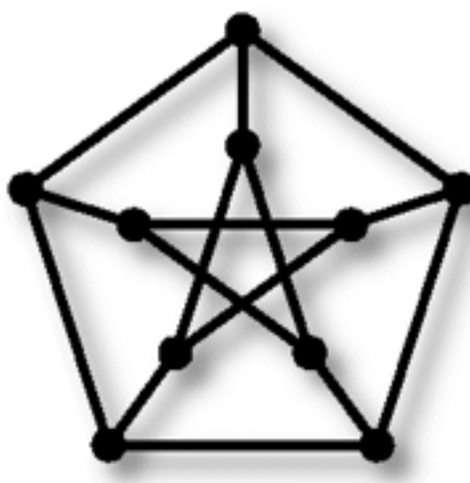
Green Wired Networks: Present and Future

Frédéric Giroire

E3-RSD
Dinard, May 25, 2016

Who we are?

- Working in the **team COATI** at Sophia Antipolis (Inria and I3S/CNRS/University of Nice Sophia Antipolis)



- **Expertise:**
  - **In General:** Algorithmics, combinatorics and optimization for telecommunication networks.
  - **On Energy Efficiency**: mostly **Backbone** (and **backhaul**) **networks**. **SDN paradigm.**

Members of the Team

- **Permanent:** Mostly Joanna Moulierac and myself

- **PhD. students:**

  - Khoa T. Pham 2011-2014
  - Nicolas Huin: 2014-2017

Projects on Energy Efficiency

- **3ROAM** (RAISOM. . .) (2007-2010) **Backhaul networks**

- **ANR ECOSCELLS** (2009-2011) **Cellular networks**
INRIA (Mascotte, Maestro, Swing), Alcatel-Lucent, Orange, Eurecom, 3ROAM, LAAS, Supelec, Univ. Avignon, Sequans, Siradel.

- **ANR-JCJC DIMAGREEN** (2009-2012) **Backbone networks**

- **European NoE TREND** (2010-2013) collaborating institution.
Wired and wireless networks

- **Axis Energy** of the Labex UCN@Sophia (2012-2016)

Our Neighbors in Sophia

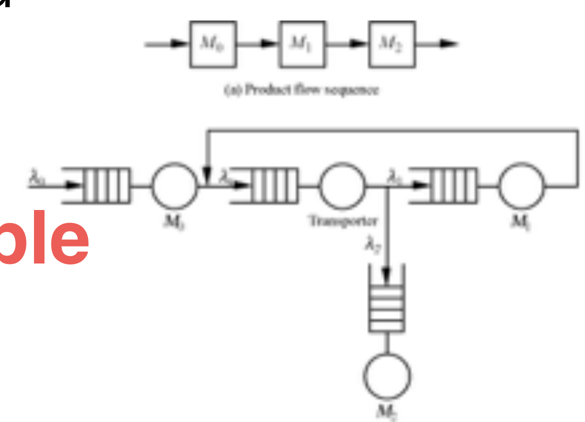
- **Team SigNet (I3S). Permanents:** Guillaume Urvoy-Keller and Dino Lopez

  - **General:** Network protocols, SDN
  - **EE: energy efficient TCP.**

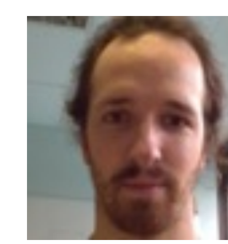
- **PhD. student:** Myriana Rifai

Our Neighbors in Sophia

- **Team MAESTRO. Permanent:** Sara Alouf
    - **General:** Models for performance analysis and control of networks



    - **EE: Wireless and cellular networks**, **renewable energy**
- **Team SCALE: Permanent:** Fabien Hermernier.



    - **General:** Distributed systems and cloud.
    - **EE: Energy efficient data centers.**

- **Common PhD. student:** Dimitra Politaki

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1. **Why caring about network energy efficiency?**
2. Methods to reduce network energy consumptions.
3. Current and Future Challenges.

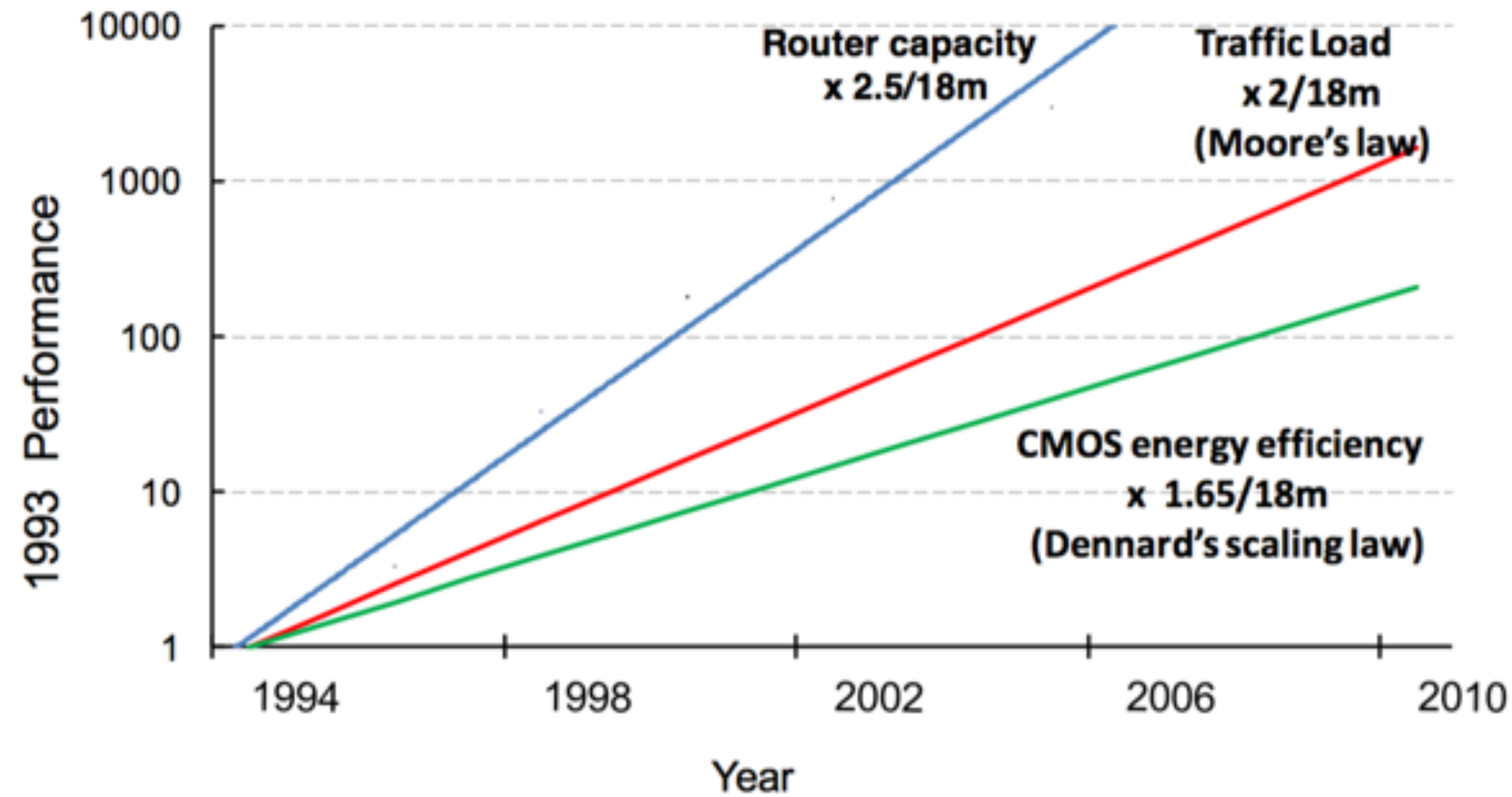
Why caring about network energy efficiency?

- Power consumption traditionally only considered for **devices on batteries**: e.g. lots of works on sensor networks, cellular phones.

- ICT has been historically and fairly considered as a **key objective to reduce and monitor "third-party" energy wastes** and achieve higher levels of efficiency. Classical example: Smart Electrical Grid

- However, **until recently, ICT has not applied the same efficiency concepts to itself**, not even in fast **growing sectors like telecommunications and the Internet.**

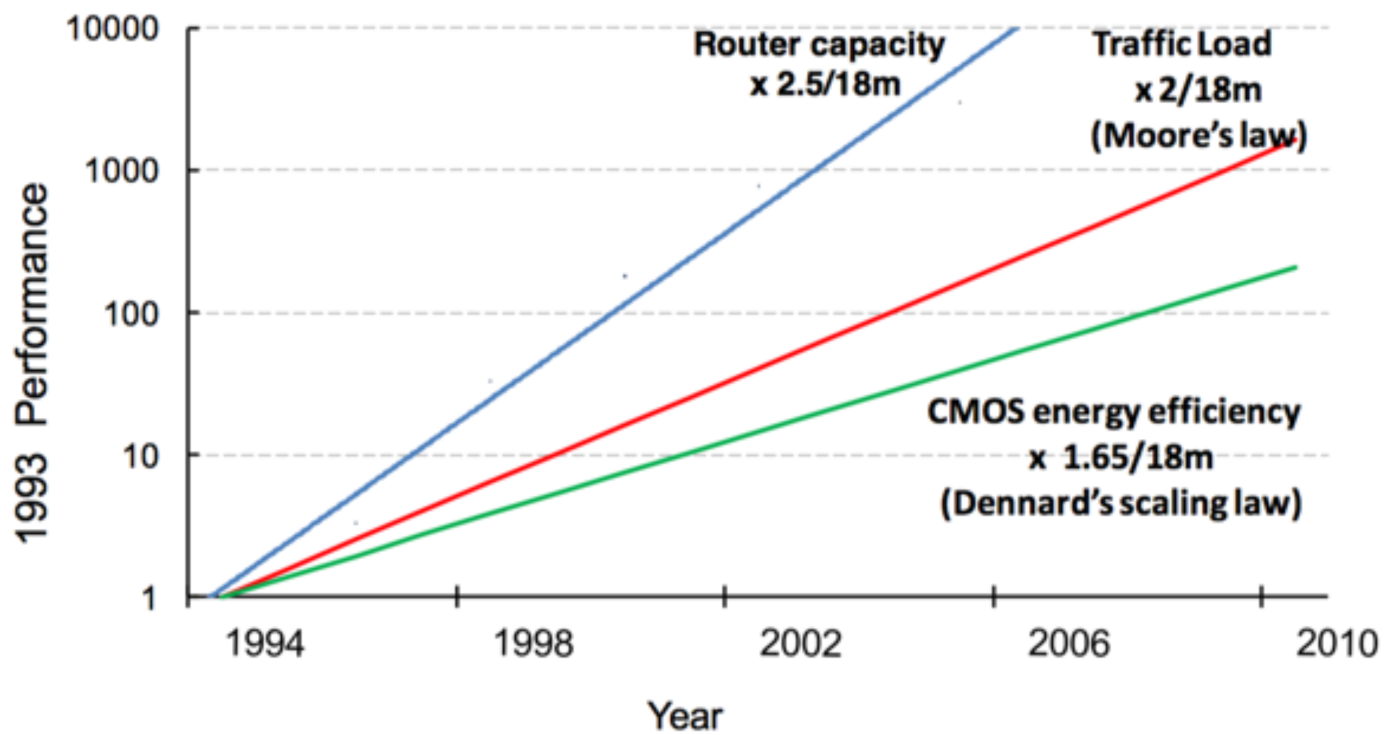
Long-Term Sustainability



Evolution from of high-end IP routers' capacity vs traffic volume and energy efficiency in silicon technologies

Traffic increases following Moore's law: doubling every 18 months [Zhang et al. 2008]

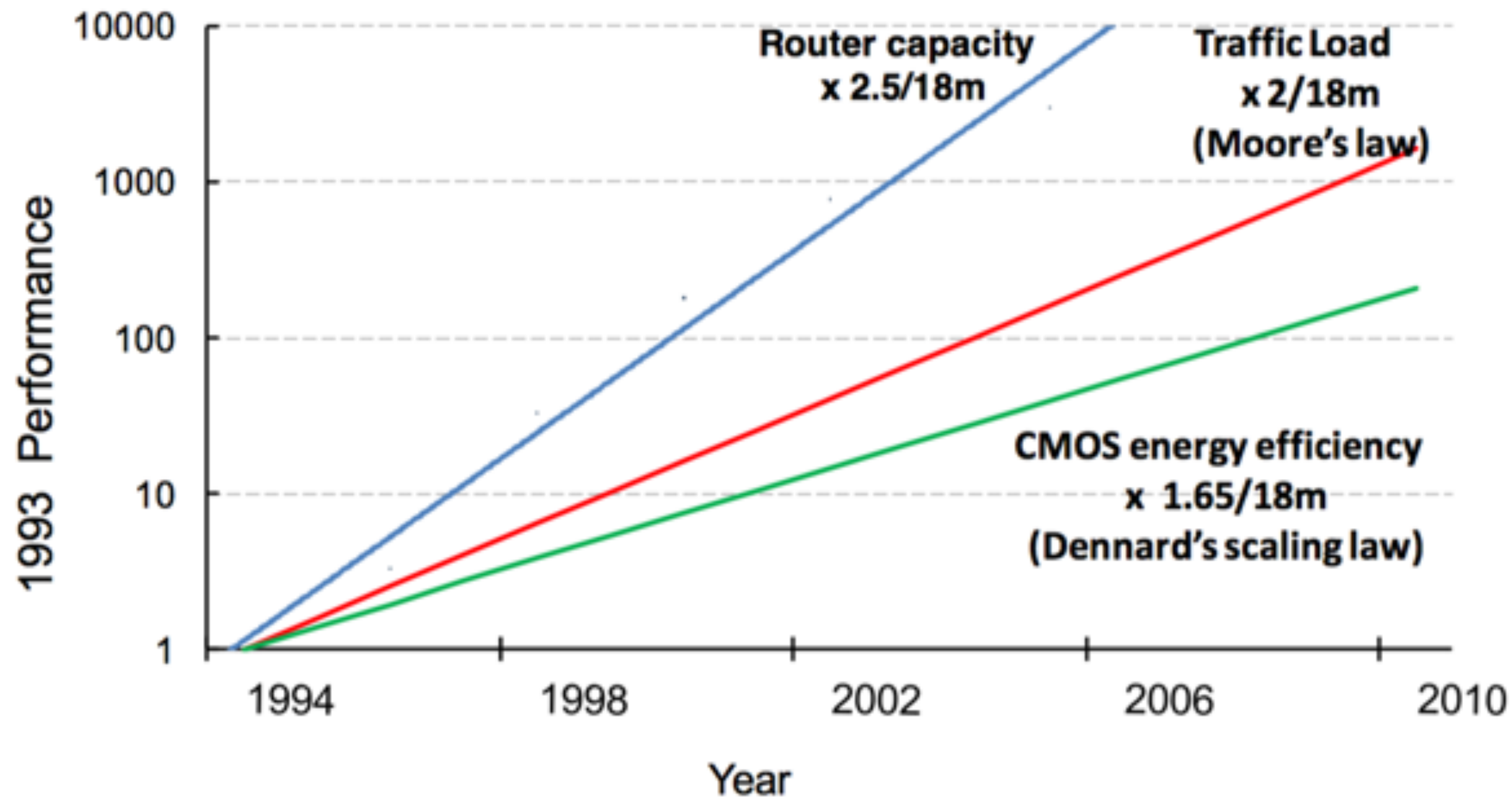
Long-Term Sustainability



Evolution from of high-end IP routers' capacity vs traffic volume and energy efficiency in silicon technologies

- Growing customer population and **New services** offered.
- Telcos and ISPs need new generation network infrastructures and related services with **an ever larger number of devices**, with sophisticated architectures able to perform **increasingly complex operations in a scalable way**.

Long-Term Sustainability

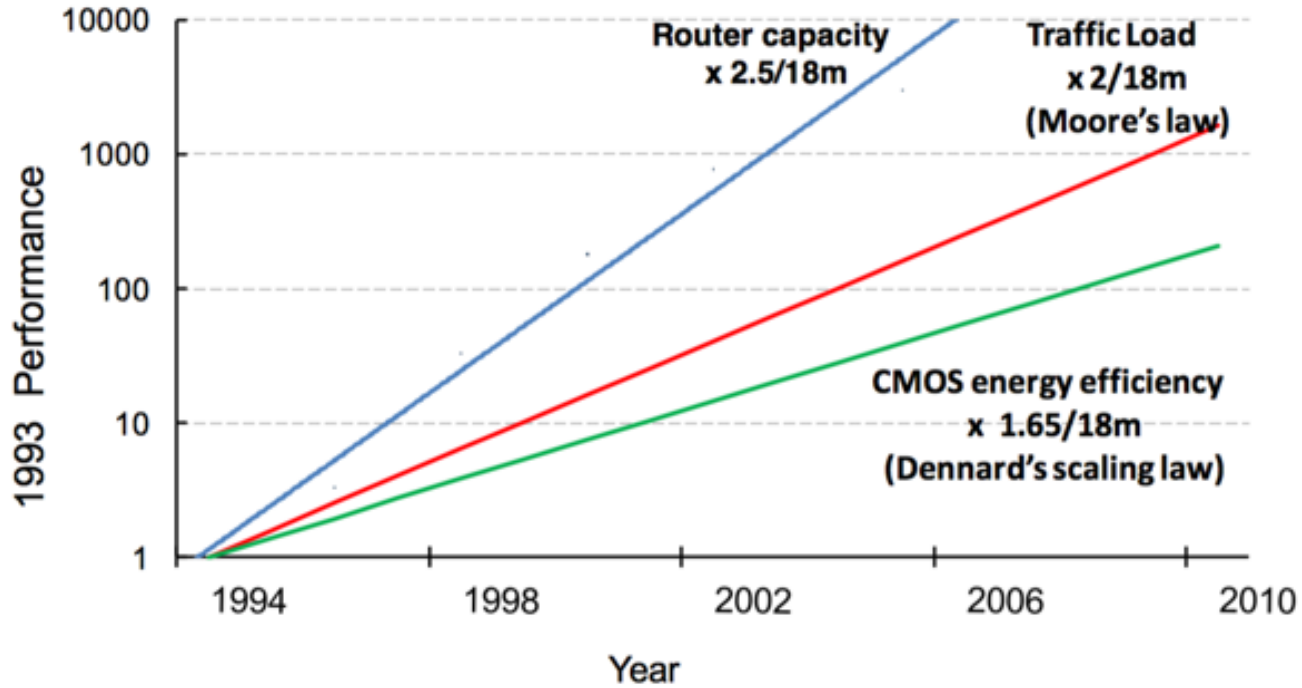


Evolution from of high-end IP routers‘ capacity vs traffic volume and energy efficiency in silicon technologies

For instance, **high-end IP routers** with complex multi-rack architectures:

- more network functionalities and continue to
- **increase their capacities** with an increase **factor of 2.5 every 18 months**

Long-Term Sustainability

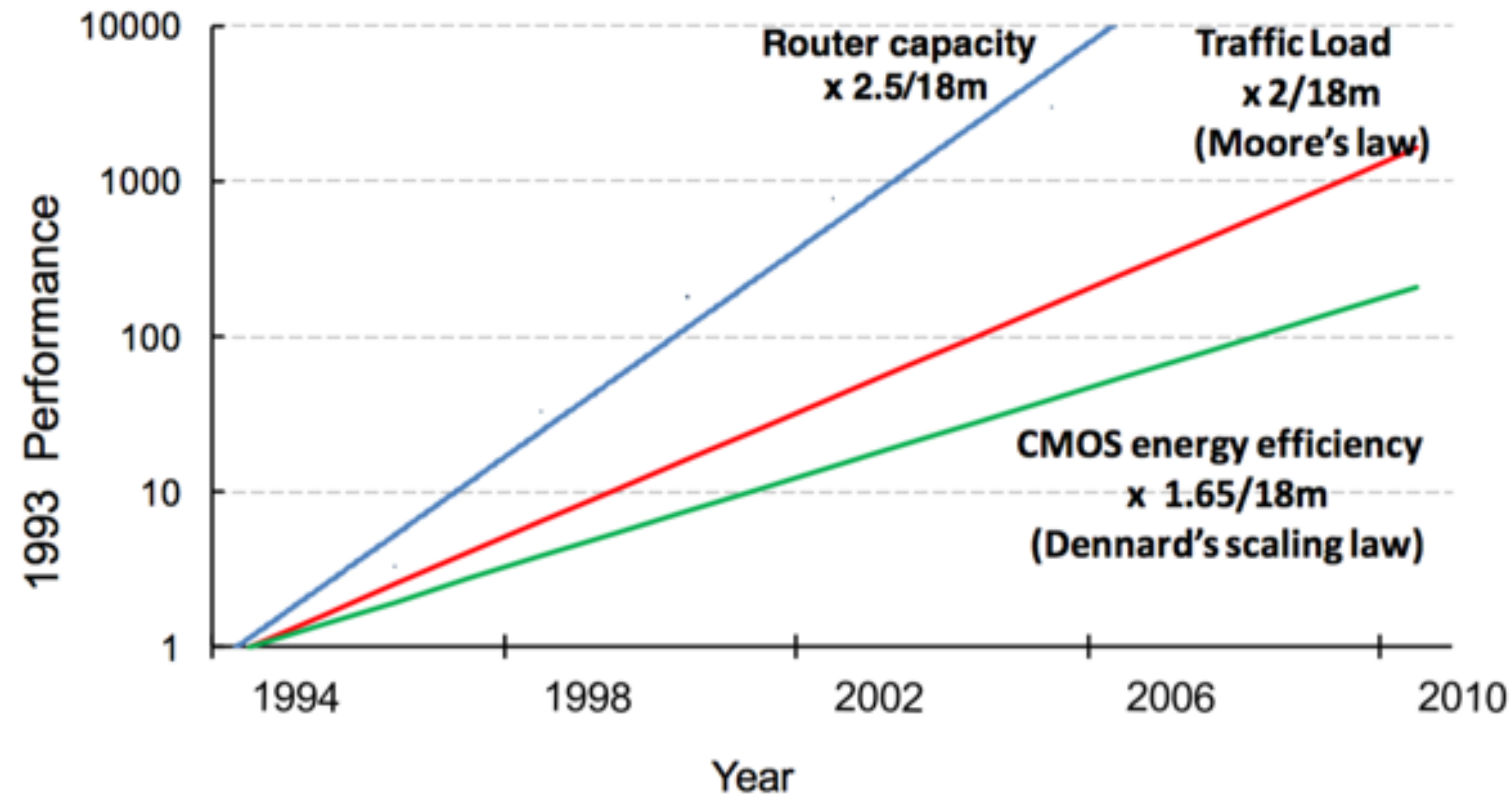


Evolution from of high-end IP routers‘ capacity vs traffic volume and energy efficiency in silicon technologies

- At the same time, **Dennard's scaling law** [Bohr 2007]: **silicon technologies** (e.g., CMOS) improve their **energy efficiency** with a, by increasing of **a factor 1.65 every 18 months.**

- **Lower rate** with respect to routers‘ capacities and traffic volumes

Long-Term Sustainability



Evolution from of high-end IP routers' capacity vs traffic volume and energy efficiency in silicon technologies

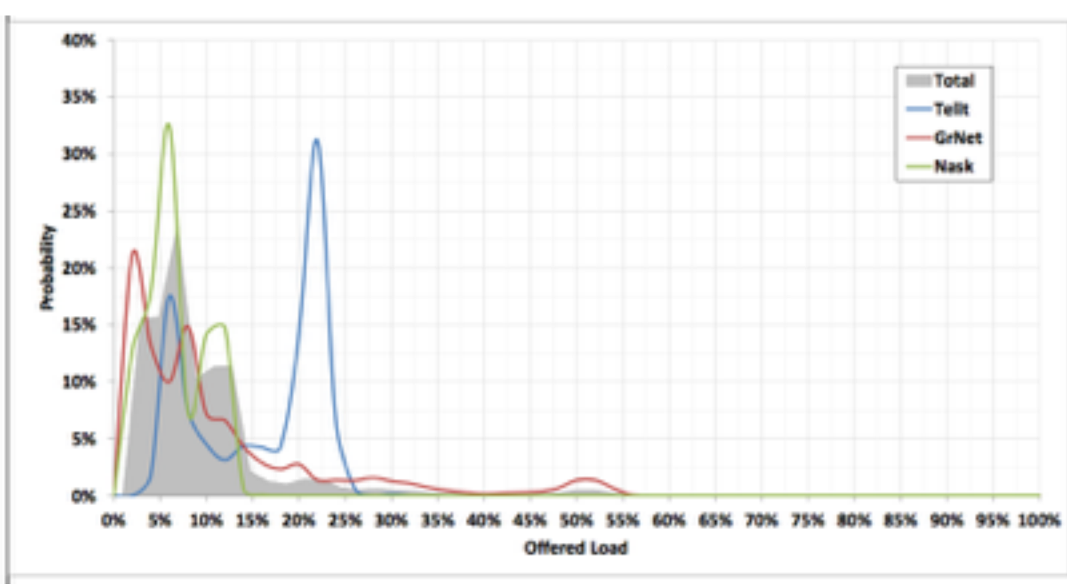
-> **Sole introduction of novel low consumption HW technologies cannot clearly cope with increasing traffic and router capacity trends**,

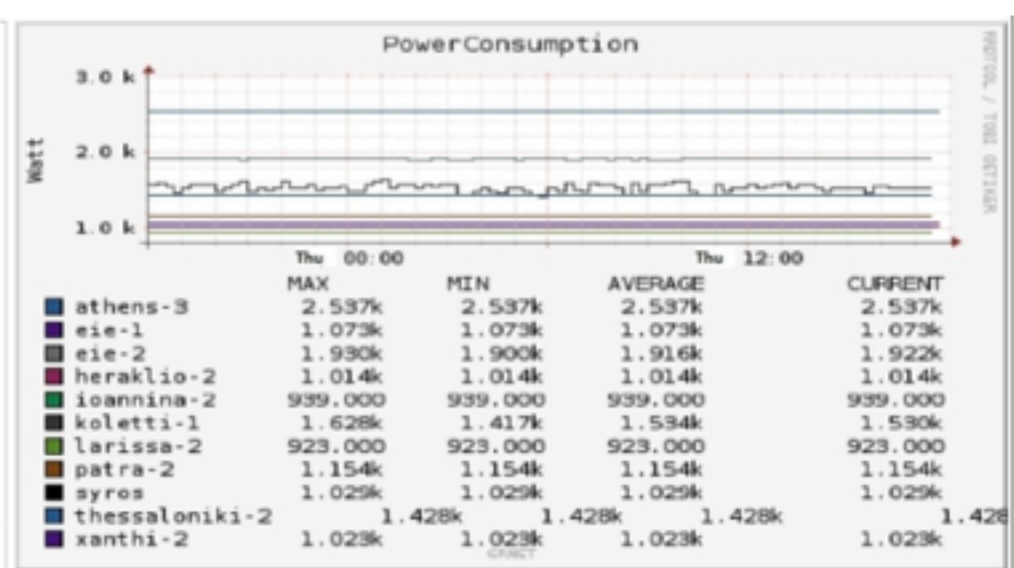
Reasons for energy inefficiencies...

- The origin of these trends can be certainly found in current Internet infrastructures, technologies and protocols, which are designed to be extremely **over-dimensioned** and **available 24/7**.

- Links and devices are **provisioned for rush hour load**.

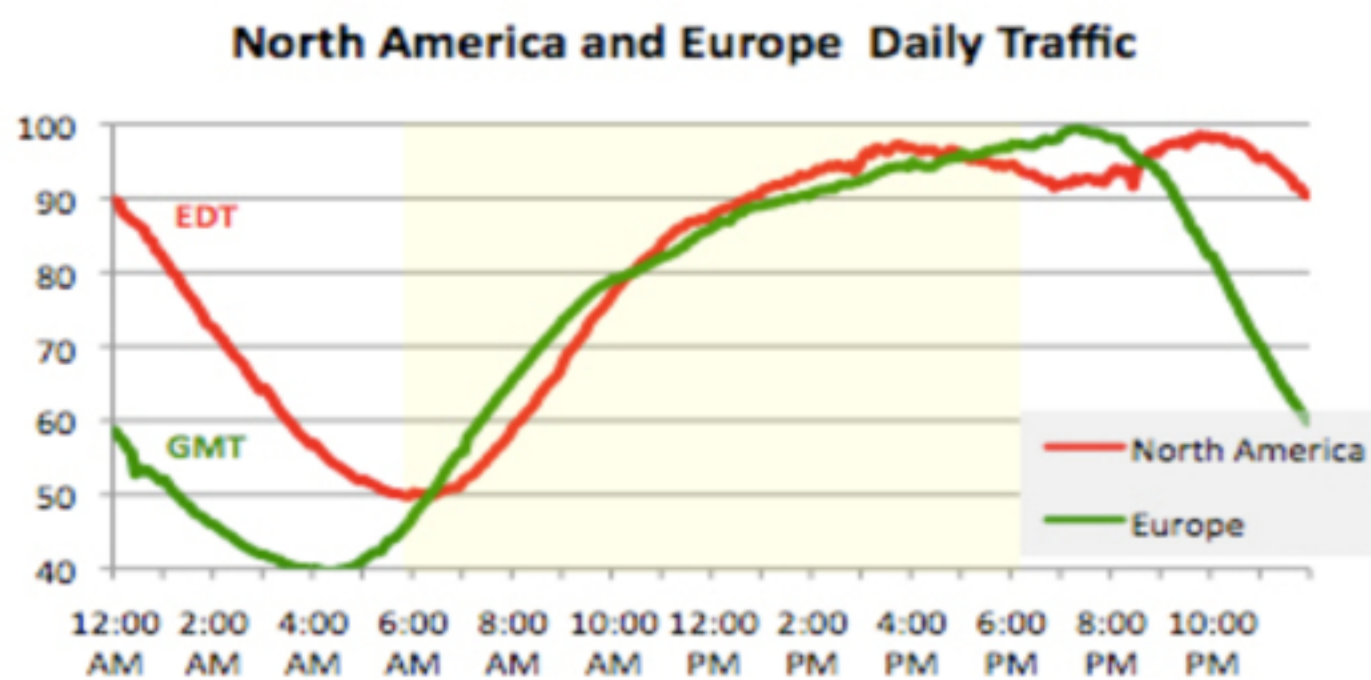
- The **overall power consumption** in today's networks **remains more or less constant** even in the presence of **fluctuating traffic loads.**





...despite wide traffic variations

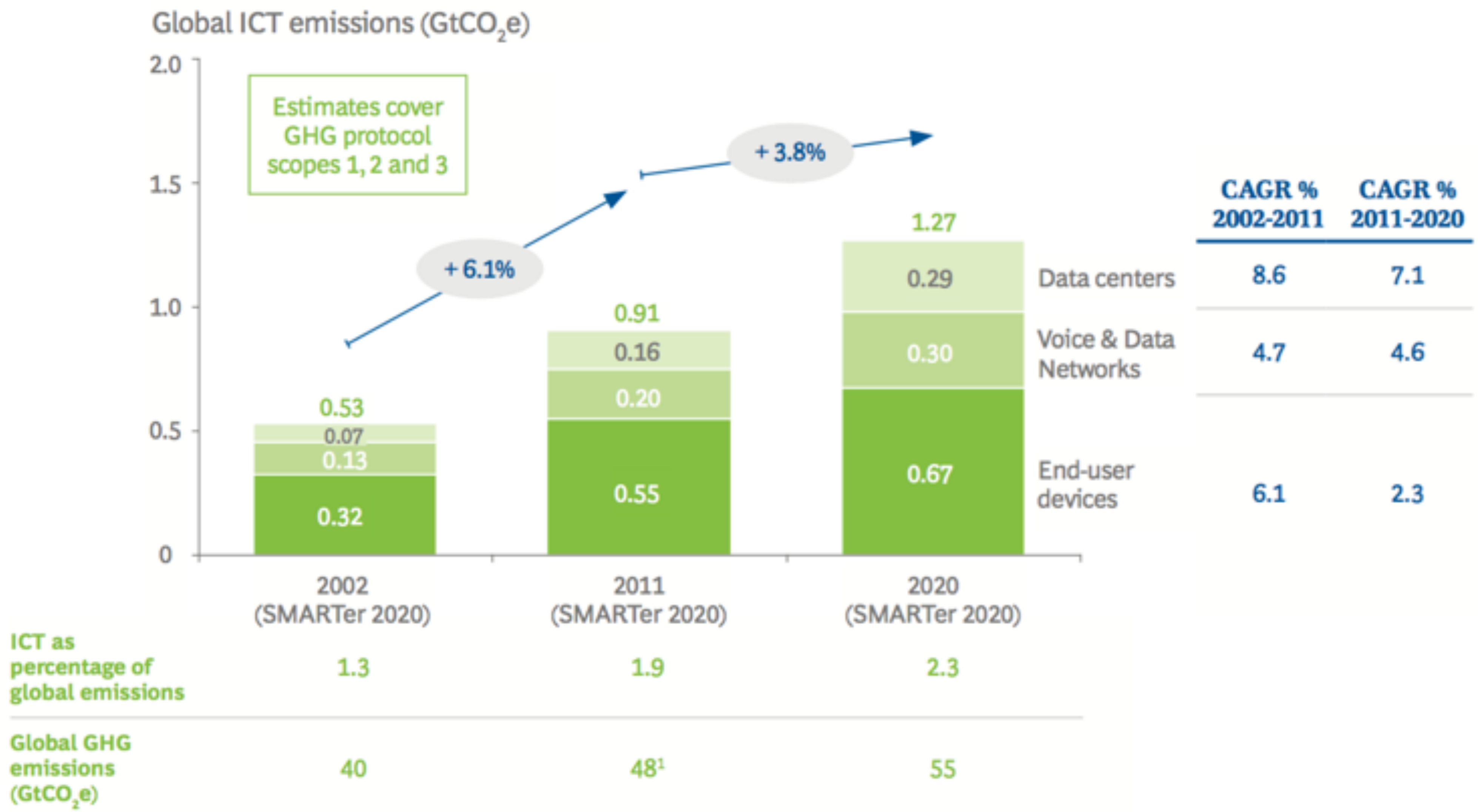
- The profiles exhibit regular, daily cyclical traffic patterns with Internet traffic dropping at night and growing during the day.



Traffic load fluctuation at peering links for about 40 ISPs from USA and Europe (percentage / peak level)

Source: http://asert.arbornetworks.com/2009/08/what-europeans-do-at-night/

The carbon footprint of ICT



Source: *Global e-Sustainability Initiative (GeSI), "SMARTer2020: The Role of ICT in Driving a Sustainable Future," Report, URL: http://gesi.org/SMARTer2020.*

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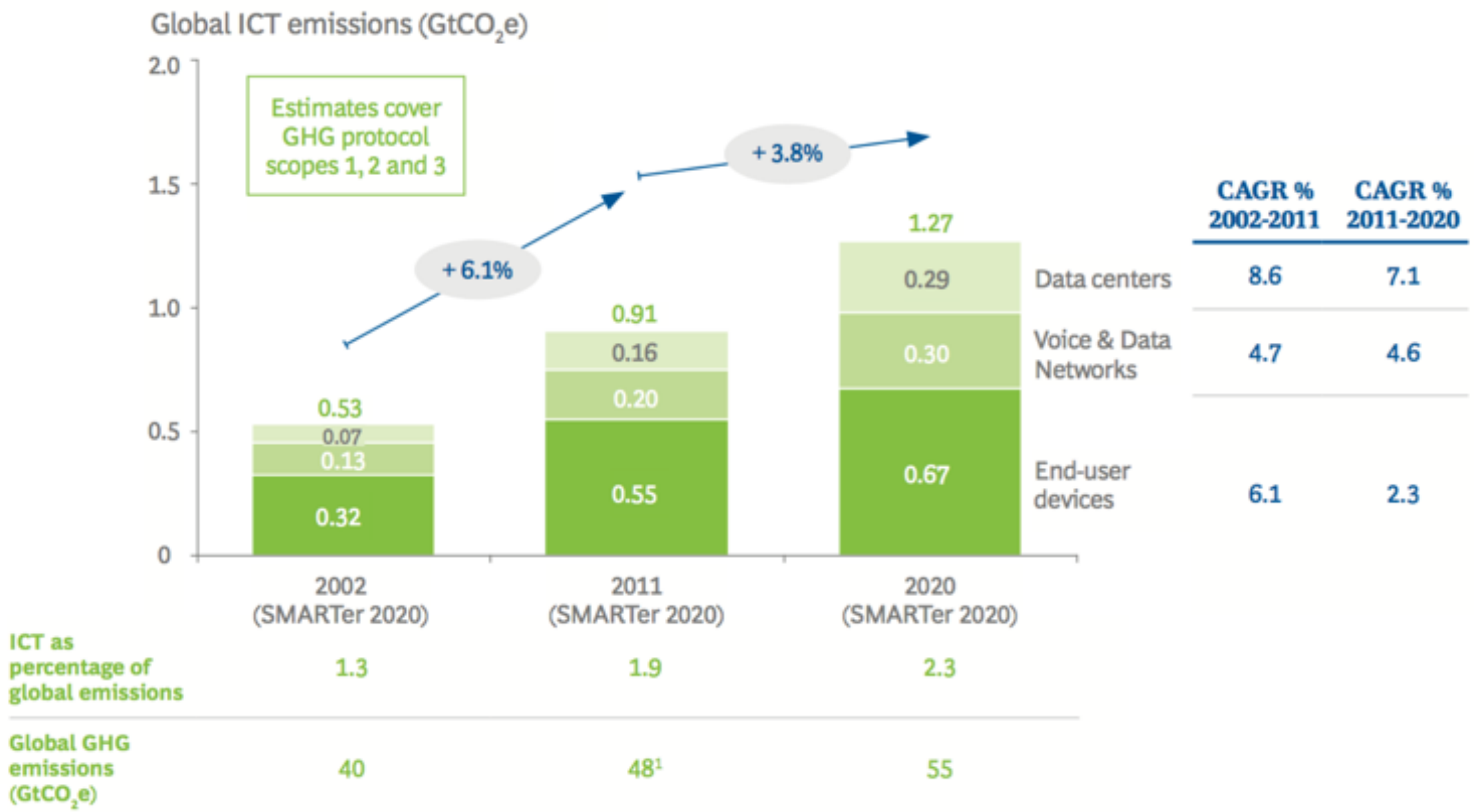

- **In 2011: ICT represents 1.9% of global emissions**

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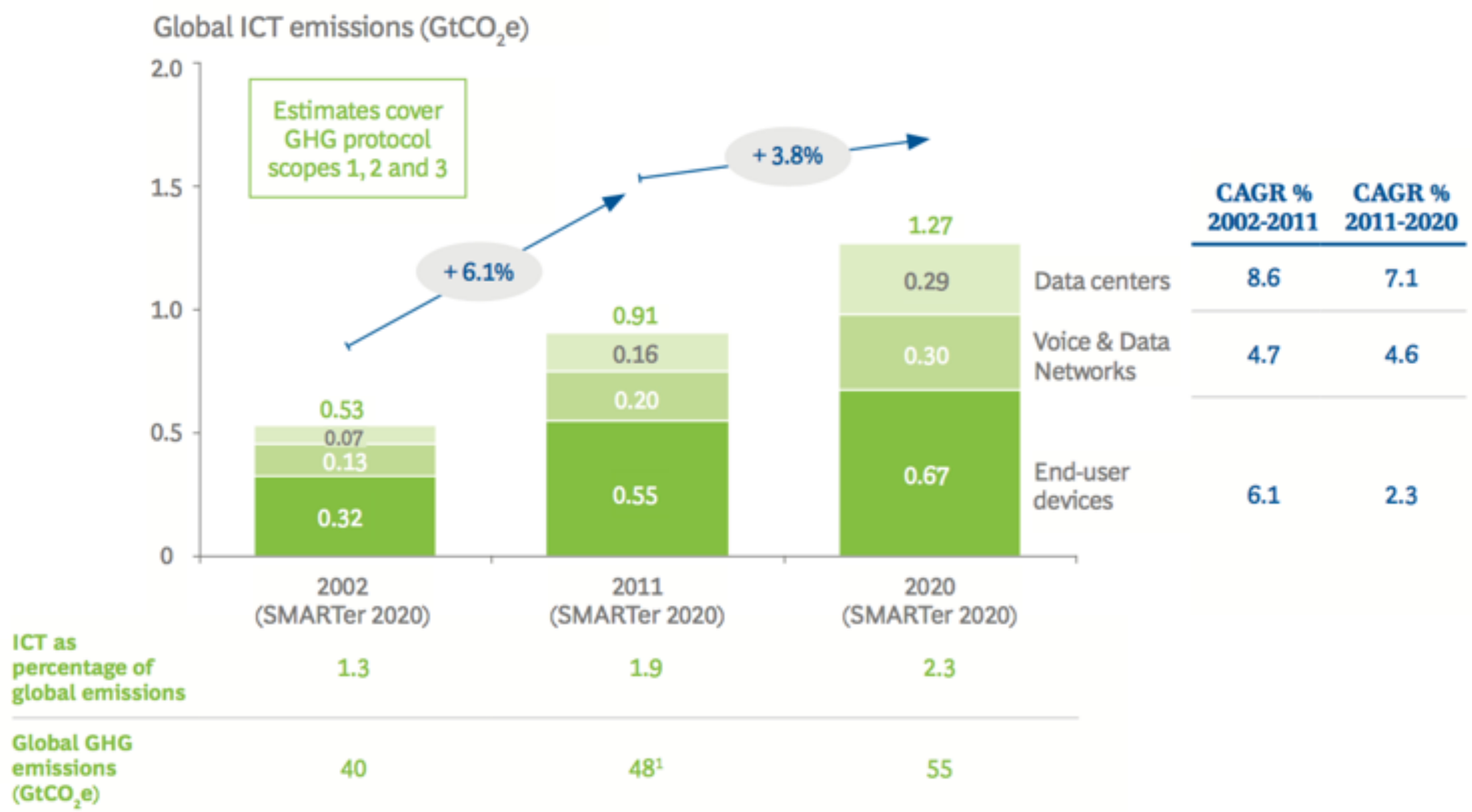

- In 2011: ICT represents 1.9% of global emissions

- **In 2002: 1,3% and in 2020 an expected 2.3%**
- -> ICT footprint increases at a faster rate than the global footprint

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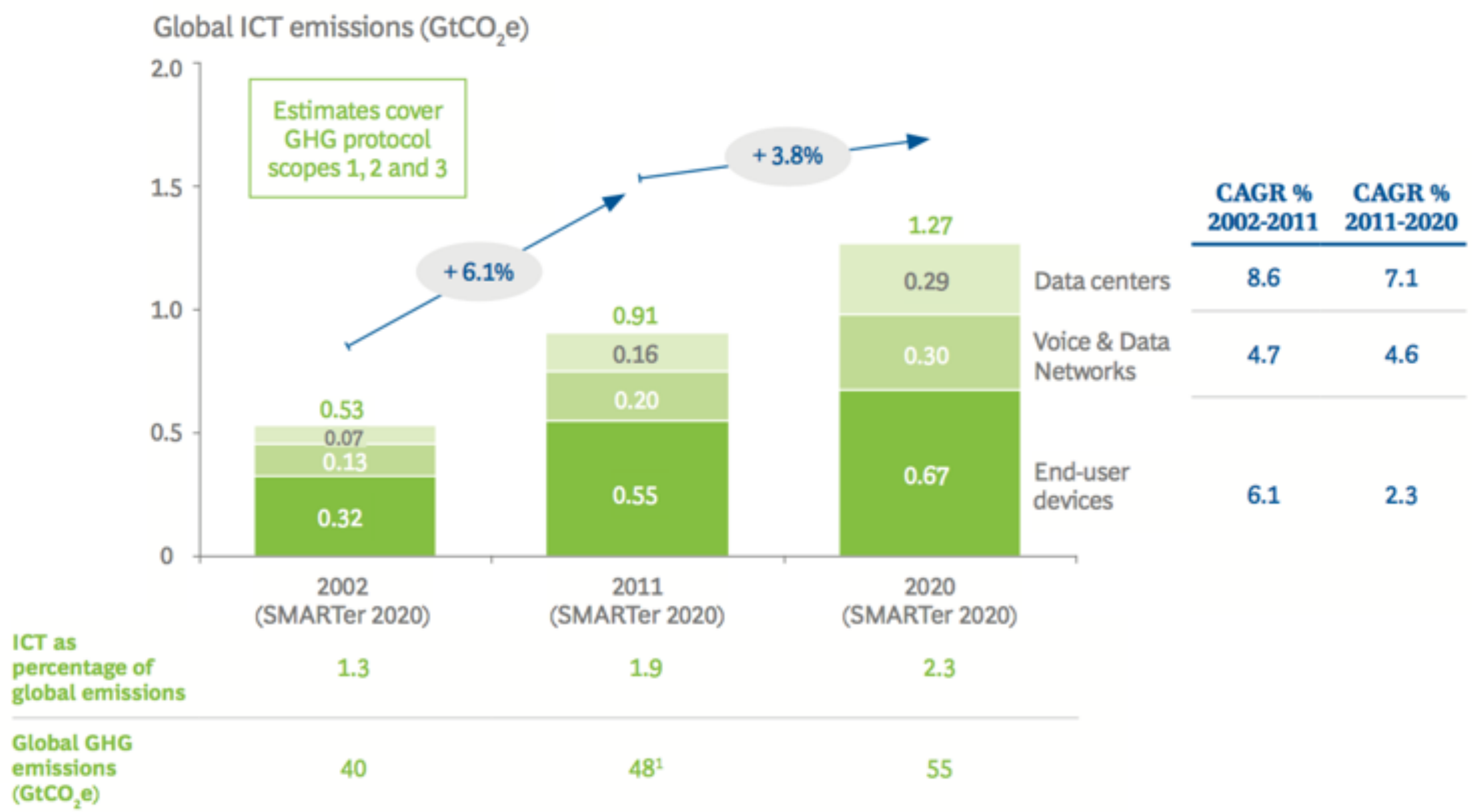
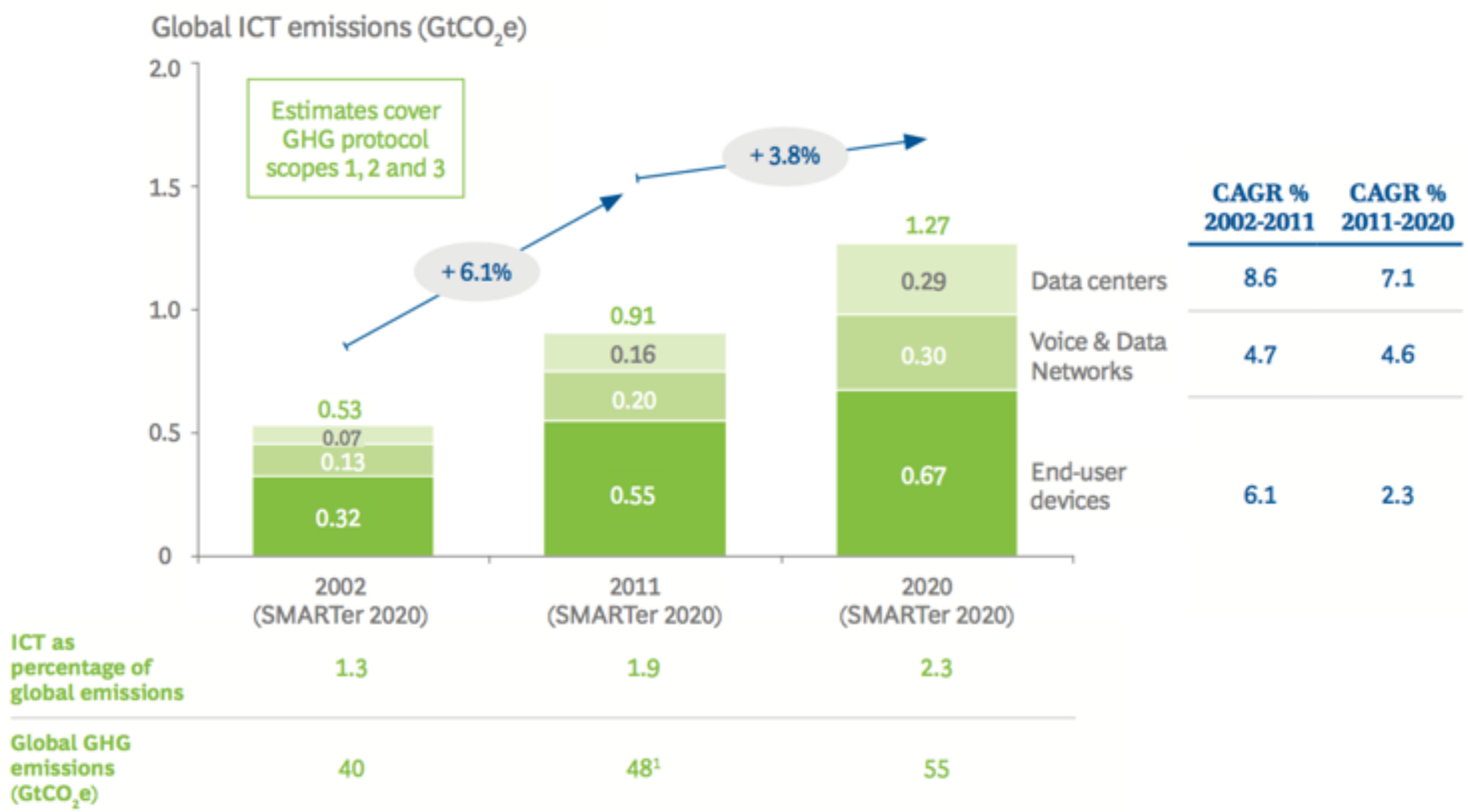


- **Increase of 6.1% between 2002 and 2011**
- **Increase of 3.8% estimated between 2011 and 2020**
- **-> Due to more efficient devices.**

The carbon footprint of ICT



- **Data center** and **voice & data networks**: **Equivalent footprint** in 2020.
- **End-user-devices:** Twice as much

ICT Energy Consumption

Thanks to: *Reducing the Energy Consumption of Networked Devices*

- Ken Christensen (Univ. of South Florida)
- Bruce Nordman (Lawrence Berkeley National Laboratory)

Caveats: Hard to measure, somehow old numbers (2006).
Keep in mind: large increase of ICTs and energy costs.

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All electronics (Big IT)

- PCs, networks, consumer electronics, telephony
- residential commercial industrial
- Consumption:
  - 200 TWh/year (Nuclear power plant: about 7 TWh/yr)
  - correspond to $16 billion/year
  - 150 million tons CO_2/an. (about 2.5% global greenhouse gas emissions. Estimate (Int. Tel. Union): 4% by 2020).

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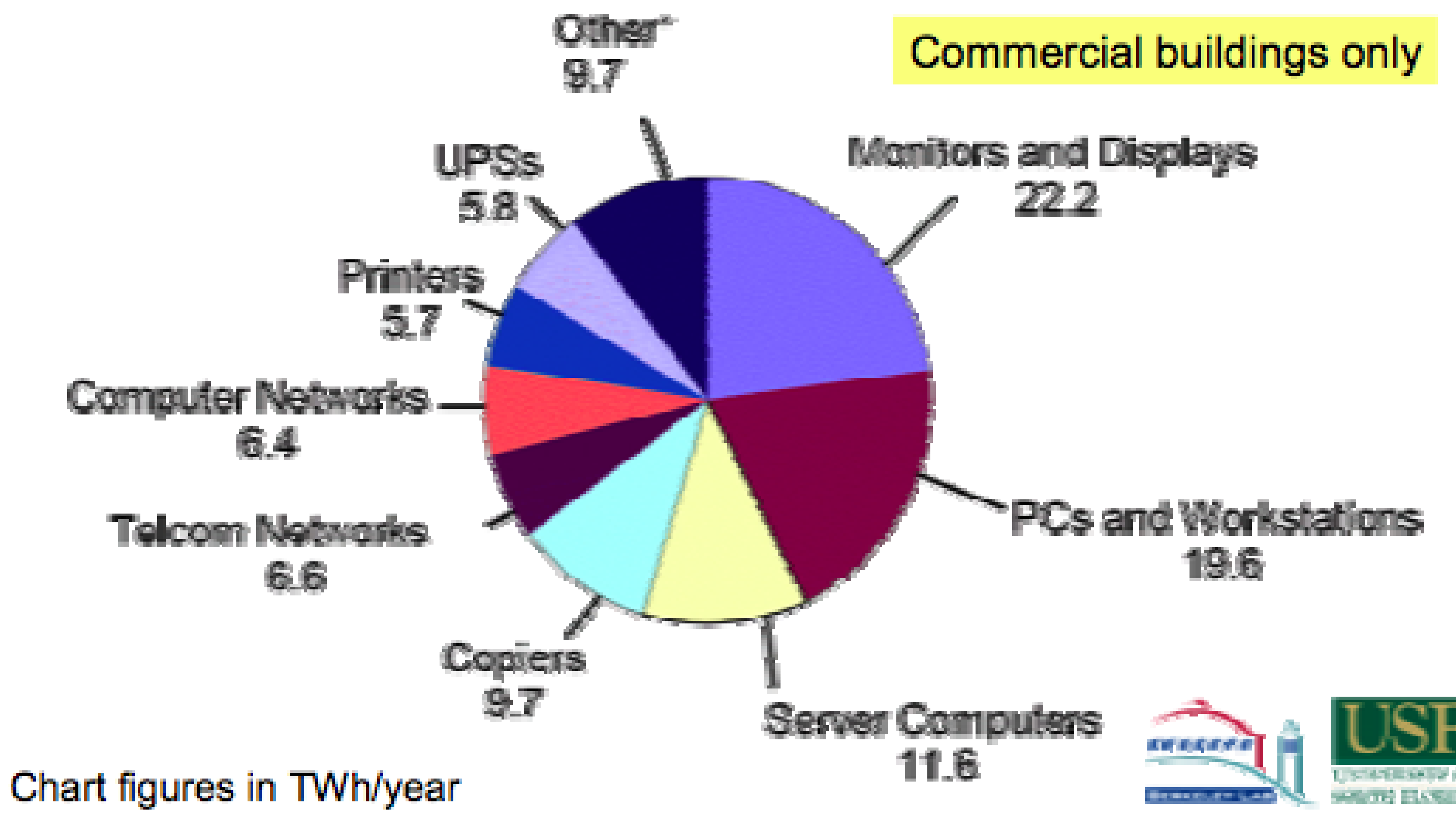
→ Somehow large numbers → increased society sensibility

ICT Energy Consumption

Little IT: office equipment, telecom, data centers

- 97 TWh/year
- 3% of national electricity;
- 9% of commercial building electricity



Networks' Energy Consumption

- Switches, Hubs, Routers (commercial sector only)
  6.05 TWh/year \$500 million/year
- Telecom equipment (mobile, local, long distance,. . .)
  6.1 TWh/year \$500 million/year
- NICs (Network Interface Cards) alone
  5.3 TWh/year \$400 million/year

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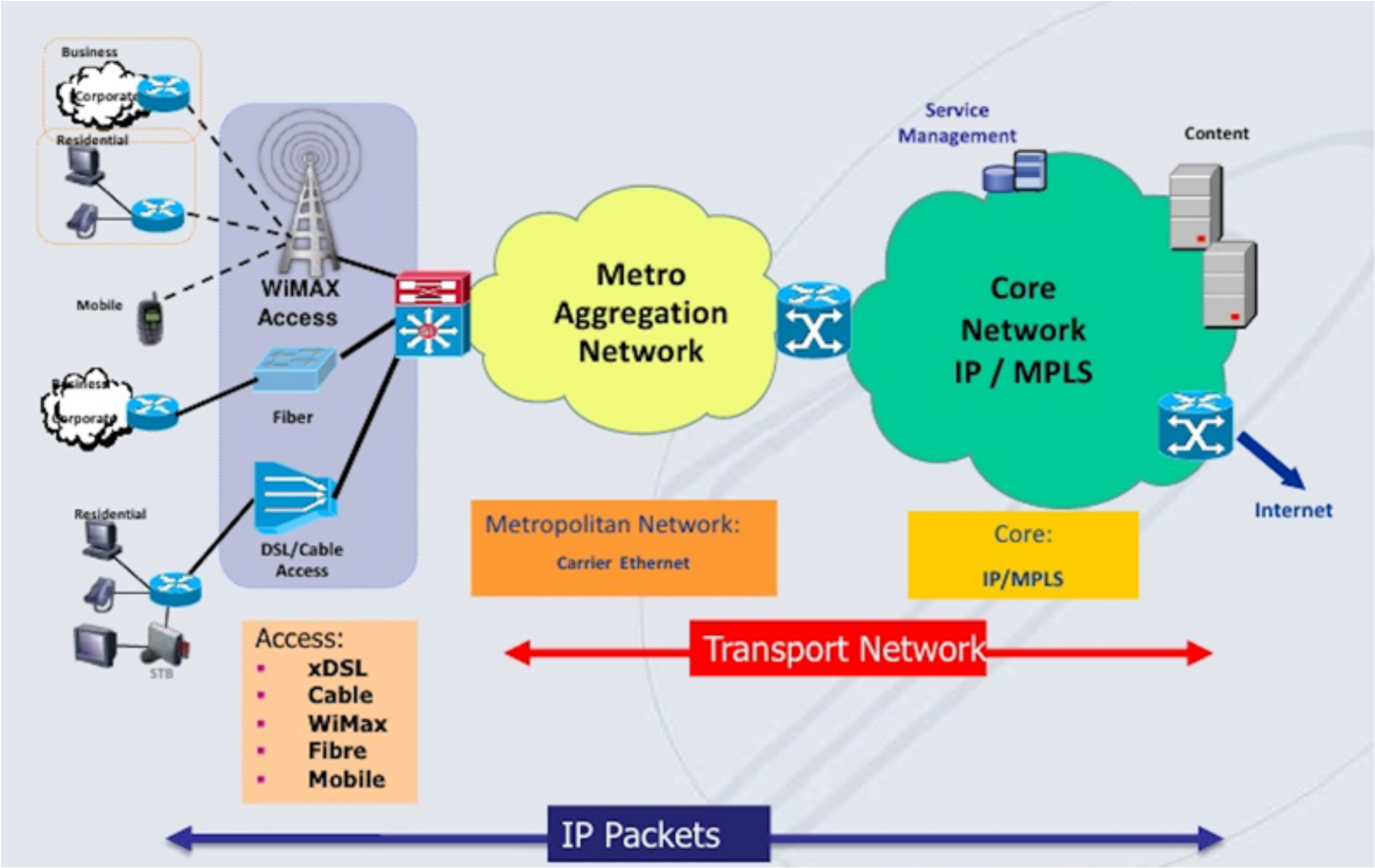
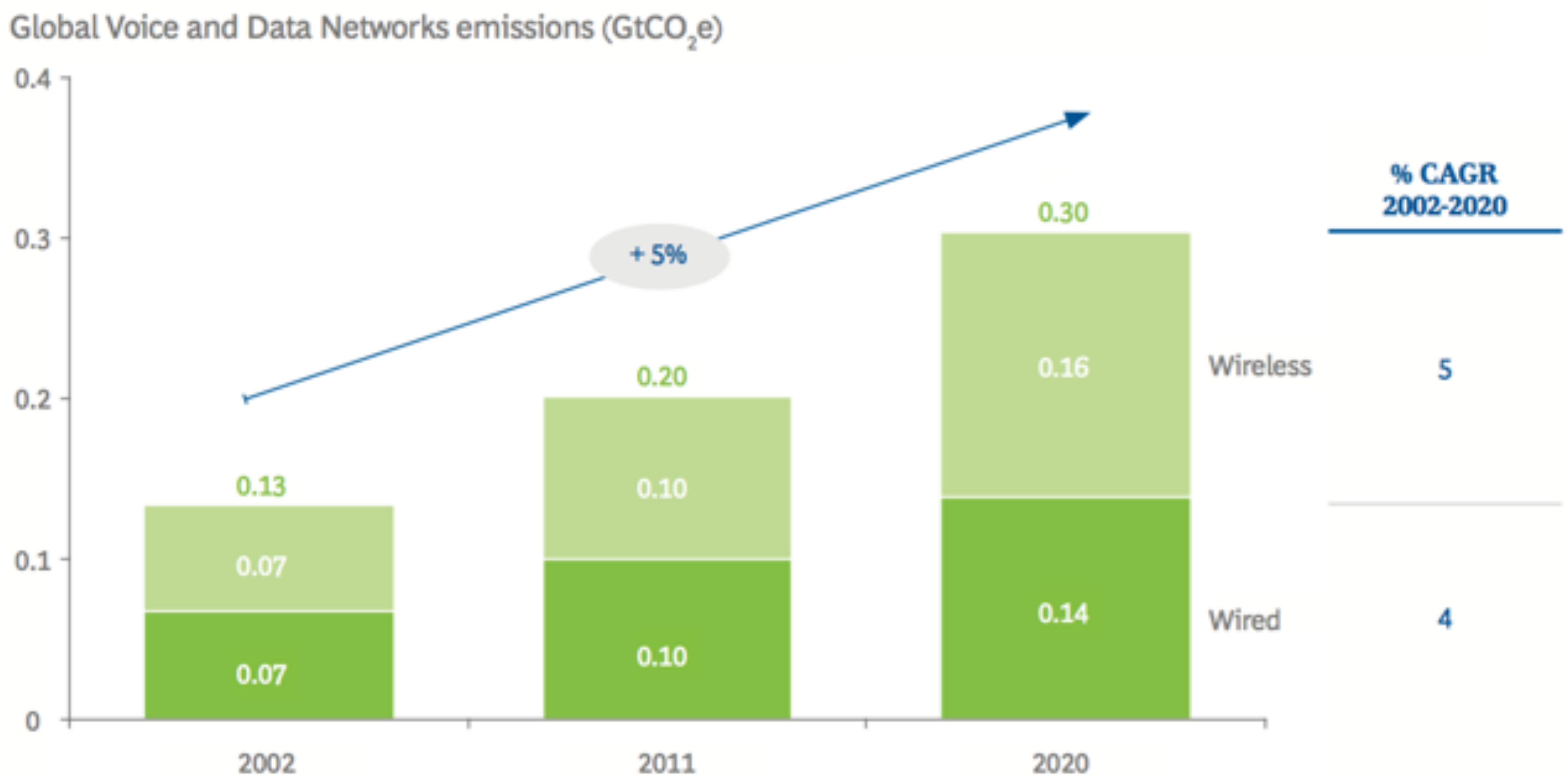
Summary ($\approx$ 2006):

- All electronics: 200 TWh/year - \$16 billion
- Networked electronics: 100 TWh/year - \$8 billion
- Network equipment & NICs: 25 TWh/year - \$2 billion
- Data center energy use: 35 TWh/year - \$3 billion.

Networks: Large building blocks

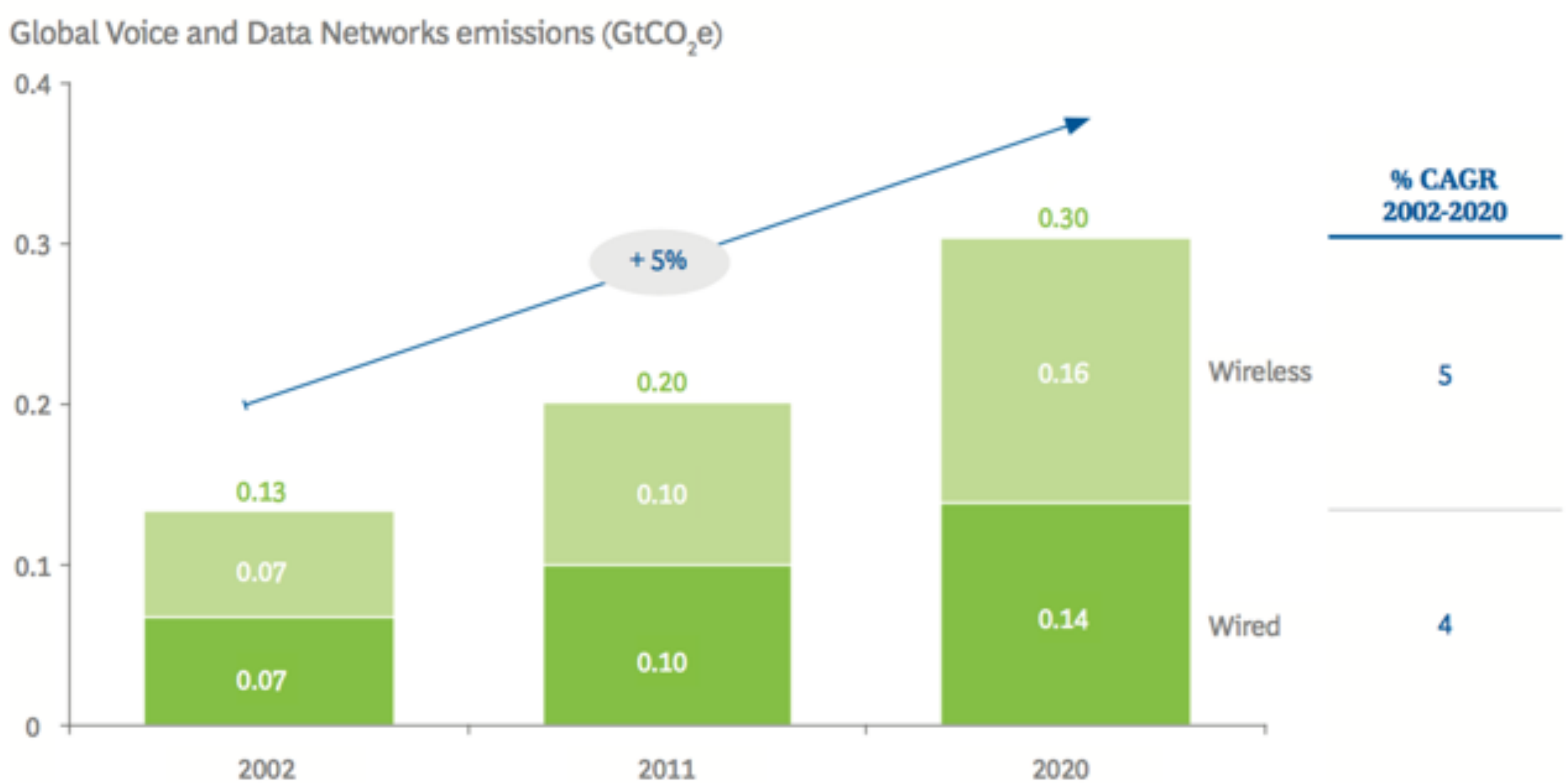


Wired vs Wireless Networks



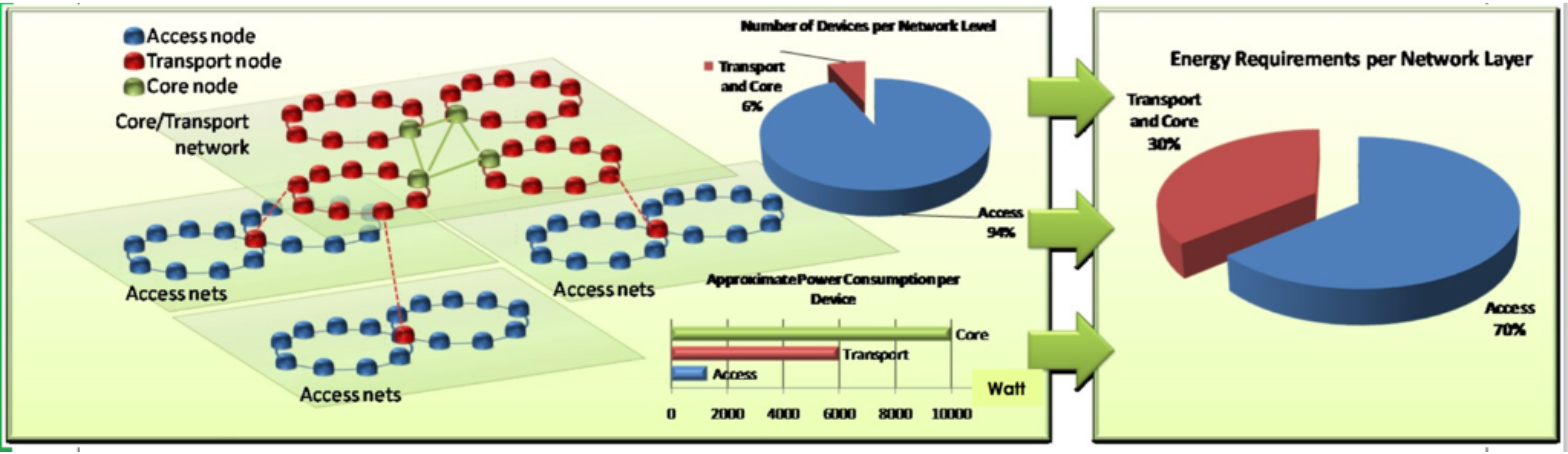
- **Wired network footprint = Wireless network footprint.**

Wired vs Wireless Networks



- **Wired network footprint = Wireless network footprint.**
- But **Mobile network emissions expected to grow faster** than wired networks emissions

Decomposing the Energy Consumption



- *Typical* ***access, metro and core device density and energy requirements*** *in today's typical networks deployed by telcos, and ensuing overall energy requirements of access and metro/core networks.*

- Source: R. Bolla, R. Bruschi, F. Davoli, F. Cucchietti, "Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures," *IEEE Communications Surveys & Tutorials*, vol. 13, no. 2, pp. 223-244, 2nd Qr. 2011.

Last significant numbers

Telecom Italia
2009 Sustainability Report

2.1 TWh ~ 0.3 billion US$

Annual Corporate Responsibility Report
Telefónica

4.5 TWh ~ 0.7 billion US$

france telecom

3.7 TWh ~ 0.5 billion US$

verizon
Corporate Responsibility

9.9 TWh ~ 1.5 billion US$

Last significant numbers

- CO_2 produced by ICT ~ **2% - 10%** of the total man-made emissions by 2020.
- Telecom infrastructure and devices account for **25% of the ICT's energy consumption** by 2020.
- The challenge of the European Commission: a **20% improvement in the EU's energy efficiency** by 2020.

Experimentation and Power Models

- **Difficulties of getting numbers and good power models.**
    - Lots of different hardware.
    - Lots of possible configurations.
    - Power measurement of real live traffic is intrusive.

Experimentation and Power Models

- **Difficulties of getting numbers and good power models.**
  - Lots of different hardware.
  - Lots of possible configurations.
  - Power measurement of real live traffic is intrusive.
- **Some initiatives:**
  - Companies.
  - Academy. **Powerlib** http://powerlib.intec.ugent.be/database/
    Database of power consumption values for ICT network equipment.
    - Started in September 2012, and its main and initial
    - **Purpose:** collect and provide this data for use in research towards more power-efficient ICT networks.
    - **Provide a single source** for different data sheets, experimentation and (academic) publications.

How to manage this trend ?

- Today's (and future) network infrastructures characterized by:
  - **Design capable to deal with strong requests and constraints in terms of resources and performance** (large loads, very low delay, high availability, ...)
  - **Services characterized by high variability of load and resource requests along time** (burstiness, rush hours, ...)
- The current feasible solutions:
  - **Smart power management:** energy consumption should follow the dynamics of the service requests.
  - **Flexibility in resource usage:** virtualization to obtain an aggressive sharing of physical resources

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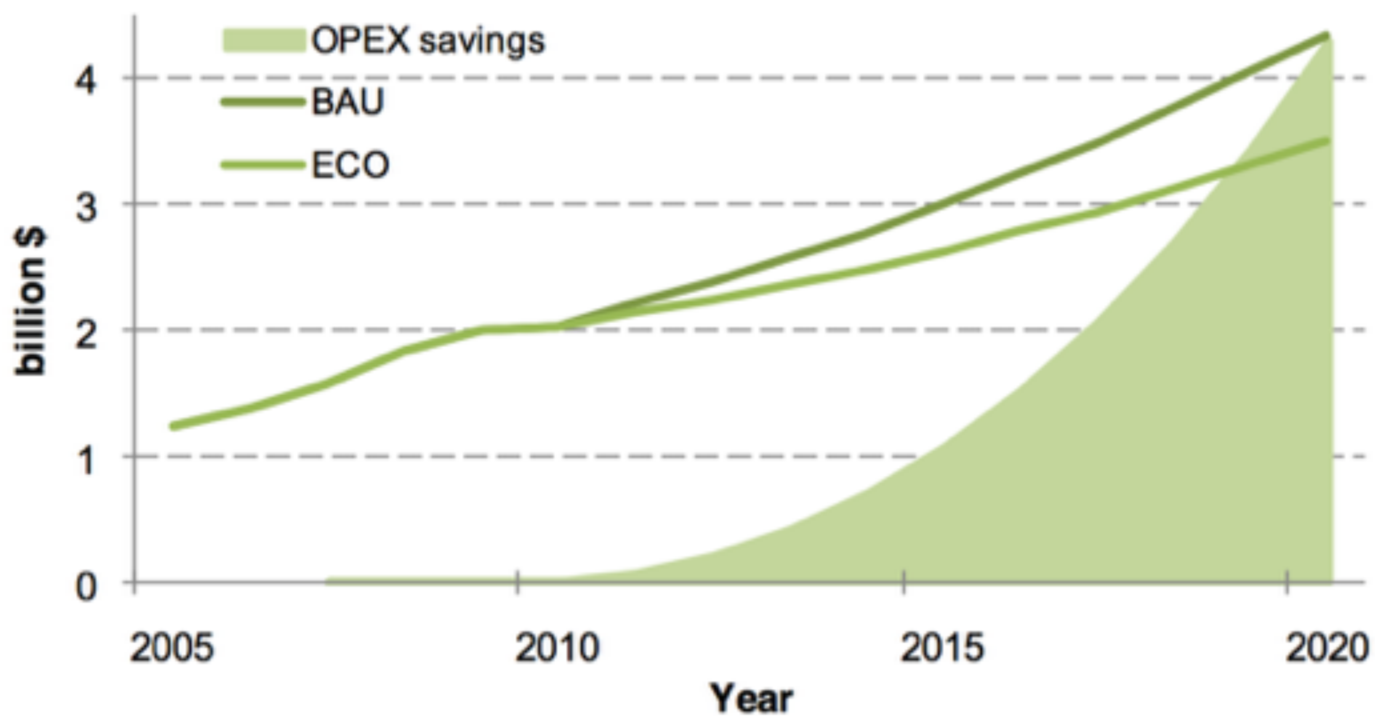
What could be gained?

Comparison of Business-As-Usual (BAU) and Eco sustainable (ECO) scenario: [European Commission DG INFSO report]

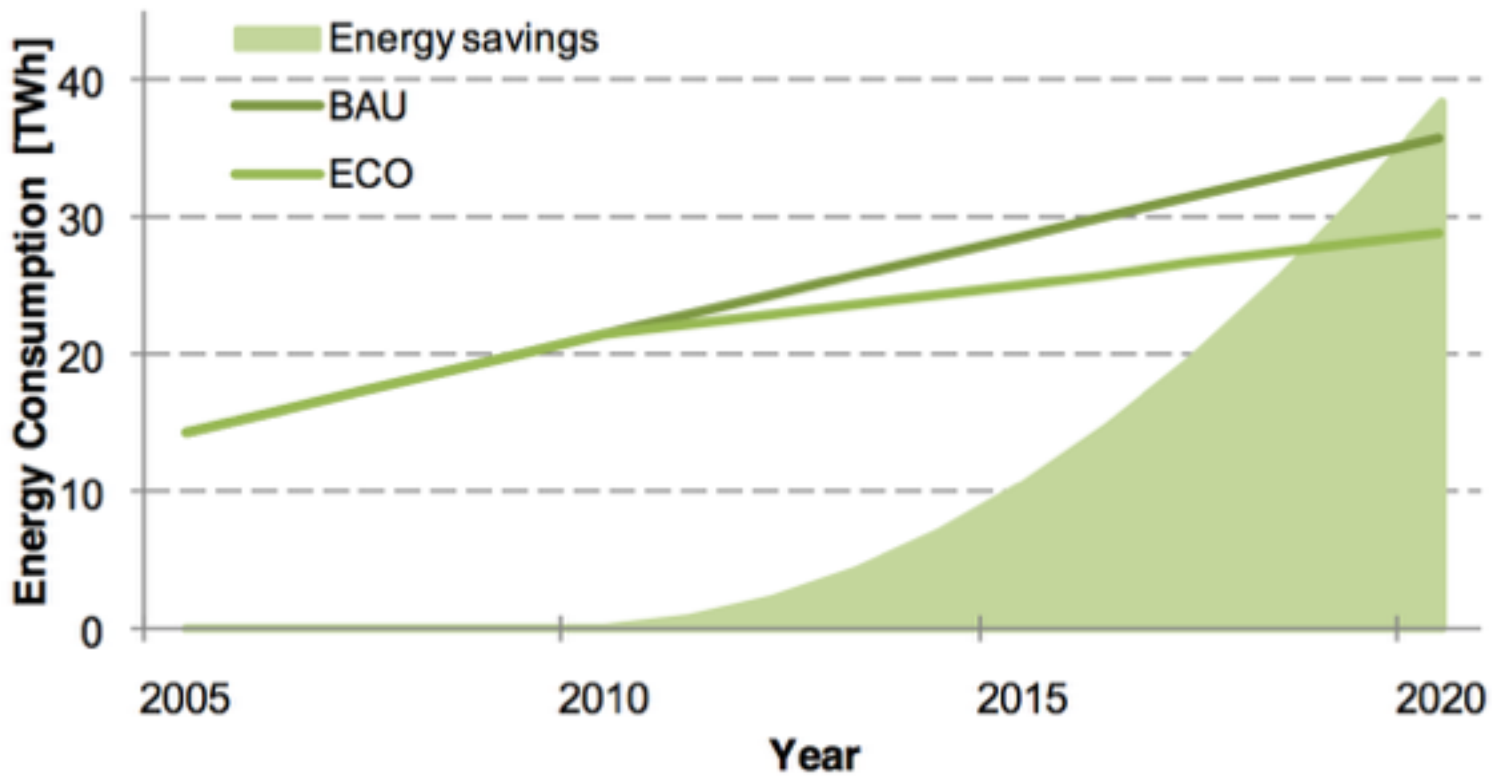


OPEX estimation related to energy costs for the European telcos' network infrastructures

-> $4 billion saved in 2020

What could be gained?

Comparison of Business-As-Usual (BAU) and Eco sustainable (ECO) scenario:



Energy consumption estimation for the European telcos' network and cumulative energy savings..

-> 40 TWh saved in 2020

History

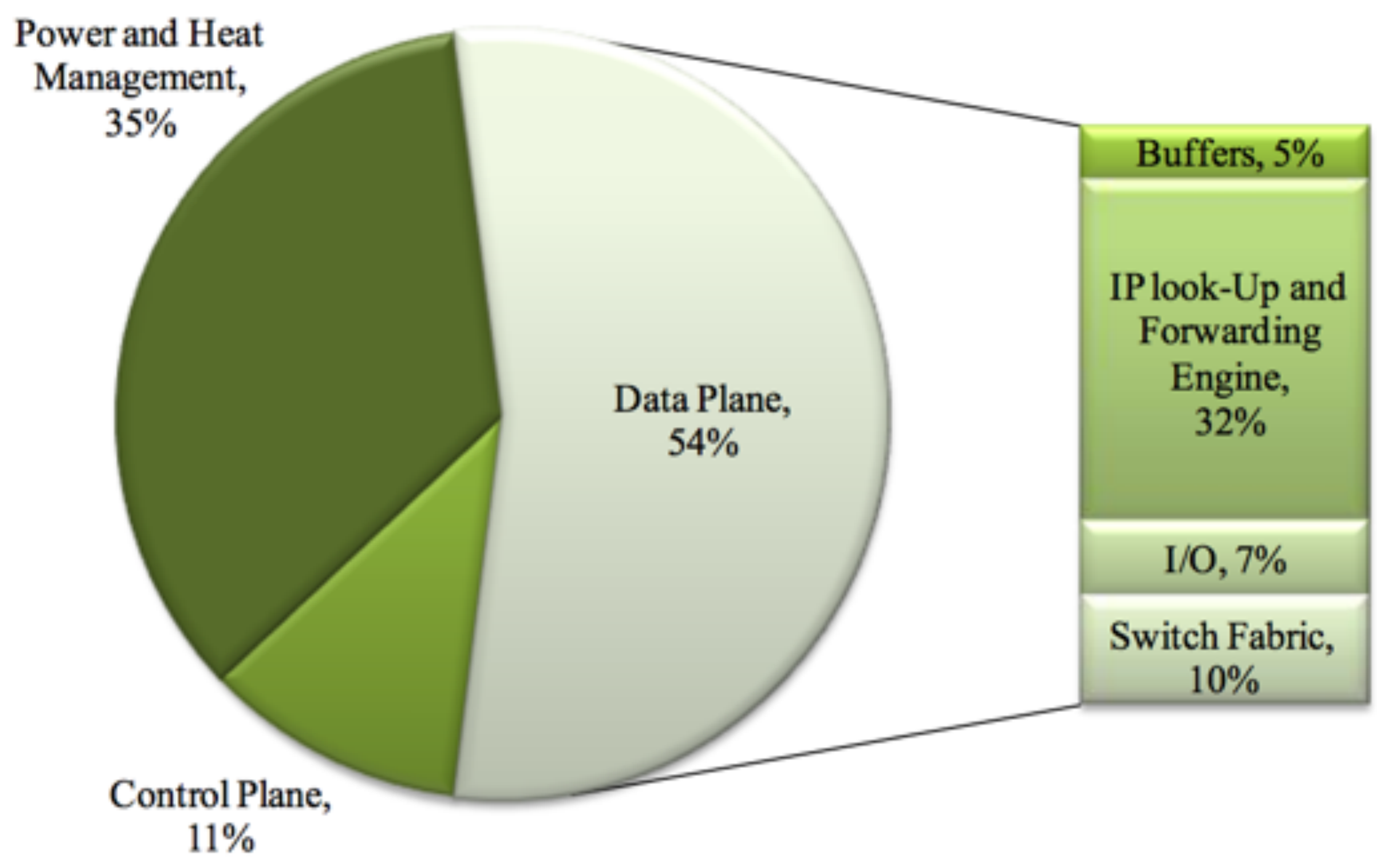
- **Ground-breaking works on energy consumption in the Internet:** [Gupta et al. 2003], [Christensen et al. in 2004], showing that this is a mandatory issue to improve the energy efficiency of the whole Internet.

- However, **massive effort** in this direction by researchers, operators, and device manufacturers only **2008-2009**.

Energy Efficiency in Networks

- **Specificity of energy efficiency in networks.**
  - High Operational power requirements
  - due to **specialized hardware**
  - realizing **network-specific functionalities**
    - e.g. functionalities of the data- and control-planes

Power Model of Routers



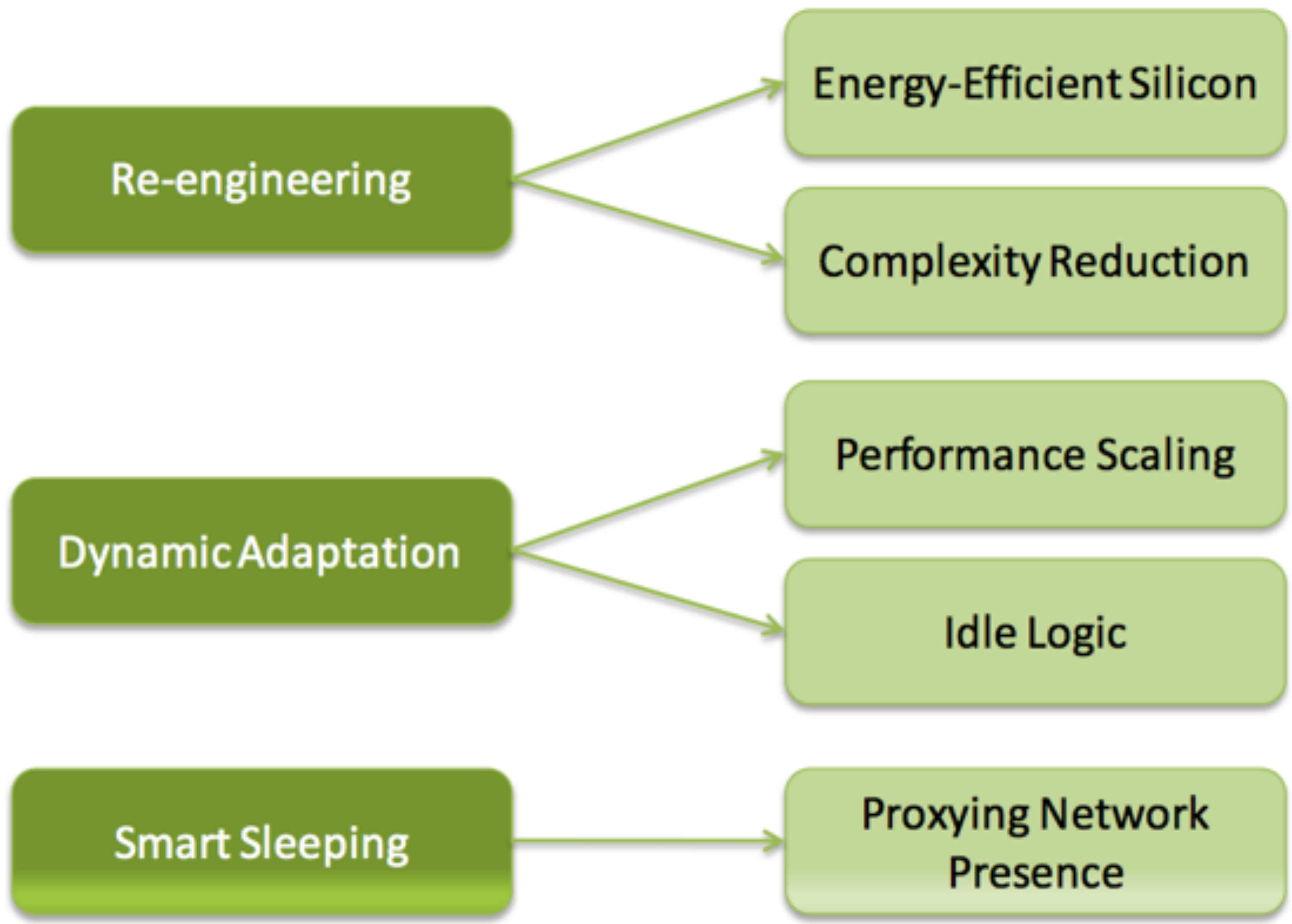
Estimate of power consumption sources in a generic platform of high-end IP router.

- [Tucker et al. 2009] estimated that the **data-plane weighs for 54%** including **32% for IP look-up and forwarding engine**

Power Model of Routers

- **The data-plane = the most energy-starving and critical element** in the largest part of network device architectures
- Since it is generally composed by **special purpose HW elements** (packet processing engines, network interfaces, etc.) that have to perform per-packet forwarding operations at very high speeds.

Classifying Proposed Methods



Taxonomy of undertaken approaches for the energy efficiency of the Future Internet.

Re-engeenering approaches

- **Re-engineering approaches** aim
  - at **introducing and designing more energy-efficient elements** for network device architectures,
  - at suitably dimensioning and **optimizing internal organization devices**, as well as
  - at **reducing their intrinsic complexity levels**.

Re-engeenering approaches

- **Example:**
  - adoption of **pure optical switching architectures** for replacing the **current electronic based devices.**
  - They can potentially provide terabits of bandwidth at **much lower power dissipation than current network devices**
  - **Lots of work [Baliga 2007] but adoption still far from reality.** Current technological problems mainly regard the Control Plane.

Dynamic Adaptation

- **Dynamic adaptation of network/device resources:** modulate capacities of packet processing engines and of network interfaces, to meet actual traffic loads and requirements.

- This can be performed by using two main power aware capabilities, namely,

  - **dynamic voltage scaling** and

  - **idle logic**,

Dynamic Adaptation: Power scaling

- Key feature in today's processors
- But, nowadays, **not included in the largest part of current network equipment**.
- Power scaling capabilities allow **dynamically reducing the working rate** of processing engines or of link interfaces. This is usually accomplished by tuning the **clock frequency** and/or the **voltage of processors**

Dynamic Adaptation: Power scaling

- For instance, the **power consumption of a CMOS based silicon** can be roughly characterized as follows:

$$P = CV^2 f$$

  - where P is the active power wasted,
  - C the capacitance of CMOS, and
  - V and f are the operating voltage and frequency values, respectively.
  - Decreasing operating frequency and the voltage of a processor, or throttling its clock, **reduces the power consumption and of heat dissipation at the price of slower performance.**

Dynamic Adaptation: Idle logic

- Idle logic allows reducing power consumption by **rapidly turning off sub-components** when no activities are performed, and by **re-waking them up** when the system receives new activities.

- In detail, wake-up instants are triggered by a **system internal scheduling process** (e.g., the system wakes itself up every certain time periods, and controls if there are new activities to process).

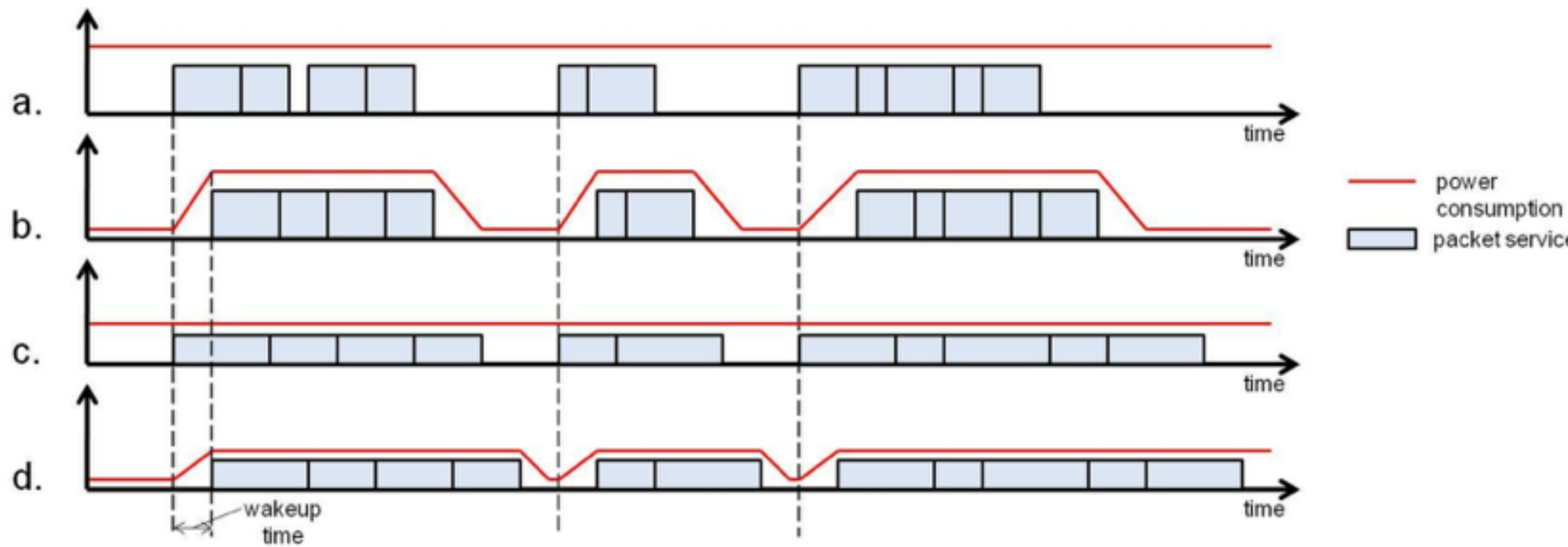
Dynamic Adaptation

- **HW implementation** of both idle logic and performance scaling solutions:

  preselection a set of feasible and stable HW configurations,

  which provide **different trade-offs** between **energy consumption and performance states**.

Dynamic Adaptation



Packet service times and power consumptions in the following cases [Nevedschi et al. 2008]:

(a) no power-aware optimizations,
(b) only idle logic,
(c) only performance scaling,
(d) performance scaling and idle logic.

Sleeping/standby Approaches

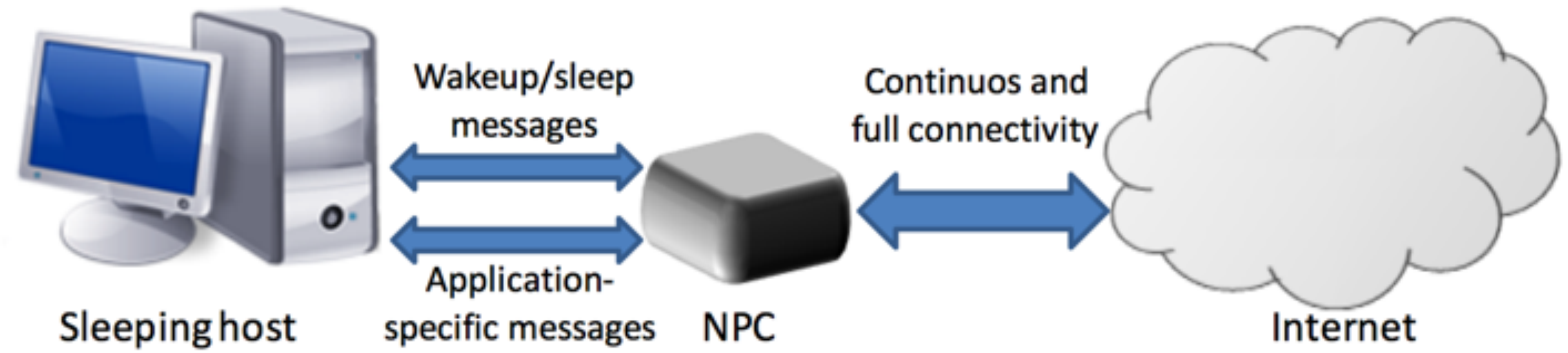
- **Sleeping/standby approaches** are used to **smartly and selectively drive unused network/device** portions to low standby modes, and to **wake them up** only if necessary.

- However, today's networks and related services and applications designed to be **continuously and always available.**

- Standby modes have to be explicitly supported with **special proxying techniques** able to maintain the —network presence of sleeping nodes/components

Sleeping/standby Approaches

- [Christensen and Nordman 2004] directly faced energy efficient enhancements in such kind of scenario.



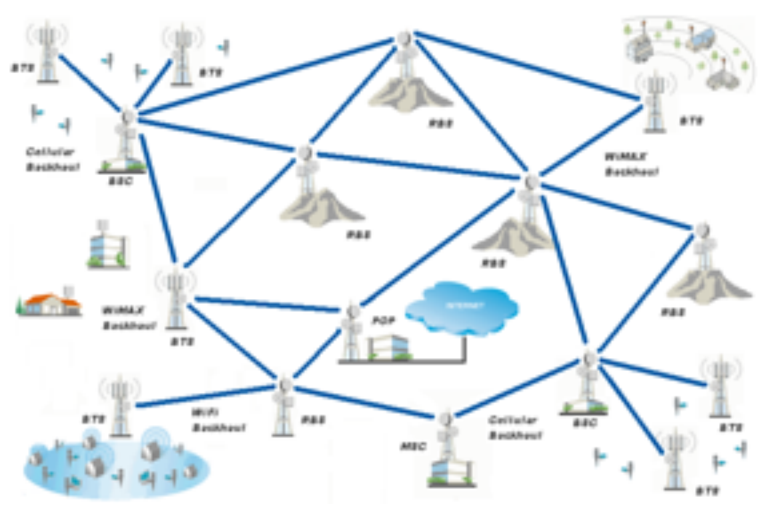
Example of Network Connection Proxy.

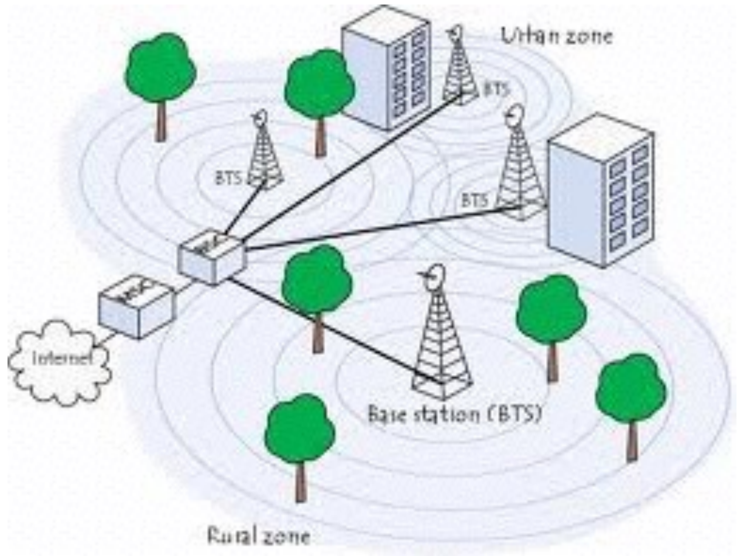
- **Solution:** maintain continuous network presence by having ***a network host transfer network presence to a proxy***, namely Network Connectivity Proxy (NCP), when entering sleep mode.

Classifying Proposed Methods

- All these approaches are not exclusive among themselves,
- All such directions in order to effectively develop new-generation green networks.

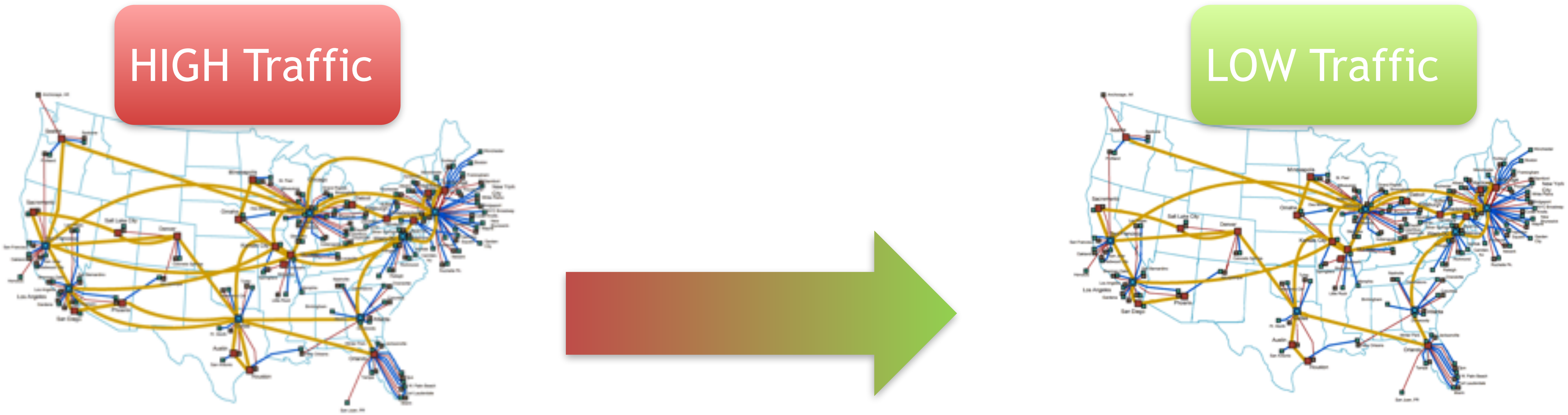
Work we did in COATI





- EE in
  - backbone networks (Dimagreen)
  - backhaul networks (with 3ROAM)
  - cellular networks (Ecocells)
- On backbone:
  - Energy efficient routing with impact on route length and protection
  - Theoretical analysis of specific graphs (cycles, grids, …)
  - Using Redundancy elimination
  - Content distribution: CDNs and in-network caches

Energy Efficient routing



30% of turned-off interfaces, but with impact on

- **route length** (spanner graphs)
- **Fault tolerance** (number of disjoint paths)

[*Giroire et al., 2010*] : F. Giroire, D. Mazauric, J. Moulierac and B. Onfroy **Minimizing Routing Energy Consumption: from Theoretical to Practical Results,** *IEEE/ACM GreenCom* 2010

[*Giroire et al., 2012*] : F. Giroire, D. Mazauric, J. Moulierac **Energy Efficient Routing by Switching-Off Network Interfaces** *Ch. 10 - Energy-Aware Systems and Networking for Sustainable Initiatives* 2012

What can we do? Basic Principles of Power Management

To save Energy we can:

- use more efficient chips and components
- better power manage components and systems
- turn off lights of the corridor.

To power manage: two main methods

- Do less work: e.g. transmit less in wireless networks.
- Turn-off devices: not being used
  - within a chip (e.g., floating point unit)
  - within a component (e.g., disk drive)
  - within a system (e.g., server in a cluster)

"Most electronics are lightly utilized"

- $\rightarrow$ 2/3 of PC energy use when no one present
- Typical commercial server utilization: 15 to 20%
- Typical (edge) network link usage: few percents.

Problem: Finding energy efficient routings

Measurement campaigns on routers: small influence of the traffic load
[*Power Awareness in Network Design and Routing*, Chabarek et al., INFOCOM 2008]
$\longrightarrow$ importance of the number of switched-on elements

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$\longrightarrow$ importance of the number of switched-on elements

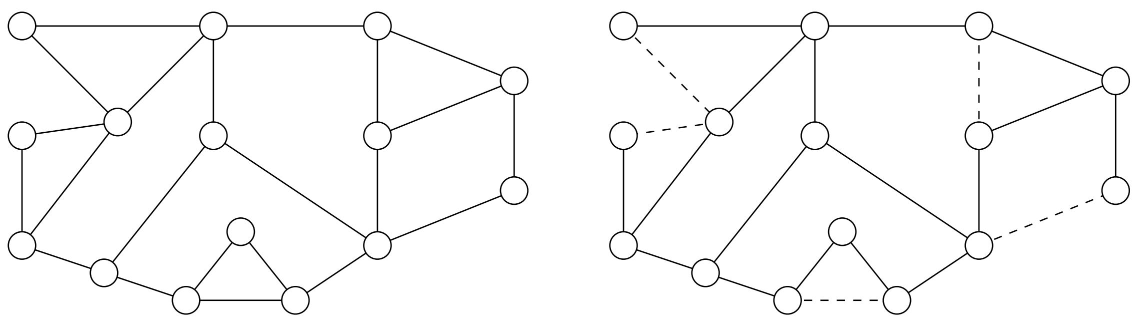
Thus we looked at

- finding energy efficient routings
- using a simplified cost function: number of switched-on devices
- on a simplified network architecture: only one kind of network devices can be turned-off.

Problem: Finding energy efficient routings

Problem statement:

Given a graph with capacities on edges and a demand function, find the subgraph with the minimum number of edges satisfying the demands.



→ Five edges can be spared while satisfying demands (all-to-all capacity 50).

Related Work

Closely related to classic problems

- Routing: limit case of a maximum flow with a step cost function.
- Design: finding the minimum cost design (mostly the starting graph is a complete graph).
- RO: instance of FIXED CHARGE TRANSPORTATION PROBLEM.

But with new angle (e.g. dynamicity), new applications (energy cost and specifics) and a lot of open problems.

Modeling: what do we know?

Optimization program: can be modeled classically.

- Variables: for each edge $e \in E$, binary variable x_e saying if the edge e is used.
- Objective function: $\min \sum_{e \in E} x_e$
- Classic flow and capacity constraints.

Complexity:

- $\rightarrow$ NP-complete.
- Even when the subgraph is fixed.
- Classic approximations by linearization behave very badly.
- In practice: 10 hours to solve a 4×4-grid (16 nodes, 24 edges) using CPLEX.

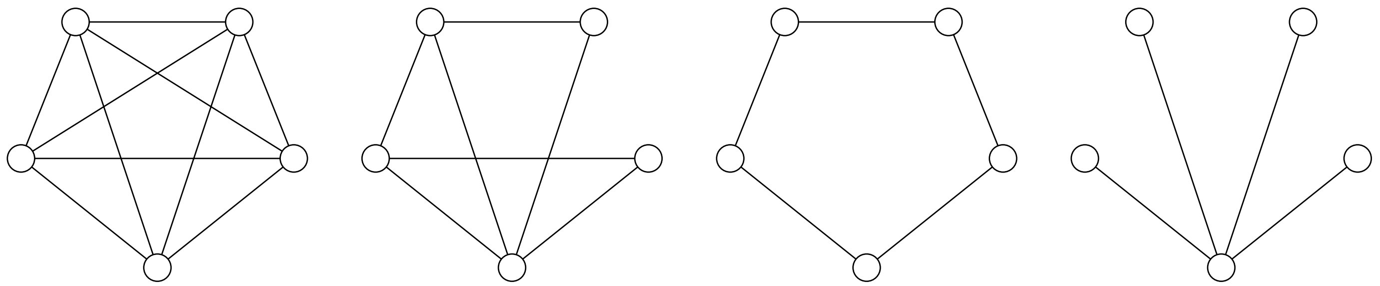
Study and Problem Illustration

We test network topologies:

- Regular topologies: complete graphs, square grid, cycles,. . .
- Practical Network topologies.

For different ranges of operations (meaning percentage of full capacity). Correspond to

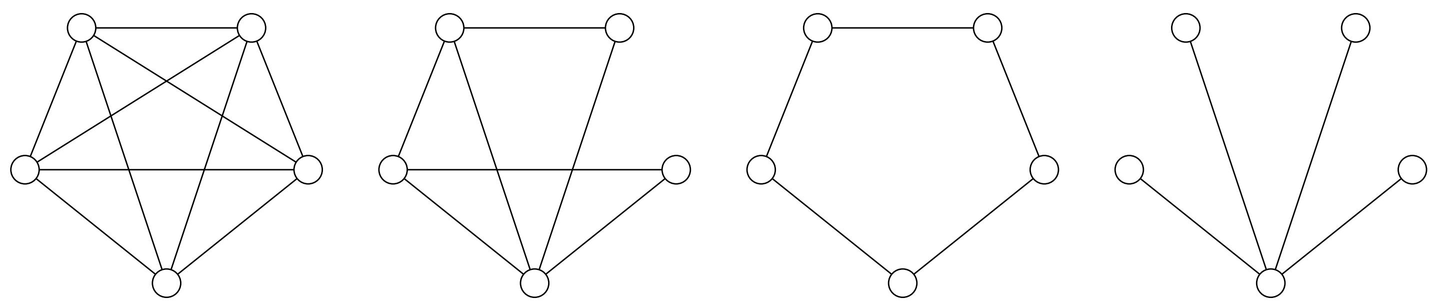
- different network provisionnings.
- different demands during the day/night.



$c = 2$, $\bar{d}(G) = 1.0$ | $c = 4$, $\bar{d}(G) = 1.3$ | $c = 6$, $\bar{d}(G) = 1.5$ | $c = 8$, $\bar{d}(G) = 1.6$

A Toy example, complete graph with 5 vertices

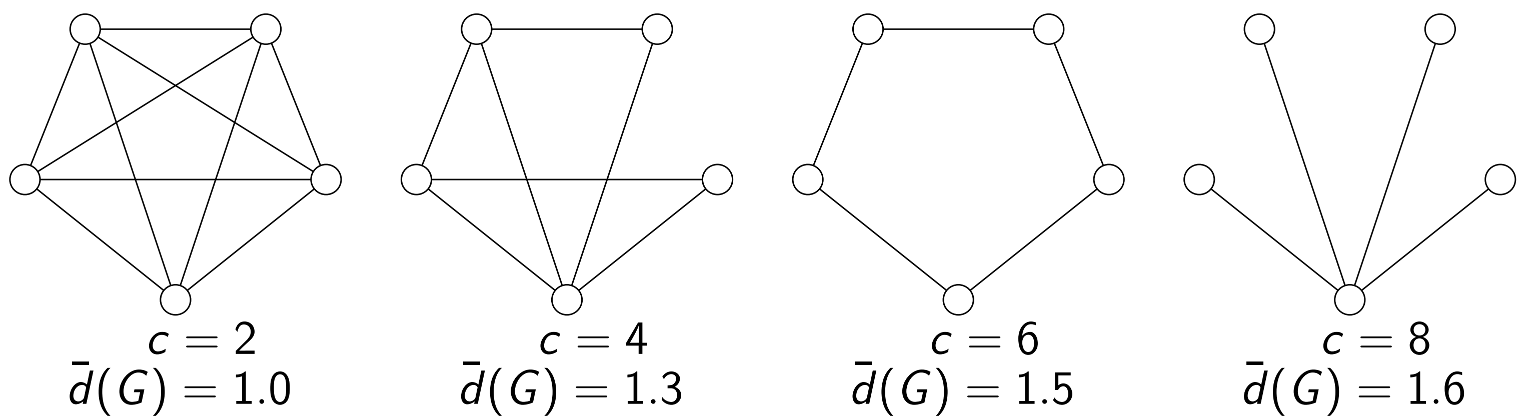
Study



$c = 2$ $\bar{d}(G) = 1.0$ | $c = 4$ $\bar{d}(G) = 1.3$ | $c = 6$ $\bar{d}(G) = 1.5$ | $c = 8$ $\bar{d}(G) = 1.6$

- Weak demand: best configuration = spanning tree. What is the best spanning tree (with minimum load)?
- High demand: how much can be routed with all the edges?
  - load: bound given by sum of the route length
  - finding the min cut
  - good indication: bissection width.

Study



- Weak demand: best configuration = spanning tree. What is the best spanning tree (with minimum load)?
- High demand: how much can be routed with all the edges?
  - load: bound given by sum of the route length
  - finding the min cut
  - good indication: bissection width.
- Hard question: And in between ?

Results on specific topologies

- **Problem:** Find the minimum subgraph to carry the demands.
  - Goal: size of subgraph in function of load.
  - Theoretical bounds for grids, rings, trees, etc…

Edges	subgraph	load
$n-1$	tree	$\frac{3}{8}n^2$
$n+p-2\sqrt{p}$		$\frac{1}{2}\frac{n^2}{\sqrt{p}}+\frac{3}{8}\frac{n^2}{p^2}$
$2n-2\sqrt{n}$	grid	$\frac{1}{2}n^{3/2}$

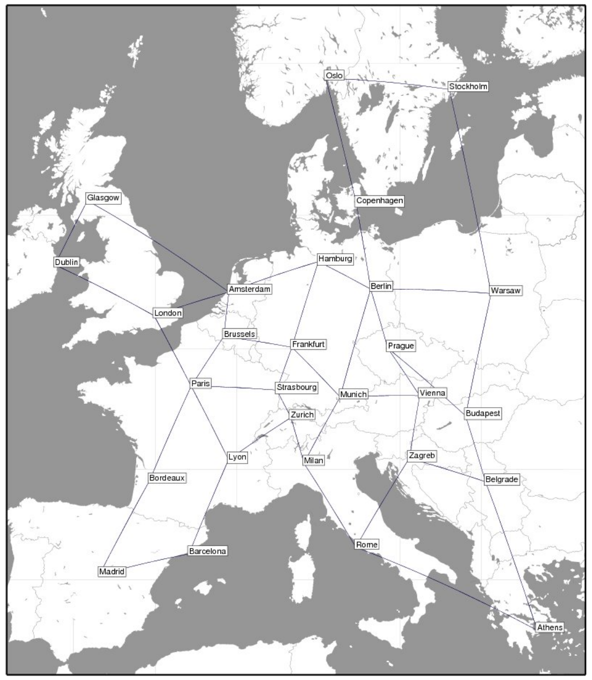
[*Coudert et al., 2012*] : D. Coudert, F. Giroire, S. Perennes, I. Tahiri **Green subgraphs and efficient routing,** *submitted 2012.*

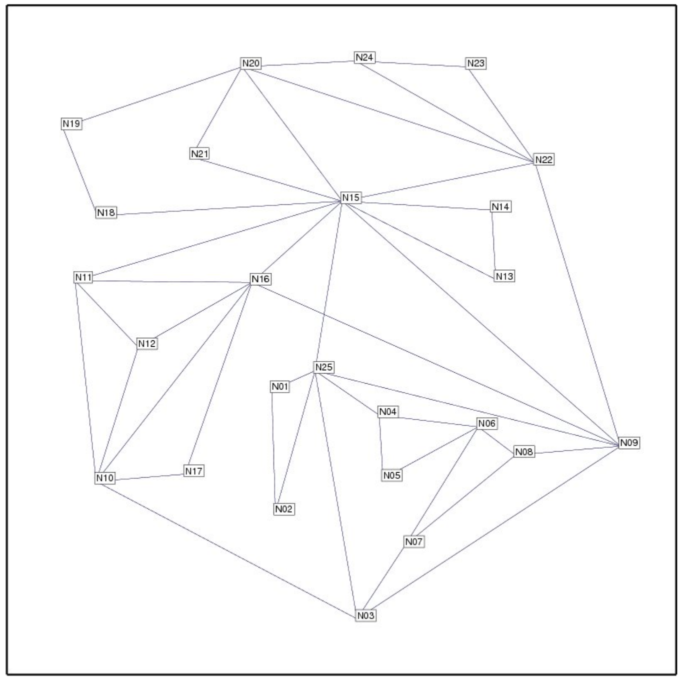
Results on Network Topologies

Topologies extracted from SNDLib

We tested how many interfaces can be spared for different range of network operations on 10 topologies.

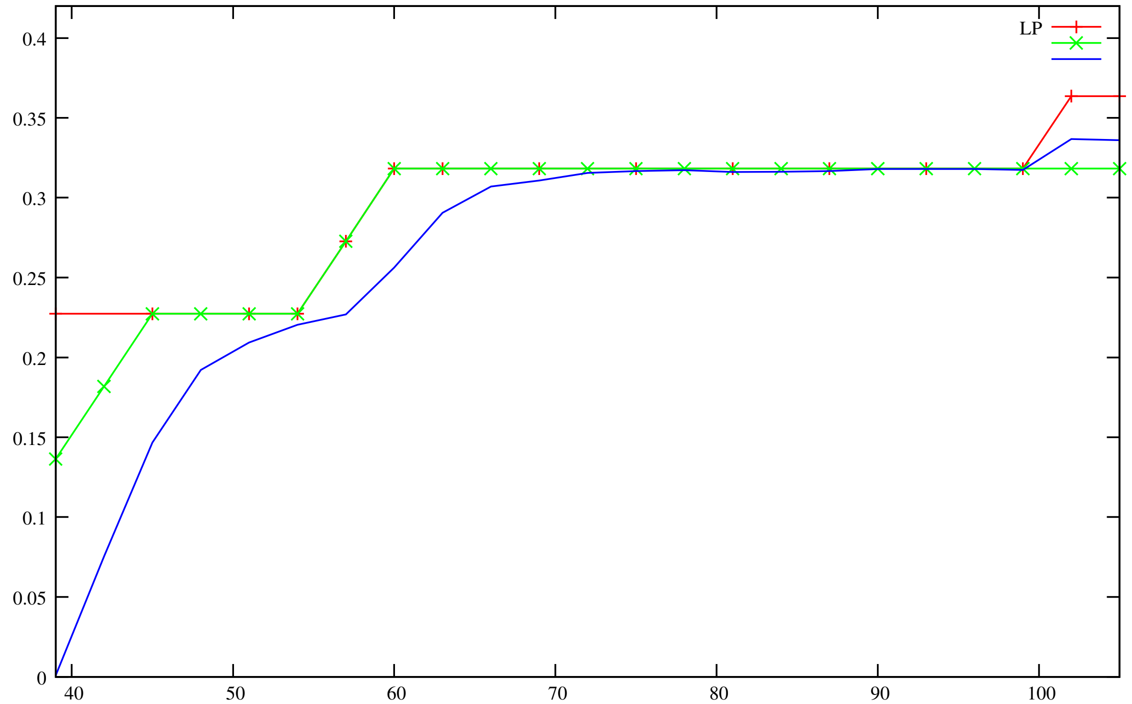
Also looked at the impact on route lengths and on fault protection.





An example

Small sized network (15 nodes and 22 edges: we can solve the linear program).



Heuristic behaves not too badly.

How many interfaces can be spared in practice?

	$\|V\|$	$\|E\|$	Overprovisioning factor 1	2	3	4	Tree OF	%SNE
Atlanta	15	22	0%	32%	36%	36%	2.66	36%
France	25	45	0%	42%	44%	47%	3.13	47%
Nobel EU	28	41	12%	32%	34%	34%	2.76	34%
Nobel Germany	17	26	0%	35%	39%	39%	2.75	39%
Cost266	37	57	3.5%	32%	35%	37%	3.65	37%
Guil39	39	86	0%	45%	50%	52%	8.25	56%
Norway	27	51	12%	43%	47%	47%	4.71	49%
Zib54	54	80	0%	30%	33%	33%	4.71	34%
Pioro40	40	89	0%	53%	54%	55%	5.12	56%
New York	16	49	2.0%	59%	63%	67%	5.2	69%

(a) Gain of network equipments (in %).

- Best configuration saves from 35 to 55 % for practical networks
- But with a demand of half the capacity (usual demand at least during nigth or usual overprovisioning factor): already a 30% to 50% saving.

Impact on the Route Length (Stretch)

	$\|V\|$	$\|E\|$	Overprovisioning factor 1	2	3	4	Tree OF	SF
Atlanta	15	22	1.000	1.186	1.255	1.255	2.66	1.255
France	25	45	1.000	1.096	1.123	1.167	3.13	1.158
Nobel EU	28	41	1.080	1.143	1.241	1.242	2.76	1.247
Nobel Germany	17	26	1.000	1.112	1.176	1.132	2.75	1.179
Cost266	37	57	1.045	1.112	1.195	1.314	3.65	1.319
Guil39	39	86	1.000	1.179	1.208	1.280	8.25	1.497
Norway	27	51	1.024	1.170	1.184	1.205	4.71	1.248
Zib54	54	80	1.000	1.019	1.067	1.097	4.71	1.110
Pioro40	40	89	1.000	1.254	1.320	1.382	5.12	1.424
New York	16	49	1.005	1.240	1.262	1.282	5.2	1.325

(a) Average multiplicative stretch factor

- We get the tree with 2.5 to 8 stretch.
- But possible to have most of the energy savings with a weak impact on the stretch: 35-45% of edges saved and strechs of 1.1-1.3.

Impact on Fault Protection

			Overprovisionning factor				Tree	
1	2	3	4	OF	DP			
Atlanta	15	22	2.352	1.095	1.000	1.000	2.66	1.000
France	25	45	2.483	1.023	1.010	1.000	3.13	1.000
Nobel EU	28	41	1.817	1.074	1.000	1.000	2.76	1.000
Nobel Germany	17	26	2.353	1.044	1.000	1.000	2.75	1.000
Cost266	37	57	2.467	1.122	1.068	1.000	3.65	1.000
Guil39	39	86	3.677	1.412	1.138	1.065	8.25	1.000
Norway	27	51	2.613	1.137	1.043	1.009	4.71	1.000
Zib54	54	80	2.164	1.048	1.015	1.002	4.71	1.000
Pioro40	40	89	4.058	1.124	1.086	1.027	5.12	1.000
New York	16	49	4.892	1.242	1.190	1.025	5.2	1.000

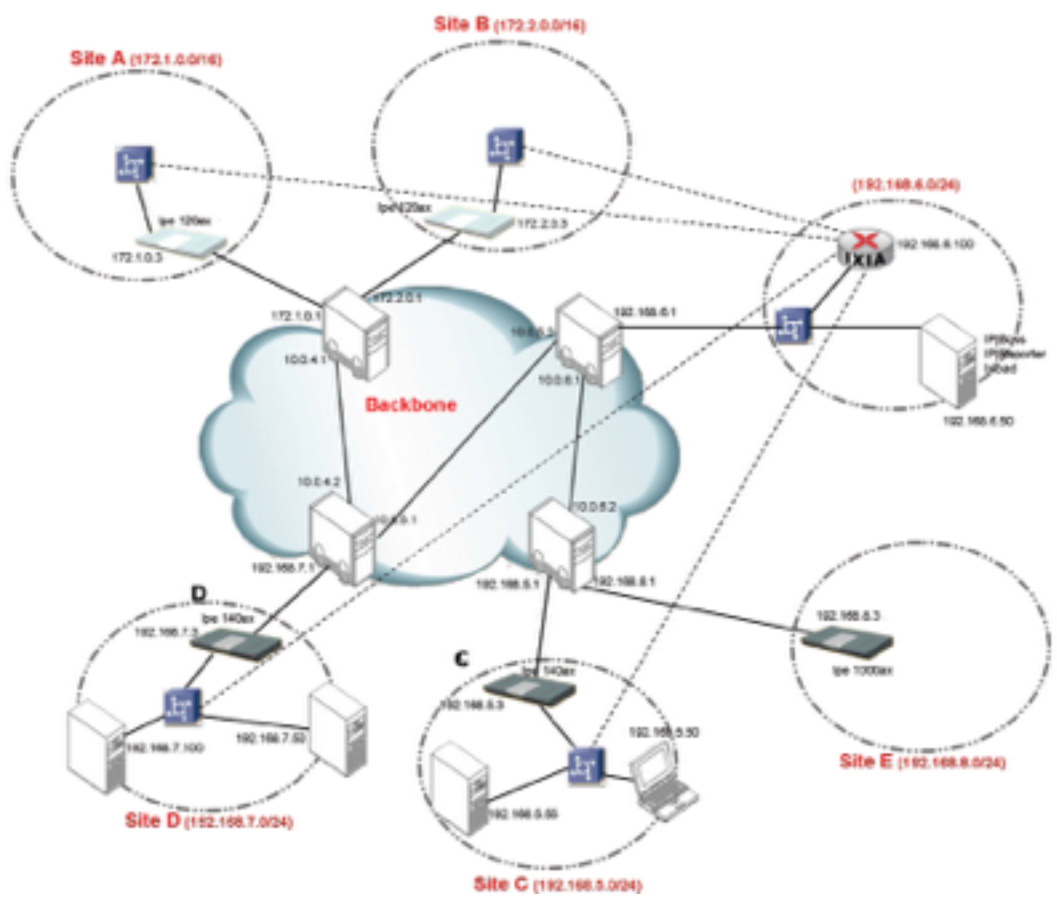
(b) Average number of disjoint paths

From an average of 2.5 with all the edges to 1.2 with overprovisioning factor of 2 (and of course 1 for the tree).
Two remarks:

- The impact depends on the technology: how long to turn-on interfaces (compare that with classic rerouting time).
- Add fault protection constraints: e.g. at least two disjoint paths

Using Redundancy Elimination

- Identification of the **parameters** influencing the power consumption of WAN optimization controllers
- Definition of **realistic cost functions**

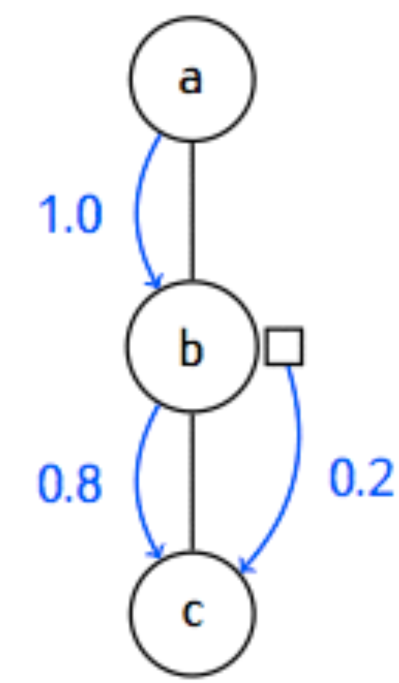


[*Giroire et al., 2012*] : F. Giroire, J. Moulierac, T. K. Phan, F. Roudaut **Minimization of Network Power Consumption with Redundancy Elimination**, *IFIP Networking* 2012

Energy efficient content distribution

- Context:
  – Some Data replicated on CDN servers
  – Content caches located at routers

- Optimization Problem:
  Select the best source(s) for each demand



[*Araujo et al., 2013*] : J. Araujo, F. Giroire, Y. Liu, R. Modrzejewski, J. **Moulierac Energy Efficient Routing with Network Caches** *ICC 2013*.

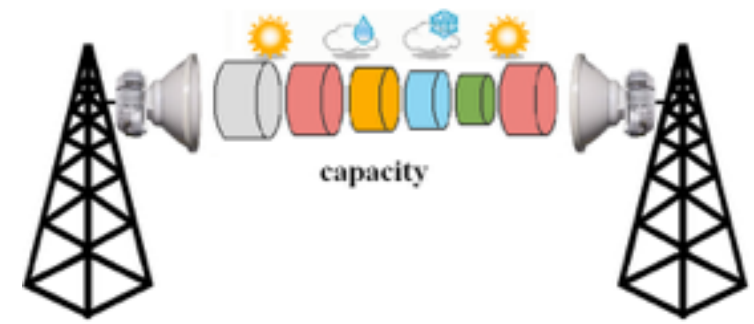
Microwave Backhaul Networks

- **Dynamic behavior of microwave links**

Environmental conditions

Impact on signal propagation

Variation of the capacity



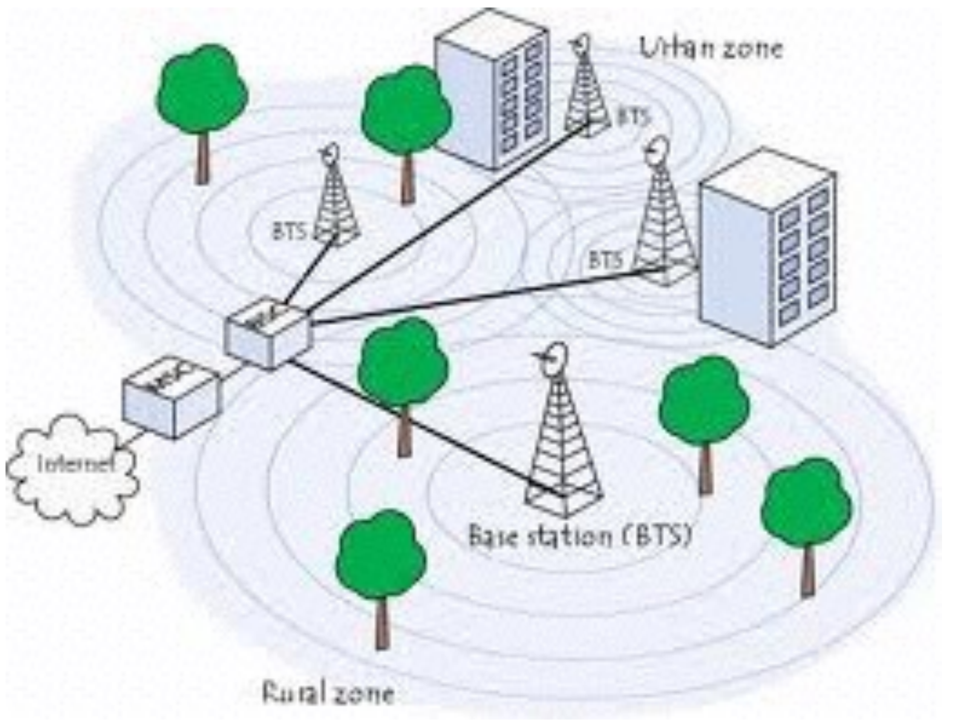
- **Problems:**
  - **Design/operation** of networks with respect to link capacity dynamics
  - Optimization of the **power consumption**
  - **Robust** solutions with low impact on routing

[*Coudert et al., 2010*] : *D. Coudert, N. Nepomuceno and I. Tahiri*, **Energy saving in fixed wireless broadband networks**, *INOC* 2010.

[*Coudert et al., 2009*] : *D. Coudert, N. Nepomuceno and H. Rivano* **Power-Efficient Radio Configuration in Fixed Broadband Wireless Networks**, *Computer Communications* 2009.

Work of our neighbors in Sophia

- Several works on reducing the energy consumption of cellular networks



- Sara Alouf webpage:

[Alouf et al. 2012] *S. Alouf, V. Mancuso, N. Choungmo Fofack, **Analysis of power save and its impact on web traffic in cellular networks with continuous connectivity**. Pervasive and Mobile Computing, 2012.*

[Alouf et al. 2012] *V. Mancuso, S. Alouf, **Analysis of power saving in cellular networks with continuous connectivity**. Computer Networks, 2012.*

[Azad et al. 2011] *A. Azad, S. Alouf, E. Altman, **Analysis and Optimization of Sleeping Mode in WiMAX via Stochastic Decomposition Techniques**. IEEE Journal on Selected Areas in Communications, 2011.*

[Azad et al. 2011] *A. Azad, S. Alouf, E. Altman, V. Borkar, G. Paschos, **Optimal Control of Sleep Periods for Wireless Terminals**. IEEE Journal on Selected Areas in Communications, 2011.*

[Mancuso et al. 2011] *V. Mancuso , S. Alouf, **Reducing costs and pollution in cellular networks**. IEEE Communications Magazine, August 2011.*

Work of our neighbors in Sophia

Presented in the **Energy Workshop of the Labex.** (http://www.ucnlab.eu/fr/node/66) 2014

- Cecile Belleudy – Maître de Conférences (LEAT – UNS): Energy-aware architecture for WBAN **sensor node**
- Trong-Nhan LE – Post doc Labex UCN – (LEAT – Labex UCN): Efficient MAC protocol for multi-hopping in **autonomous WSN**
- Fabien Hermenier - Maitre de conférences, équipe SCALE (UNS-I3S-CNRS-INRIA): Energy efficient resource management in **virtualized datacenters**
- Dino Lopez - Maitre de conférences, équipe SIGNET (UNS-I3S-CNRS): **Software defined network** and energy efficiency
- Joanna Moulierac (ou Frédéric Giroire) - équipe COATI (UNS-CNRS-I3S-INRIA): Energy efficient **content distribution**

Work of our neighbors in Sophia

Presented in the **Energy Workshop of the Labex.** (http://www.ucnlab.eu/fr/node/66) 2014

- Navid Nikaein (ou Thrasyvoulos Spyropoulos) – Maitre de Conférences, Communications mobiles (EURECOM): Wifi offloading and energy efficiency for **mobiles**
- Pietro Michiardi – Maître de Conférences, Distributed Systems Group (EURECOM): On the Impact of Socio-economic Factors on **Power Load Forecasting**
- Giovanni Neglia - chercheur, équipe MAESTRO (INRIA): Optimizing **smart grids**
- Vivien LENG (Ingénieur, CEVA (ex-RivieraWaves)): Using **Bluetooth Low Energy in IOT applications**

Table of contents

1. Why caring about network energy efficiency?
2. Methods to reduce network energy consumptions.
3. **Current and Future Challenges:**
    - Putting into practice with SDN.
    - Using virtualization technics: NFV.
    - Joint optimizations:
        - Networks and Data centers
        - How will IoT be managed?

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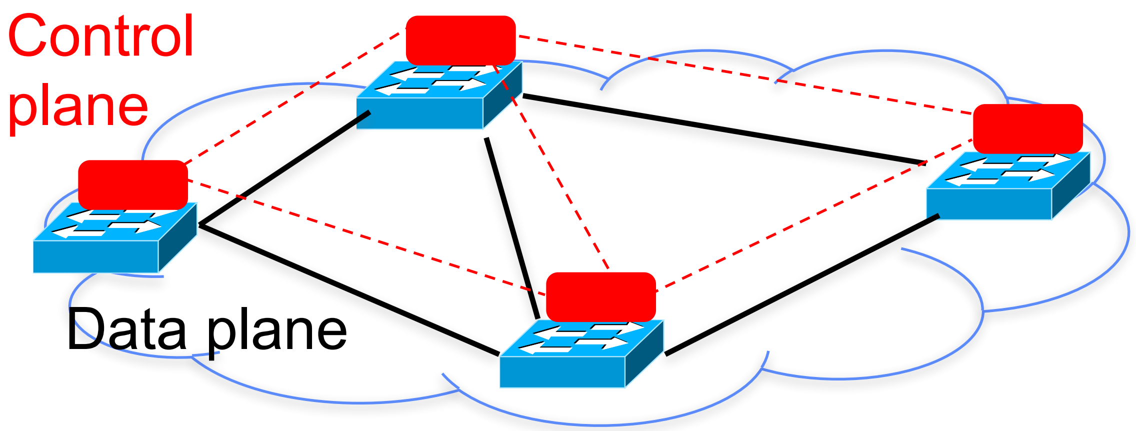
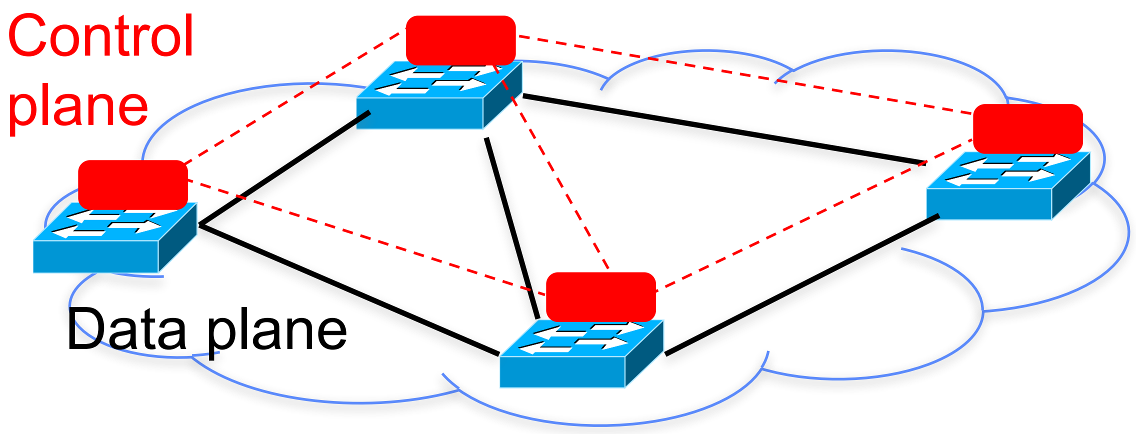
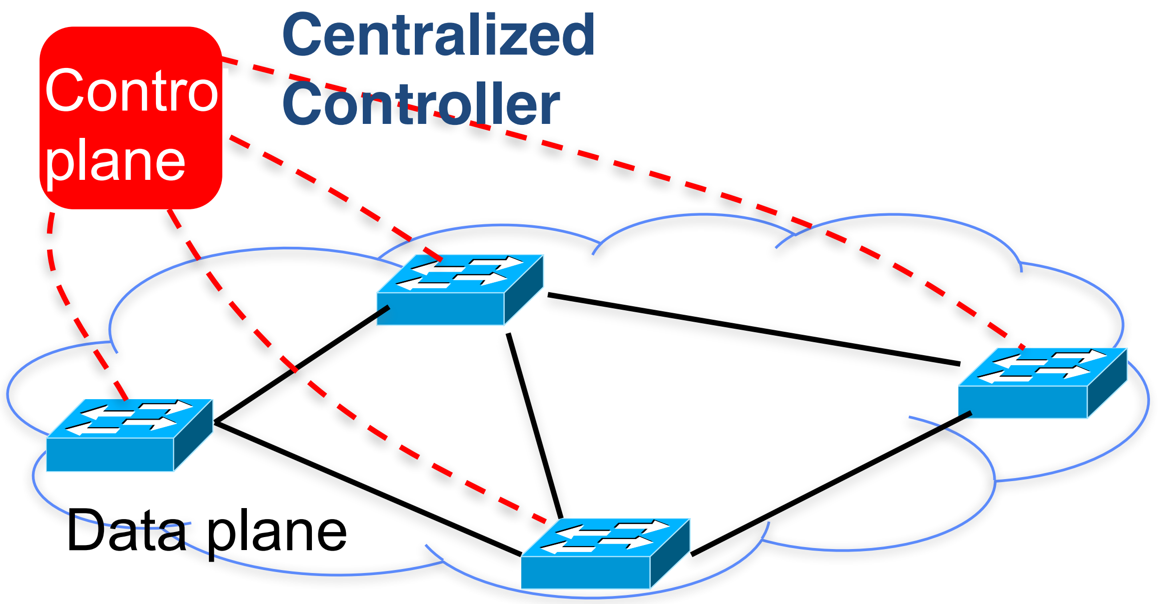
Traditional Networks vs Software Defined Networks



Routers and switches are "closed systems"

Traditional Networks vs Software Defined Networks

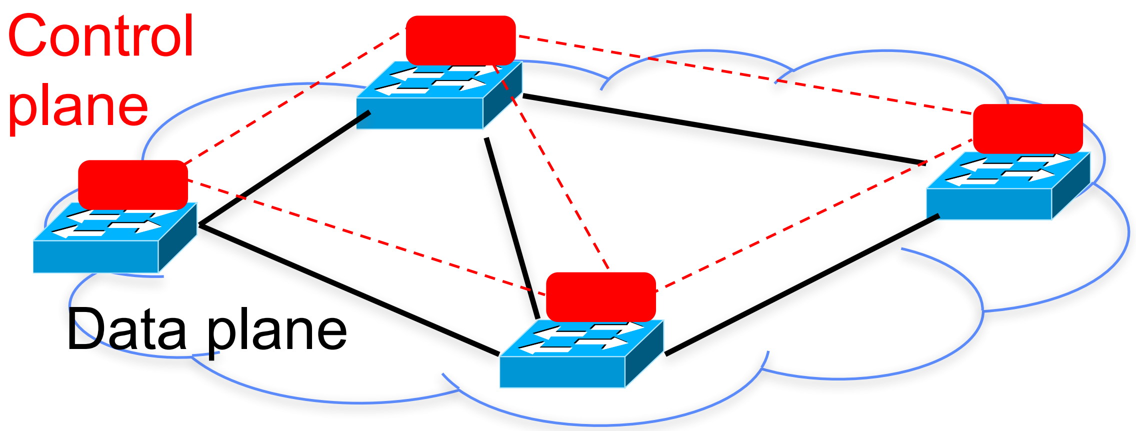


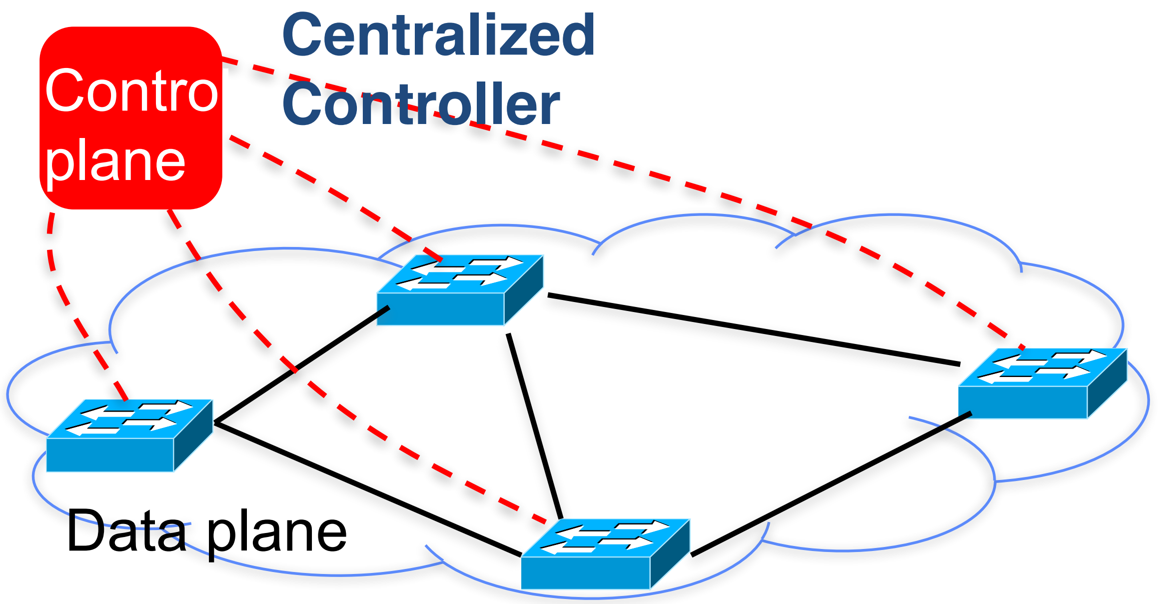


Routers and switches are "closed systems"

Network elements: elementary switches. Intelligence implemented by a centralized controller managing the switches
(i.e., install forwarding rules).

Traditional Networks vs Software Defined Networks





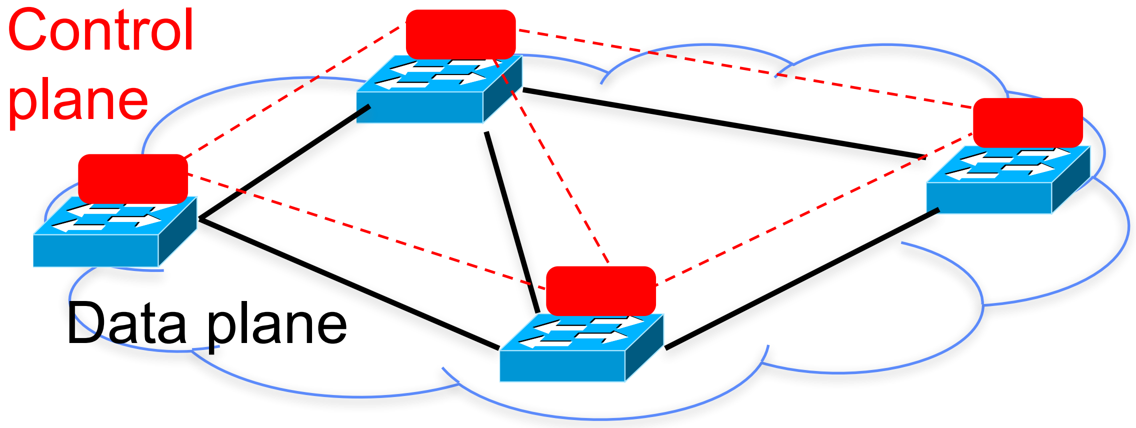
Networks are managed by **configurations** but

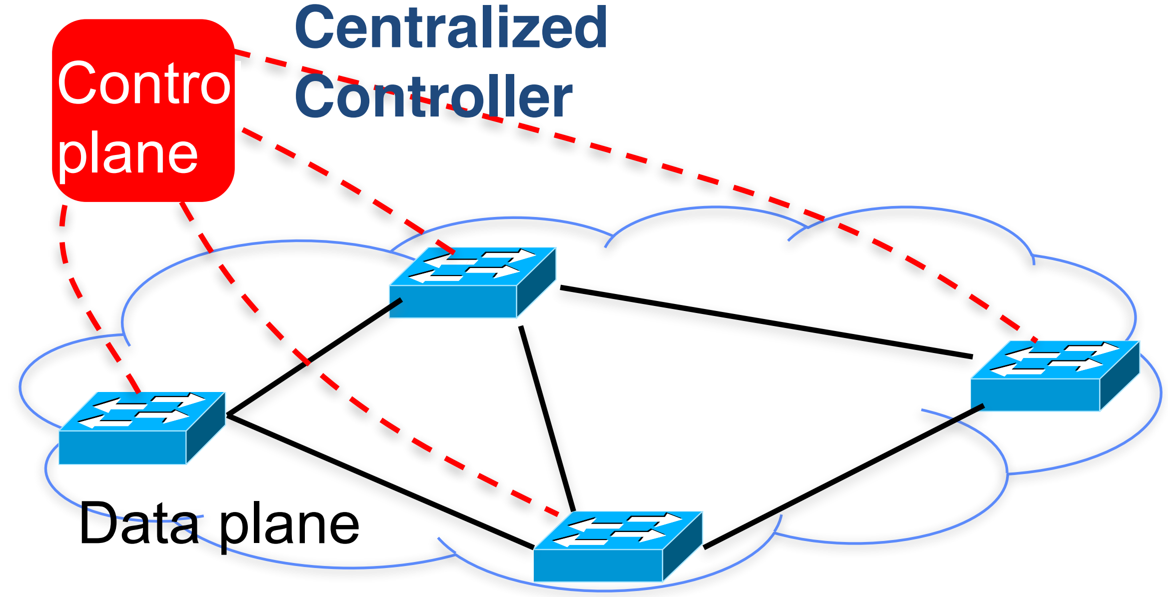
- each protocol has its own configuration set,
- each constructor has its own configuration language,
- it is hard to construct configurations that support all the possible cases.

SDN conceives the network as a **program**:

- Operators do not configure the network, they program it.
- Operators do not interact directly with devices.
- Network logic is implemented by humans but network elements are never touched by humans.

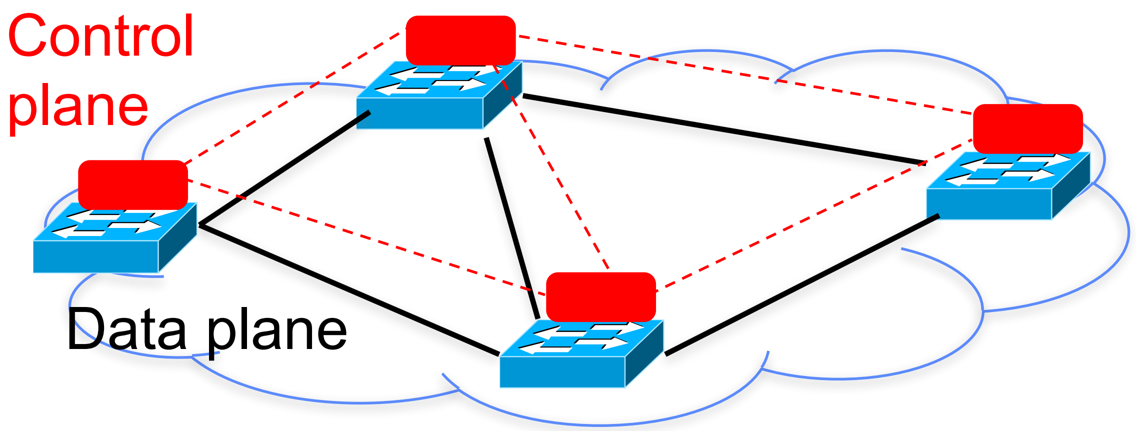
Traditional Networks vs Software Defined Networks

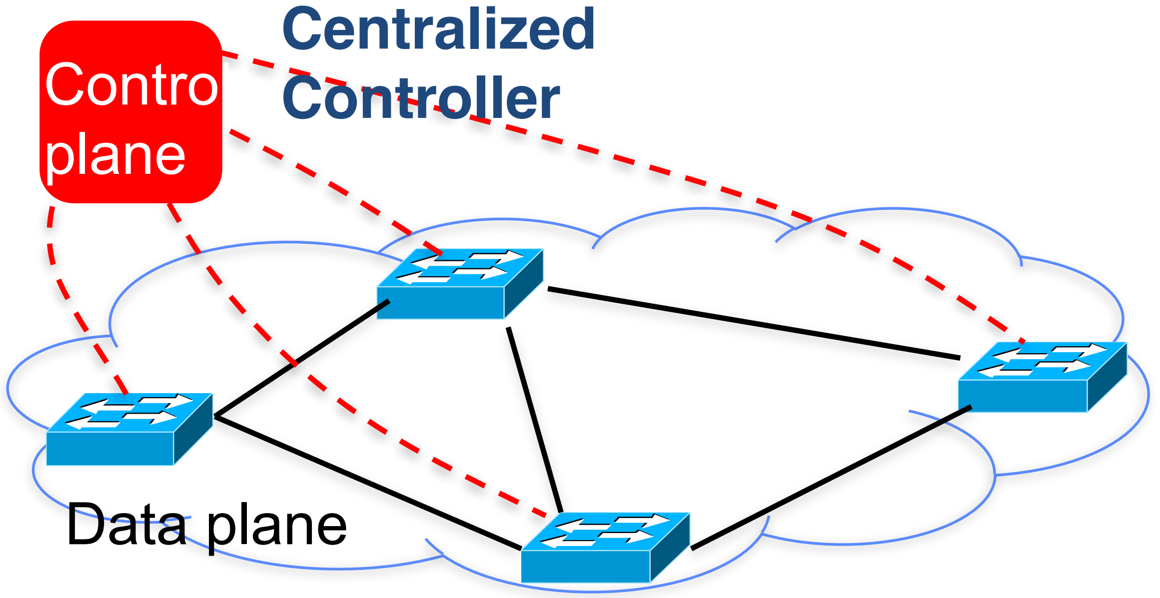




-> Important difficulties to deploy new protocols

Traditional Networks vs Software Defined Networks



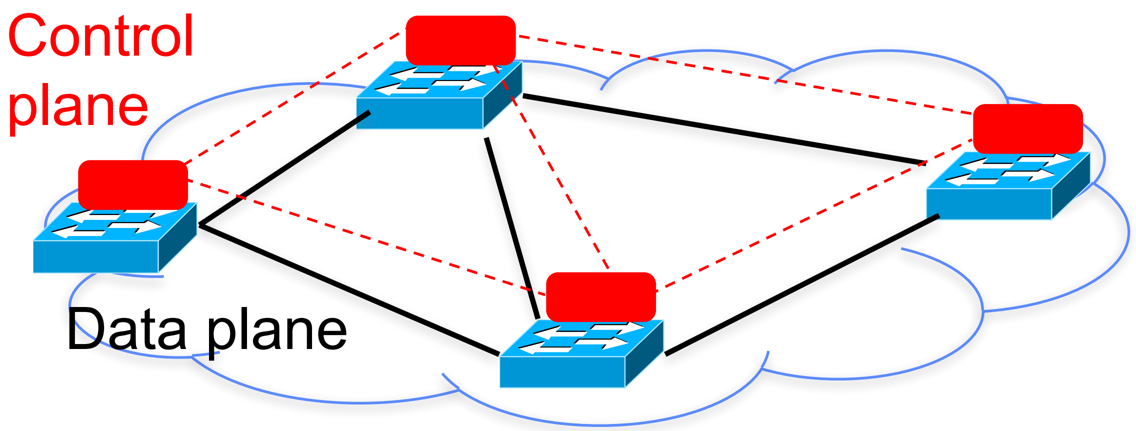


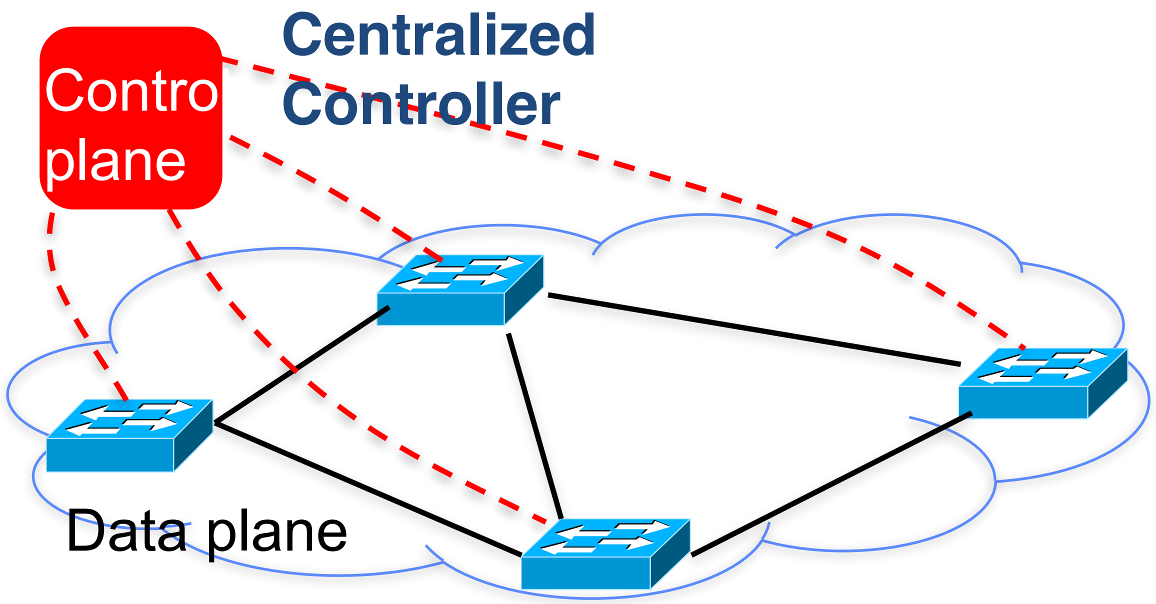
-> Important difficulties to deploy new protocols

SDN enables

- Reporting of nodes/links **metrology data**
- **Centralized management** using this data
  - → Introduction of advanced protocols
  - → **Finer** network optimization

Traditional Networks vs Software Defined Networks





-> **Important difficulties to deploy new protocols**

SDN enables

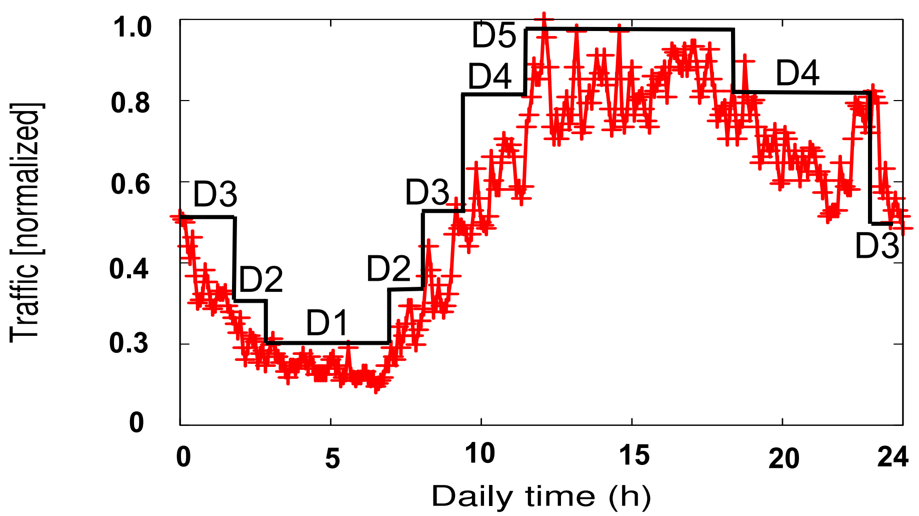
- Reporting of nodes/links **metrology data**
- **Centralized management** using this data
  - → Introduction of **advanced protocols**
  - → **Finer network optimization**

Of particular interest, **dynamic routing.**

SDN and Energy Efficiency

- Core of solutions for energy efficiency: Dynamic adaptation of resource usage to traffic changes.

- Example, Energy Aware Routing:

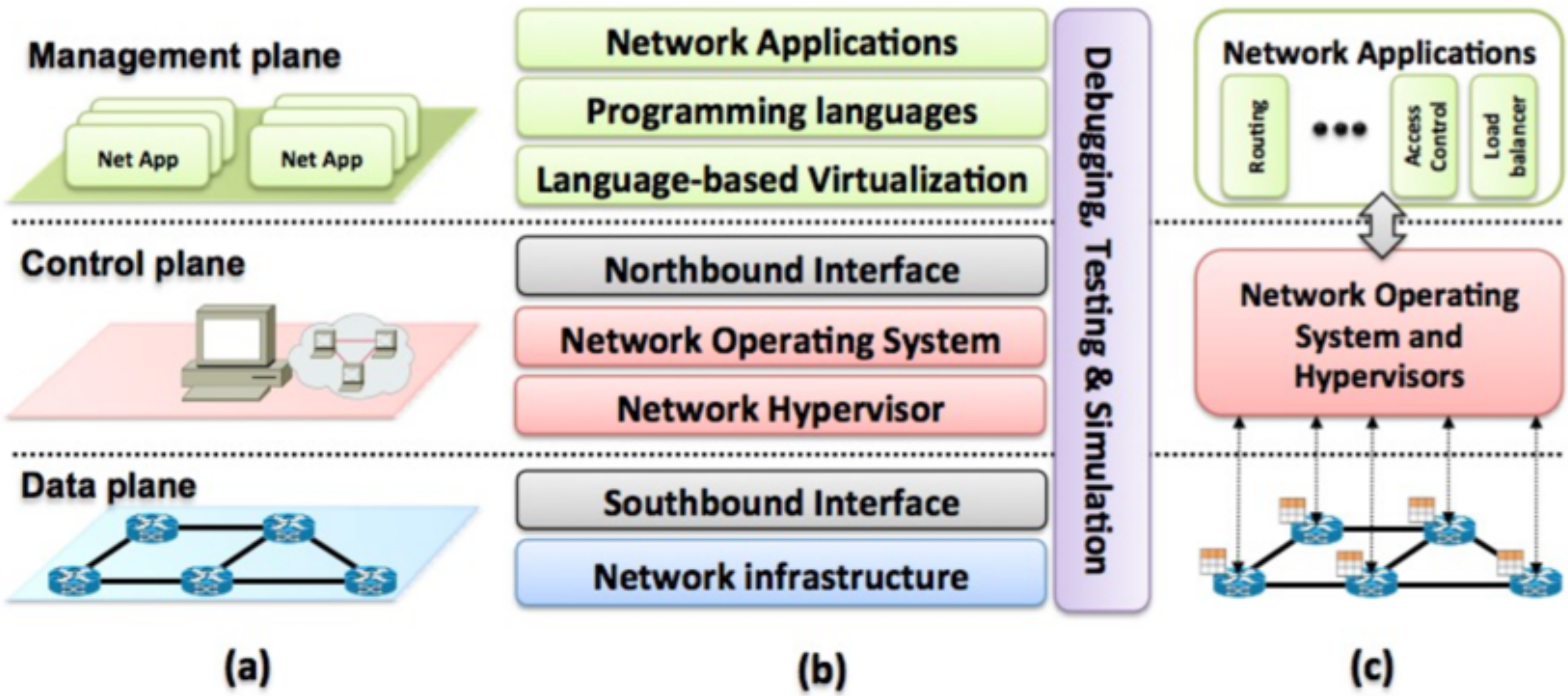


Other applications: energy efficient data centres (virtual machine assignment), wireless networks (base-station assignment)…

-> SDN has the potential of Putting energy-efficient schemes into reality

The revolution SDN

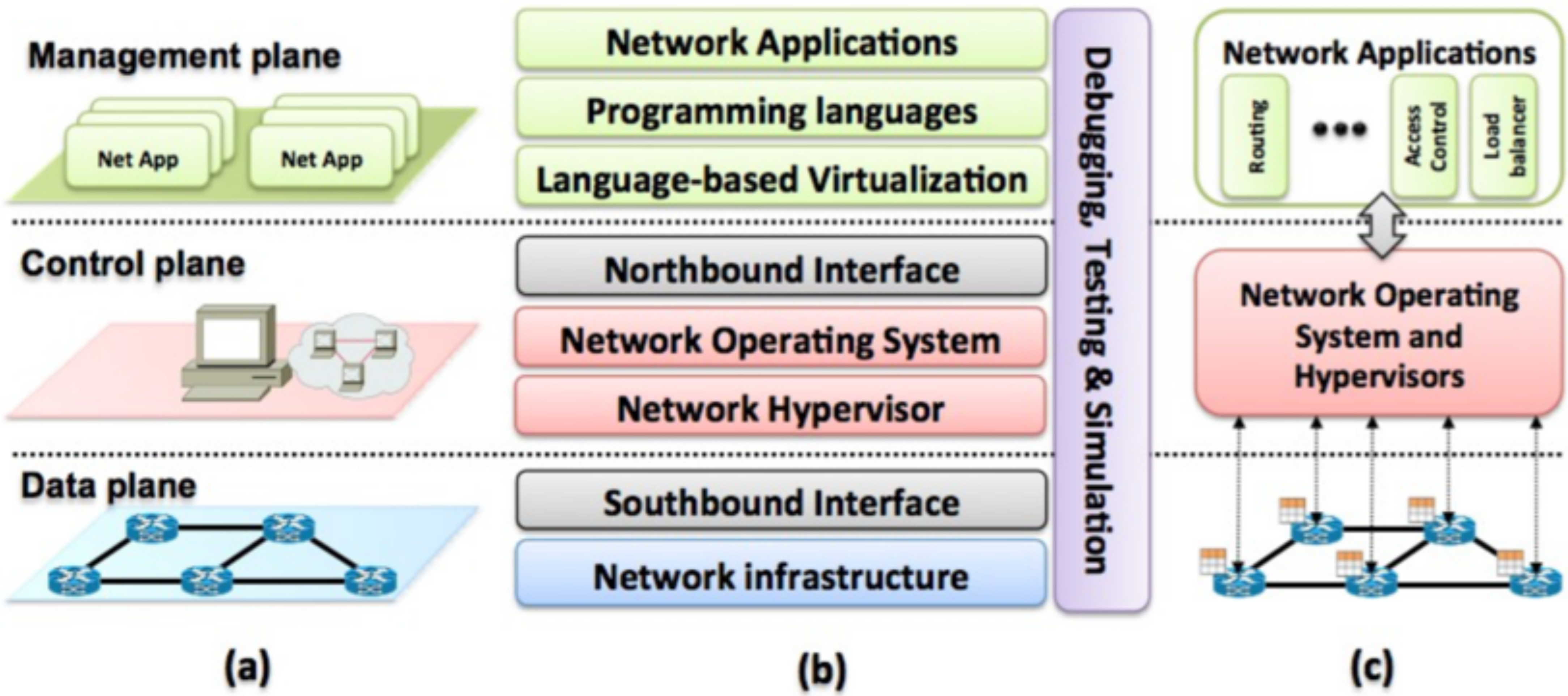
- **A new Network Operating System**



Plane, Layers and System design architecture

The revolution SDN

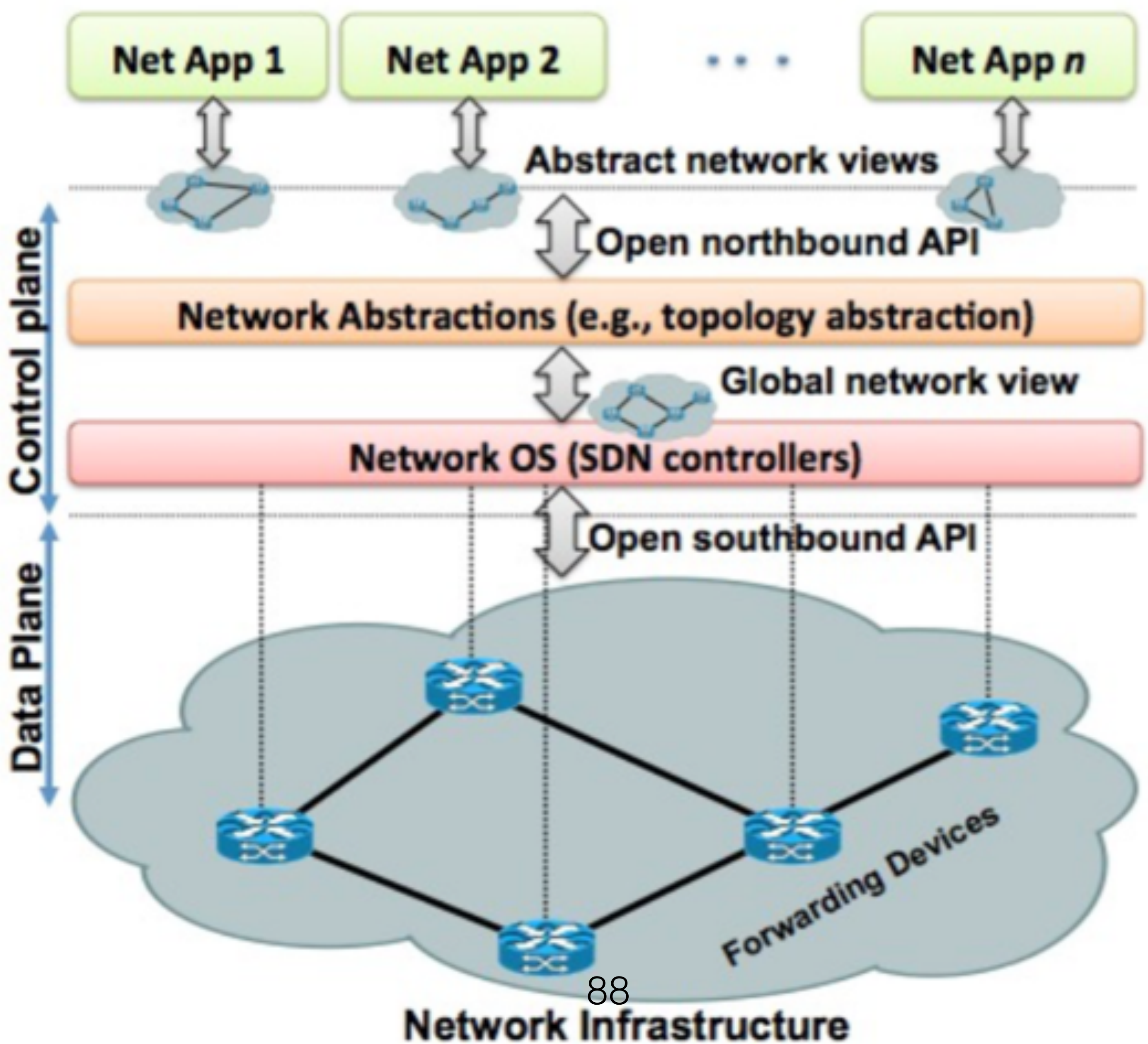
- **A Network OS: with Network Applications**



Plane, Layers and System design architecture

The revolution SDN

- **And Network Abstraction (Network virtualization).**



The revolution SDN

- Not only nice words.
  - SDN started with the OpenFlow project at the Stanford University (just for routing)
  - Open Flow protocols already implemented and running.
  - Supported by major manufacturers, e.g., HP, Juniper, IBM as well as
  - Open source virtual switches like Open vSwitch

The revolution SDN

- Not only nice words.
  - **Large scale experiment reported by Google** on its inter-data center networks [Jain 2013].

    -> reach nearly 100% utilization of links under stringent QoS constraints

B4 worldwide deployment (2011)

SDN Challenges

- Several challenges to be faced
  - Scalability of the SDN environment
    - avoiding excessive flow table entries
    - avoiding Control – Data Plane communications overhead
    - managing short- & long-lived flows
  - Controller placement and (dynamic) allocation of switches
  - Cross-domain solutions
  - Defining Northbound APIs to enable real network programmability
  - Security

SDN and Energy Efficiency

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SDN and Energy efficiency

- Topic of a project between EPI COATI and laboratory I3S (SigNet).



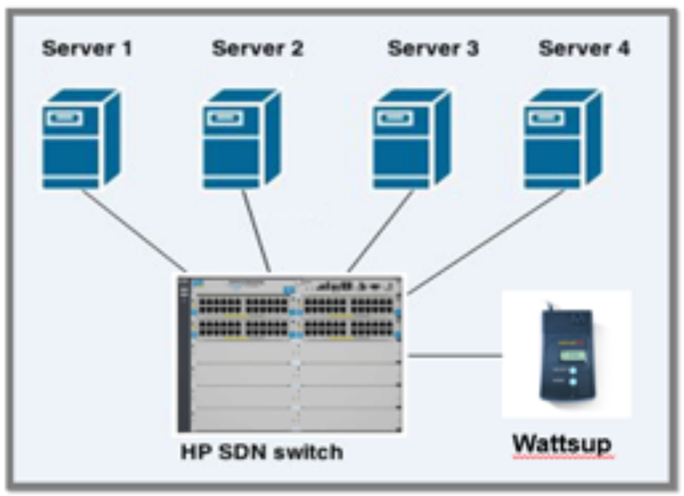


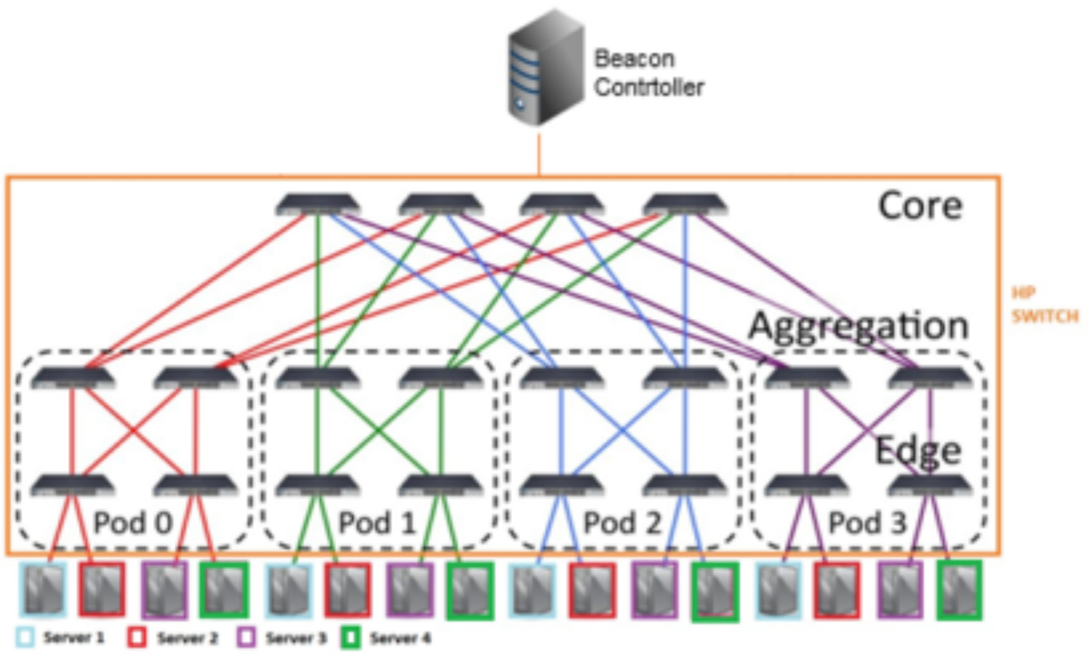

- Inside the axis Energy of labex UCN@Sophia

- Two phd students:
  - Labex grant, Nicolas Huin, 2014-2017
  - Ministry grant, Myriana Rifai, 2014-2017


SDN and Energy efficiency

- **Small experimental platform.**





Problem

- SDN enables dynamic routing but at the cost of **limited forwarding table size.**

Legacy rule:

destination	Output port

1 tuple

SDN rule:

Input port	Vlan ID	Vlan pcp	Src. MAC	Dst. MAC	Src. IP	Dst. IP	…	action

12 tuples

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$\underbrace{\text{destination}}_{\text{1 tuple}}$	Output port

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12 tuples

- SDN rules are flow oriented –> more complex
- SDN forwarding tables stored with **TCAM memory** which is expensive, power-hungry and with a limited size.

  → Constraint on number of forwarding rules (around 1000)

How do we deal with small rule tables?

- Eviction (e.g., LRU) or remove the least interesting rule when a new rule must be added.
  Frequent contact with controller

- Split and distribute the rules in network.[cohen et al. 14]
- Use a minimum number of paths. Xpath [Hu et al, ‘15]: Relabeling and aggregation of paths
  Increased path length and thus delay

- Decrease the rule size by matching only on flow ID that is inserted as a small tag in the packet header.[Kannan et al, ‘13] [Banerjee et al, ’14]
  Need to modify end hosts.

- **Compressing using wildcard rules.**

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  → Need to modify end hosts.

- **Compressing using wildcard rules.**

Compression problem

Original Table:

Flow	Output port
(0, 4)	Port-1
(0, 5)	Port-2
(0, 6)	Port-2
(1, 4)	Port-3
(1, 5)	Port-1
(1, 6)	Port-3
(2, 4)	Port-1
(2, 5)	Port-2
(2, 6)	Port-3

Reduce the size of the table using wildcard rules and default rule.

Compression problem

Original Table:

Priority ⇓

Flow	Output port
(0, 4)	Port-1
(0, 5)	Port-2
(0, 6)	Port-2
(1, 4)	Port-3
(1, 5)	Port-1
(1, 6)	Port-3
(2, 4)	Port-1
(2, 5)	Port-2
(2, 6)	Port-3

$\Rightarrow$

Compressed Table:

Flow	Output port
(1, 5)	Port-1
(2, 6)	Port-3
$(1, *)$	Port-3
$(*, 4)$	Port-1
$(*, *)$	Port-2

Reduce the size of the table using wildcard rules and default rule.

Compression problem

Original Table:

Priority ⇓

Flow	Output port
(0, 4)	Port-1
(0, 5)	Port-2
(0, 6)	Port-2
(1, 4)	Port-3
(1, 5)	Port-1
(1, 6)	Port-3
(2, 4)	Port-1
(2, 5)	Port-2
(2, 6)	Port-3

⇒

Compressed Table:

Flow	Output port
(1, 5)	Port-1
(2, 6)	Port-3
(1, $*$)	Port-3
($*$, 4)	Port-1
($*$, $*$)	Port-2

Beware the order. The **first matching rule** is applied

Example: If `(*,4)`→`1` is before `(1,*)`→`3`, then `(1,4)` will be routed through `1`, and not `3`.

Contributions

1. **Contribution 1:** Study of the **theoretical problem** of compressing a two dimensional routing table using wildcard rules with an order on the rules.
   [Submitted to Algorithmica. Short version INOC 2015]



2. **Contribution 2:** Study of the joint problem of routing and compressing for an SDN data center network.
   [Submitted to Computer Networks. Short version Globecom 2015]







3. **Contribution 3:** Study of the joint problem of routing, compressing and minimizing energy consumption for an ISP network.
   [Submitted to Computer Communications. Short version Globecom 2014]



Contribution 1: Compressing two dimensional routing tables with orders

- **Link with Feedback Arc Set**.

- Study of **different problems: Routing List**, **List Reduction** with (*,*) or not, fixed number of ports or not.

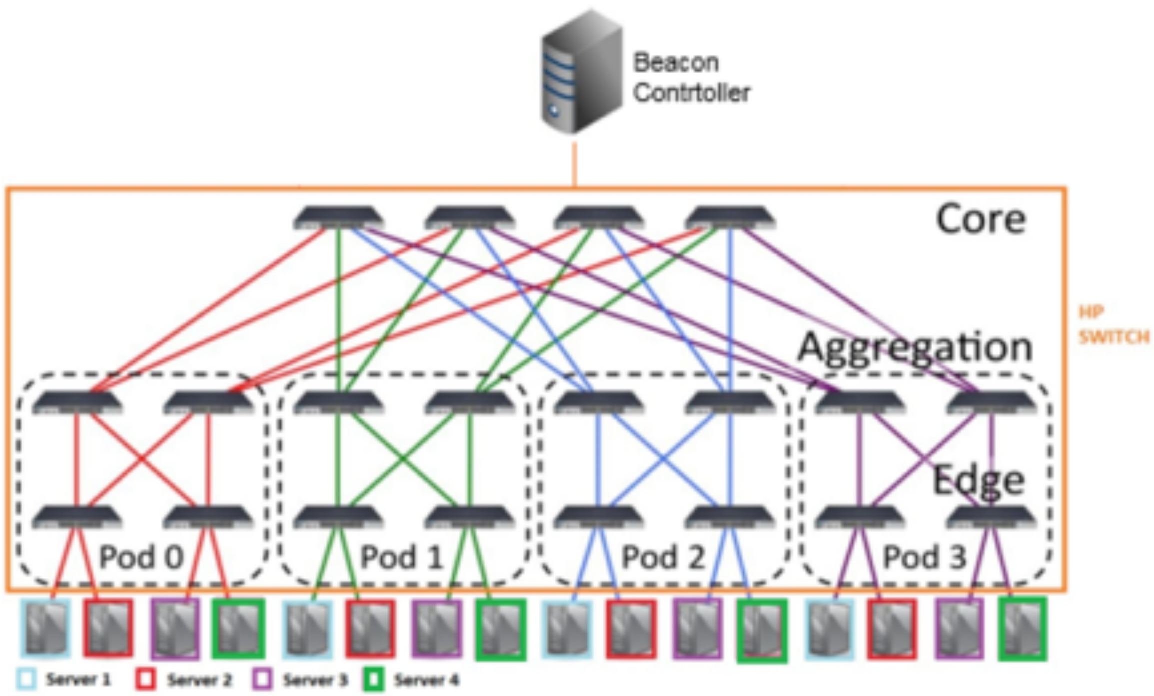
- **Hardness results:**
  - Polynomial pour 1 port
  - NP-complete 2 ports or more

- **Approximation algorithms**
  - a **simple 3-approximation for List Reduction: Direction-Based Heuristic.**
  - a 4-approximation for Routing List.

- **Study of the Fixed Parameter Tractability (FPT)**. **Polynomial kernels** for most of the problems considered.

Contibution 2: routing in an SDN Data center network

- **Problem: jointly solve the routing and compressing problems.**



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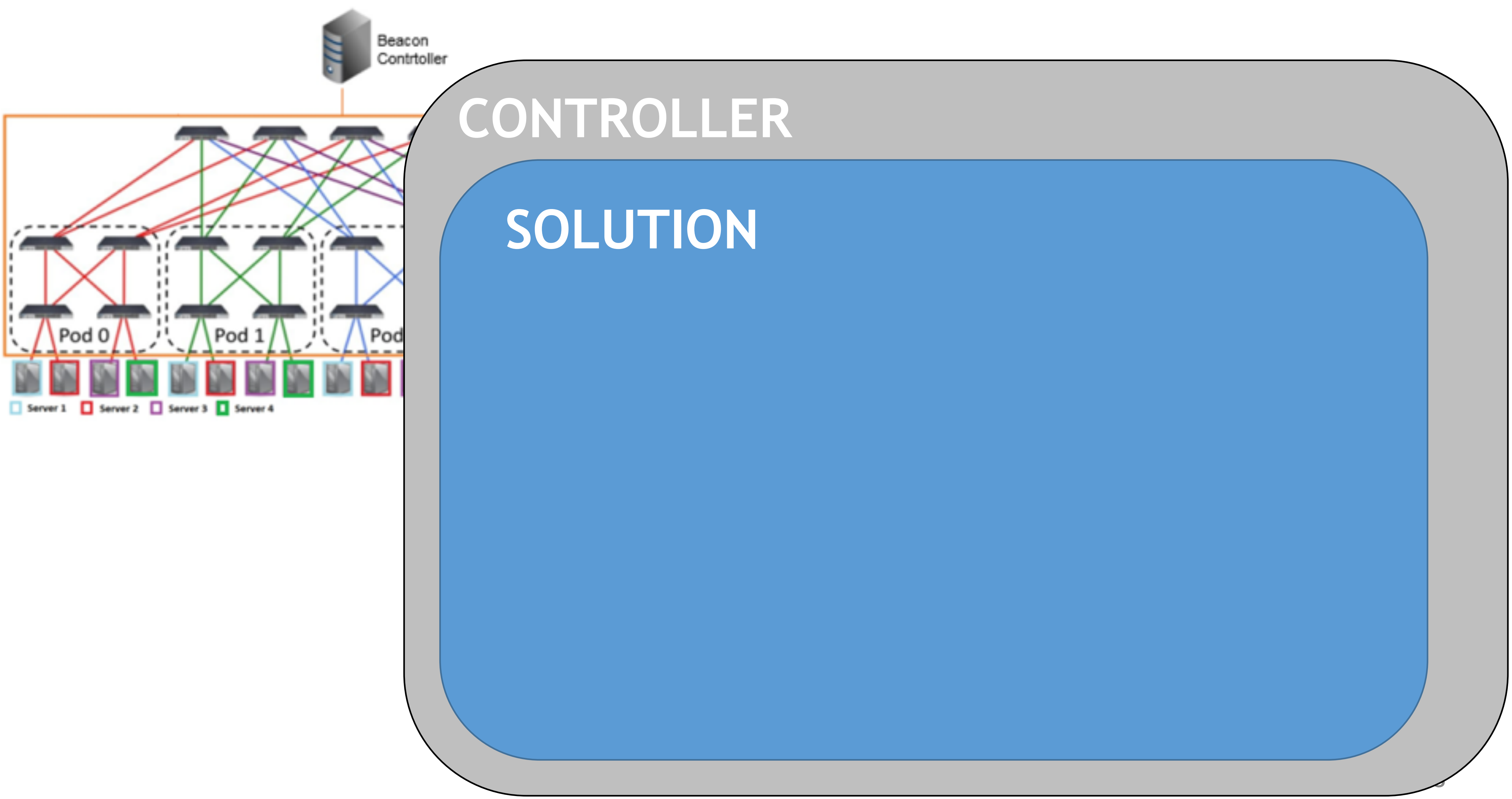

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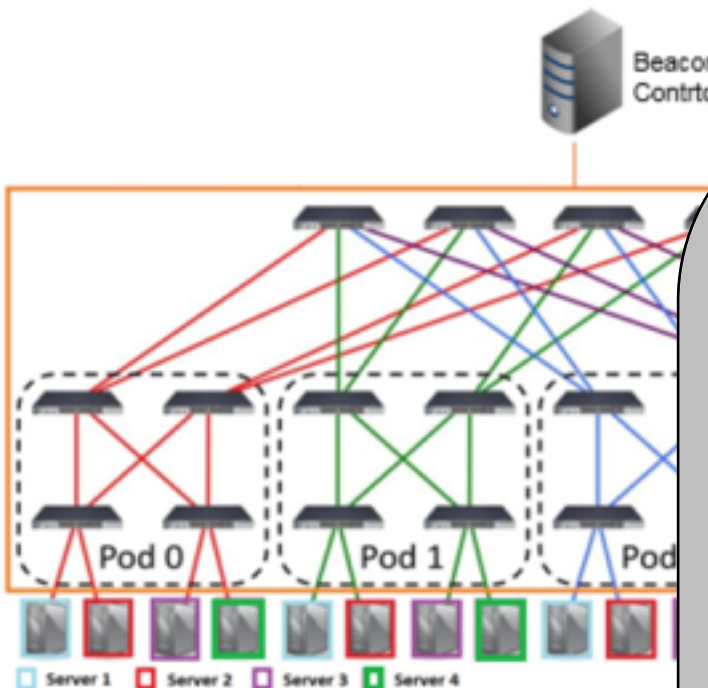

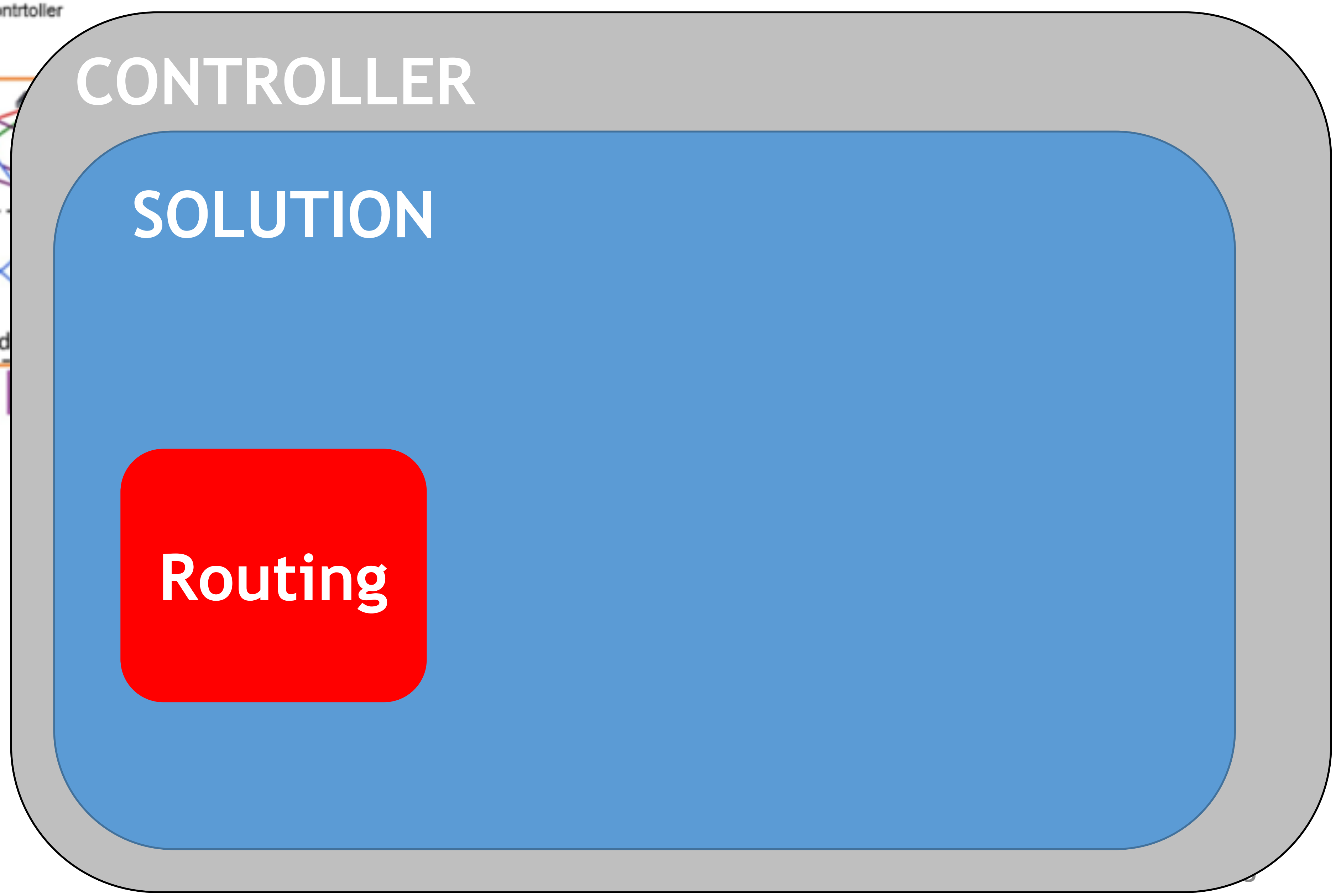

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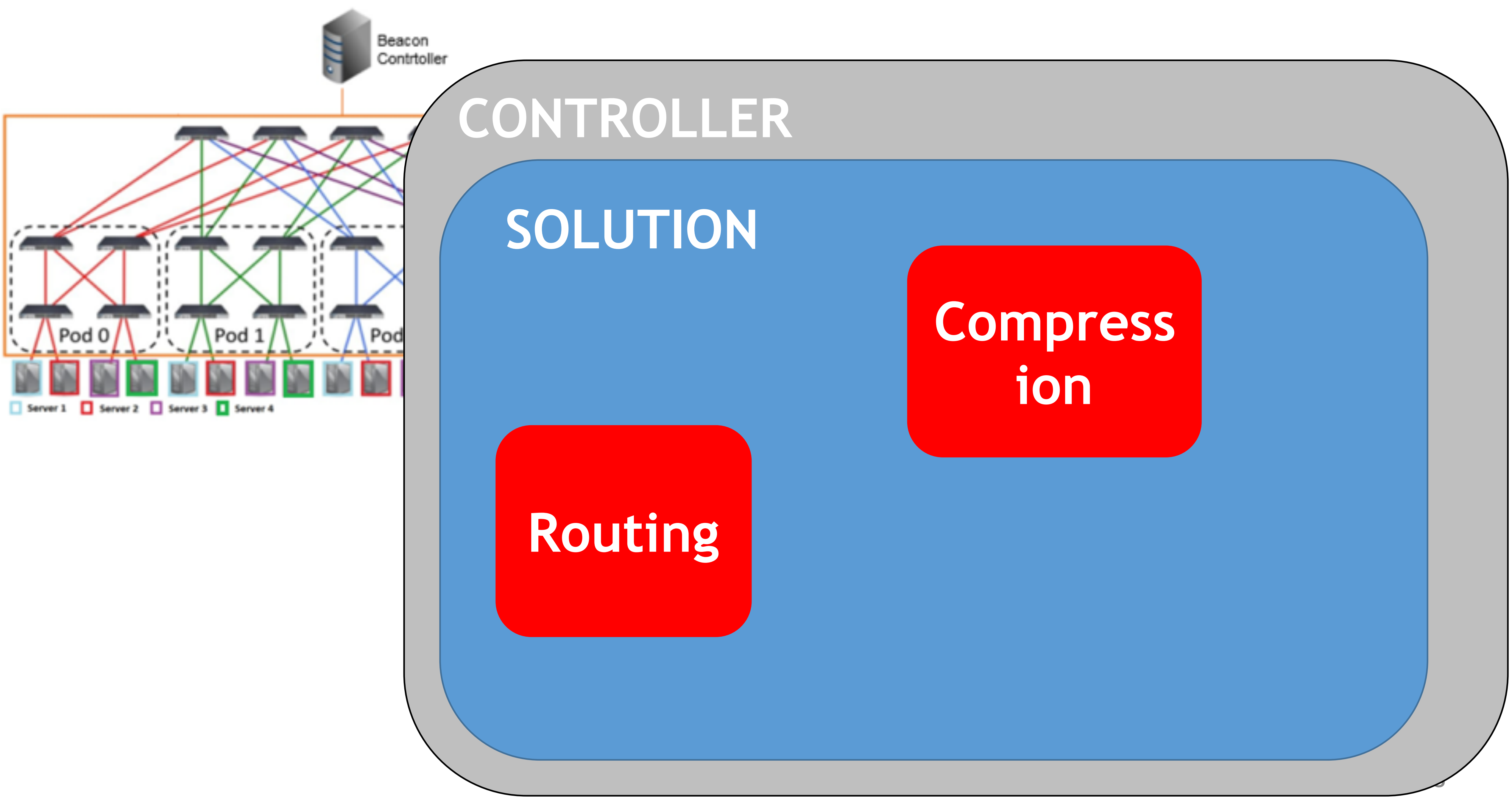

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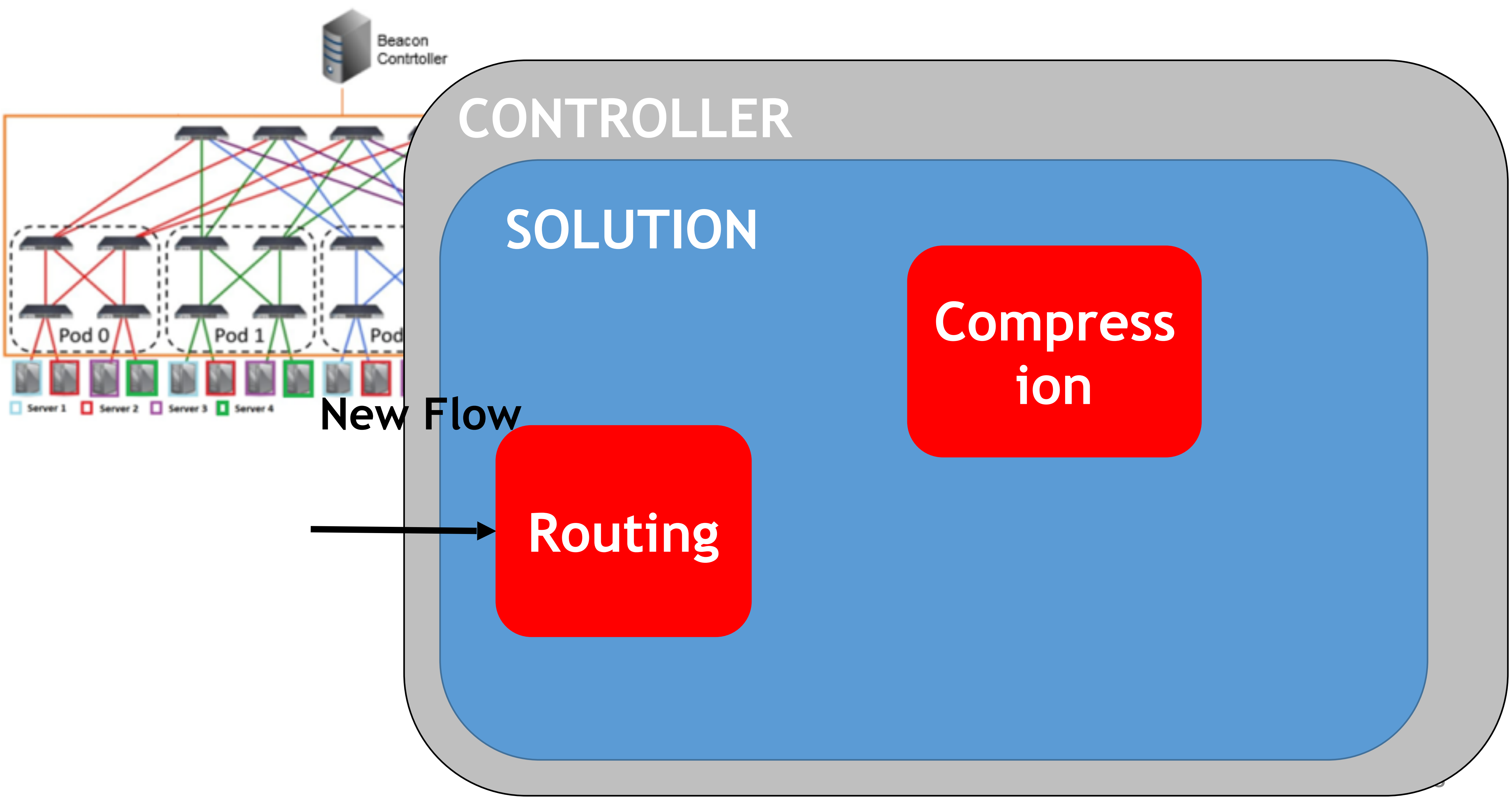

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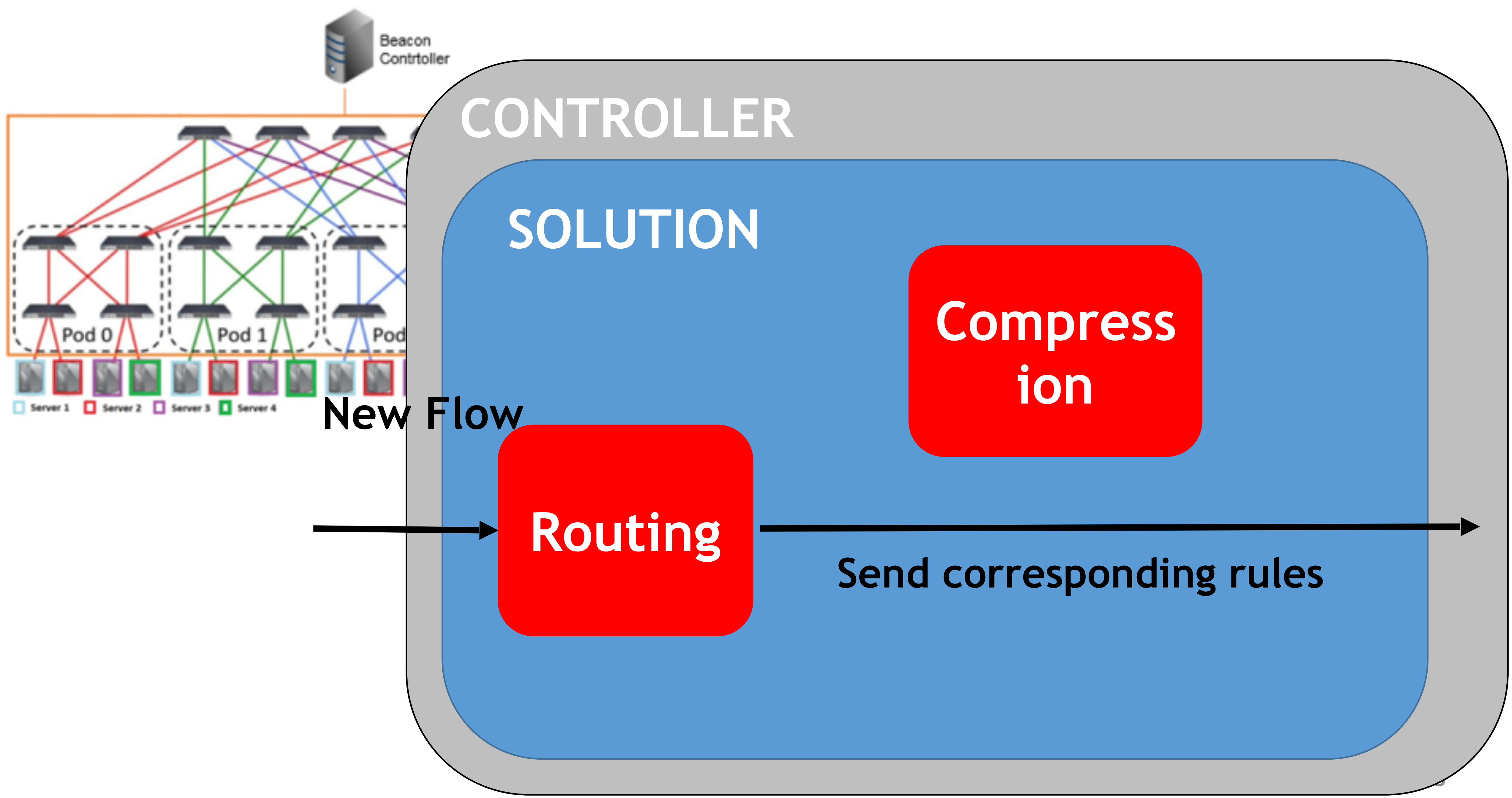

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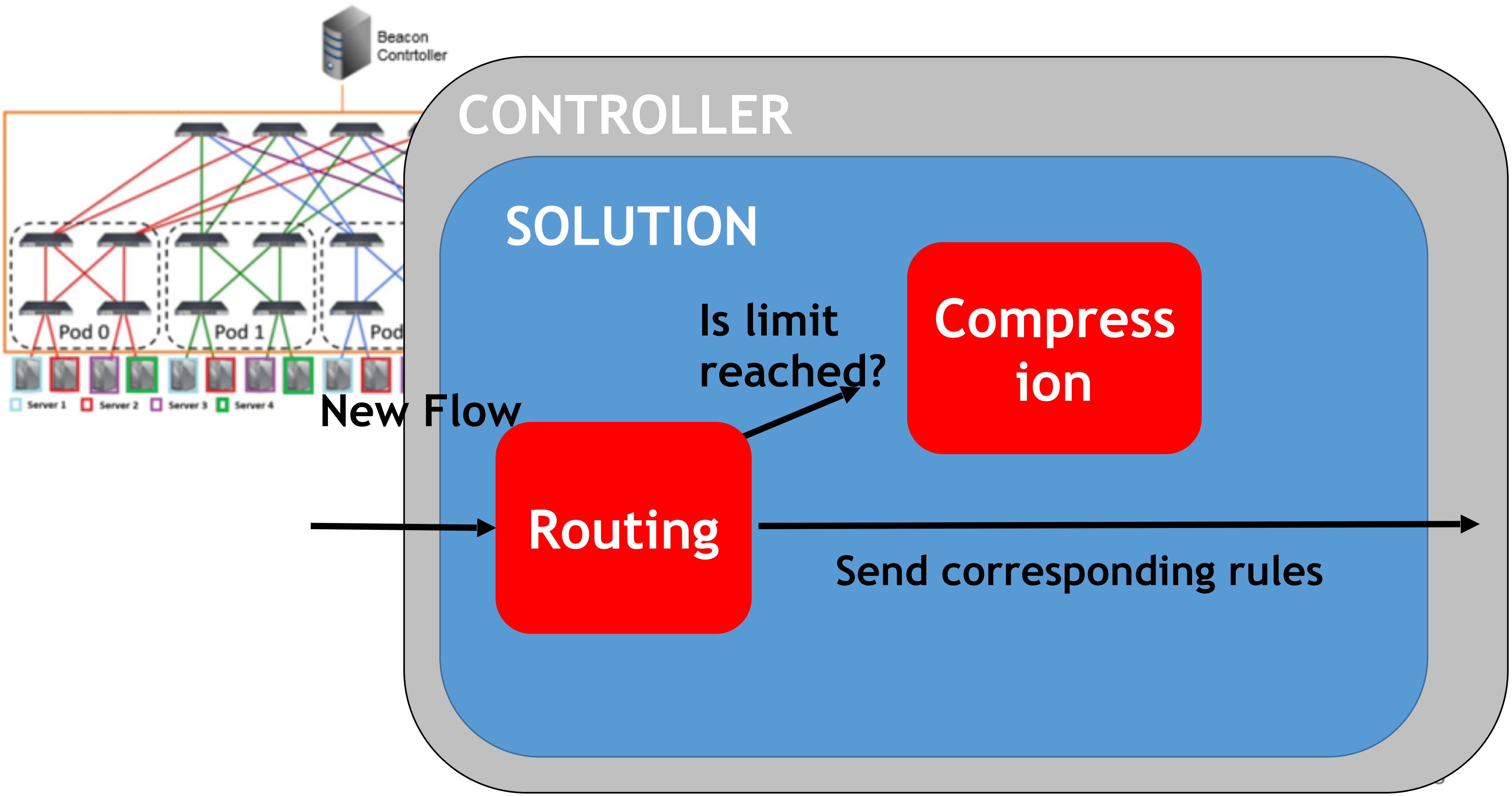

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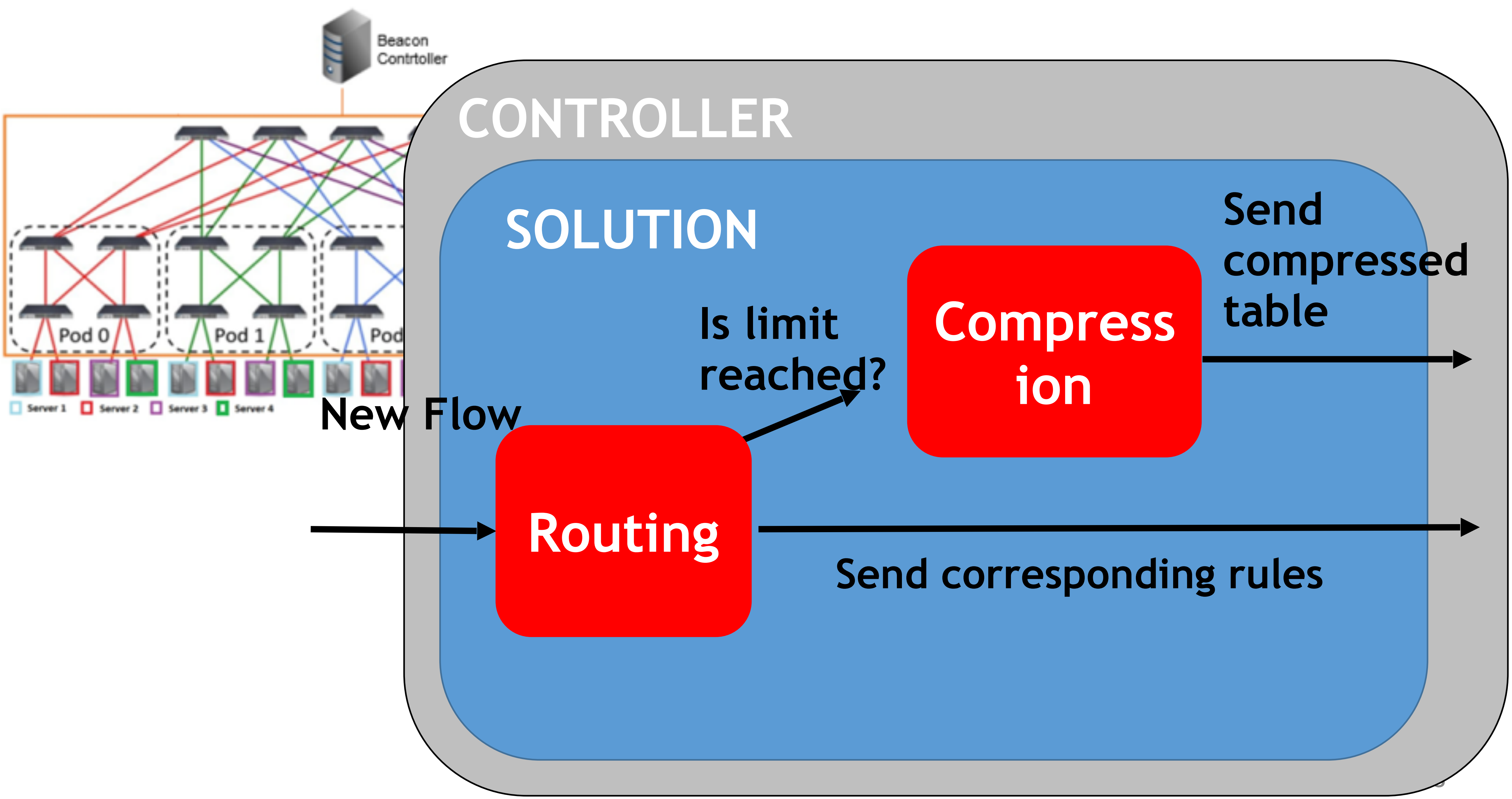

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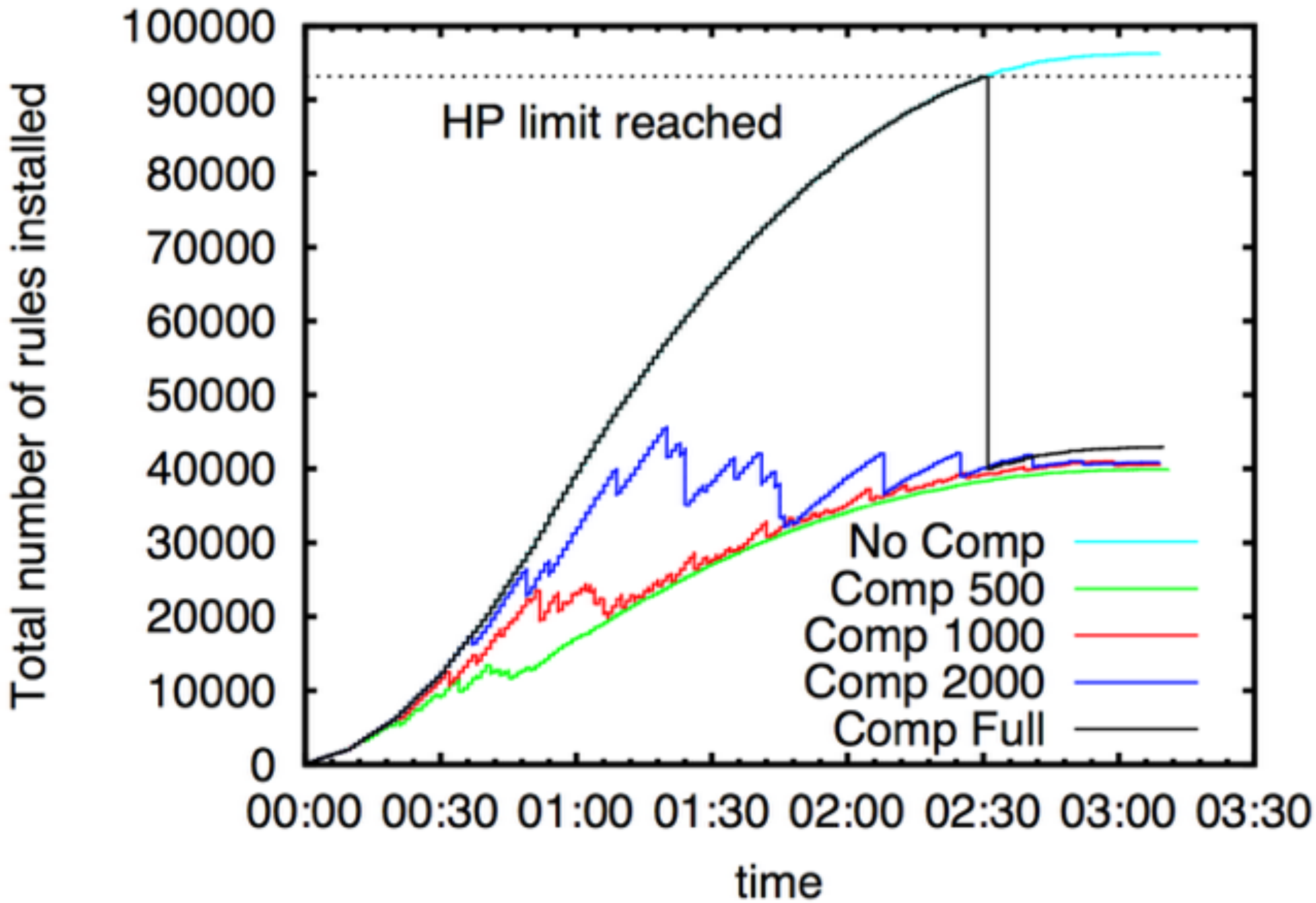
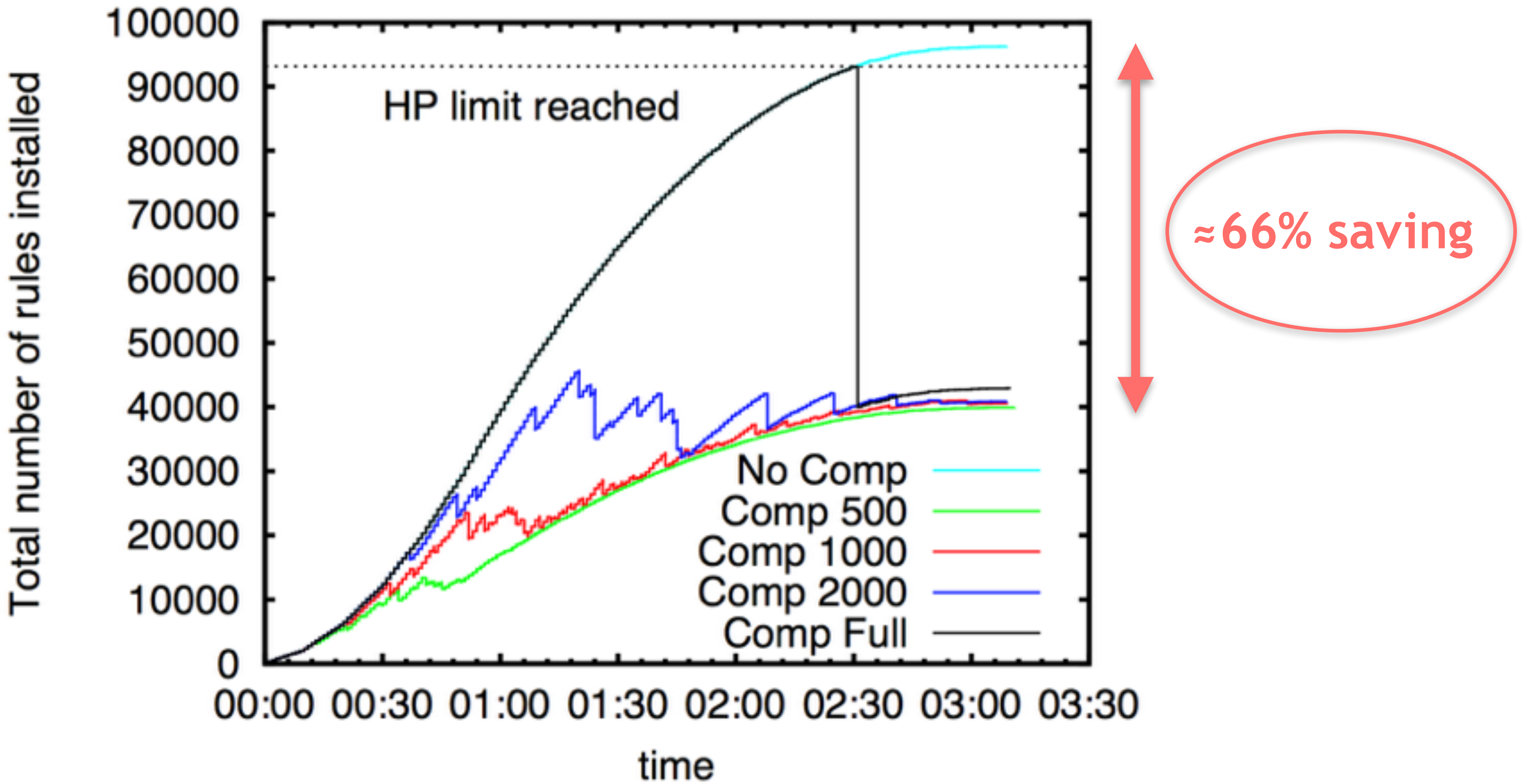


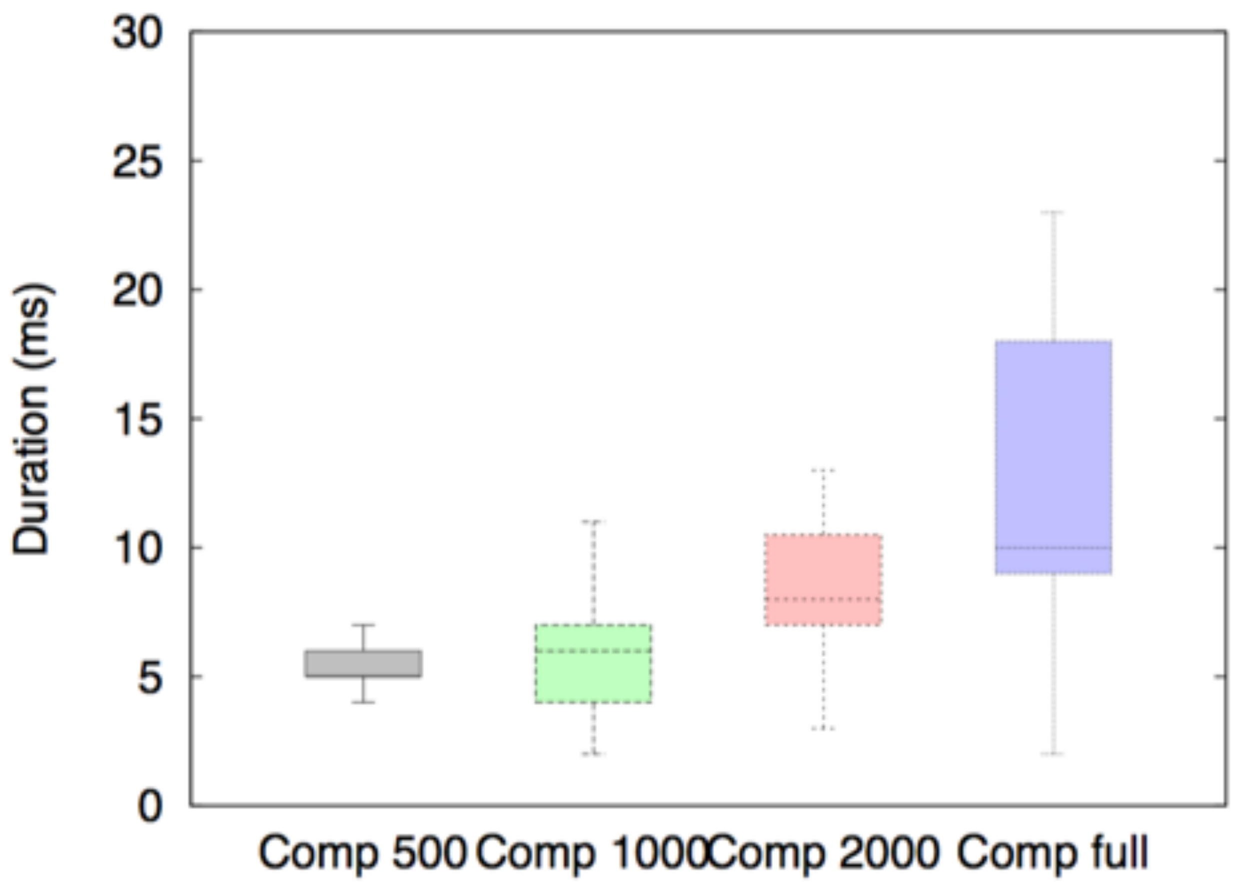
Total number of rules installed for the fat-tree

Contibution 2: routing in an SDN Data center network



Total number of rules installed for the fat-tree

Compression duration and loss rate



Duration= Compression + table modification

Threshold	No Comp	Comp 500	Comp 1000	Comp 2000	Comp full
# of compressions	NA	16 594	95	28	20
% pkt loss	6.25×10^{-6}	0.003	5.65×10^{-4}	2.83×10^{-5}	3.7×10^{-4}

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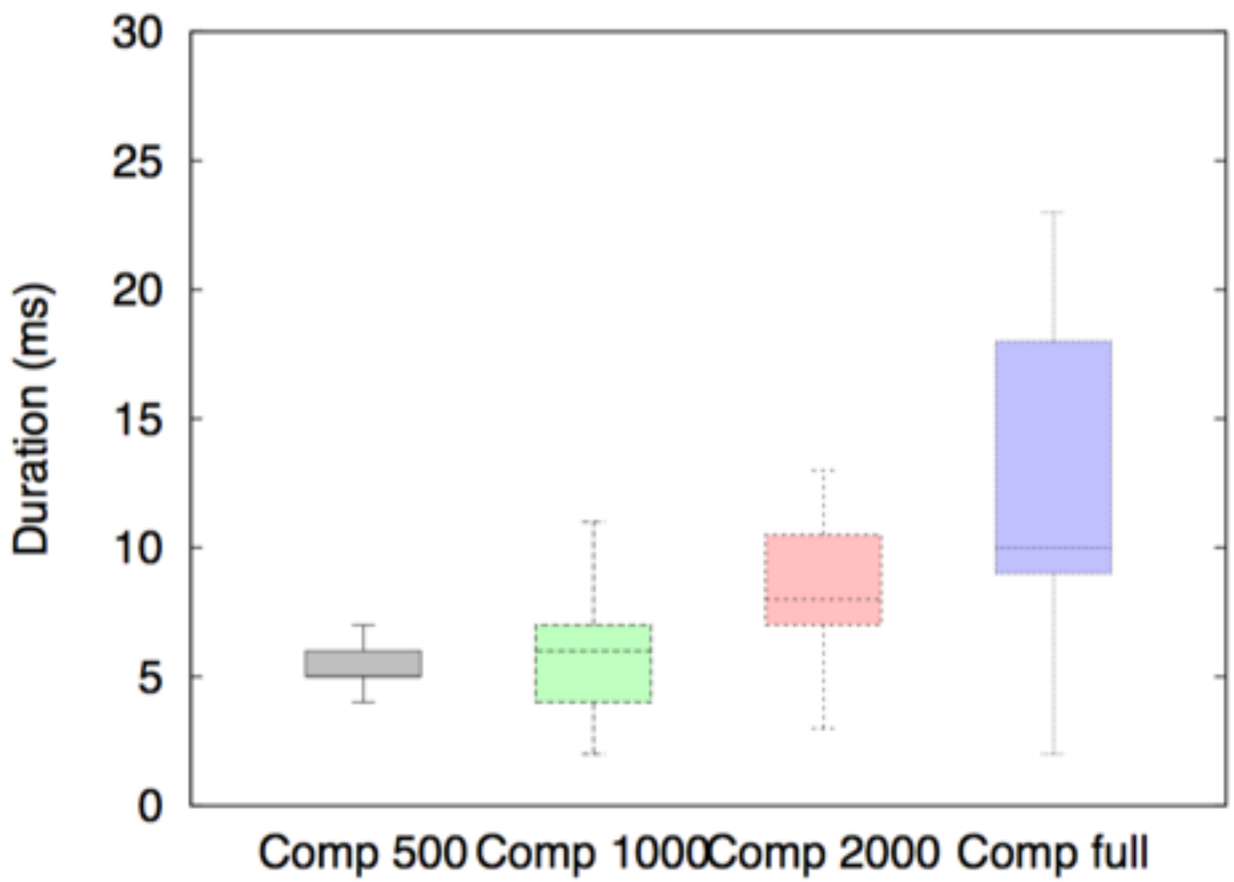

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Loss rate ≈0%

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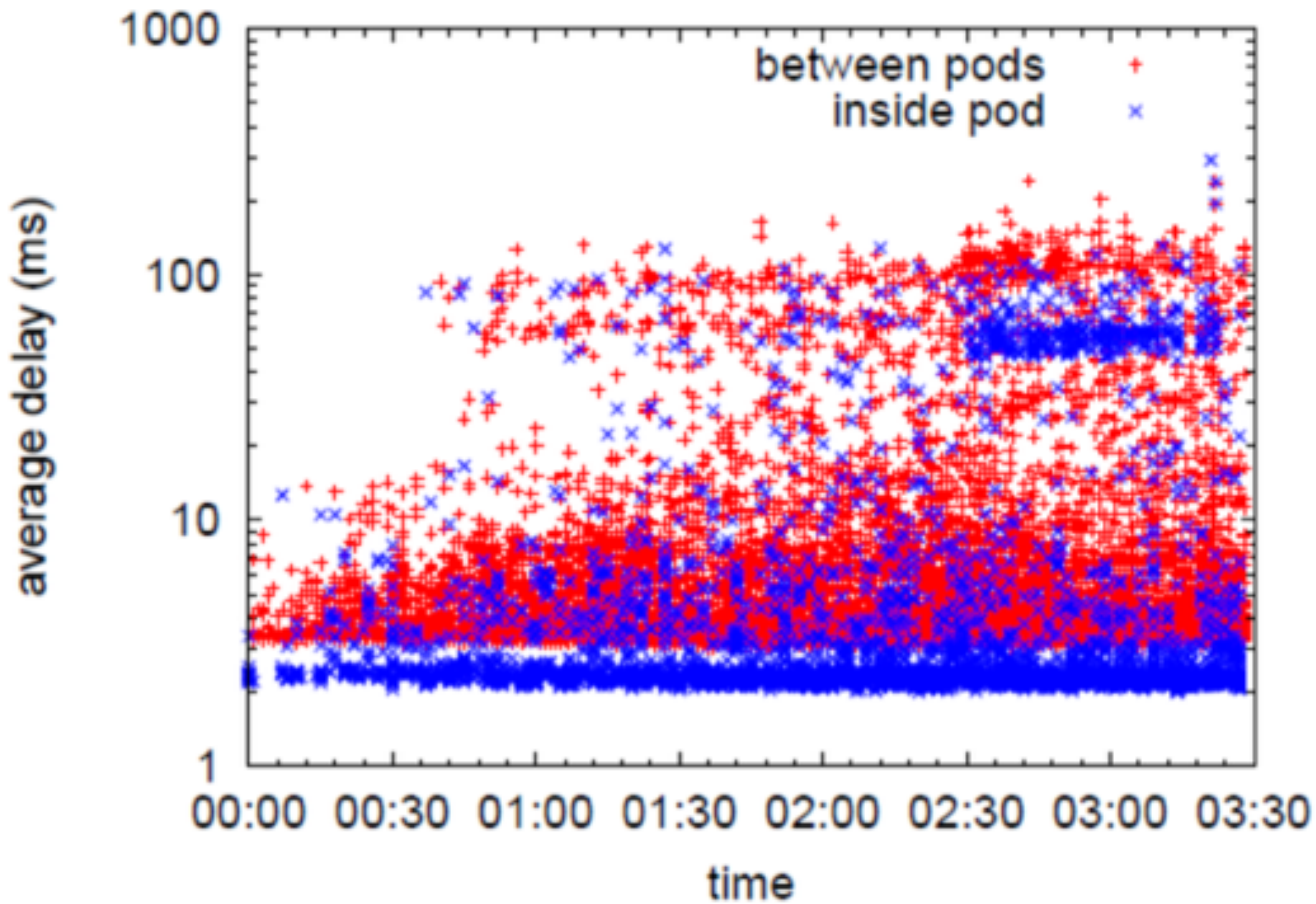
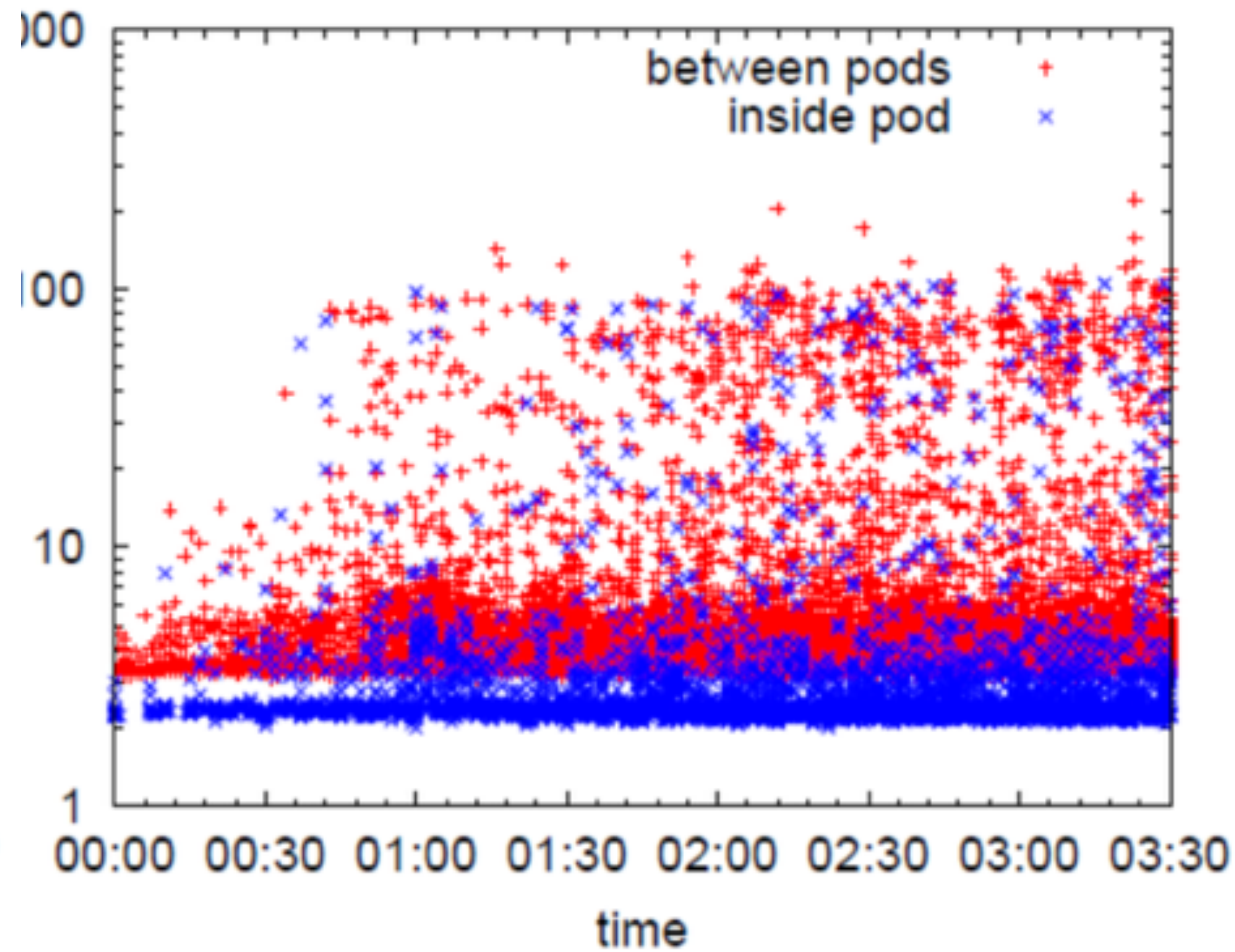


Without Compression

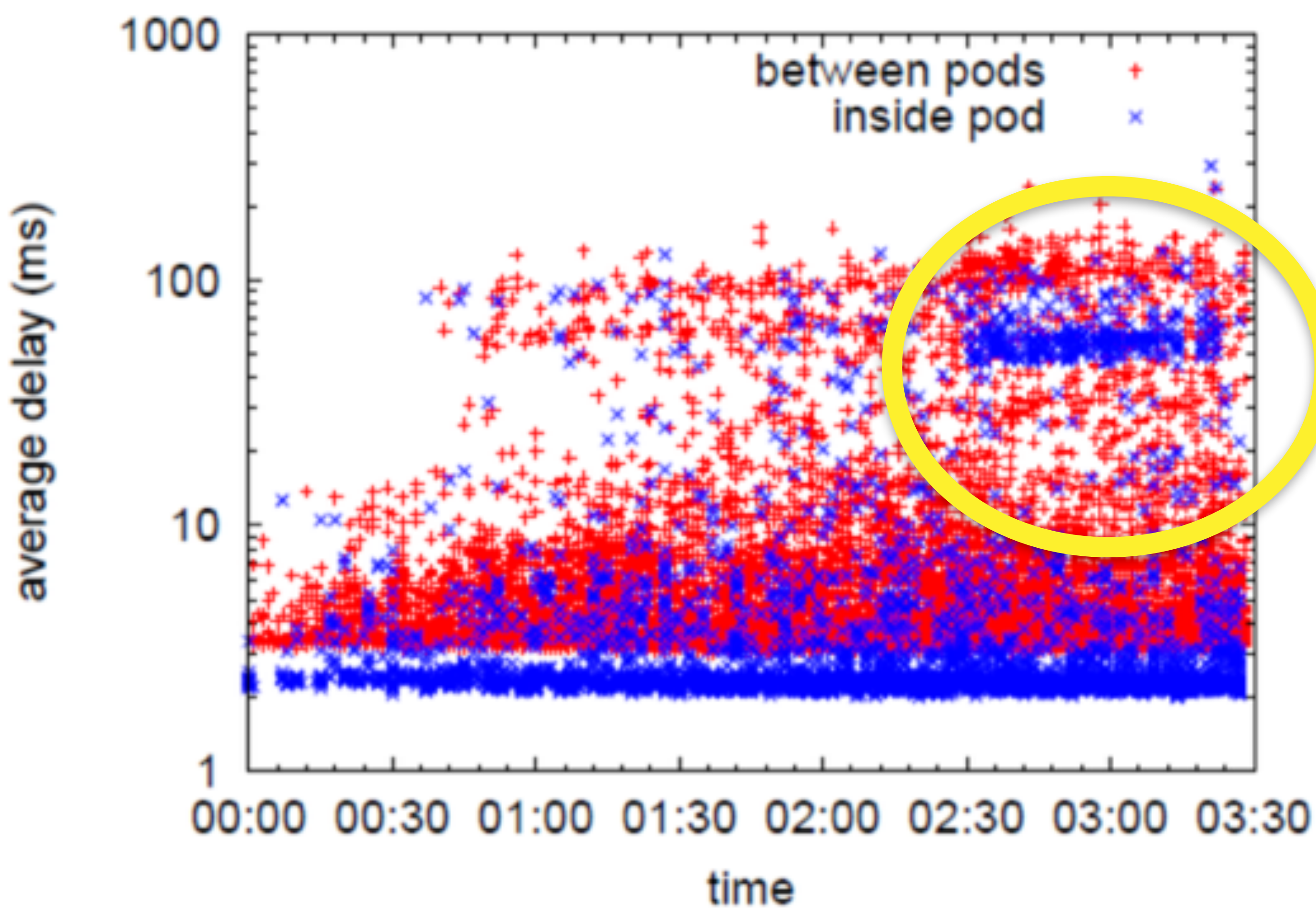


With Compression

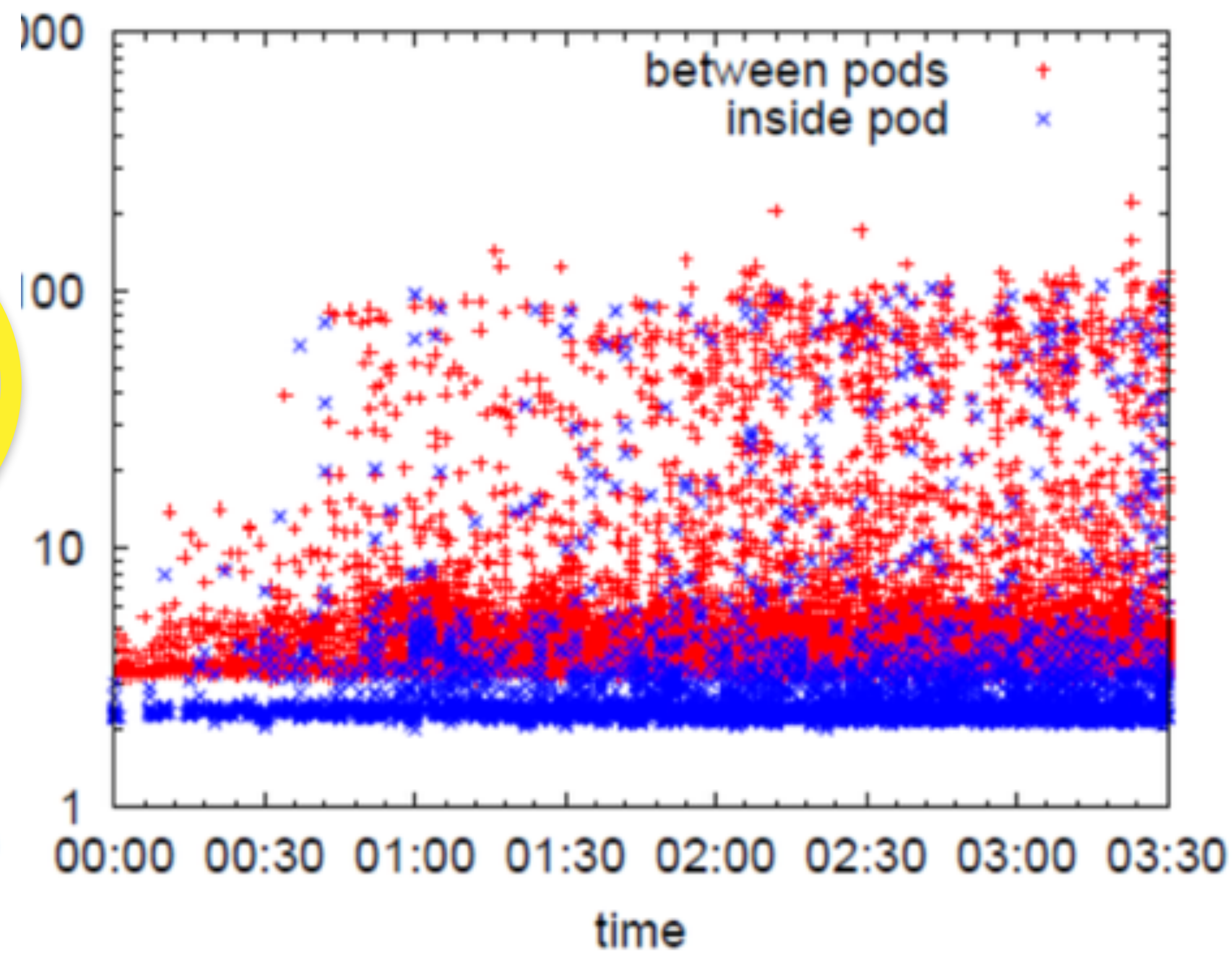
When the switch reaches its limit, no more rules installed -> need to contact the controller for every packet received -> **high delay**

No problem. Delay is not increased.

Contibution 2: routing in an SDN Data center network



Without Compression

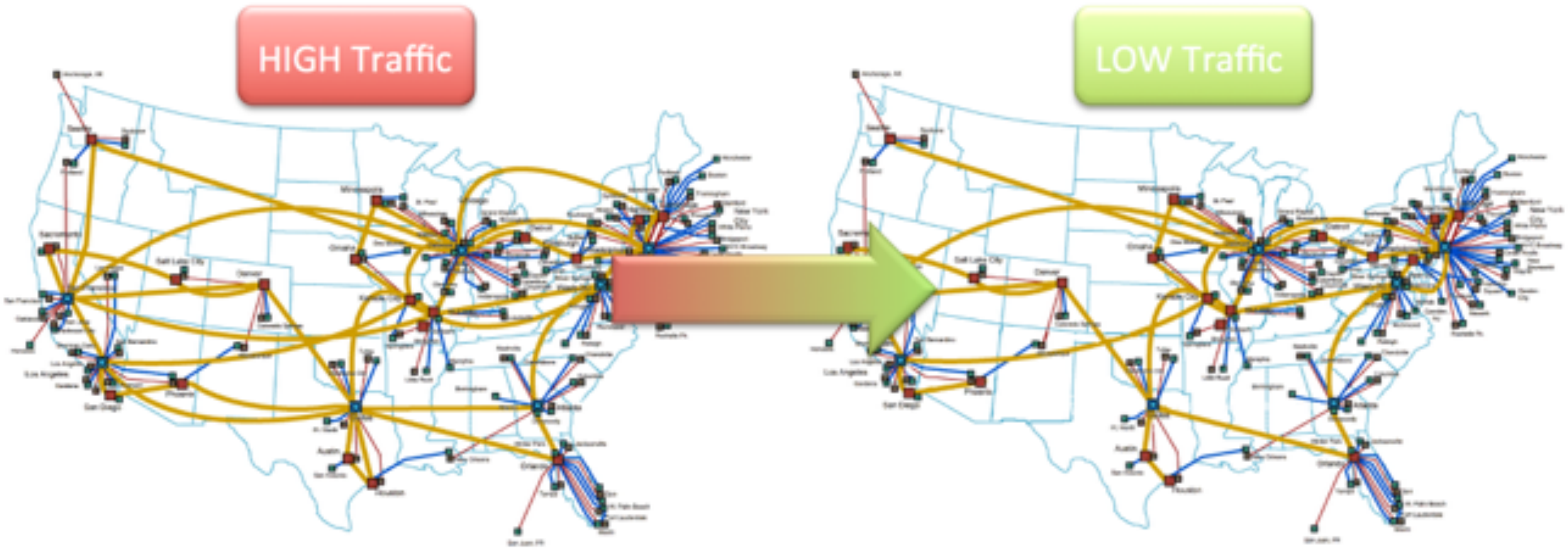


With Compression

When the switch reaches its limit, no more rules installed –> need to contact the controller for every packet received -> **high delay**

No problem. Delay is not increased.

Contribution 3: Energy efficient routing in an SDN ISP network.

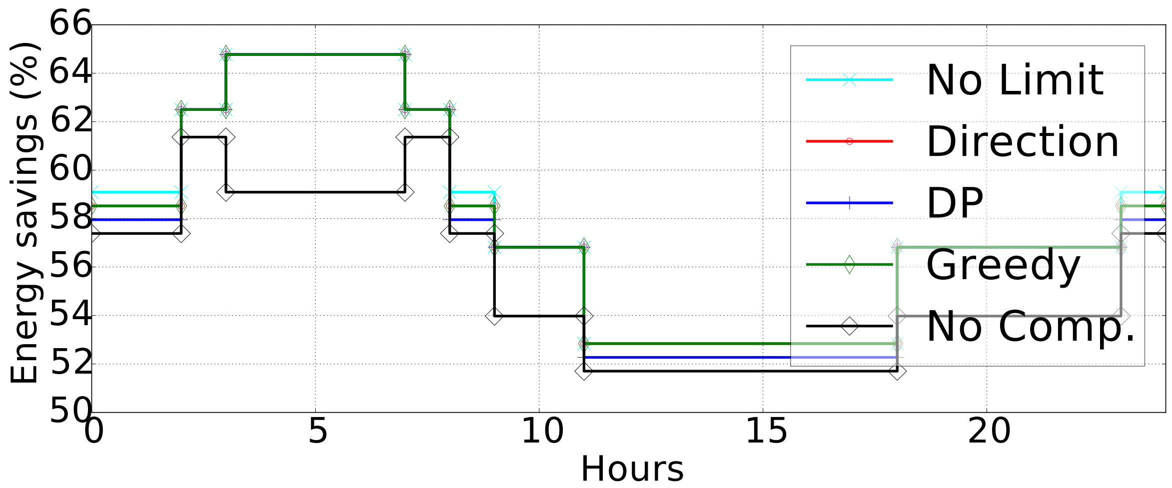


Contribution 3: Energy efficient routing in an SDN ISP network.

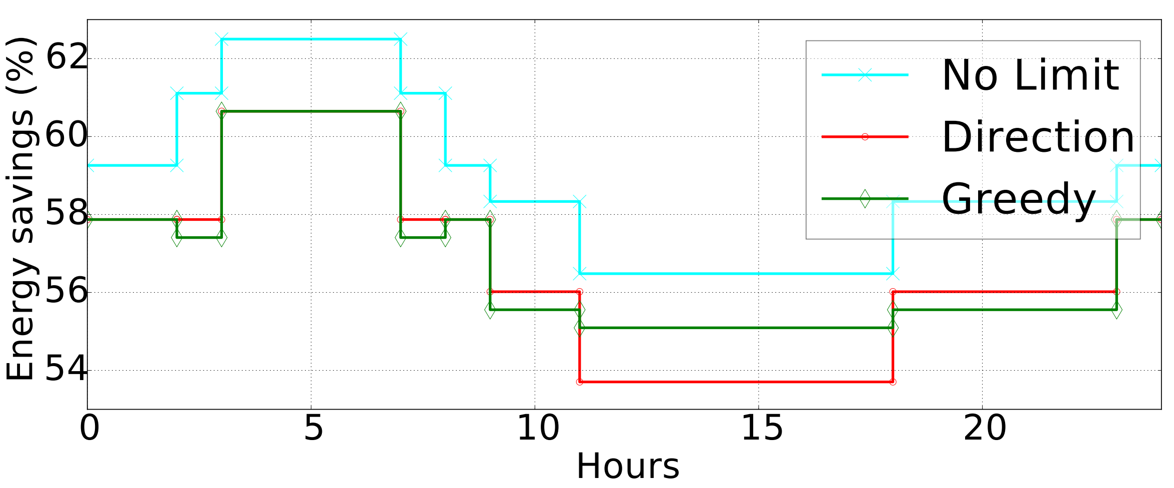
- **Contributions:**
  - Model the problem with **Integer Linear Programs**
  - Propose **several heuristic solutions.**
  - Test the solutions by simulations on **topologies and traffic matrices from SNDLib.**
    - Optimal solutions found for small networks Atlanta (15 nodes, 44 links)
    - Efficient solutions found for larger networks

Contribution 3: Energy efficient routing in an SDN ISP network.

Energy savings of different solutions for two networks



Zib54 (52 nodes, 216 links)



Ta2 (81 nodes, 162 links)

- **Take aways:**
  - **No feasible solutions** without compression for some networks (or with only the default port)
  - **With compression, results almost as good than without the limit due to TCAM memory** for SDN: between 52% and 65% of savings.

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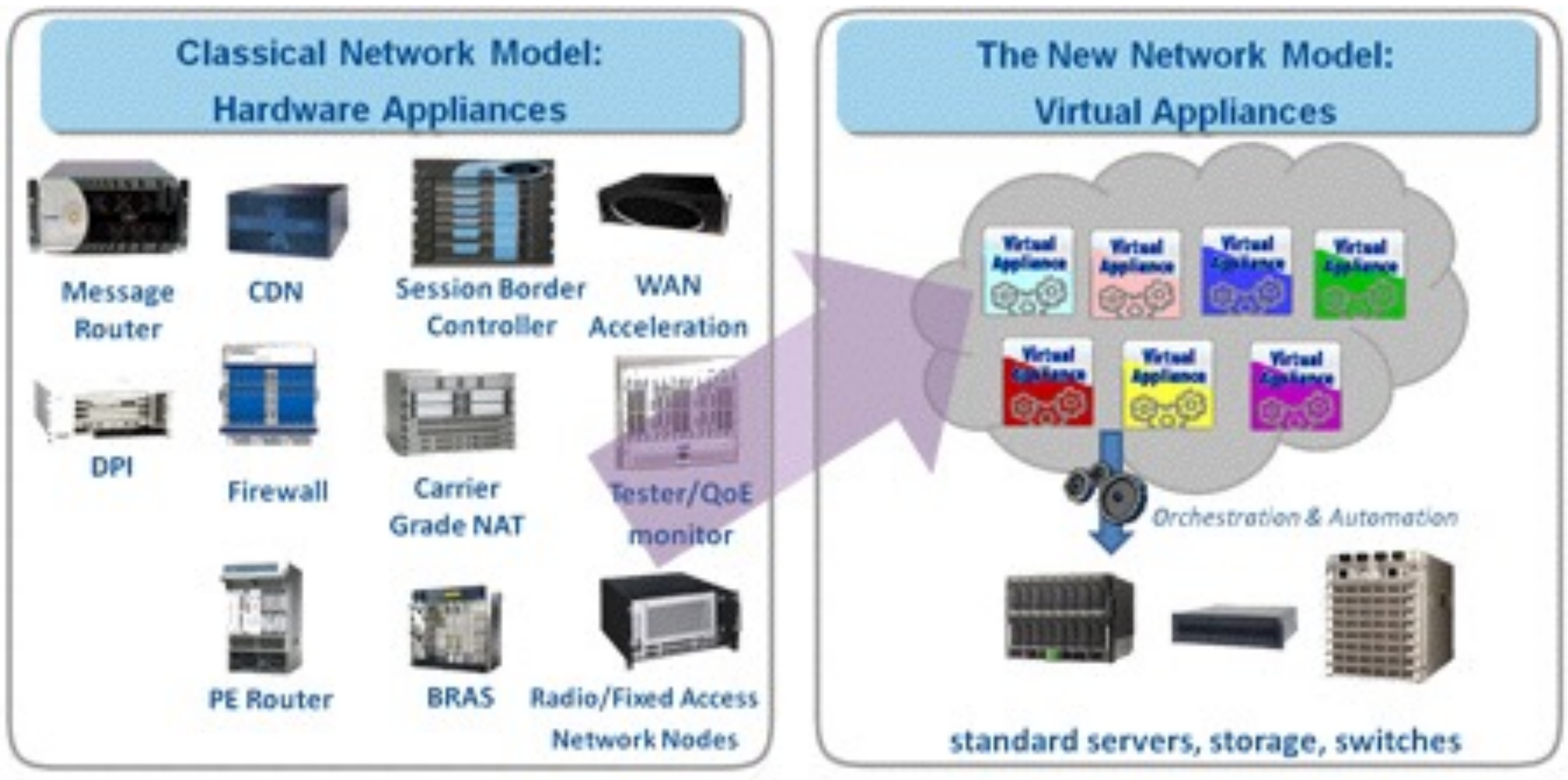
    - **Using virtualization technics: NFV.**
    - Joint optimizations:
        - Networks and Data centers
        - How will IoT be managed?

Network Function Virtualization

- What is **Network Function Virtualization** or **NFV** in short?
- Inside today's networks, ***different hardware*** *carry out* ***different Network Functions (NF)***. Examples:

Hardware	Network Function
Routers	Route flows
Forwarding devices	Forward packets
Load balancers	balance the flows between several routes
Firewall	check flow headers and prevent access
Deep Packet Inspection	check more carefully packets (for example compare with the hash of known virus)
Caches	store redundant traffic (e.g. a popular video)
WAN optimizers	optimize TCP parameters, compress traffic…

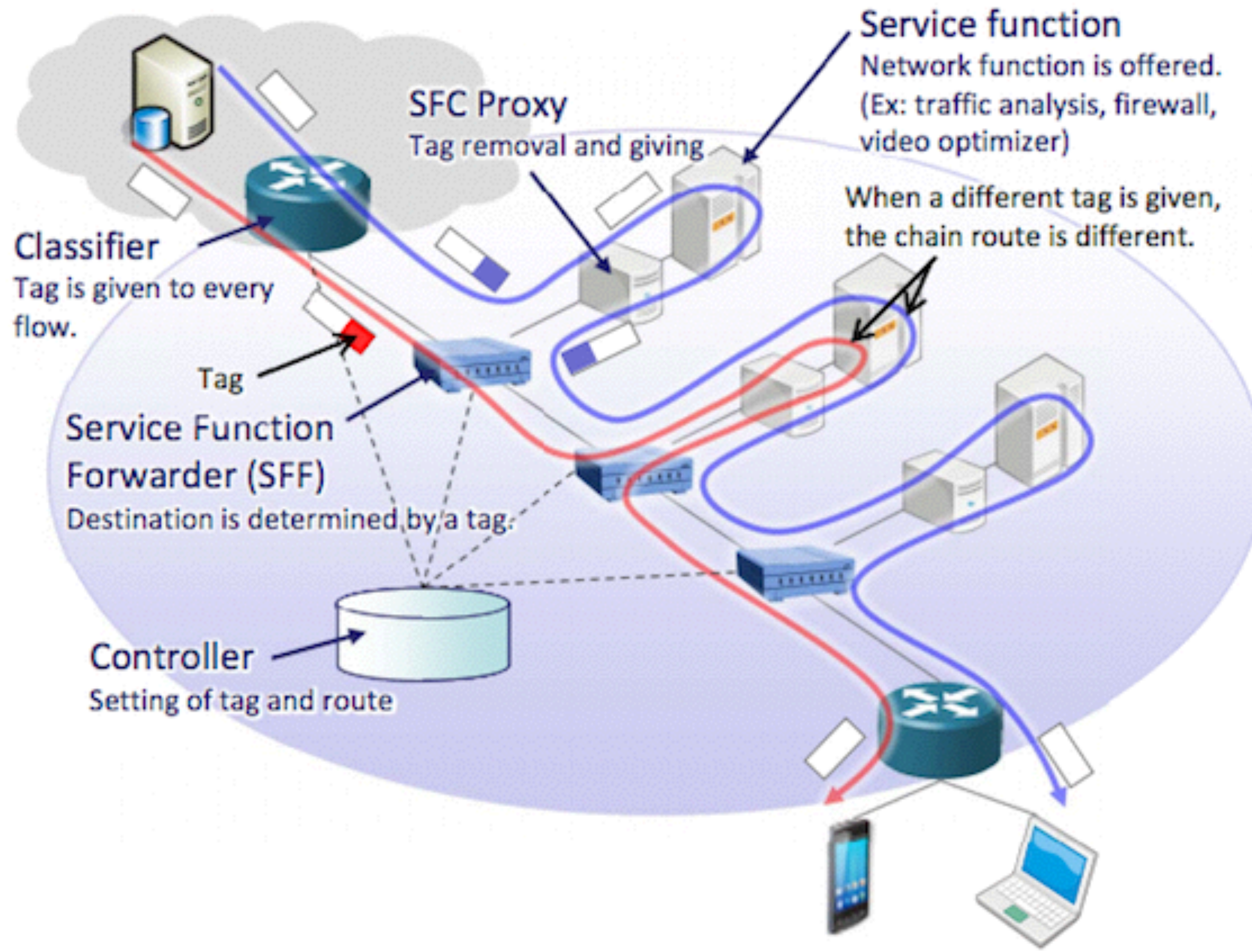
Network Function Virtualization



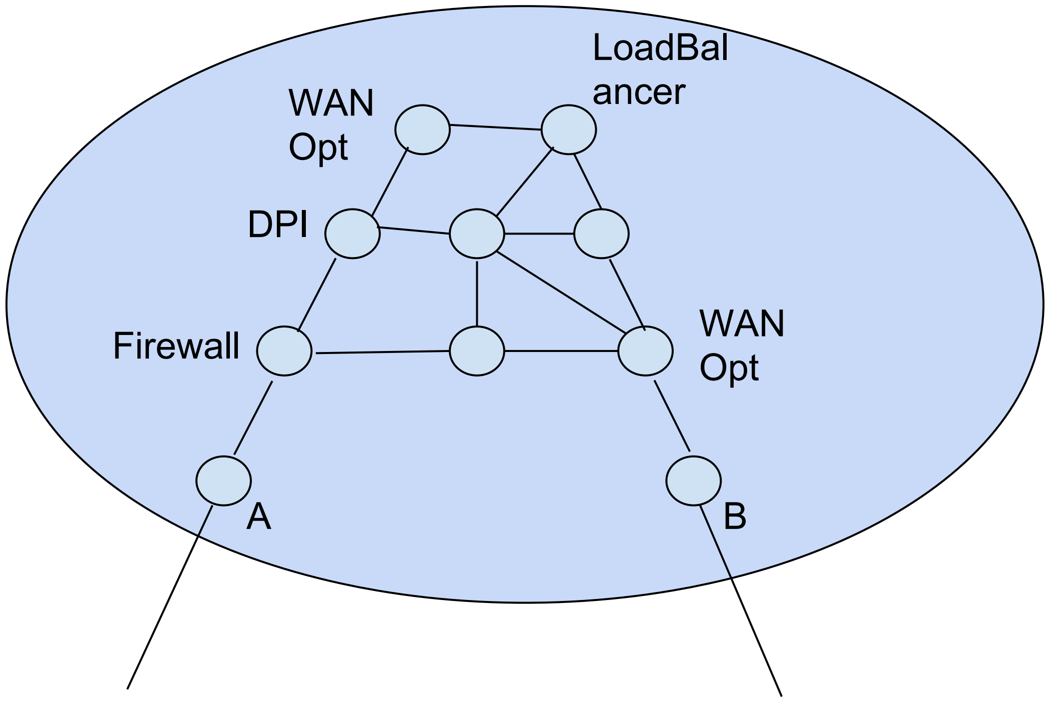
- Following the trend of **network softwarization** (SDN), **network functions may be virtualized:**
  -> ***Any hardware may implement one or several Virtualized Network Function VNF***
- (of course if it has the CPU power or storage power)
- Equivalent of Virtual Machines (VM) in datacenters.

Network Function Virtualization

- **Complex things** can be done:
  - Per flow **choice of VNF and of routes** by an SDN controller
  - **Dynamic** choice

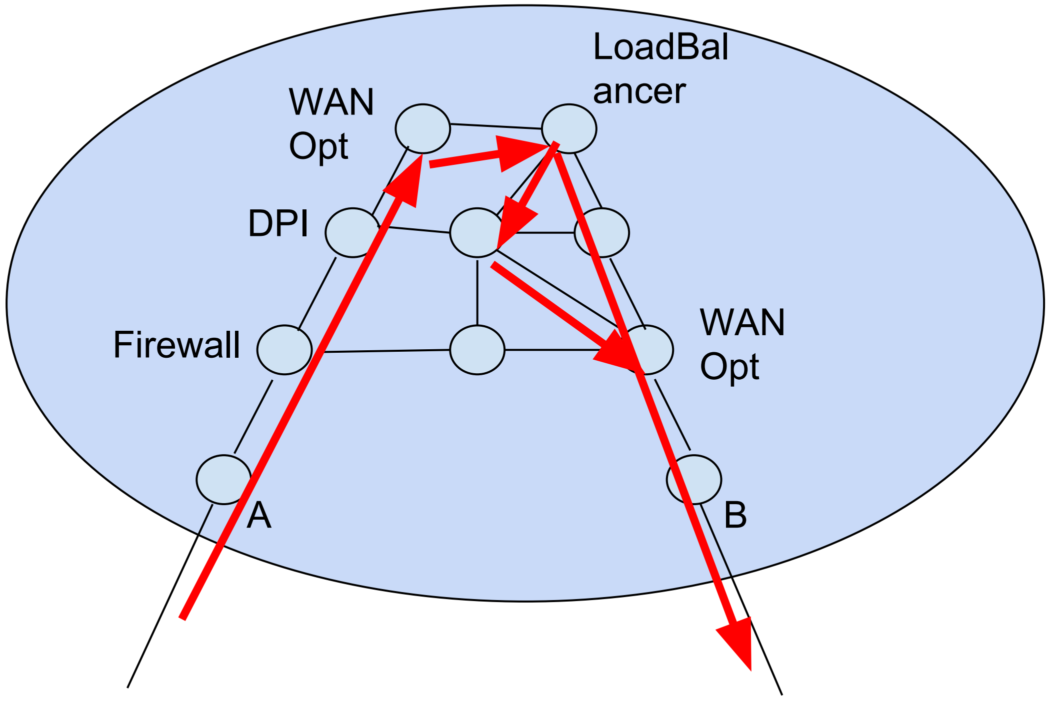


NFV and Energy Efficiency



- A typical network scenario.

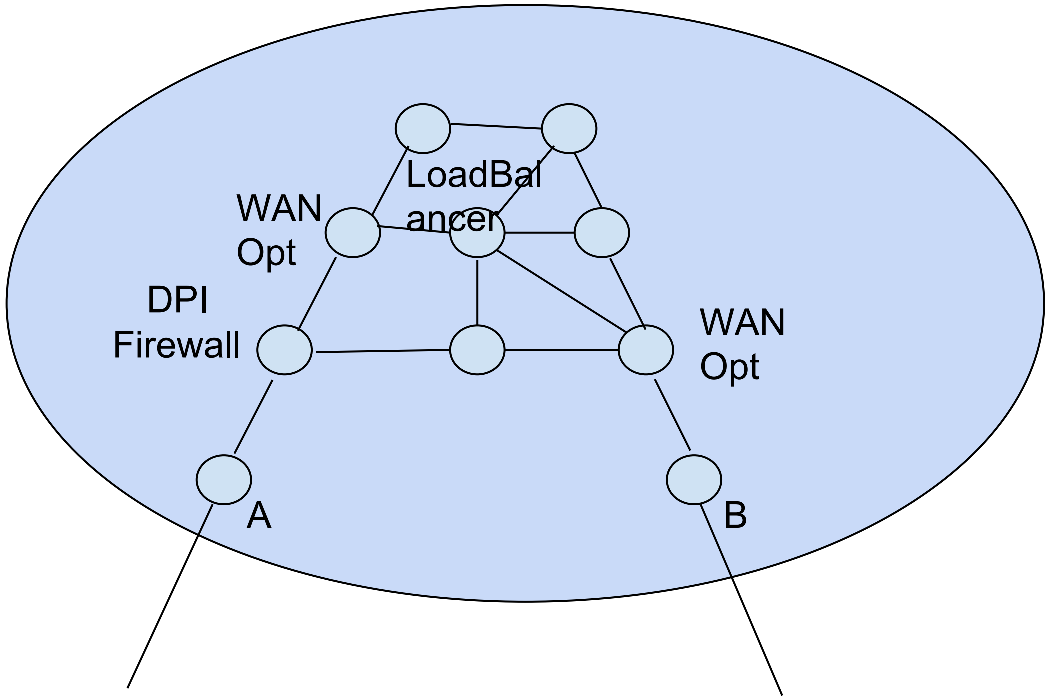
NFV and Energy Efficiency



NFV and Energy Efficiency

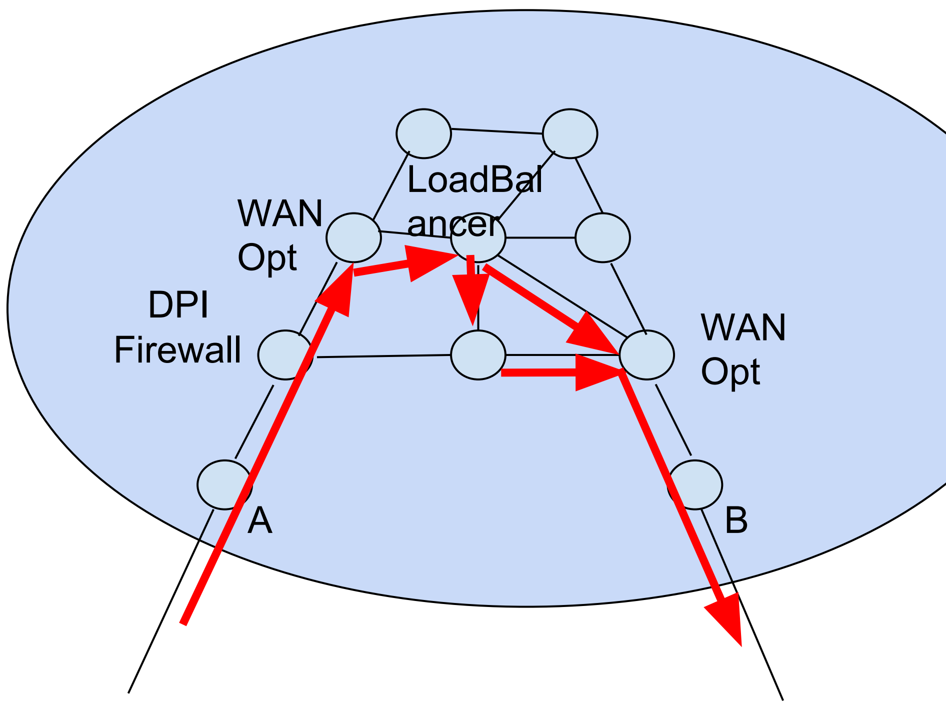
- We now use Virtual Network Functions

- Several VNF can be placed in one node (if CPU allows)



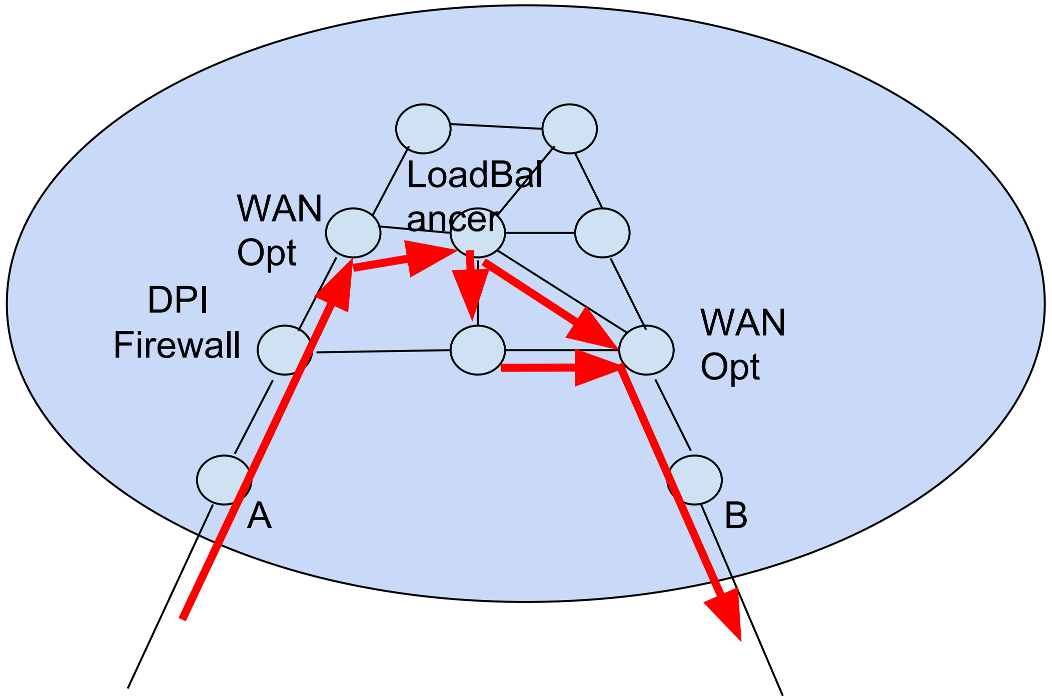
NFV and Energy Efficiency

- New Routes.



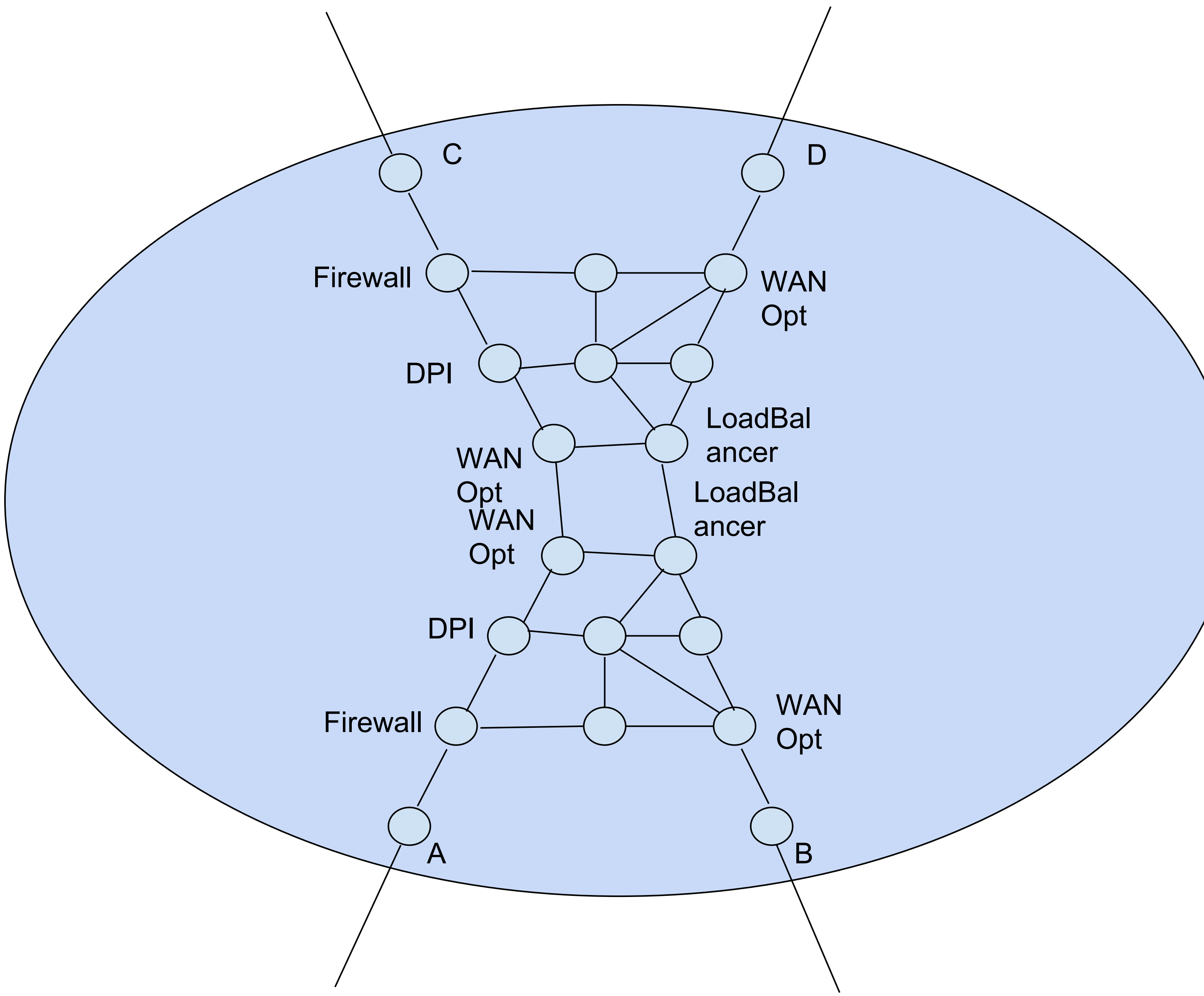
NFV and Energy Efficiency

- Savings:
  - shorter delay
  - save energy
    - less specific hardware
    - devices can be turned off



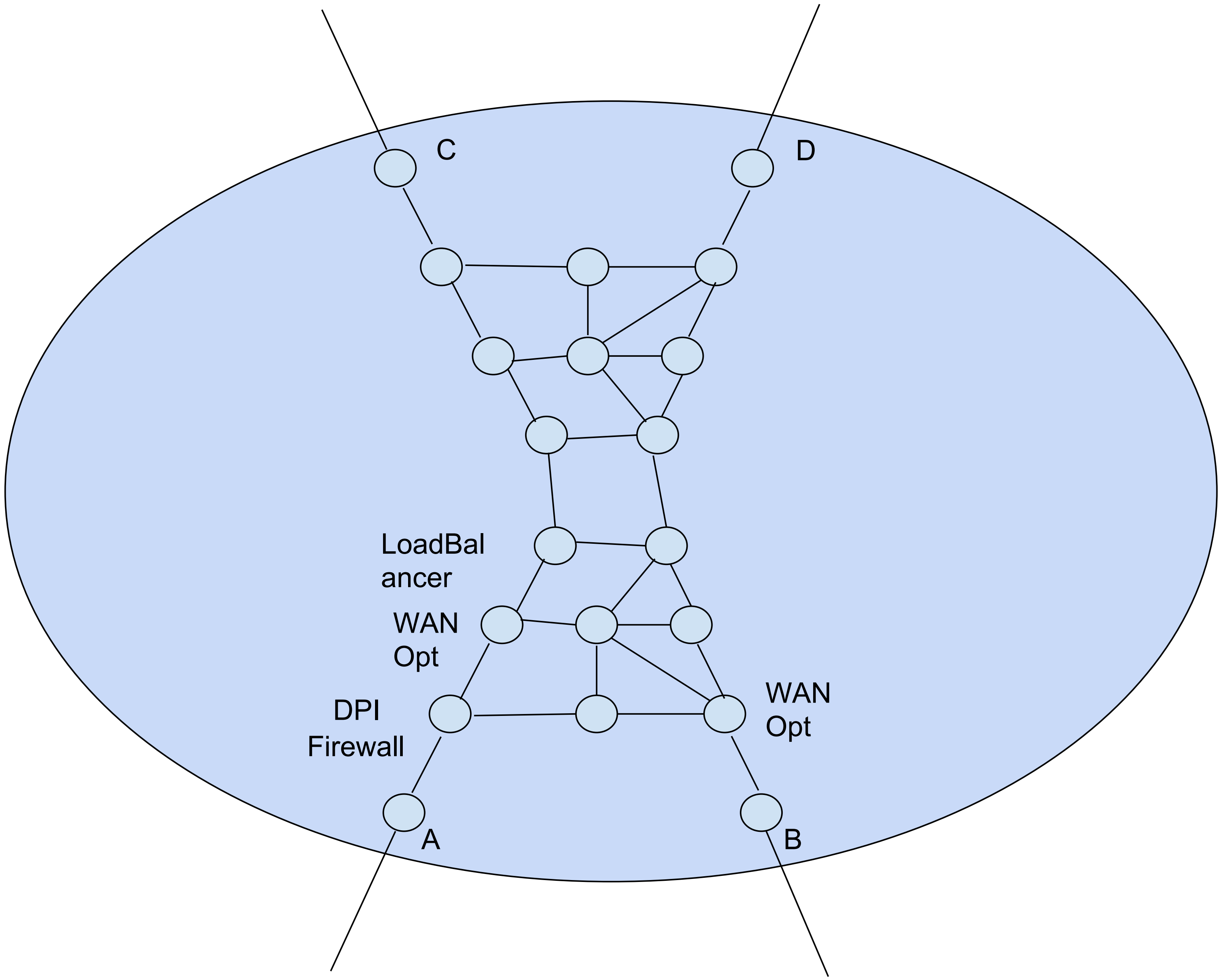
NFV and Energy Efficiency

- **A dynamic scenario**
  - **Time 1:** a flow A->B
  - **Time 2:** a flow C->D



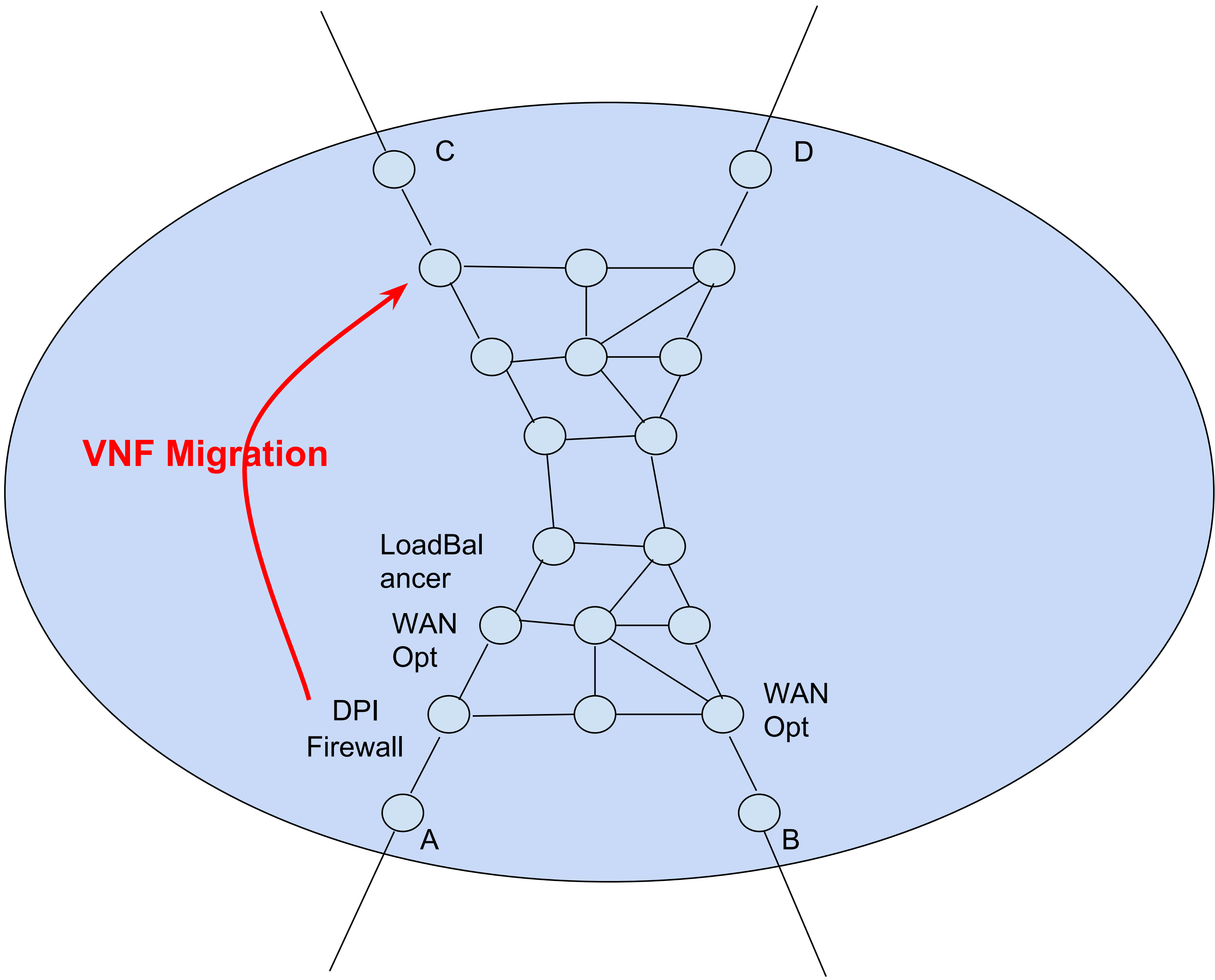
NFV and Energy Efficiency

- **A dynamic scenario**
  - **Time 1:** a flow A->B
  - **Optimization for flow A->B.**



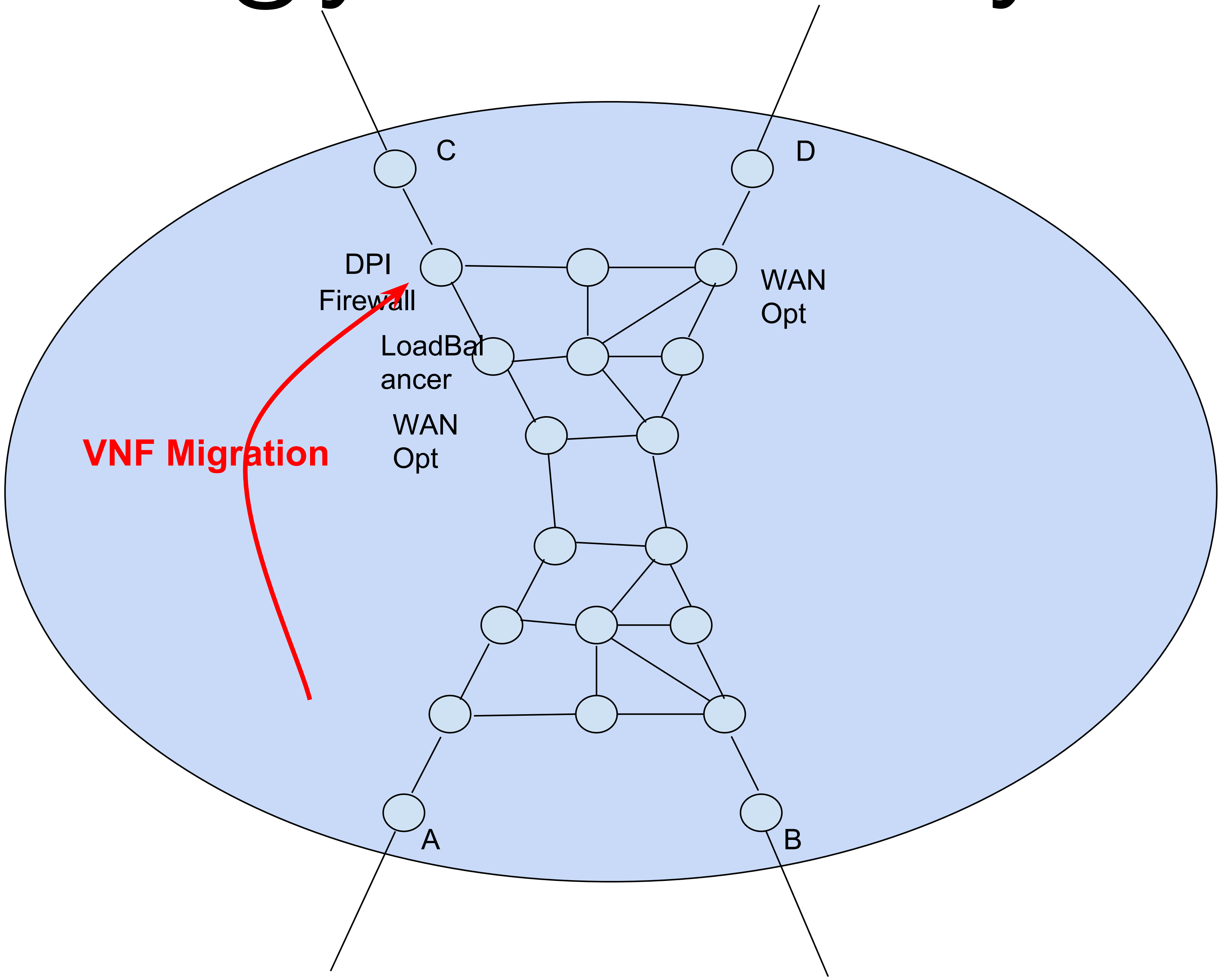
NFV and Energy Efficiency

- A dynamic scenario
  - Between Time 1 and Time 2:
    - Virtual Network Function Migrations
  - Optimization for flow C->D.



NFV and Energy Efficiency

- **A dynamic scenario**
  - **Time 2:**
    - **Virtual Network Function Migrations**
  - **Optimization for flow C->D.**



NFV and Energy Efficiency

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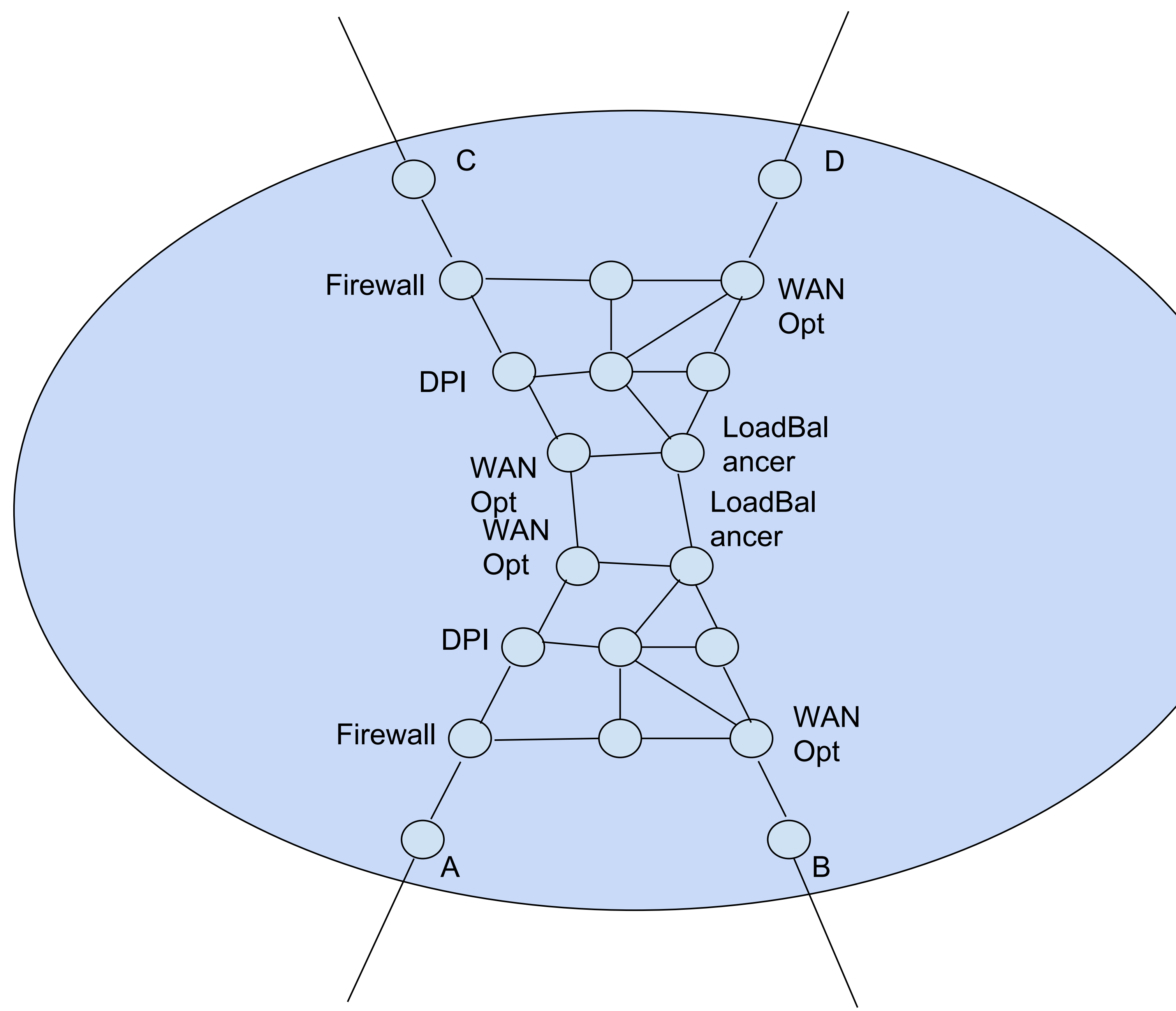

NFV and Energy Efficiency

- A large number of **optimization problems:**
  - **VNF placement**
  - **Choosing routes** passing through VNF
  - **joint VNF placement and route selection**
  - **Dynamic problem:** How to **efficiently migrate VNF** with **traffic variations**?

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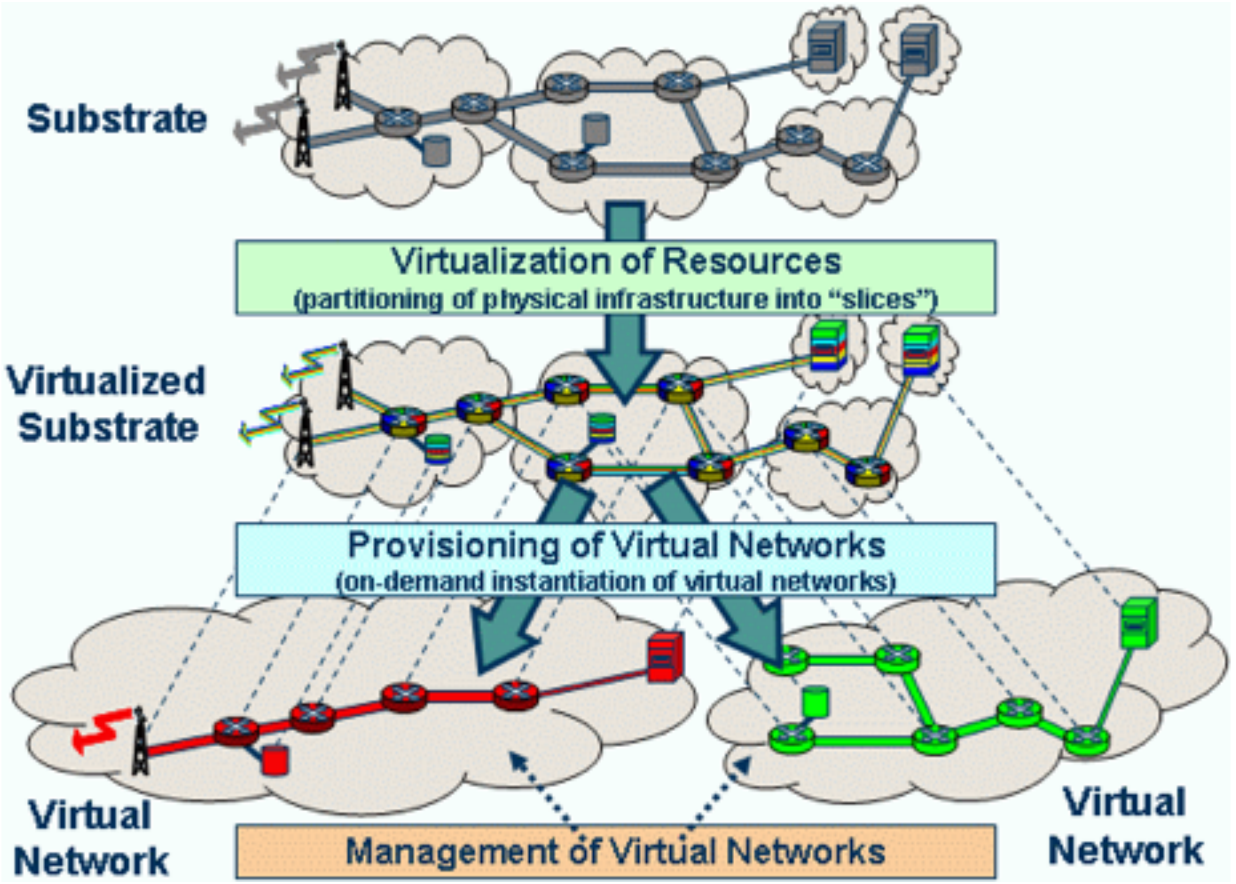
Network Virtualization

- More generally, **a whole network may be virtualized.**



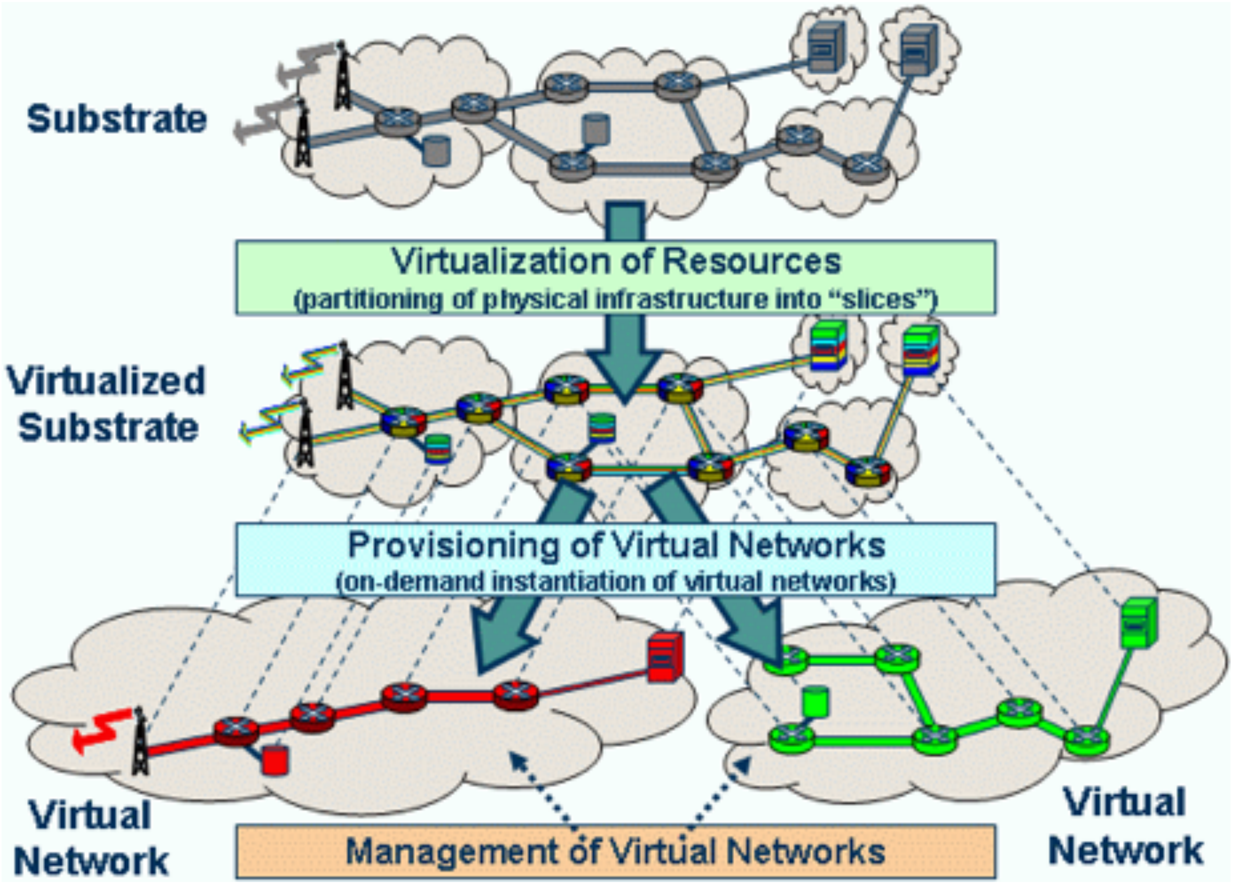
Network Virtualization

- More generally, **a whole network may be virtualized.**

- **Typical examples:**

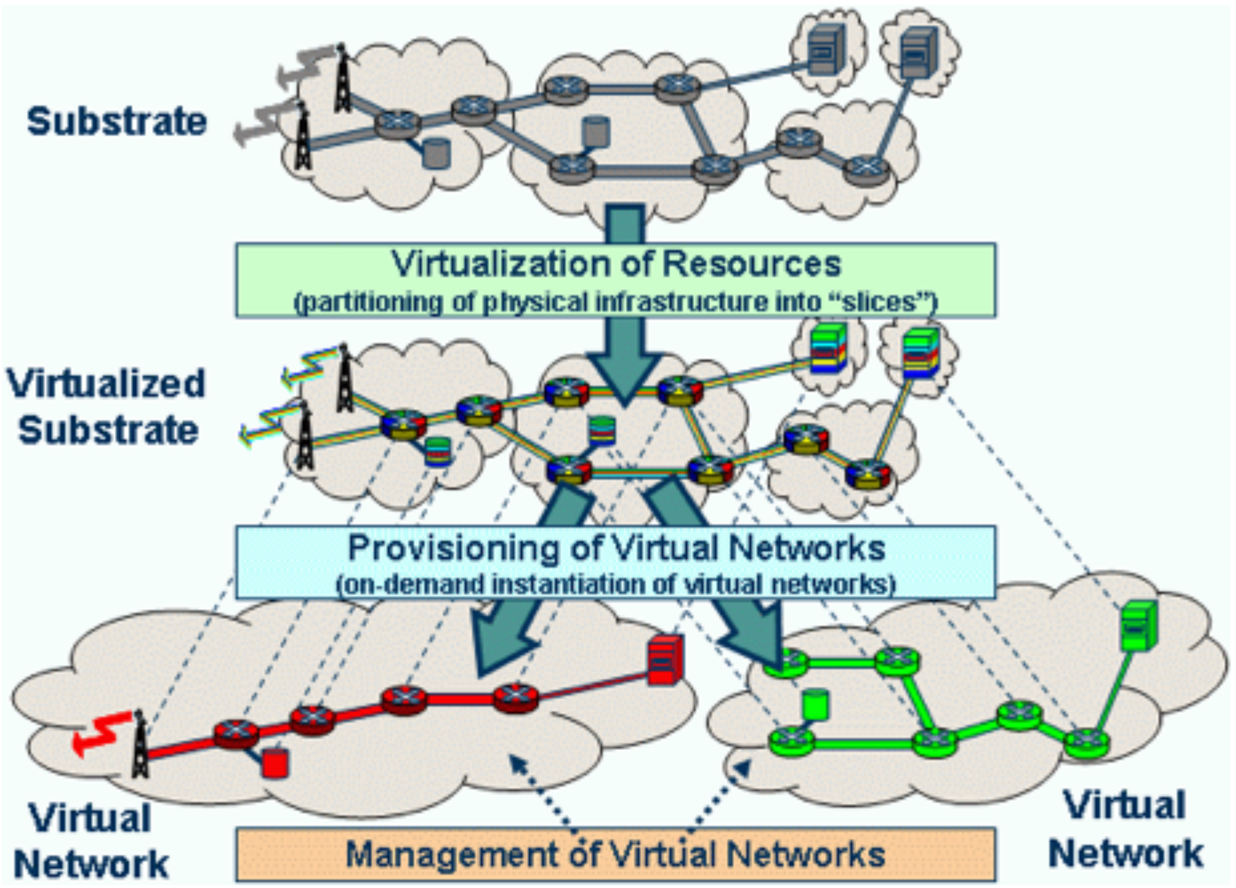
    - an **operator renting its network for several other operators** (e.g. Orange rents to Free Telecom)

    - **reserving machines and bandwidth** in a computation grid such as Grid500 or on Amazon.



Network Virtualization

- **Hard questions:**
  - e.g. Orange has its physical network. Free ask for some capacities in different region of France. **How to map** Free virtual network on Orange network?



Network Virtualization and Energy Savings

- An operator (Orange, Amazon, …) has several clients asking for a network. It has to map several of them on a single network.

- With a **smart mapping**, It may thus

  - **Save redundant hardware** which should appear in both networks

  - **Mutualize link usage** (in particular, it may share some **protection parts**)

Virtualization and Energy Efficiency: a summary

- To summarize, **virtualization can help saving energy** by:
  - saving on **redundant hardware**
  - in particular by introducing **dynamic networks** with changes of nodes and links
  - **reducing route length**, thus more devices and links may be turned off
  - **mutualizing ressources** between networks

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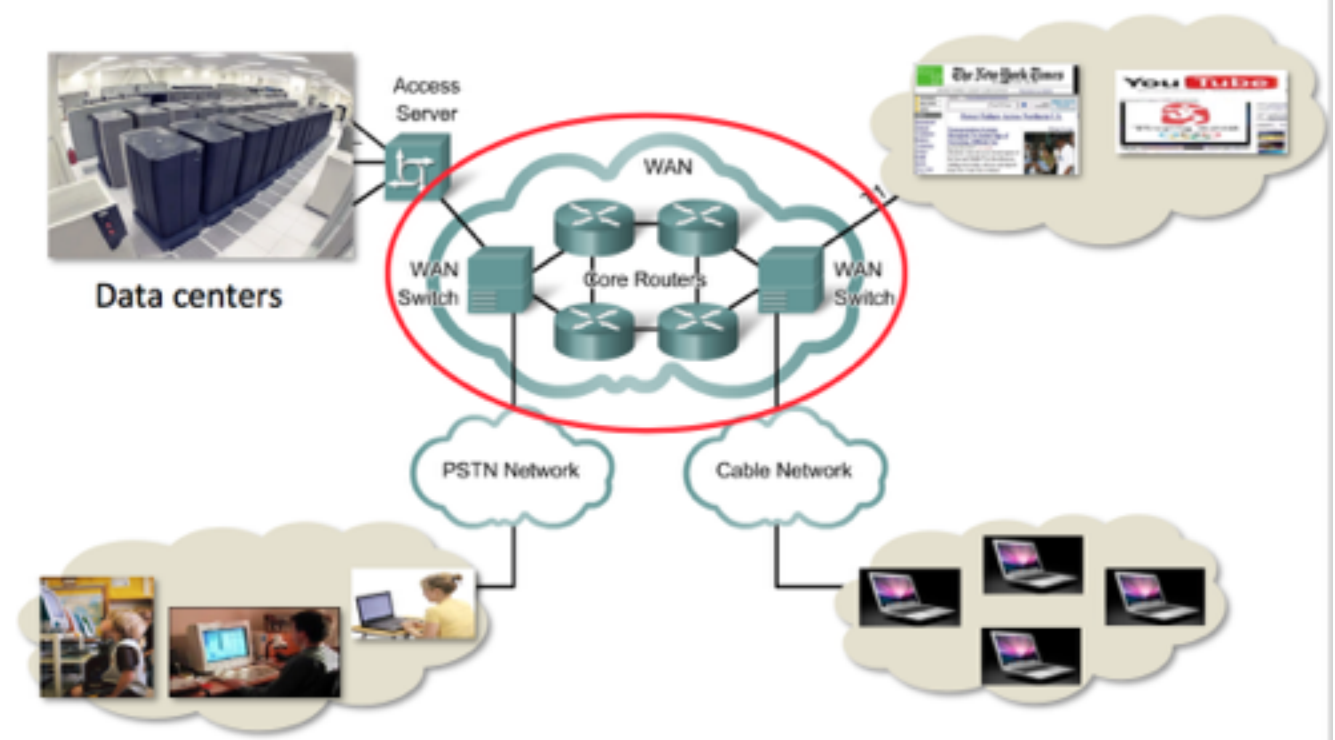
Joint optimization of Networks and Data centers

- Motivation: Data center are processing large amount of data generating a large amount of traffic and a huge load on the networks, either:
  - inside data center
  - between several data centers
  - between data centers and the end users.
- Example: video. 80% of the traffic is video. A large amount is served by CDN.



Joint optimization of Networks and Data centers

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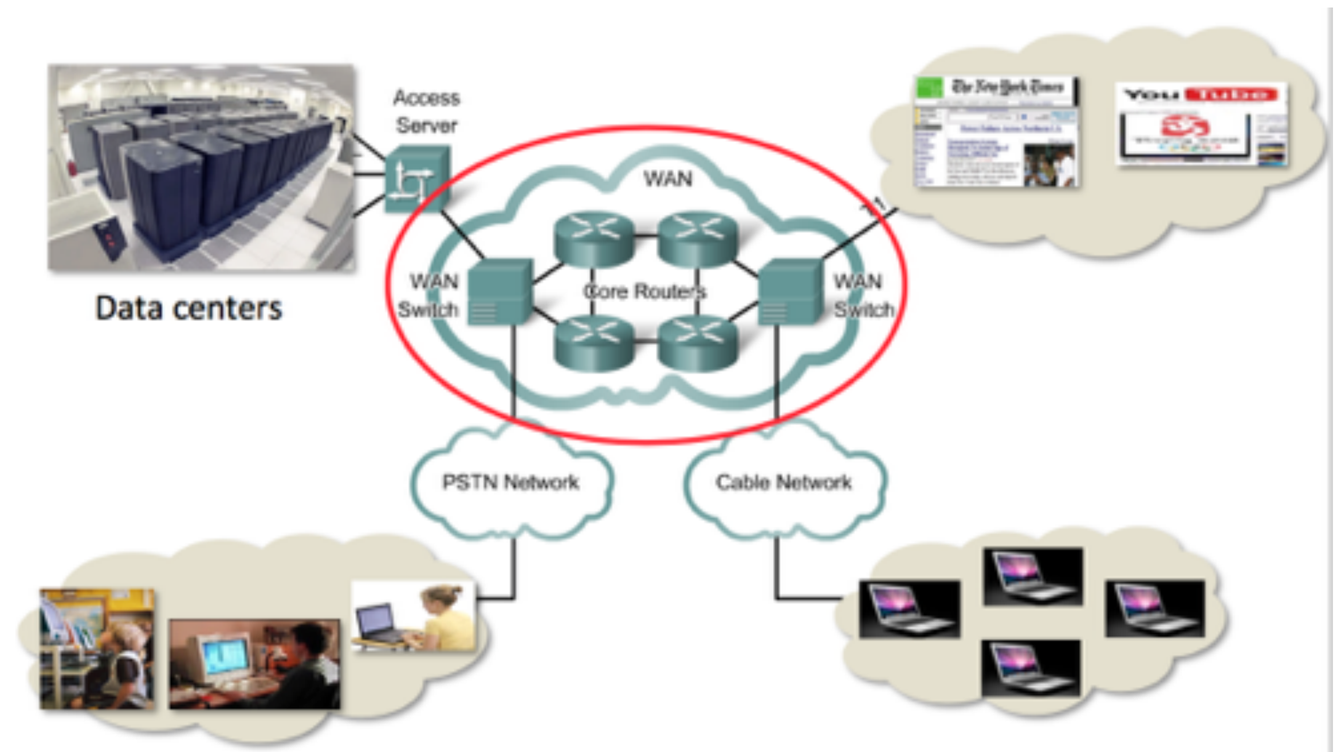

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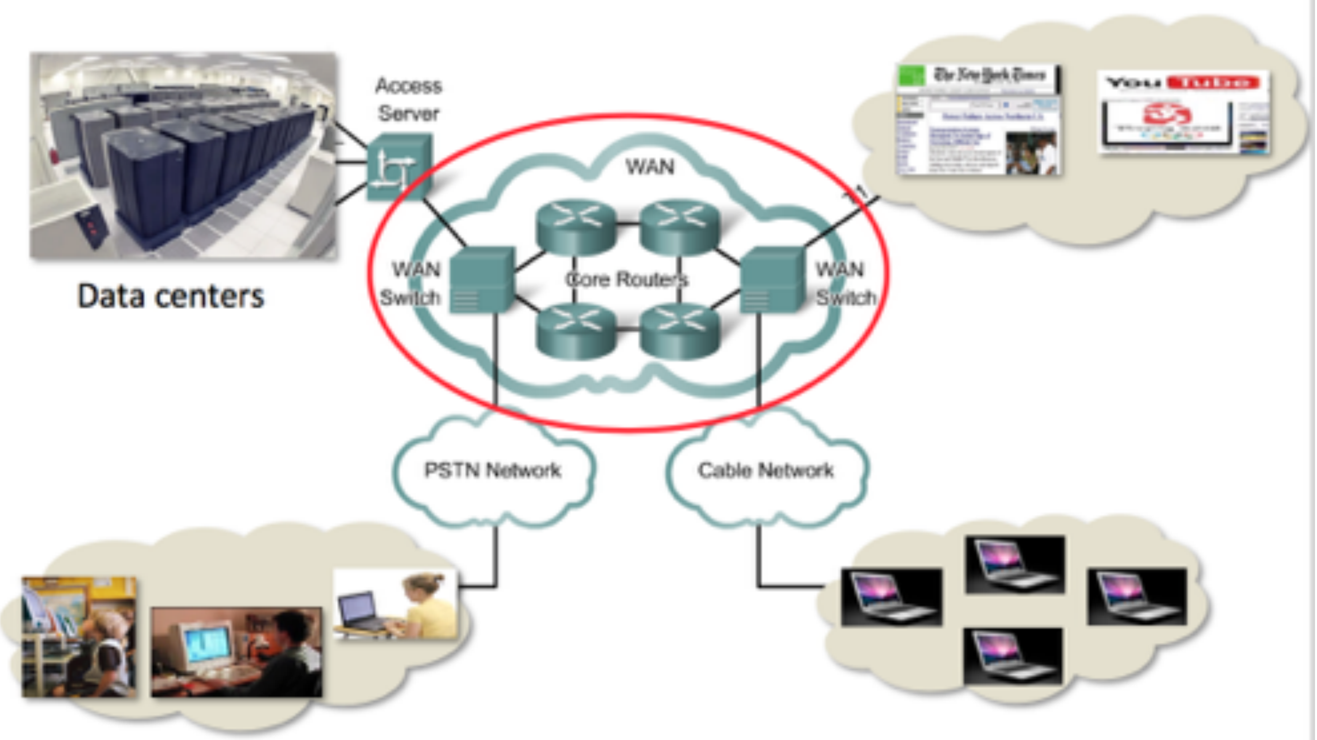

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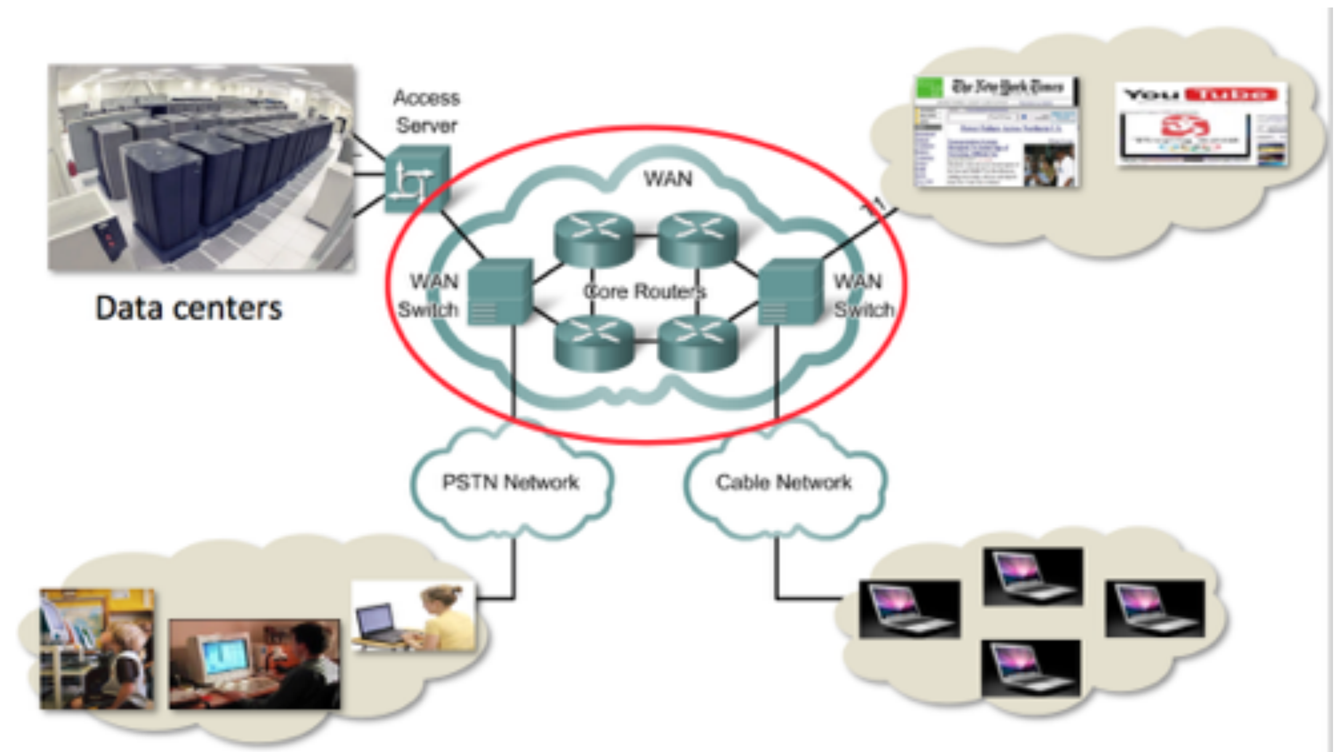
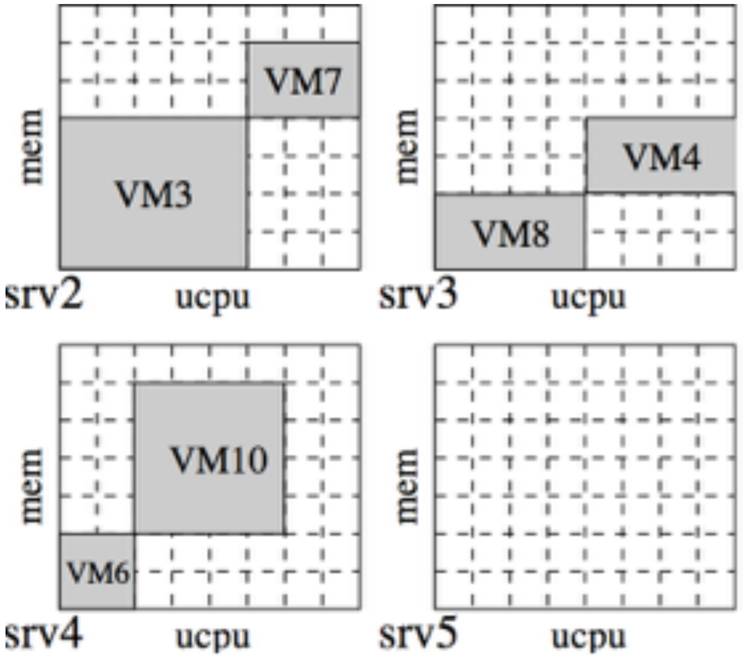


Optimization of Data Centers

- Before: independant optimization.
- In **Datacenters**, we have
  - **Tasks** (compute a route, an algorithm) in an environment -> **Virtual Machines**.
  - **Classical optimization task:** assign Virtual Machines to Computers.
  - **Classical model: Scheduling**.



Optimization of Networks

- Before: independant optimization.

- In **networks**, we have
  - large **aggregate traffic demands**.
  - **Classical optimization task:** We are looking for routes for demands
  - **Classical models: multicommodity flows**

Joint optimization of Networks and Data centers

- **Difficulty:** **Very different models.**

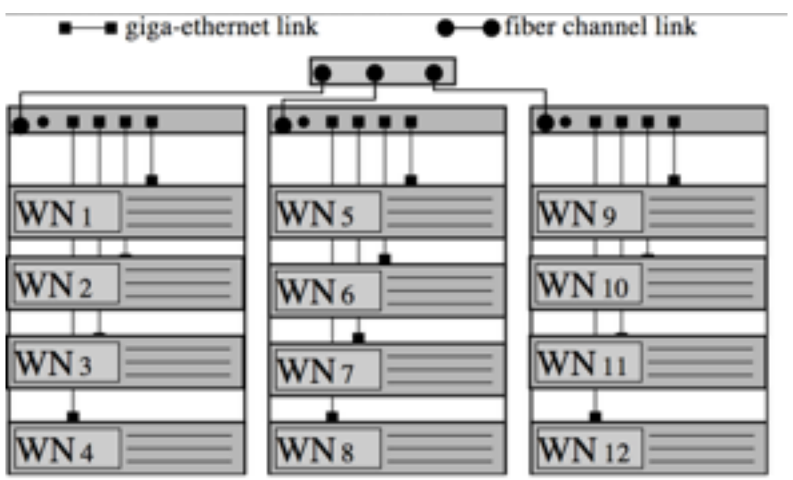
- **Goal:** **minimize jointly energy consumption** of the **tasks in the data center** and of **the traffic in networks**.

- While: taking into account network architecture constraints

  - Link and device capacities

  - Link failure protection

  - Quality of service (QoS)



Some models exists

- For example, **scheduling with network costs**.
- However:
- **does not take into account** the **real topology of the networks and its capacities.**
    - good for models inside a data center for which networks are very symmetric and hierarchical and organized
    - -> if we consider the ISP networks from data center to end users. Very different networks

But new solutions have to be defined

- Lots of work here. Difficult problem.
- Especially if we want to do a **dynamic optimization** for **energy** (problem not solved for a static setting).

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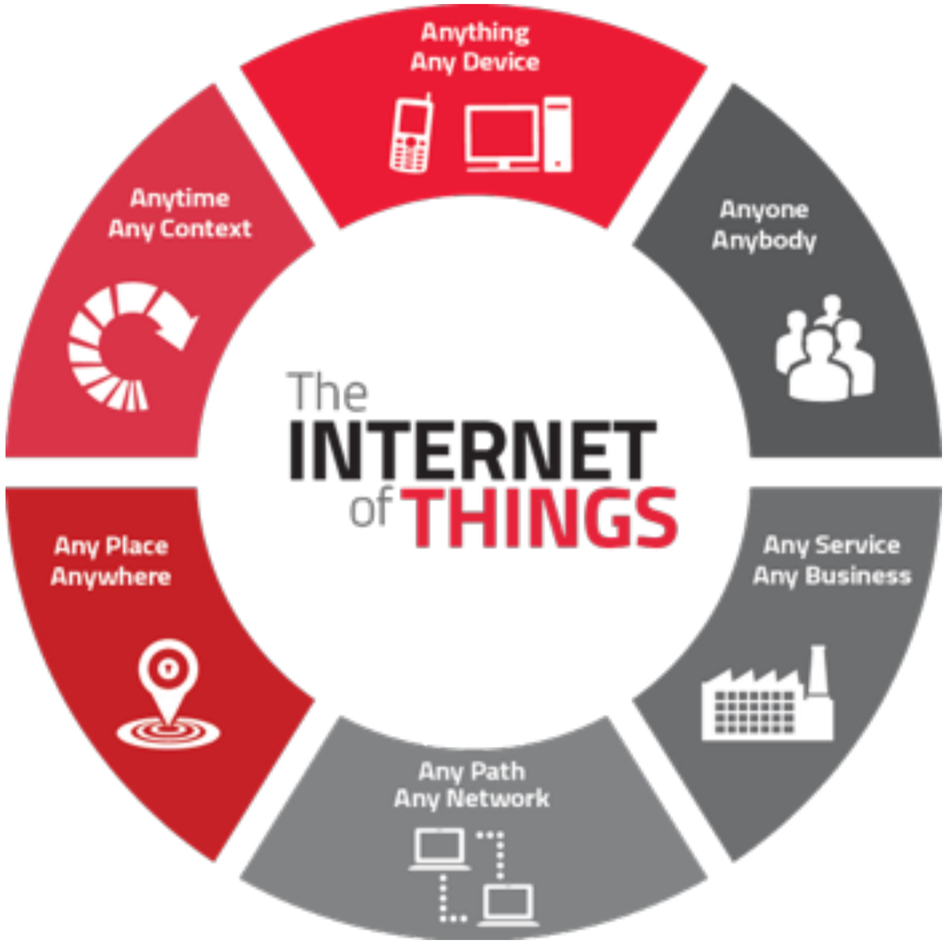
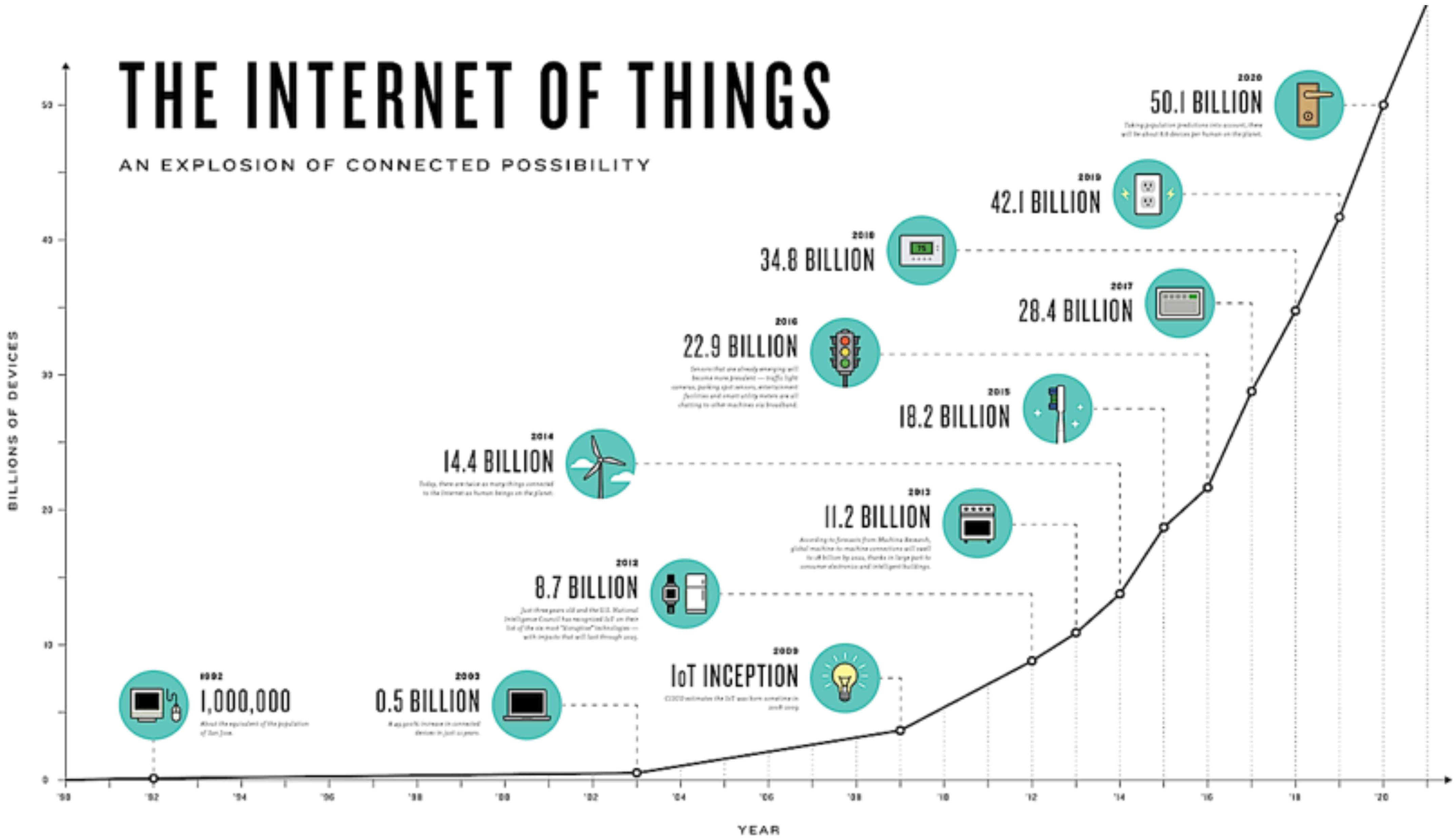
Internet Of Things

- **Another** **revolution** **is starting:**



Internet Of Things

- **A very large challenge:**



IoT Challenges

- A lot of question:
  - which hardware?
  - which networks?
  - security? (information, control (e.g. cars))
  - and energy?

IoT and Energy

- How to limit the ***energy consumption of networks with tens of billions of nodes***?
  - Help of very large number of works for sensors networks.
  - Largely open challenge.

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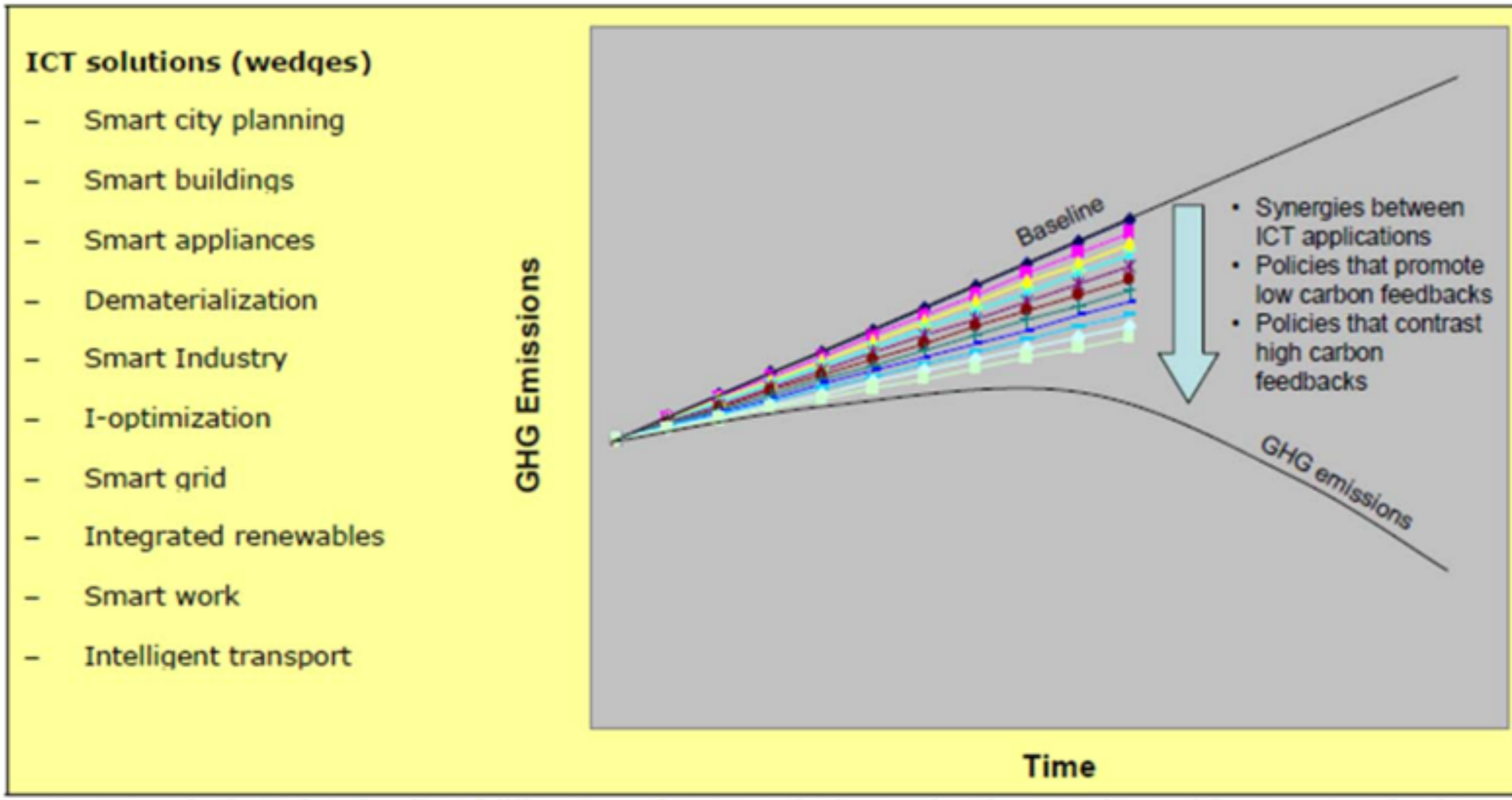
    - Good news: IoT may be indirectly more a source of savings than of consumption. (Smart counter, car traffic optimization, smart cities, …)

Finishing with good news

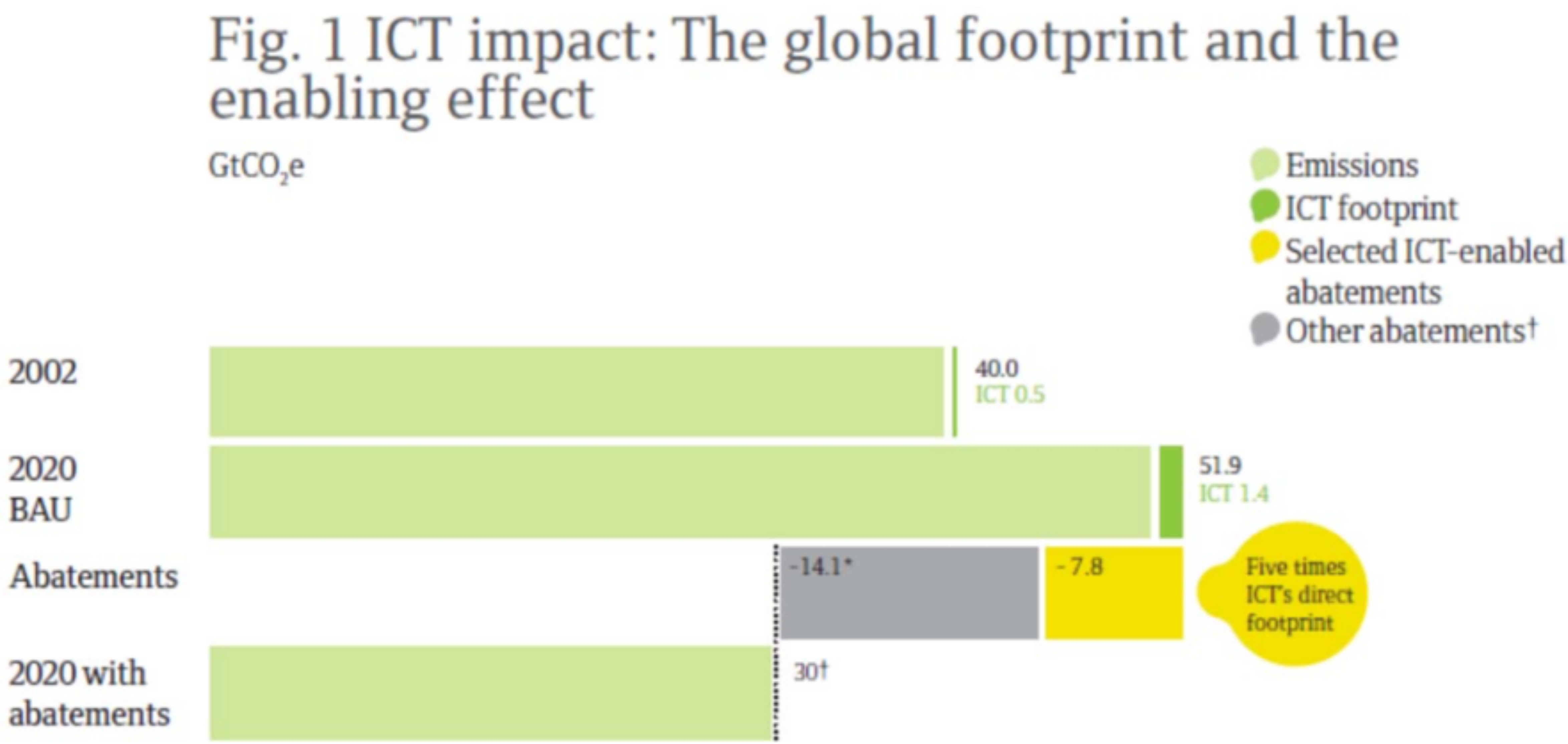
- **Prediction: ICT will save more energy than it will consume.**



ICT Solutions to achieve systemic changes

Finishing with good news

- **Prediction: ICT will save more energy than it will consume.**



Source: The Climate Group, GeSI report "Smart 2020"

Conclusions

- A lot proposed since 2008.
- A lot remains to be put into reality (good for us :-)

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*This is not a tree

Conclusions

- Encouraging technology advances and challenges:
  - More energy efficient hardwares
  - SDN revolution and virtualisation
  - Ubiquitous networking and multiple joint optimization

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Conclusions

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Thanks for your attention!!!

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Credits due to:

- **Surveys:**
  - Bolla, R., Bruschi, R., Davoli, F., & Cucchietti, F. (2011). Energy efficiency in the future internet: a survey of existing approaches and trends in energy-aware fixed network infrastructures. *Communications Surveys & Tutorials*, IEEE, 13(2), 223-244.
- **Slides:**
  - F. Davoli. Green Networking and Network Programmability: A Paradigm for the Future Internet? 22d ITC Specialist Seminar. 2013
  - Christensen, K., & Nordman, B. Reducing the energy consumption of networked devices. IEEE 802.3 tutorial.
  - D. Kilper, Tutorial: Energy Efficient Networks.
  - D. Lopez & F. Giroire, Green Networks, Master Course, University Nice-Sophia Antipolis, 2016.
  - Design and Management of Networks with Low Power Consumption, Truong Khoa Phan, *PhD Defense*, Sophia Antipolis, 2014
  - Slides from presentations from J. Moulierac, N. Huin and M. Rifai.
- **Reports:**
  - Global e-Sustainability Initiative. (2012). GeSI SMARTer 2020: the role of ICT in driving a sustainable future. *Global e-Sustainability Initiative*, Brussels, Belgium.