TRENDs in Green Networking

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Objectives of this tutorial

- *General issues*
  - Learn motivations to green ICT as a research field
  - Enlighten the positive and negative role of ICT
- *Networking: focus on wireless*
  - Review some of the approaches under investigation by the scientific community
  - Identify challenges that need further studies

Objectives of this tutorial

- What the tutorial does *not* provide
  - View of the problem in terms of energy production
  - Overview of electronic and physical layer solutions (focus on networking)
  - Definite solutions/answers to the most important questions related to energy efficiency in networking
  - Tools to evaluate the environmental impact of energy consumption and ICT devices production and dismissal

Agenda

- Energy as a major issue
- Energy as an issue for ICT
- A few data on data centers
- Consumption in the networks
- The case of cellular access networks
  - Sleep modes
  - Network sharing
  - Powering with renewable energy sources

A project on energy efficiency

- TREND – http://www.fp7-trend.eu/
  *Towards Real Energy-efficient network des*ign
  - FP7 - Network of Excellence with **12 partners** (2 manufacturers + 3 telecom operators + 7 university groups) + Collaborating Institutions
  - Coordinated by Marco Ajmone Marsan in my group
  - Duration: September 2010 – November 2013
  - Effort: 483 person/months
  - Project budget: 4.5 M€, EC contribution: 3.0 M€

TREND Consortium

Politecnico di Torino
Universidad Carlos III de Madrid
Interdisciplinary Institute for Broadband Technology
Technische Universitat Berlin
Ecole Polytechnique Federale de Lausanne
Consorzio Interuniversitario per le Telecomunicazioni
Panepistimio Thessalias

Academic

Alcatel- Lucent Bell Labs France
Huawei Technologies Duesseldorf GmbH

Manufacturers

Telefonica Investigacion Y Desarrollo SA
France Telecom SA
FASTWEB SPA

Operators

Current Collaborating Institutions

- Fondazione Ugo Bordoni, Italy
- Technische Universitat Dresden, Germany
- Deutsche Telekom Laboratories, Germany
- Institute IMDEA Networks, Spain
- ICAR-CNR (CNR Inst. for High Performance Computing and Networking), Italy
- International Hellenic University, Greece
- INRIA (Inst. National de Recherche en Informatique et en Automatique), France
- Boston University, USA
- Zuse Institut Berlin, Germany (signature pending)

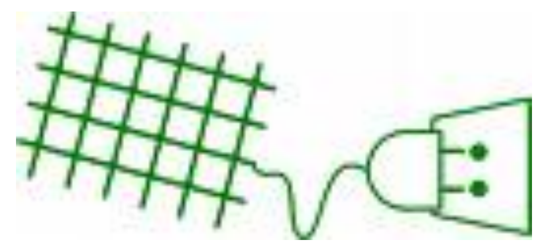
TREND actions

- Holistic view of green networking, putting together different competence and research interests
- Coordination and creation of an identity for the European research on energy-efficient networking through integration and collaboration
- Work on specific technical objectives jointly pursued within the Network of Excellence
- Establishing contacts and links among FP7 projects, national programmes and with projects outside the FP7-framework (i.e., GreenTouch)
- Dissemination of the TREND know-how and view on green networking

Introduction

Data and motivations

What's all this "green networking" about?



The Problem

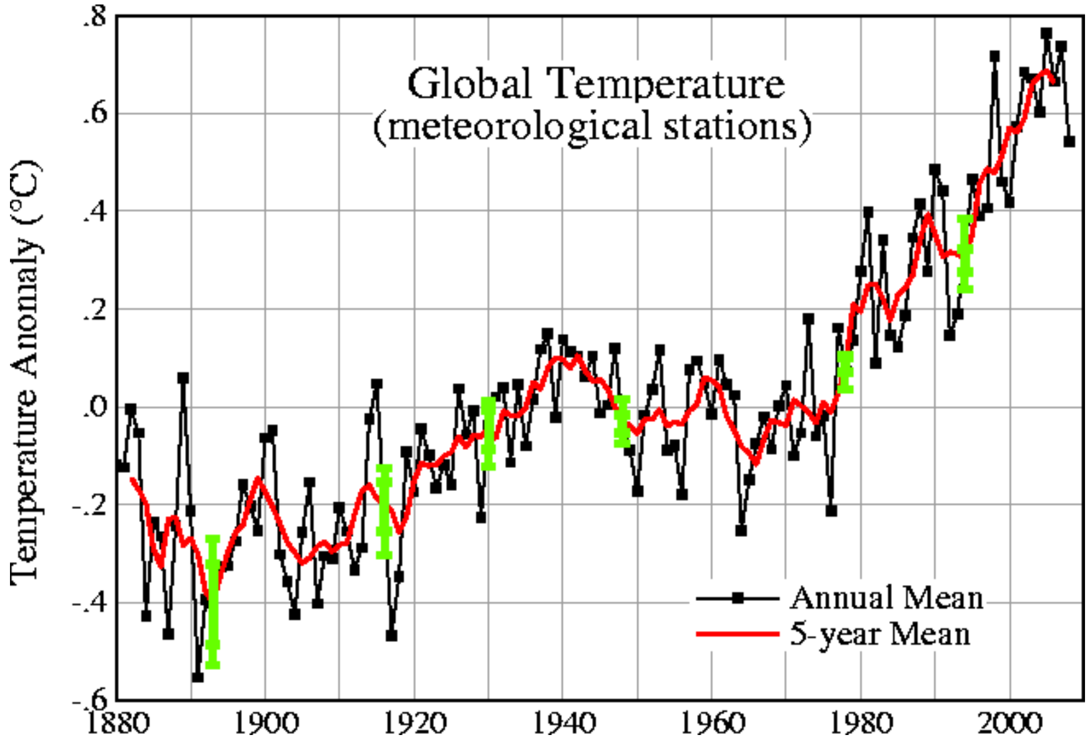
- Energy is becoming *the issue* of our future
  - Energy consumption is causing dramatic *climate changes*
  - We depend on energy which is becoming *scarce*

- We must cope with this and reduce energy consumption in all sectors,

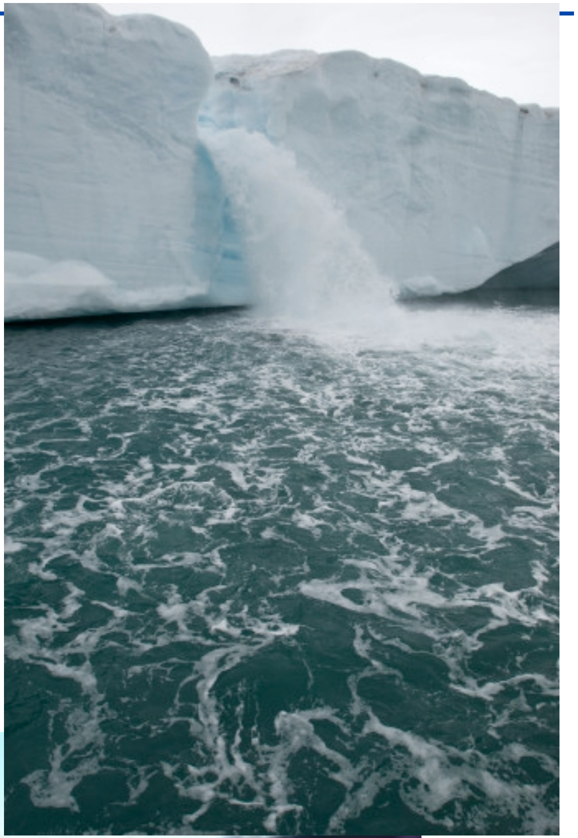
ICT and networking included

Climate changes

The atmosphere is threatened by human inducted climate changes



Climate changes

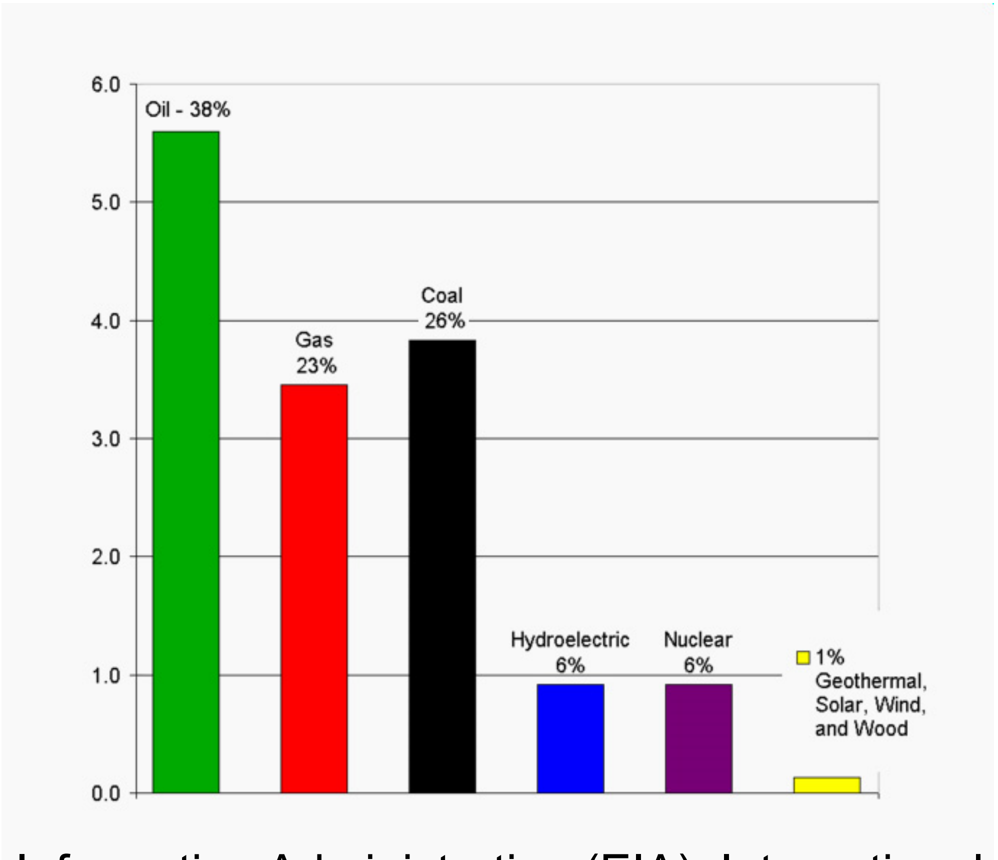


Who is the culprit?

- The main global warming culprit is carbon dioxide, CO_2
- Gases that react to form smog
- Fine particles such as black carbon

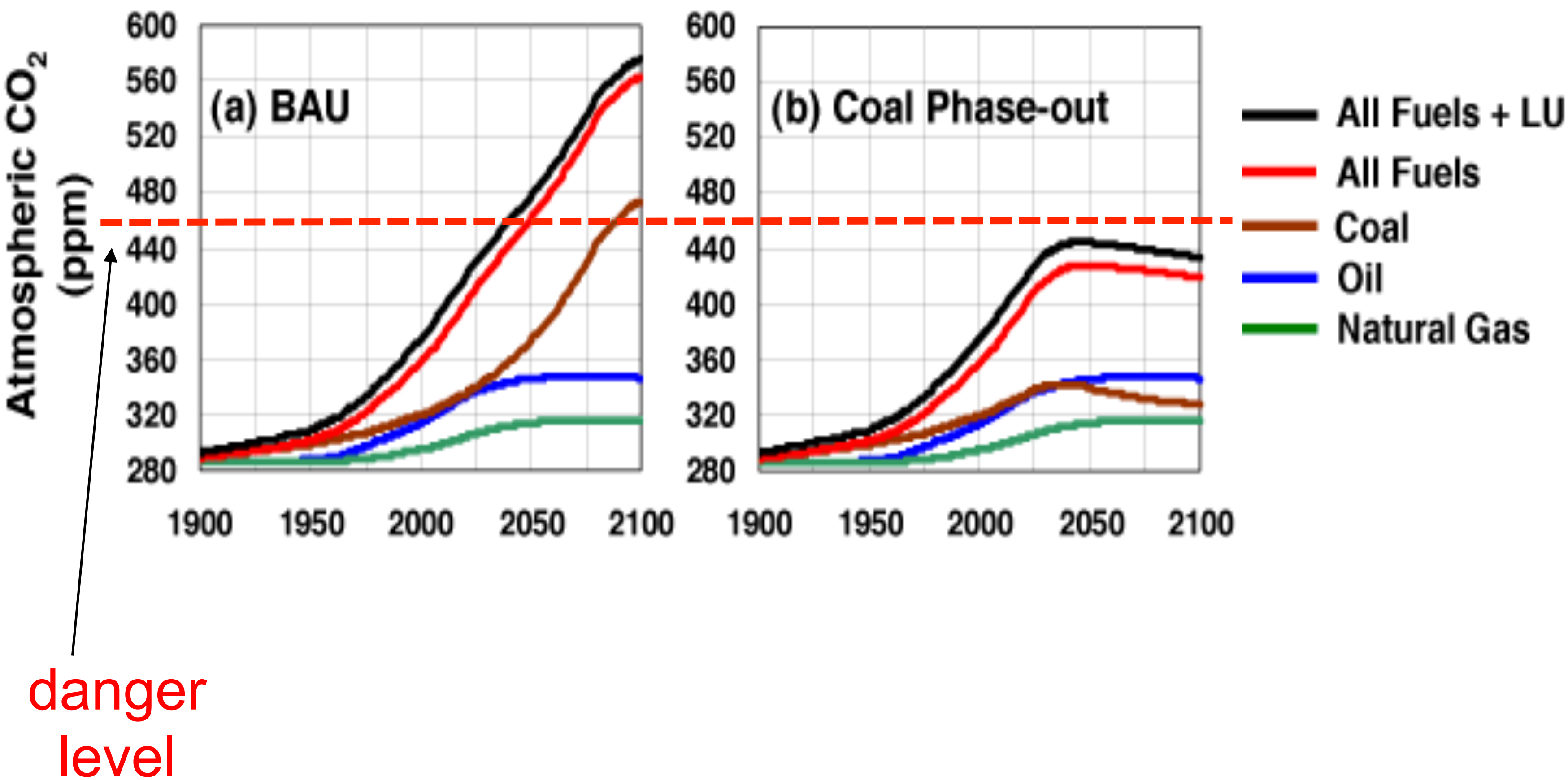
- 80% of the increase of CO_2 in the air in the last century is due to fossil fuel burning (20% deforestation)

Energy sources



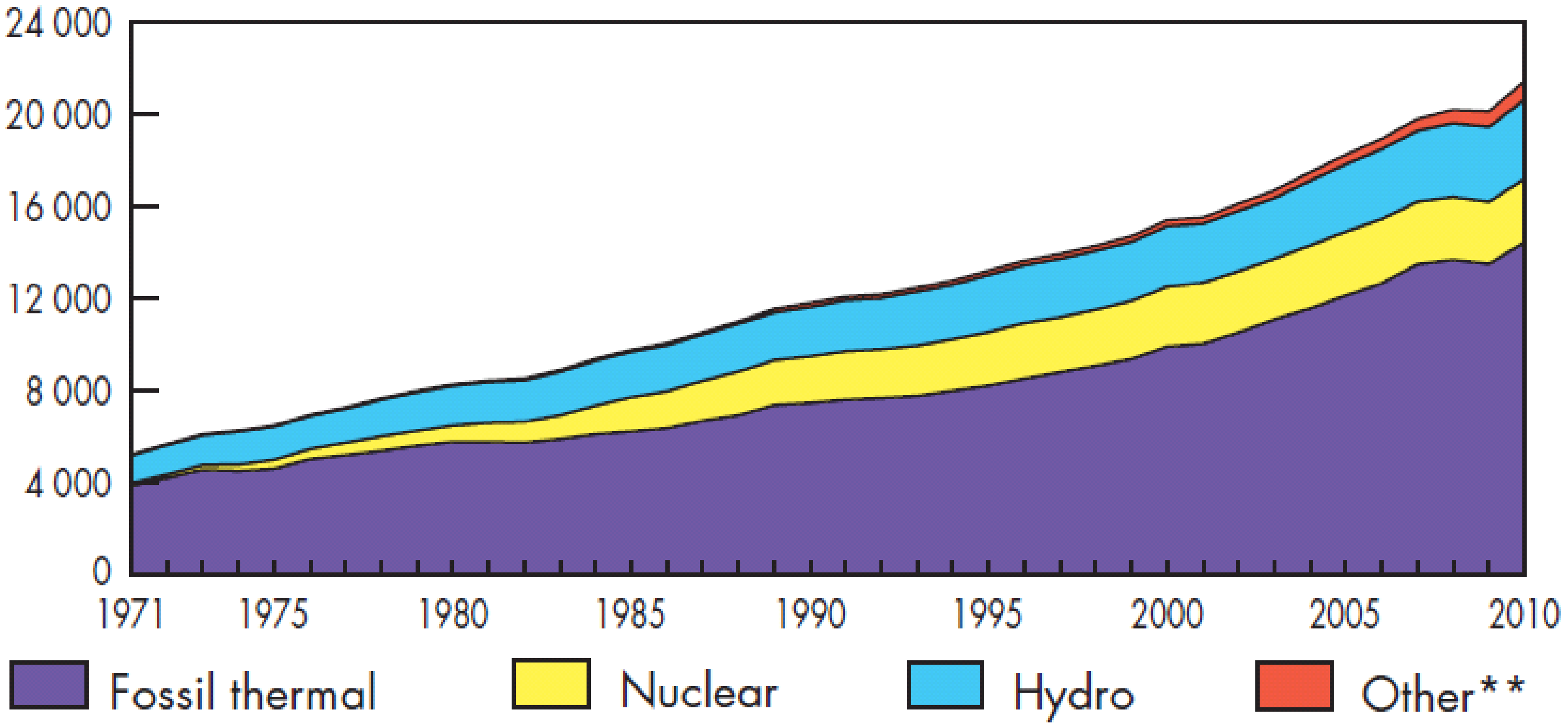
Source: Energy Information Administration (EIA), International Energy – Annual Energy Outlook 2009

Energy sources



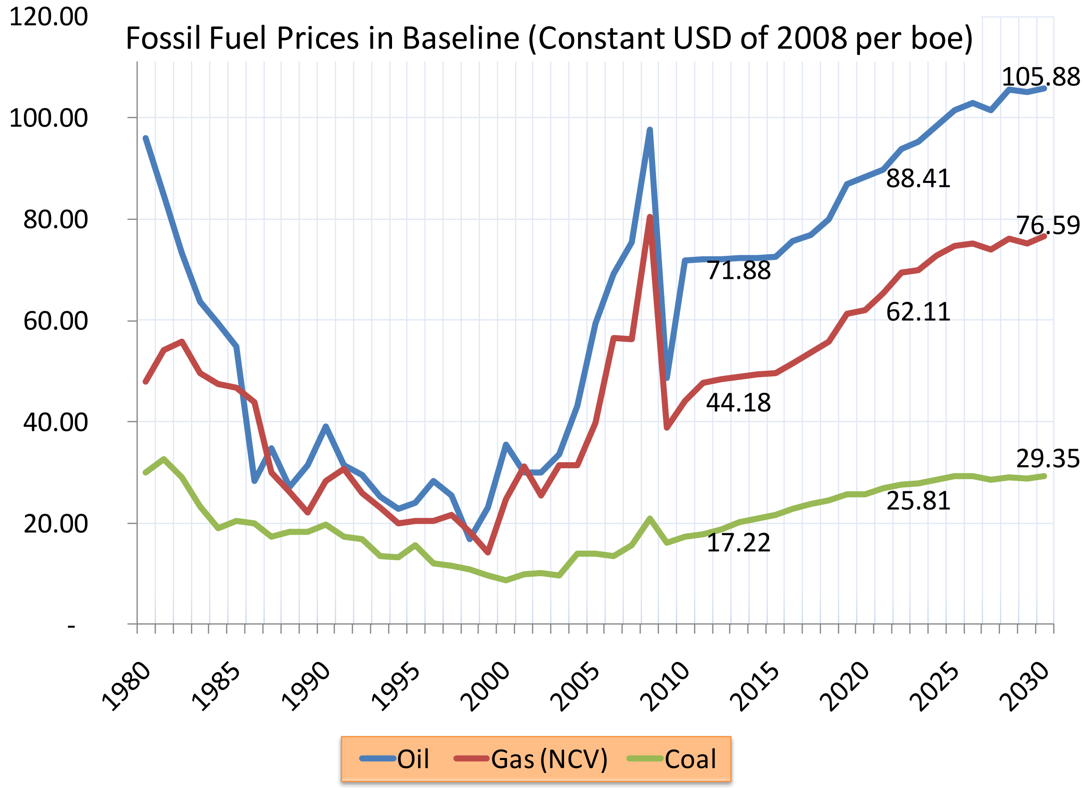
Source: NASA, Goddard Institute for Space Studies, NY, USA.

Fossil technologies



World electricity generation from 1971 to 2010 by fuel (TWh) [source IEA]

Fossil fuel prices



Source: EU Energy Trends to 2030, European Commission.

What about ICT?

- Information and Communication Technologies (ICT) plays a positive role for energy saving:
  - *moving bits instead of atoms*
    - intelligent transport systems
    - teleworking and telecommuting
    - e-commerce
    - electronic billing
  - new manufacturing systems
  - sensors to monitor and manage our environment
    - smart buildings, neighborhoods, cities …

ICT positive role

- ICT will allow saving of the order of
  - 25-30% in manufacturing
  - 26% in transport sector
  - 5-15% in buildings

  for a total of about 17-22%
- Moreover, ICT is expected to significantly improve the energy generation, transport and utilization through the novel concept of *Smart Grid*

Source: Ad-hoc Advisory Group „ICT for Energy Efficiency“ of the European Commission DG INFSO, 2008.

… but

ICT sector is also a great consumer!

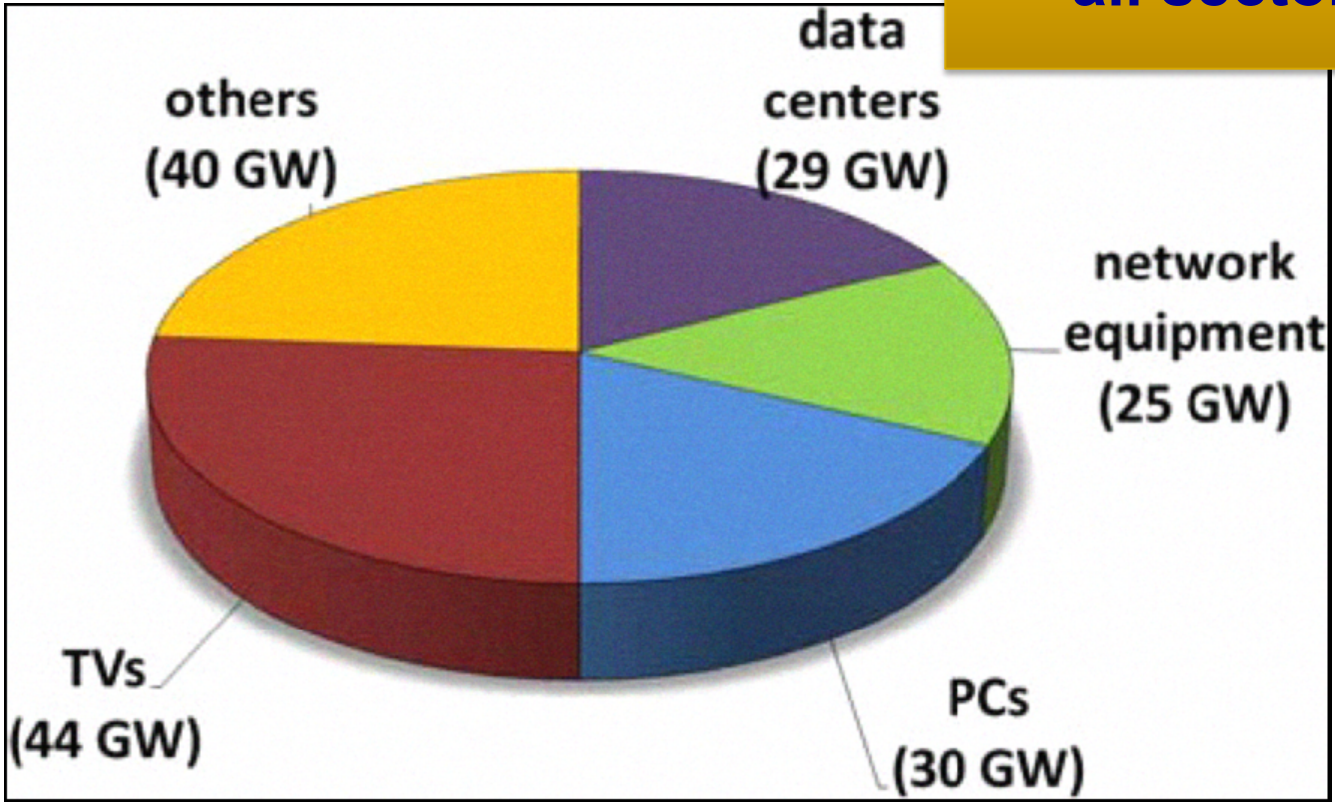
"ICT alone is responsible of a percentage which vary from 2% to 10% of the world power consumption."

"Electricity demand of ICT is almost 11% of the overall final electricity consumption in Germany."

"ICT sector produces some 2 to 3%of total emissions of greenhouse gases."

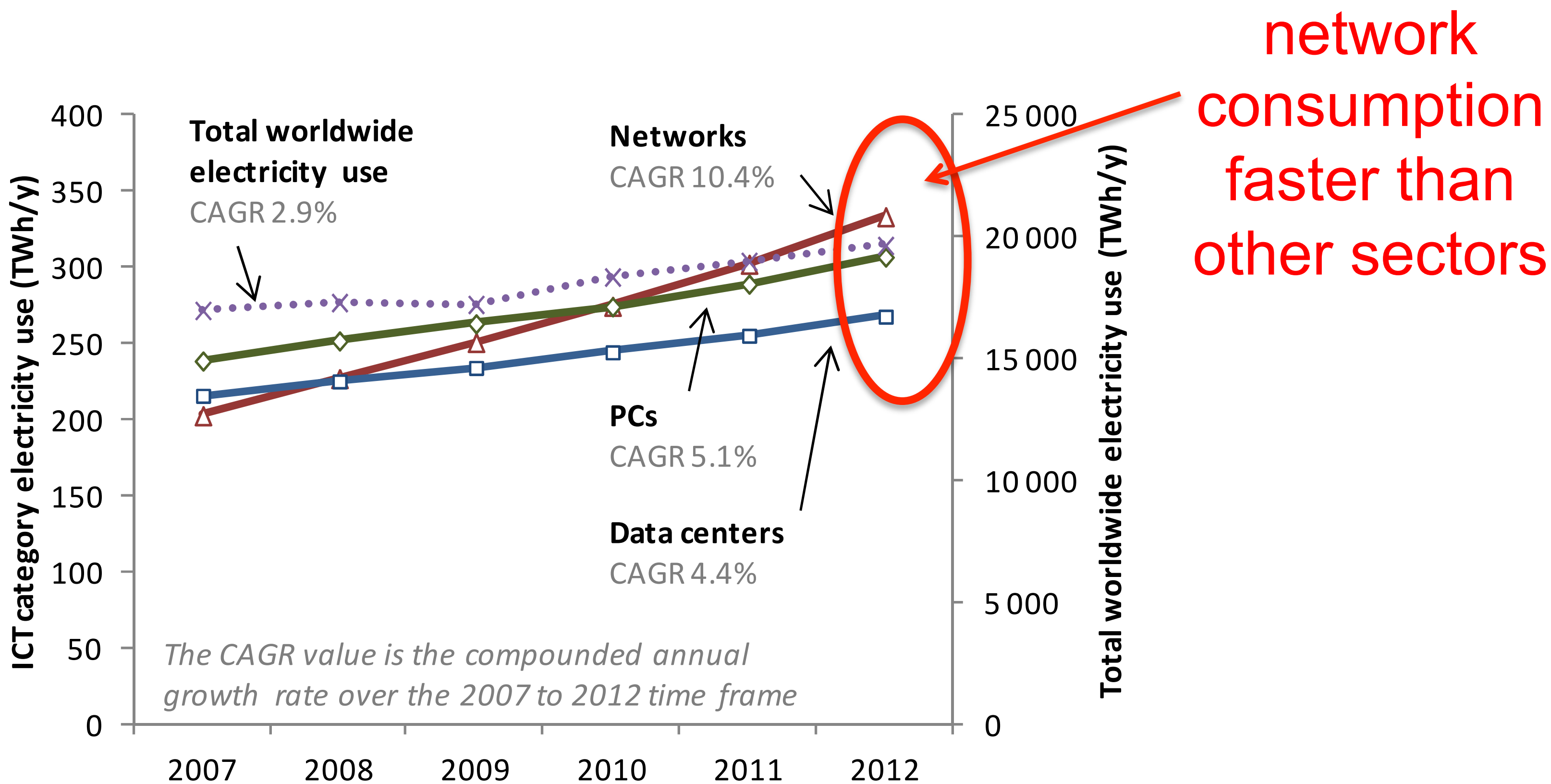
Which ICT?

need to work on all sectors



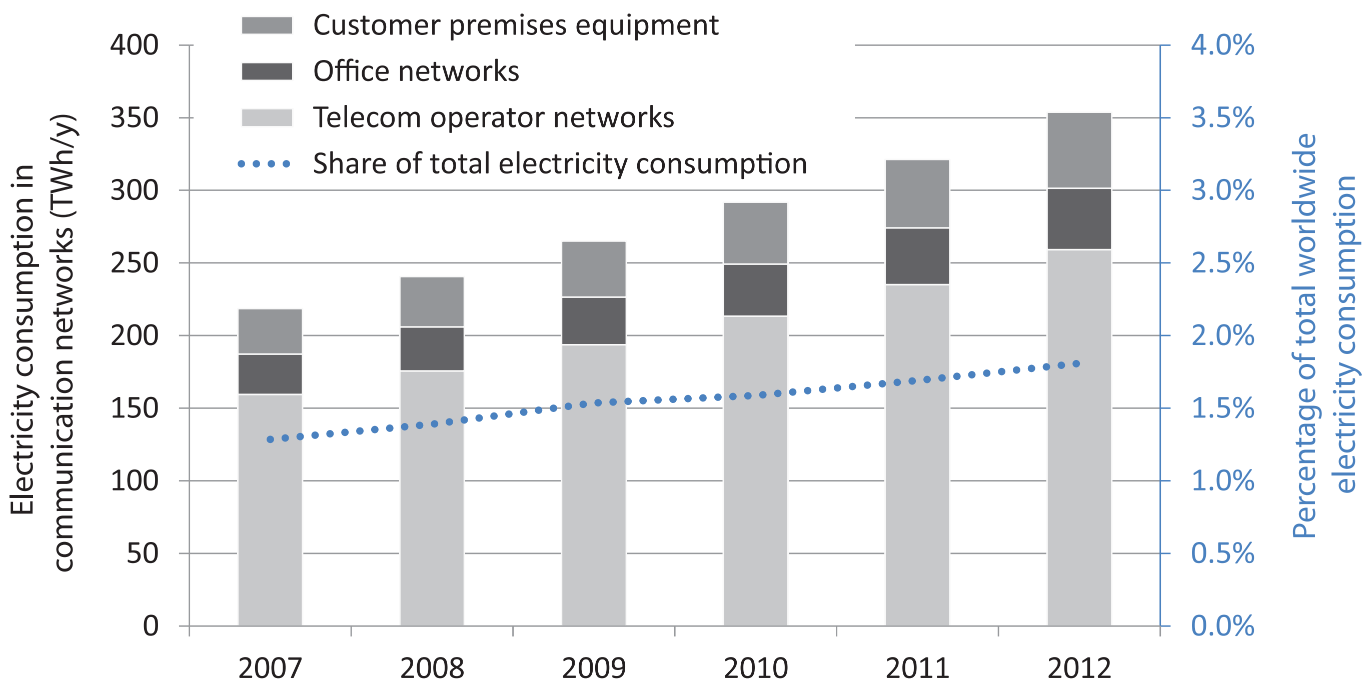
Source: M. Pickavet et al, "Worldwide Energy Needs for ICT: the Rise of Power-Aware Networking," in IEEE ANTS Conference, Bombay, India, Dec. 2008.

Consumption is increasing



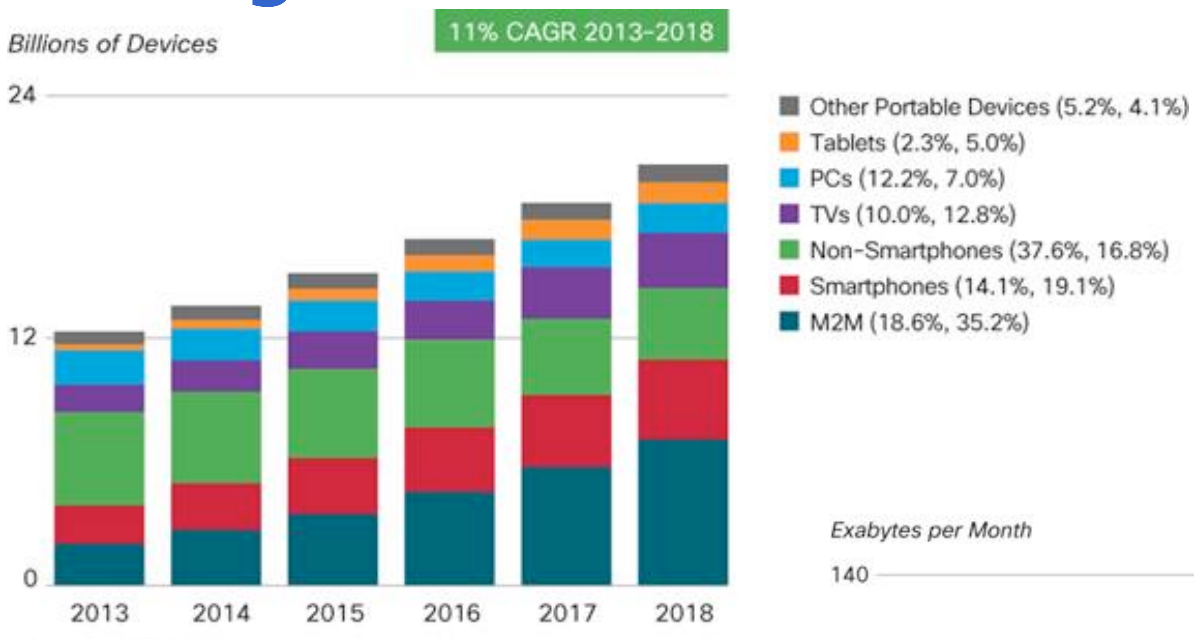
Source: TREND Final Deliverable on "Assessment of power consumption in ICT", 2013.

Consumption is increasing



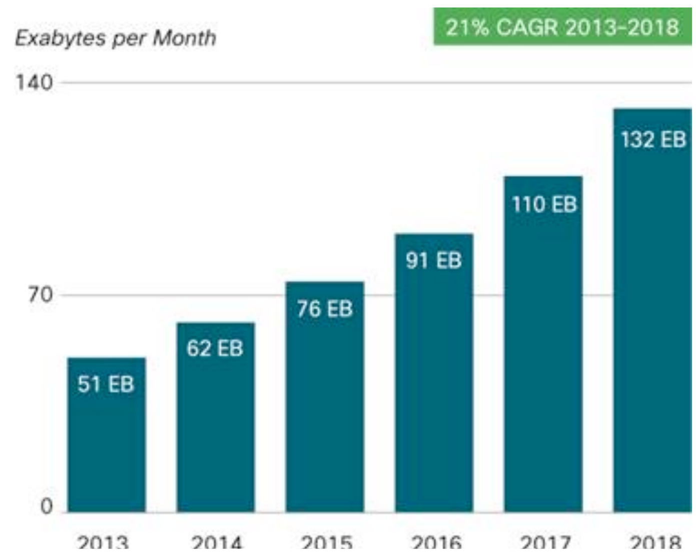
Source: S. Lambert et al., "Worldwide electricity consumption of communication networks," Optics Express, Vol. 20, Issue 26, 2012

Traffic growth



number of devices grows (new markets)

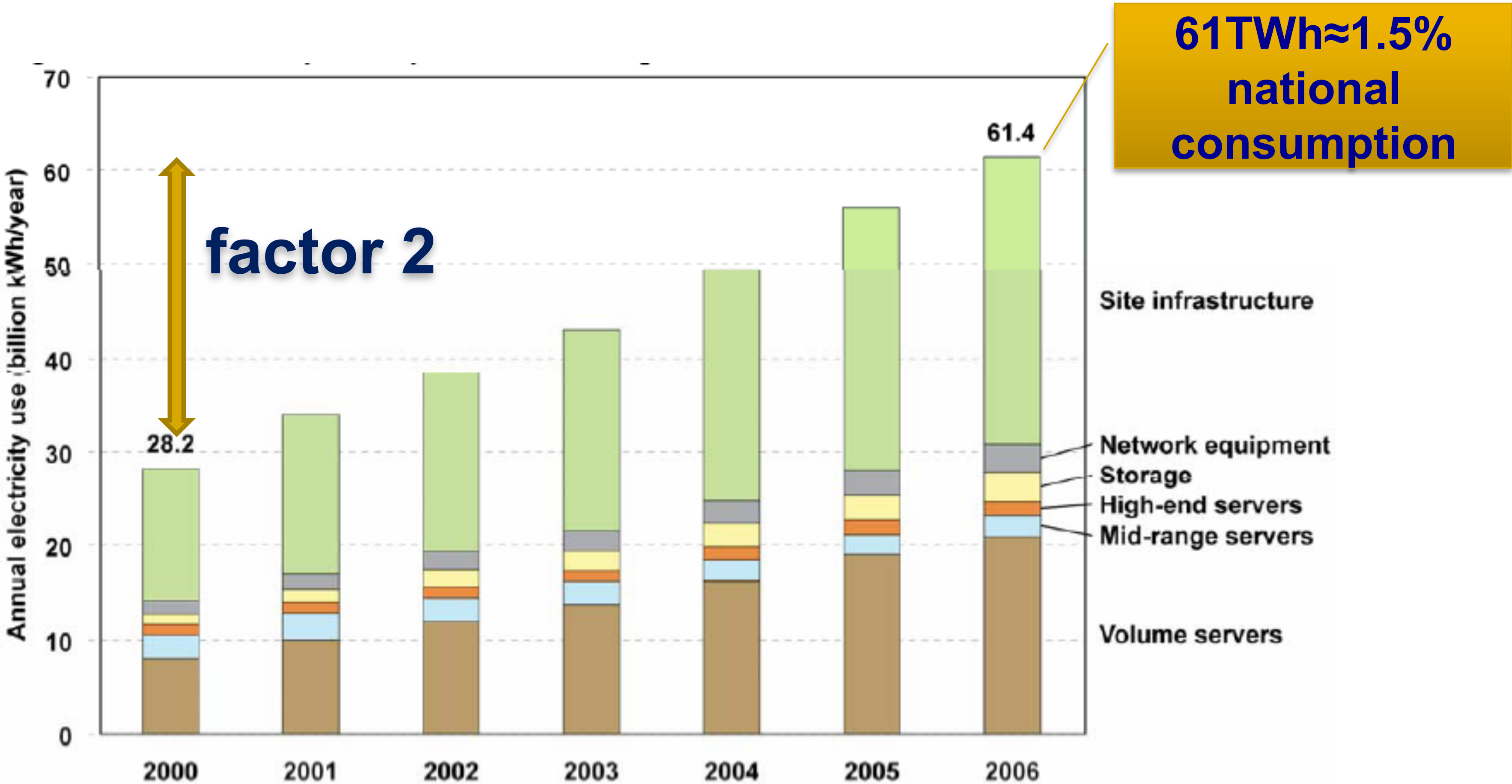
new and more traffic intensive services



Source: Cisco VNI, 2014.

Data Centers

Consumption due to data centers



Source: Report to Congress on Server and Data Center Energy Efficiency Public Law 109-431. U.S. Environmental Protection Agency ENERGY STAR Program , August 2007

Power Usage Effectiveness (PUE)

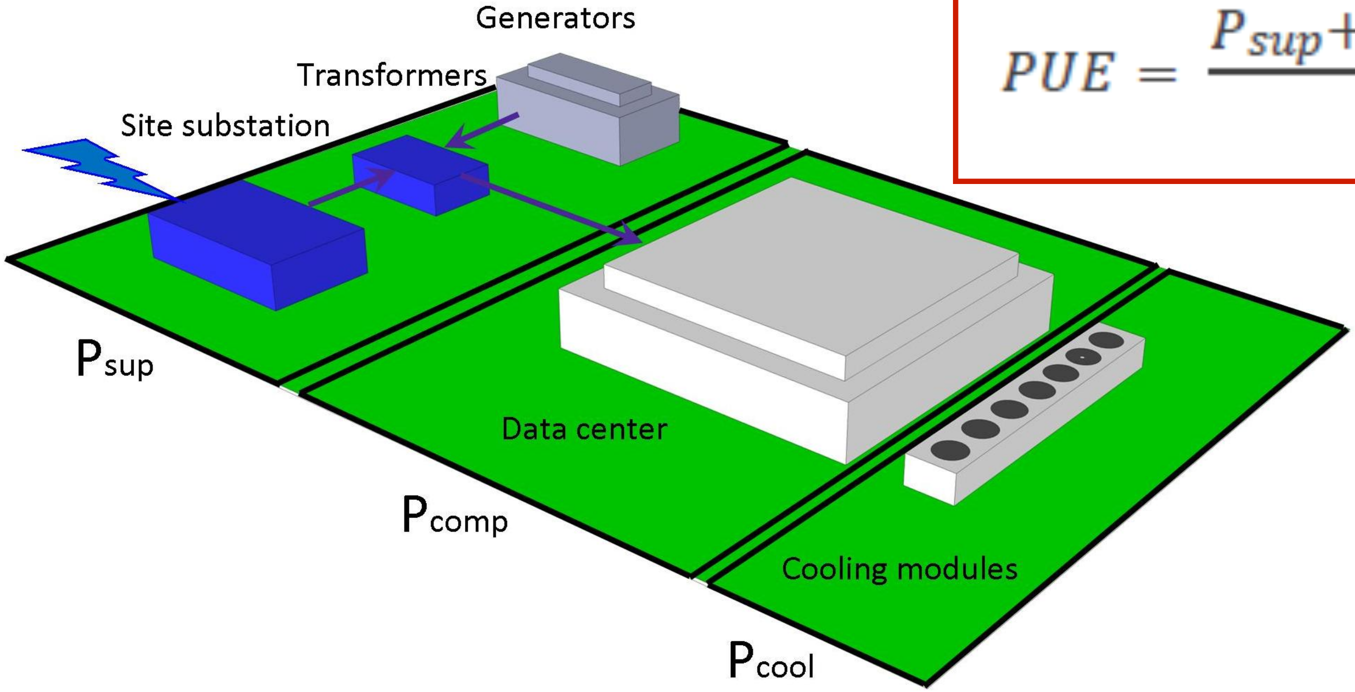
Metric used to evaluate the efficiency of the Data Center

$$PUE = \frac{P_{DC}}{P_{comp}}$$

P_{DC}: power to the DC

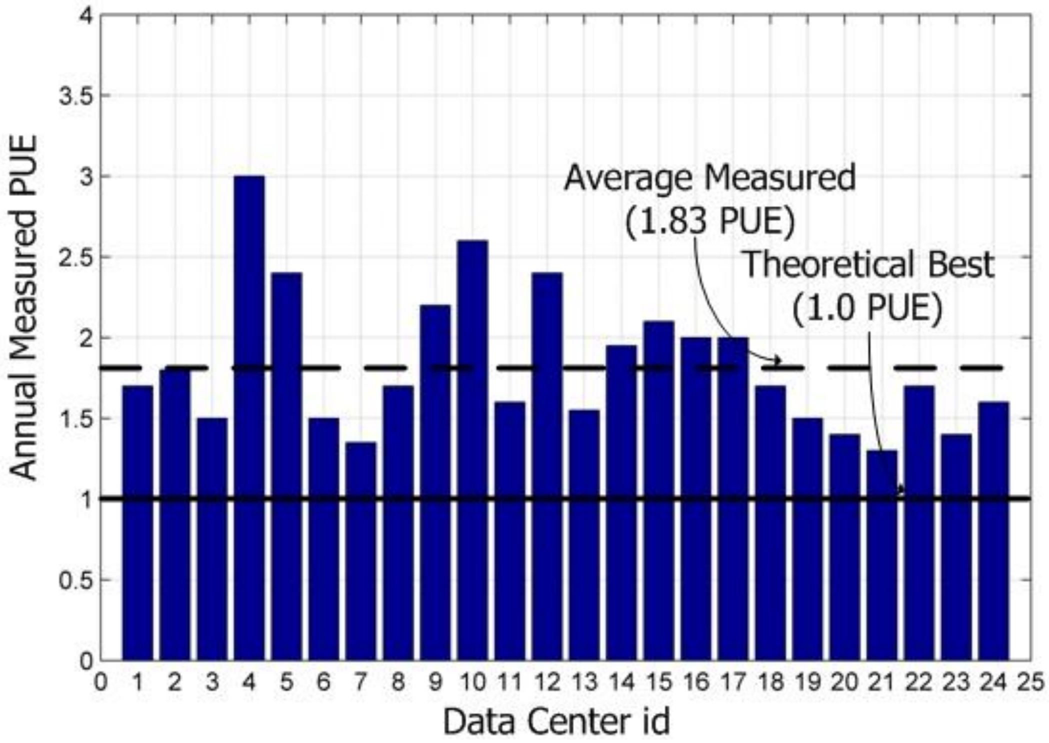
P_{comp}: power for computing elements

$$PUE = \frac{P_{sup} + P_{cool} + P_{comp}}{P_{comp}}$$



Power Usage Effectiveness (PUE)

High values of PUE in many data centers

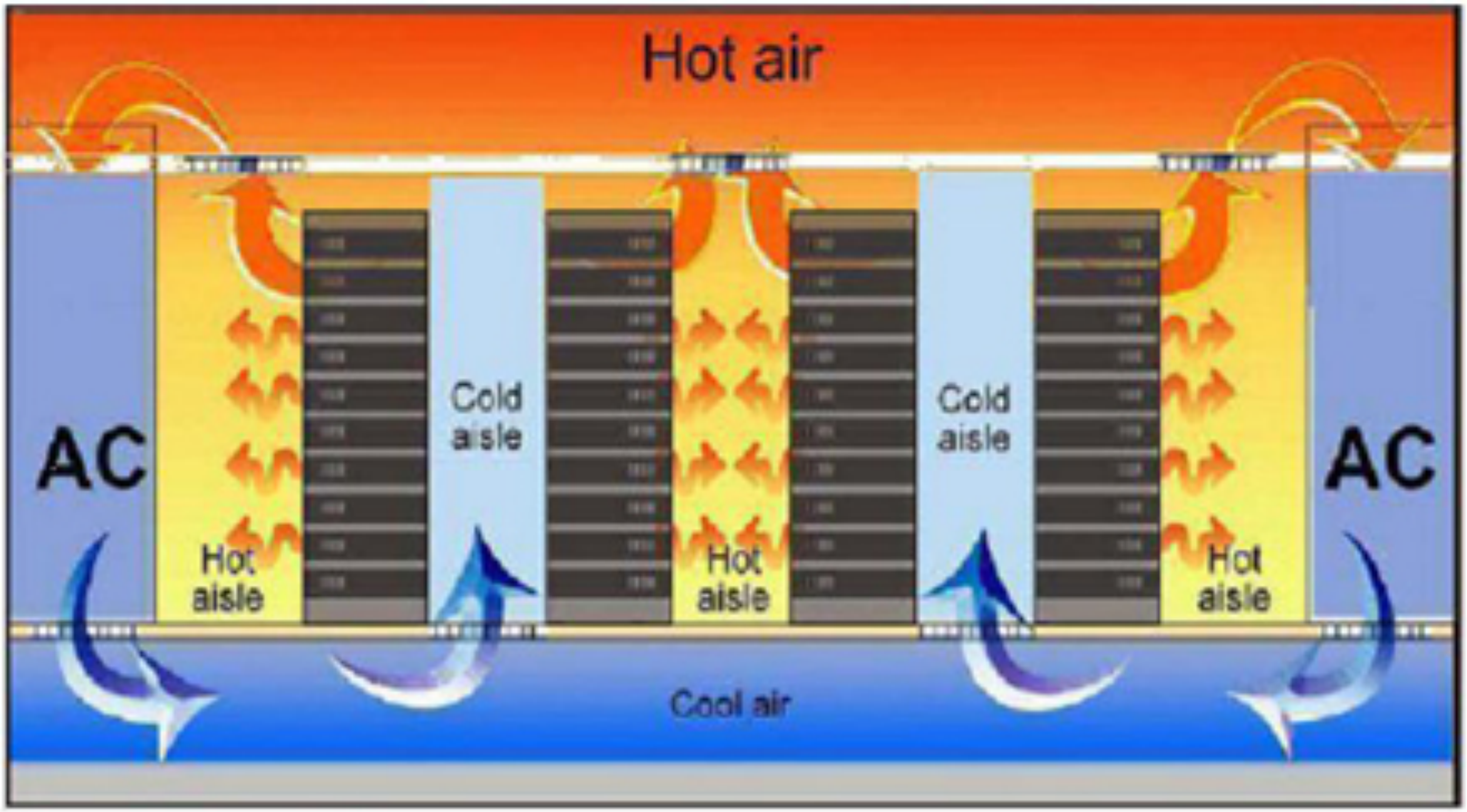


Source: "Self-benchmarking guide for high-tech buildings," data from the LBLN data base centers in the LBNL database, http://hightech.lbl.gov/

Current solutions for data centers

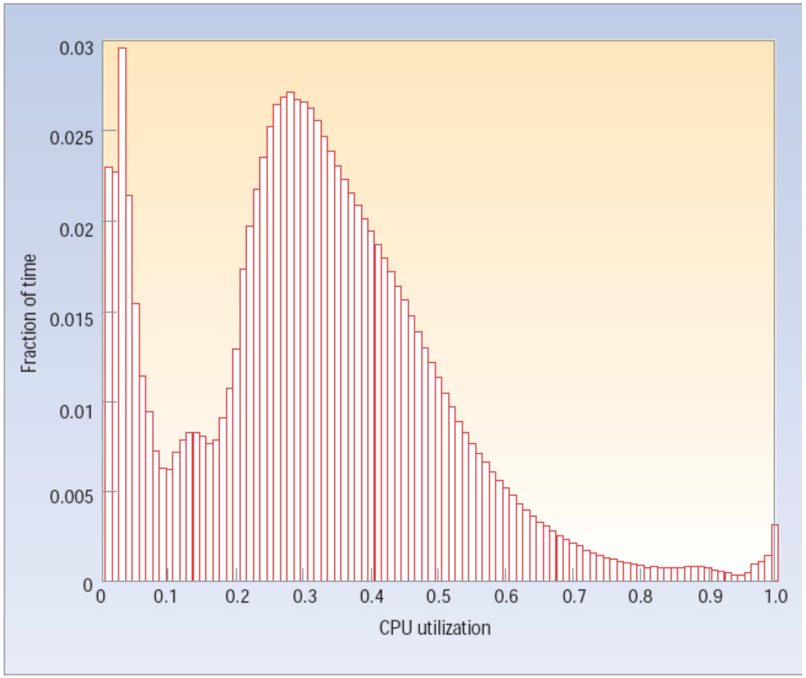
- Improve infrastructure (power and cooling)
  - Liquid cooling
  - Improve efficiency of chillers, funs and pump
  - Improve transformers and power supplies
- Reduce cooling needs (cooling consumes as much as 40% of the operating costs) through specific physical layouts

Current solutions for data centers



Beyond PUE

Servers generally operate in a low utilization region



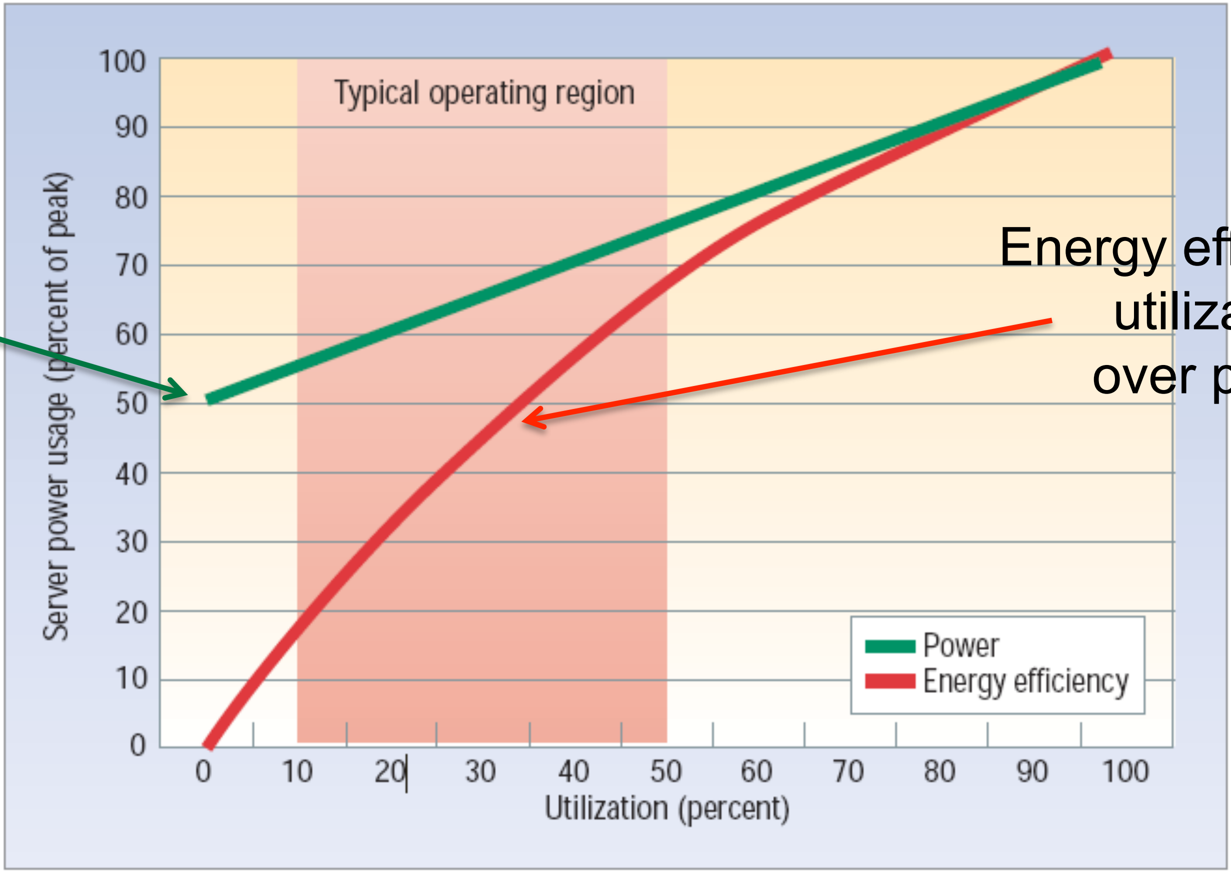
Most mass is in 20% to 40% range

Source: L.Barroso, U.Holzle, The case of energy proportional computing, ACM Computer Journal, Volume 40 Issue 12, December 2007.

Servers

current design

When idle, power is 50% of full load

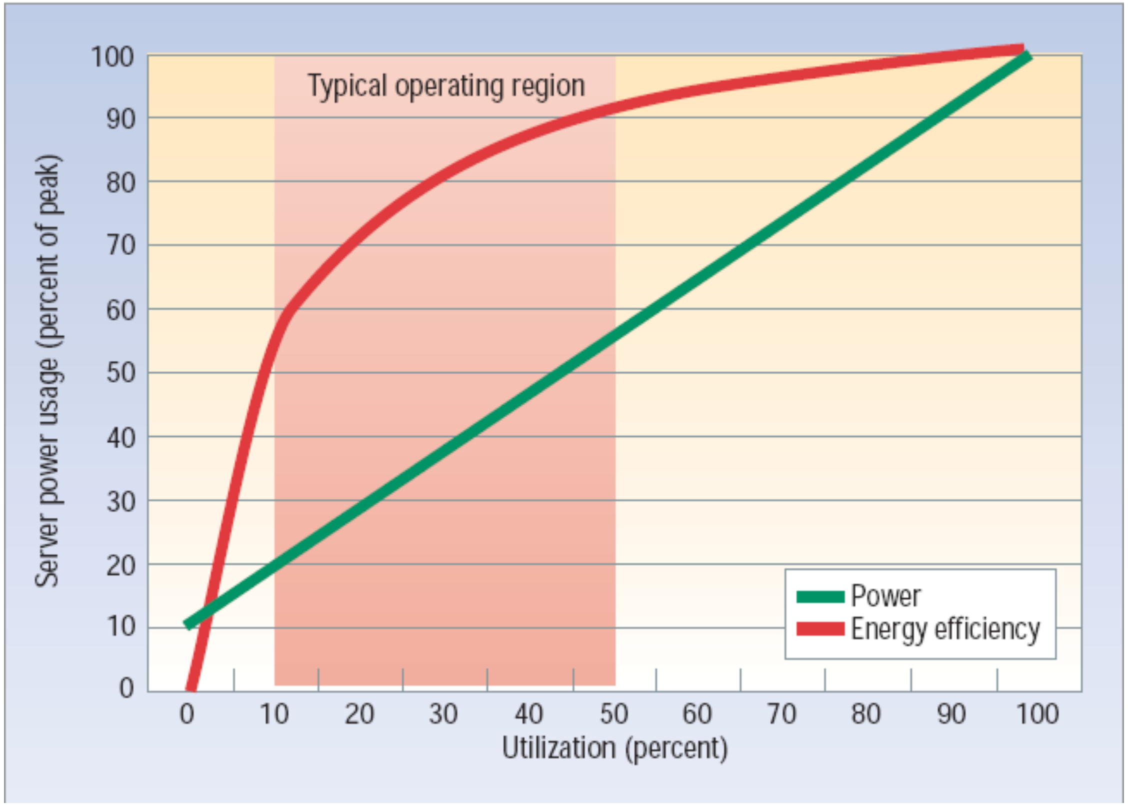


Energy efficiency = utilization over power

Source: L.Barroso, U.Holzle, The case of energy proportional computing, ACM Computer Journal, Volume 40 Issue 12, December 2007.

Servers

Ideal load proportional design



Power use is almost proportional to utilization

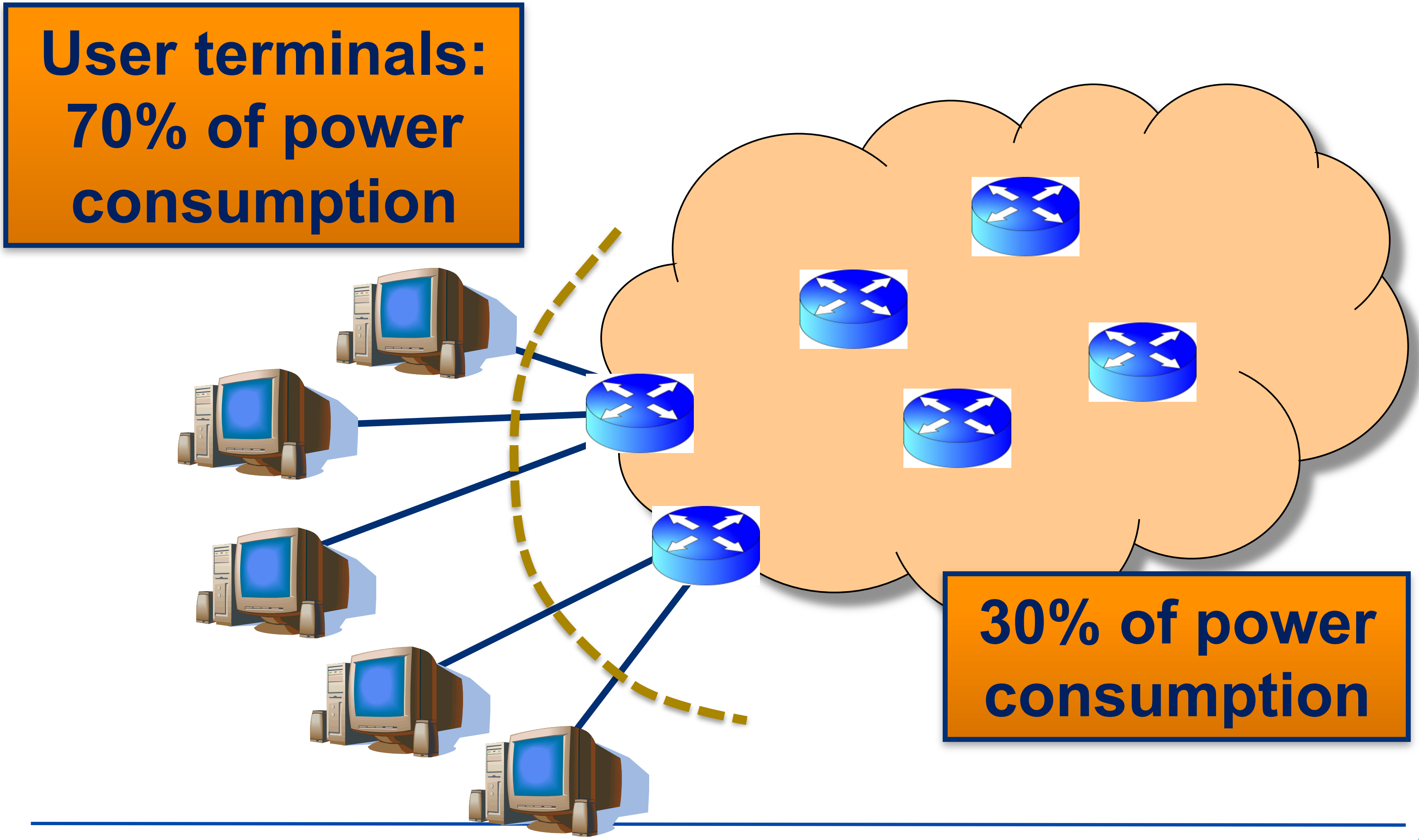
Source: L.Barroso, U.Holzle, The case of energy proportional computing, ACM Computer Journal, Volume 40 Issue 12, December 2007.

Current solutions for data centers

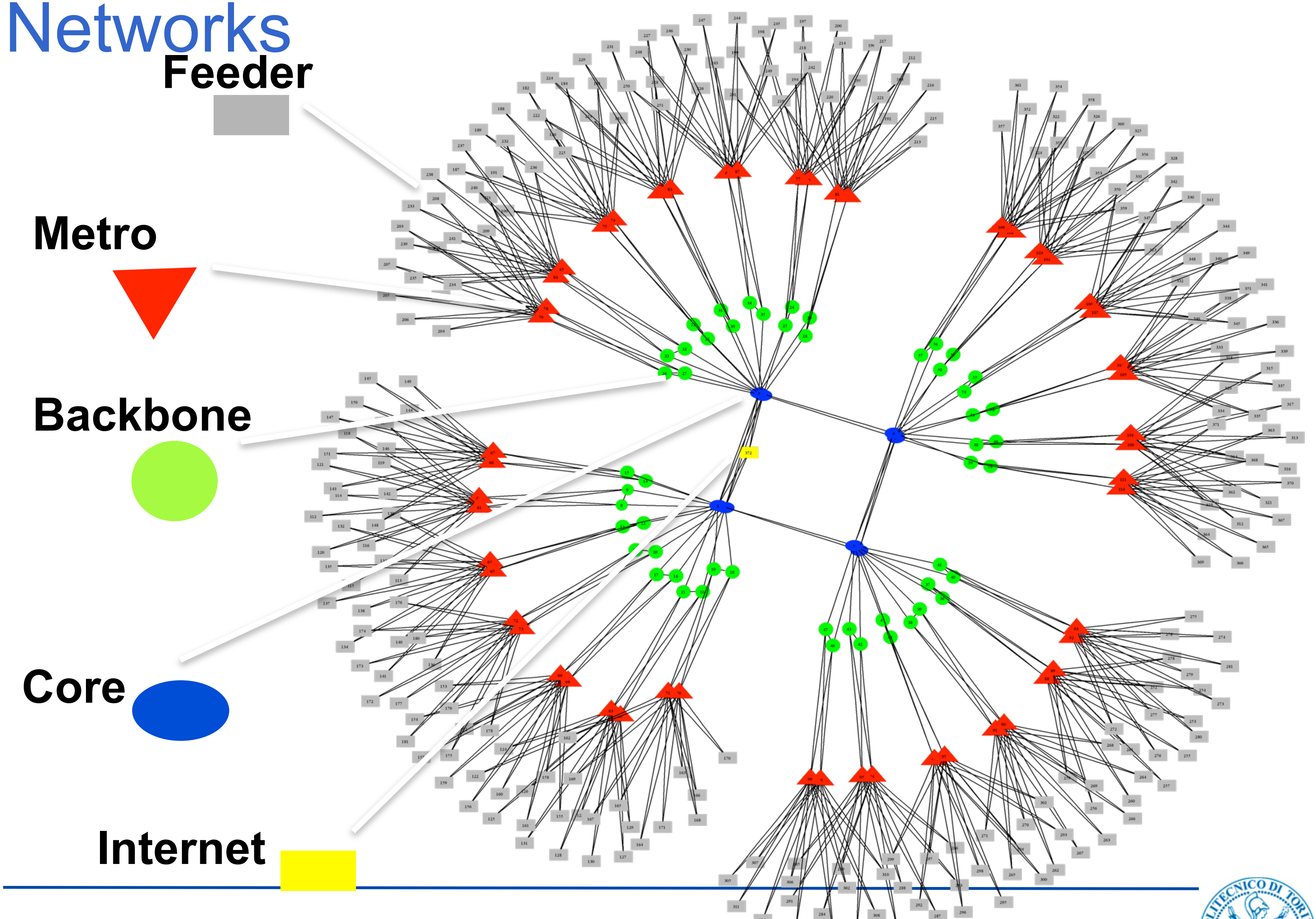
- Consolidate servers and storage & eliminate unused servers
  - Algorithms to free up servers and put them into sleep mode or to manage loads on the servers in a more energy-efficient way
  - Sensors identify which servers would be best to shut down based on the environmental conditions
- Adopt “energy-efficient” servers or more efficient components
- Enable power management at level of applications, servers, and equipment for networking and storage

Networks

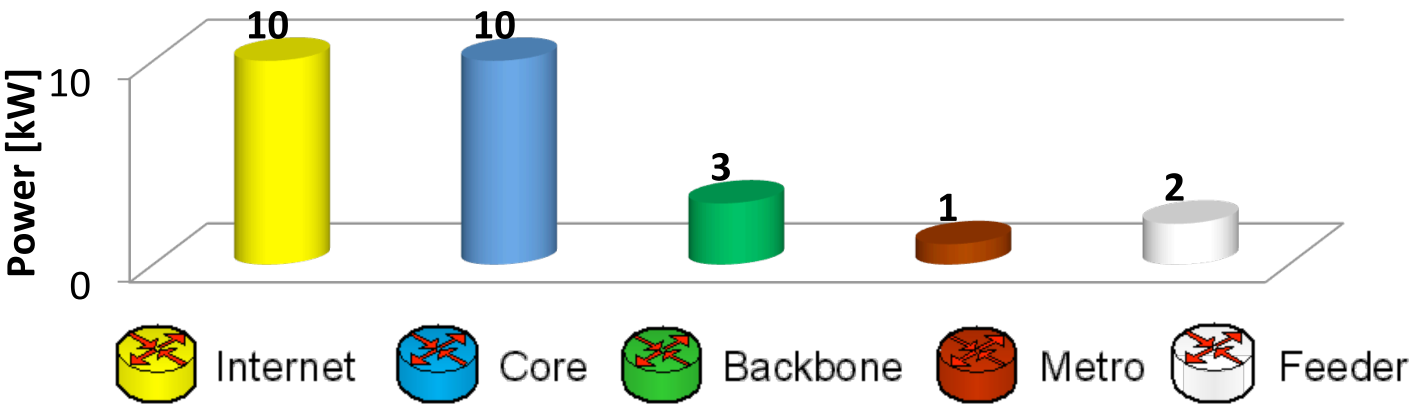
Wired network

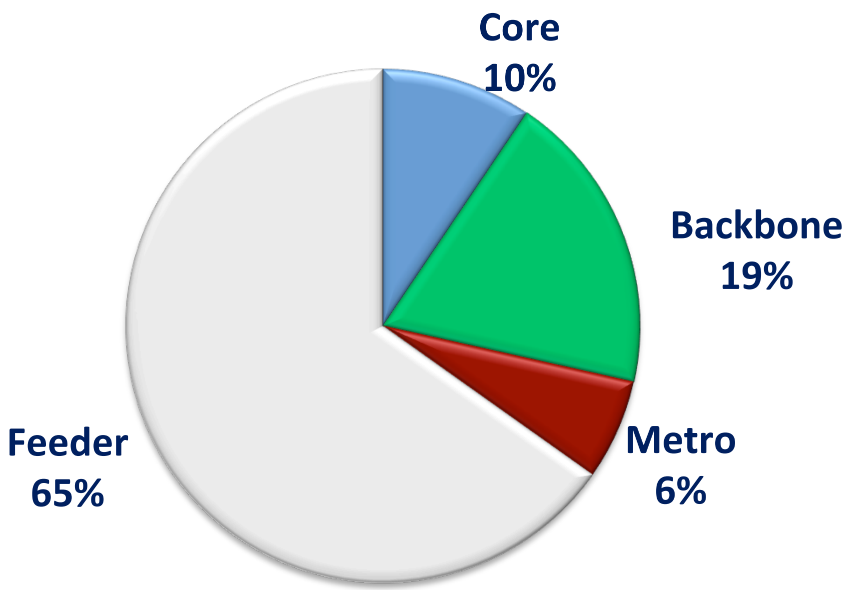


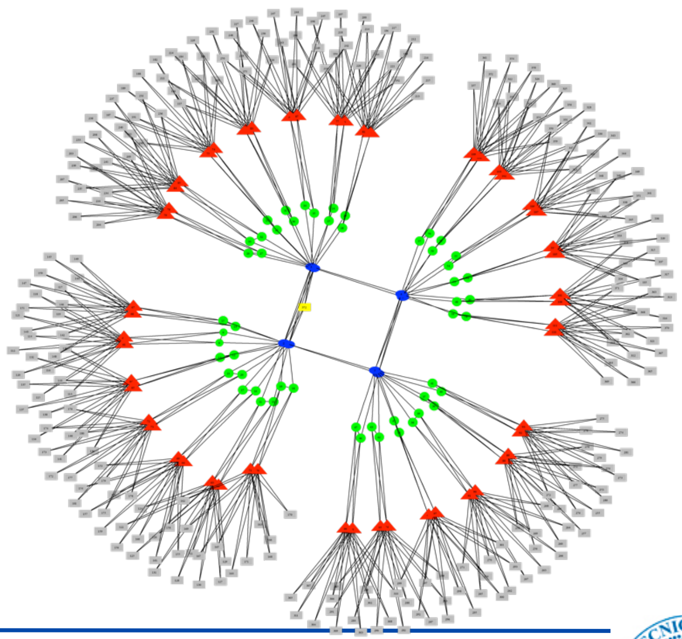
Networks



Network devices

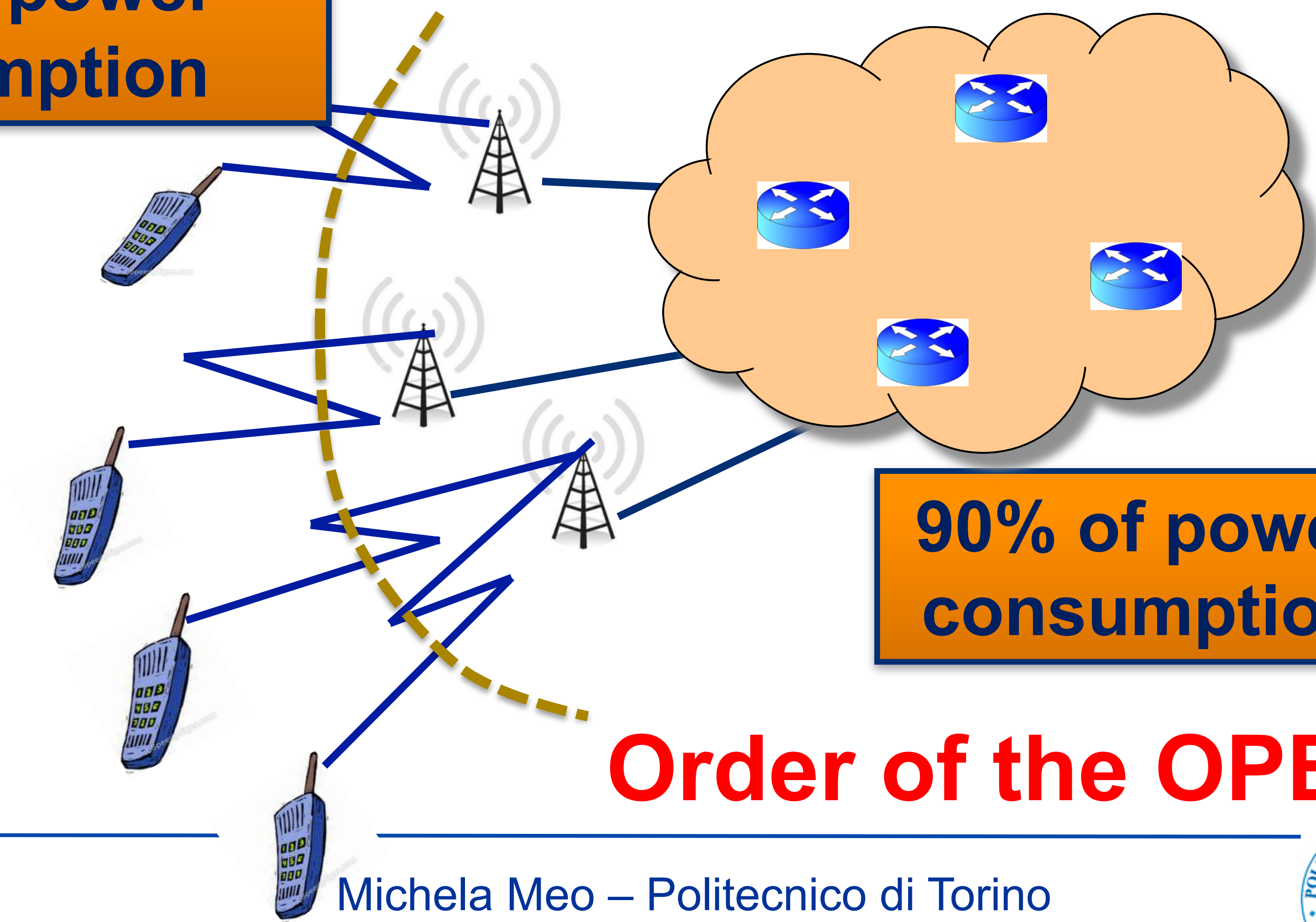






Mobile networks

Users terminals: 10% of power consumption

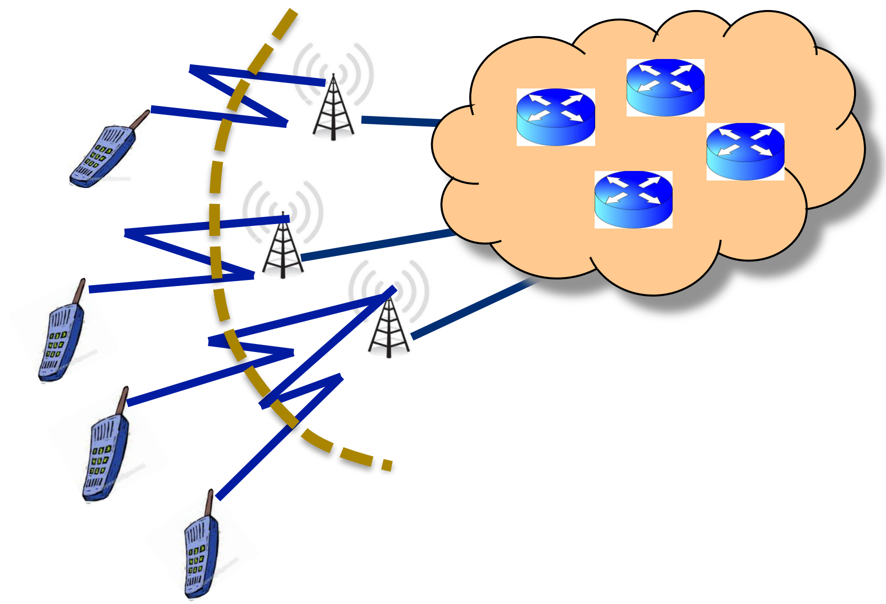


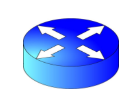
90% of power consumption

Order of the OPEX!

Mobile networks

According to an estimate of Nokia Siemens Networks, worldwide…



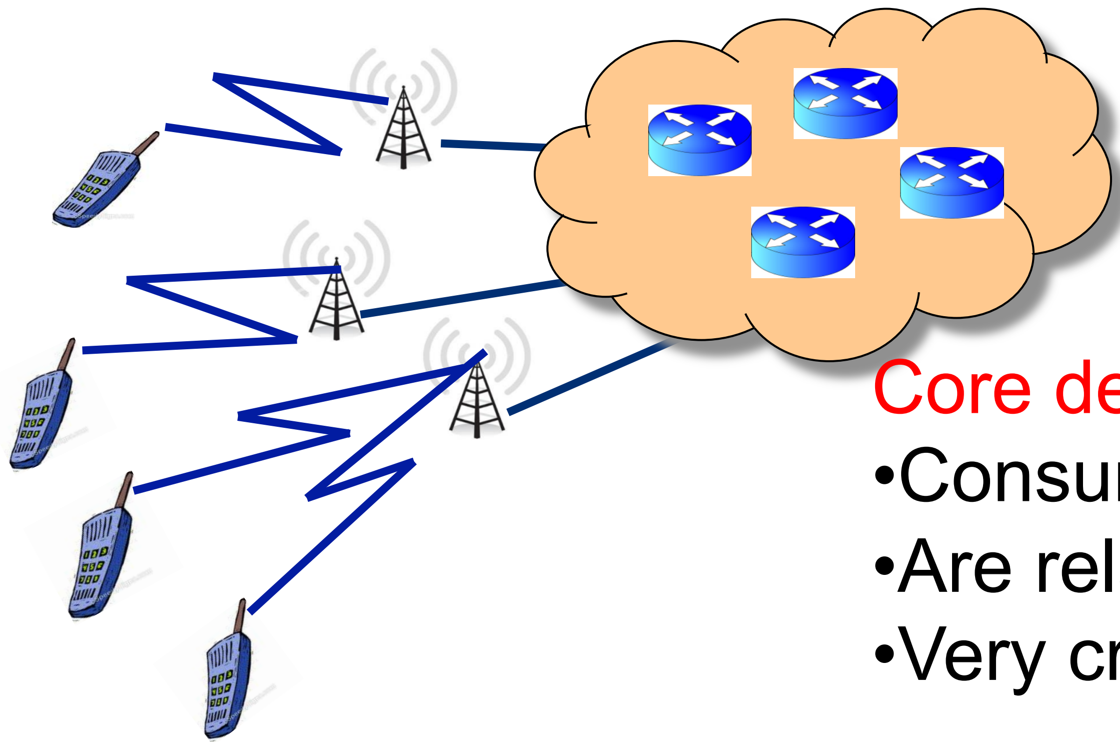


3 billion x 0.1 W = **0.3GW**

3 million x 1.5 kW = **4.5GW**

10,000 x 10 kW = **0.1GW**

Which segment of the network?



Core devices:

•Consume much

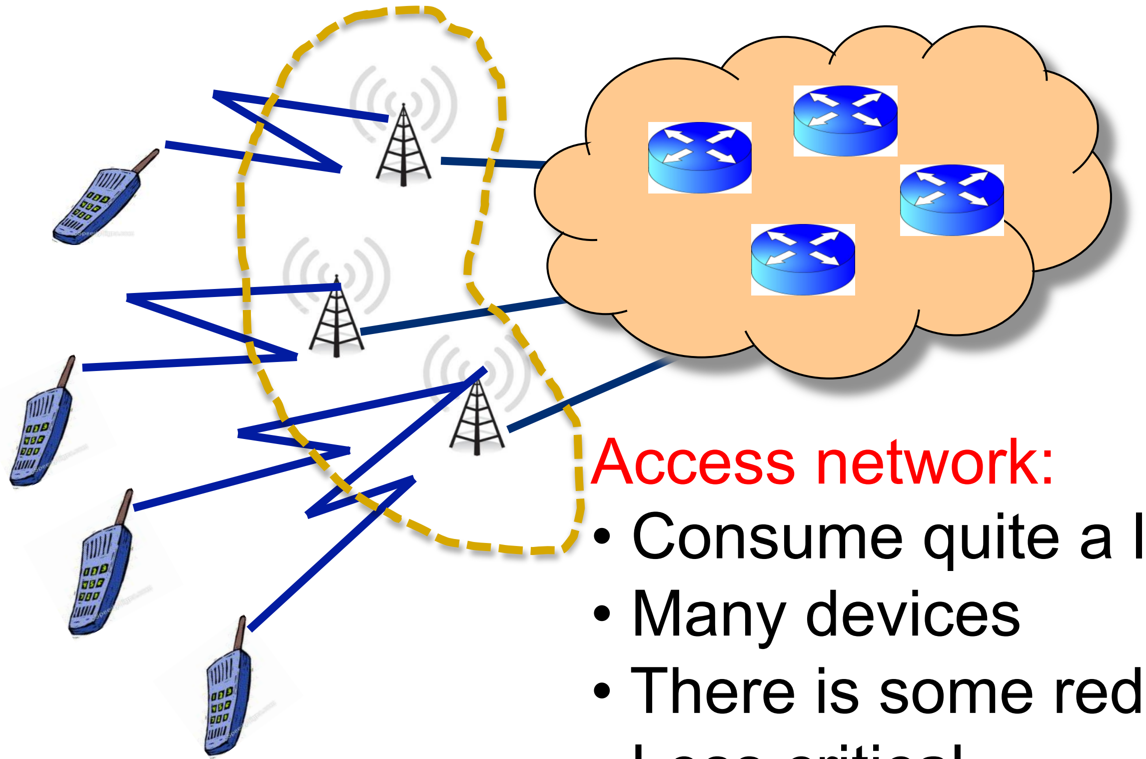
•Are relatively few

•Very critical

Terminals:

Already very efficient by design

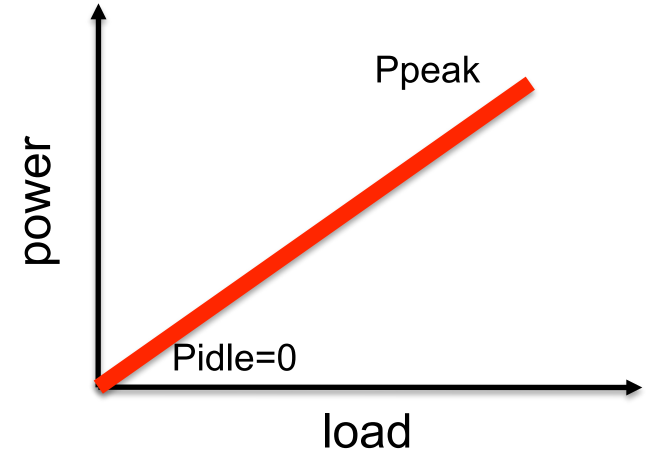
Which segment of the network?

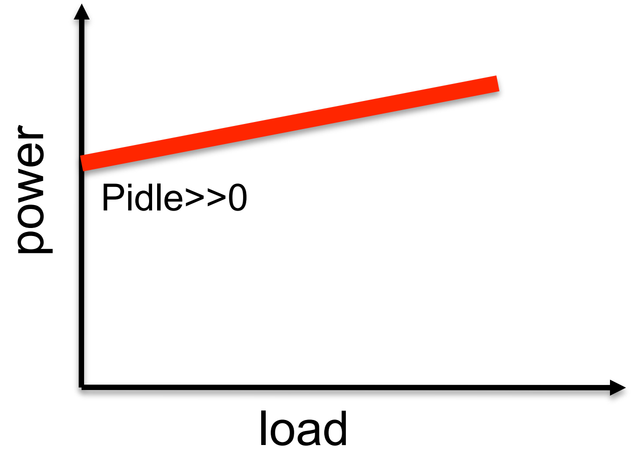


Access network:

- Consume quite a lot
- Many devices
- There is some redundancy
- Less critical
- Very close to the user, high traffic variability

A key concept: load proportionality





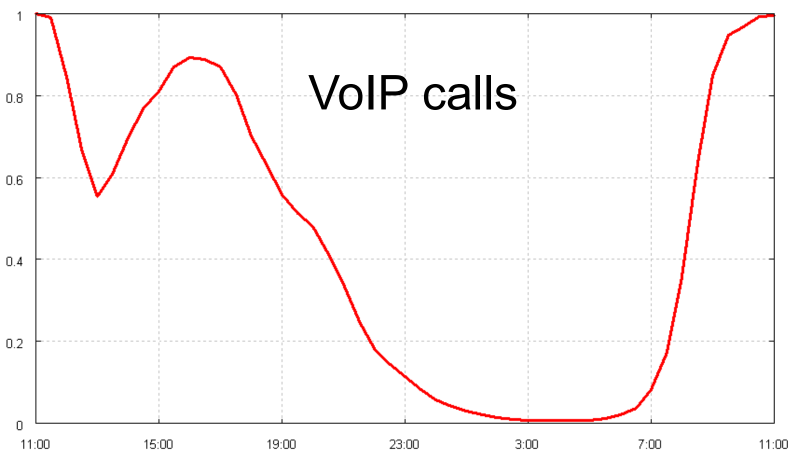
Ideal situation:

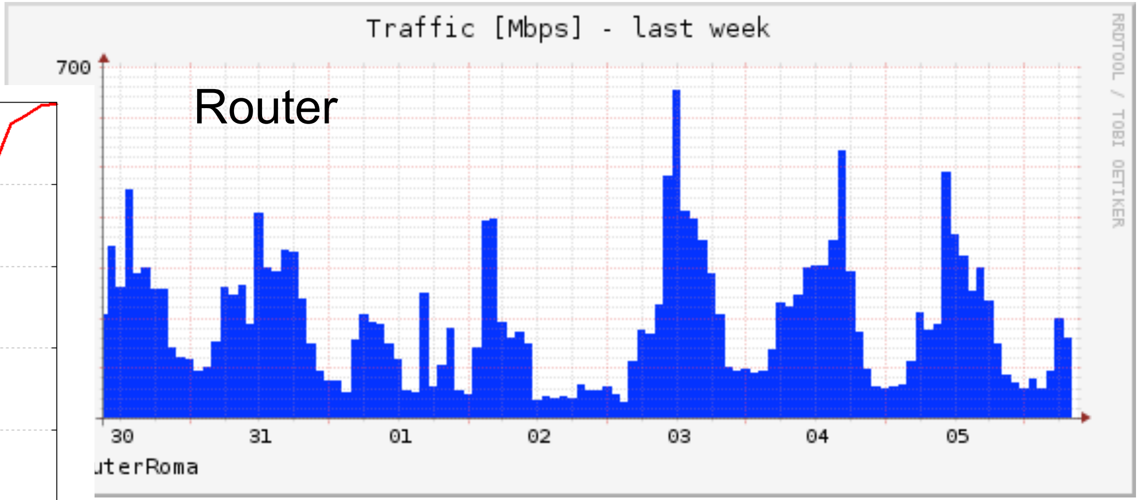
Power consumption depends on load

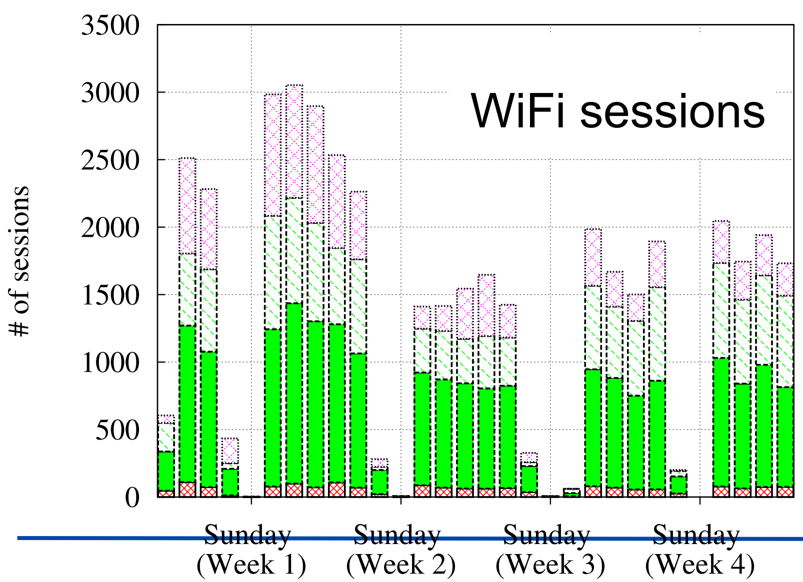
Actual situation:

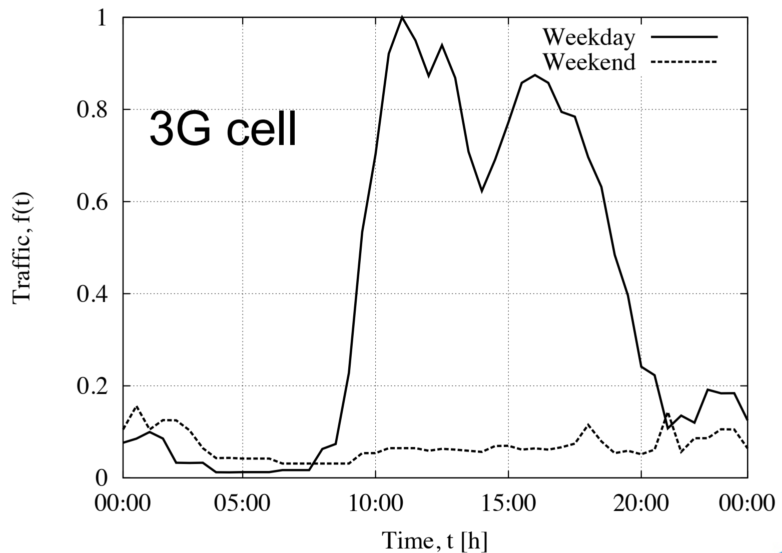
Power consumption only (very) *marginally* depends on load

Traffic is variable









Network solutions: adapt capacity

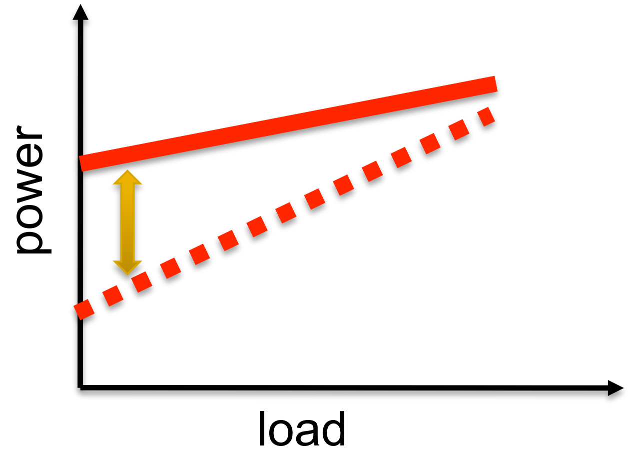
- Network consumption mainly depends on the *deployed* capacity not on the *used* capacity
- Due to natural traffic variability, the network results over-dimensioned and **wastes energy** for long periods of time

Adapt capacity to actual traffic needs

Possible approaches

- Use *adaptive speed* techniques at links/devices
  - Can work on different (usually small) time scales
  - Need to manage interactions between devices
  - Need to cope with distributed decisions locally taken by the devices

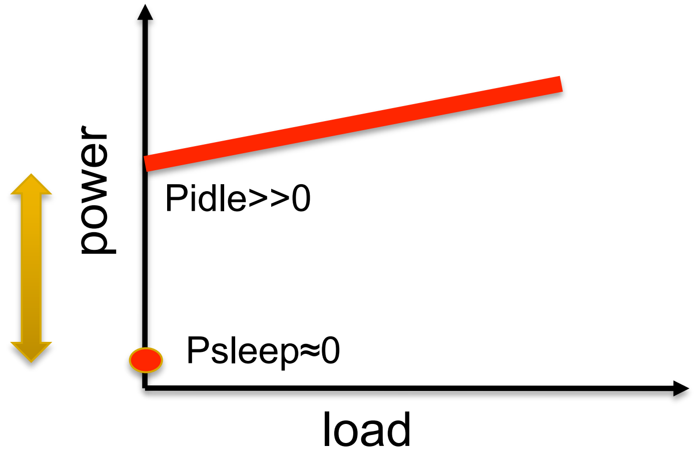
Gain by making consumption more load proportional



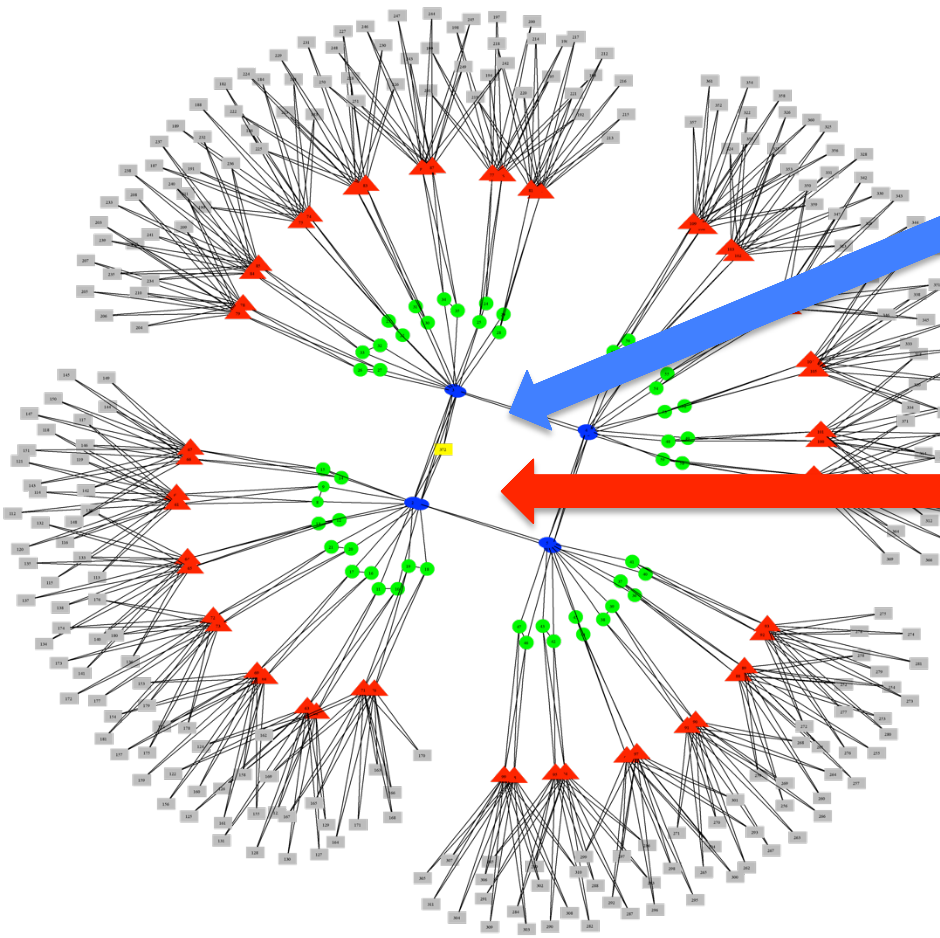
Possible approaches

- Use *sleep modes* in portions of the network, need to
  - Guarantee connectivity
  - Provide service continuity during transient periods
  - Update routing and distributed state information

Gain by reducing the effect of Pidle



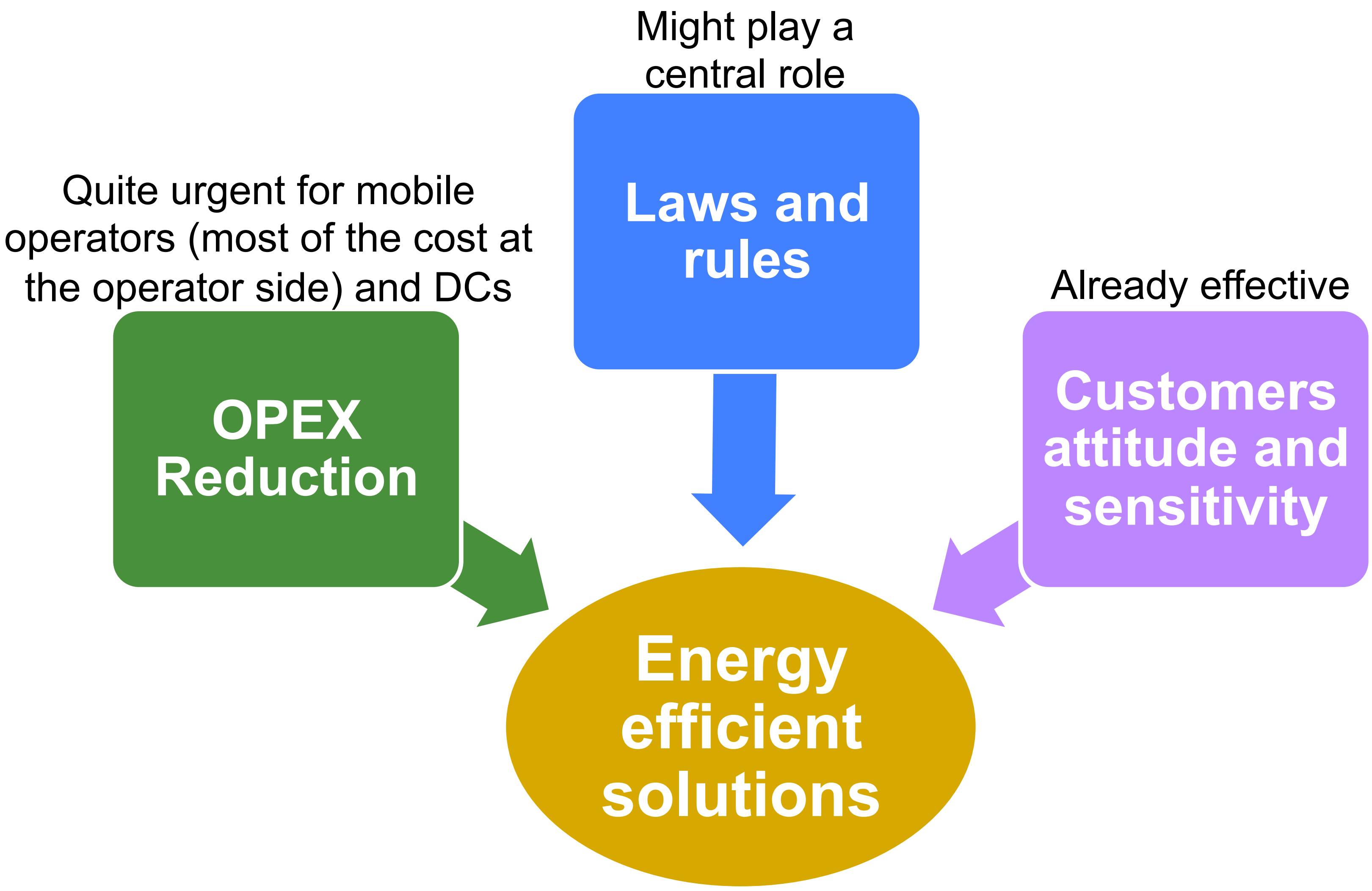
Where in the network?



High connectivity →feasibility

High aggregation levels
→ vulnerability
→ smooth profiles
(less effective)

Which business model?



- Solutions to reduce power consumption
  - Technologies
    - Innovative materials with higher heat dissipation
    - Increase use of photonic
  - Use of low consuming power states and/or speed adaptation
    - Portions of the devices
    - Whole devices through consolidation
    - Portions of the network

Solutions for individual devices

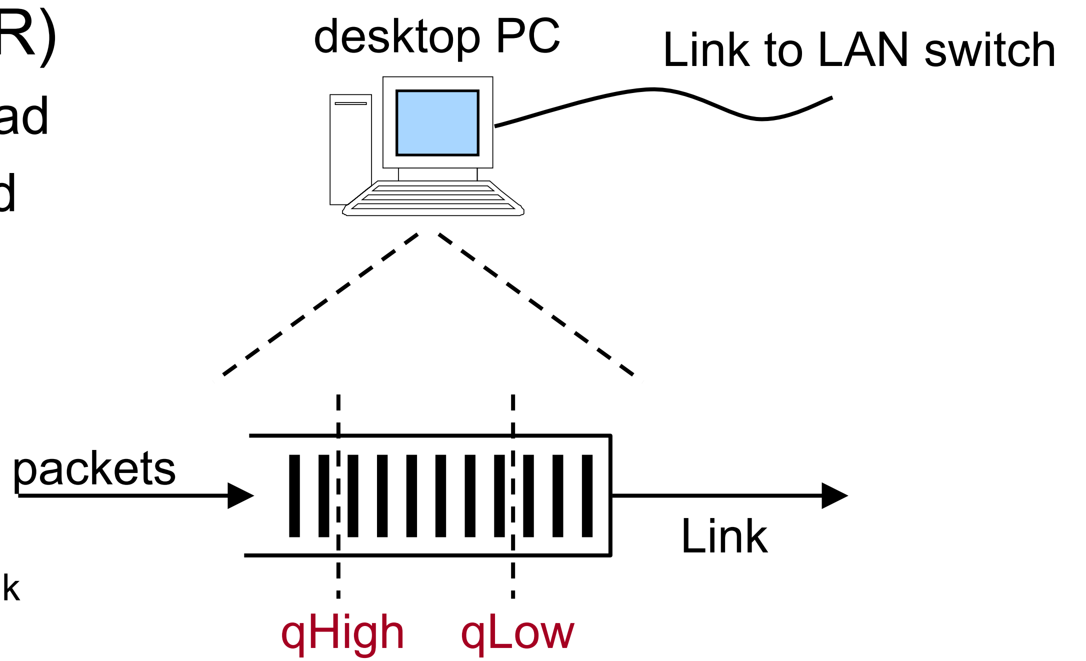
- Use low clock frequencies/link rates to reduce consumption when load is low
- Use dynamic voltage scaling (DVS) in the internal electronics
  - CMOS circuits can operate at varying voltage levels
  - Voltage levels vary dynamically jointly achieving desired performance level and energy minimization
  - Low voltage → low consumption &
    → increased delay

Individual devices: Discussion and open issues

- The use of rate adaptation/dynamic scaling require
  - Careful choice of the time scale
  - Need for accurate load predictions
  - Risks of bad interaction with other devices close by
- Trade-off between saving/reactivity to traffic variations → saving/performance
- They tend to provide load proportionality working at small time scale

Solutions at the link level: Energy Efficient Ethernet

- Links are typically lightly used
- Lower data rates consume less power
- Adapt link bandwidth or data rate to actual load
  Adaptive Link Rate (ALR)
  - High data rate for high load
  - Low data rate for low load (most of the time)



Source: C. Gunaratne, K. Christensen, B. Nordman, S. Suen. Reducing the Energy Consumption of Ethernet with Adaptive Link Rate (ALR), IEEE TRANSACTIONS ON COMPUTERS,VOL. 57,NO. 4,APRIL 2008.

Link level: Discussion and open issues

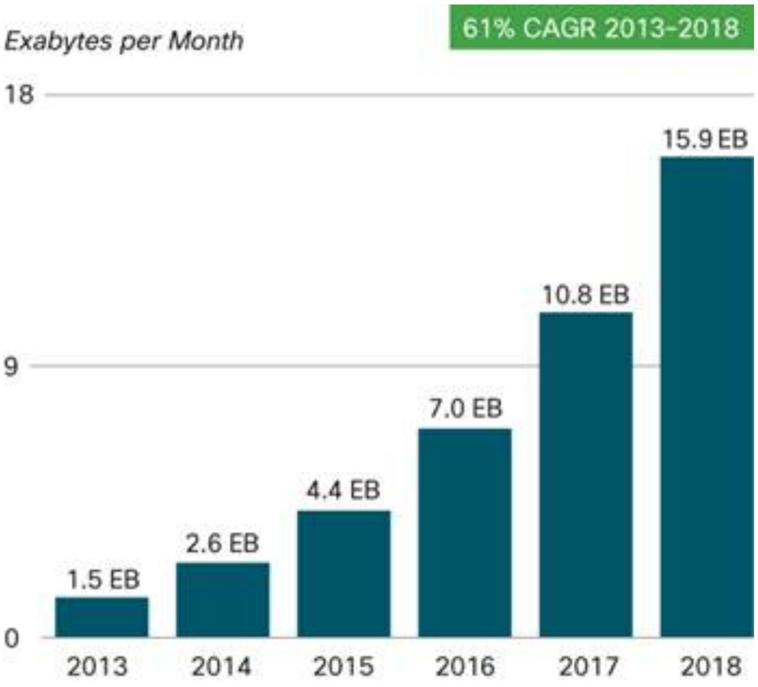
- Some energy savings is possible at link
  - Due to low utilization levels of the link
  - Bursty need for high bit-rates
- Saving/performance deterioration trade-off
- Possible critical interactions with higher level protocols:
  - When TCP ACK flow is regular, little saving
  - TCP control loop might have bad interactions with ALR control loop

Cellular access networks

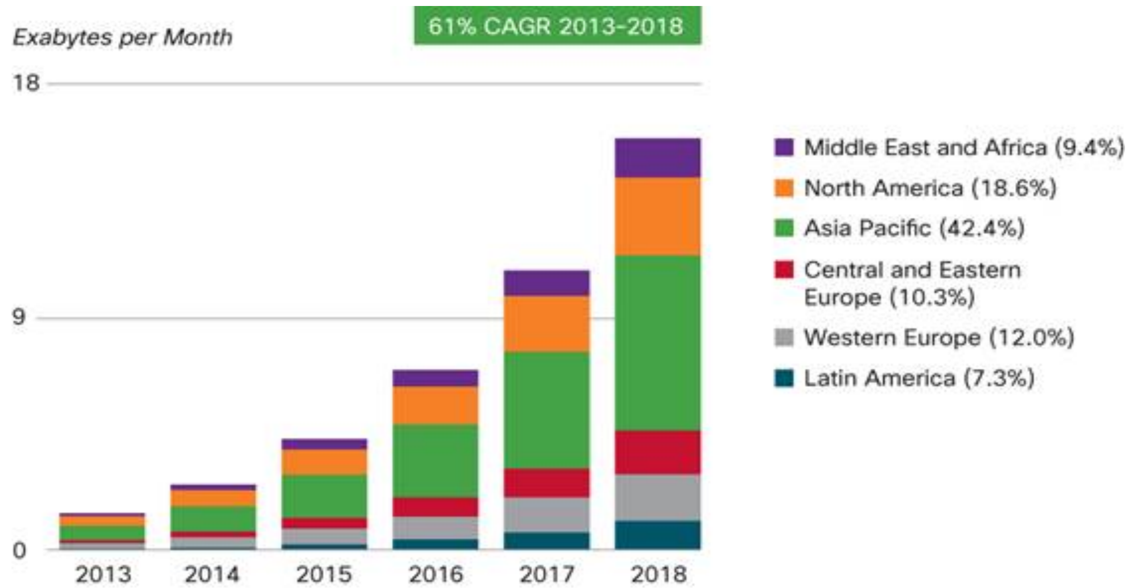
Consumption figures

- Access+backhaul account to 0.3% of global consumption
- The consumption of a typical BS varies between 0.5kW to 2kW
- Elements on the core network consume up to 10kW, but they are much fewer
- Mobile terminals consume very little, no more than 10% of the total

Traffic growth

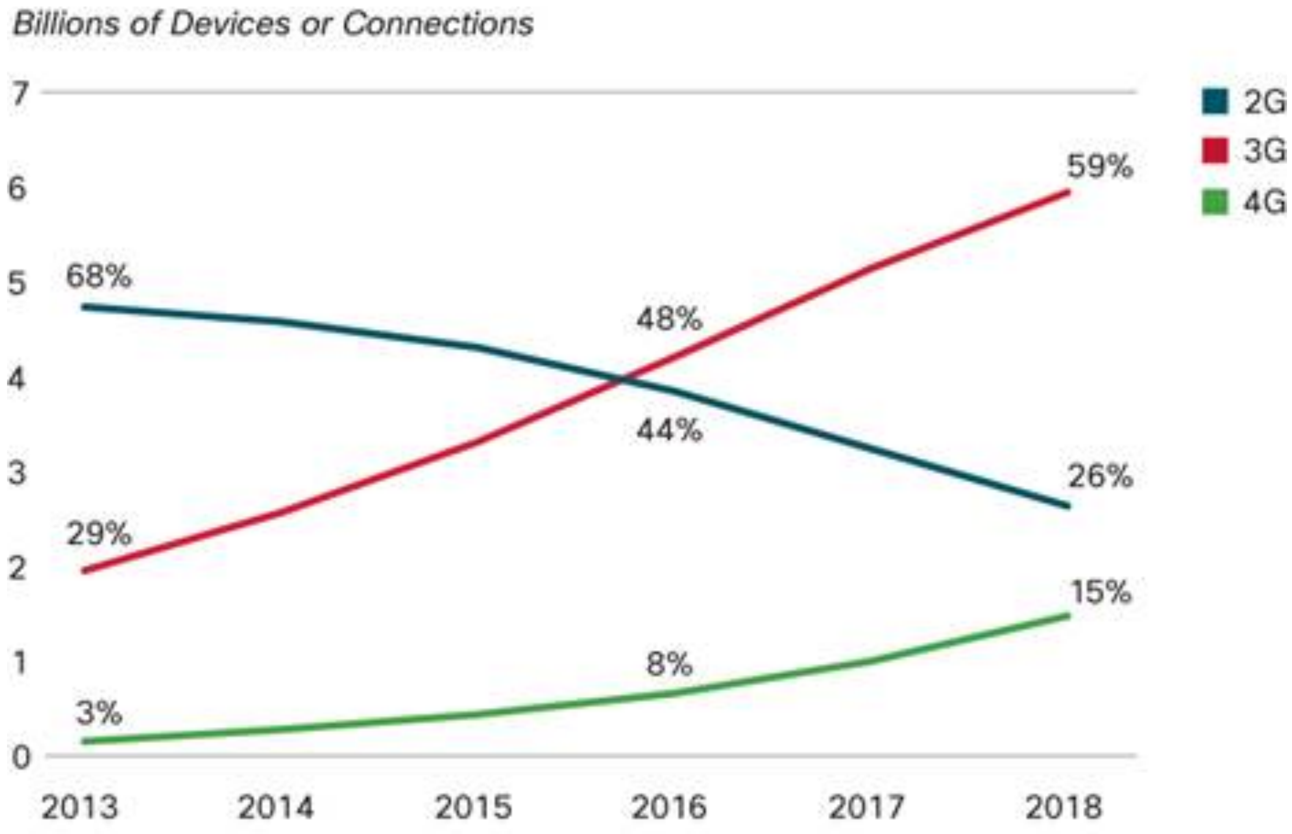


Mobile network traffic is expected to grow by an order of magnitude in 5 years



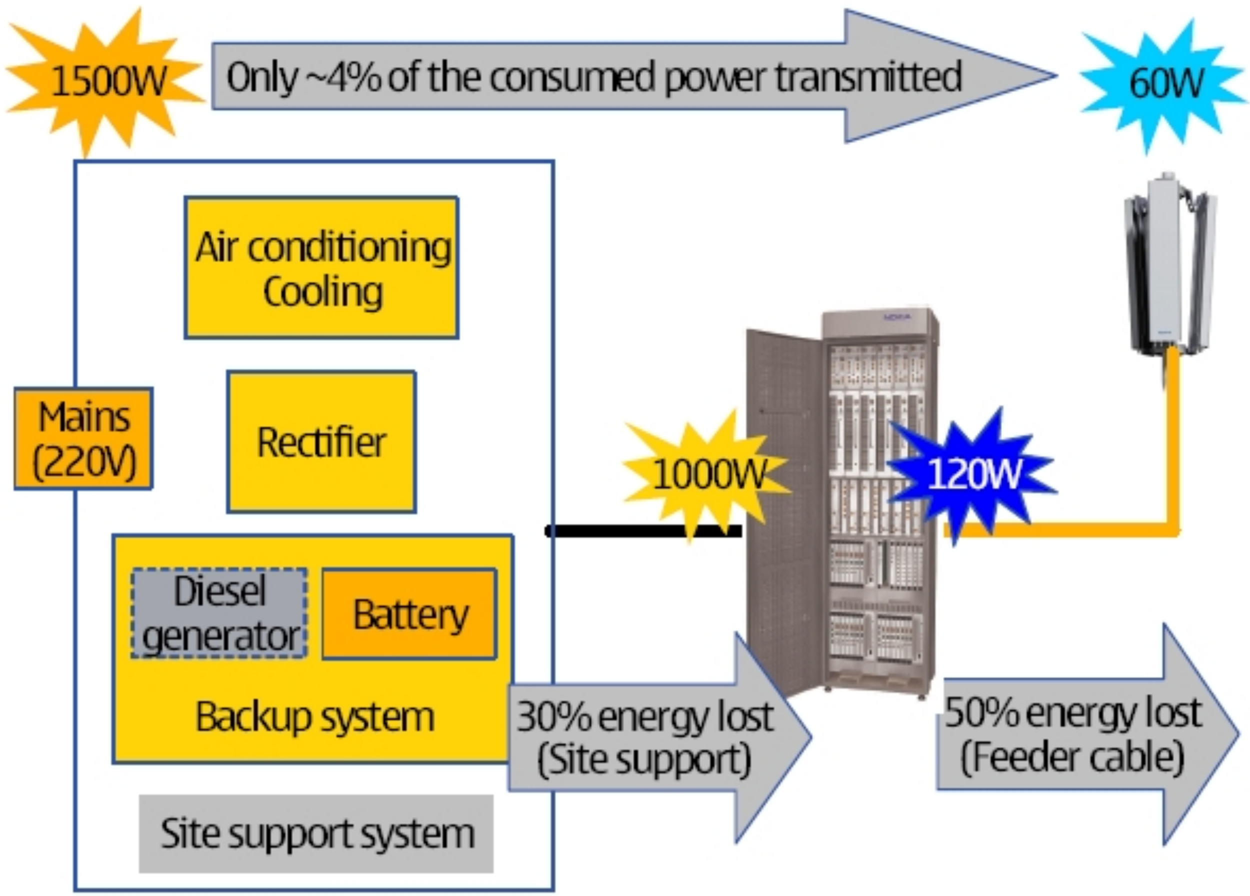
Source: Cisco VNI Mobile, 2014.

Traffic growth



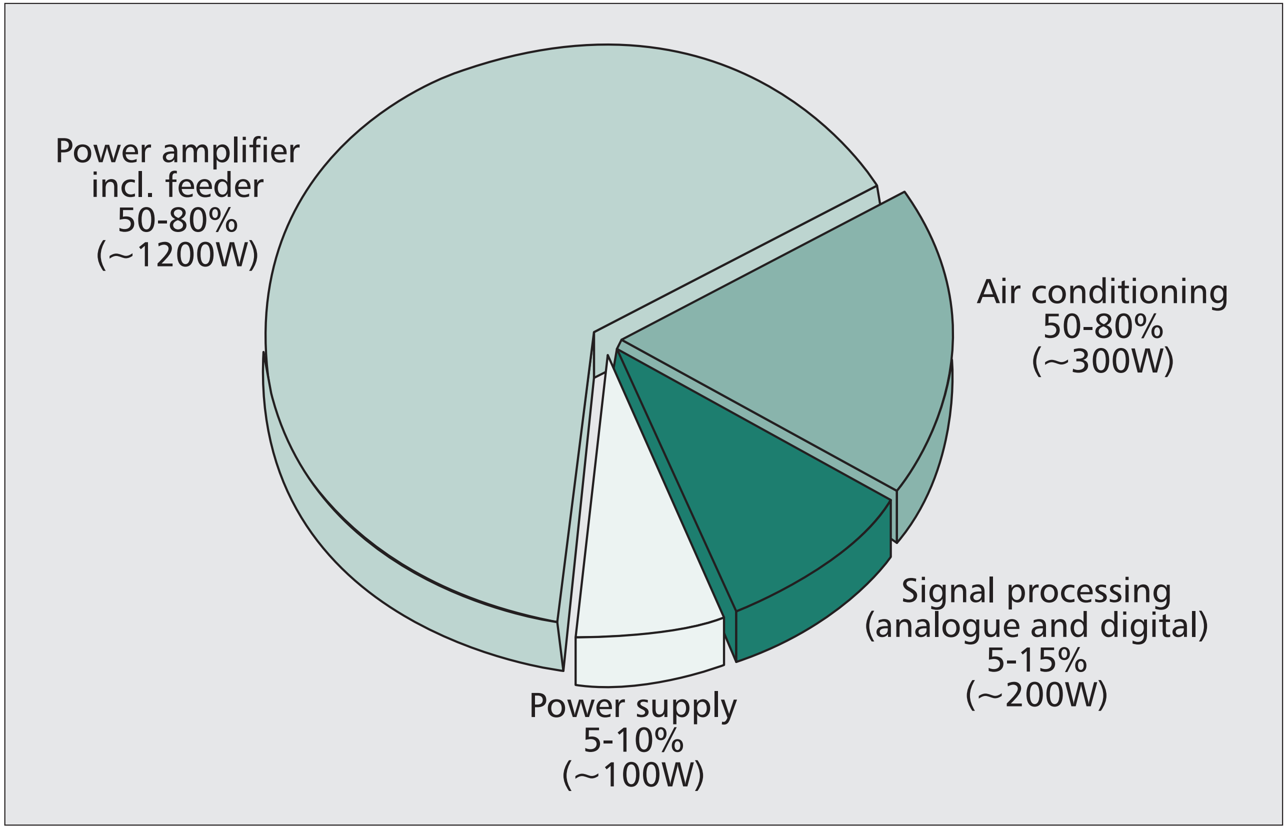
Source: Cisco VNI Mobile, 2014.

Base station consumption



BS efficiency

Typical 3G BS power consumption



Source: L. M. Correia et al. Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks. IEEE Communications Magazine, Nov. 2010.

Efficiency improvement

- Reducing consumption in cooling
  - Open-air devices
  - For indoor devices, alternative or less cooling
- RF close to the antenna to reduce losses in the feeder cable
- Use of renewable sources
  - Solar
  - Wind

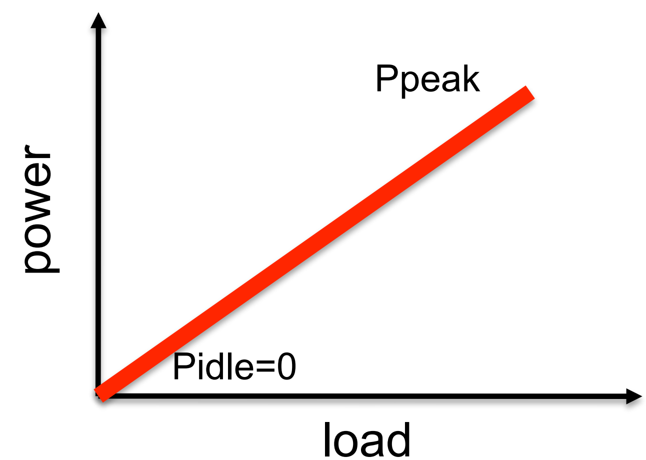
Some shortcoming of actual approaches

- System performance is optimized for capacity and evaluated at full load
  - the system is poorly configured at low loads
- The output power at the antennas is taken as performance measure
  - to evaluate the energy consumption, one should considered the total input power
- Reference performance metrics to measure energy efficiency are limited

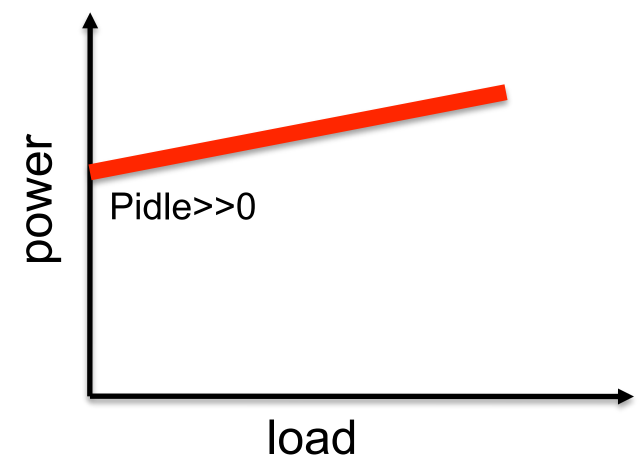
Power vs load in cellular networks

Cellular network devices

All devices are little load proportional
Many access devices that consume quite a lot



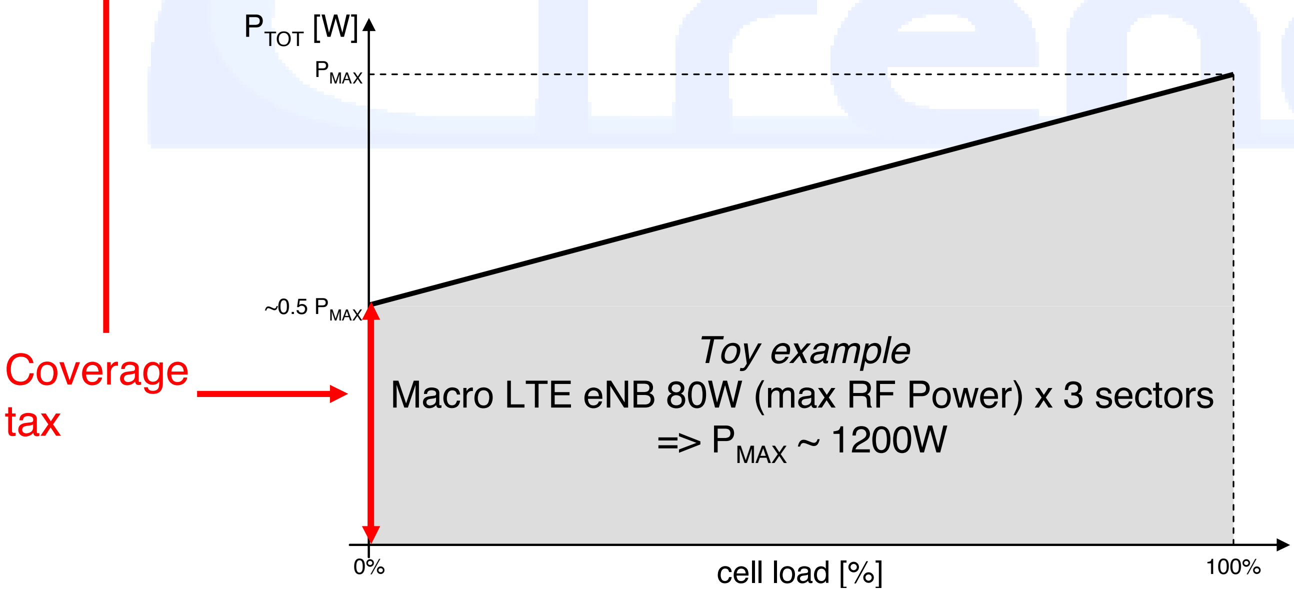
Ideal situation



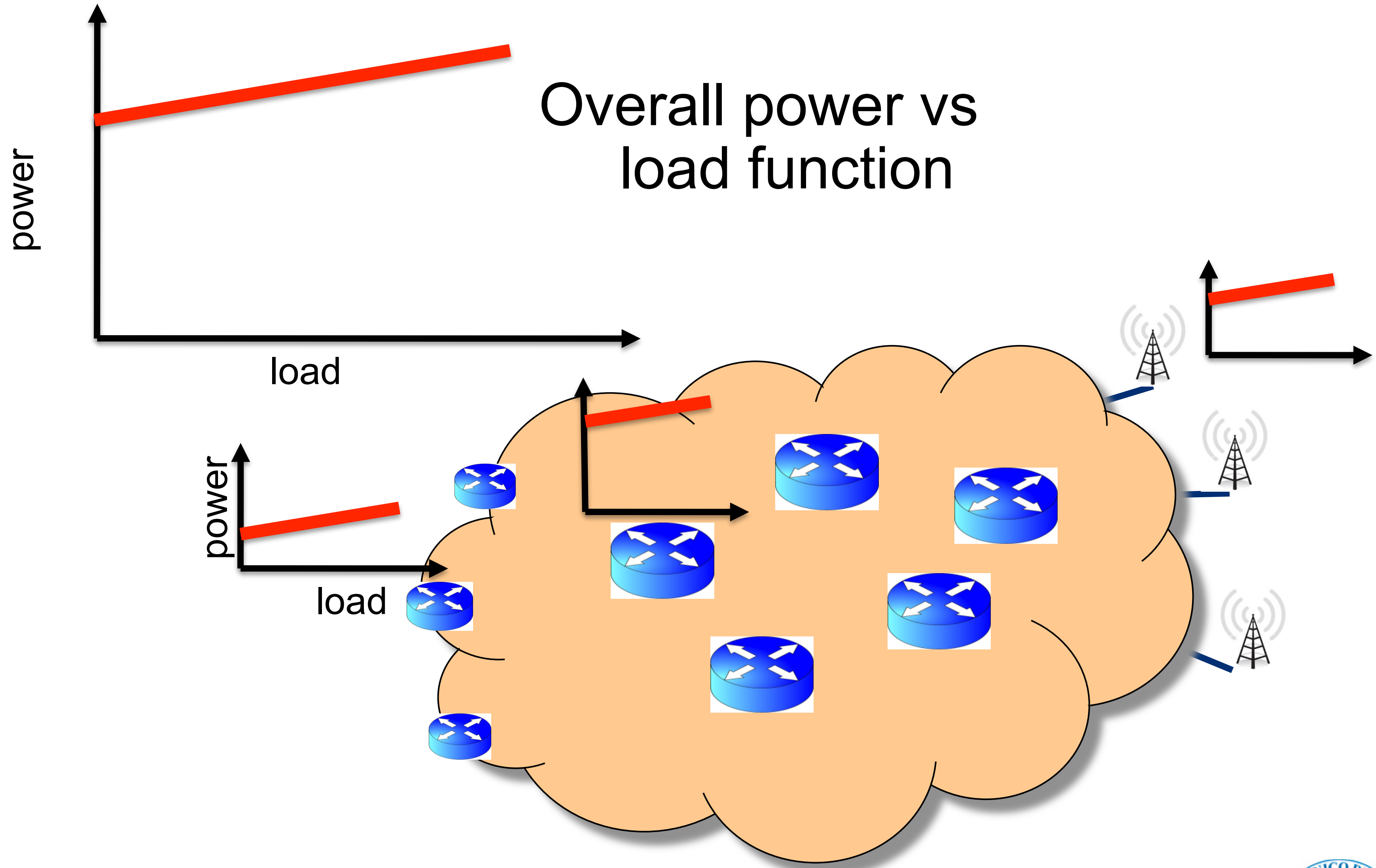
Actual situation

PA efficiency in BSs

- Broadcast channels: continuously emitted (10-15% of RF power) even at 0 load



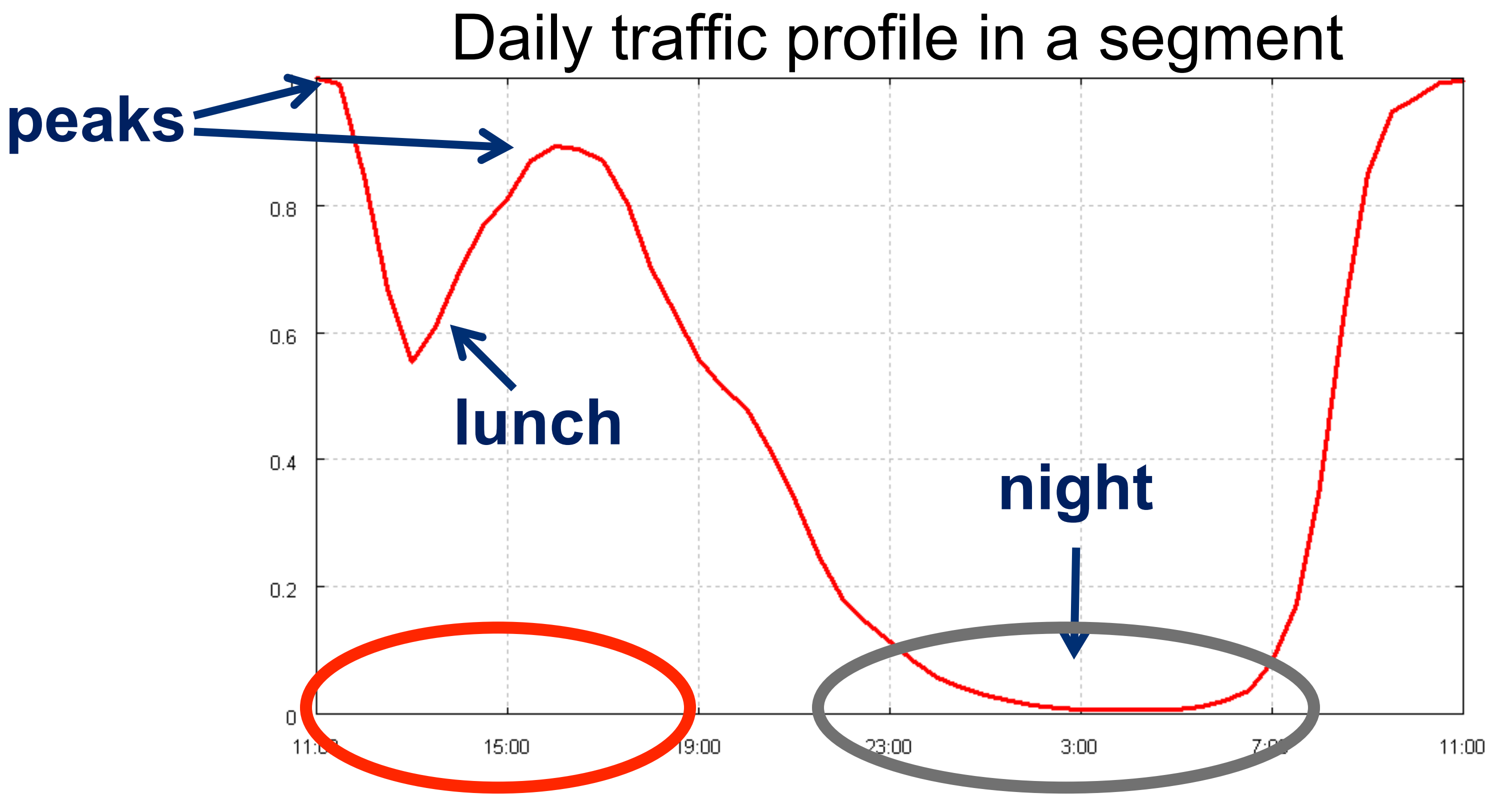
Little load proportionality



Cellular Networks with Sleep Modes

Basic idea

Planning and dimensioning



high capacity to carry all the traffic

over-provisioning: "waste" of capacity

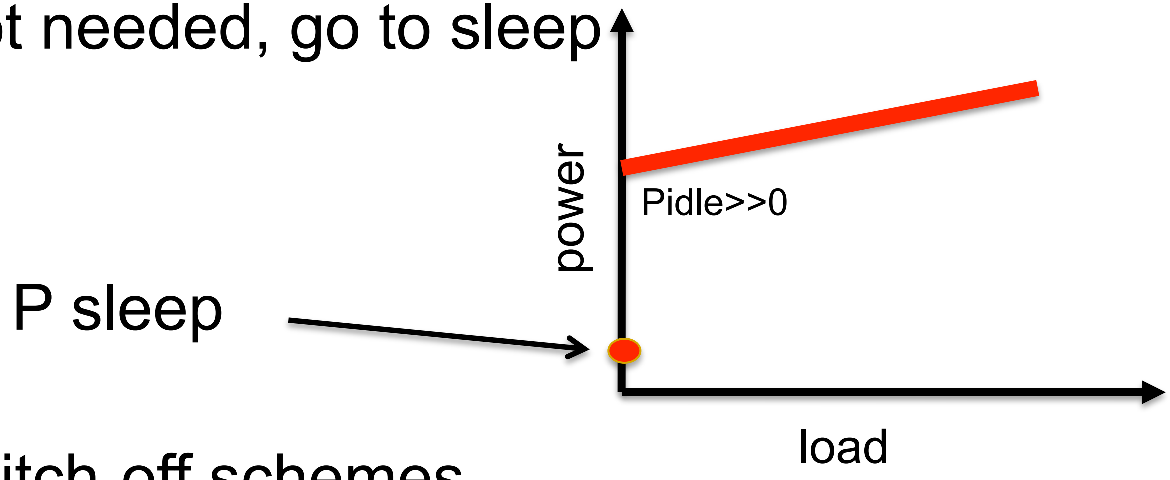
Sleep modes of devices or portions of the network

- Due to natural traffic variability, the network is over-dimensioned and **wastes energy** for long periods of time

Adapt capacity to actual traffic needs by putting to *sleep mode* devices or portions of the network when traffic is low

Sleep modes

- Since Pidle>>0, we need to
  - Look for a *switch-off* scheme (when capacity is not needed, go to sleep mode)

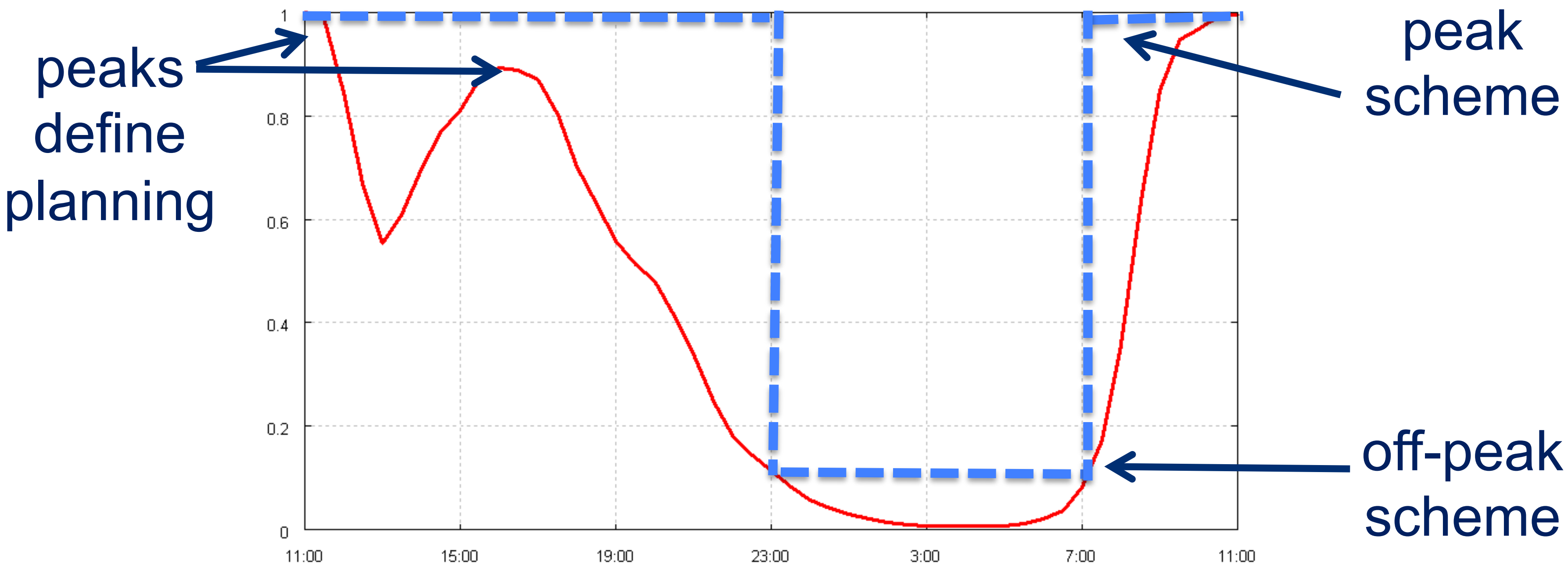


- Problems with switch-off schemes
  - Guarantee connectivity
  - State transitions add latency and possible discontinuities
  - State information (and protocols) needed

Network planning with sleep modes

Since energy consumption only marginally depends on load,

over-provisioning → waste of energy



Adapt capacity to traffic by using sleep modes

Sleep modes

- Adapt capacity to traffic by means of sleep modes

Switch off some devices when the traffic is low and the capacity is large

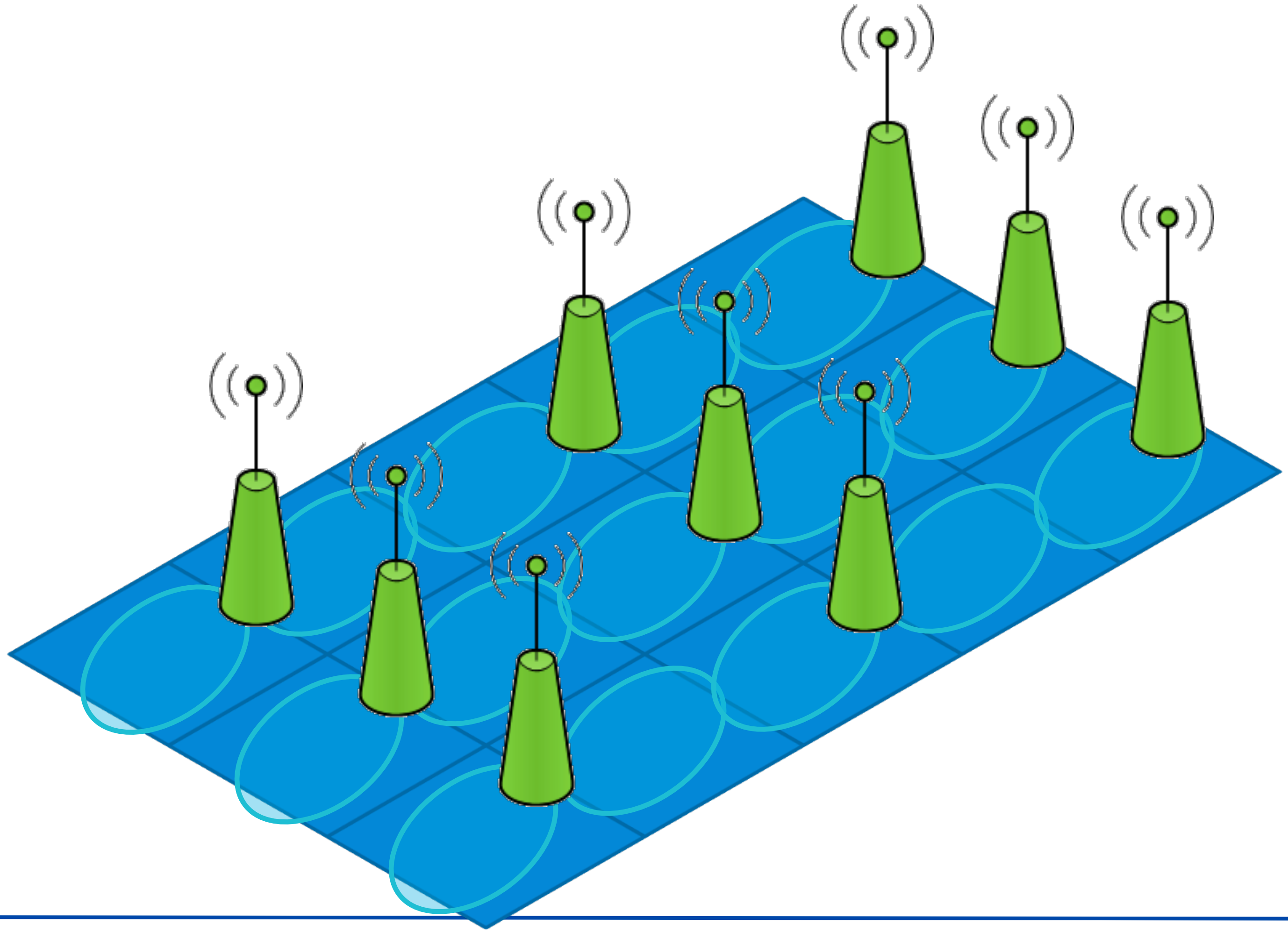
- At the access:
  - Some BSs enter sleep mode when traffic is low
  - BSs that remain on manage all traffic

Sleep modes at the cellular access

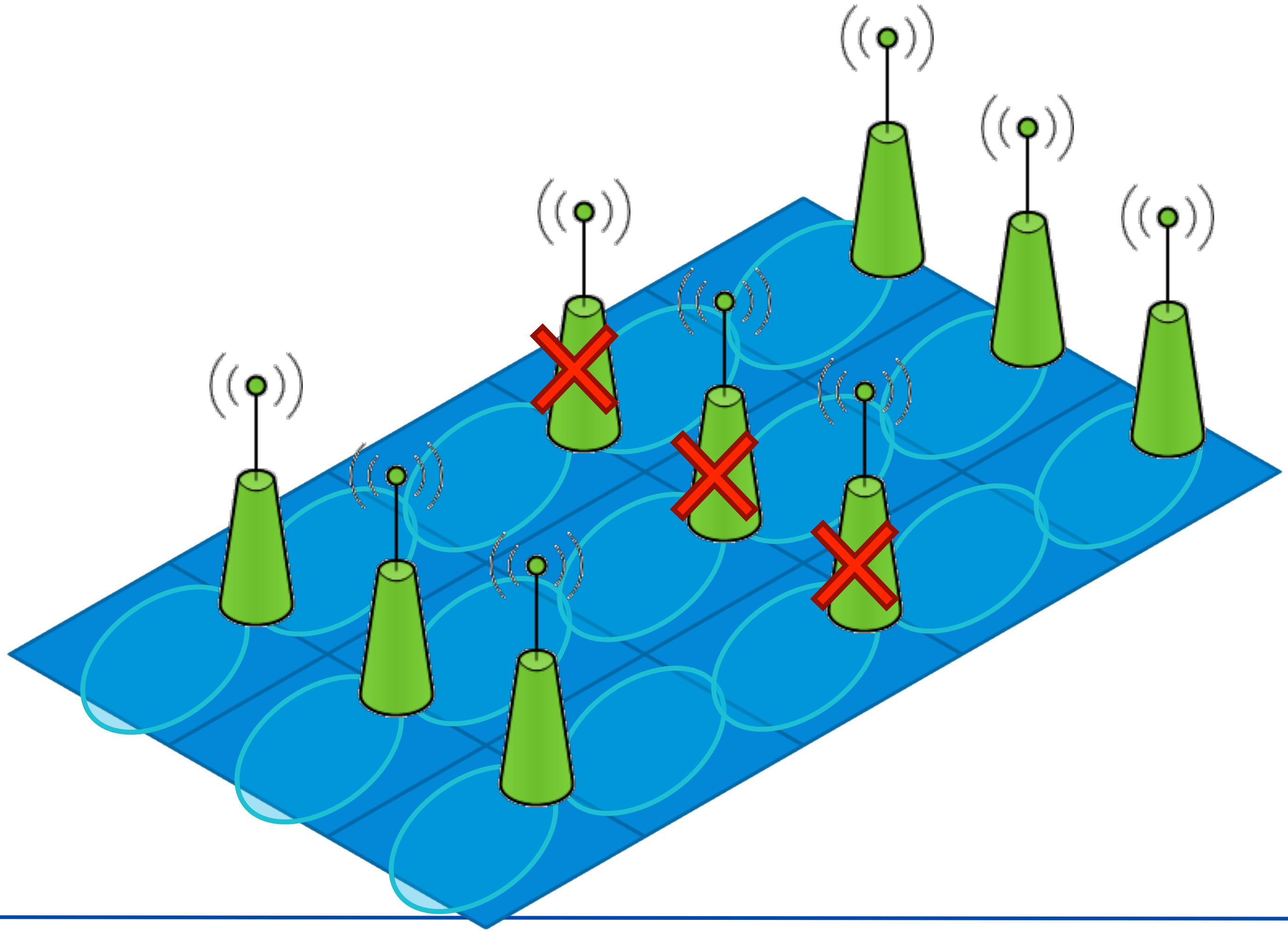
- Assume that a fraction 1-x of the base stations (cells) is switched off, a fraction x is active
- The BSs that remain on are in charge of
  — the traffic of the cells that are off (the desired QoS must still be guaranteed)
  — the radio coverage (transmission power might be increased to guarantee coverage)

Source: L. Chiaraviglio, D. Ciullo, M. Meo, M. Ajmone Marsan, Energy-Efficient Management of UMTS Access Networks. 21st International Teletraffic Congress (ITC 21), Paris, France

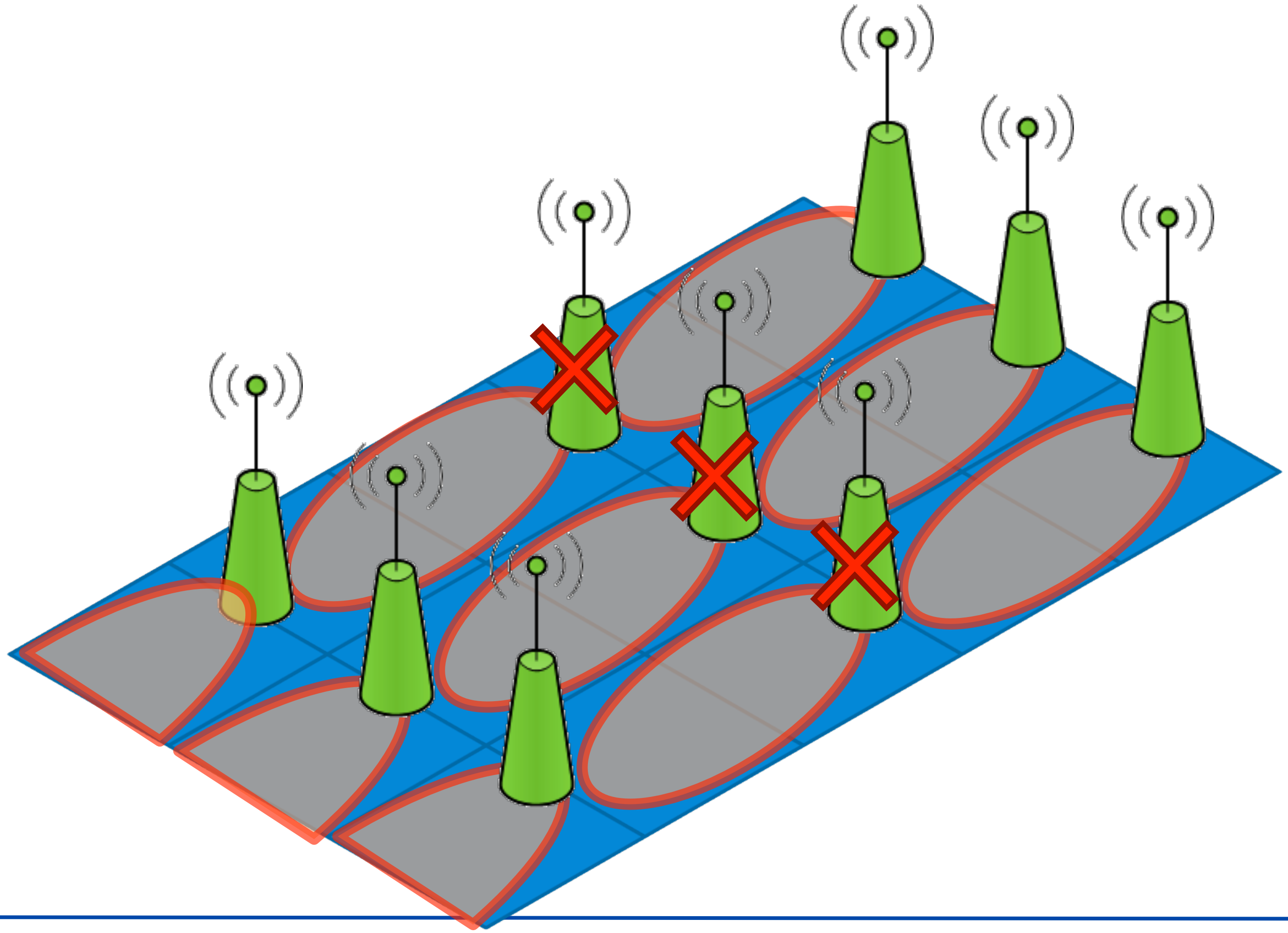
A NodeB controls 2 microcells



Switch *half* of the NodeB, x=1/2



Switch *half* of the NodeB, x=1/2



Looking for a switching scheme

1. Assume that, for each cell remaining on, 1-x cells can be switched off

In the cells that remain on:

- New traffic is $\lambda' = \lambda\left(1 + \frac{1-x}{x}\right) = \lambda\frac{1}{x}$
- New cell radius *is R'*=*KR* (*K* depends on geometry)

Looking for a switching scheme

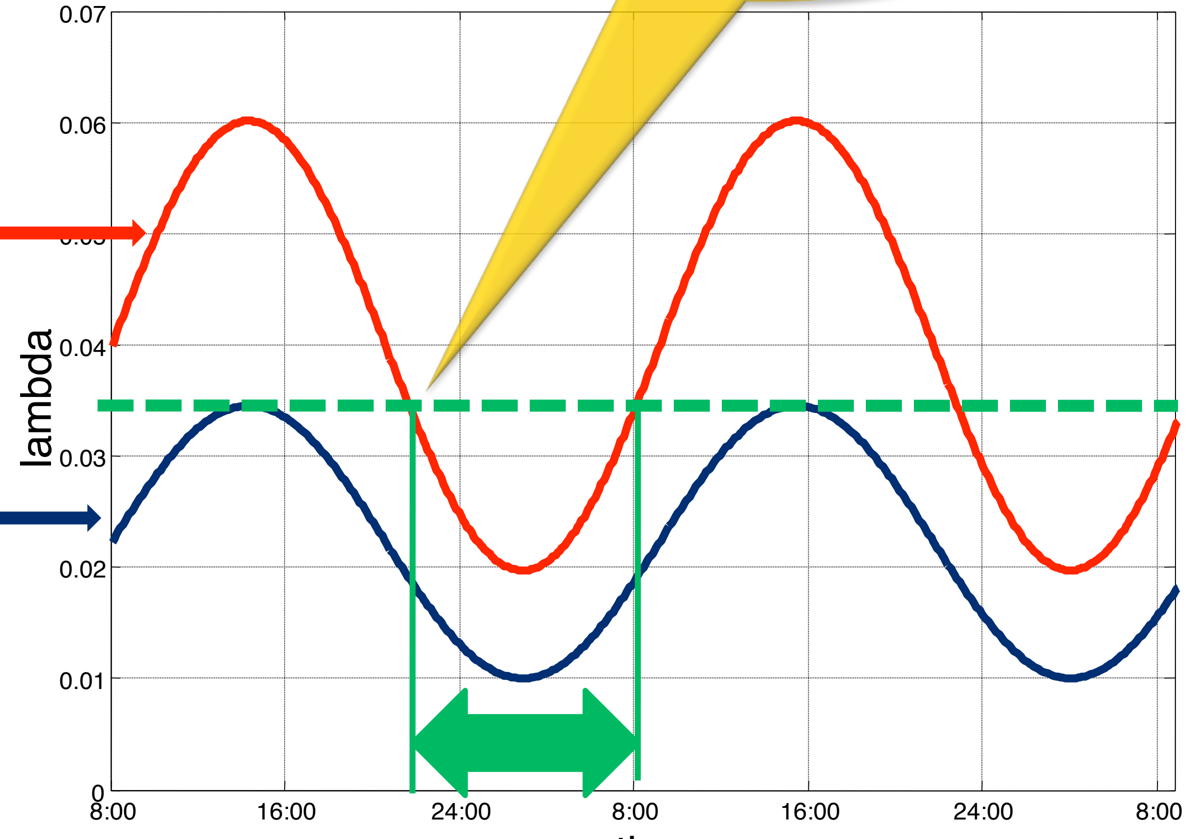
2. Find the low traffic threshold and compute the *sleep zone* (period in which the switching off scheme can be applied), based on
   - day/night traffic pattern
   - QoS constraint (i.e., blocking probability < 1%)

Looking for a switching scheme

Traffic threshold:
QoS is
guaranteed

traffic in cells that remain on, factor 1/x

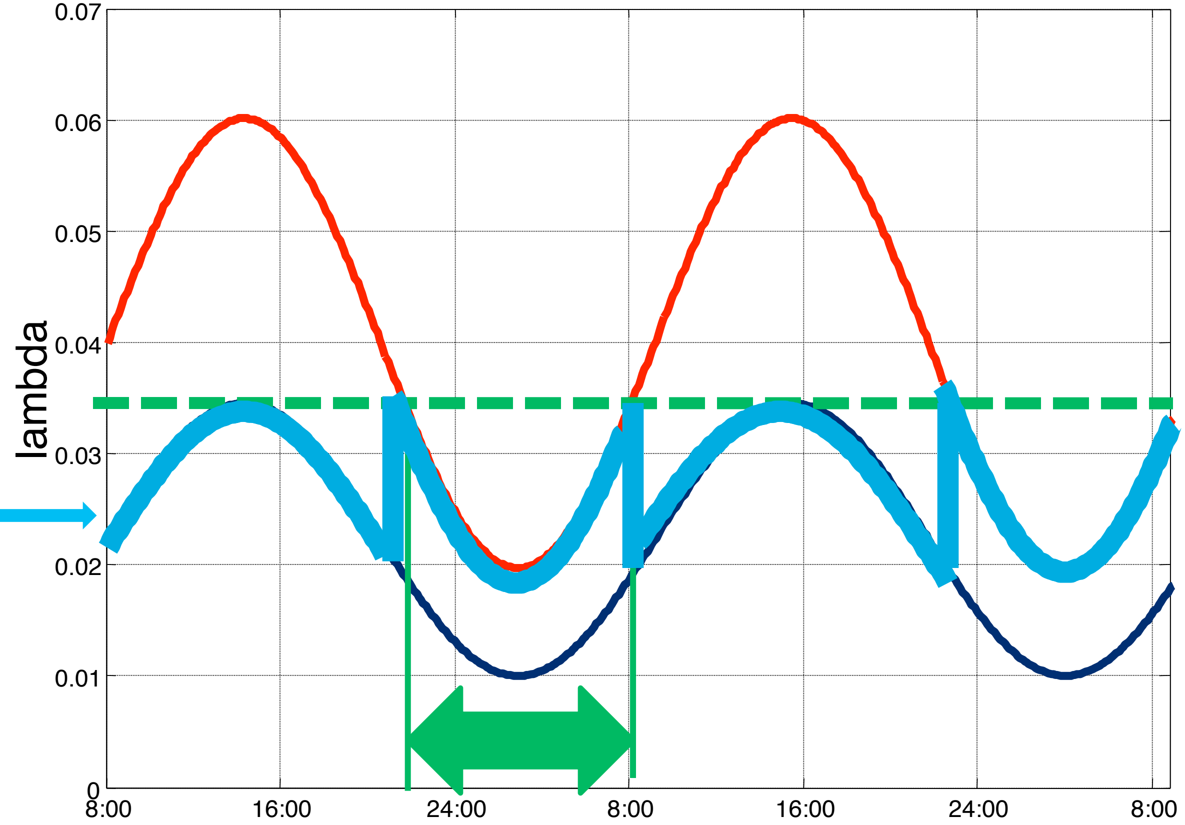
day/night traffic pattern



sleep zone

Looking for a switching scheme

traffic pattern
for cells
remaining on



sleep zone

Looking for a switching scheme

3. Check the maximum cell radius, R_{MAX}

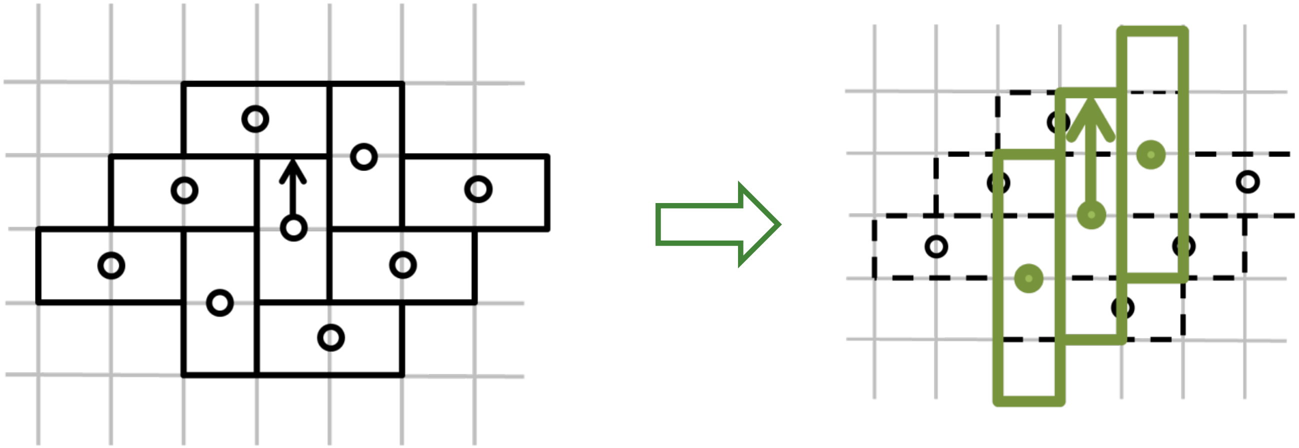
   If $R' < R_{MAX}$ → DONE

   else

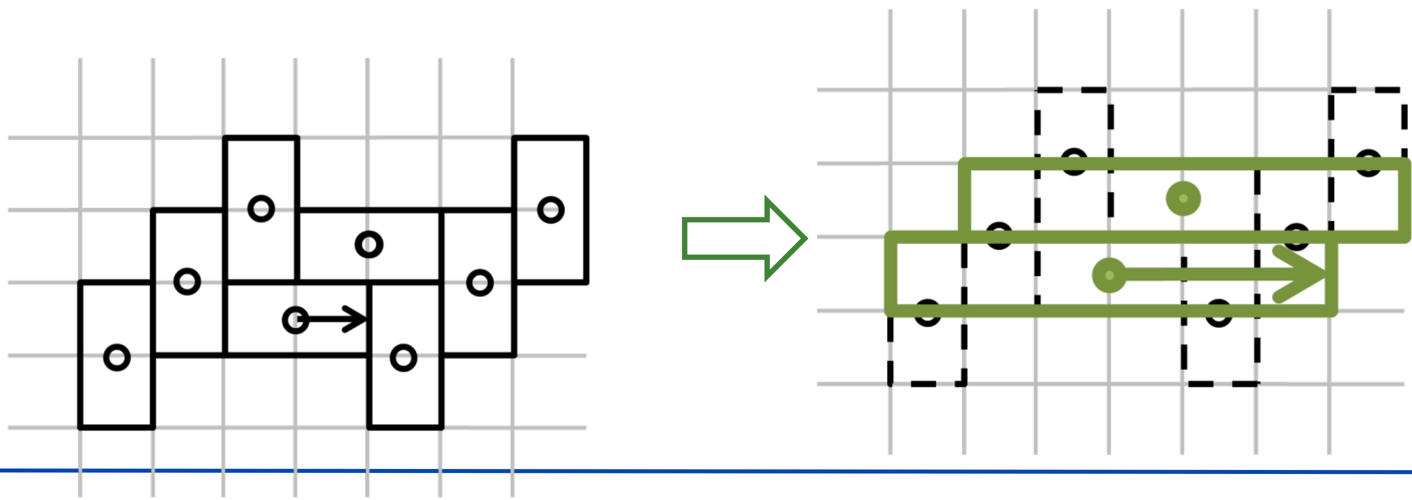
   - increase transmission power during sleep zone OR
   - reduce the sleep zone

Possible configurations

Manhattan configurations (linear)



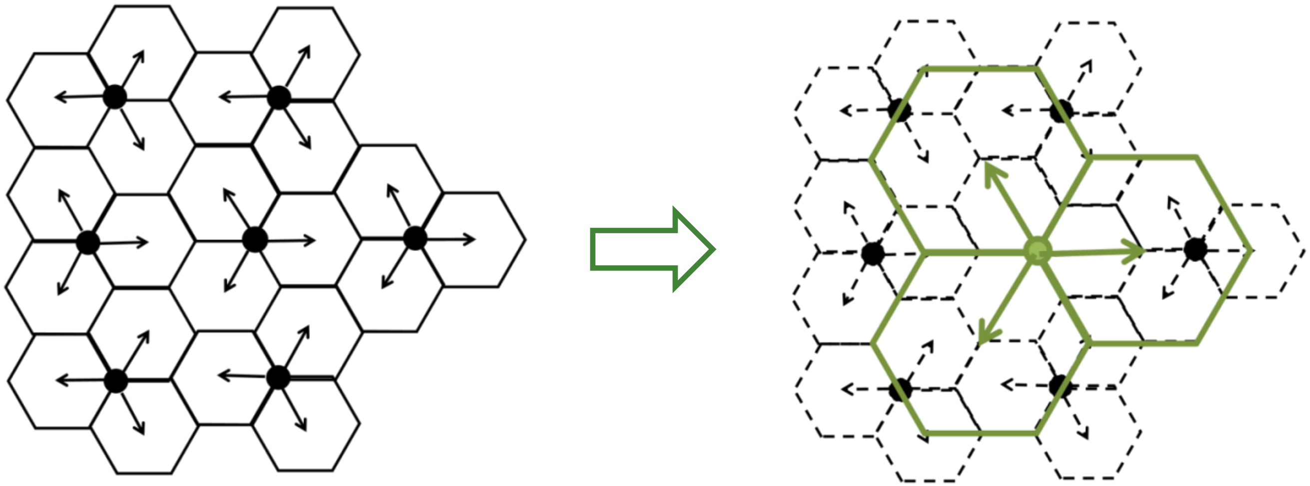
(1,2)



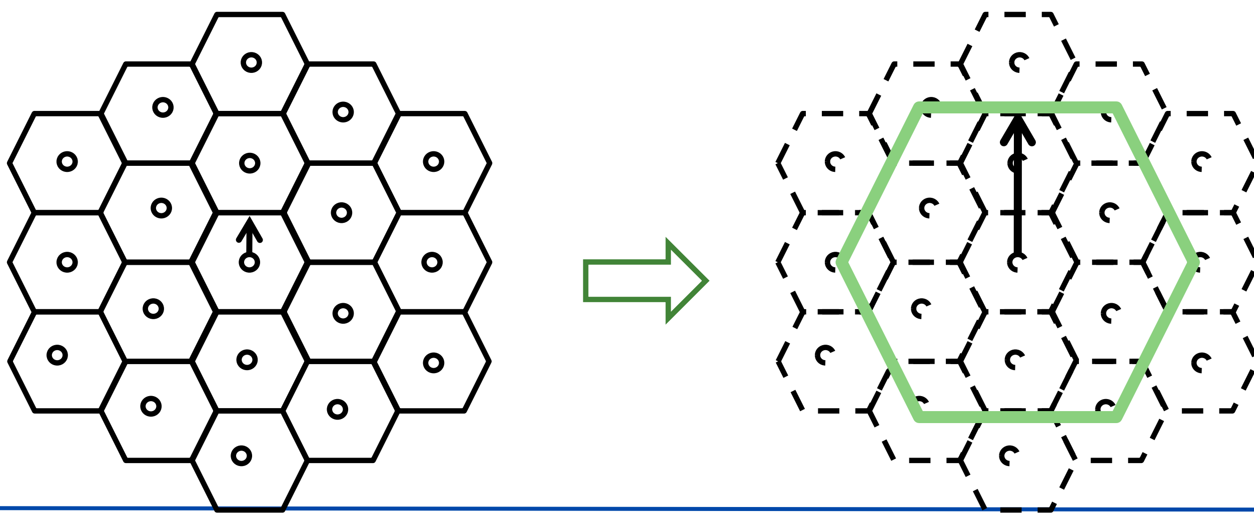
(2,3)

Possible configurations

Hexagonal configurations (squared)



(3,4)



(8,9)

Switch off scheme	Node-B saving [%]	Network saving [%]
(1,2) Manhattan/ linear	52.3	26.16
(2,3) Man[illegible] linea[illegible]	[illegible]	[illegible]
(3,4) hexa[illegible] squa[illegible]	[illegible]	[illegible]
(4,5) cros[illegible]	[illegible]	[illegible]
(6,7) hexagonal	36.8	31.60
(8,9) square	33.9	30.13

Switching more does not always mean saving more!

A few remarks

- Sleep modes are effective but they are possible only in dense (urban) environment where there is redundancy of coverage
- Saving can be remarkable
- The switching strategy is not straightforward
  - Switching more devices is not always the best choice
  - The duration of the sleep zone (period in sleep mode) should also be taken into account

Cellular Networks with Sleep Modes

Optimizing sleep mode decisions

Optimal choice

- The effectiveness of the switching strategy depends on
  - Number of devices that can be switched off
  - The period of sleep for a given scheme

Can we find an optimum combination of no. of devices and sleeping period?

Source: L. Chiaraviglio, D. Ciullo, M. Meo, M. Ajmone Marsan. Optimal Energy Savings in Cellular Access Networks. GreenComm'09 - First International Workshop on Green Communications, Dresden, Germany.

What is the optimum?

- Keep on a fraction x of the cell
- Switch off a fraction 1-x

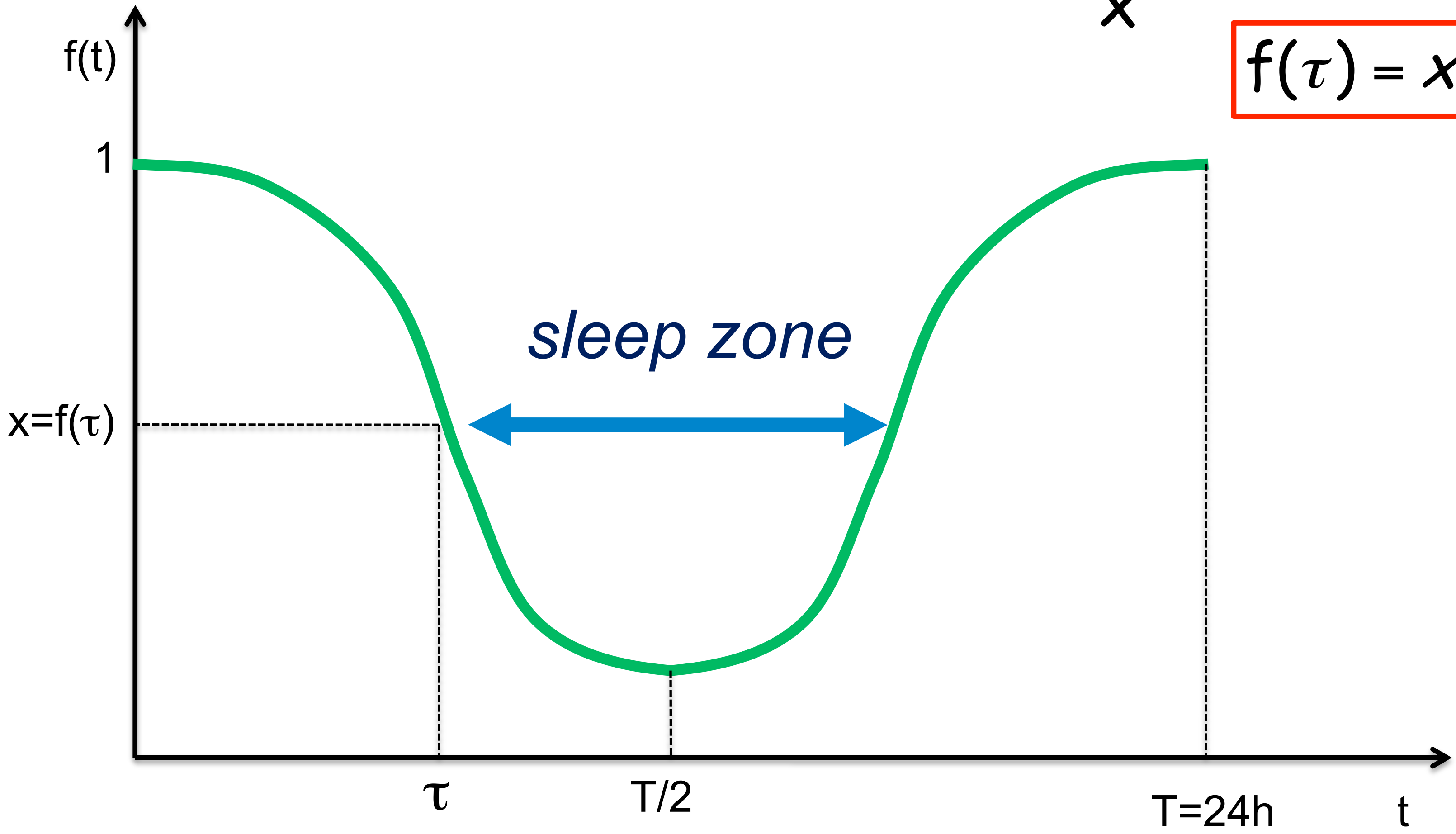
- Given a traffic profile f(t), in the sleep zone the traffic the on cells have to sustain is

$$f_n(t) = f(t) + \frac{1-x}{x} f(t) = \frac{1}{x} f(t)$$

Define the sleep zone

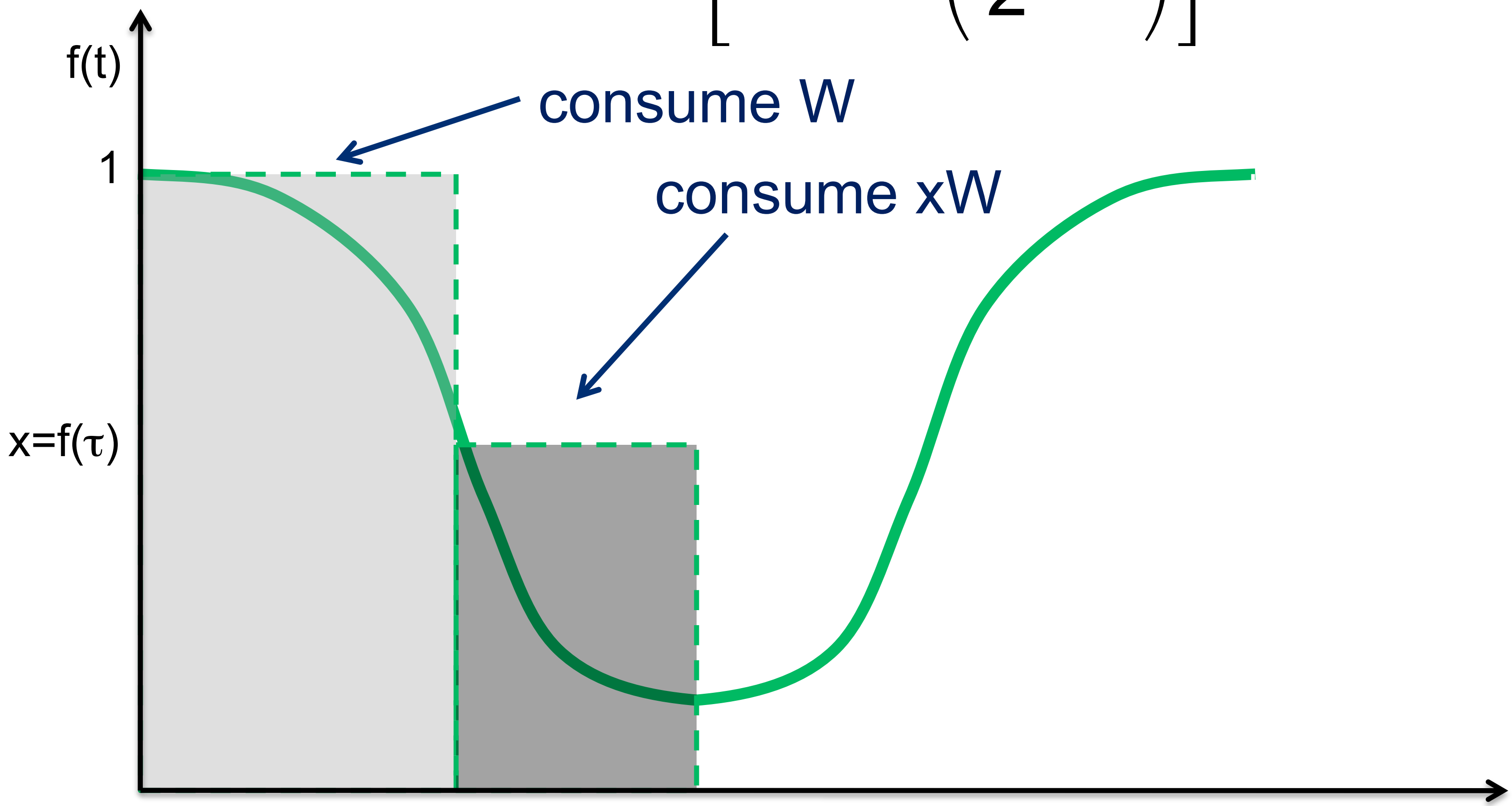
Given x, switch in τ, with $f_n(\tau) = 1 \;\Rightarrow\; \frac{1}{x} f(\tau) = 1$

$$f(\tau) = x$$

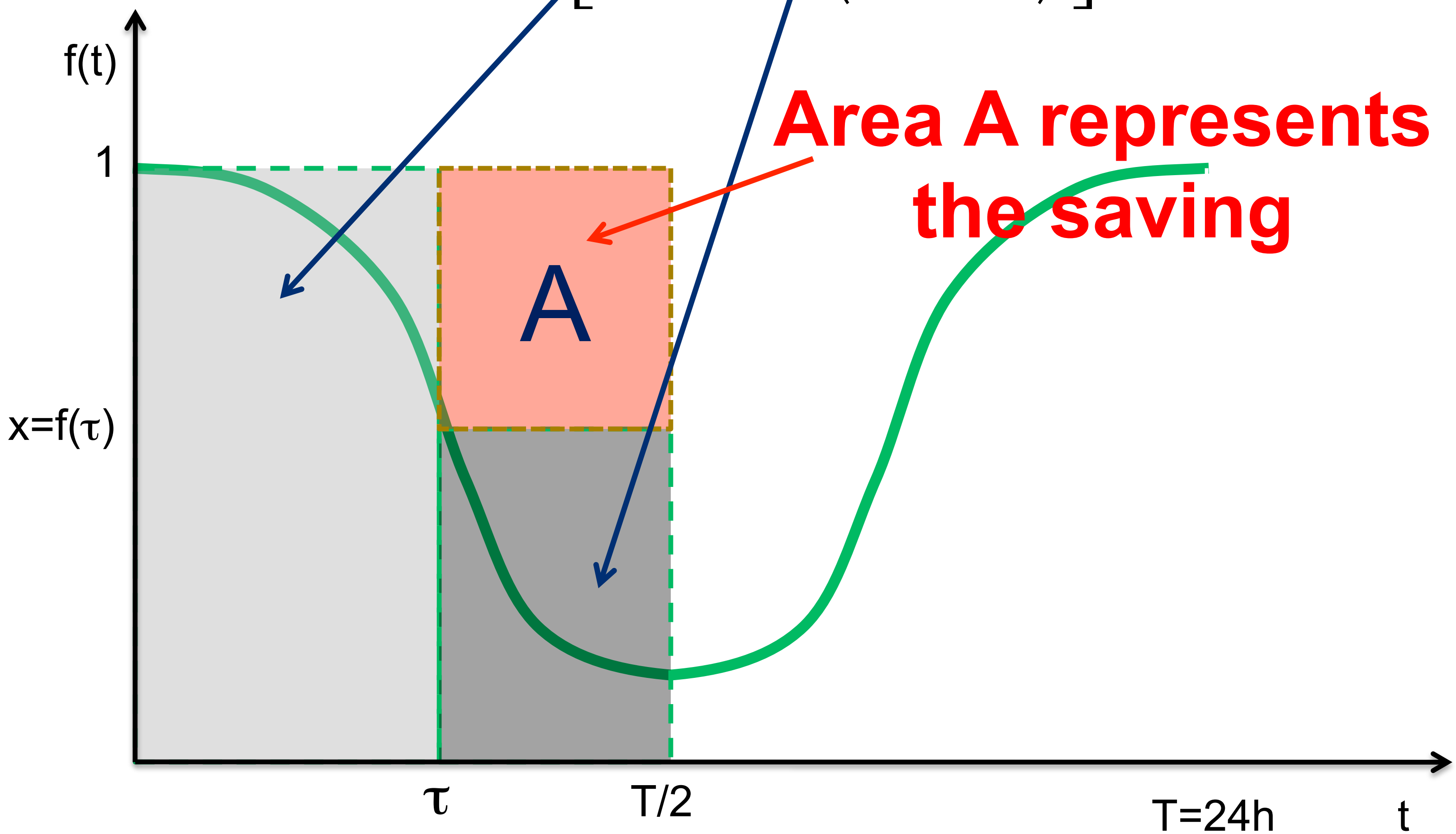


Define consumption

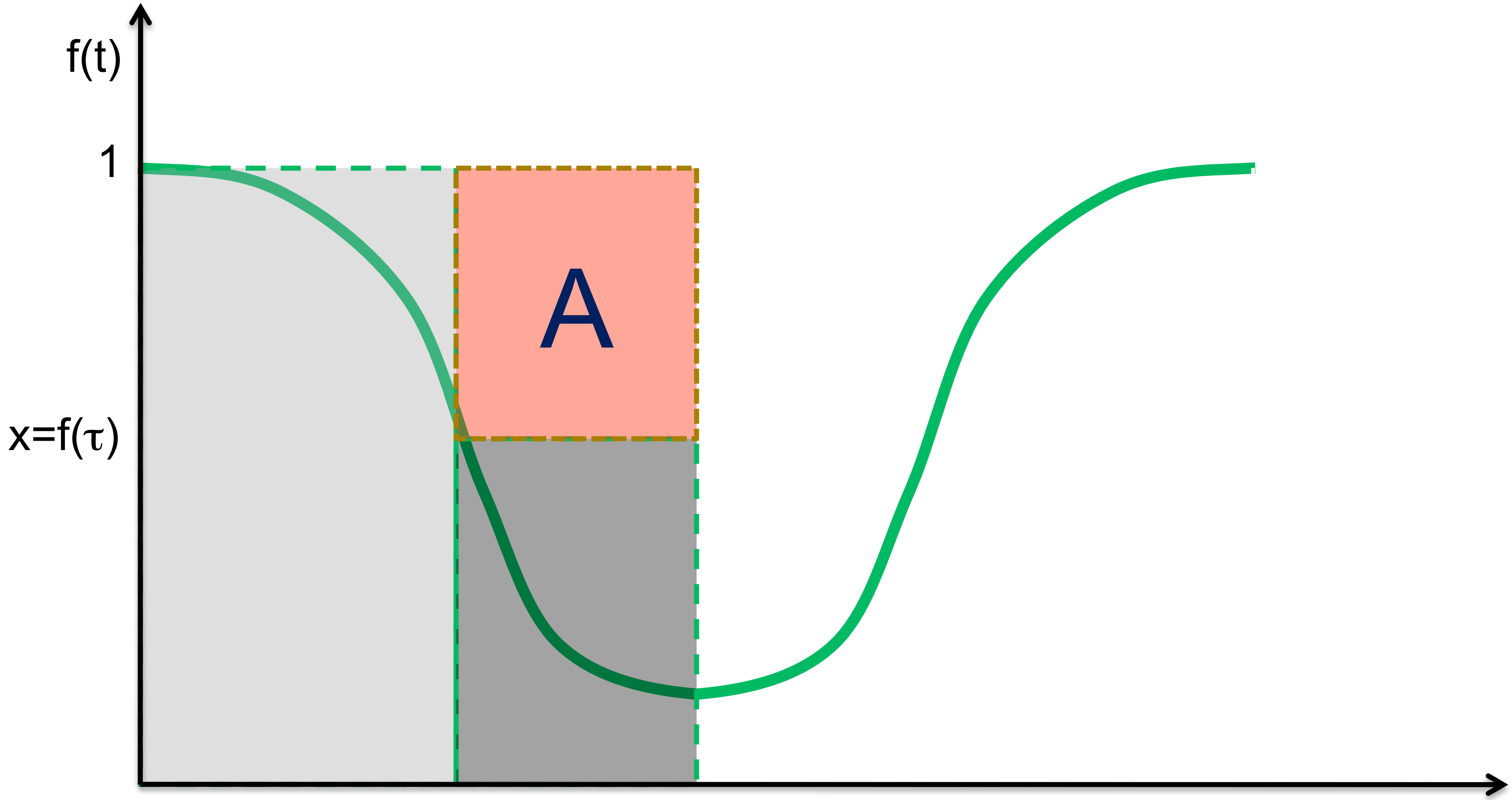
$$C(\tau) = 2W\left[\tau + f(\tau)\left(\frac{T}{2} - \tau\right)\right]$$



$$C(\tau) = 2W\left[\tau + f(\tau)\left(\frac{T}{2} - \tau\right)\right]$$



Look for the value of τ leading to the maximum value of area A



Optimal switching scheme

- Average daily consumption is

$$C(\tau) = 2W\left[\tau + f(\tau)\left(\frac{T}{2} - \tau\right)\right]$$

- By deriving $C(\tau)$ is possible to obtain the optimal scheme, i.e., the value of τ (and x) corresponding to the minimum consumption

Cellular Networks with Sleep Modes

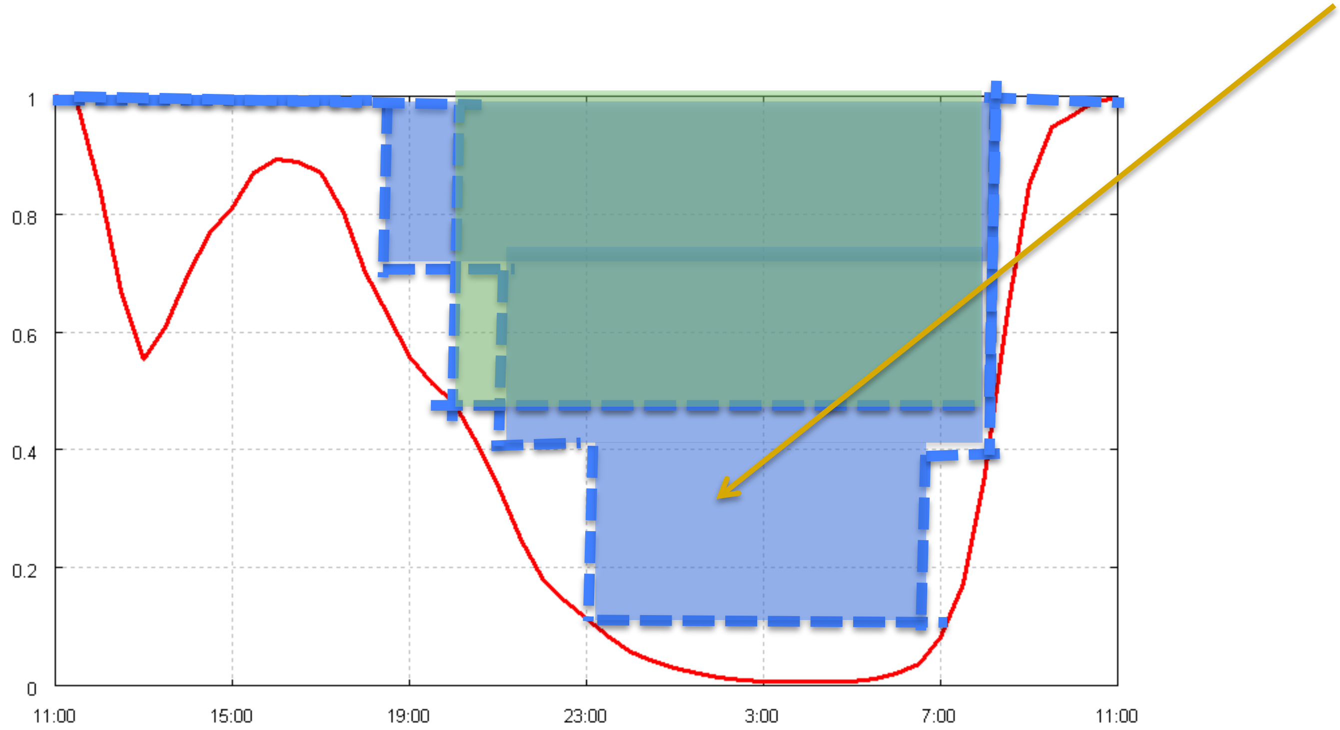
Multiple switching schemes

Multiple switching schemes

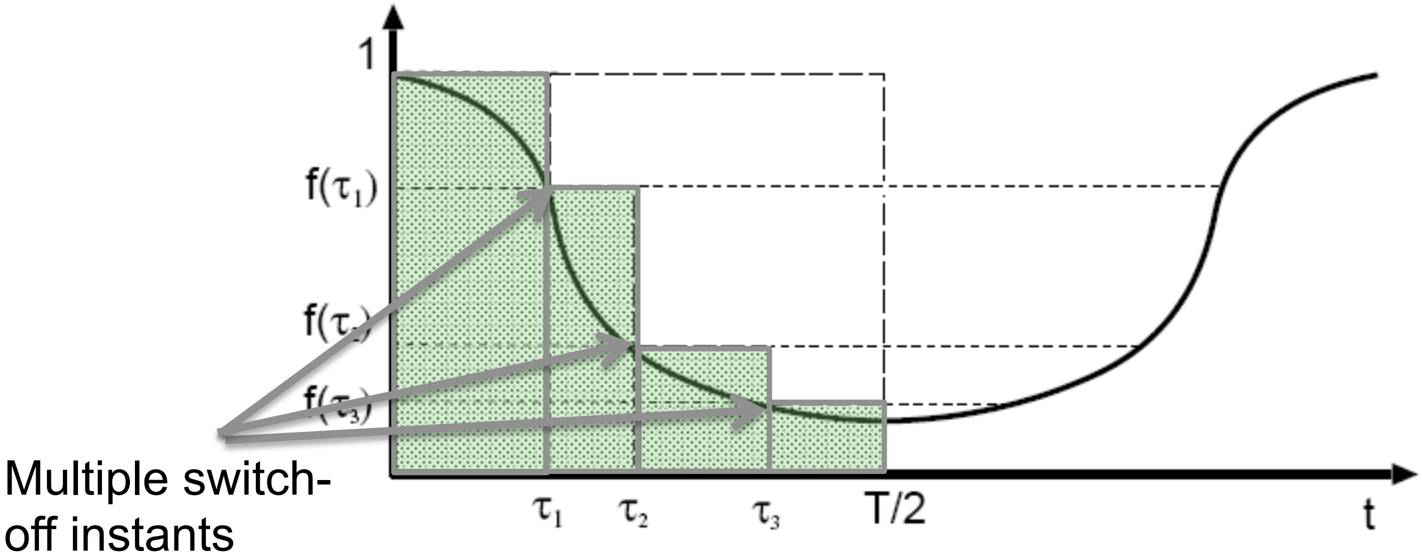
- The optimum is based on the alternate use of two configurations:
  - Peak hour configuration
  - Sleep configuration
- Operators might accept larger (but small in absolute value) number of configurations
  - Larger no. configurations means larger saving
  - More complex, costly and critical planning
  - More transients, risks of instability and discontinuity

Multiple switching schemes

More steps lead to larger saving



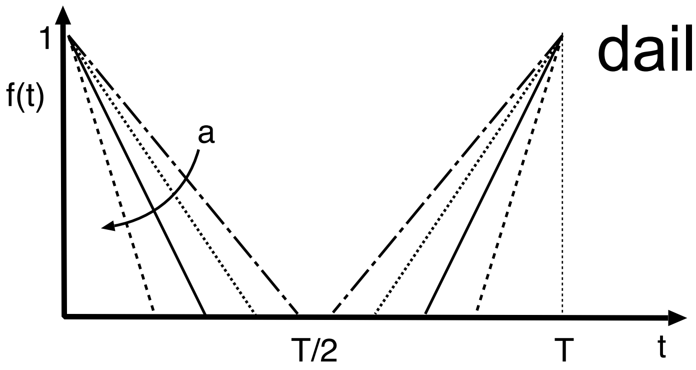
Multiple switch-offs



Again, the optimal choice minimizes the area

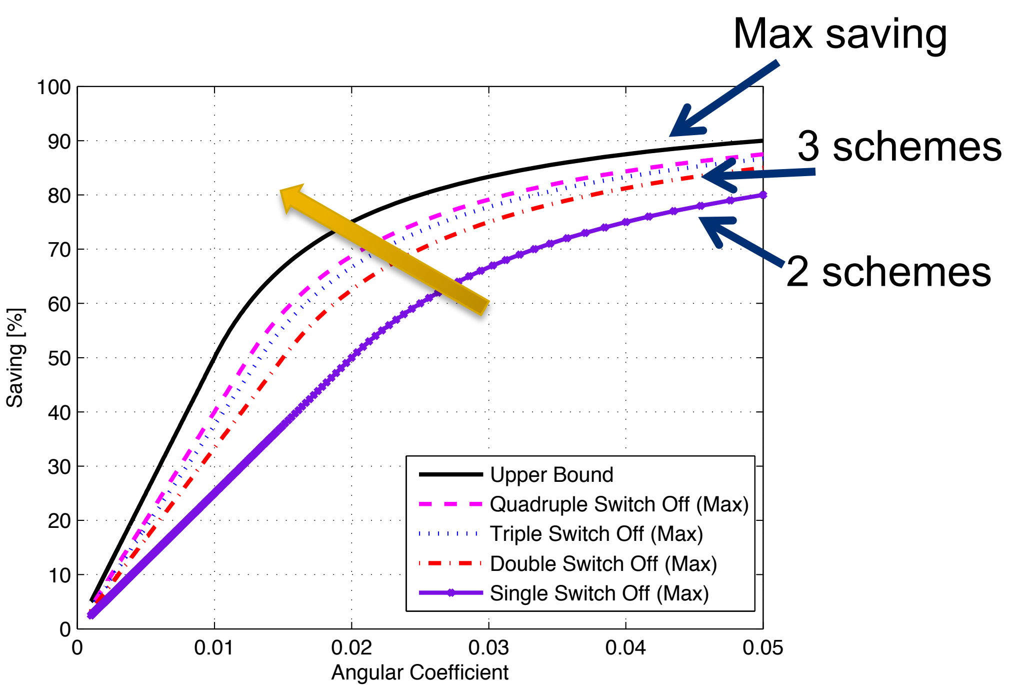
Lower bound on consumption: $C^* = \int_0^{T/2} f(t)\,dt$

How much can we gain with multiple schemes?

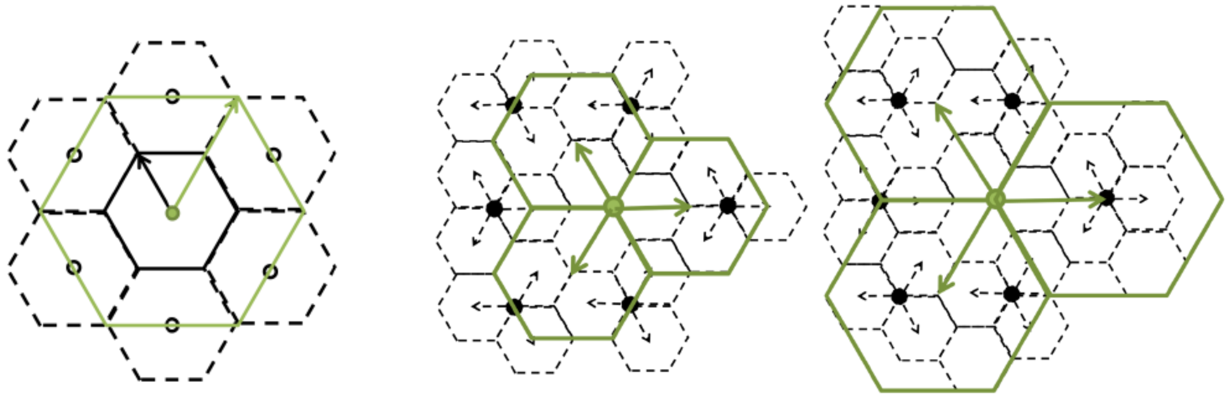


daily traffic pattern

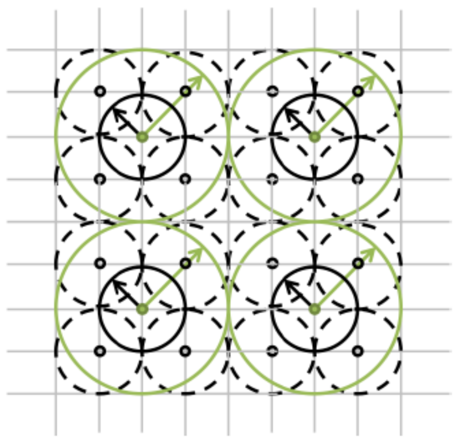
Little saving with more than 2 or 3 schemes



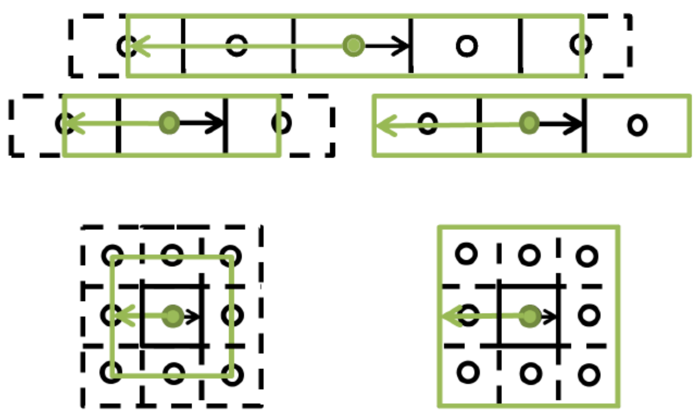
What is the effect of layout constraints?



Hexagonal: omnidirectional/three-sectorial configurations

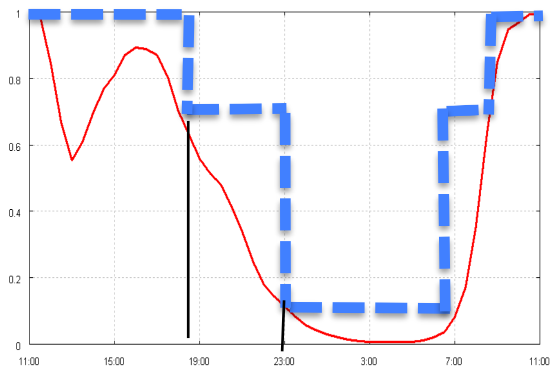


Crossroad

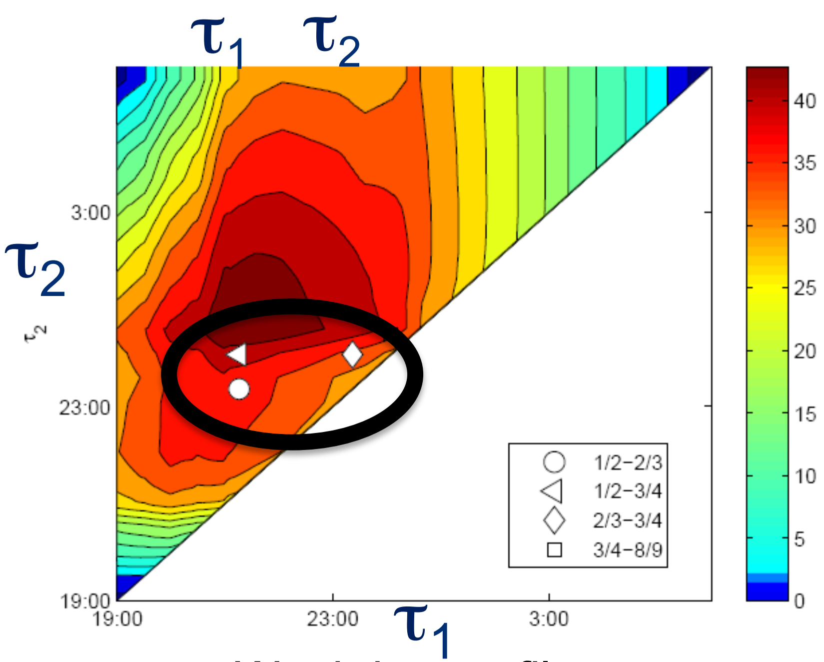


Manhattan layouts (linear/squared)

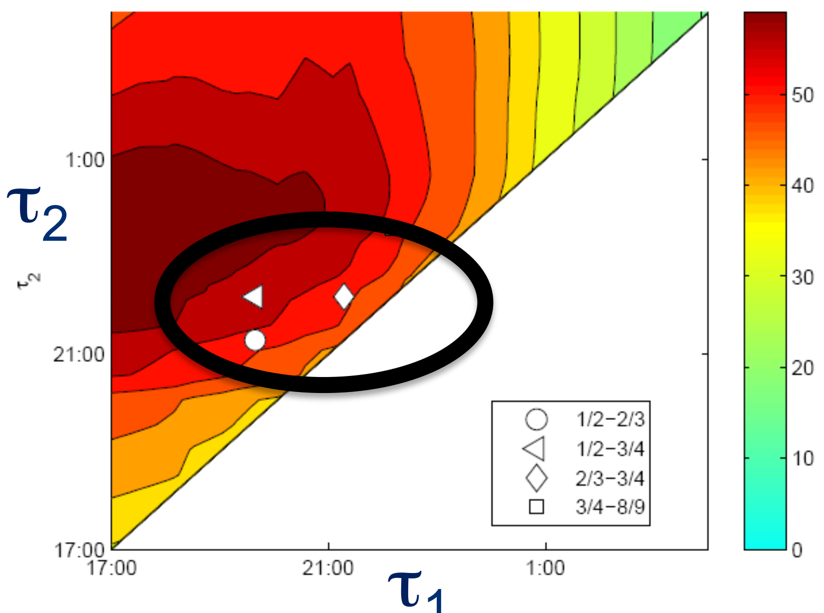
Double switch-off



Real layout constraints limit benefits



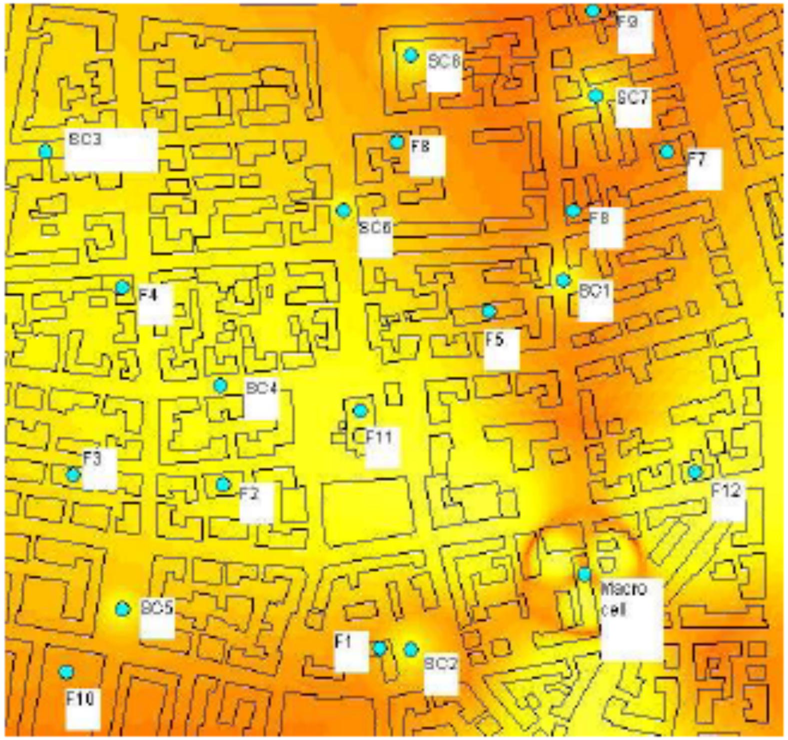
Weekday profile

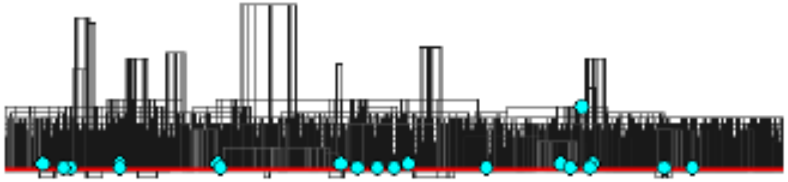


Weekend profile

Case-study: Scenario by Alcatel·Lucent

1 macrocell, 40 W per sector
8 microcells, 1 W
12 femtocells, 20 mW





Case-study: Switch-off policies comparison

Switch-off scheme	Saving [%]
Single (8/9)	40.8
Double (5/9)-(8/9)	45.7
Triple (3/9)-(5/9)-(8/9)	46.9
Maximum (Least-Loaded)	48.7

+4.9%

+1.2%

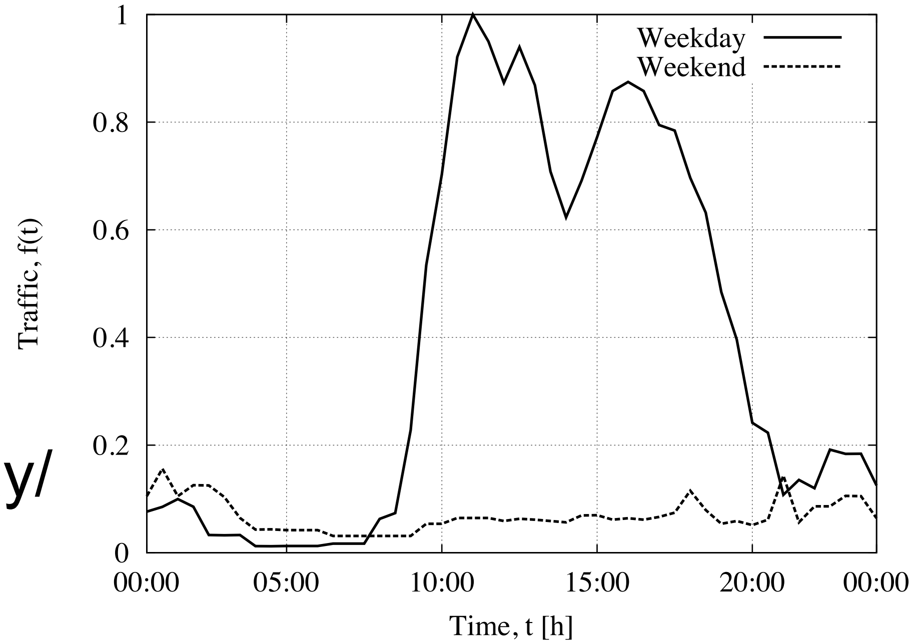
✓ Significant savings can be achieved with only one switch-off per day, the benefit of multiple switch-offs is minor!

Large differences in different areas

- Savings depend on traffic profile that can be highly dependent on the area

Business:

- Fast transitions
- Peaks during the day
- Large difference weekday/ weekend

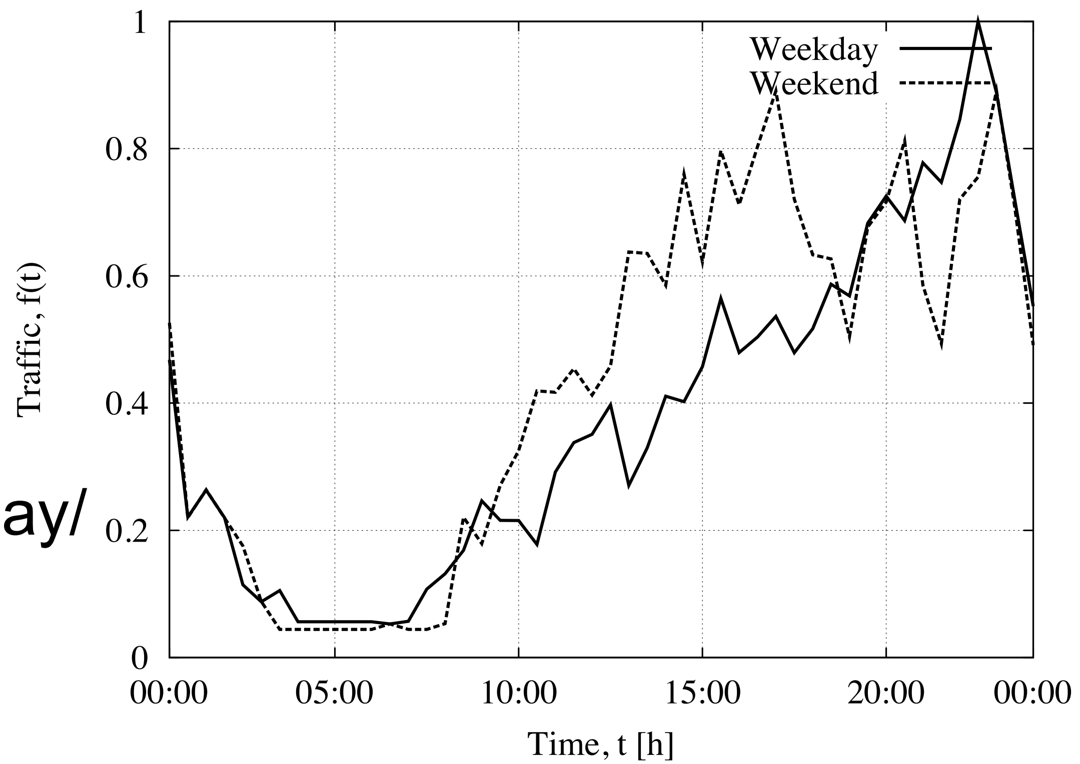


Large differences in different areas

- Savings depend on traffic profile that can be highly dependent on the area

Consumer:

- Long transitions
- Peaks in the evening
- Little difference weekday/ weekend



Discussion and open issues

- Mobile operators' energy costs are large and increasing
- The most energy demanding segment of the network is the access
  - Many devices of quite high consumption
- Sleep modes can be applied in scenarios with high capacity/high density of devices

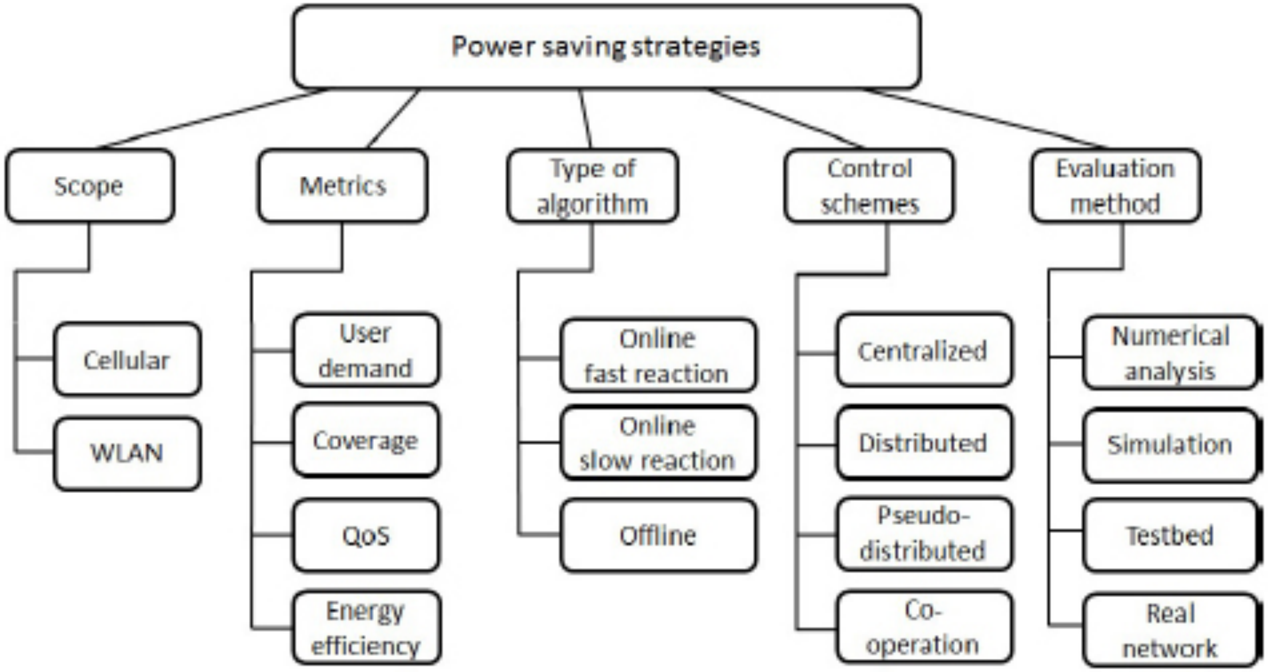
Discussion and open issues

- Critical issues
  - Possible coverage holes
  - QoS degradation during switching on and off transients (call dropping, connectivity interruption, variable channel conditions, …)
- Multiple planning schemes might help but
  - the no. of planning schemes is a critical design choice
  - Frequent activation/deactivation of a BS should be avoided

Cellular Networks with Sleep Modes

Management schemes

BS/AP management schemes - taxonomy



Proposed framework points out:

- the most important design aspects
- shortcomings and advantages
- energy-saving potential

Flat network with *non-overlapping* architecture

- BS switching on/off schemes
  - Shut down a *central* BS, and increase the cell range of the neighboring BSs
  - Shut down the *neighboring* BSs, and increase the cell range of the central_BS
- Two control schemes:
  - Centralized approach: a central controller sends commands to BSs
  - Distributed approach: each (group) of BSs in the network decides to change their state of operation

Sources:

- M. Ajmone Marsan, L. Chiaraviglio, D. Ciullo, and M. Meo, “Optimal energy savings in cellular access networks,” in IEEE International Conference on Communications (ICC ’09) Workshops, Jun. 2009, pp. 1–5.
- Z. Niu, Y. Wu, J. Gong, and Z. Yang, “Cell zooming for cost-efficient green cellular networks,” IEEE Communications Magazine, vol. 48,no. 11, pp. 74–79, 2010.
- L. Chiaraviglio, D. Ciullo, G. Koutitas, M. Meo, and L. Tassiulas, “Energy efficient planning and management of cellular networks,” in IEEE Wireless on-demand Network Systems and Services (WONS ’12), Jan. 2012, pp. 159–166.

Flat network with *overlapping* architecture

- Micro stations are used to provide the required capacity under the coverage umbrella of macro stations
- Two types of BSs:
  - **Critical stations**: usually the macrocells, which cannot be put into sleep mode, due to coverage issues
  - **Flexible stations**: the BSs that can be set in sleep mode
- No need to increase the cell ranges or the parameters of the BSs remaining on
  - low probability of coverage holes

Source:
S. Kokkinogenis and G. Koutitas, "Dynamic and static base station management schemes for cellular networks," in IEEE Global Communications Conference (GlobeComm '12), Dec. 2012.

Multi-Tier Network

- Marco-micro network co-exists and cooperates with other technologies, e.g. *femto cell* and *WiFi*
- Main objective: provide an online user association algorithm (or offloading solution)
- Limitations and constraints for integration with existing BS system
  - Guarantee that coverage holes do not occur (especially indoor scenarios)
  - Software and hardware limitations of real equipment (availability of low power states, transient times)

Sources:

- S. Bhaumik, G. Narlikar, S. Chattopadhyay, and S. Kanugovi, “Breathe to stay cool: adjusting cell sizes to reduce energy consumption,” in rhe 1st ACM SIGCOMM workshop on Green Networking, 2010, pp. 41–46.
- A. De Domenico, R. Gupta, and E. Calvanese Strinati, “Dynamic traffic management for green open access femtocell networks,” in IEEE 75th Vehicular Technology Conference (VTC ’12-Spring), May 2012.
  S. Kokkinogenis and G. Koutitas, “Dynamic and static base station management schemes for cellular networks,” in IEEE Global Communications Conference (GlobeComm ’12), Dec. 2012.
- I. Haratcherev and A. Conte, “Practical energy-saving in 3g femtocells,” in IEEE Green Broadband Access (GBA) workshop, in conjunction with ICC 2013, Jun. 2013.
- I. Haratcherev, M. Fiorito, and C. Balageas, “Low-power sleep mode and out-of-band wake-up for indoor access points,” in GLOBECOM Workshops, 2009 IEEE, 2009, pp. 1–6.

Network Sharing

Multiple operators

$$P = P_{const} + f(load)$$

Service provisioning cost (waste)

- The presence of multiple infrastructures multiplies the waste
- Take a global vision, make the operators *cooperate* → **network sharing concept**

Network sharing

- Several *competing* mobile operators cover the same area with their equipment
- Networks are dimensioned over the peak hour traffic
- During low traffic periods the resources of one operator are sufficient to carry all the traffic

⬇

Make operators *cooperate* to reduce energy consumption

Network sharing

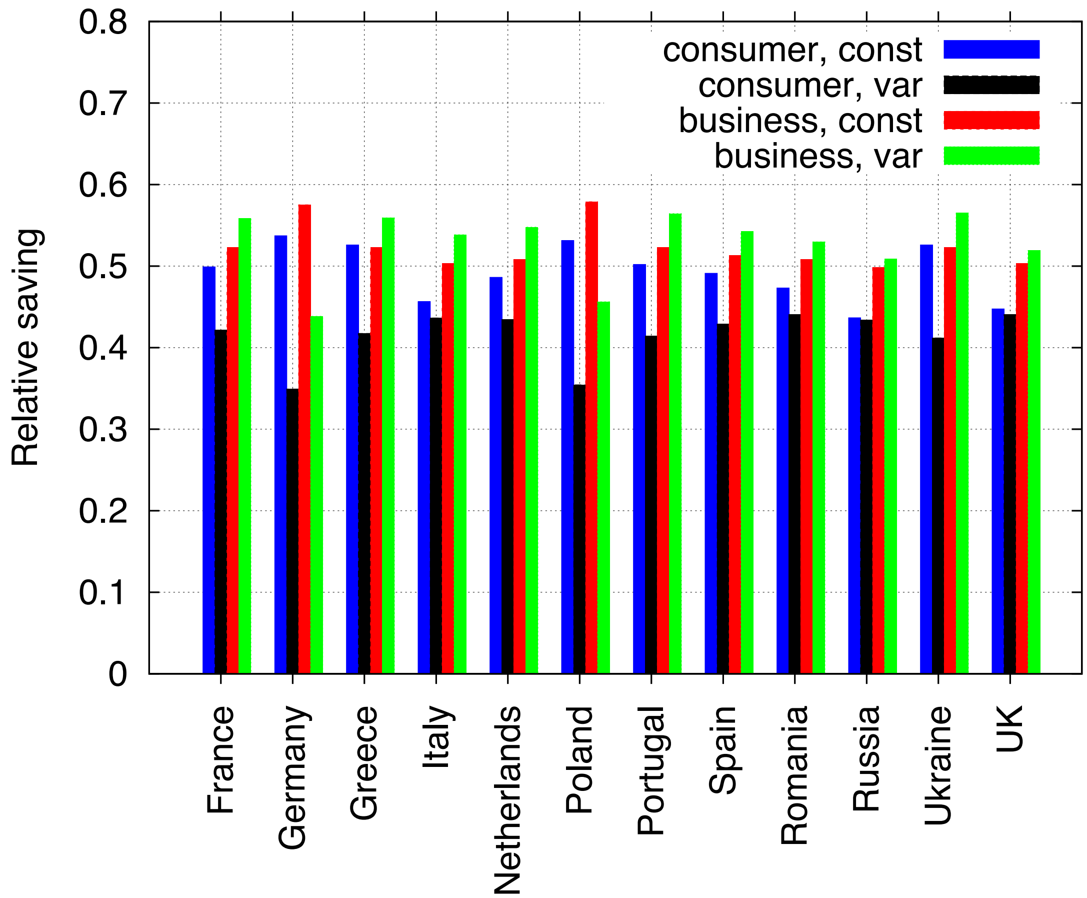
- In turn,
  - Switch off the network of one operator, when traffic is low and the active operators can carry all the traffic
  - Let users roam to other operators
  - Balance costs

Source: M. Meo, M. Ajmone Marsan. Energy efficient wireless Internet access with cooperative cellular networks. Computer Networks, Volume 55, Issue 2, February 2011, Pages 386-398.

Case study: Some European Countries

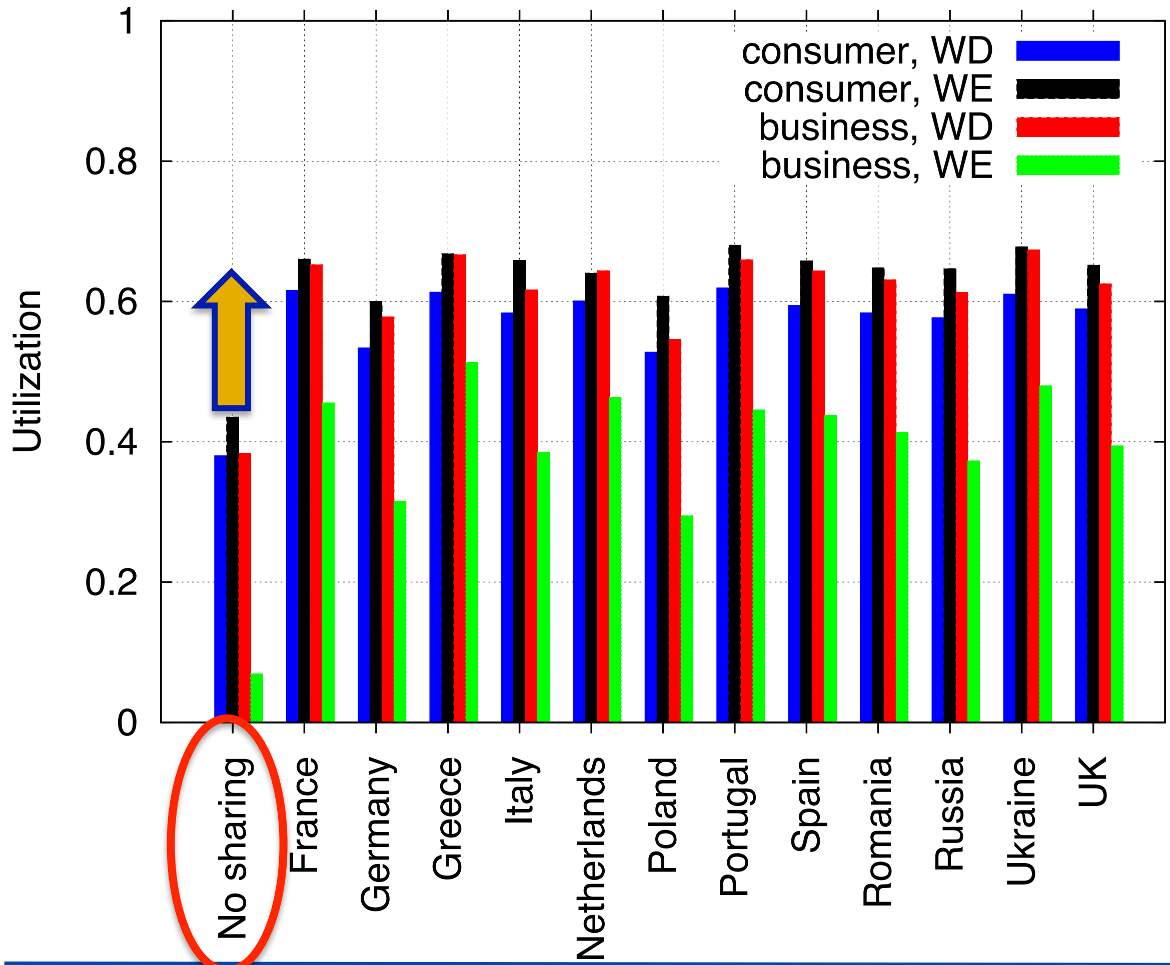
Country	MNOs	Market share [%]				Subscr. [M]
France	3	46	36	19	-	58.2
Germany	4	32	31	21	16	113.6
Greece	3	51	28	21	-	15.4
Italy	3	38	36	26	-	84.0
Netherlands	3	46	26	28	-	19.0
Poland	4	29	29	28	14	47.5
Portugal	3	45	40	15	-	16.4
Spain	3	44	34	22	-	51.4
Romania	3	41	32	26	-	24.2
Russia	3	37	33	30	-	189.7
Ukraine	3	48	37	15	-	52.3
U.K.	3	39	33	28	-	68.5

Energy saving



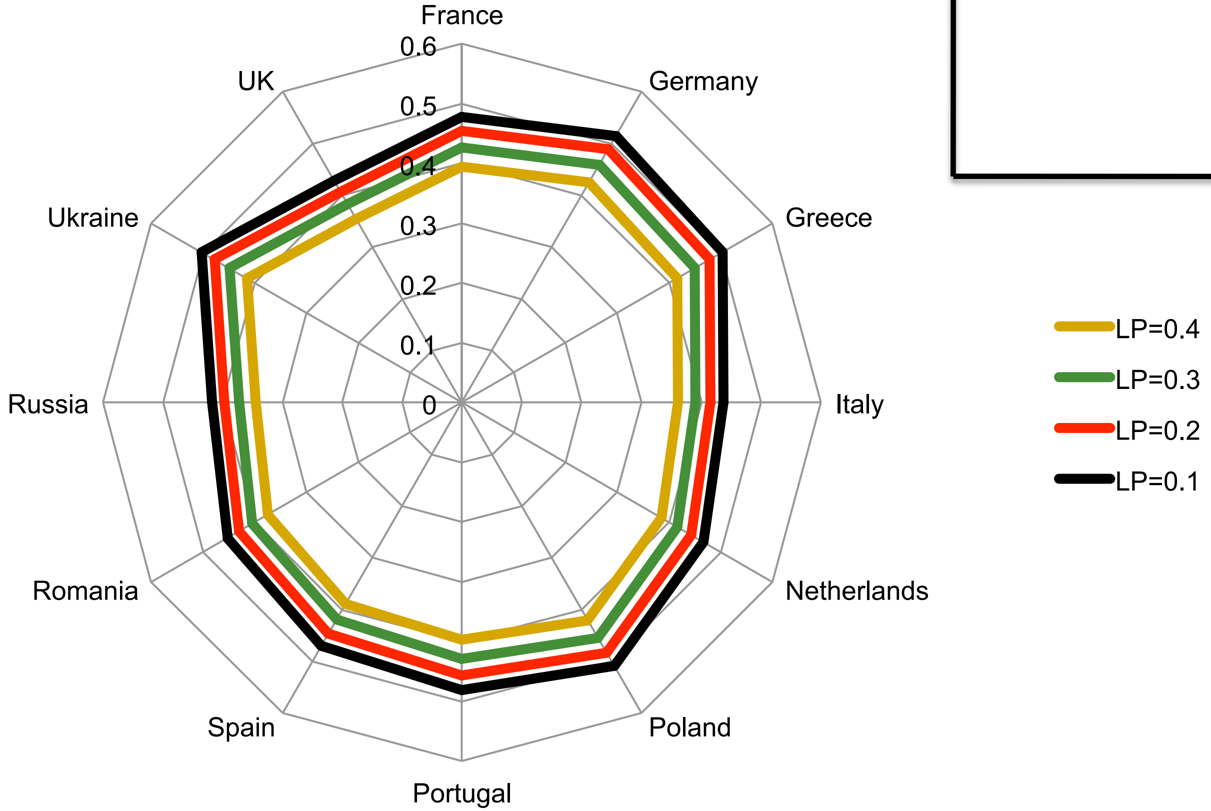
Large savings, more than 30-40%!

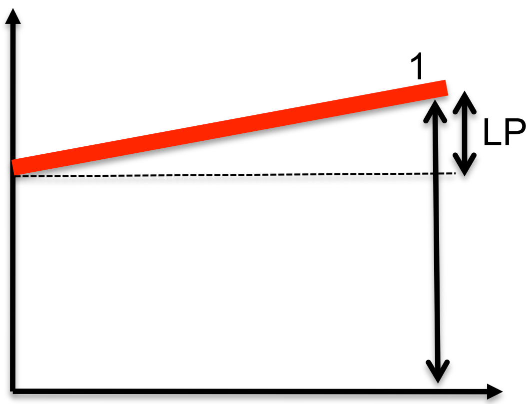
Utilization



The key point is increasing utilization

Impact of load proportionality





Network sharing

- In the short term, *inter-operator switching schemes* can reduce the waste
- In the long term, *a unique efficient infrastructure with multiple virtual operators might be a wise choice*

Discussion and open issues

- Mobile operators' energy costs are large and increasing
- Cooperation between operators can be **very effective** in consumption reduction
  - Allow for the whole network or large portions to switch off
  - Reduce the problems related to coverage holes and propagation issues

Discussion and open issues

- Operators are very reluctant to cooperation with competitors, that might:
  - Profile their users
  - Have the possibility to propose alternative offers
  - Favor their own users
- Roaming cost definition is critical
- Transient phases might be difficult to manage

Discussion and open issues

- Governments and institutions have to play a role and, in particular, they should
  - Provide **incentives** for cooperation
  - Enforce forms of cooperation
- Virtual operators might be a good solution
  - For networks to be deployed, this reduces also the cost of deployment and future dismissal phases

From Energy-efficiency to Sustainable Networking

Micro and macro effects of energy efficiency

Jevons paradox:

Increase of energy efficiency to produce a good/service

↓

reduces cost of the production and, hence, its price

↓

increases the demand

↓

increases the energy consumption

From energy efficient networking to sustainable networking

Energy efficiency is good since it leads to

- Greater production → higher quality of life & larger population affording it
- Reduction of price increase and energy shortage
- *Global environmental advantage* if coupled with green taxes to keep the price constant

but,
for sustainability, it must be coupled with new energy generation principles

Energy from renewable sources

Instead of only reducing use of energy produced with fossil fuel, exploit also renewable energy sources

Renewable source: Any energy resource that is naturally regenerated over a short time scale or are practically inexhaustible:

- Sun
- Wind
- Waves
- Flowing water
- Geothermical heat flow
- …

Powering BSs with renewables

Zero grid-Electricity Networking (ZEN):

BSs rely purely on renewable energy sources and are not connected to a power grid

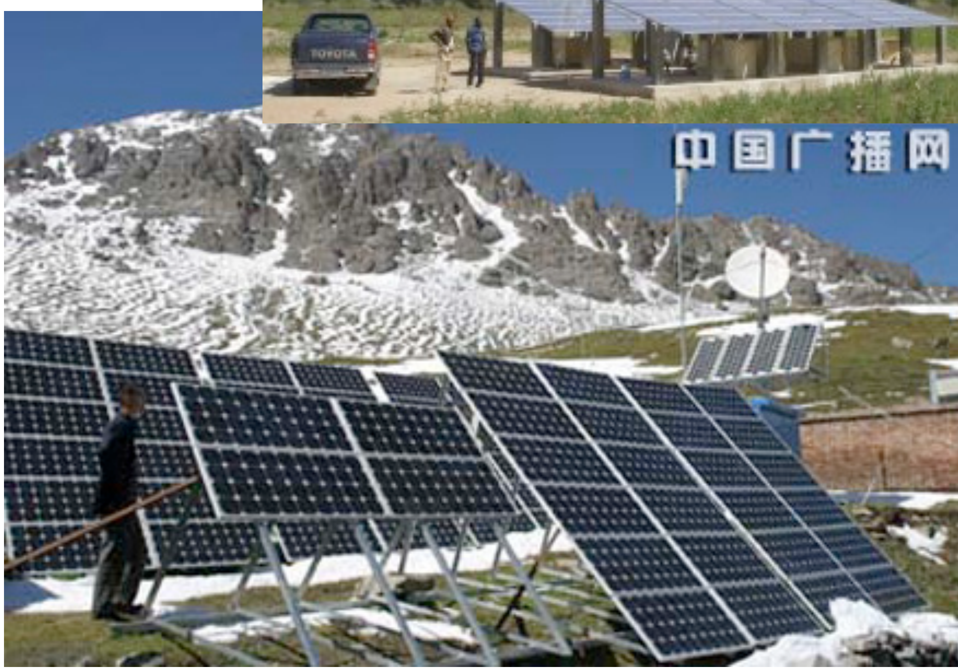
- Can acquire limited amounts of energy from (intermittent) local generators exploiting renewable sources
- Any energy surplus is stored in a battery
- The BS can operate also in periods of low or no production, as long as energy is available, but it is forced to switch off when the battery is depleted

or **hybrid** systems that rely also on the power grid

Possible scenarios

1. ZEN: New opportunities for the development of networks in regions where
   - energy grids are inexistent
   - energy grids are unreliable
   - energy is temporarily unavailable (because of earthquakes, wars, terrorism, …)
   - energy is too expensive for operators to provide services at reasonable cost

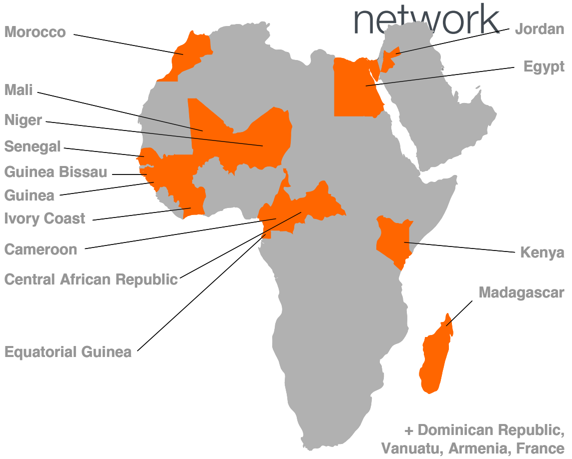
Possible scenarios



ZEN: an example

Orange green strategy for AMEA zone

Project : optimized power consumption and solar powered mobile network

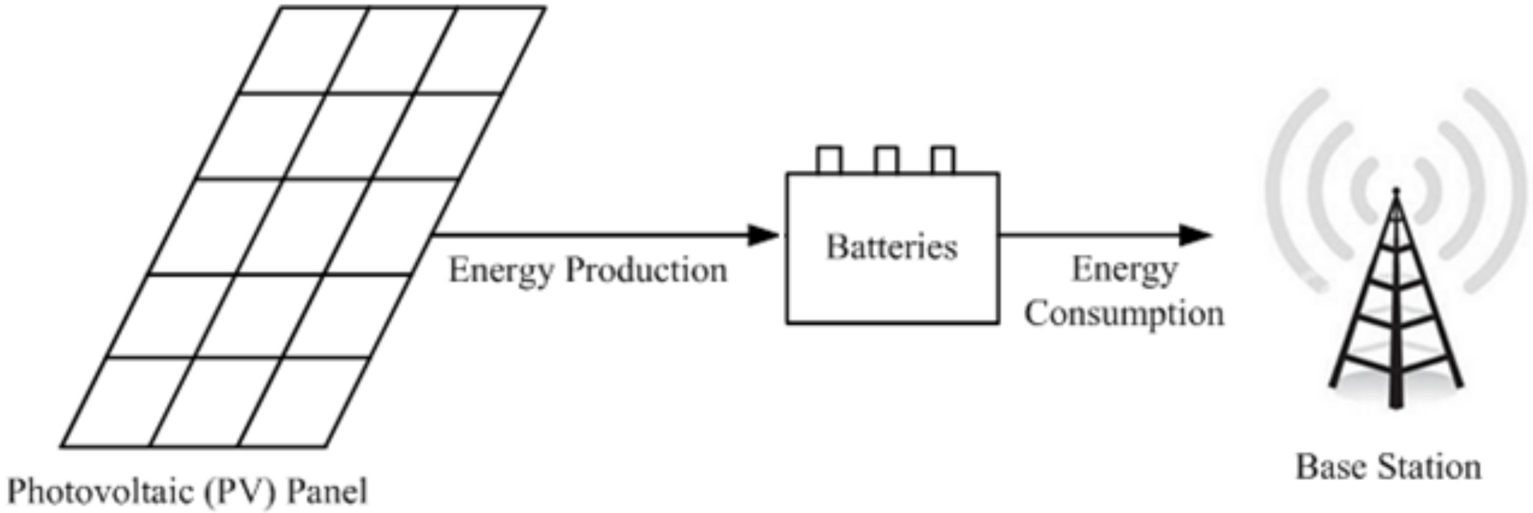


the project was initiated in Africa and is now deployed in 18 countries of France Telecom-Orange

fully integrated photovoltaïc solution

- 2065 access network sites, for 3.3 M people
- 13GWh solar energy produced in 2011
- 25 Mliters fuel 67 Ktons CO_2 saved in 2011

Scenario 1 (emerging regions): PV-only systems for powering BSs



Zero grid-Electricity Networking (ZEN)

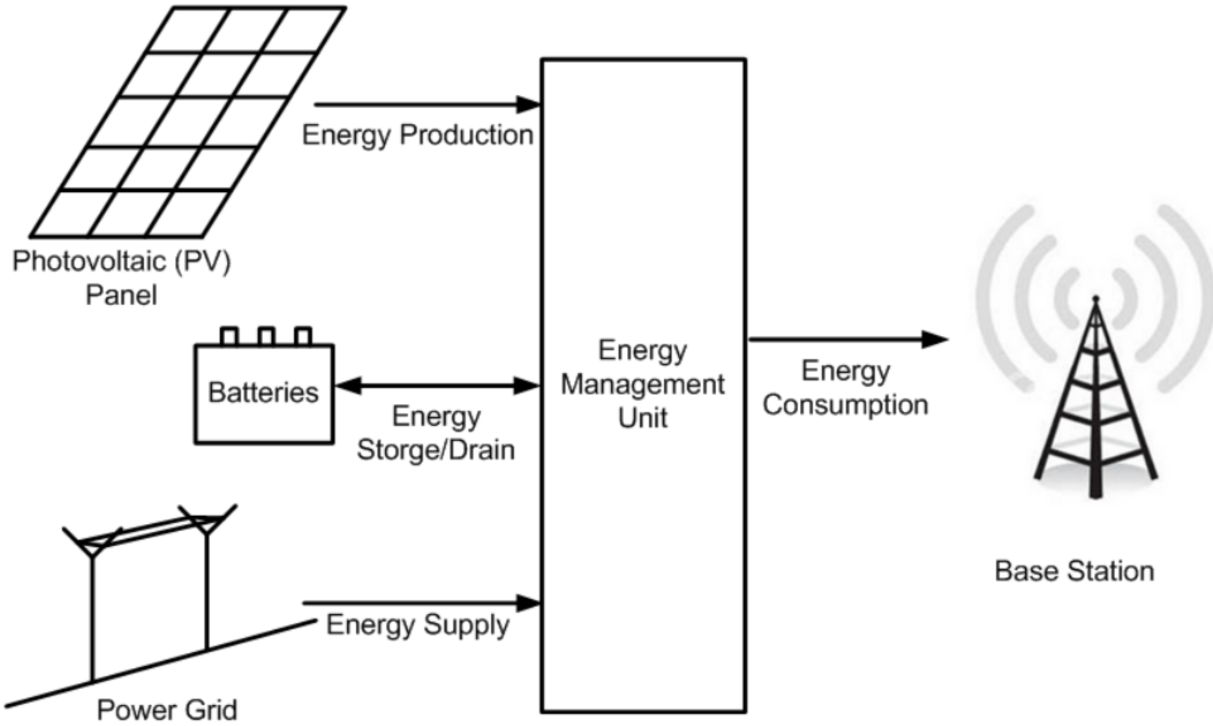
ZEN: some issues

- How to **dimension** BSs, their power generators and energy storage
- How to design distributed, but **coordinated BS sleep** modes in periods of low traffic, in order to reduce energy consumption
- How to **design a distributed mesh** network of ZEN BSs that can provide the necessary bandwidth
- How to **route** data and **schedule** transmissions on such BS mesh networks
- How to **guarantee** uninterrupted service, fault tolerance and survivability, so as to provide carrier-grade services to end users

ZEN: possible scenarios

2. Hybrid: New business models when
   - energy cost is large and producing energy reduces the amount bought from the grid
   - green taxes incentivate the use of renewable sources
   - reducing consumption of energy from traditional sources is good for customer sensitivity to ecological issues

Scenario 2 (new business models): Hybrid solar-grid systems



Get part of energy from the Power Grid when production is low (e.g., in winter) so as to keep small the size of PV panel & number of batteries

Hybridisation

- PT = 100%: guarantee that the battery charge is above 30% *for 100% of the time in a year* (ZEN)
- PT = 90%: … for 90% of the time in a year
- PT = 80%: … for 80% of the time in a year
- PT = 70%: … for 70% …

- Buy energy from the Power Grid when the battery charge becomes 0% (empty)

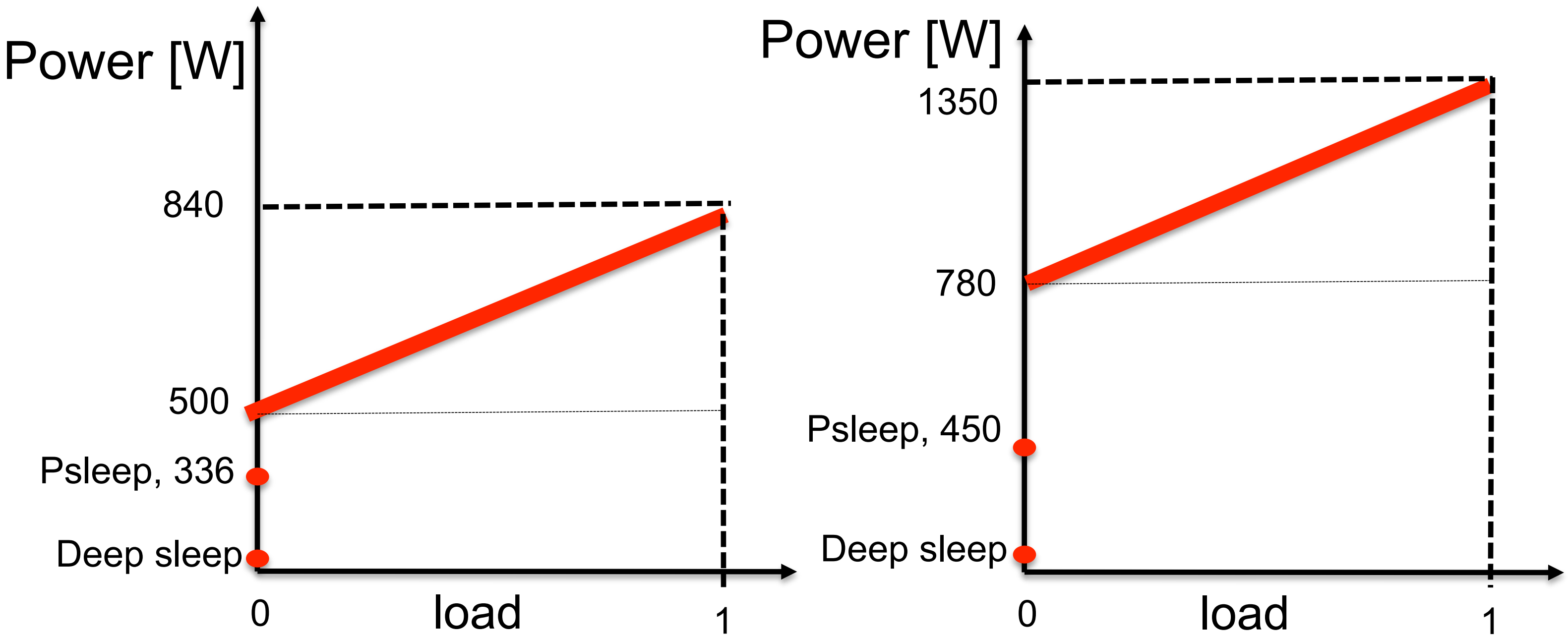
Methodology for system dimensioning

- Consider a typical BS
  - Energy consumption
  - Traffic

  } ⟶ energy need
- Choose a location
- Simulate energy production
- Simulate battery charge and discharge
- Decide **system dimensioning** based on cost (CAPEX+OPEX) minimization

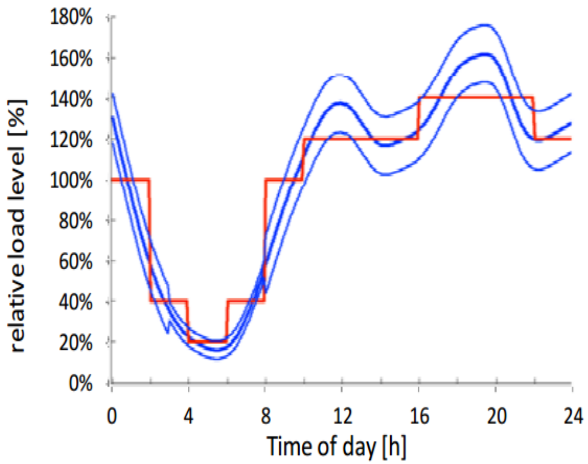
BS consumption

Macro cell with LTE technology, with and without Remote Radio Unit (PA close to antenna)



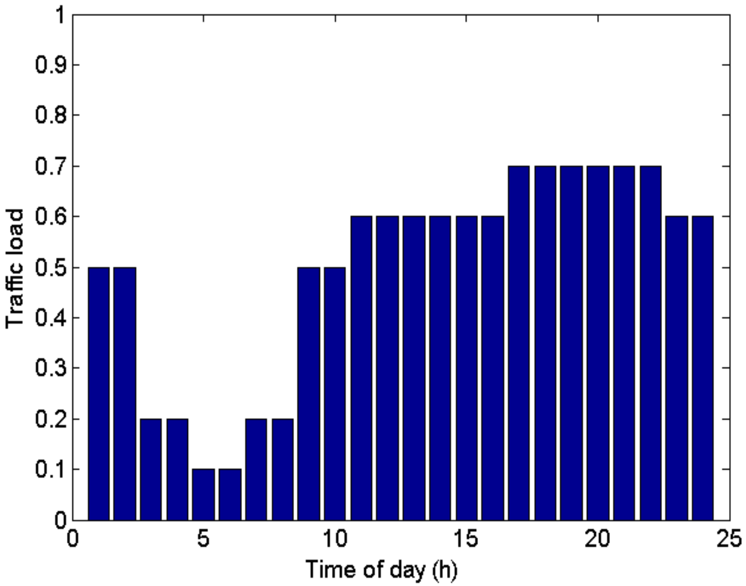
- When needed (no TLC infrastructure) wireless backhauling consumes additional 200-250W, for a total of 30KWh/day

Traffic profile



Traffic Profile	
Level	Duration
20%	2h
40%	4h
100%	4h
120%	8h
140%	6h

Source: O. Blume, A. Ambrosy, M. Wihelm, U. Barth, "Energy Efficiency of LTE networks under traffic loads of 2020," The Tenth International Symposium on Wireless Communication Systems, 2013.



Assume the 140% load level corresponds to 70% traffic load, due to overprovisioning

BS power consumption model

- Model LTE BSs, with and without Remote Radio Unit (RRU)

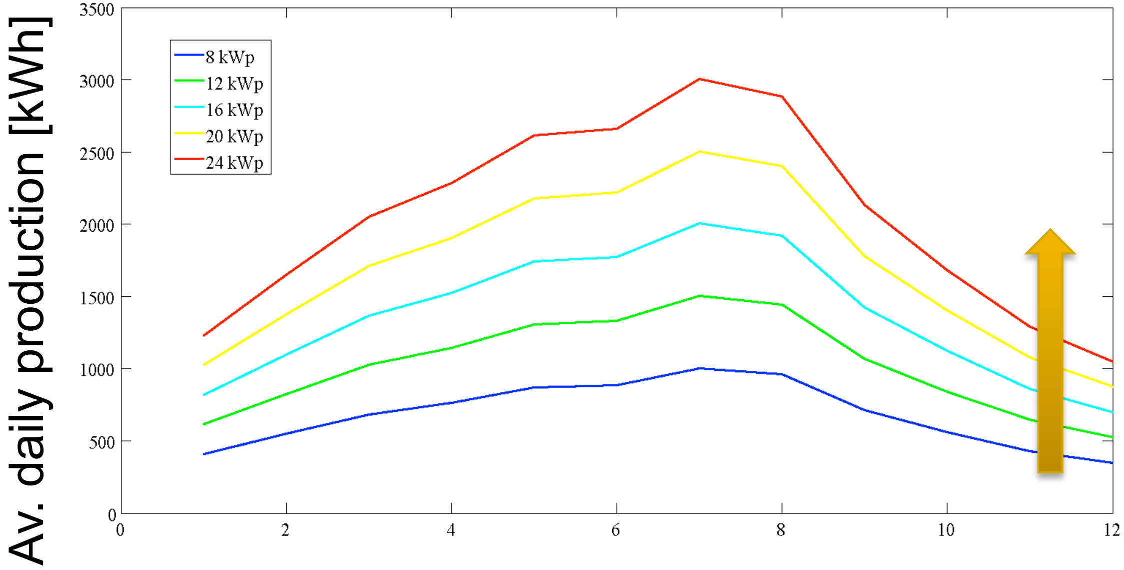
$$P_{in} = \begin{cases} N_{TX}\left(P_0 + \Delta_p P_{out}\right) & 0 < P_{out} < P_{max} \\ N_{TX} P_{sleep} & P_{out} = 0 \end{cases}$$

Macro BS type	N_{TX}	P_{max} [W]	P_0[W]	Δ_p	P_{sleep} [W]
No RRU	6	20	130	4.7	75
With RRU	6	20	84	2.8	56

Source: EARTH project deliverables.

Simulate energy production

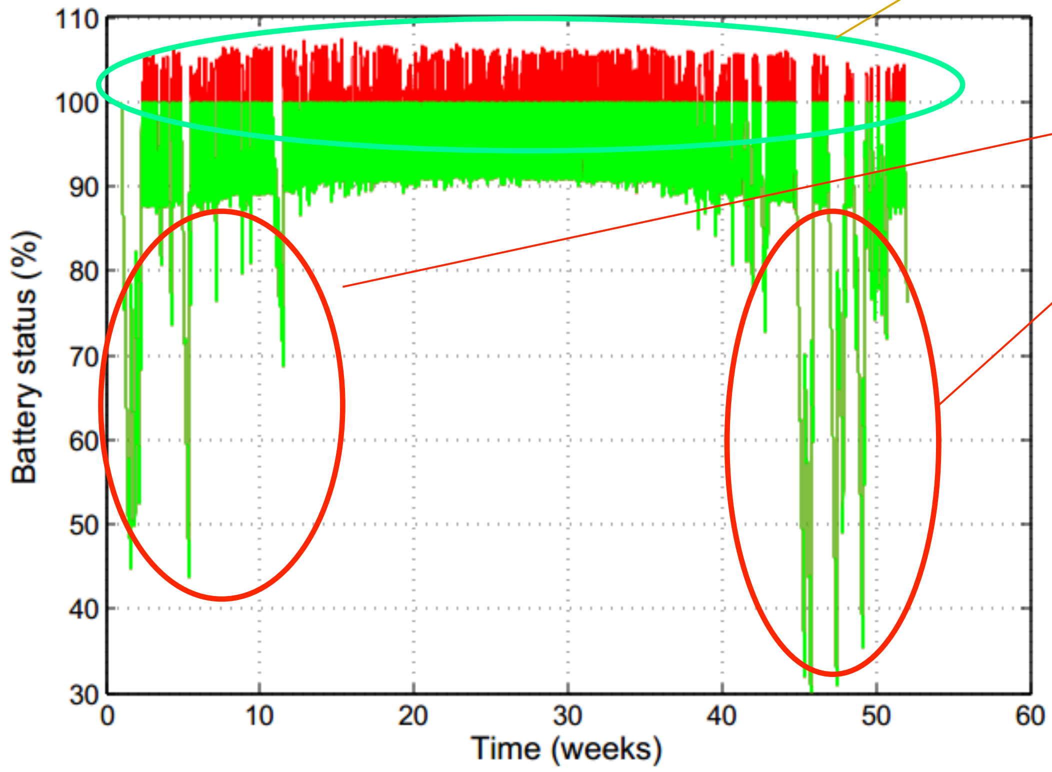
- Consider historical meteo data (typical meteorological year)
- Model the PV system and compute production



- Larger systems allow for larger production
- Production changes according to season, while BS traffic and energy consumption do not change

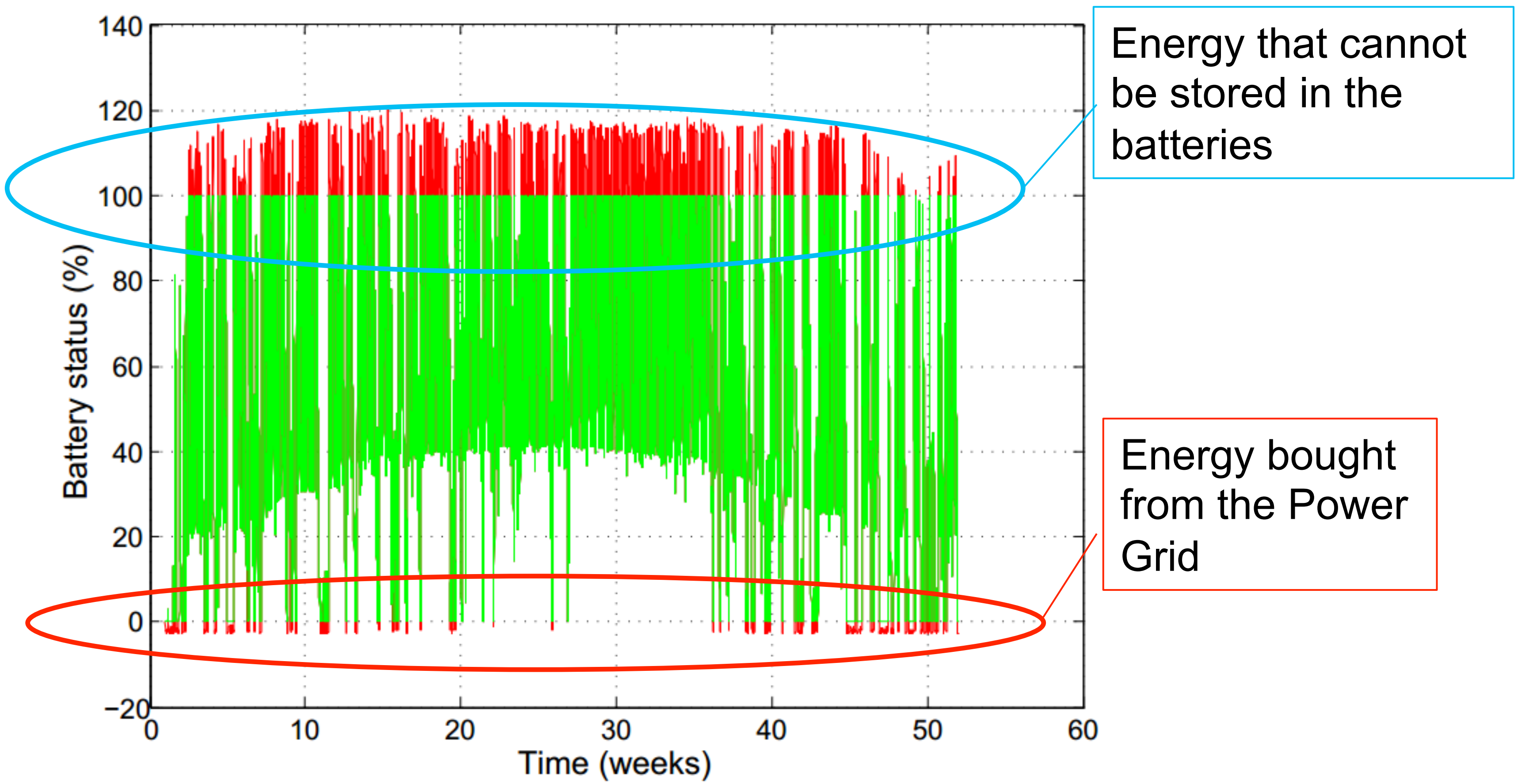
Simulate battery status: Scenario 1 (ZEN)

Energy wasted (this part cannot be stored in batteries)



The bottleneck for the dimensioning is in winter

Simulate battery status: Scenario 2 (PT=70%)



Comparison

System Type	Size of PV (kWp)	Size of PV (m^2)	Number of initial batteries	Number of battery packs (replacements)
ZEN (PT=100%)	9.7	47.4	38	2
Hybrid (PT=90%)	6.4	31.3	12	5
Hybrid (PT=80%)	4.7	23.0	7	8
Hybrid (PT=70%)	4.4	21.5	6	9

But more battery replacements are needed

The PV panel size reduces up to 55% in hybrid systems

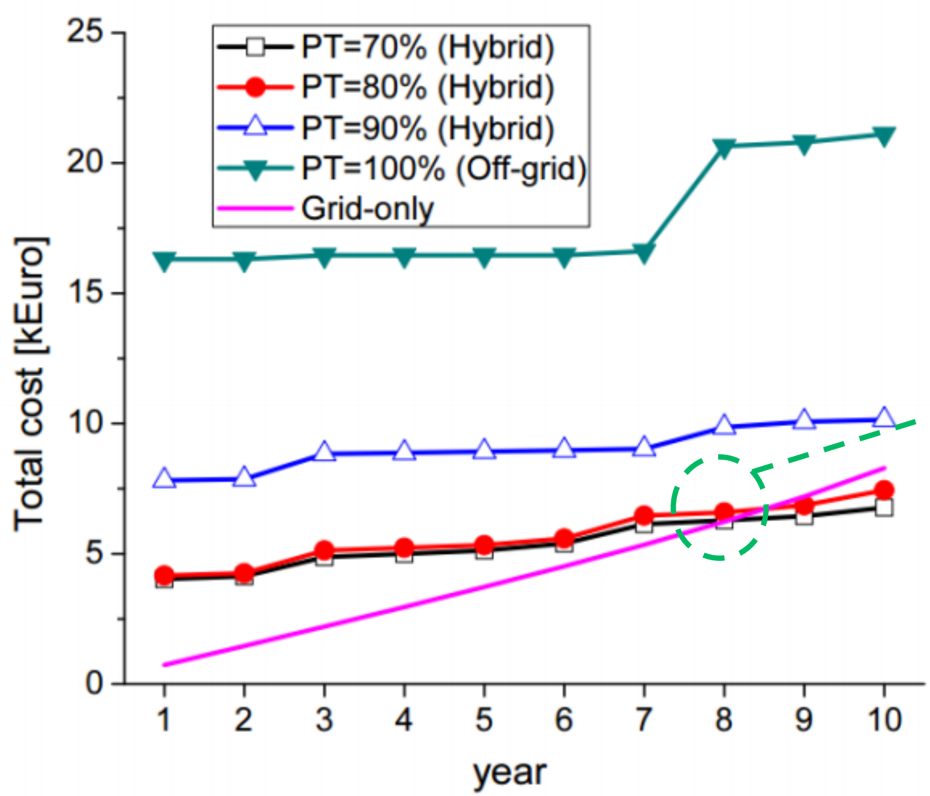
The battery number reduces up to 80% in hybrid systems

Update of the model

- A more accurate model should take into account that the system evolves with time
- Dimensioning with parameters at the first year yields to optimistic dimensioning: as time goes by,
  - Traffic increases (50%, annual)→ higher energy need
  - PV panel efficiency decreases (1%) → lower production
  - Electricity cost increases (3%) → higher cost for buying electricity

Cost: CAPEX+OPEX

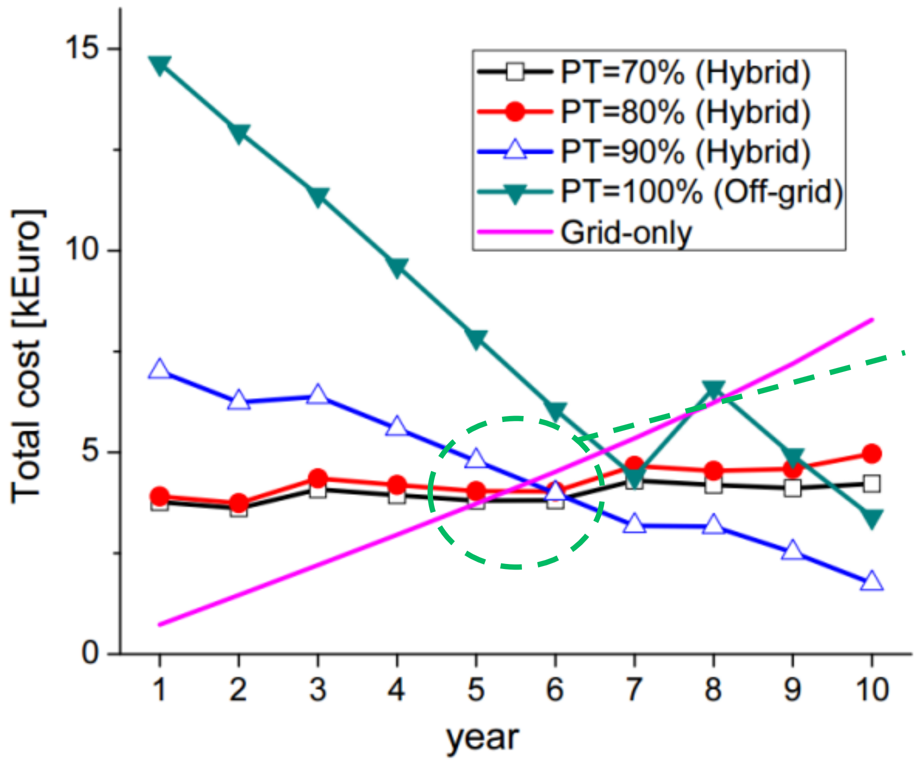
- Total cumulative cost



Save from the 8th year wrt the grid-only case

Selling back energy

- Total cumulative cost, with the possibility to sell back energy



Save from the 6th year wrt grid-only case

Conclusion and discussion

- ZEN approach is feasible and needed in several scenarios
- Hybrid systems
  - Reduce the PV panel size and number of batteries up to 55% and 80%, respectively, with respect to ZEN
  - Are very cost-effective, and efficient especially when seasonal variations exist
  - Smaller systems are more environment-friendly
- Whenever possible, energy selling back can be very convenient

Summarizing

Wrap-up

- Energy consumption reduction is needed in all sector of ICT
- System design in ICT must include energy as a key variable
- In networking, inefficiencies mainly come from
  - Systems are little load-proportional
  - Systems tend to be under-utilized

Wrap-up

Networks with wireless access are

- Among the most urgent segments to act on for energy saving
  - High cost for operating networks, order of the OPEX
  - Dramatic traffic growth is expected
- Solutions for the wireless access can benefit of
  - The natural flexibility (wireless) and
  - Redundancy due to the deployment of many devices for capacity purposes

Wrap-up

- For sustainability, energy-efficiency must be coupled with new energy generation principles
  - The characteristics of energy production might influence the need for new networking solutions and paradigms
  - Networks should start being designed having in mind energy generation
- New (promising) markets call for new solutions that account for the interaction between energy production and traffic needs

Teletraffic and modeling challenges

- Definition of new KPIs (Key Performance Index) that include
  - energy consumption/efficiency
  - kind of used energy (brown/green)
- Update of the concept of QoS that include aspects related to possible EE solutions implemented in the network
  - degree of requested service continuity
  - degree of rate adaptability
  - sensitivity to response time

Teletraffic and modeling challenges

- Traffic models to describe daily, weekly and seasonal patterns
- Scheduling and resource allocation strategies that can include the amount and the kind of energy
- Models of the user's behavior, like
  - willingness to accept some QoS degradation for a more sustainable service provisioning
  - reaction and attitude towards incentives to resource sharing and pricing policies

Teletraffic and modeling challenges

- Models of energy production and consumption
  - to optimize energy production to power ICT devices and infrastructure
  - for the smart grids
  - for deciding pricing policy
- ...

Thank you!

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