
- Conclusions

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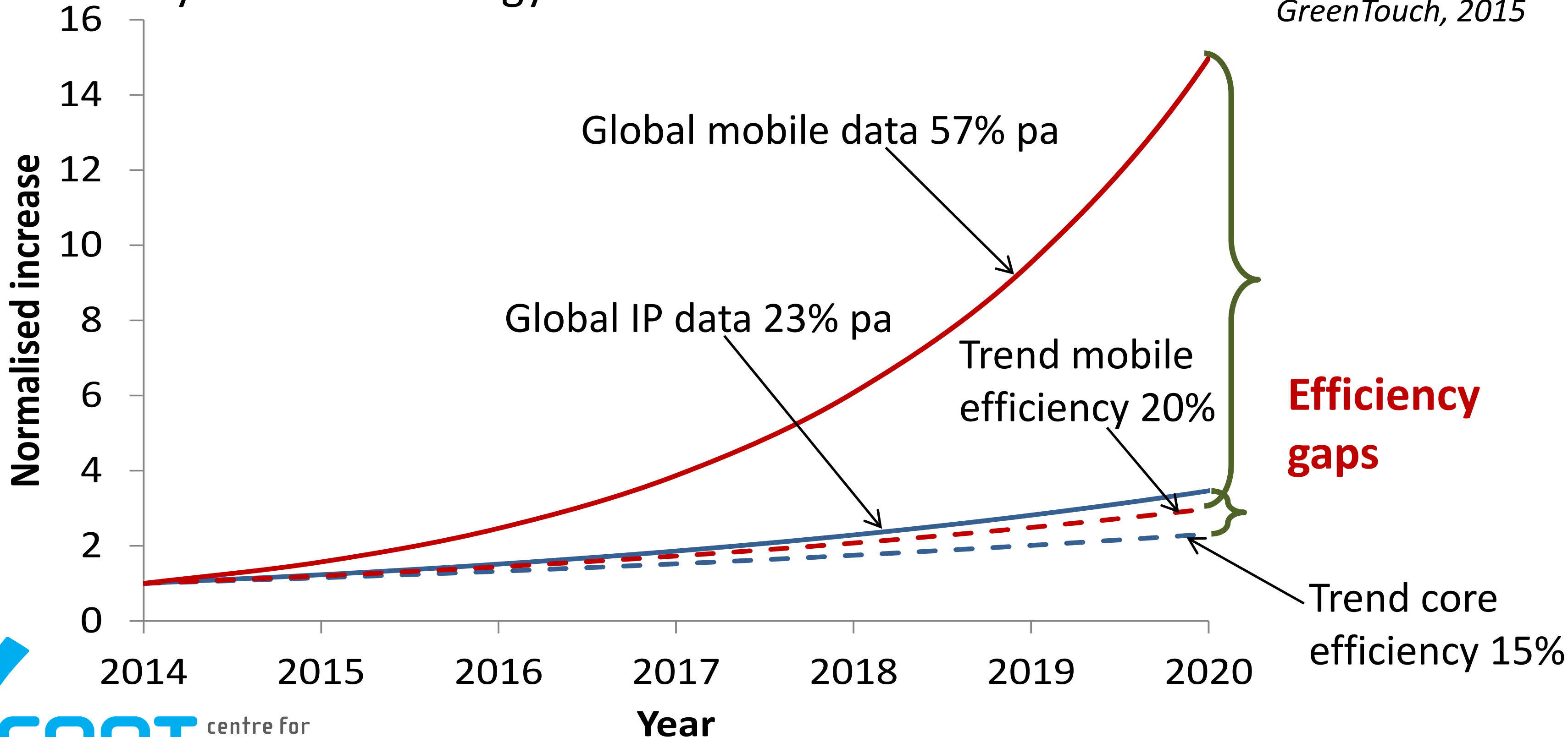
The future energy efficiency gaps

- Current data growth rate >> traditional energy efficiency improvement rate
- Technology is not keeping up with traffic growth
  - May suffer an "energy bottleneck"

Cisco, 2015
GreenTouch, 2015



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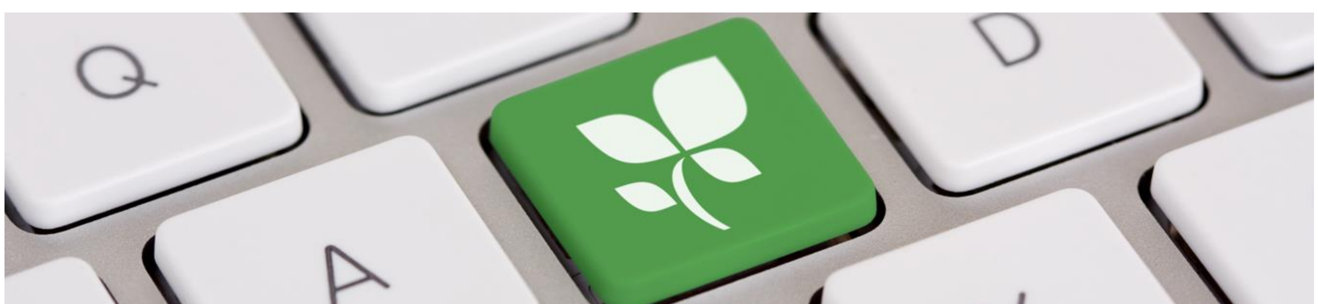
Centre for Energy-Efficient Telecommunications

- Research centre located in the University of Melbourne
- Launched in March 2011
- Partnership between Alcatel-Lucent, the University of Melbourne and Victorian State Government
  - $10 million for 2011 to 2015
  - Additional funding of $2 million has extended CEET to 1st July 2016
- World's first research centre focusing on energy-efficient telecommunication technologies
- Focus on collaboration between business and academia
- Major contributor to GreenTouch international consortium



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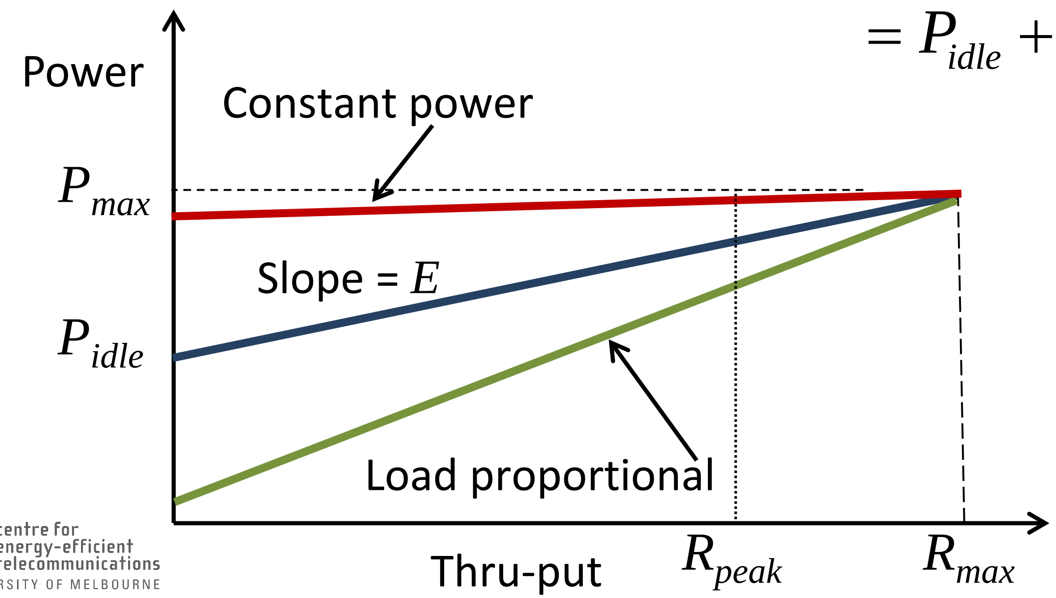
Service power

- "Consequential" and "attributional" power
  - "Consequential"
    - Additional network power to support a service
      - Current power is "sunk"
    - How much extra power does e-banking require?
    - Focus is on increase in power consumption
    - Estimates only additional network power for additional services
  - "Attributional"
    - Share of network power / carbon footprint of Internet service
      - Includes current power
    - What is the carbon footprint of e-banking?
    - Distributes total network power / carbon footprint across all services

Equipment power

- All equipment has approx. "affine" power profile
  - Constant plus a linear slope component
- Two extremes:
  - $P_{idle} >> ER_{max}$ (constant power)
  - $P_{idle} << ER_{max}$ (load proportional)
- Traffic has a diurnal cycle
  - $R(t_{peak}) = R_{peak} < R_{max}$

$$P(t) = P_{idle} + ER(t)$$
$$= P_{idle} + \frac{(P_{max} - P_{idle})}{R_{max}} R(t)$$



Network power and traffic

- Network power is sum power of network elements, j

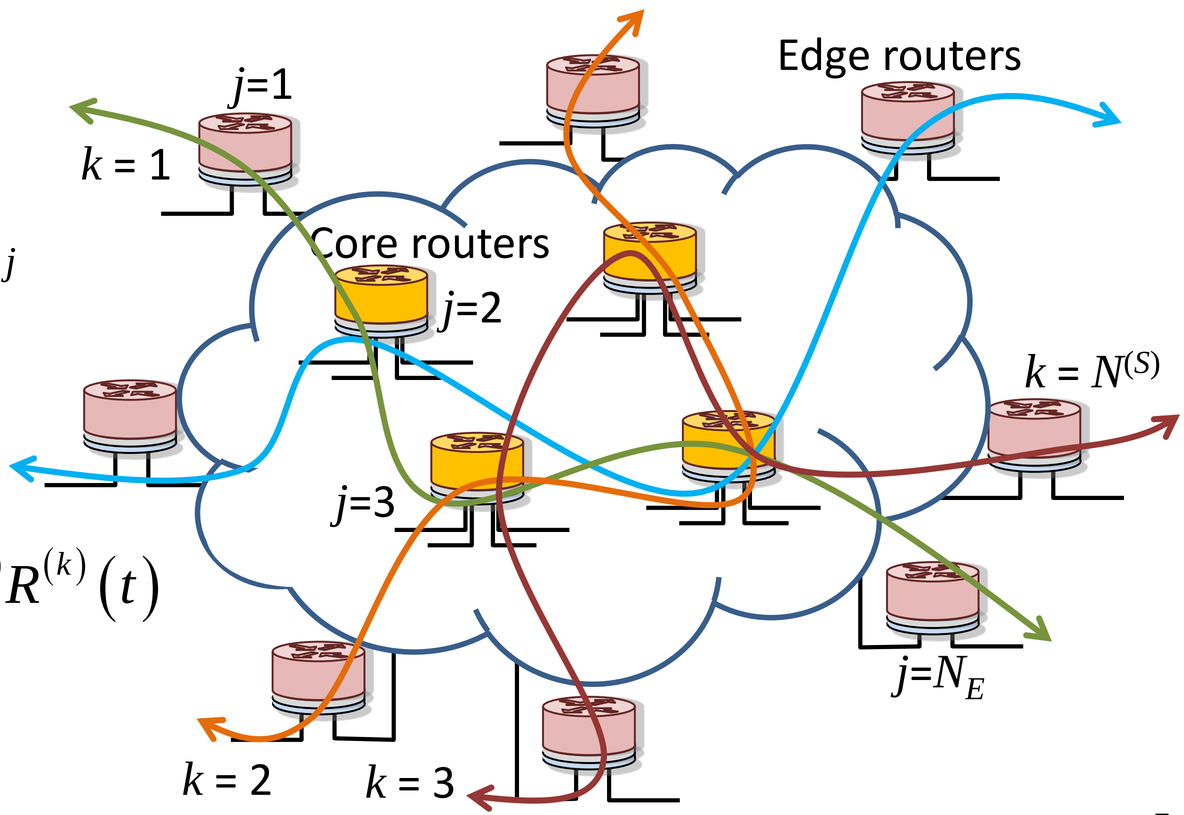
$$P_{Ntwk}(t) = \sum_j \left(P_{idle,j} + E_j R_j(t) \right)$$

- Network traffic is sum of service traffics, k

$$R_{Ntwk} = \sum_k R^{(k)} \le \sum_j R_j$$

- Element traffic

$$R_j(t) = \sum_{k=1}^{N^{(S)}} R_j^{(k)}(t) = \sum_{k=1}^{N^{(S)}} \alpha_j^{(k)} R^{(k)}(t)$$



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Constructing service power model

- Internet service power modelling is more complicated than equipment and network power modelling
- Services share network resources with other services and data flows
- Need to proportion power to each service or flow
- Assume for traffic flows and service powers, k;

$$R_{Ntwk}(t) = \sum_{k=1}^{N^{(S)}} R^{(k)}(t) \text{ and } P_{Ntwk}(t) = \sum_{k=1}^{N^{(S)}} P^{(k)}(t)$$

- Need to include entire service eco-system
  - CPE & access
  - Edge & core
  - Data centre

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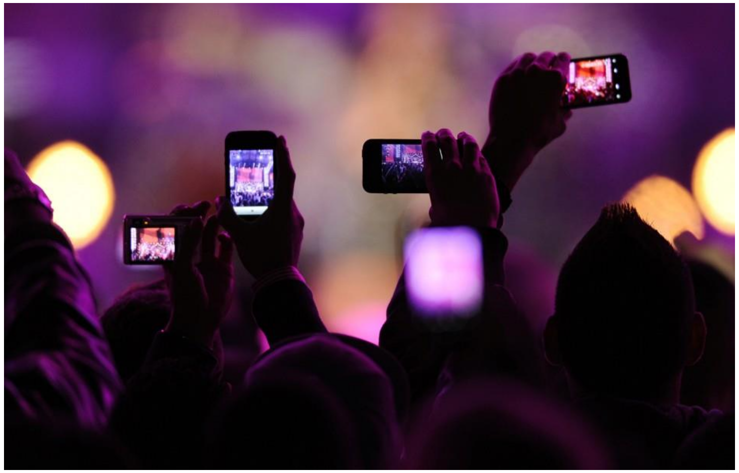
Case study: Photo sharing via cloud

- Stunning growth of Facebook traffic:
  - 240+ billion photos
  - 350+ million photos added per day
  - 750+ million photos were uploaded over New Year's Eve
  - 7000+ Tera-Byte memory added per month
- Facebook reports its annual data center energy consumption

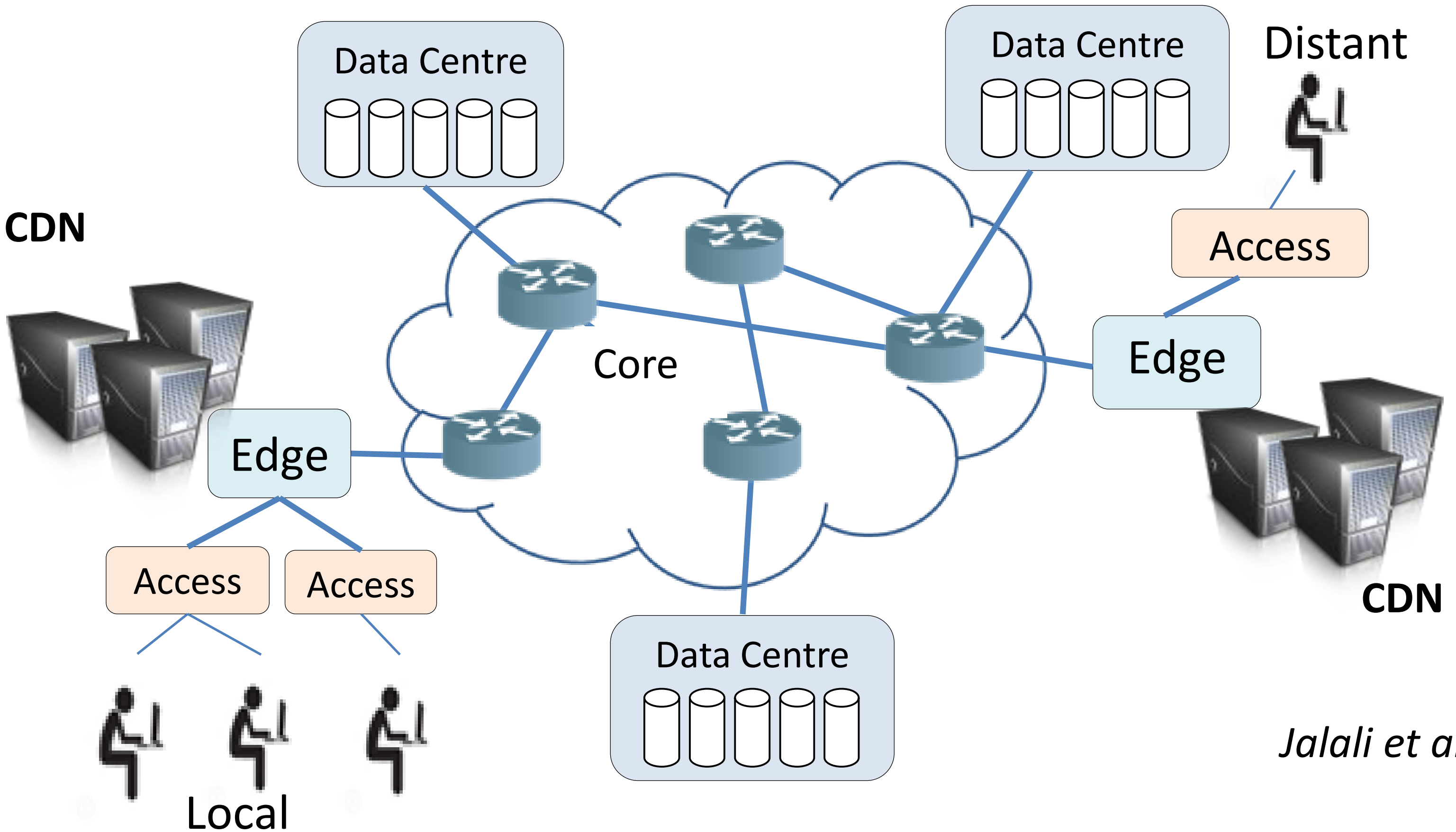
Then



Now

Jalali et al. 2014

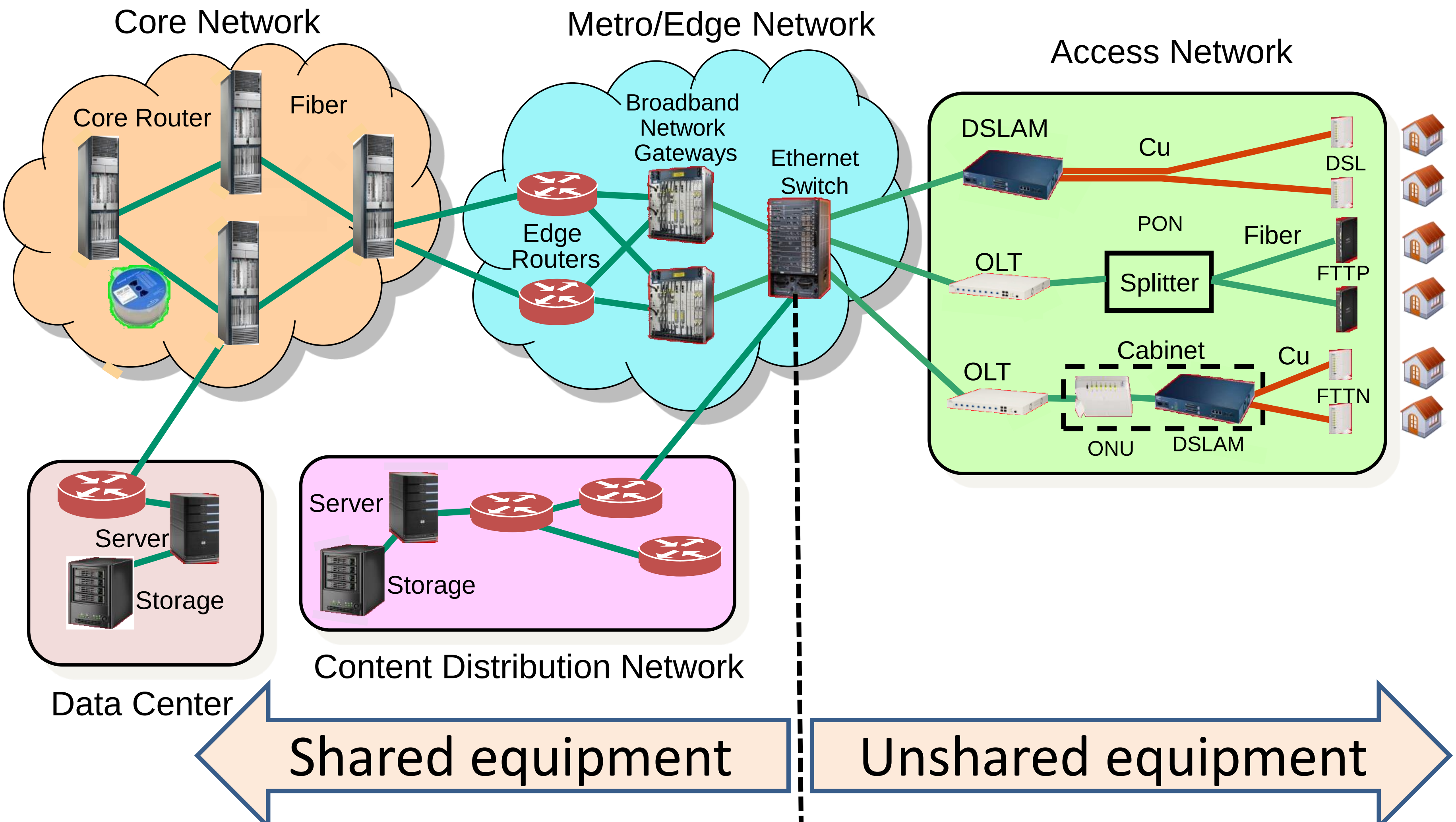
Facebook eco-system



Jalali et al. 2014

- Hot & Warm photos are distributed by a Content Delivery Network
- Cold Photos are distributed directly from data centres

Internet service eco-system



Capacity based model | Time based model

Service energy consumption modelling

- Components of the Internet service eco-system energy model:
  - Traffic
  - Energy consumption of end-user premises
    - Customer device: Laptops, Smartphones
    - Home network: Modems, Gateways
  - Energy consumption of the transport networks
    - Access Network
    - Edge Network
    - Core Network
  - Energy consumption of data centers

Measured /estimated

Unshared consumption model

shared consumption model

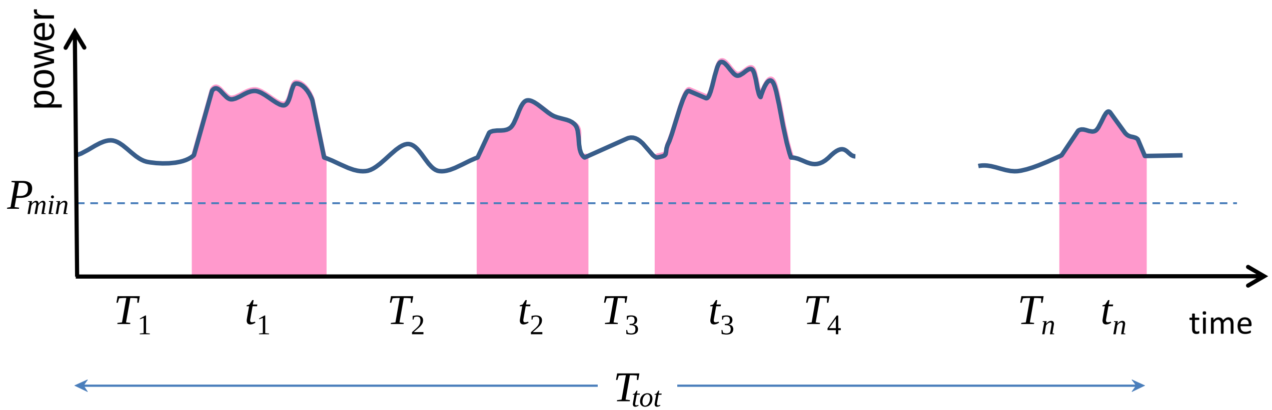
Company reports

CPE & Access equipment (lightly shared)

- "Time based access model"
  - Allocate energy according to duration of service use:

$$t^{(k)} = \sum_{l=1}^{N^{(k)}} t_l$$

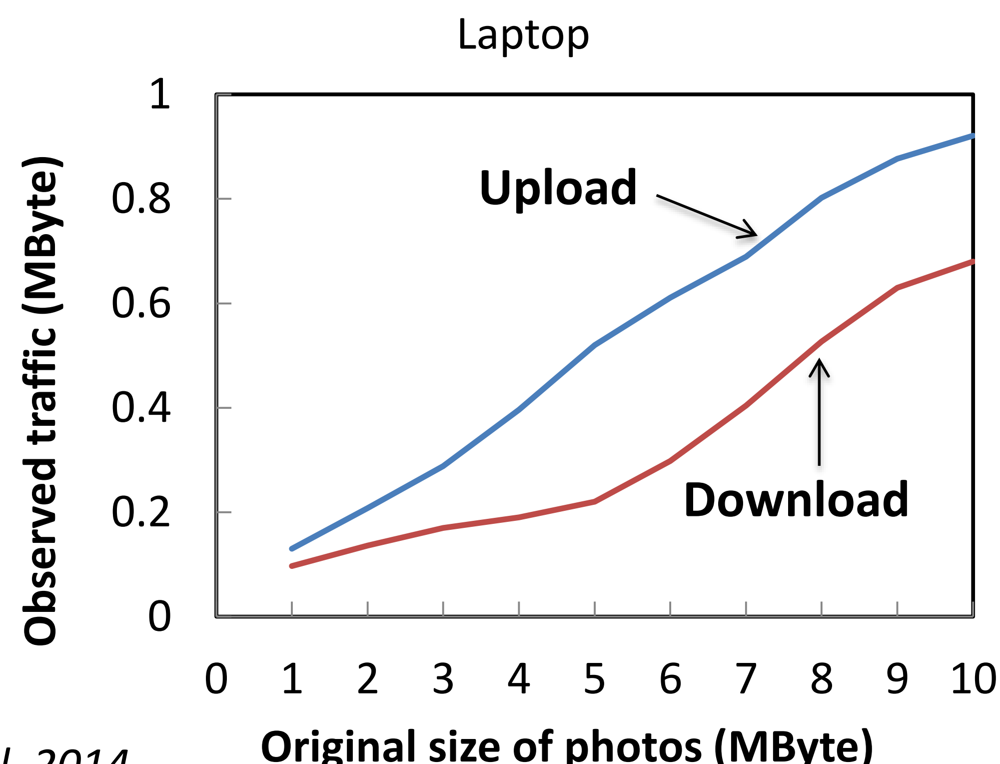
  - Total energy = sum of service energies $Q_{tot}(T_{tot}) = \sum_k Q_A^{(k)}(T_{tot})$
  - Total service bits $B^{(k)}$ = sum of service time x access rate = $t^{(k)}R^{(k)}$



Jalali, 2014
Hinton, 2015

Traffic measurements

- Used packet analyser software utility (Wireshark)
- Photos compressed in user browser before uploading to Facebook
- Exchanged Bytes for a 5MB Photo:
  - Laptop (Ethernet, WiFi)
    - Upload = 500KB
    - Download = 200KB
  - Smartphone (4G, WiFi)
    - Upload = 1.1 MB
    - Download = 120K



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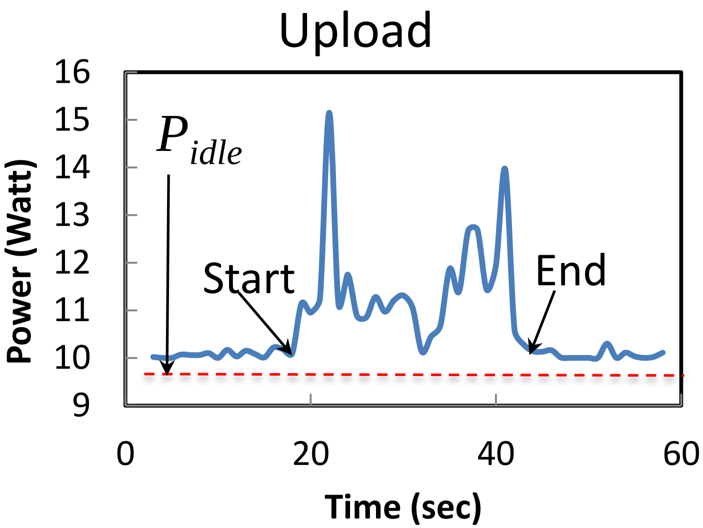
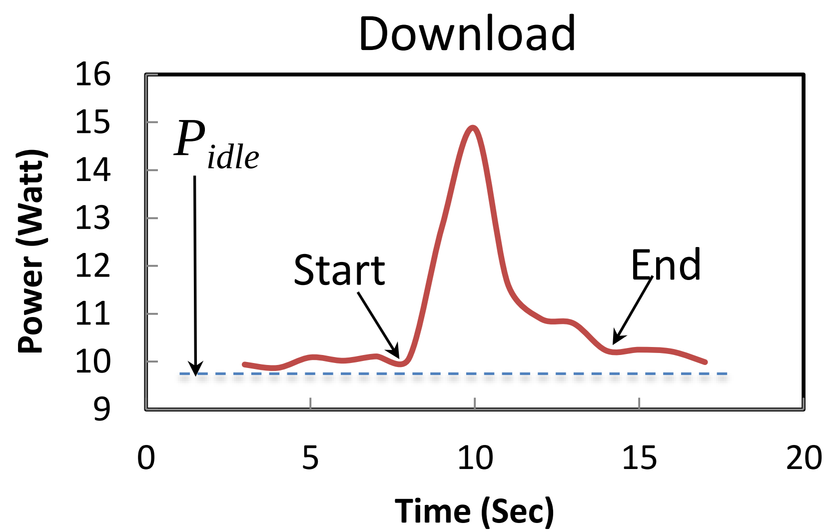
User device measurements

- Direct measurement : Power-mate (resolution of 10 mW)
  - Plots below are for laptop connected via Ethernet
- Uploading and downloading same 5 Mbyte photo





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5MB photo	Laptop		Mobile Phone	
	Ethernet	WiFi	4G	WiFi
Upload	106 J	114 J	40 J	23 J
Download	23 J	33 J	18 J	8 J

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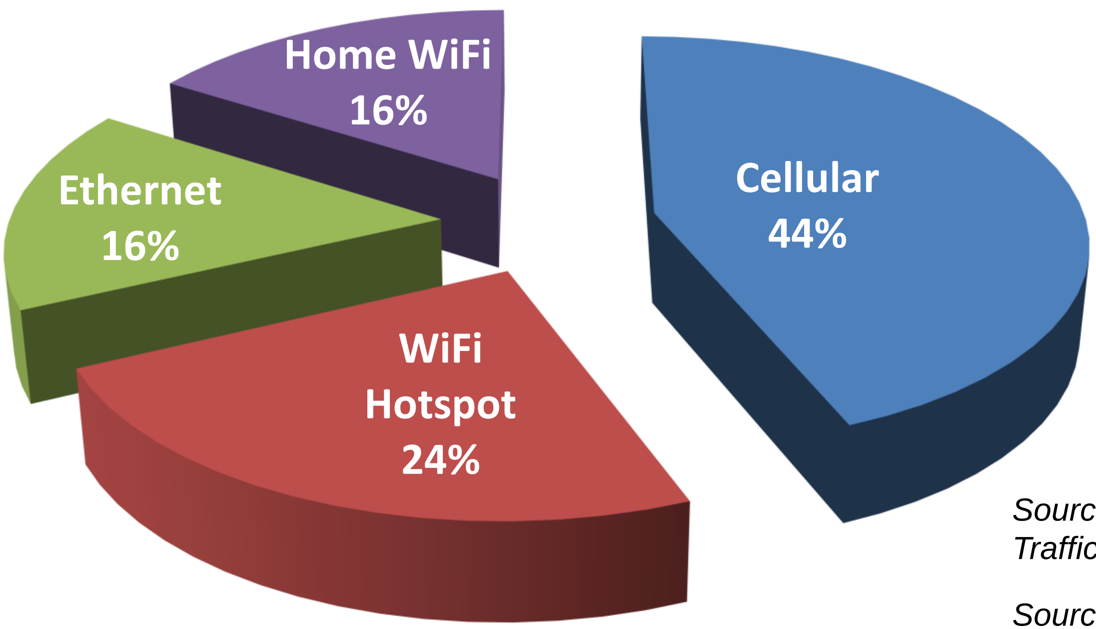
Users' traffic profile

- 350+ million photos upload every day
- Users have 140 friends on average.
- For a new uploaded photo
  - Assume 90% of friends wants to look at the photo (126 friends)

Friend access technologies



Source: Cisco VNI, Global Mobile Data Traffic Forecast Update, 2012–2017

Source: Cisco The zettabyte era, 2012-2017

Network power of a service

(Consequential)

- Two aspects to network power modelling of a service
  1) Individual user model
     - Energy of a single use of the service
       – E.g. Single user accessing their personal Social Network
  2) Global service model
     - Total energy summed over all users of the service
       – E.g. Global energy consumption of a Social Network service

1) Single user involves a small amount of additional data:

– Small increase in network traffic: $\delta R^{(k)} << R_{max}$,

– Don’t need to deploy any additional equipment

$$\delta P^{(k)} = \left\langle \delta P_A^{(k)} \right\rangle + \underbrace{\left(M_E \left\langle E_E \right\rangle + M_C \left\langle E_C \right\rangle \right) \delta R^{(k)}}_{\text{Added metro \& core power}}$$

Added access power

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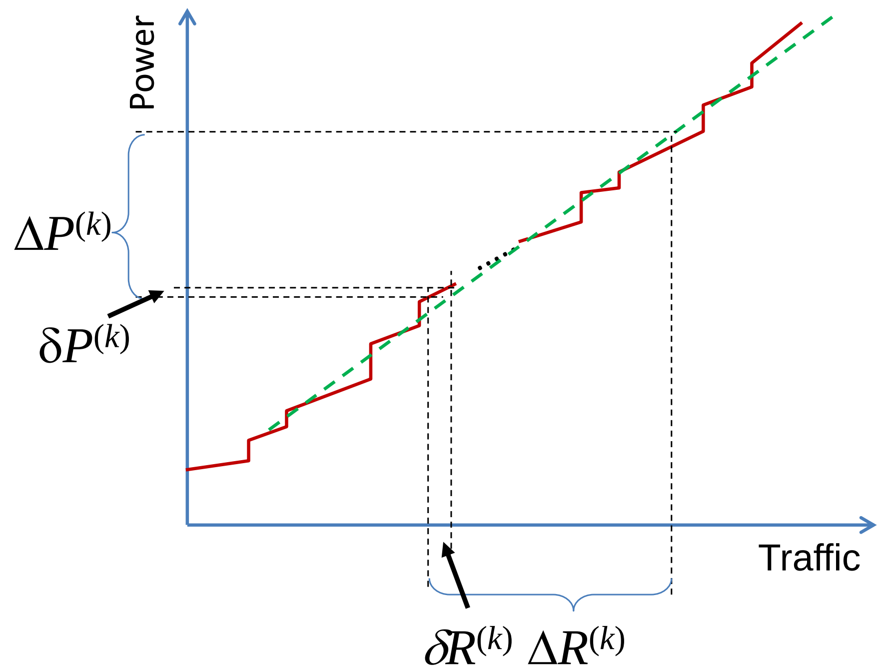
Network power of a service

(Consequential)

- 2) Cumulative increase in network data from all service users
  - Large increase in edge & core network traffic $\Delta R^{(k)} >> R_{max}$
  - Deploy additional edge and core equipment to accommodate ΔR
  - Design rules keep utilisation of equipment below ρ_{max}

$$\Delta N_E = \frac{M_E \Delta R^{(k)}}{\rho_{max} \langle C_{E,max} \rangle}, \qquad \Delta N_C = \frac{M_C \Delta R^{(k)}}{\rho_{max} \langle C_{C,max} \rangle}$$

$$\Delta P^{(k)} = N_{user}^{(k)} \left\langle P_A^{(k)} \right\rangle_{T_{tot}} + \left(\frac{M_E}{\rho_{max}} \left(\frac{\langle P_{idle,E} \rangle}{\langle C_{E,max} \rangle} + \langle E_E \rangle \right) + \frac{M_C}{\rho_{max}} \left(\frac{\langle P_{idle,C} \rangle}{\langle C_{C,max} \rangle} + \langle E_C \rangle \right) \right) \Delta R^{(k)}$$



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Energy consumption of a service

- For edge and core networks (shared equipment) have

$$\Delta P^{(k)} = \left(\frac{M_E}{\rho_{max}} \left(\frac{\langle P_{idle,E} \rangle}{\langle C_{E,max} \rangle} + \langle E_E \rangle \right) + \frac{M_C}{\rho_{max}} \left(\frac{\langle P_{idle,C} \rangle}{\langle C_{C,max} \rangle} + \langle E_C \rangle \right) \right) \Delta R^{(k)}$$

$$= H_{Ntwk} R^{(k)} = \left(Energy / Bit \right)_{Ntwk} \Delta R^{(k)}$$

And for service energy in edge and core networks

$$Q^{(k)} = H_{Ntwk} B^{(k)}$$

- Using $(Energy/bit)_{Ntwk}$ is widely adopted to estimate service energy, user energy and network power

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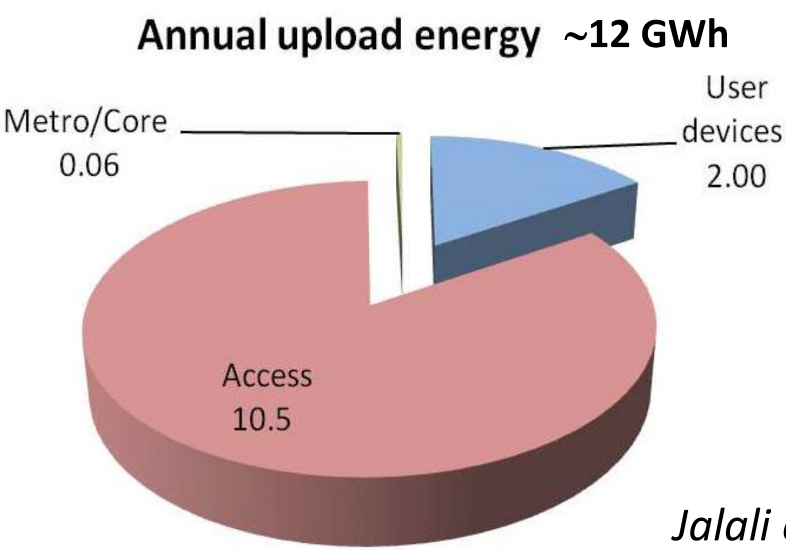
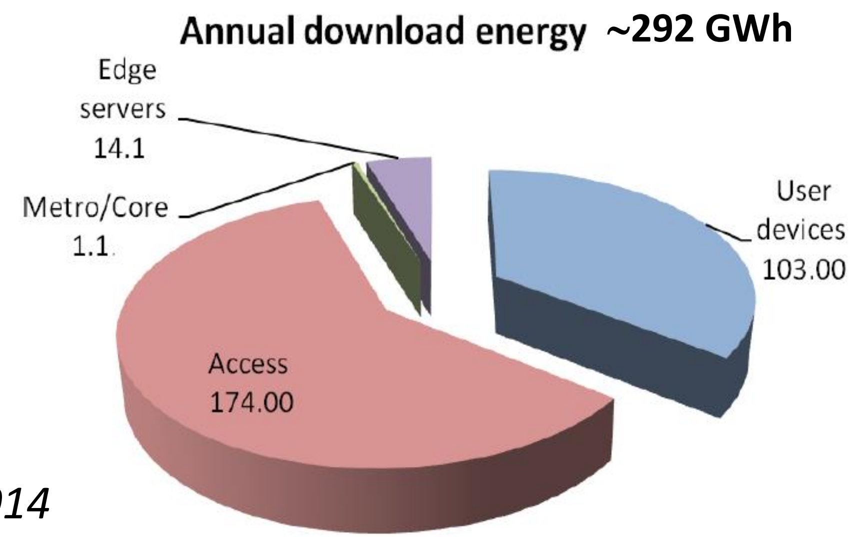
Sharing online network energy

- Total network energy consumption: 304 GWh
- Facebook 2012 total data centre IT energy : 516 GWh

  (Facebook, 2012)
- Photo sharing network energy ~ **60%** of FB total data centre IT energy
  - Wireless (4G/LTE) access network is main energy consumption



Upload energy consumption (GWh)

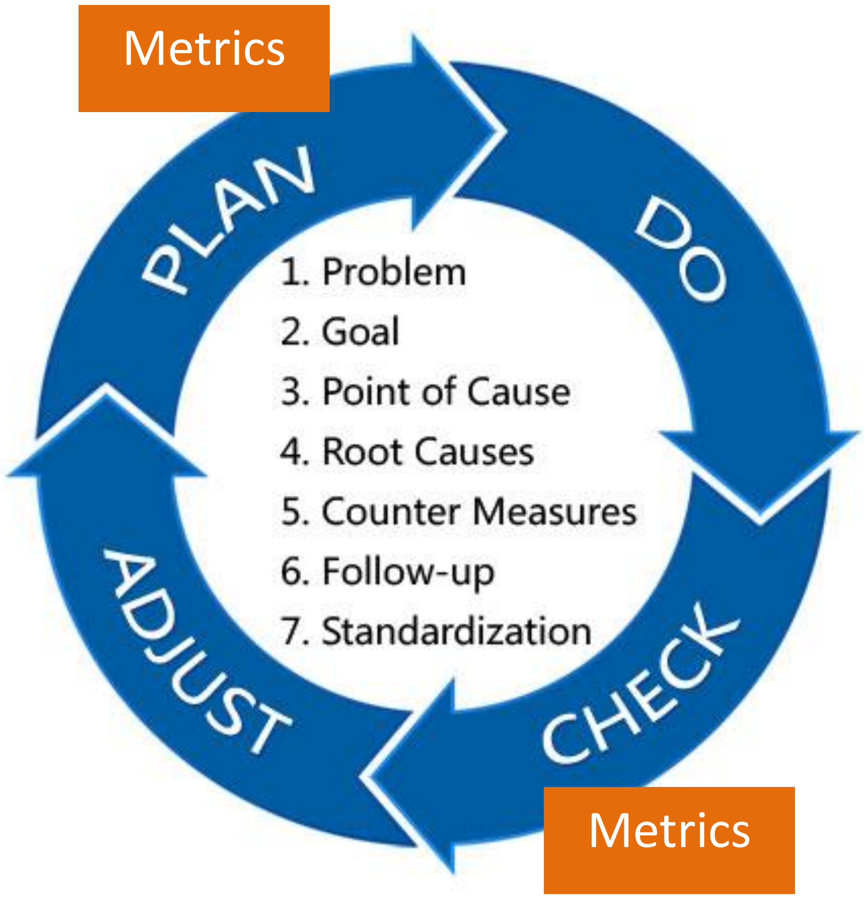


Download energy consumption (GWh)

Jalali et al. 2014

Power & energy efficiency metrics

- To improve a system we must measure it
- Metrics used for:
  - Improvement of a system
    - Reduce energy/bit
  - Comparing systems
    - Benchmarking
  - Identify system parts that require attention
    - Prioritise changes
- Choice of metric is important
  - Diurnal traffic cycle, $C(t)$, is given
  - Metrics drive behaviours



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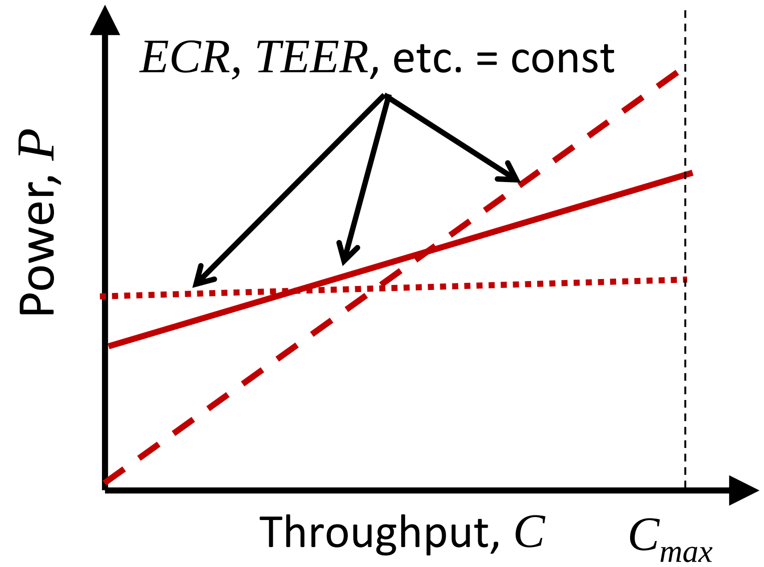
Standardised metrics

- Energy efficiency of equipment
  - Several similar metrics exist

$$ECR, TEER, TEEER, EER = \frac{\sum_{m=1}^{M}\left(a_m \times P_m\right)}{\sum_{m=1}^{M}\left(a_m \times R_m\right)}$$

  - Values a_m set by the definition of ratio
- Same ECR value for very different power profiles
- How are applied for networks & services?



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Energy efficiency: Network operator

- Instantaneous power/bit/sec: (*Baliga J. et al. JLT Vol.27, 2009*)

$$\frac{P_{Ntwk}\left(t_{Peak}\right)}{R_{Ntwk}\left(t_{Peak}\right)}$$

- Mean energy/bit: (*GreenTouch, 2013, 2015*)

$$\frac{\langle P_{Ntwk}\rangle_T}{\langle R_{Ntwk}\rangle_T} = \frac{Total\ Energy_{Ntwk}(T)}{Total\ Bits_{Ntwk}(T)} = \frac{\int_T P_{Ntwk}(t)\,dt}{\int_T R_{Ntwk}(t)\,dt}$$

- Mean instantaneous power/bit/sec (*ITU-T Y.3022, 2013*)

$$\left\langle \frac{P_{Ntwk}}{R_{Ntwk}} \right\rangle_T = Ave.\left(\frac{Power_{Ntwk}}{Thruput_{Ntwk}}\right) = \frac{1}{T}\int_0^T \frac{P_{Ntwk}(t)}{R_{Ntwk}(t)}\,dt$$

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GreenTouch energy efficiency

GreenTouch™

- Used to quantify GreenTouch goals
  - Total energy for years 2010 and 2020
  - Total network traffic for years 2010 and 2020

INCREASE

GROWTH

Revenue from Services

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

Bytes

Watt-hours

REDUCE

Costs

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Energy efficiency: Service provider

- Instantaneous energy per bit: (*Coroama V. et al. Jour. Ind. Ecol., Vol. 47, 2013*)

$$\frac{P^{(k)}(t)}{R^{(k)}(t)}$$

- Mean energy per bit: (*Chen C. et al. Envrion. Sci. Technol., Vol. 17, 2013*)

$$\frac{\left\langle P^{(k)}\right\rangle_T}{\left\langle R^{(k)}\right\rangle_T} = \frac{Mean\ Power^{(k)}(T)}{Mean\ Data\ Rate^{(k)}(T)} = \frac{Energy^{(k)}(T)}{Bits^{(k)}(T)}$$

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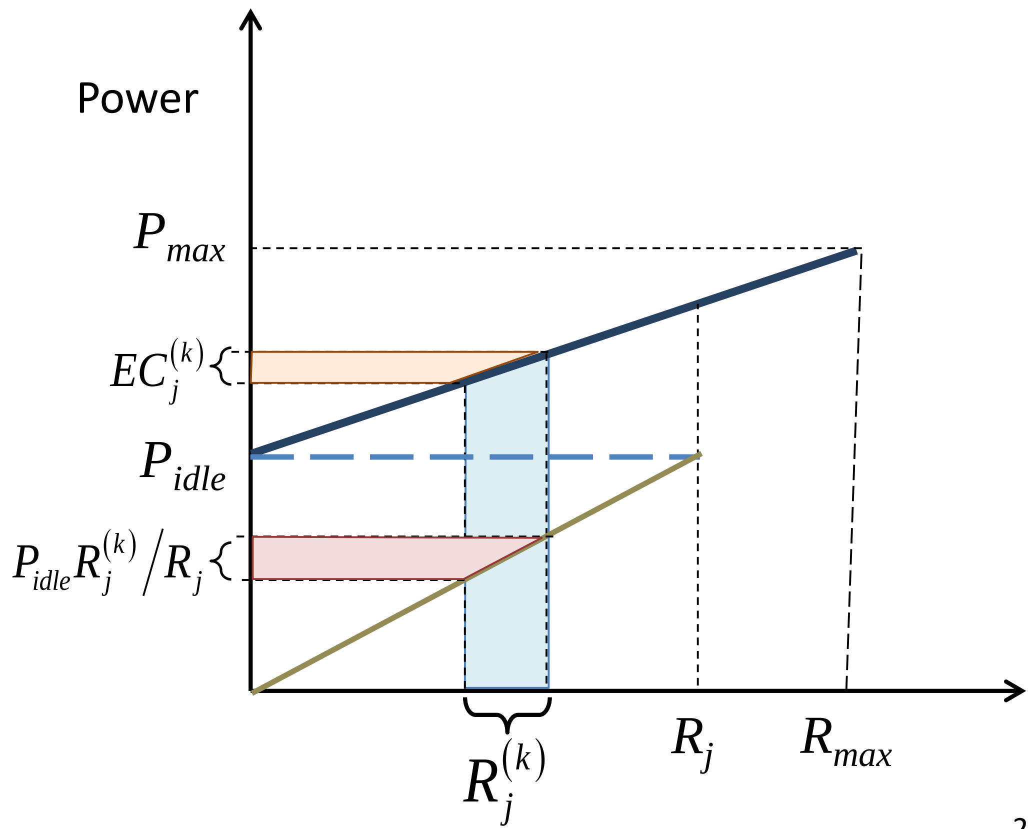
Service power consumption (Attributional)

- Need to allocate P_{idle} across services, k, through network element j
- We require: $$P_{idle,j}(t) = \sum_{k=1} P_{idle,j}^{(k)}(t)$$
- Allocate pro-rata:

$$P^{(k)}(t) = \sum_j \left(\boxed{\frac{P_{idle,j}}{R_j(t)}} + \boxed{E_j} \right) \boxed{R_j^{(k)}(t)}$$

Element j total traffic

Service k traffic thru element j



Service power model

(Attributional)

- For CPE & access equipment have for power of *k*-th service

$$\left\langle P_A^{(k)} \right\rangle = \frac{1}{T_{tot}} \sum_{l=1}^{N^{(k)}} \int_{t_l} P_A(t) - P_{idle} dt + \frac{P_{idle}}{T_{act}} \sum_{l=1}^{N^{(k)}} t_l$$

- For the *j*-th edge or core network element power consumption of *k*-th service is

$$P_j^{(k)}(t) = \frac{P_{idle,j}}{R_j(t)} R_j^{(k)}(t) + E_j R_j^{(k)}$$

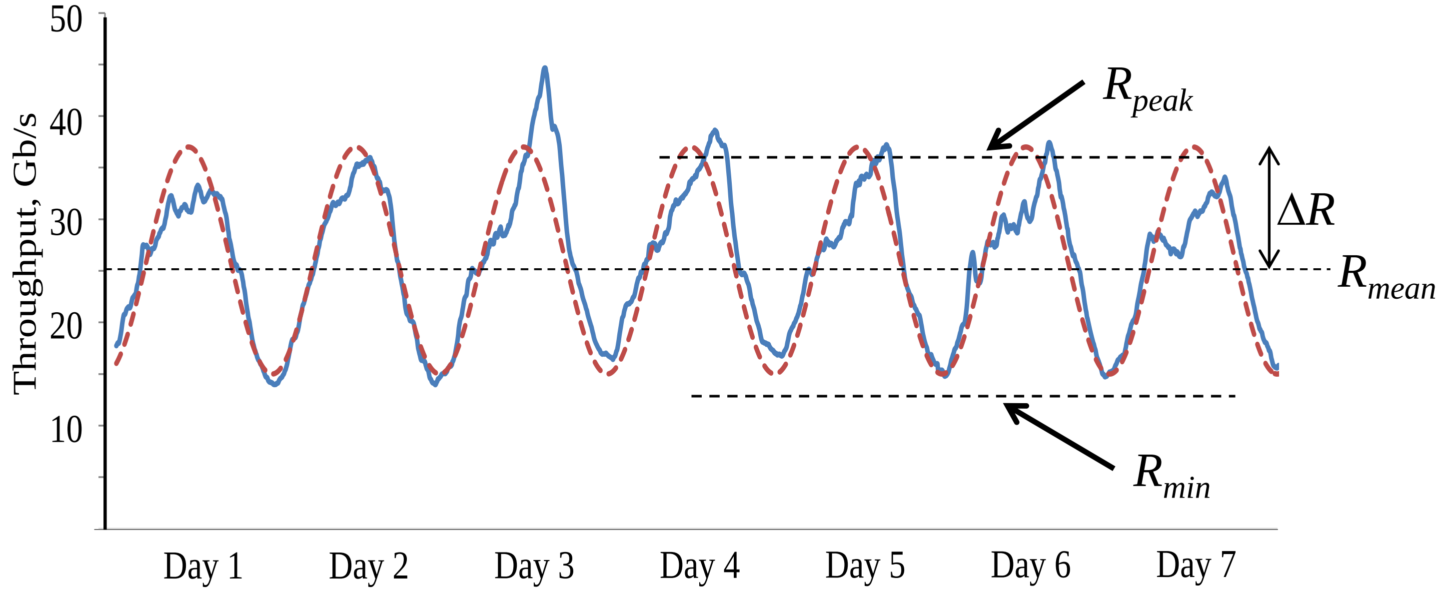
where $R_j^{(k)}$ is the *k*-th service traffic through the *j*-th network element

- Edge, core network power of *k*-th service

$$P_{E+C}^{(k)}(t) = \sum_{j=1}^{N_{N+E}} P_j^{(k)}(t) = \sum_{j=1}^{N_{N+E}} \left(\frac{P_{idle,j}}{R_j(t)} + E_j \right) R_j^{(k)}(t)$$

Diurnal Cycle

- Measured diurnal cycle
  - Has 24 hour period



- Approximate diurnal cycle with a sinusoid

$$R(t) \approx R_{mean} + \Delta R \cos(2\pi t/T)$$

  - Provides closed forms for metrics

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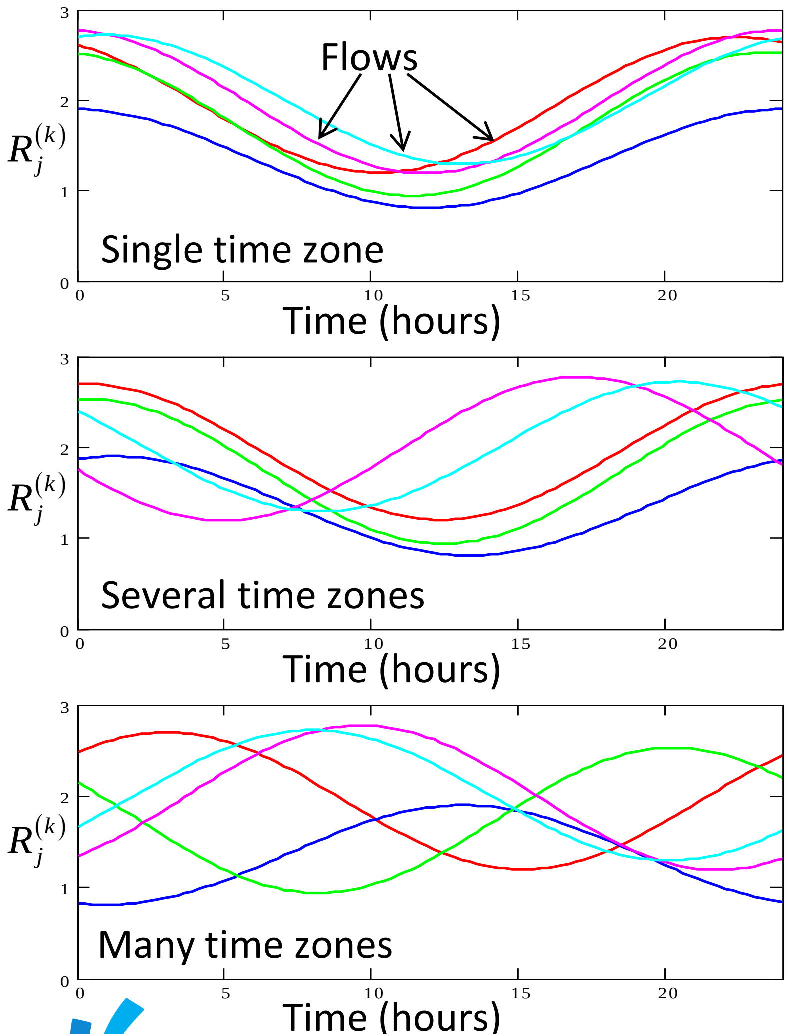
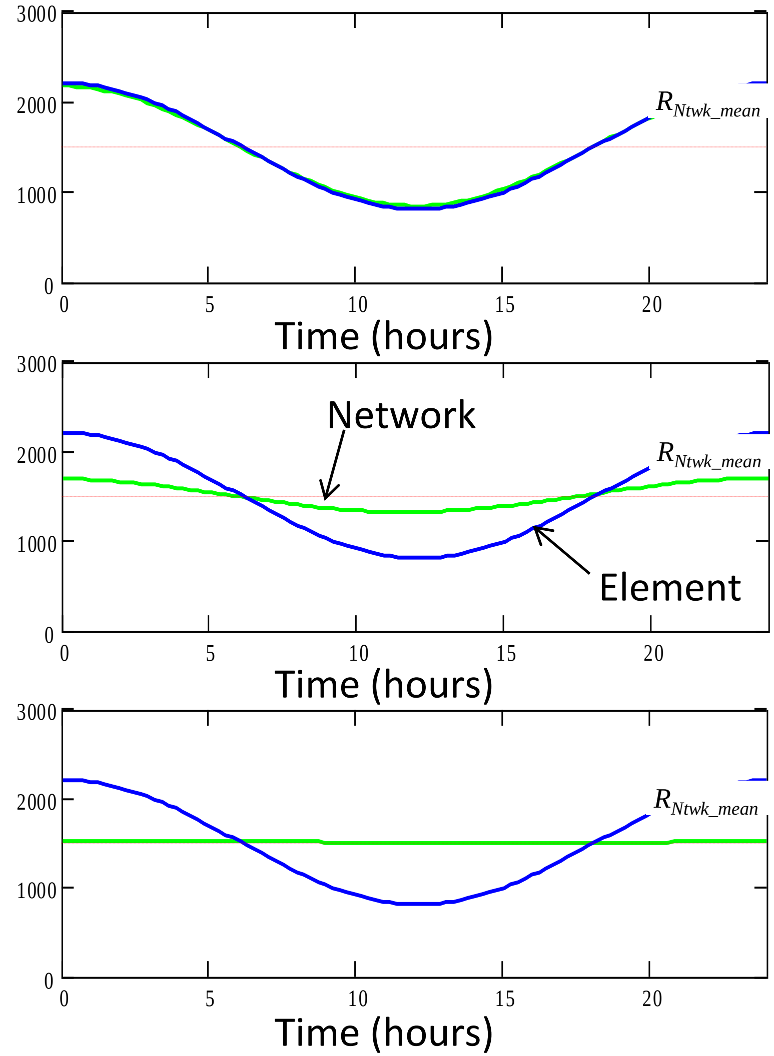
Synchronicity & the diurnal cycle

Service Flows



Element or Network



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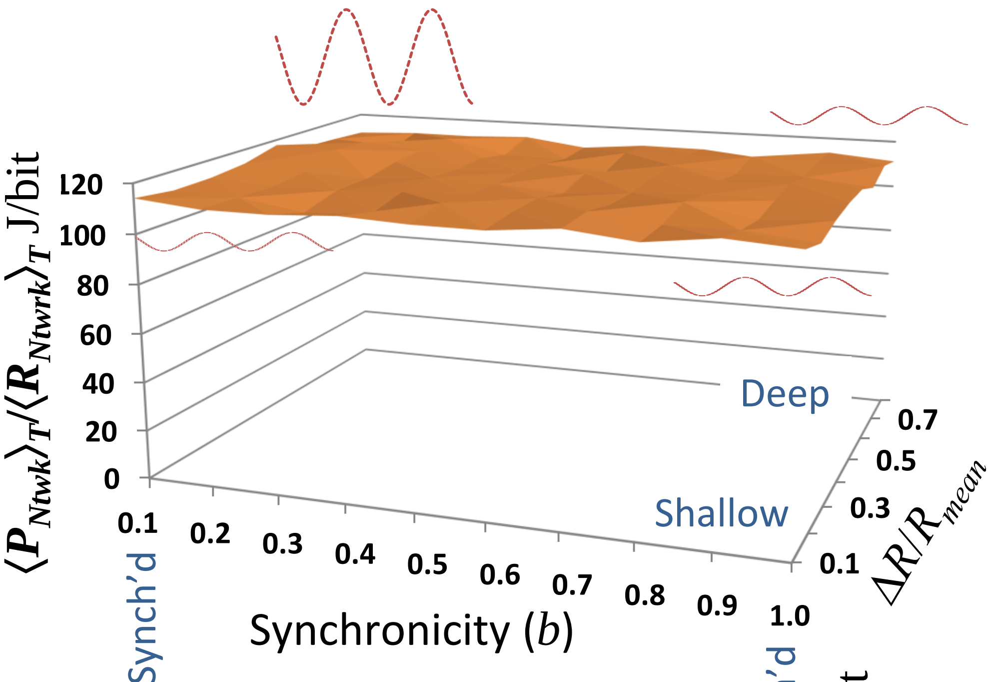
Network energy efficiency

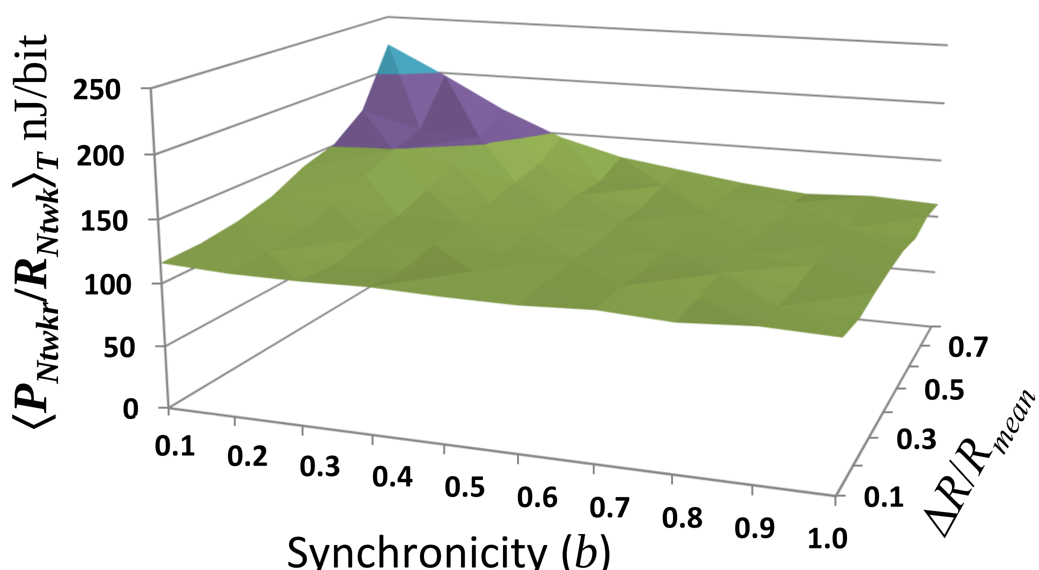


$\langle P_{Ntwk}\rangle_T/\langle R_{Ntwk}\rangle_T$

- Independent of flow synchronisation & cycle depth

$\langle P_{Ntwk}/R_{Ntwk}\rangle_T$

- Dependent on synchronisation & cycle depth



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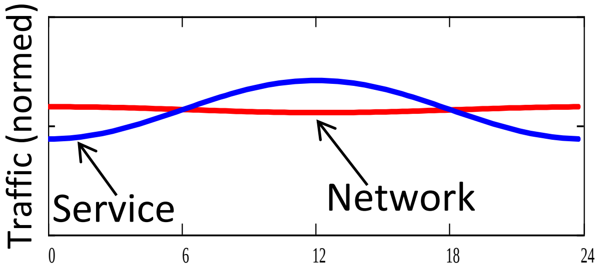
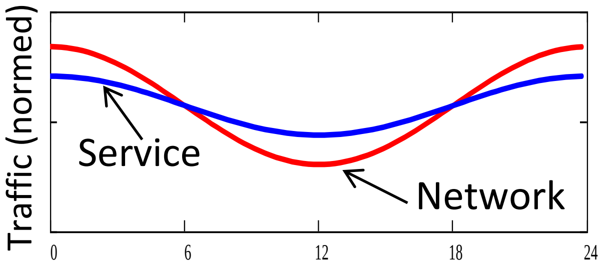
Service energy efficiency

$\langle P \rangle / \langle R \rangle$ metric :

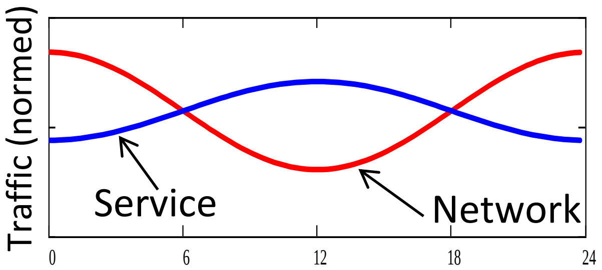
- Synchronisation of service traffic is important
  - Unsynchronised network traffic
    - Energy per bit independent of its service cycle phase



  - Synchronised network traffic
    - Energy per bit lower when service is synchronised with network



    - Energy per bit higher when service is anti-synchronised with network



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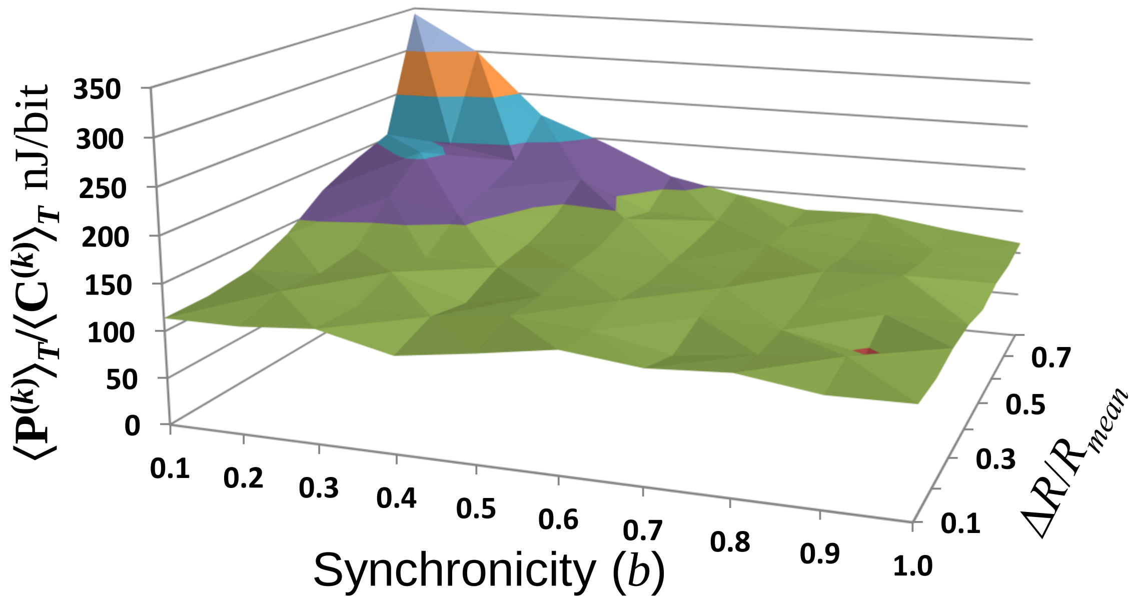
Synchronisation: Service energy efficiency

- Service with fixed out-of-synch cycle ($\phi^{(k)} = \pi$)



- Energy per bit for out-of-synch service
  - Lowest when network has shallow diurnal cycle
  - Highest for anti-synch with deep network diurnal cycle

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Outcomes

Must be careful on how metrics are used

The $\langle P \rangle / \langle R \rangle$ metric:

- Estimating service energy

$$Q^{(k)} = H_{Ntwk} B^{(k)} = \left(\left\langle P_{Ntwk} \right\rangle_T / \left\langle R_{Ntwk} \right\rangle_T \right) B^{(k)}$$

  - This requires k-th service is not “out-of-synch” with network traffic
- When used by Network Operators
  - Metric not impacted by diurnal cycle shape
    - Metric $\langle P_{Ntwk} / R_{Ntwk} \rangle$ can show impact of shape
- When used by Service Providers
  - Energy per bit reduced by synchronising traffic with diurnal cycle
    - This increases R_{peak} requiring more network equipment
- A metric can give different players conflicting strategies

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Thank you