Optimization of Network Infrastructures.

A little bit of green in networks and other problems of placement and management of resources.

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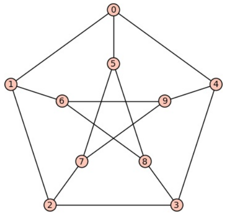
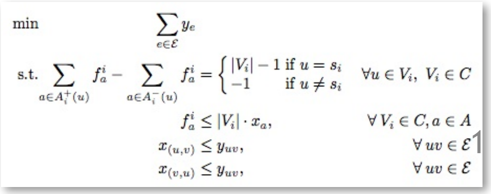
HdR — October 23, 2018

*Combinatorics, Optimisation et Algorithms For Telecommunications

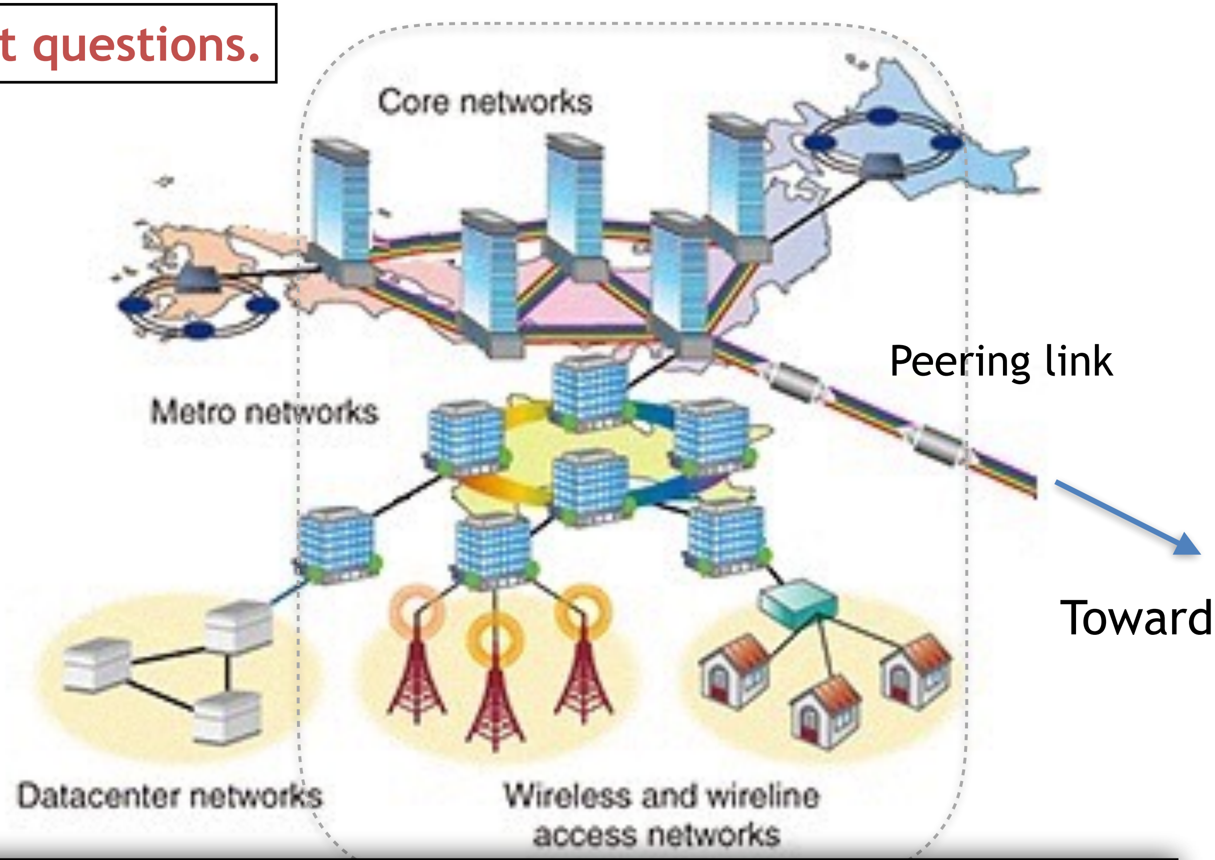




$$\begin{array}{lll}
\min & \displaystyle\sum_{e\in\mathcal{E}} y_e & \\
\text{s.t.} & \displaystyle\sum_{a\in A_i^+(u)} f_a^i - \sum_{a\in A_i^-(u)} f_a^i = \begin{cases} |V_i|-1 \text{ if } u = s_i \\ -1 \qquad\;\; \text{if } u \neq s_i \end{cases} & \forall u \in V_i,\ V_i \in C \\
& f_a^i \leq |V_i| \cdot x_a, & \forall\, V_i \in C, a \in A \\
& x_{(u,v)} \leq y_{uv}, & \forall\, uv \in \mathcal{E} \\
& x_{(v,u)} \leq y_{uv}, & \forall\, uv \in \mathcal{E}
\end{array}$$

Optimization of Network Infrastructures

Lots of different questions.



Towards other ISPs

I answered some of them using tools from **algorithmics**, **optimization**, **combinatorics (graph theory)**, **simulations** and **experimentations**.

Optimization of Network Infrastructures

Manuscript Content

How to know the traffic?
Probabilistic algorithms for cardinality
PhD Inria Rocquencourt + Paris 6
P. Flajolet and M. Soria

Tool: Analysis of algorithms

Traffic Analysis - Security

PhD
(Rocq.)

2003

2006

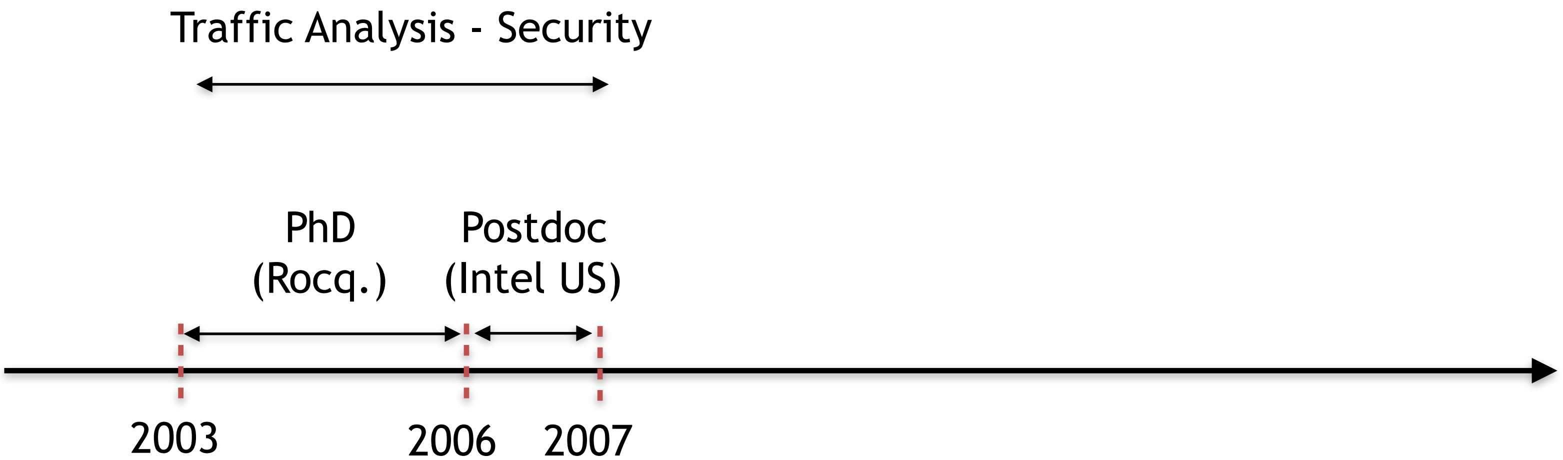
Optimization of Network Infrastructures

How to secure the traffic?
Anomaly detection. DDoS and botnets
PhD
Postdoc Intel Research Berkeley
N. Taft and J. Chandrashekar

Tools: Analysis of Traffic - Algorithms

Manuscript Content

- Appendix Section 1.2
    - Traffic analysis and security
- Part I
- Part 2



Traffic Analysis - Security

PhD
(Rocq.)

Postdoc
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2003

2006

2007

Optimization of Network Infrastructures

How to back up data?
Analysis of P2P storage systems

Postdoc Sophia
J.-C. Bermond and S. Pérennes

Tools : Markov chains

Manuscript Content

- Appendix Section 1.2
    - P2P storage
    - Traffic analysis and security
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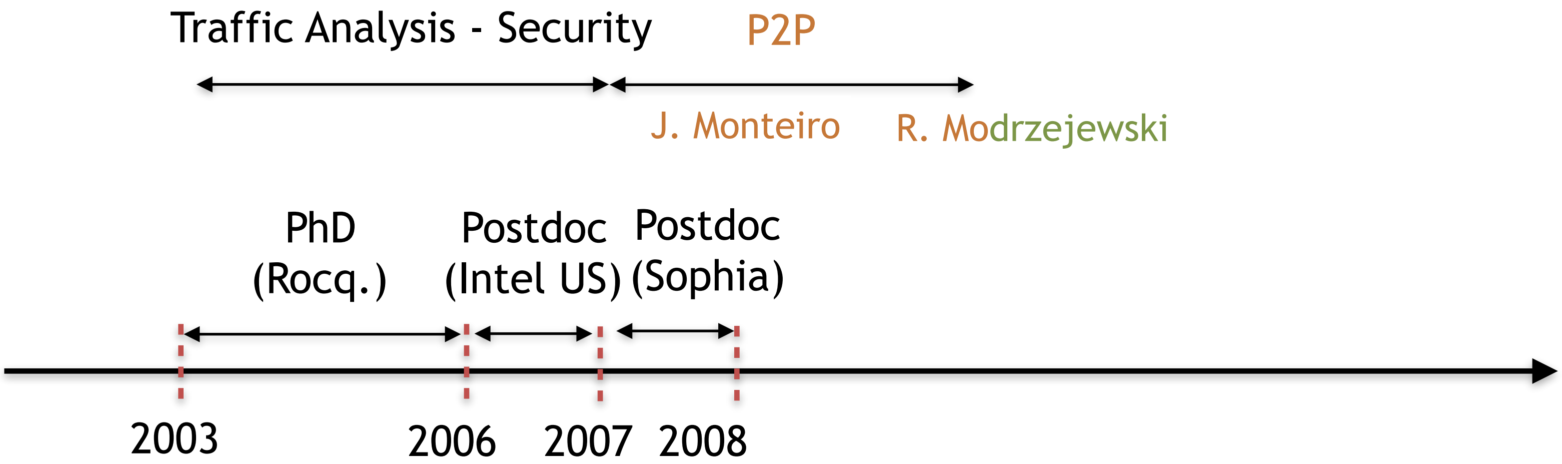

Traffic Analysis - Security

P2P

J. Monteiro

R. Modrzejewski

PhD (Rocq.)

Postdoc (Intel US)

Postdoc (Sophia)

2003

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2007

2008

Optimization of Network Infrastructures

How to back up data?
Analysis of P2P storage systems
Section 1.2.3
CR CNRS - I3S/Mascotte

Tools: Markov chains

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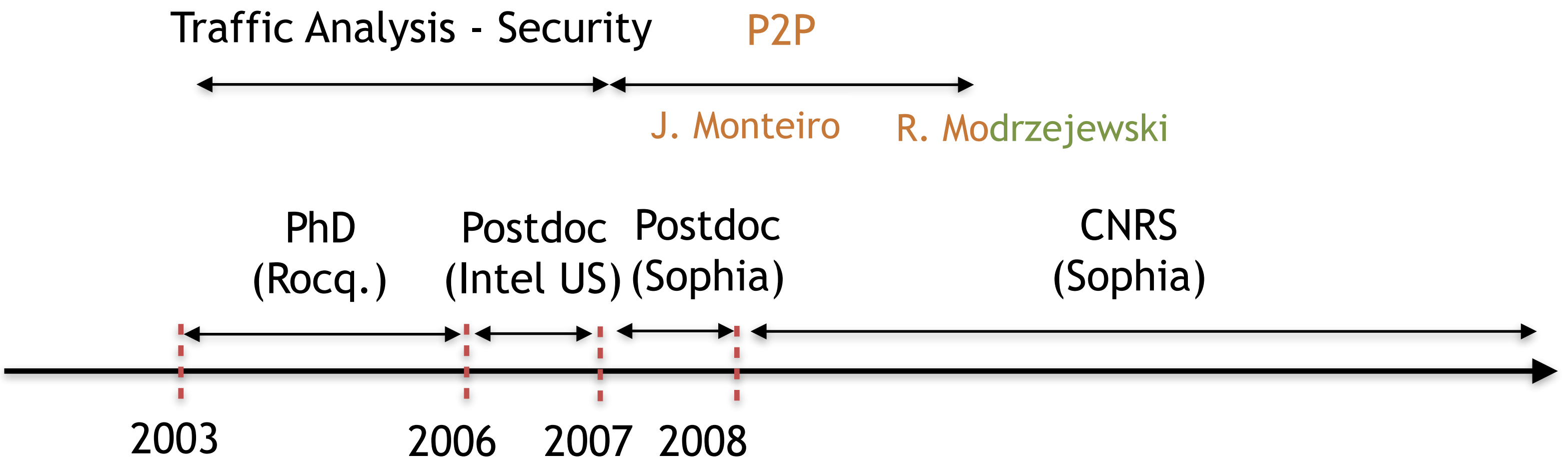

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CNRS
(Sophia)

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2008

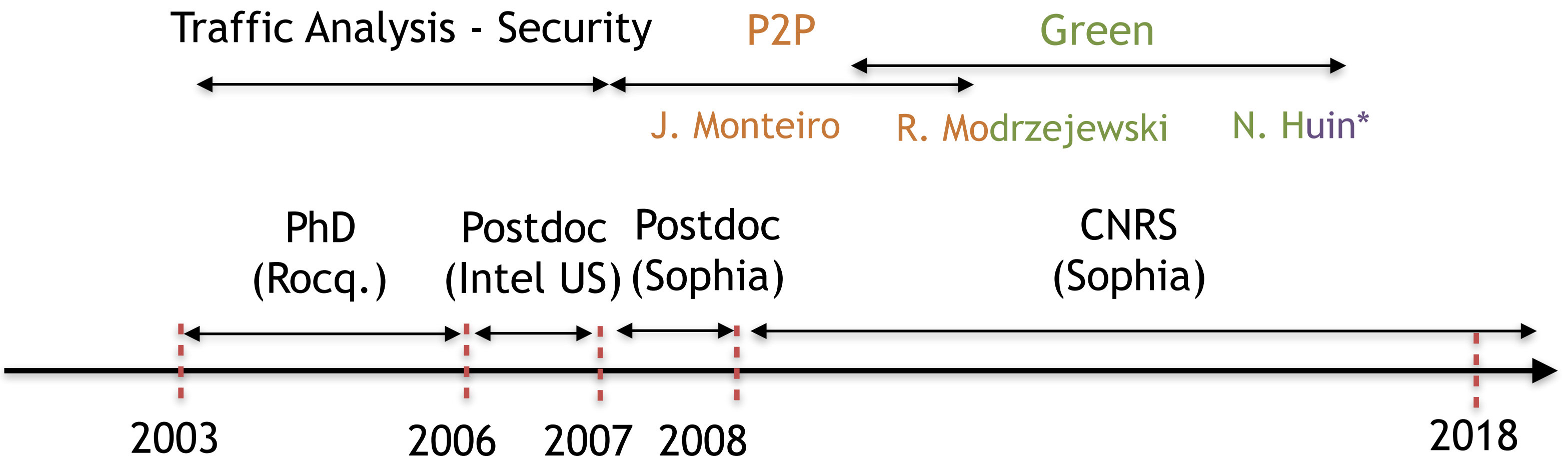
Optimization of Network Infrastructures

How to build green networks?
Energy Aware Routing
Part I

Tools: Optimization, Algorithmics, Simulations

Manuscript Content

- Appendix Section 1.2
  - P2P storage
  - Traffic analysis and security
- Part I Green Networks
  - Chap 3 Practical scenarios
    Chap 4 Graph Theory
- Part 2



Optimization of Network Infrastructures

How to control the network in real time?
Software Defined Networks (SDN)
Part 2

Tools: Algorithms, FPT, Simulation, Experiments

Manuscript Content

- Appendix Section 1.2
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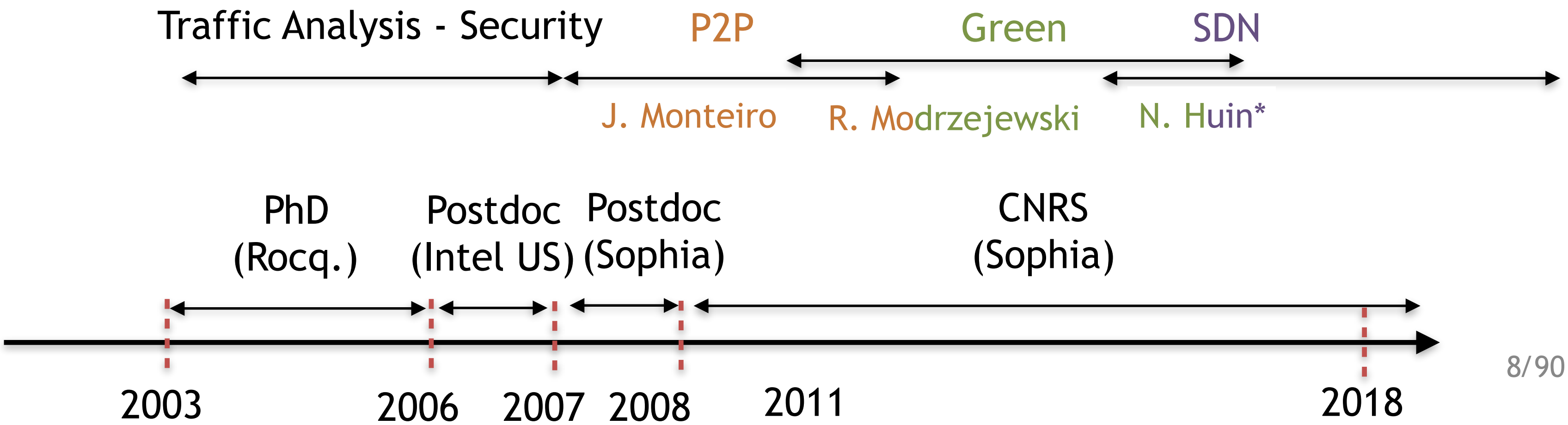
  - Chap 3 Practical scenarios
    Chap 4 Graph The
- Part 2 Virtualized SDN
  - Chap 6 SDN



Traffic Analysis - Security

P2P

Green

SDN

J. Monteiro

R. Modrzejewski

N. Huin*

PhD
(Rocq.)

Postdoc
(Intel US)

Postdoc
(Sophia)

CNRS
(Sophia)

2003

2006

2007

2008

2011

2018

Optimization of Network Infrastructures

How to place (virtual) resources?
Provisioning of Virtual Network Functions
Part 2

Tools: Column generation,
Approximation algorithms.

Manuscript Content

- Appendix Section 1.2
  - P2P storage
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- Part I Green Networks
  - Chap 3 Practical scenarios
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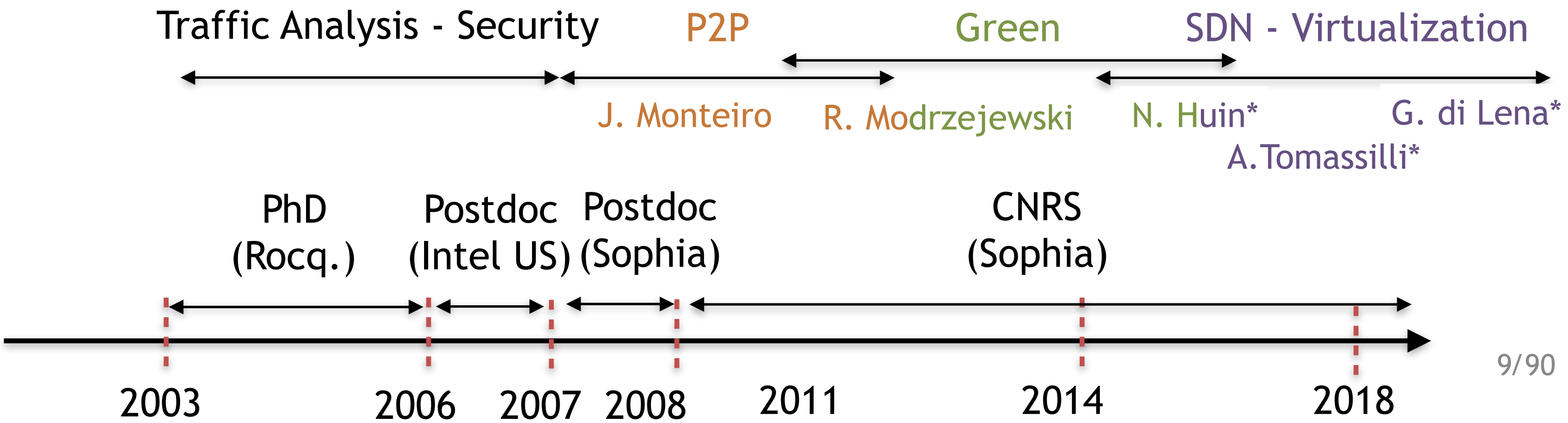
  - Chap 6 SDN
  - Chap 7 NFV
  - Chap 8 Green networks in practice



Optimization of Network Infrastructures

How to model networks with graphs?
Coloring for wireless,
Random graphs for social networks

Appendix 3.

Tools: Graph theory.

Manuscript Content
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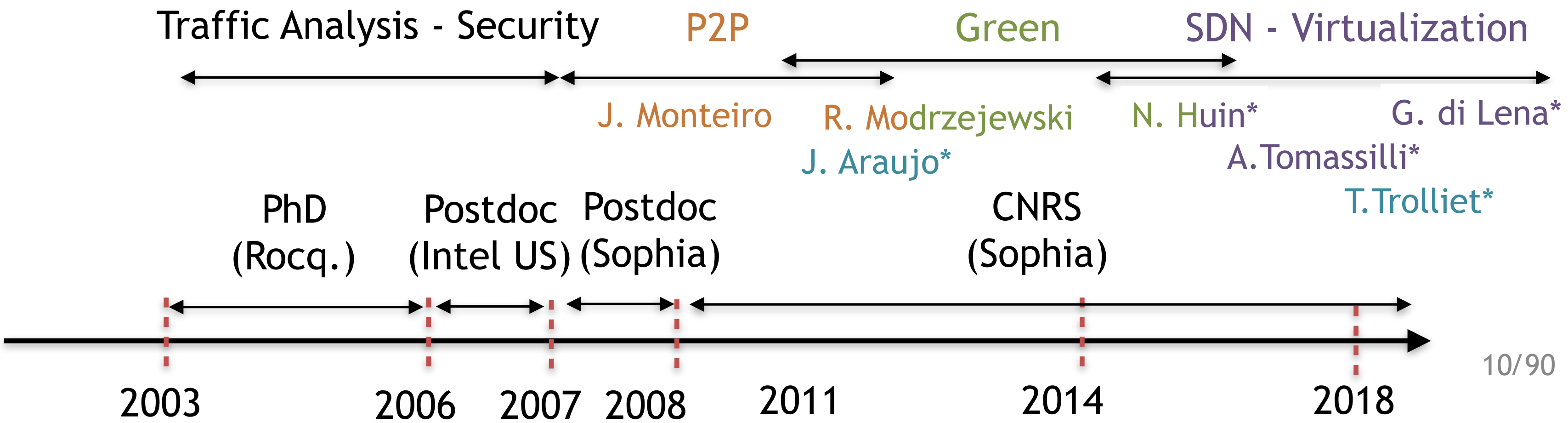


Traffic Analysis - Security

P2P

Green

SDN - Virtualization

J. Monteiro

R. Modrzejewski

N. Huin*

G. di Lena*

J. Araujo*

A.Tomassilli*

T.Trolliet*

PhD
(Rocq.)

Postdoc
(Intel US)

Postdoc
(Sophia)

CNRS
(Sophia)

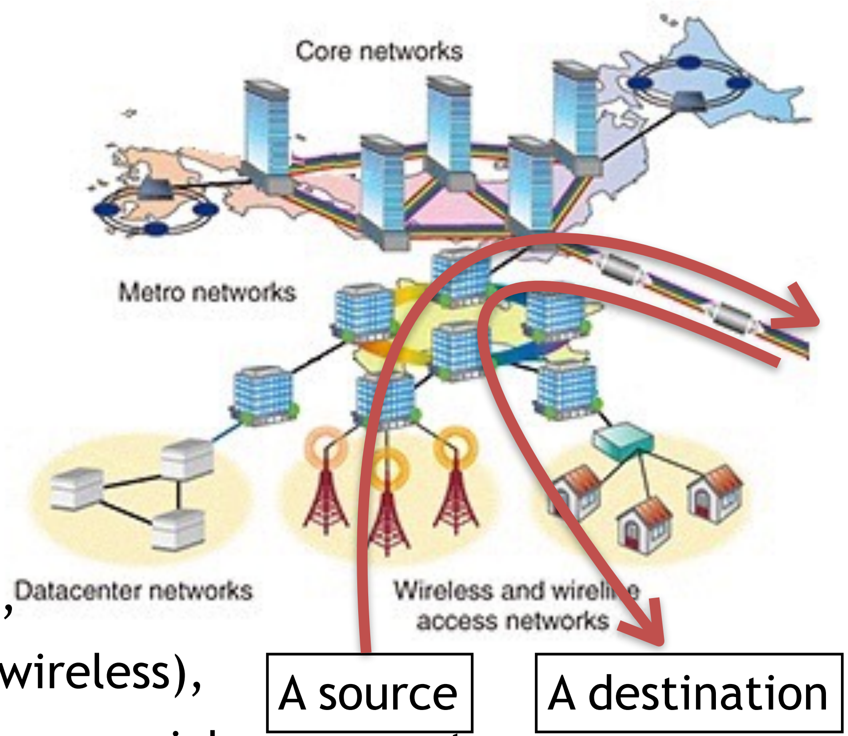
Supervised students

- **Phd Supervisions (3 in progress)**
  - 2018-2021. Giuseppe di Lena with Thierry Turletti, (EPI DIANA), and Chidung Lac (Orange Labs). **Resilience of virtualized networks.**
  - 2017-2020. Thibaud Trolliet with Arnaud Legout (EPI DIANA). **Analysis of large social networks.**
  - 2016-2019. Andrea Tomassilli with Stéphane Pérennes.
    Next generation virtualized networks.
- **Phd Supervisions (4 defended) :**
  - 2014-2017. Nicolas Huin with Dino Lopez (SIGNET).**Energy-efficient Software Defined Networks.**
    Now : Huawei Research Lab, Paris.
  - 2010-2013. Remigiusz Modrzejewski with J.-C. Bermond. **Content Distribution and Storage.**
    Now : Google, Dublin, Irlande.

- **Phd Supervisions (defended) :**
  - 2009-2012. Julio Araujo with Jean-Claude Bermond et Claudia Linhares (Ceara, Brazil). **Graph Coloring and Graph Convexity.**
    Now : Assistant Professor Fortaleza, Brésil.
  - 2007-2010. Julian Monteiro with Olivier Dalle and S. Pérennes. **Modeling and Analysis of P2P Data Storage Systems.**
    Now : Team leader in Cittati Tecnologia. Co-Founder and CTO of Lejour startup.
- **Postdocs: 2**
  - 2012-2013. Luca Chiaraviglio with Joanna Moulierac. **Energy-efficient Networks.**
    Now : Assistant professor (Tenure-Track) University Roma Tor Vergata.
  - 2011-2012. Yaning Liu with Joanna Moulierac. **Energy-efficient Networks.**
    Now : JCP-Consult R&D research and management of european projects.
- **Masters: 10 students.**

Routing

How to route?



However: not a simple shortest path.

Due to:

- capacities and multiple demands (NP-hard),
- heterogeneous infrastructures (e.g. wired/wireless),
- private owners of the infrastructure with commercial agreements,
- frequent failures.

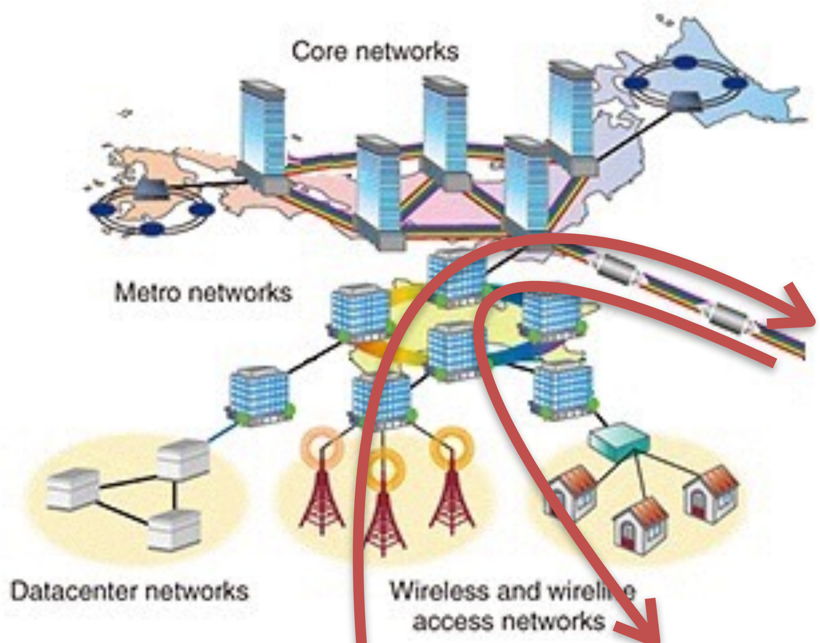
What’s needed from a routing solution?

- Efficient in terms of delay/bandwidth/cost/failure protection.

Routing

How to route?

Legacy solutions: Distributed protocols, such as OSPF, BGB.



A source

A destination

Context has changed.

Routing: A new Context

- Career Routing. Introduction

1. Routing in an energy aware world.
   (Part I)

2. Routing in an SDN world without (a lot of) rules.
   (Part 2. Chapter 6)

3. Routing in a virtualized world.
   (Part 2. Chapter 7)

- End of the route ? Conclusions and Perspectives

Routing: A new Context

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- End of the route ? Conclusions and Perspectives

Energy Consumption of Networks

- ICT electricity consumption represents 2-10% of global consumption.
  - Telecom infrastructure and devices account for 25% of ICT’s energy consumption.

3.7 TWh ~ 0.5 billion US$

Corporate Responsibility

9.9 TWh ~ 1.5 billion US$

- Politics. Challenge of the European Commission: a 20% improvement in energy efficiency by 2020.

- Networking research community.
  - Pioneering work [Gupta et al. SIGCOMM 2003]
  - Strong interest from 2008
  - ANR-JCJC DIMAGREEN 2009-2012 (leader)

What can we do? Basic Principles of Power Management

To save Energy we can:

- use more efficient chips and components
- power manage components and systems

To power manage: two main methods

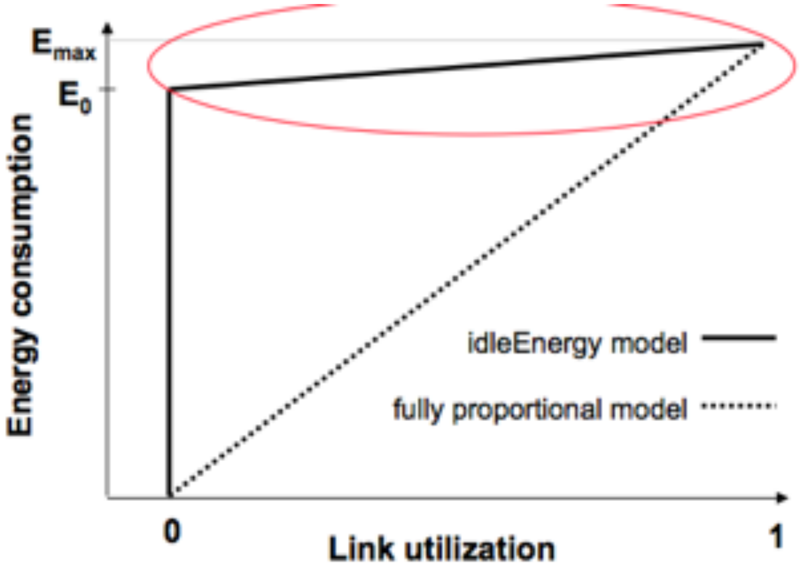
- Do less work: e.g. transmit less in networks. [Nedevschi et al. NSDI 2008.]
- Turn-off devices: not being used [Beloglazov, CCGrid 2010]
  - e.g., floating point unit, disk drive, server in a cluster.

"Most electronics are lightly utilized"

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

Energy Consumption of Networks

Measurements campaigns on routers: small influence of the traffic load on energy consumption on [Chabarek et al. Infocom08]:



—> To save energy: **switch-off** interfaces, chassis.

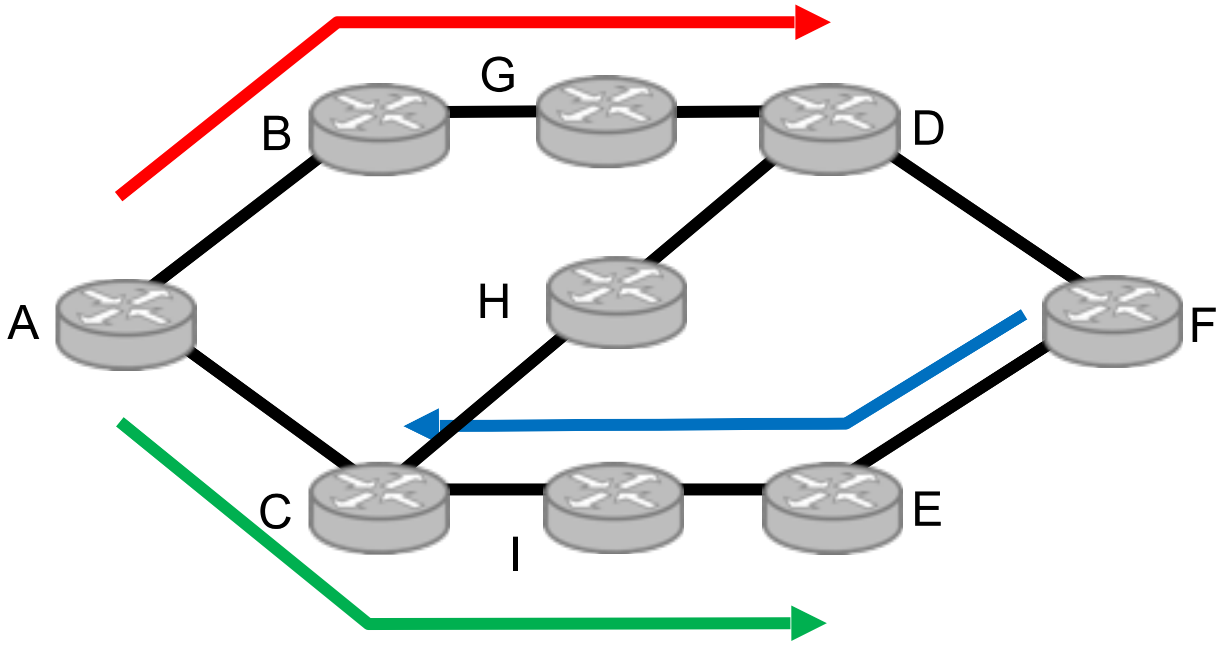
Energy Aware Routing (EAR)

Path between:

A and D

F and C

A and E



Legacy routing: using shortest paths.

Energy Aware Routing (EAR)

Path between:

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F et C

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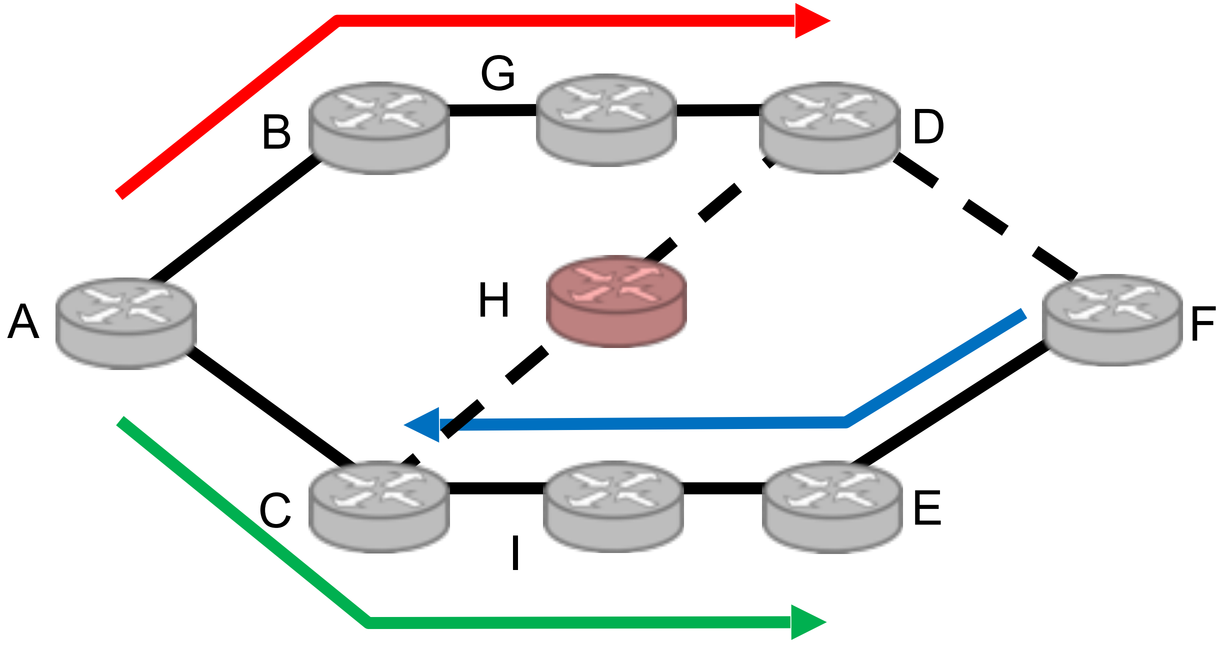


Shortest path routing

Putting unused network equipments (routers and/or links) into sleep mode

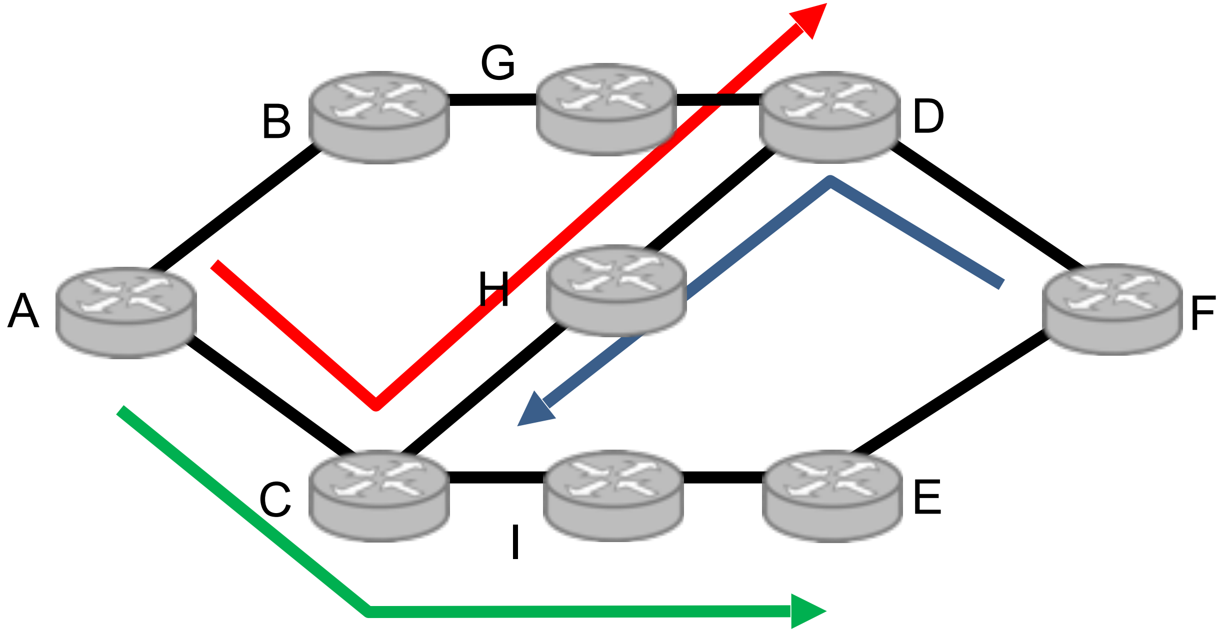
Energy Aware Routing (EAR)

Path between:

A et D

F et C

A et E



EAR: Routing requests while minimizing the number of active network equipments

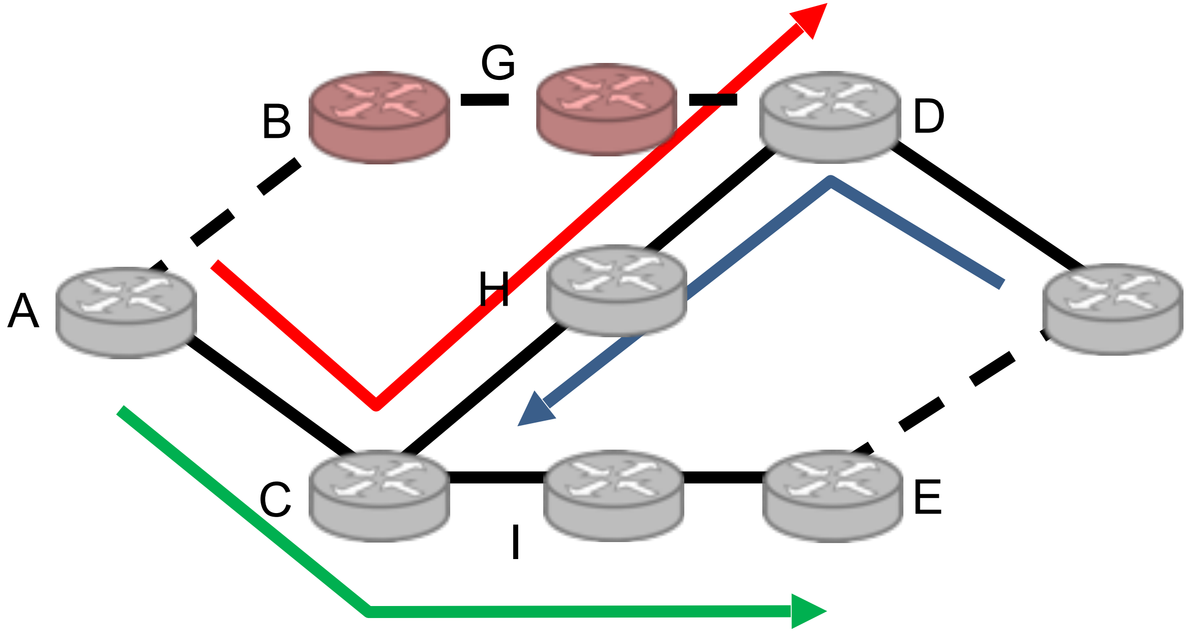
Energy Aware Routing (EAR)

Path between:

A et D

F et C

A et E



Energy Aware Routing

EAR: Routing requests while minimizing the number of active network equipments

Energy Aware Routing (EAR)

- Closely related to classic problems.
  - Routing: Maximum multicommodity flow with a specific cost function [Even. SIAM Journal of Computing 1976]
  - Design: Finding the minimum cost to build a network [Johnson et al. Networks 1978].
  - OR: instance of the Fixed charge Transportation Problem [Gray. Operations Research 1971]

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

My contributions

- Practical Scenarios [Chap. 3]
  - Study of ISP networks [Chap. 3.1]
  - Using redundancy elimination [Chap. 3.2]
  - For content delivery [Chap. 3.3]

- Using Algorithm Complexity and Graph Theory
  - Hardness results (No-APX) [Chap. 3.1]
  - Theoretical bounds for specific topologies (grids, rings, trees, etc...) and all-to-all [Chap. 4]

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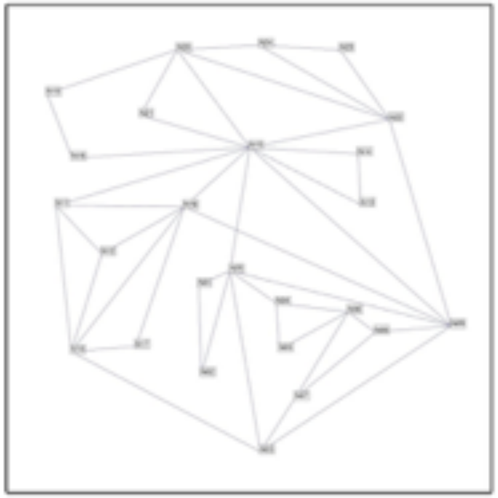
Results on ISP Topologies

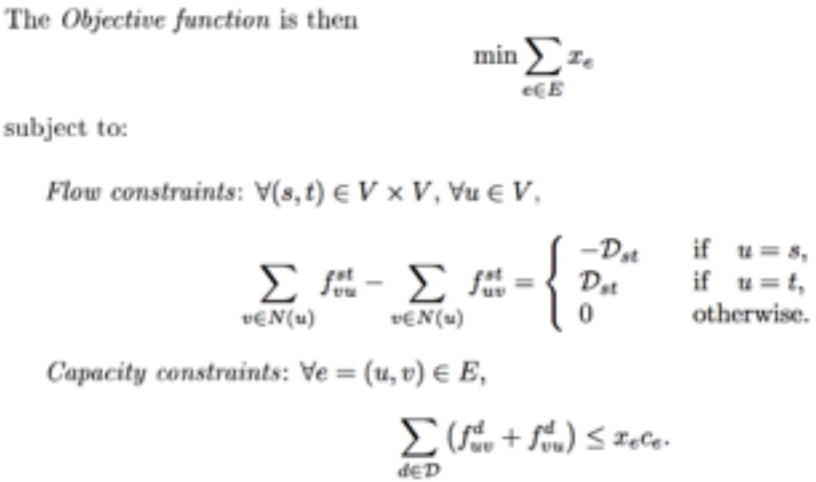
- Topologies extracted from SNDLib
- Tested how many interfaces can be spared for different ranges of operation on 10 topologies
- Also looked at the impact on route length and on fault protection



[Greencom 2010]
[Chapter 2012]

EAR Modelling

Linear program



The *Objective function* is then

$$\min \sum_{e \in E} x_e$$

subject to:

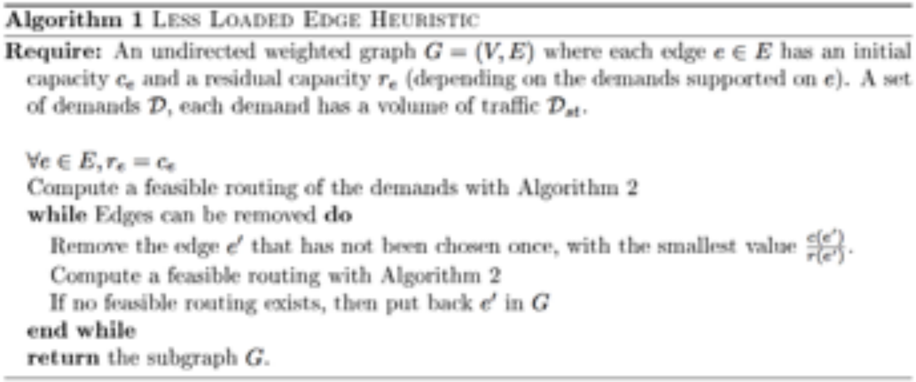
Flow constraints: $\forall (s,t) \in V \times V, \forall u \in V,$

$$\sum_{v \in N(u)} f^{st}_{vu} - \sum_{v \in N(u)} f^{st}_{uv} = \begin{cases} -\mathcal{D}_{st} & \text{if} \quad u = s, \\ \mathcal{D}_{st} & \text{if} \quad u = t, \\ 0 & \text{otherwise.} \end{cases}$$

Capacity constraints: $\forall e = (u,v) \in E,$

$$\sum_{d \in \mathcal{D}} (f^d_{uv} + f^d_{vu}) \leq x_e c_e.$$

Heuristic algorithm

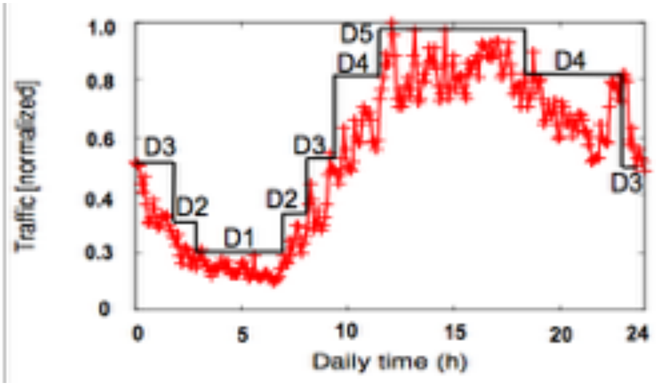


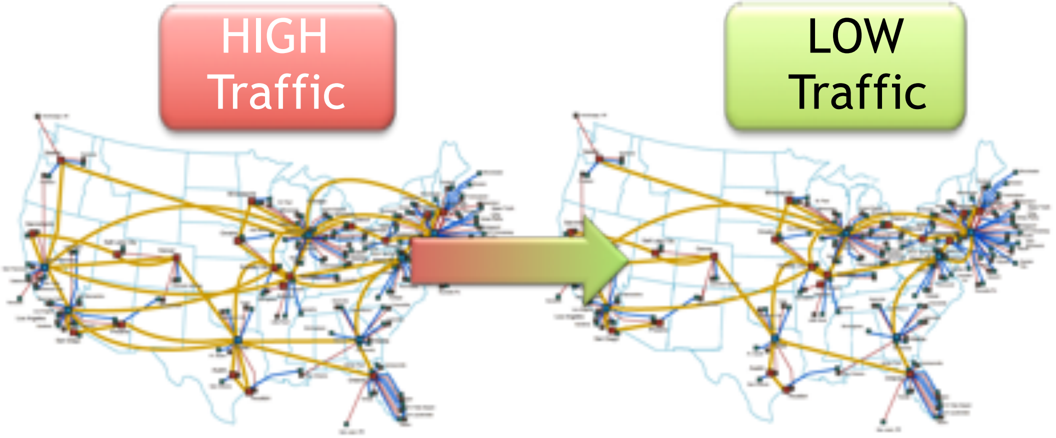
```
Algorithm 1 LESS LOADED EDGE HEURISTIC
Require: An undirected weighted graph $G = (V, E)$ where each edge $e \in E$ has an initial
  capacity $c_e$ and a residual capacity $r_e$ (depending on the demands supported on $e$). A set
  of demands $\mathcal{D}$, each demand has a volume of traffic $\mathcal{D}_{st}$.

  $\forall e \in E, r_e = c_e$
  Compute a feasible routing of the demands with Algorithm 2
  while Edges can be removed do
    Remove the edge $e'$ that has not been chosen once, with the smallest value $\frac{c(e')}{r(e')}$.
    Compute a feasible routing with Algorithm 2
    If no feasible routing exists, then put back $e'$ in $G$
  end while
  return the subgraph $G$.
```

Principle: remove the least loaded edge.

Results on ISP Topologies



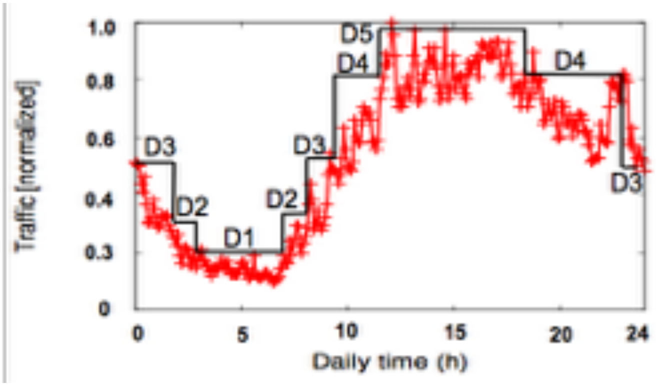


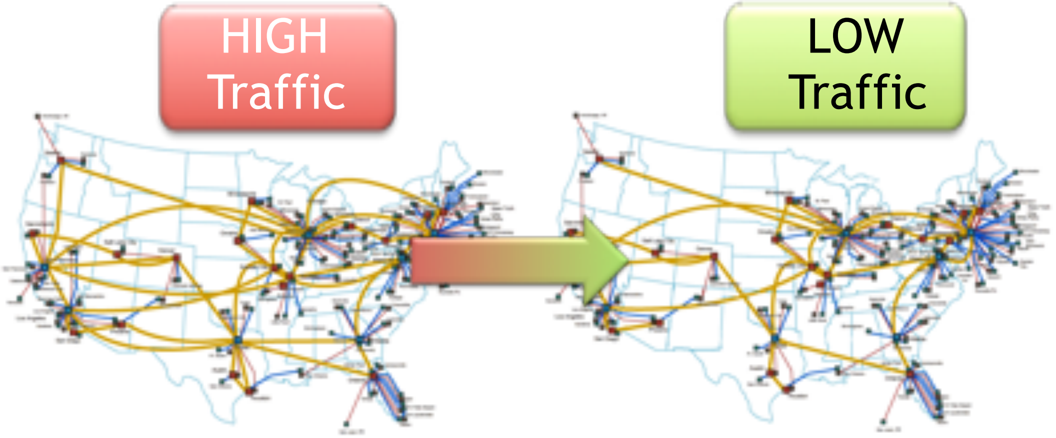
HIGH Traffic

LOW Traffic

- Between 30-60% of spared network equipements for usual range of operations
- But with impact on
  - route length (however limited average impact)
  - failure protection (usually single existing path)

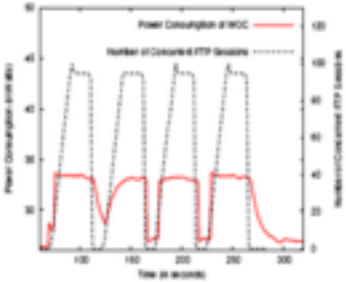
Results on ISP Topologies





- Failure protection:
  - Add fault protection constraints
  - Impact depends on the technology: How long to switch back on vs rerouting time? [experiments of Chap 8]

My contributions



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[ComCom 2015]

[Networking 2012]

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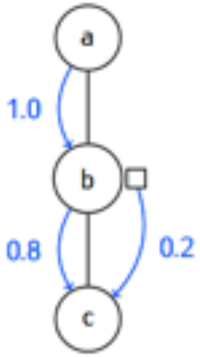
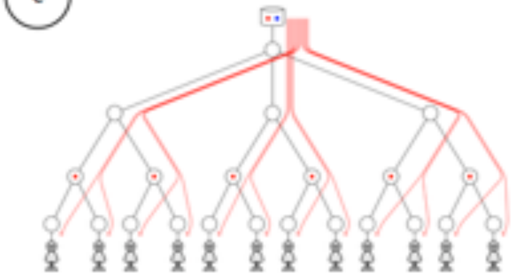
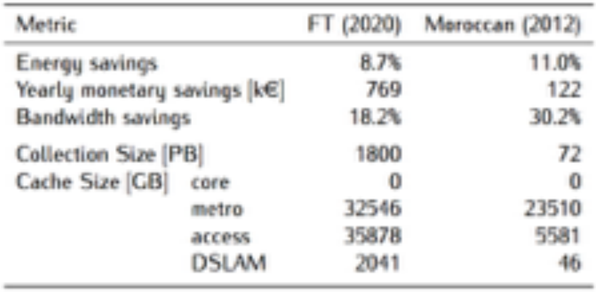


Level(3)
HIGHWINDS
Akamai
Limelight
Ustream





Metric		FT (2020)	Moroccan (2012)
Energy savings		8.7%	11.0%
Yearly monetary savings [k€]		769	122
Bandwidth savings		18.2%	30.2%
Collection Size [PB]		1800	72
Cache Size [GB]	core	0	0
	metro	32546	23510
	access	35878	5581
	DSLAM	2041	46

[CompJ 2016]

[Globecom ICC 2013]

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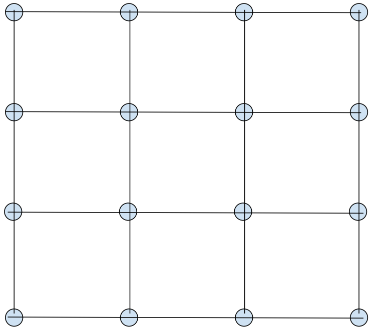


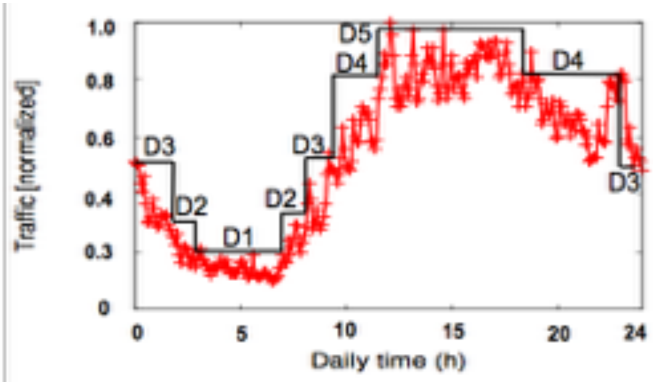
- Using Algorithm Complexity and Graph Theory
  - Hardness results (No-APX) [Chap. 3.1]
  - Theoretical bounds for specific topologies (grids, rings, trees, etc...) and all-to-all [Chap. 4]
    - Grid [Chap 4.2]
    - Given a number of edges and nodes, what are the graphs with the lowest forwarding indices? [Chap. 4.3]

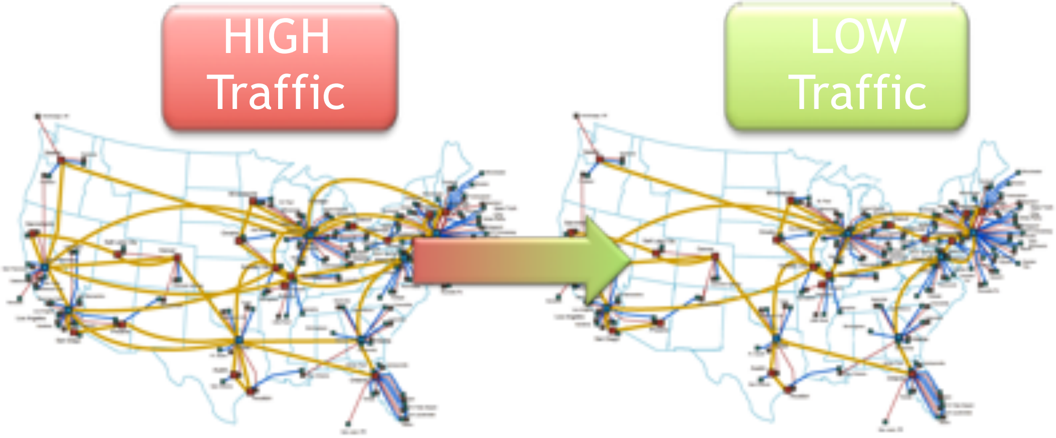
[DAM 2018]

[Inoc Iwoca 2015]

Energy Efficiency

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

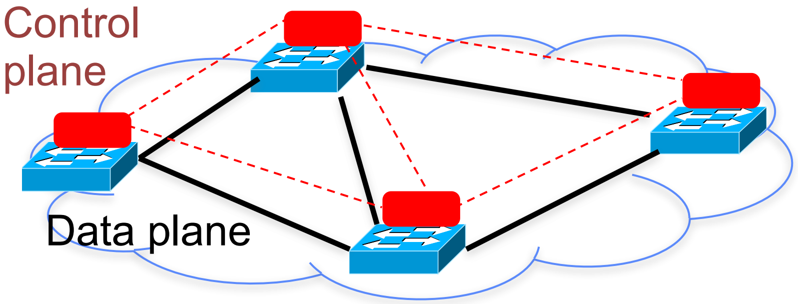




Other applications: energy efficient data centers (virtual machine assignment), wireless networks (base-station assignment)…

Legacy networks

However, network operators reluctant to change the routing.



- **Router=closed systems.** Any change has to be done **manually.**

- Networks are managed by complex **configurations.**

—> Important difficulties to deploy new protocols

-> Energy efficient solutions **not yet successfully implemented** in networks.

Routing: A new Context

- Career Routing. Introduction

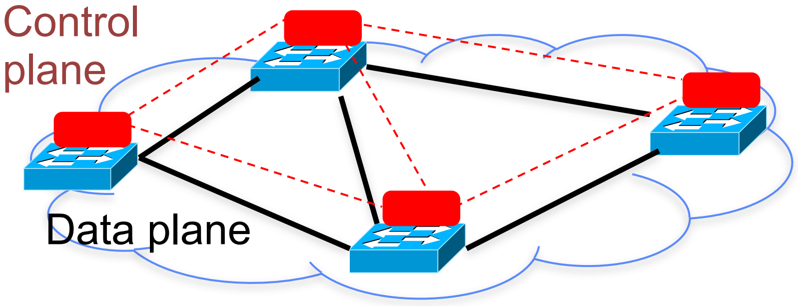
1. Routing in an energy aware world.
   (Part I)

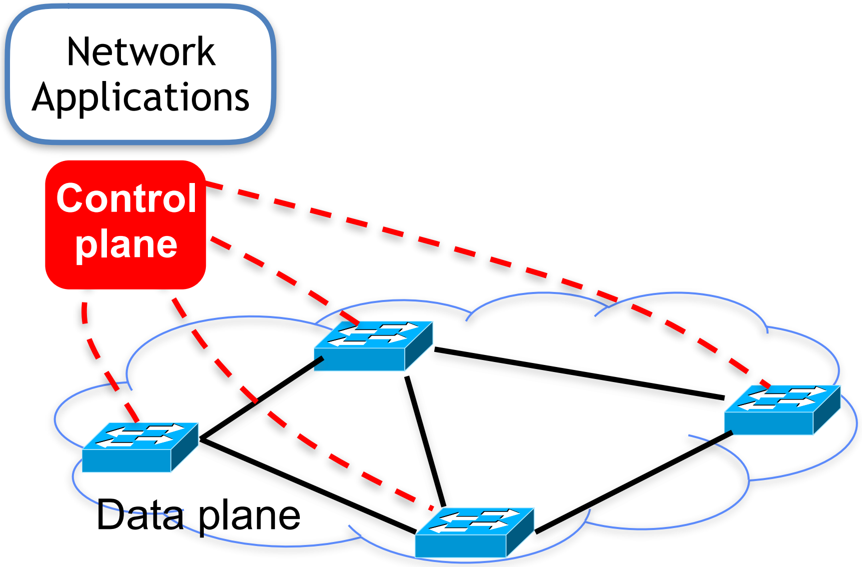
2. Routing in an SDN world without (a lot of) rules.
   (Part 2. Chapter 6)

3. Routing in a virtualized world.
   (Part 2. Chapter 7)

- End of the route ? Conclusions and Perspectives

Software Defined Networks





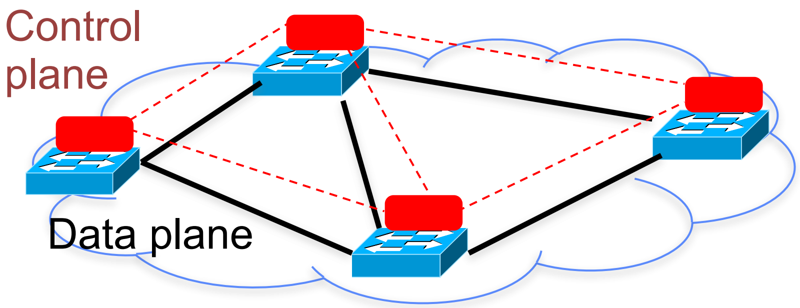
- **Router=closed systems.** Any change has to be done **manually.**
- Networks are managed by complex **configurations.**

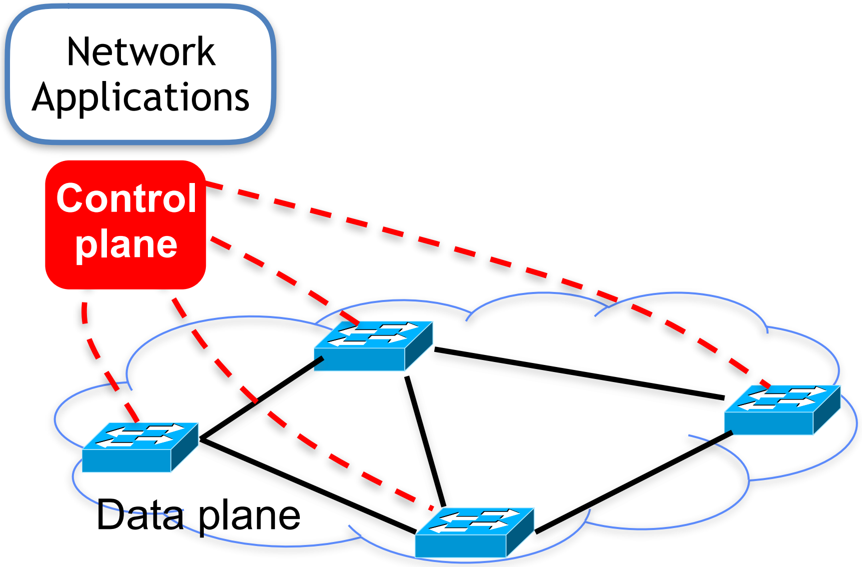
—> Important difficulties to deploy new protocols

- Intelligence implemented by a **centralized controller** managing **elementary** switches
- SDN conceives the network as a **program.**

—>Allows the deployment of advanced (dynamic) protocols

Software Defined Networks





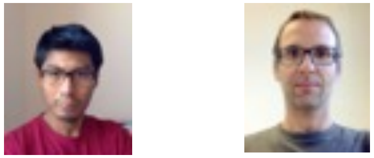
—> SDN has the potential to put into practice energy efficient solutions

- Intelligence implemented by a **centralized controller** managing **elementary** switches
- SDN conceives the network as a **program.**

—>Allows the deployment of advanced (dynamic) protocols

SDN and Energy efficiency

- Topic of a project between COATI and SIGNET



- Inside the axis Energy of labex UCN@Sophia
- Two Ph.D. students:
  - Nicolas Huin, 2014-2017
  - Myriana Rifai, 2014-2017

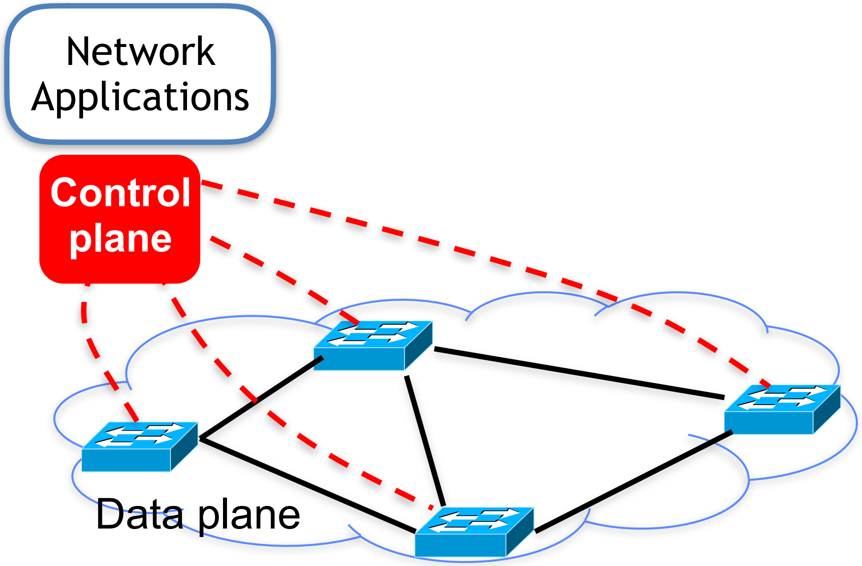
Software Defined Networks

- Pushed by open source communities + large software and telecommunication companies.
  - **Large eco-system:** Open Flow / Open Day Light / Open Stack / Open vSwitch
  - **Software companies:** Google B4 large scale experiment on its inter-data center networks [Jain 2013].

B4 worldwide deployment (2011)

  - **Telcos:** e.g. AT&T targets 75% of network functions as a software by 2020.

SDN Challenges



- **Defining the architecture.**
  - e.g. northbound **APIs** to enable real network programmability
- **Security**
  - e.g. single point of failure
- **Scalability of the SDN environment**
  - e.g. avoiding Control – Data Plane communications overhead

- **avoiding excessive flow table entries**

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

40 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

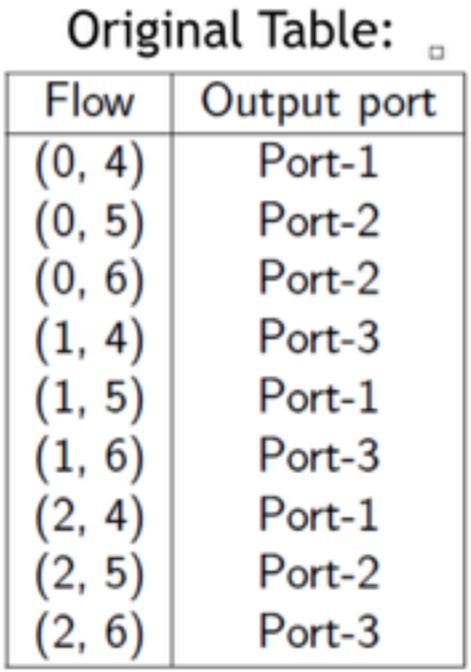
- **Split and distribute the rules** in network [cohen et al. 14]

- Use a minimum number of paths. Xpath: **Relabeling and aggregation of paths** [Hu et al, '15].
  -> Increased path length and thus delay

- Decrease rule size by matching only on **small tag in packet header** [Kannan et al, '13][Banerjee et al, '14].
  -> Need to modify end hosts.

- Our solution: **Compressing using wildcard rules.**

Compression problem

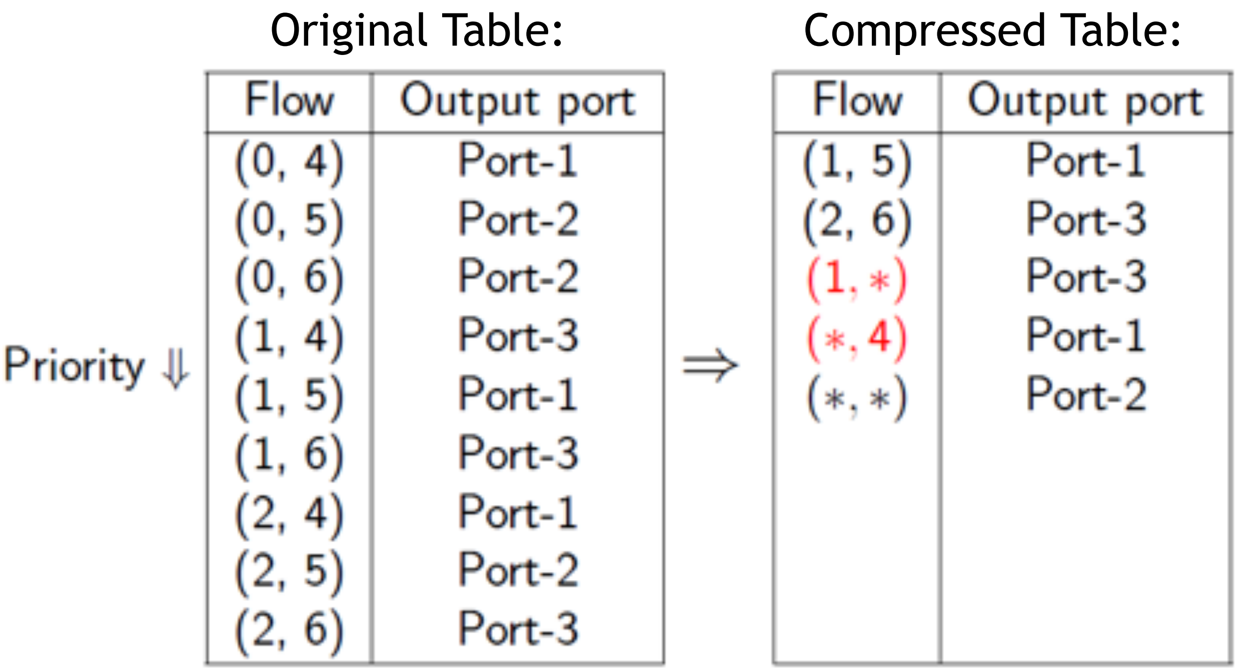


Original Table:

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

⇒

Compressed Table:

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

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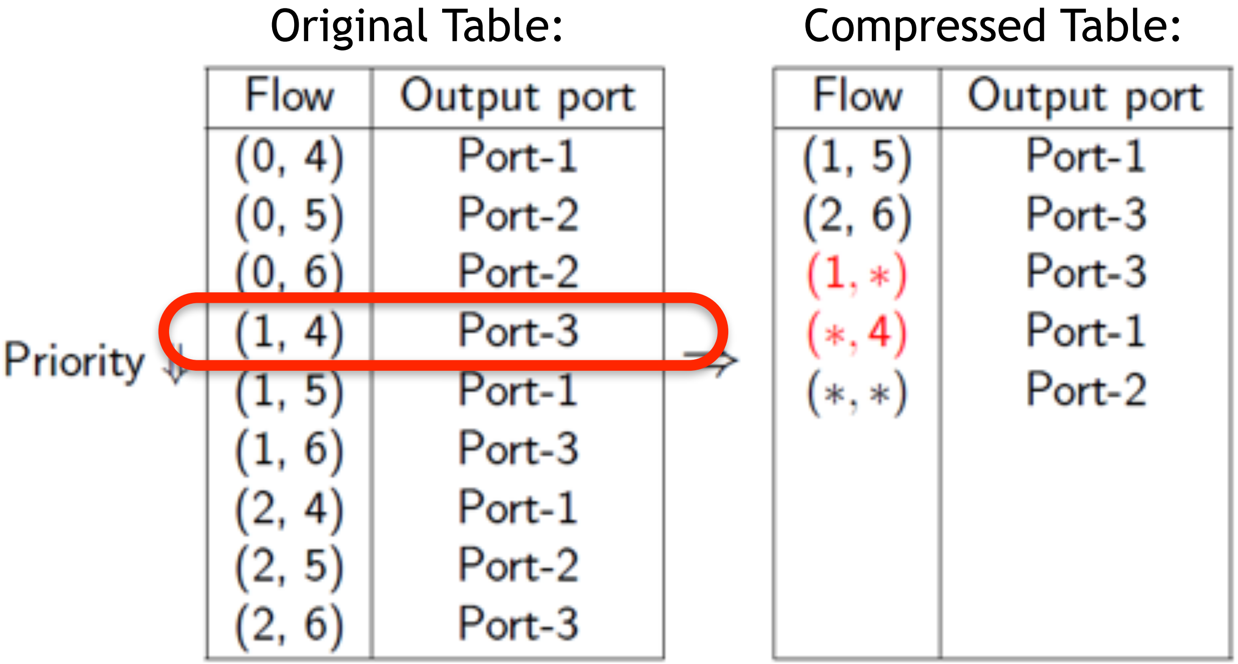

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(2, 6)	Port-3

Priority ↓

⇒

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(∗, ∗)	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

Problem: how to routing using compression while minimizing energy consumption.

My Method

- Algorithmic complexity
- Efficient solutions
  - with proved warranties
  - Optimization methods
  - Heuristic solutions
  - Decompose the problem
- Test in practice
  - Simulations
  - Experimentations

Contributions

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Contribution 1: Compressing two dimensional routing tables with orders

- **Algorithmic complexity**
  - Link with a classic graph problem, **Feedback Arc Set**.
  - Hardness results:
    - Polynomial pour 1 port
    - **NP-complete** 2 ports or more

Solved on open problem stated in [Suri et al. Algorithmica 2003]

- **Efficient solutions with proved warranties**
  - 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.

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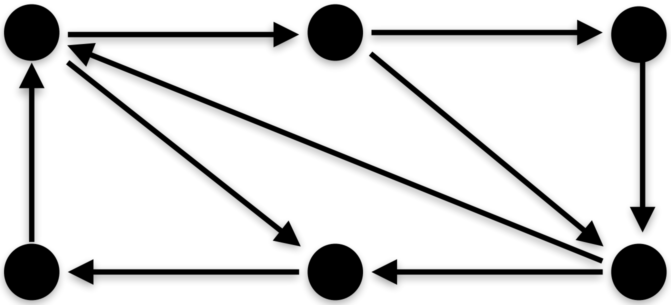
Feedback Arc Set: set of edges removing all cycles in a digraph



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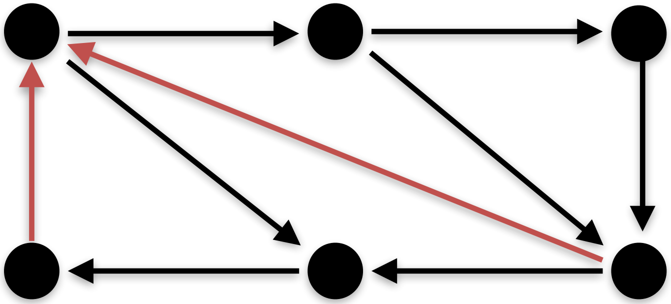
Feedback Arc Set: set of edges removing all cycles in a digraph



Decision problem: “can all cycles be broken by removing k edges?” is one of Karp’s NP-complete problem.

Contribution 1: Compressing two dimensional routing tables with orders

Link with Feedback Arc Set: A simple example with 2 ports

(Src, Dst)	Output port
(1, 2)	**0**
(1, 4)	**0**
(3, 1)	**0**
(3, 2)	**1**
(3, 4)	**1**
(4, 5)	**0**
(6, 1)	**1**
(6, 4)	**0**
(6, 5)	**0**

Representation as a matrix

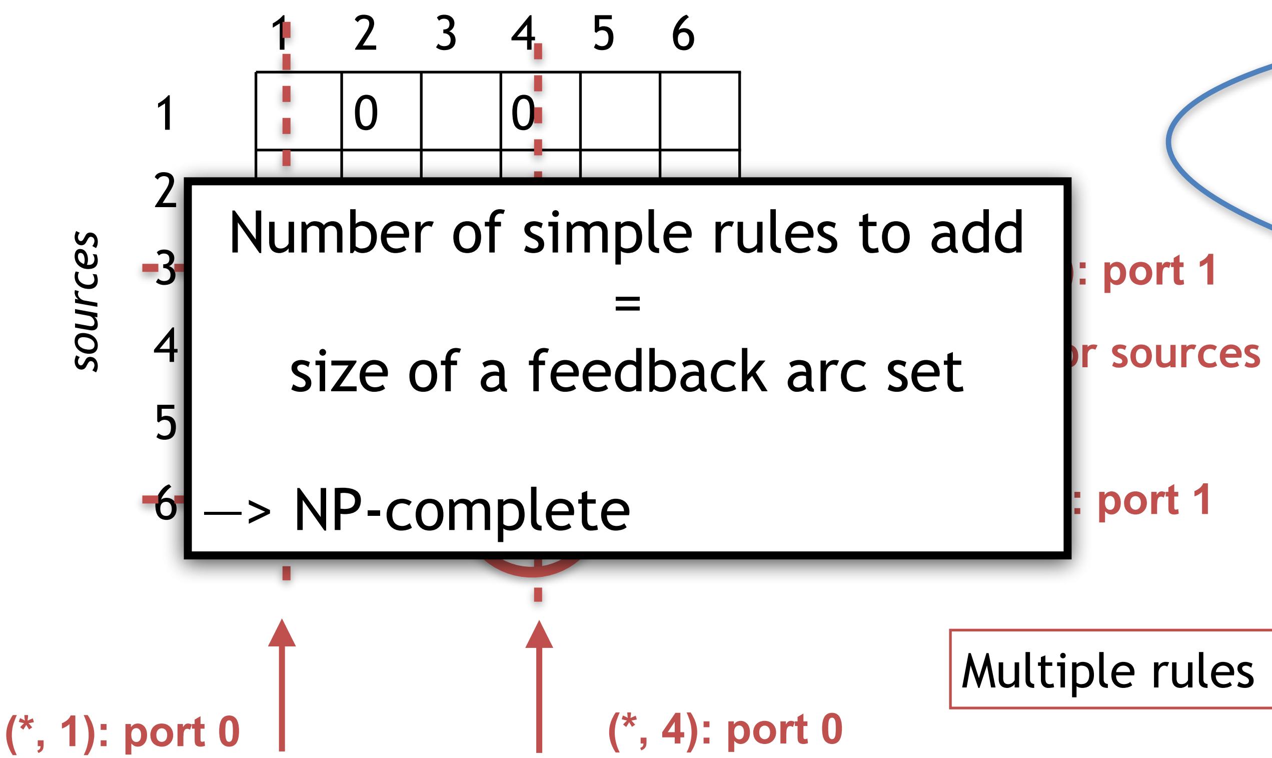
destinations

sources

	1	2	3	4	5	6
1		0		0		
2						
3	0	1		1		
4					0	
5						
6	1			0		0

Contribution 1: Compressing two dimensional routing tables with orders

A simple example with 2 ports



Number of simple rules to add

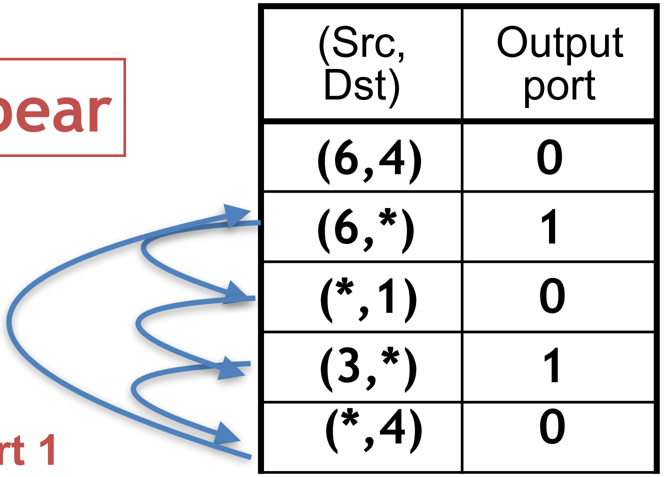
=

size of a feedback arc set

—> NP-complete

Aggregation for destinations

Cycle appear



(Src, Dst)	Output port
(6,4)	**0**
(6,*)	**1**
(*,1)	**0**
(3,*)	**1**
(*,4)	**0**

Multiple rules -> importance of order

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Used for practical applications presented later

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

Direction-Based Heuristic

Compress using source aggregation, destination aggregation or default rule
$\Rightarrow$ Take the best table

- For each source `s`, **# source aggregation**
  - Find the most occurring port k.
  - Add the aggregation rule `(s,*):k`
  - Keep the non matching rules `(s,t):k'` with higher priority

  -> Table T_s

- Do the same for each destination `t` **# destination aggregation**

  -> Table T_t

- Find the most occurring port **# default port**
  Add the aggregation rule `(s,*):k`
  Keep the non matching rules `(s,t):k'` with higher priority

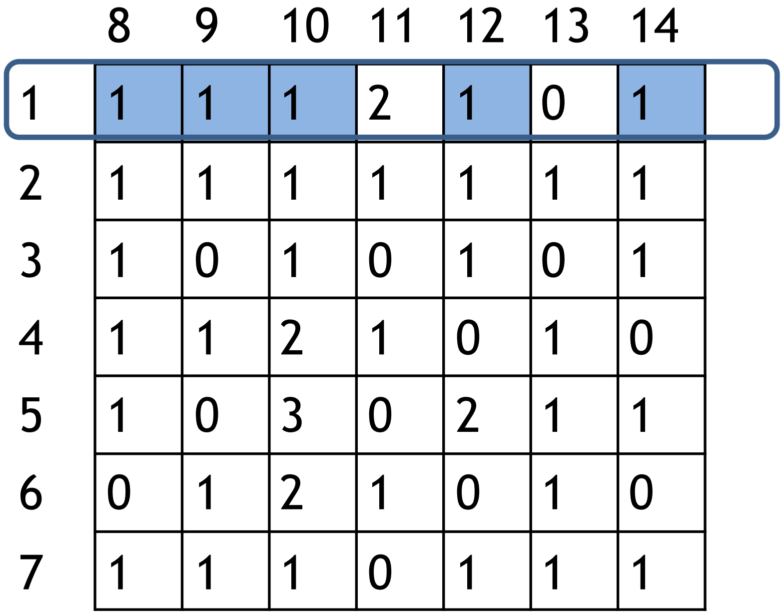
  -> Table T_d

- Choose min(T_s,T_t, T_d)

Direction-Based Heuristic

	8	9	10	11	12	13	14
1	1	1	1	2	1	0	1
2	1	1	1	1	1	1	1
3	1	0	1	0	1	0	1
4	1	1	2	1	0	1	0
5	1	0	3	0	2	1	1
6	0	1	2	1	0	1	0
7	1	1	1	0	1	1	1

Direction-Based Heuristic



	8	9	10	11	12	13	14
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3	1	0	1	0	1	0	1
4	1	1	2	1	0	1	0
5	1	0	3	0	2	1	1
6	0	1	2	1	0	1	0
7	1	1	1	0	1	1	1

(1,11)→2
(1,13)→0
(1,*)→1

(Src, Dst)	Output
(1, 11)	**2**
(1, 13)	**0**
(1, *)	**1**

Direction-Based Heuristic

	8	9	10	11	12	13	14
1	1	1	1	2	1	0	1
2	1	1	1	1	1	1	1
3	1	0	1	0	1	0	1
4	1	1	2	1	0	1	0
5	1	0	3	0	2	1	1
6	0	1	2	1	0	1	0
7	1	1	1	0	1	1	1

(2,*)→1

(Src, Dst)	Output
(1, 11)	**2**
(1, 13)	**0**
(1, *)	**1**
(2, *)	**1**

Direction-Based Heuristic

	8	9	10	11	12	13	14
1	1	1	1	2	1	0	1
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5	1	0	3	0	2	1	1
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(3,9)→0
(3,11)→0
(3→13)→0
(3,*)→1

(Src, Dst)	Output
(1, 11)	**2**
(1, 13)	**0**
(1, *)	**1**
(2, *)	**1**
(3,9)	**0**
(3,11)	**0**
(3,13)	**0**
(3,*)	**1**

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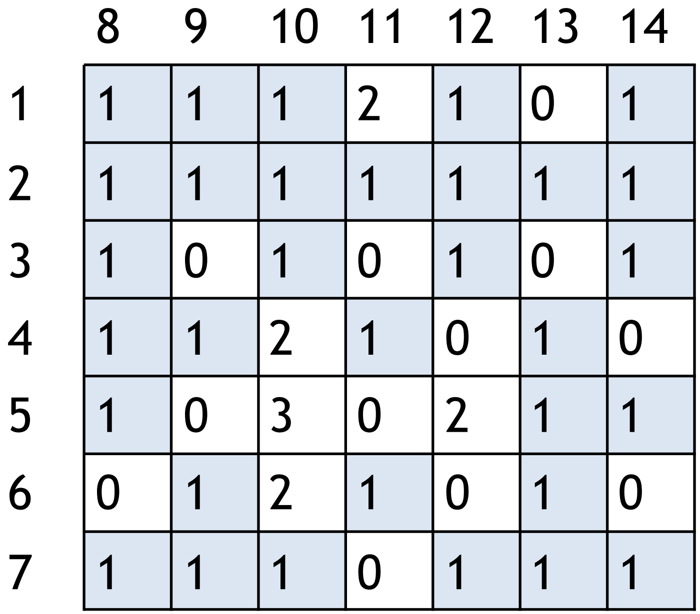
(6,8)→0
(*,8)→1

The heuristic does the same for the destinations.

Direction-Based Heuristic



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7	1	1	1	0	1	1	1

Table :
Non matching rules
Default rule (*,*)→1

Theorem: This gives a 3-approximation of the List-reduction problem:

Input: A set C of communication triples and integer z

Output: sav(C) is the maximum number of saved rules.

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FPT Algorithms

FPT **Algorithms**: computation time in

$$f(z) \cdot |x|^{O(1)}$$

with

- z (well chosen) parameter,
- f any function.

⇒ if z is small, inputs can be solved by brute force.

Theorem: For every l ≥ 1, List-Reduction-with-k-ports admits a linear kernel and so is FPT.

A rule is **isolated** if its shares neither source nor destination.

Kernelization algorithm:

1- Remove isolated rules ⇒ table S_1.

2- Apply the Destination-Based Heuristic ⇒ table T .

3- If $|S_1| - |T|$ = $sav_{DBH}(S_1) \geq z$, return 'Yes'.
Else return T.

Proof of validity: If T is returned, we show that $|T| \leq (4z - 4)k$.

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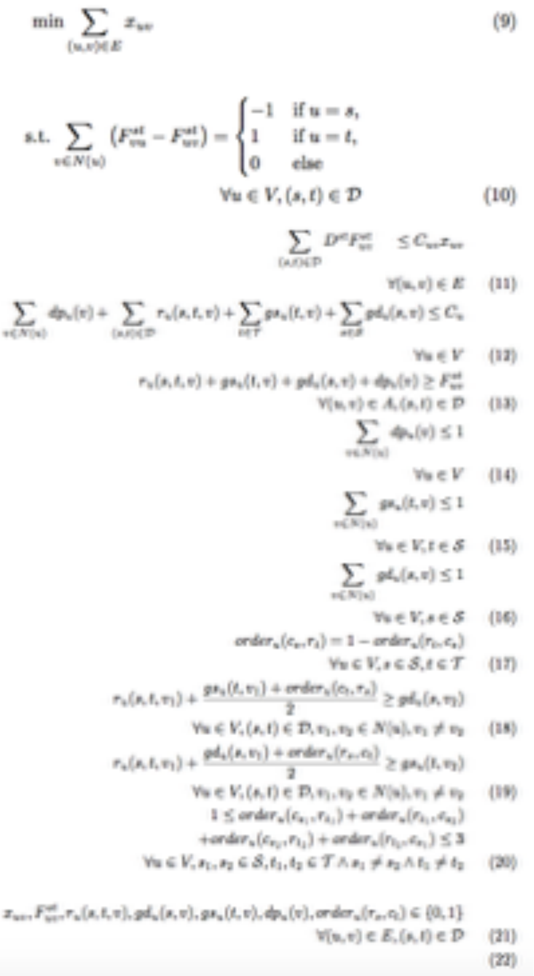
Contribution 2: Energy efficient routing in an SDN ISP network.

Problem can be modeled by an **ILP.**

The ILP **runs for a small network:** Atlanta.

Propose several **efficient heuristic solutions** (using different compression methods) for larger networks.



$$\min \sum_{(u,v)\in E} x_{uv} \tag{9}$$

$$\text{s.t.} \sum_{v\in N(u)} \left(F^{st}_{vu} - F^{st}_{uv}\right) = \begin{cases} -1 & \text{if } u = s, \\ 1 & \text{if } u = t, \\ 0 & \text{else} \end{cases} \qquad \forall u \in V, (s,t) \in \mathcal{D} \tag{10}$$

$$\sum_{(s,t)\in\mathcal{D}} D^{st} F^{st}_{uv} \le C_{uv} x_{uv} \qquad \forall (u,v) \in E \tag{11}$$

$$\sum_{v\in N(u)} dp_u(v) + \sum_{(s,t)\in\mathcal{D}} r_u(s,t,v) + \sum_{t\in\mathcal{T}} ga_u(t,v) + \sum_{s\in\mathcal{S}} gd_u(s,v) \le C_u \qquad \forall u \in V \tag{12}$$

$$r_u(s,t,v) + ga_u(t,v) + gd_u(s,v) + dp_u(v) \ge F^{st}_{uv} \qquad \forall (u,v) \in A, (s,t) \in \mathcal{D} \tag{13}$$

$$\sum_{v\in N(u)} dp_u(v) \le 1 \qquad \forall u \in V \tag{14}$$

$$\sum_{v\in N(u)} ga_u(t,v) \le 1 \qquad \forall u \in V, t \in \mathcal{S} \tag{15}$$

$$\sum_{v\in N(u)} gd_u(s,v) \le 1 \qquad \forall u \in V, s \in \mathcal{S} \tag{16}$$

$$order_u(c_s, r_t) = 1 - order_u(r_t, c_s) \qquad \forall u \in V, s \in \mathcal{S}, t \in \mathcal{T} \tag{17}$$

$$r_u(s,t,v_1) + \frac{ga_u(t,v_1) + order_u(c_s, r_t)}{2} \ge gd_u(s,v_2) \qquad \forall u \in V, (s,t) \in \mathcal{D}, v_1, v_2 \in N(u), v_1 \ne v_2 \tag{18}$$

$$r_u(s,t,v_1) + \frac{gd_u(s,v_1) + order_u(r_t, c_s)}{2} \ge ga_u(t,v_2) \qquad \forall u \in V, (s,t) \in \mathcal{D}, v_1, v_2 \in N(u), v_1 \ne v_2 \tag{19}$$

$$1 \le order_u(c_{s_1}, r_{t_1}) + order_u(r_{t_1}, c_{s_2}) + order_u(c_{s_2}, r_{t_2}) + order_u(r_{t_2}, c_{s_1}) \le 3 \qquad \forall u \in V, s_1, s_2 \in \mathcal{S}, t_1, t_2 \in \mathcal{T} \wedge s_1 \ne s_2 \wedge t_1 \ne t_2 \tag{20}$$

$$x_{uv}, F^{st}_{uv}, r_u(s,t,v), gd_u(s,v), ga_u(t,v), dp_u(v), order_u(r_s, c_t) \in \{0,1\} \qquad \forall (u,v) \in E, (s,t) \in \mathcal{D} \tag{21}$$

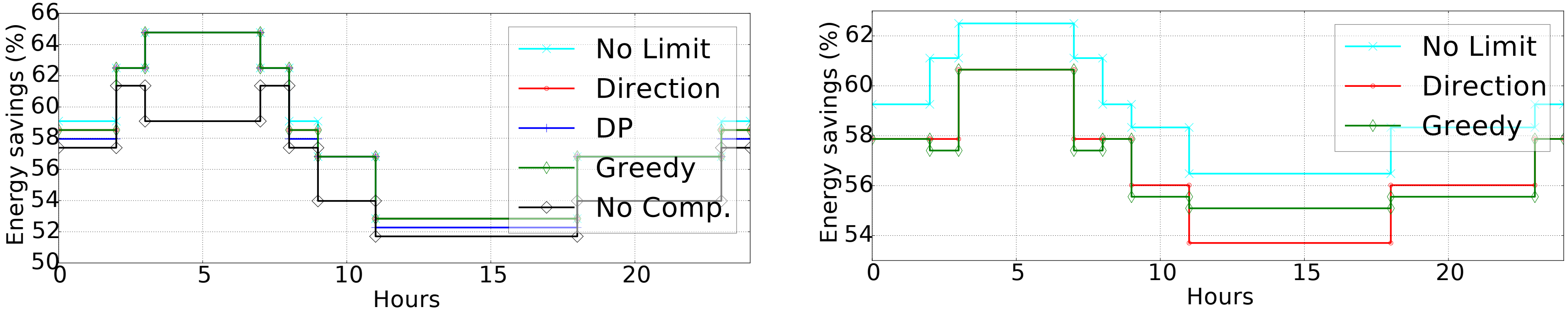
(22)

(a) atlanta (b) germany50 (c) zib54

(d) ta2

Contribution 2: 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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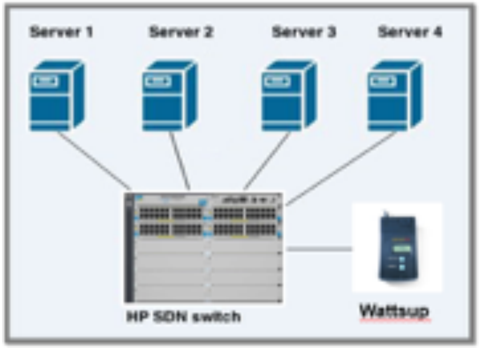
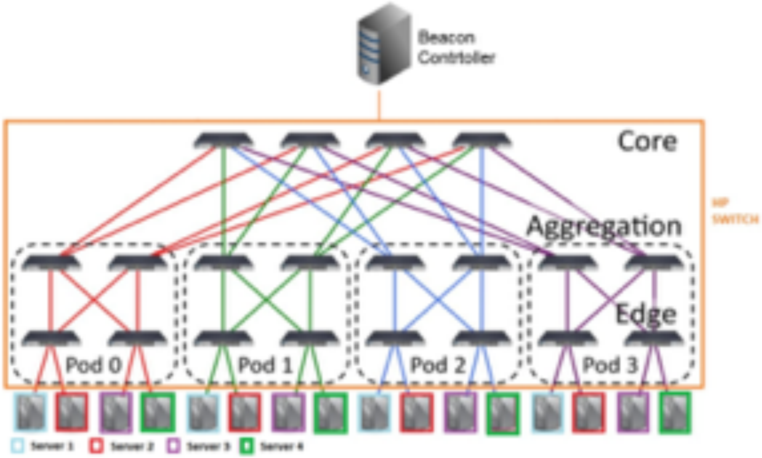
Contribution 2: Experiments for a data center network

- Small experimental platform.

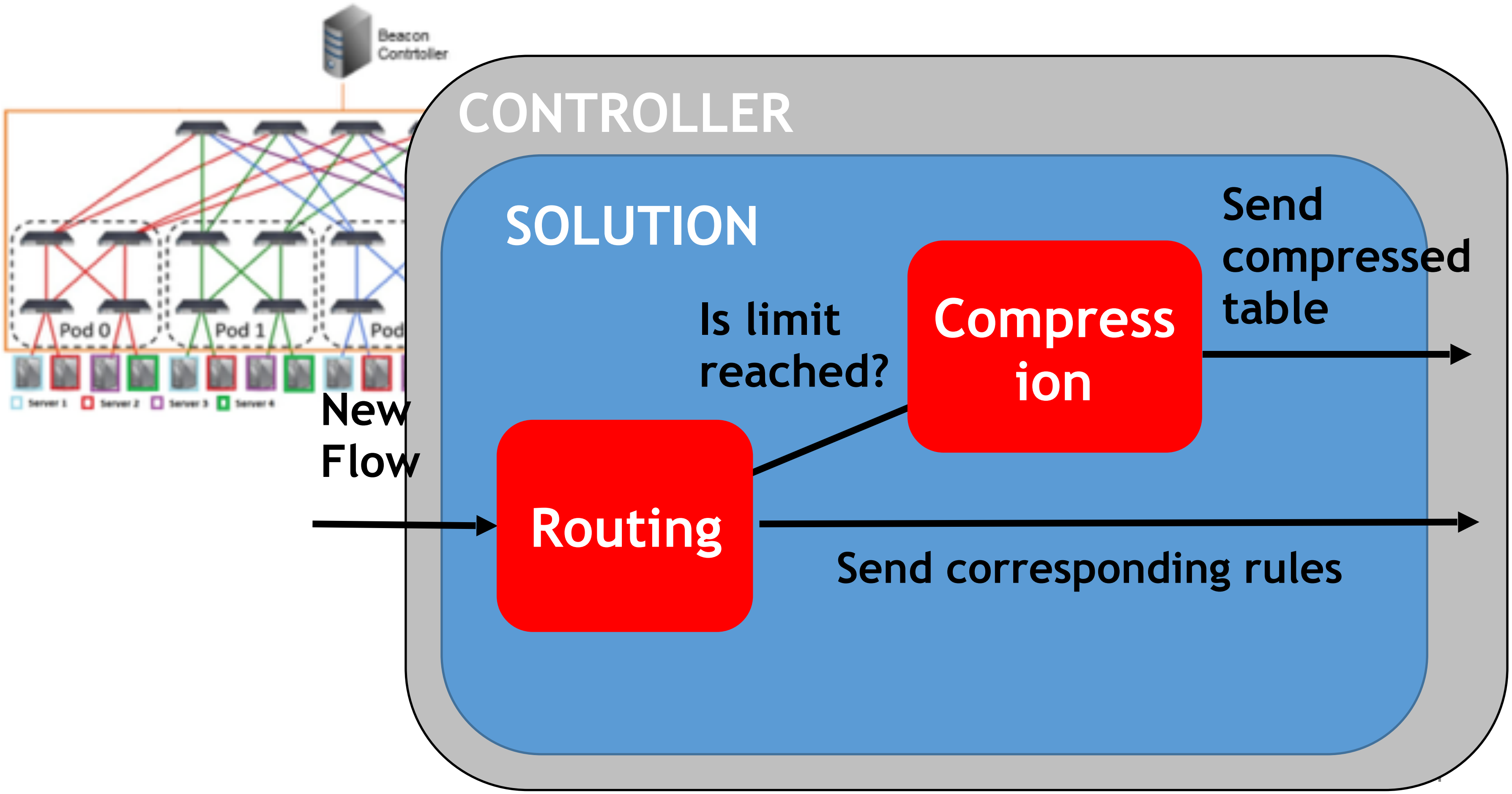




-> allowed to test impact of contacts to controller and controller optimizations

  - on packet delay
  - on packet losses

Contribution 2: Experiments for a data center network



CONTROLLER

SOLUTION

New Flow

Routing

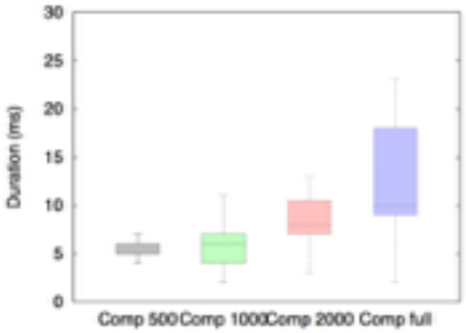
Is limit reached?

Compression

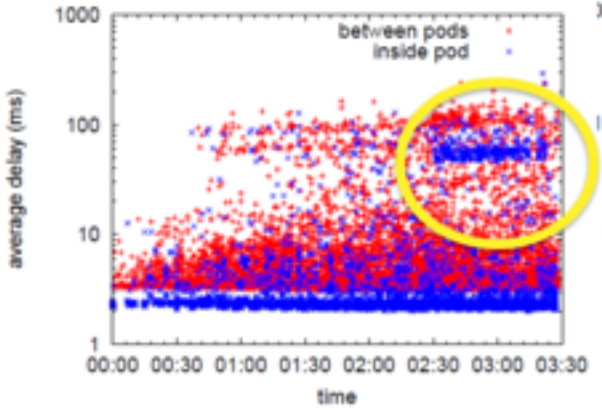
Send compressed table

Send corresponding rules

Contribution 2: Experiments for a data center network

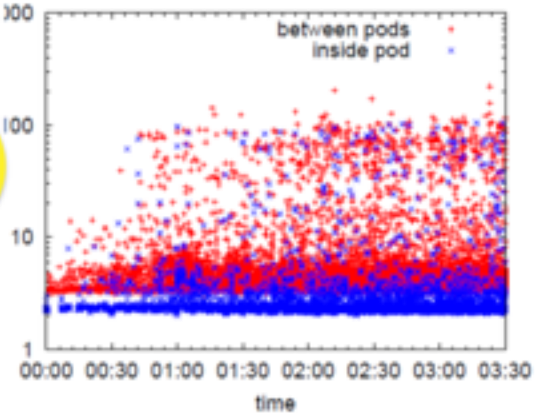


Time compression+ table modification = few ms



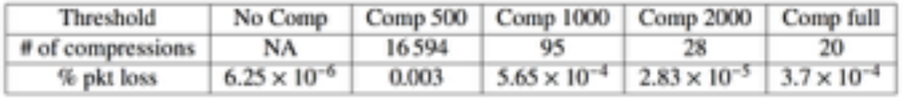
Without Compression

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



With Compression

No problem. Delay is not increased.



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}

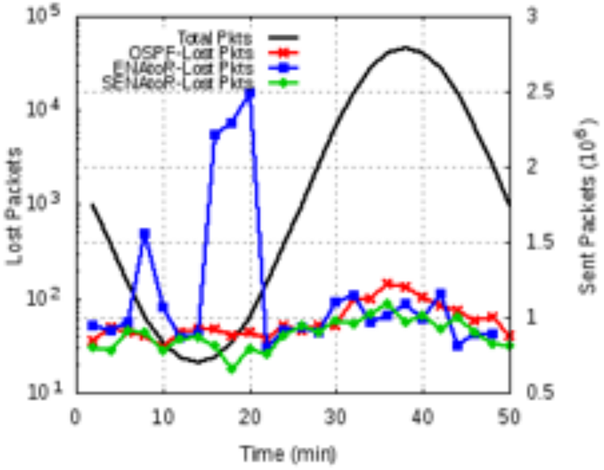
Loss rate ≈0%

Part 2 - Conclusions

- We provided efficient algorithms for doing multifield compression of routing tables: compression rates from 66 to 90%.

- Solutions for routing in an SDN world in datacenter or ISP networks
  - using compression
  - with smooth dynamic equipment extinction [Chap8]
    [Trans. Green Networking 18. Globecom 17.]

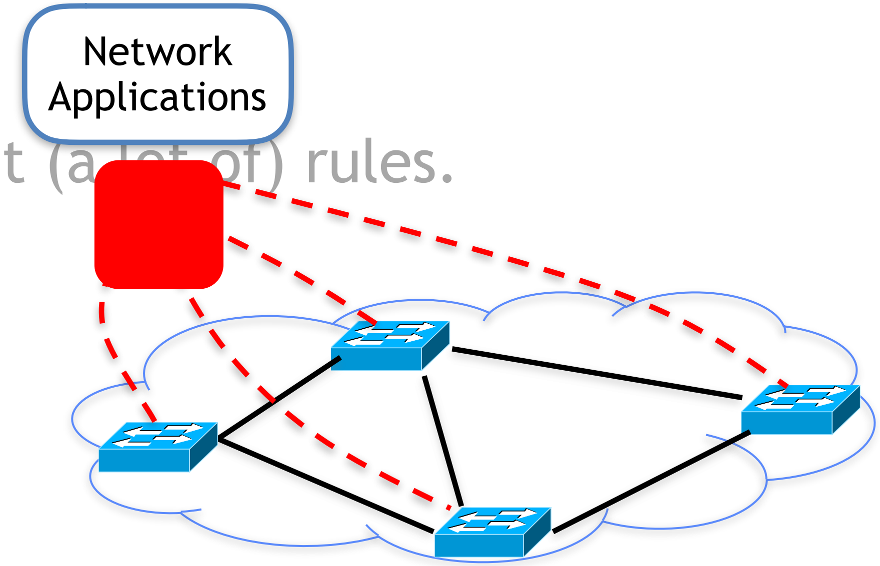
  - while preserving network stability.
    - no increased delay
    - no impact on failure rate
    - failure tolerant



Routing: A new Context

- Career Routing. Introduction

1. Routing in an energy aware world.
   (Part I)
2. Routing in an SDN world without (a lot of) rules.
   (Part 2. Chapter 6)
3. Routing in a virtualized world.
   (Part 2. Chapter 7)



- End of the route ? Conclusions and Perspectives

Network Function Virtualization

- Legacy networks implements network functions using expensive specific hardware called middleboxes.

- The NFV initiative allows functions to be run on general hardware using Virtual Machines.

Network Function Virtualization

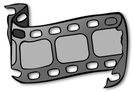
- Legacy networks implements network functions using expensive specific hardware called middleboxes.

- The NFV initiative allows functions to be run on general hardware using Virtual Machines.

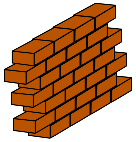
- Solve problems of cost, capacity rigidity, management complexity, and failures

Service Function Chaining

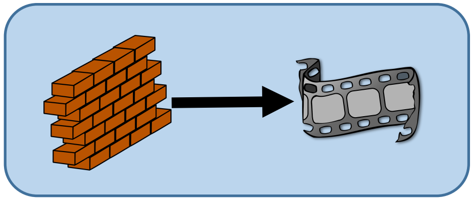
Service Function Chain: **ordered** chain of network functions to apply to flows on the network


Video optimization

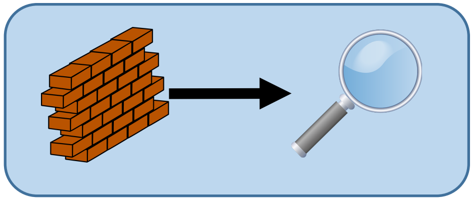

Deep packet inspection


Firewall

SFC A



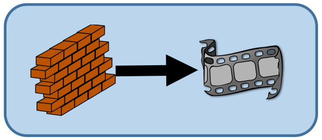
SFC B



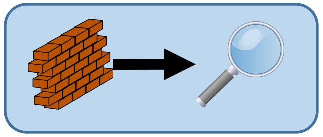
Problem: place VNFs to satisfy the **ordering constraints** of the flows with the goal of **minimizing the total setup cost** (e.g. license fees, network efficiency, or energy consumption)

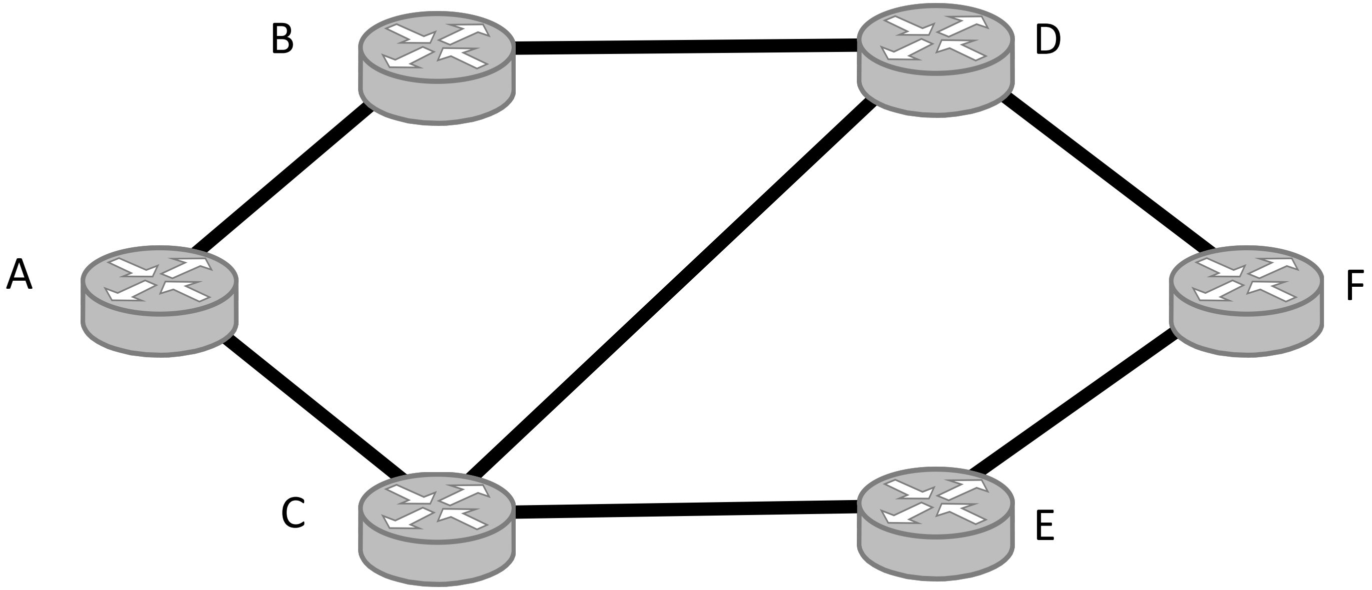
Example of Service Function Chains

3 flows: A to F — SFC A



A to E
F to C } SFC B





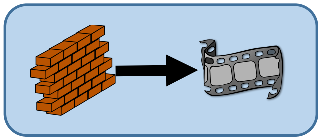
Example of Service Function Chains

3 flows: A to F

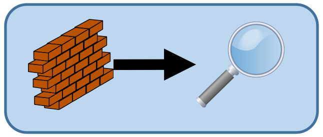
A to E

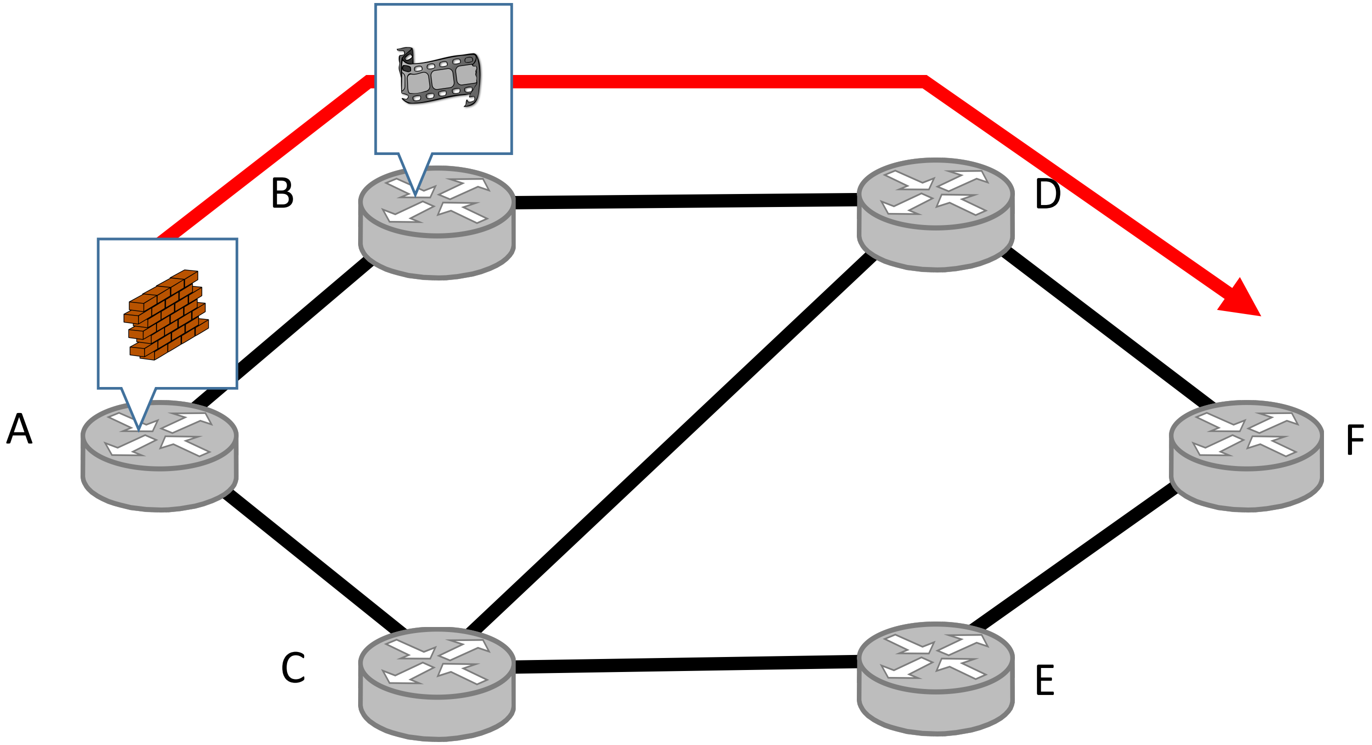
F to C

SFC A



SFC B





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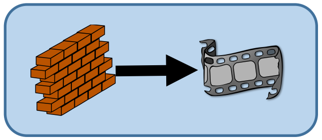
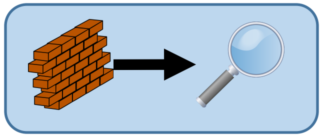
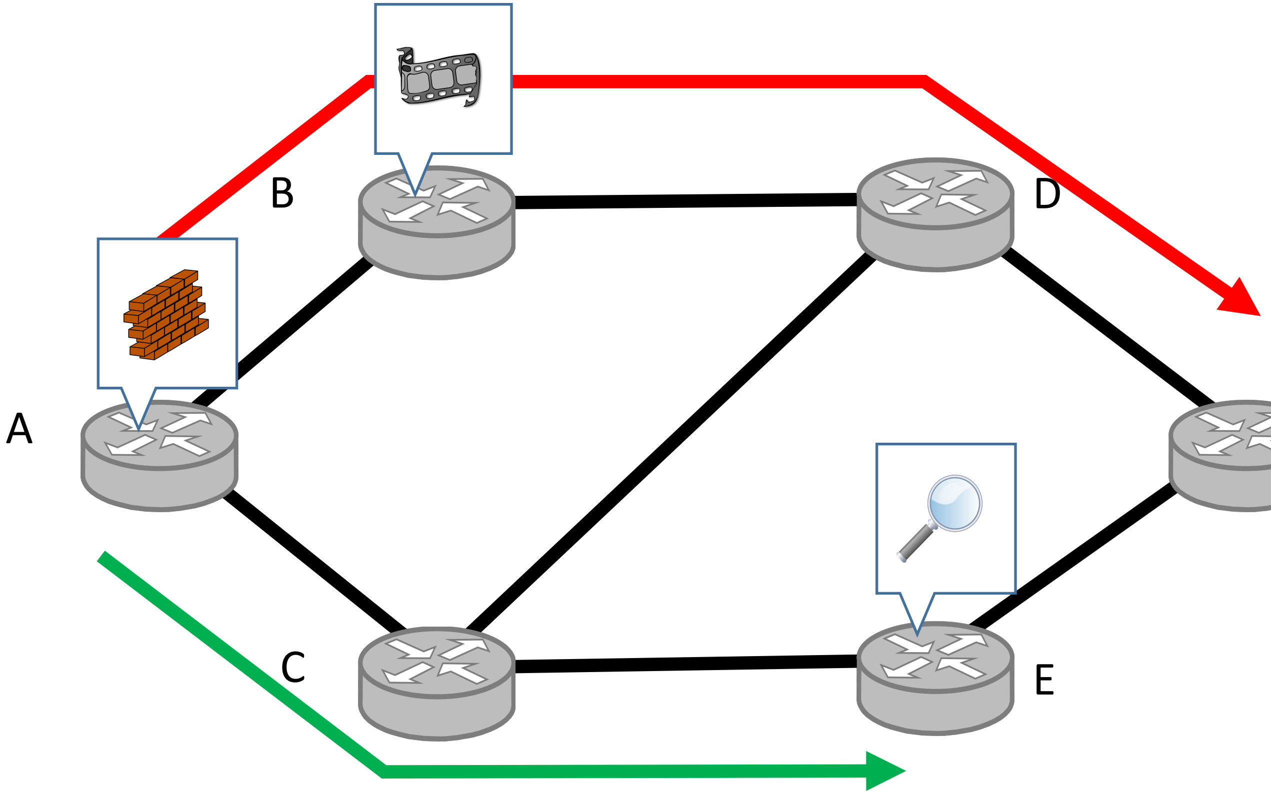


A to E }
F to C } SFC B

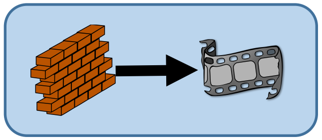


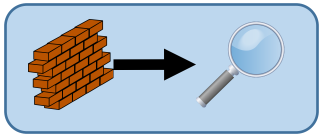


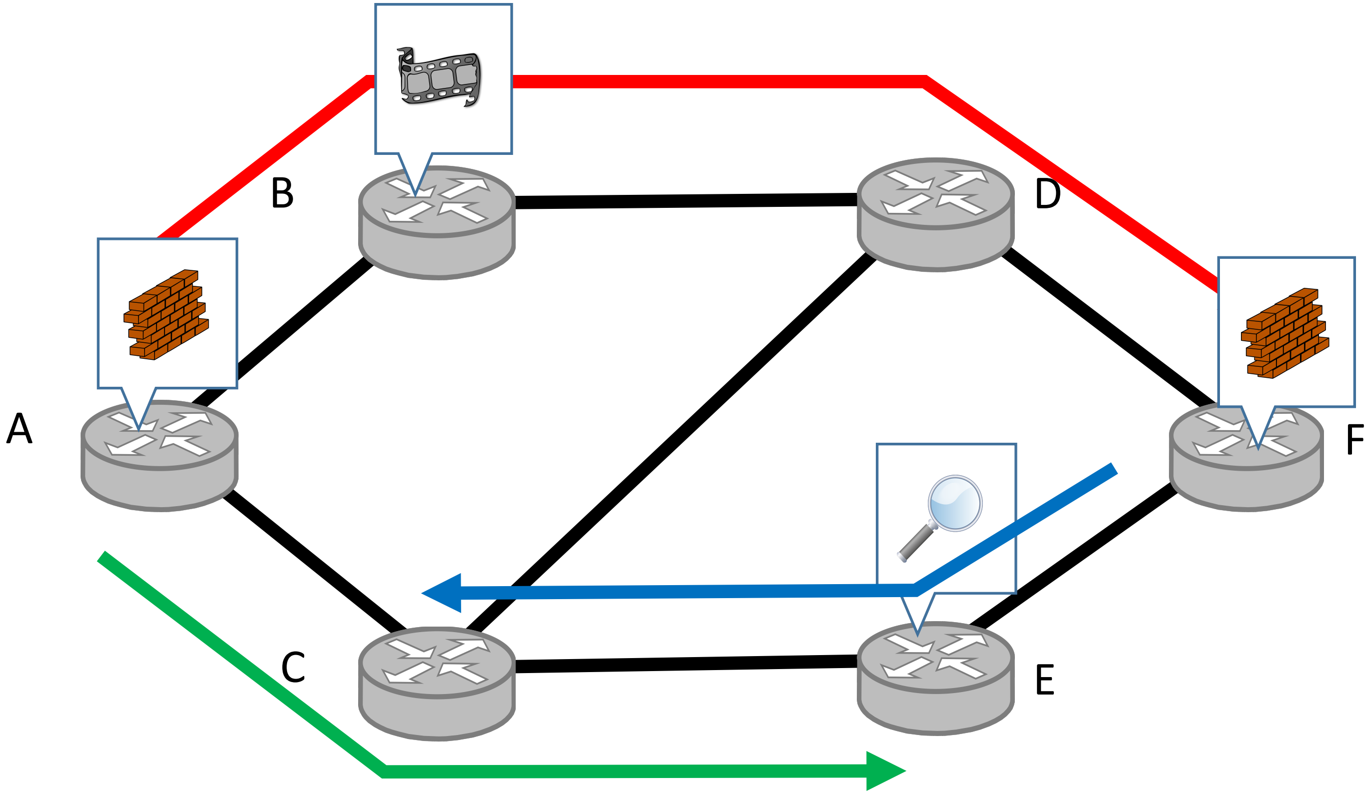
Example of Service Function Chains

3 flows: A to F SFC A

A to E }
F to C } SFC B







Related Work

- Heuristics
  - [Kuo et al. Infocom 2016] Maximizing the total number of admitted demands -> no warranties

- ILP based
  - [Mehraghdam et al. Cloudnet 2014] Minimizing the number of used nodes or the latency of the paths.

-> problem of scalability

- Approximation Algorithms
  - [Cohen et al. Infocom 2015] Minimizing setup cost near-optimal approximation algorithms with theoretically proven performance.
  - [Sang et al. Infocom 2017] Minimizing the total number of network functions. But one single network function.

-> *leave the placement of virtual functions with chaining constraint as an open problem.*

Contributions

- **Service Function Chain provisionning**
  1. using **Column Generation** [Several papers including ICC 2017-2018, ToN 2018]

     -> improved the scalability of ILP models

  2. with **Approximation Algorithms** [INFOCOM 2018]

     -> *"First approximation algorithms taking into account ordering constraints."*

     \+ optimal on trees + validation

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- End of the route ? Conclusions and Perspectives

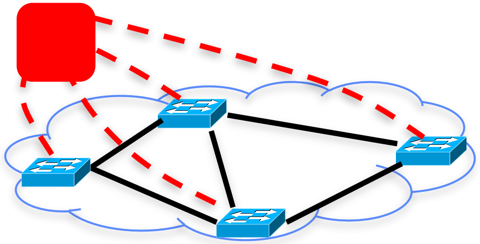
Conclusion

- I solved several problems of routing and placement of (virtual) resources.

- Lots remains to be done.

Current work and Perspectives

- Several major revolutions:
    - Diffusion in the industry of software defined networks
    - of network virtualization
    - Convergence network and data center architectures
    - 5G/IoT/M2M

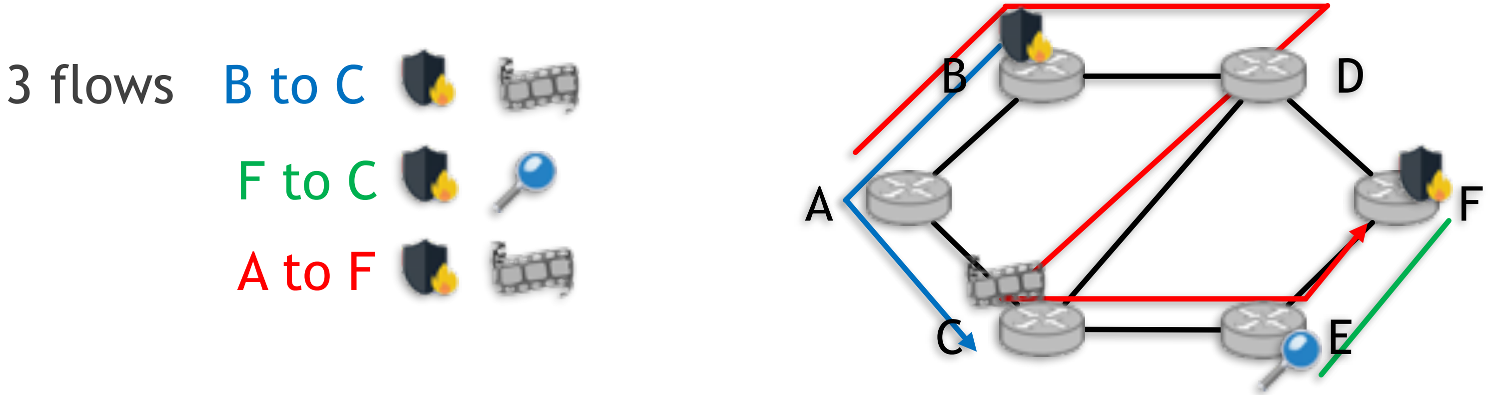


-> New algorithmic problems.

Perspectives

- Routing and placement of dynamic resources.

  -> study of the reconfiguration of virtual ressources.



3 flows B to C

F to C

A to F

PhD. Adrien Gausseran 2018-2021
(J. Moulierac and N. Nisse)

Perspectives

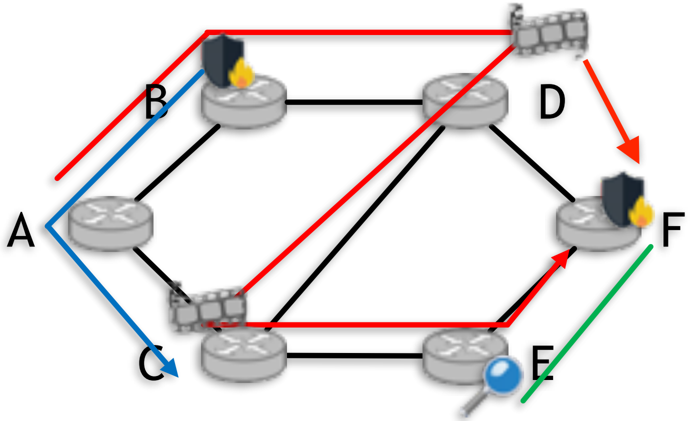
- Routing and placement of dynamic resources.

  -> study of the reconfiguration of virtual ressources.

3 flows B to C 🛡 🎞

F to C 🛡 🔍

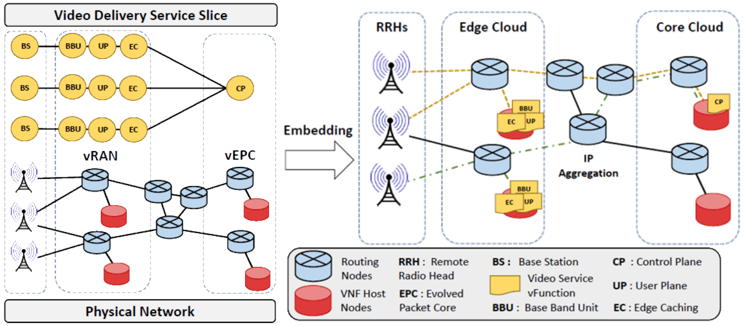
A to F 🛡 🎞

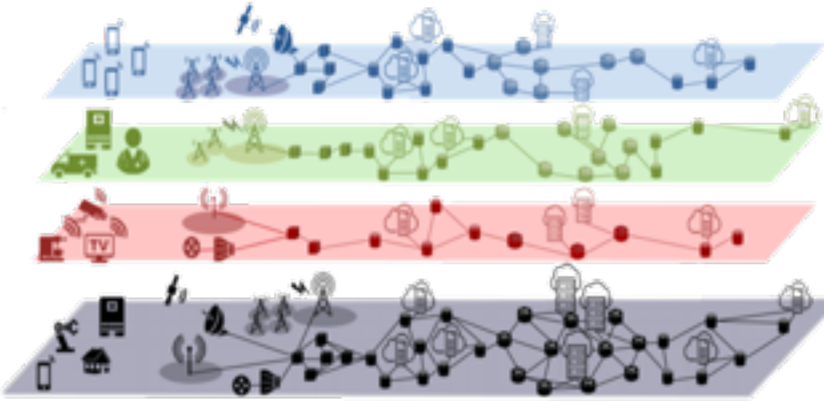


PhD. Adrien Gausseran 2018-2021
(J. Moulierac and N. Nisse)

Perspectives

- Mapping of virtual networks on physical networks. e.g slicing.





Mobile Slices

Critical Slices

IoT Slices

Physical Network

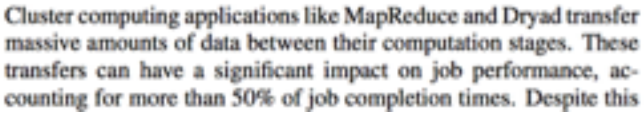
PhDs of A. Gausseran and G. di Lena 2018-2021 (Orange, C. Lac and T. Turletti)

Perspectives

- Joint optimization of applications and network traffic.

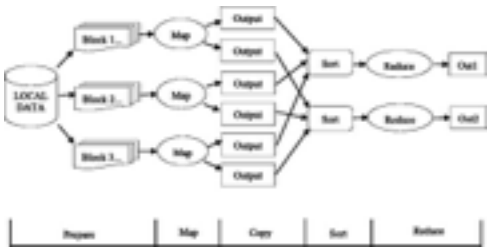
  -> introduction of a new scheduling framework scheduling data center workflows + network routes.

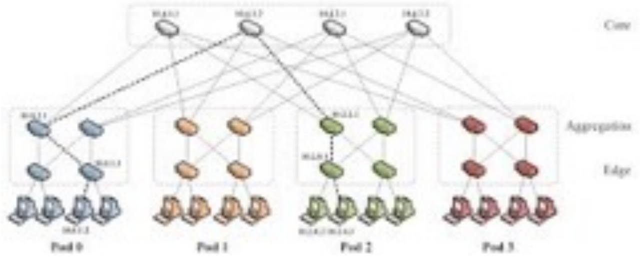
PhD. A. Tomassilli 2016-2019
with S. Pérennes



Cluster computing applications like MapReduce and Dryad transfer massive amounts of data between their computation stages. These transfers can have a significant impact on job performance, accounting for more than 50% of job completion times. Despite this

[SIGCOMM Orchestra 2011]





THANKS FOR YOUR ATTENTION!