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
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”

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Global mobile data 57% pa
Global IP data 23% pa
Trend mobile efficiency 20%
Trend core efficiency 15%

Cisco, 2015
GreenTouch, 2015
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
Service power

• “Consequential” and “attributitional” 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
  – $R(t_{peak}) = R_{peak} < R_{max}$

$$P(t) = P_{idle} + ER(t)$$
$$= P_{idle} + \left(\frac{P_{max} - P_{idle}}{R_{max}}\right) R(t)$$
Network power and traffic

- Network power is sum power of network elements, \( j \)
  \[
  P_{\text{Ntwk}}(t) = \sum_j \left( P_{\text{idle},j} + E_j R_j(t) \right)
  \]

- Network traffic is sum of service traffics, \( k \)
  \[
  R_{\text{Ntwk}} = \sum_k R^{(k)} \leq \sum_j R_j
  \]

- Element traffic
  \[
  R_j(t) = \sum_{k=1}^{N^{(S)}} R_j^{(k)}(t) = \sum_{k=1}^{N^{(S)}} \alpha_j^{(k)} R^{(k)}(t)
  \]
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, \( k \);

\[
R_{Ntwk}(t) = \sum_{k=1}^{N^{(s)}} R^{(k)}(t) \quad \text{and} \quad P_{Ntwk}(t) = \sum_{k=1}^{N^{(s)}} P^{(k)}(t)
\]

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

*Jalali et al. 2014*
Facebook eco-system

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

Jalali et al. 2014
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 = \( t^{(k)} R^{(k)} \)

\[ P_{\text{min}} \]

\[ T_1 \quad t_1 \quad T_2 \quad t_2 \quad T_3 \quad t_3 \quad T_4 \quad T_n \quad t_n \]

\[ T_{\text{tot}} \]

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

Jalali et al. 2014
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

<table>
<thead>
<tr>
<th>5MB photo</th>
<th>Laptop</th>
<th>Mobile Phone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upload</td>
<td>106 J</td>
<td>114 J</td>
</tr>
<tr>
<td>Download</td>
<td>23 J</td>
<td>33 J</td>
</tr>
</tbody>
</table>

Jalali et al. 2014
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)

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

Source: Cisco  The zettabyte era, 2012-2017
Network power of a service

- 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

\[
\delta P^{(k)} = \left< \delta P_{A}^{(k)} \right> + \left( M_E \left< E_E \right> + M_C \left< E_C \right> \right) \delta R^{(k)}
\]

- Added access power
- Added metro & core power
Network power of a service

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

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

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

**Figure:**
- Power vs Traffic graph showing $\Delta P^{(k)}$ and $\delta P^{(k)}$ as green dashed line and $\Delta R^{(k)}$ as partially filled stepwise graph.

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(Consequential)
Energy consumption of a service

• For edge and core networks (shared equipment) have

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

\[
= H_{\text{Ntwk}} R^{(k)} = \left( \frac{\text{Energy}}{\text{Bit}} \right)_{\text{Ntwk}} \Delta R^{(k)}
\]

And for service energy in edge and core networks

\[
Q^{(k)} = H_{\text{Ntwk}} B^{(k)}
\]

• Using \((\text{Energy}/\text{bit})_{\text{Ntwk}}\) is widely adopted to estimate service energy, user energy and network power
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 \(\sim 60\%\) of FB total data centre IT energy
  – Wireless (4G/LTE) access network is main energy consumption

\[\text{Annual upload energy} \sim 12 \text{ GWh}\]

\[\text{Annual download energy} \sim 292 \text{ GWh}\]

\(Jalali \text{ et al.} \ 2014\)
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
Standardised metrics

- Energy efficiency of equipment
  - Several similar metrics exist
    \[ ECR, TEER, TEEER, EER = \frac{\sum_{m=1}^{M} (a_m \times P_m)}{\sum_{m=1}^{M} (a_m \times R_m)} \]
  - Values \( a_m \) set by the definition of ratio
- Same ECR value for very different power profiles
- How are applied for networks & services?
Energy efficiency: Network operator

- Instantaneous power/bit/sec: \((\text{Baliga J. et al. JLT Vol.27, 2009})\)

\[
\frac{P_{\text{Netwk}}(t_{\text{Peak}})}{R_{\text{Netwk}}(t_{\text{Peak}})}
\]

- Mean energy/bit: \((\text{GreenTouch, 2013, 2015})\)

\[
\frac{\langle P_{\text{Netwk}} \rangle_T}{\langle R_{\text{Netwk}} \rangle_T} = \frac{\text{Total Energy}_{\text{Netwk}}(T)}{\text{Total Bits}_{\text{Netwk}}(T)} = \int_T P_{\text{Netwk}}(t) dt \\
\int_T R_{\text{Netwk}}(t) dt
\]

- Mean instantaneous power/bit/sec \((\text{ITU-T Y.3022, 2013})\)

\[
\frac{\langle P_{\text{Netwk}} \rangle_T}{\langle R_{\text{Netwk}} \rangle_T} = \text{Ave.} \left( \frac{\text{Power}_{\text{Netwk}}}{\text{Thruput}_{\text{Netwk}}} \right) = \frac{1}{T} \int_0^T \frac{P_{\text{Netwk}}(t)}{R_{\text{Netwk}}(t)} dt
\]
GreenTouch energy efficiency

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

\[
\text{Network Efficiency} = \frac{\text{Total Useful Traffic Delivered}}{\text{Total Energy Consumed}}
\]
Energy efficiency: Service provider

  \[
  \frac{P^{(k)}(t)}{R^{(k)}(t)}
  \]

  \[
  \frac{\left\langle P^{(k)} \right\rangle_T}{\left\langle R^{(k)} \right\rangle_T} = \frac{\text{Mean Power}^{(k)}(T)}{\text{Mean Data Rate}^{(k)}(T)} = \frac{\text{Energy}^{(k)}(T)}{\text{Bits}^{(k)}(T)}
  \]
Service power consumption

- Need to allocate $P_{idle}$ across services, $k$, through network element $j$
- We require:

$$P_{idle,j}(t) = \sum_{k=1}^{\infty} P_{idle,j}(t)$$

- Allocate pro-rata:

$$P^{(k)}(t)$$

$$= \sum_{j} \left( \frac{P_{idle,j}}{R_{j}(t)} \right) + E_{j} R_{j}^{(k)}(t)$$

- Element $j$
- Total traffic
- Service $k$ traffic thru element $j$
Service power model

• 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

\[ R(t) \approx R_{\text{mean}} + \Delta R \cos\left(\frac{2\pi t}{T}\right) \]

– Provides closed forms for metrics
Synchronicity & the diurnal cycle

Service Flows

Element or Network

Single time zone

Several time zones

Many time zones
Network energy efficiency

\[ \langle \frac{P_{Ntwk}}{R_{Ntwk}} \rangle_T \]
- Independent of flow synchronisation & cycle depth

\[ \langle \frac{P_{Ntwk}}{R_{Ntwk}} \rangle_T \]
- Dependent on synchronisation & cycle depth
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
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
Outcomes

Must be careful on how metrics are used

The \( \langle P \rangle / \langle R \rangle \) metric:

- **Estimating service energy**
  \[
  Q^{(k)} = H_{Ntwk} B^{(k)} = \left( \langle P_{Ntwk} \rangle_T / \langle R_{Ntwk} \rangle_T \right) B^{(k)}
  \]
  - 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**
Thank you