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SURVIVABLE ROUTING ARCHITECTURES

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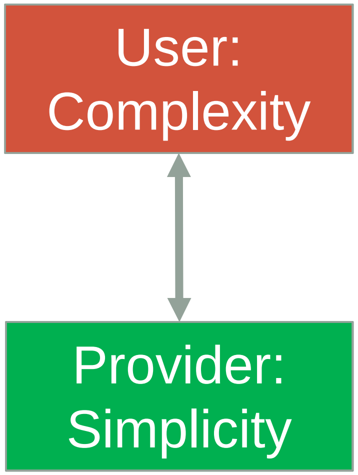
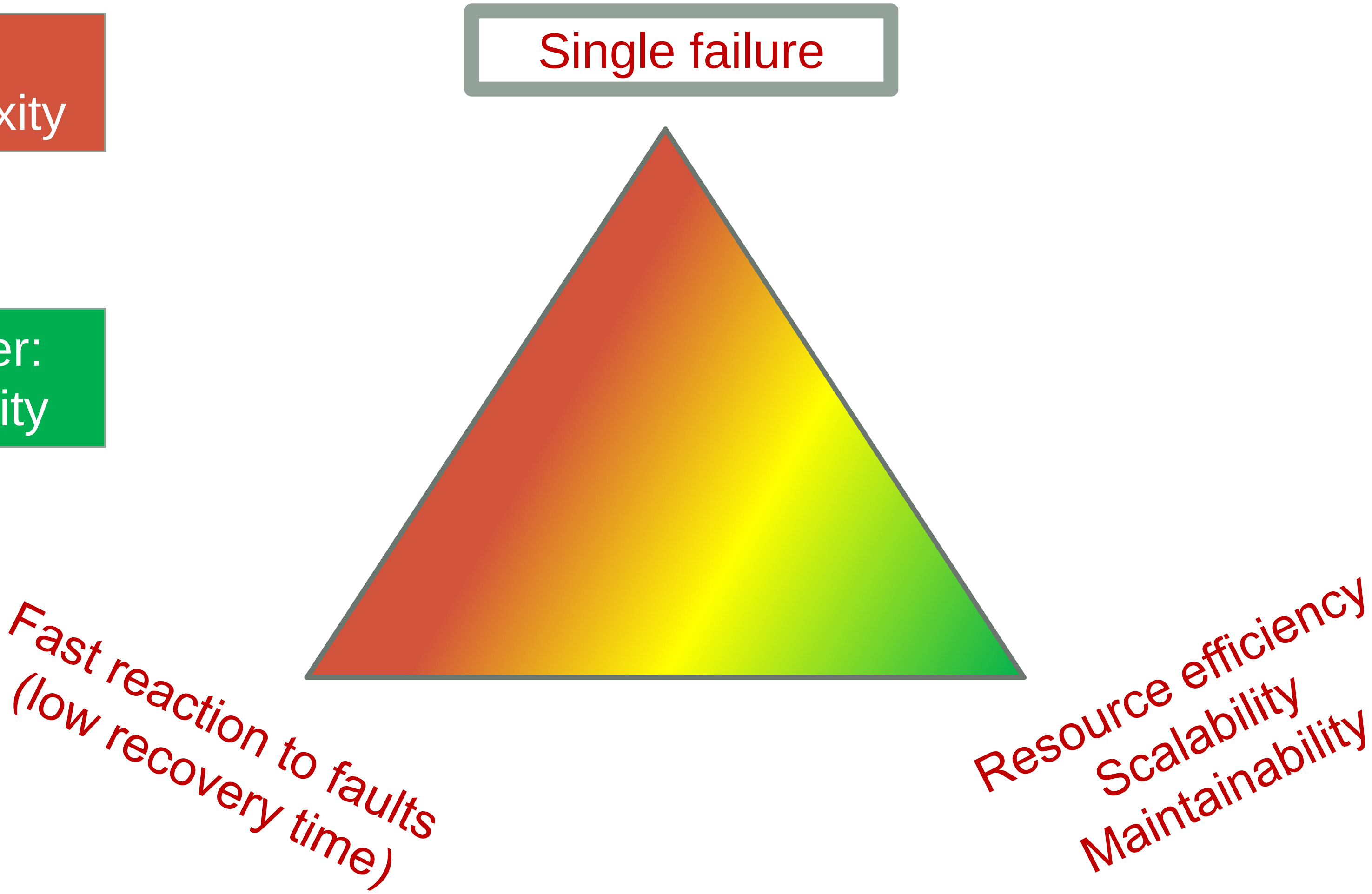
Survivable routing design

Contradicting requirements



User: Complexity

Provider: Simplicity



Single failure

Fast reaction to faults (low recovery time)

Resource efficiency
Scalability
Maintainability

Resource efficiency – recovery time trade-off

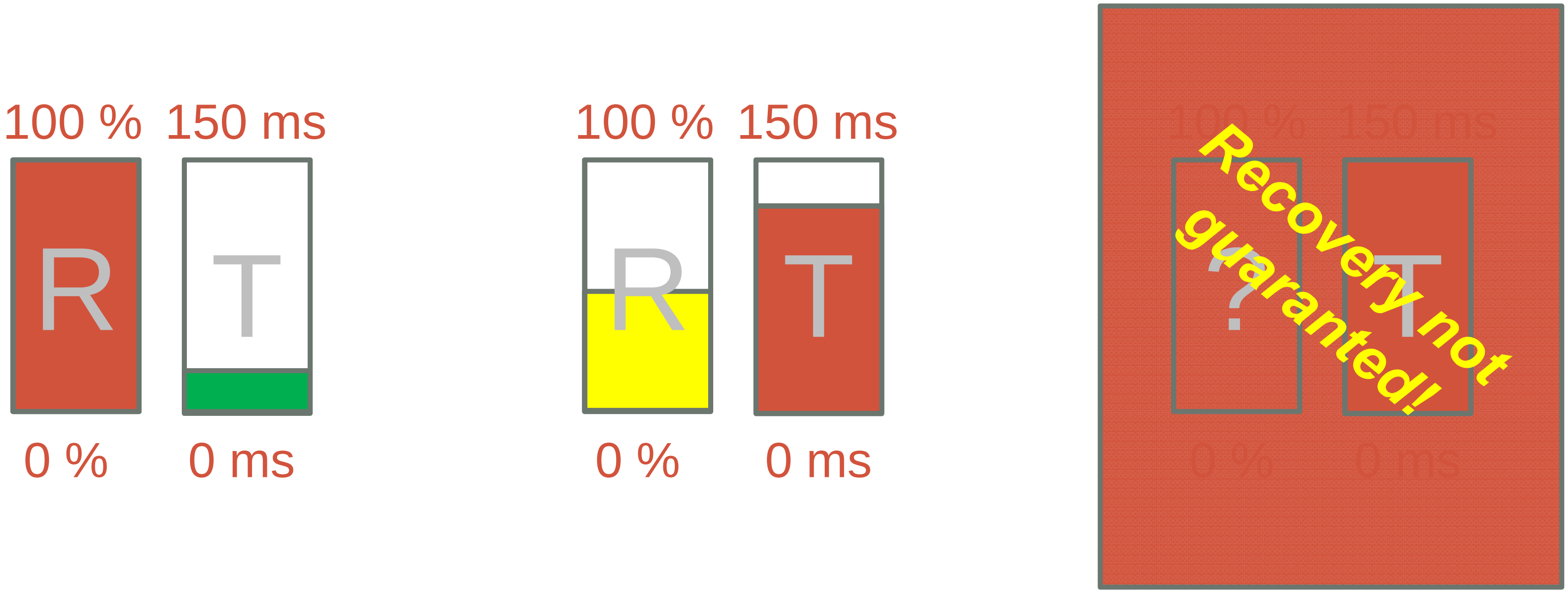
While a pre-defined availability is guaranteed

- Our goal: eliminate, or at least reduce the trade-off with state-of-the-art network coding and failure localization techniques.

Dedicated protection

Pre-planned restoration (Shared protection)

Dynamic restoration



100 % 150 ms R T 0 % 0 ms

100 % 150 ms R T 0 % 0 ms

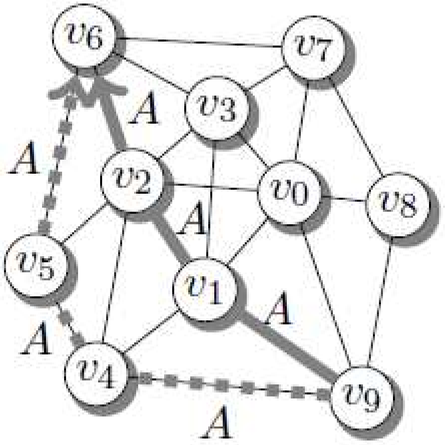
100 % 150 ms ? T 0 % 0 ms

Recovery not guaranteed!

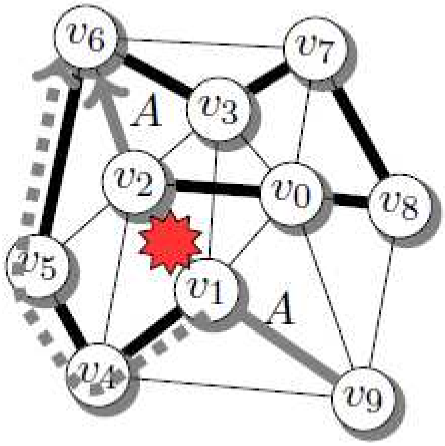
Benchmark dedicated/pre-planned protection methods

Data is sent on the working path (***W-LP***), protection path (***P-LP***) is reserved / configured

- ***1 + 1 protection** – **a survivable routing***
  - The same copy of user data *A* is sent along two disjoint paths between source node $v9$ and destination node $v6$.
  - Upon failure, only switching at the destination node required (simplest method)
  - No control plane signaling (quasi ***instantaneous recovery***)
  - **BUT:** ***More than 100% redundancy***



- ***P-Cycles*** – pre-planned but shared P-LP
  - W-LP $v_9 \rightarrow v_1 \rightarrow v_2 \rightarrow v_6$ is rerouted along the P-LP $v_9 \rightarrow v_1 \rightarrow v_4 \rightarrow v_5 \rightarrow v_6$ upon the on-cycle link failure of (v_1, v_2)
  - ***Resource efficient*** (share P-LP among multiple W-LPs): 60-70% redundancy
  - **BUT:** ***recovery is slow owing to rerouting*** (requires failure localization and switching matrix configuration of 40-50 ms)



SURVIVABLE ROUTING MEETS NETWORK CODING

- Static/dynamic dedicated protection approaches
- Instantaneous recovery with network coding
- MINERVA – Implementing network coding in SDNs

Survivable routing – Network model

Find a minimum cost (single link failure resilient) routing

- Transport network represented by a directed graph $\boldsymbol{G=(V,E,c,k)}$ with node set $\boldsymbol{V}$ and link set $\boldsymbol{E}$,
  - Free capacity $\boldsymbol{k(e)}$, i.e., number of available bandwidth units,
  - Cost $\boldsymbol{c(e)}$, i.e., cost of using one unit of bandwidth along link $\boldsymbol{e}$.
- Given a connection request $\boldsymbol{D=(s,t,d)}$,
  - with information source $\boldsymbol{s}$,
  - with information sink $\boldsymbol{t}$,
  - and the number of bandwidth units $\boldsymbol{d}$ requested for data transmission.
- Output:
  - minimum cost survivable routing in terms of cost function $\boldsymbol{c(e)}$.

  - **Definition** We say that $\boldsymbol{R=(VR,ER,f)}$ is a ***survivable routing*** of a connection $D=(s,t,d)$ in $\boldsymbol{G}$ with $\forall \boldsymbol{e} \in \boldsymbol{ER}$: $\boldsymbol{f(e) \leq k(e)}$, if there is an $\boldsymbol{s-t}$ flow $\boldsymbol{f}$ of value $\boldsymbol{F \geq d}$ in $\mathbf{R}$, even if we delete any single link of $\mathbf{R}$. On the other hand, a routing is *vulnerable* if it is not survivable.

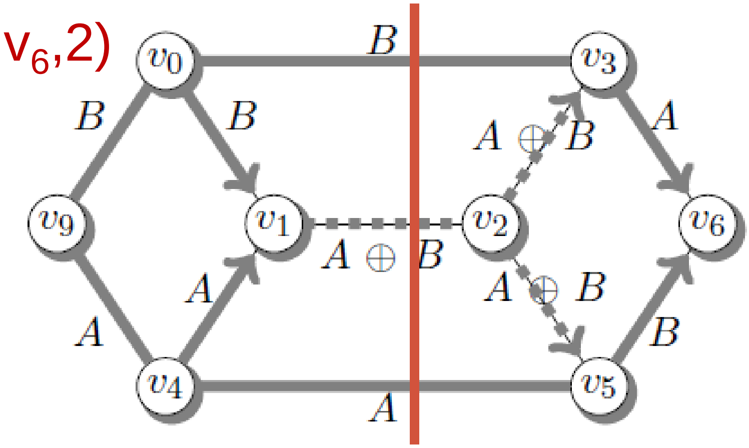
- GOAL: ***no flow rerouting or packet retransmission upon failure***

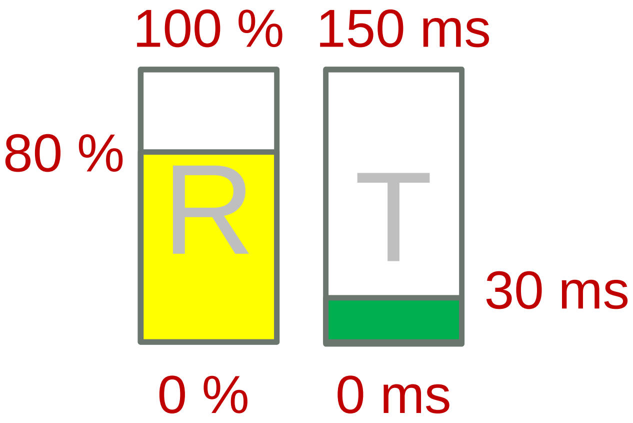
Network coding

Intermediate nodes are allowed to perform algebraic operations on the packets

- After the (link) failure is identified any routing method could be ***adopted and resend the flows*** on the intact edges of a survivable routing **R**, clearly resulting in ***slow recovery***.
- We have to break with the traditional store-and-forward networking concept to deploy optimal survivable routings
  - **(Network) coding is required to ensure *instantaneous recovery***

D=(v_9,v_6,2)

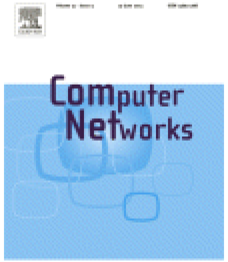




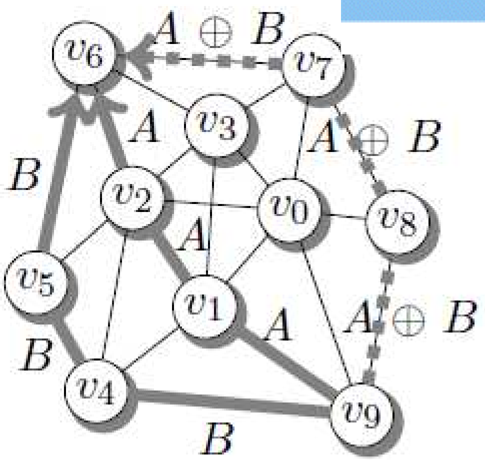
Péter Babarczi, János Tapolcai, Pin-Han Ho, and Muriel Médard, *Optimal Dedicated Protection Approach to Shared Risk Link Group Failures using Network Coding*, in Proceedings of the **IEEE International Conference on Communications (ICC)**, pp. 3051-3055, Ottawa, ON, Canada, 2013.

Dedicated protection - static routing

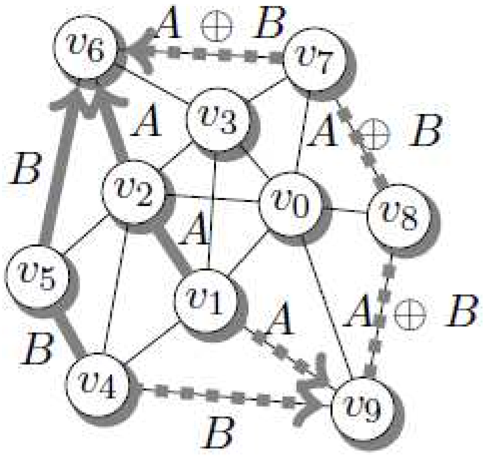
Improve resource efficiency with coding while **instantaneous recovery** is maintained



- ***Diversity coding***
  - The user data is split into two parts (*A* and *B*) and sent along three disjoint paths by adding redundancy *A XOR B*.
  - ***Good resource-efficiency*** (50% instead of 100% of 1+1)
  - **BUT**: requires 3-edge-connectivity



- ***Inter-session 1+1 network coding***
  - The data of connections v_4 to v_6 and from v_1 to v_6 is sent directly to the ***common destination*** node and to a ***coding node*** (v_9).
  - The most resource-efficient against *single link failures* (in static routing!)
  - **BUT:** ***NP-complete***

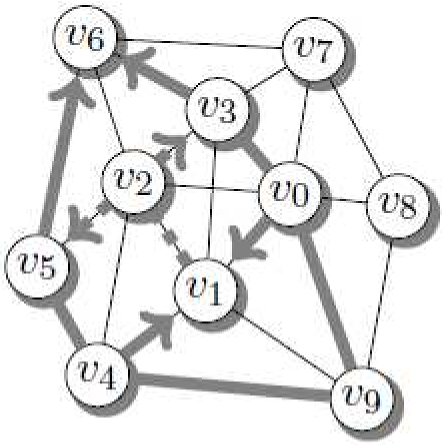


Péter Babarczi, Gergely Biczók, Harald Øverby, János Tapolcai, and Péter Soproni, *Realization Strategies of Dedicated Path Protection: A Bandwidth Cost Perspective*, **Elsevier Computer Networks (ComNet)**, vol. 57, no. 9, pp. 1974-1990, impact factor 1.282, 2013.

Dedicated protection - dynamic routing

Survivable routing methods with instantaneous recovery against multiple (shared risk link group) failures

- General Dedicated Protection (GDP)
  - Survivable routing ***does NOT have a pre-defined structure*** (e.g., disjoint path-pair)
- GDP with routing (GDP-R)
  - Traditional store-and-forward behavior
  - ***NP-complete for SRLG failures***
- GDP with network coding (GDP-NC)
  - *Intra-session network coding* is allowed
  - Minimal resource consumption among all methods ensuring instantaneous recovery (***polynomial-time***)
  - **BUT:** *User data might be split into arbitrary many parts*
    - Practically infeasible, but provides the ***theoretical lower bound***

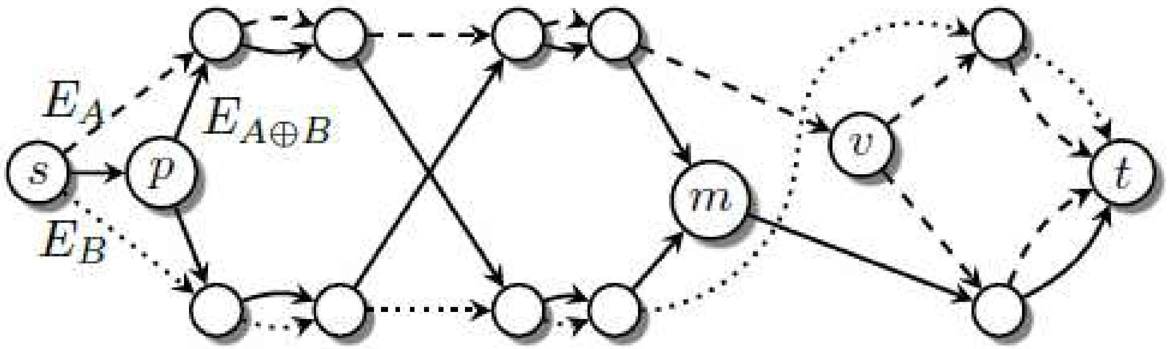


Péter Babarczi, Alija Pašić, János Tapolcai, Felicián Németh, and Bence Ladóczki, *Instantaneous Recovery of Unicast Connections in Transport Networks: Routing versus Coding,* accepted to **Elsevier Computer Networks (ComNet)**, impact factor 1.282, 2015.

Resilient Flow Decomposition (RFD)

A practical special case: single link failure resilience with two data parts

- **Theorem**: Suppose that survivable routing is ***critical***. Then there are disjoint edge sets of , called ***routing DAGs***, such that for an arbitrary edge after removing the corresponding edge(s) from at least two of the routing DAGs connect to .
  - Only splitters (***p***) and mergers (***m***) are required at the intermediate nodes, ***XOR coding is sufficient at the source and destination nodes***.
  - Network code (i.e., routing DAGs) can be found in ***linear time*** in a critical survivable routing.
  - A critical survivable routing can be found in ***polynomial time***.

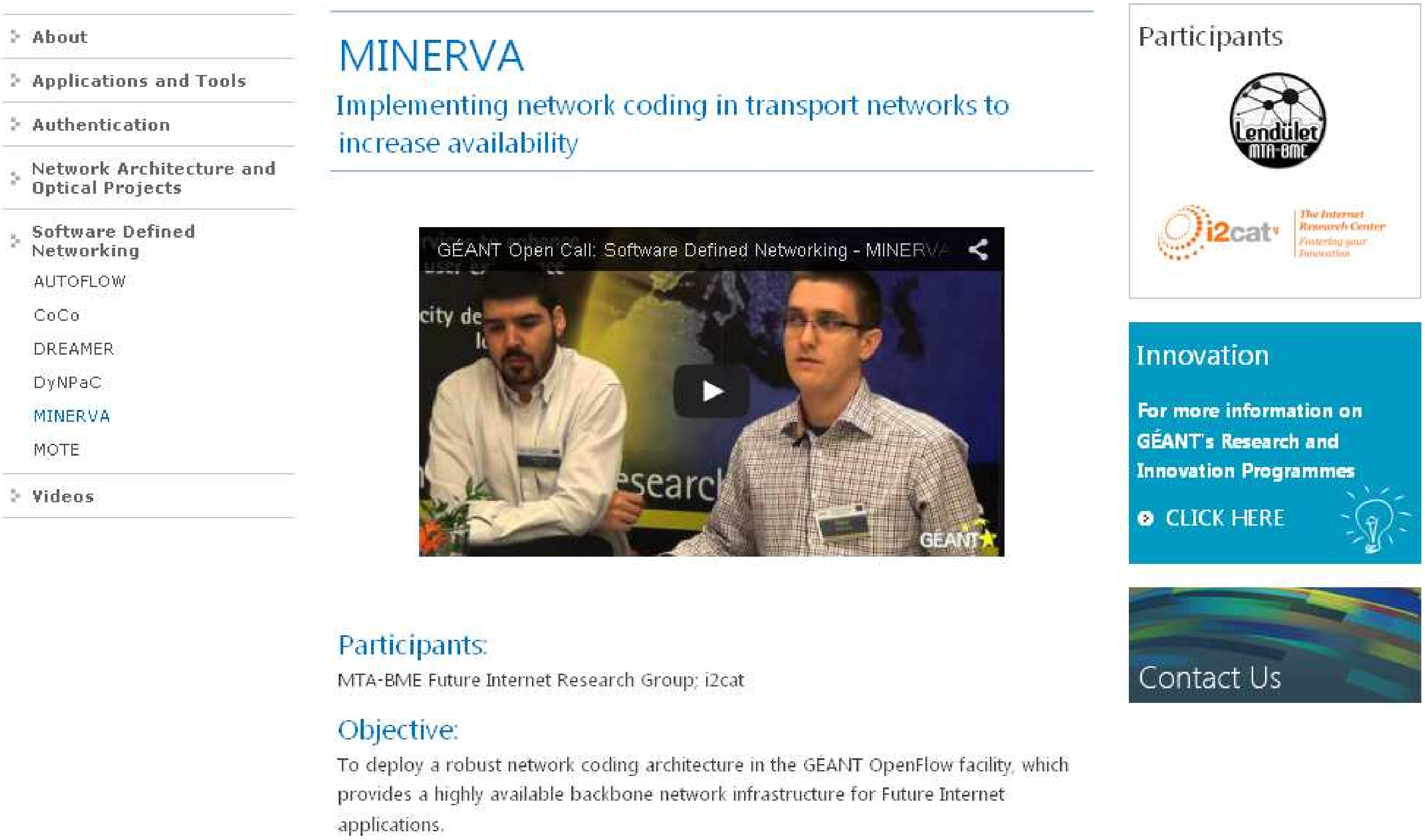


Péter Babarczi, János Tapolcai, Lajos Rónyai, and Muriel Médard, *Resilient Flow Decomposition of Unicast Connections with Network Coding*, in Proceedings of the **IEEE International Symposium on Information Theory (ISIT)**, pp. 116-120, Honolulu, HI, USA, 2014.

MINERVA

Open Call beneficiary of the GN3Plus (GÉANT) FP7 Project (2013 November – 2015 March)

- Implementing RFD in the GÉANT OpenFlow Facility (GOFF)
- http://www.geant.net/opencall/SDN/Pages/MINERVA.aspx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MINERVA

Implementing network coding in transport networks to increase availability

Participants:

MTA-BME Future Internet Research Group; i2cat

Objective:

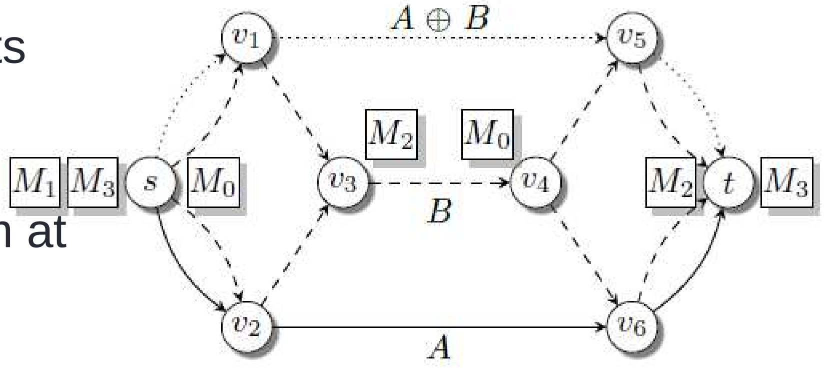
To deploy a robust network coding architecture in the GÉANT OpenFlow facility, which provides a highly available backbone network infrastructure for Future Internet applications.

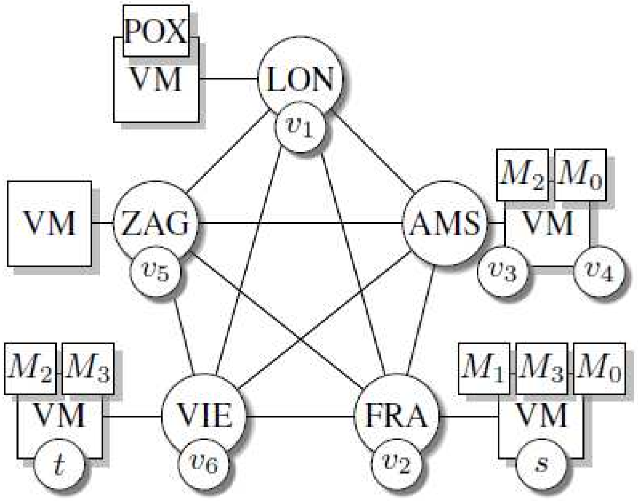
IEEE INFOCOM'15
26 APRIL - 1 MAY, 2015 • HONG KONG
SHERATON HONG KONG HOTEL AND TOWERS

Virtual Network Functions

An arbitrary RFD solution can be deployed with these NFs

- ***Splitter (M_0)***: duplicates incoming packets and forwards them through two different links (s and v_4).
- ***Sequencer (M_1)***: divides the input stream at the source node s into two parts *A* and *B* (e.g., based on parity).
- ***Merger (M_2)***: receives the same flow on two incoming links and forwards one of them (or the intact one upon link failure) through its single outgoing link (v_3 and t).
- ***Coding/Decoding (M_3)***: perform fast packet processing using XOR operation and queues to handle the incoming packets (they are always placed at s and t).





Bence Ladóczki, Carolina Fernandez, Oscar Moya, Péter Babarczi, János Tapolcai, and Daniel Guija, *Robust Network Coding in Transport Networks*, in Proceedings of the **34th IEEE International Conference on Computer Communications (INFOCOM) Demo session**, pp. 1-2, Hong Kong, 2015.

ALL-OPTICAL FAILURE LOCALIZATION

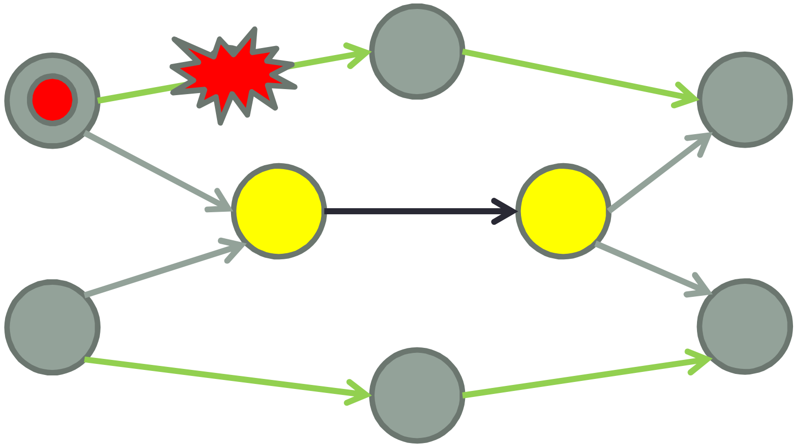
- GMPLS-based failure recovery (identifying week points)
- Failure localization via a central failure manger
- Distributed failure localization (enabling shared protection schemes in practice)

Pre-planned restoration (shared protection)

GMPLS-based failure recovery

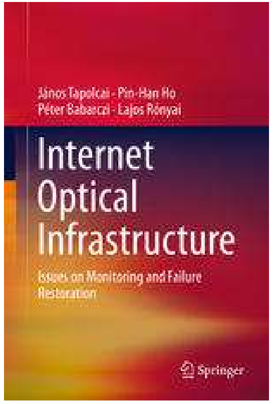
- Real-time operations after a failure (recovery time (***t_R***))
  - Failure detection
  - Failure localization (***t_l***)
  - Failure notification (***t_n***)
  - Failure correlation (***t_c***)
  - Failure restoration
    - Path selection (***t_p***)
    - Device configuration (***t_d***)

Failure management



t_R at shared protection (150 ms):

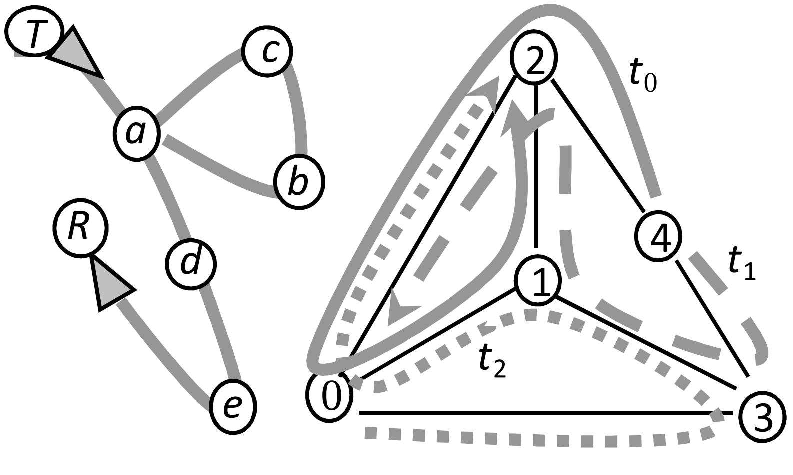
- ***t_l*** = 10 ms
- ***t_n*** = 20-30 ms
- ***t_c*** = 20-30 ms
- ***t_p*** = 0-30 ms
- ***t_d*** = 50 ms


János Tapolcai · Pin-Han Ho
Péter Babarczi · Lajos Rónyai
Internet Optical Infrastructure
Issues on Monitoring and Failure Restoration
Springer

All-optical failure localization

Introducing supervisory lightpaths (S-LPs) or m-trails

- ***Unambiguous Failure Localization***
  - Each link is traversed by a unique set of m-trails or equivalently each row of the alarm code table is unique



(a) m-trail

(b) An m-trail solution

Link	t_2	t_1	t_0	Decimal
(0,1)	1	0	1	5
(0,2)	1	1	1	7
(0,3)	1	0	0	4
(1,2)	0	1	1	3
(1,3)	1	1	0	6
(2,4)	0	0	1	1
(3,4)	0	1	0	2

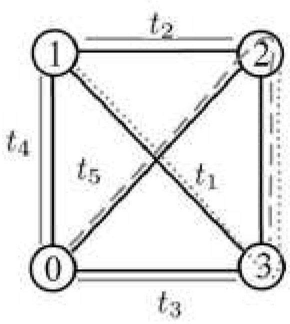
(c) Alarm code table

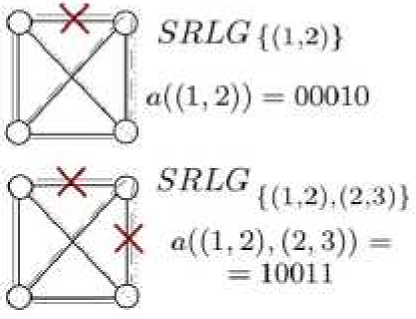
János Tapolcai, Pin-Han Ho, Péter Babarczi, and Lajos Rónyai, *Internet Optical Infrastructure - Issues on Monitoring and Failure Restoration*, pp. 1-212, **Publisher: Springer**, ISBN 978-1-4614-7737-2, 2014.

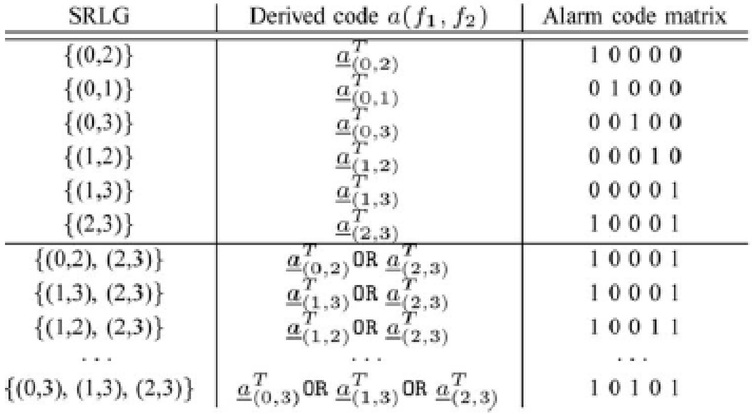
All-optical failure localization

Via a central failure manager

- Optimization goal:
  - ***Minimize the number of S-LPs*** (alarms) causing failure localization complexity (i.e., increased recovery time)
- Fast heuristics for single link failure UFL
- Localizing multiple link (shared risk link group, SRLG) failures is ***NP-complete***
  - Owing to the dependency of the physical S-LPs and logical m-trails





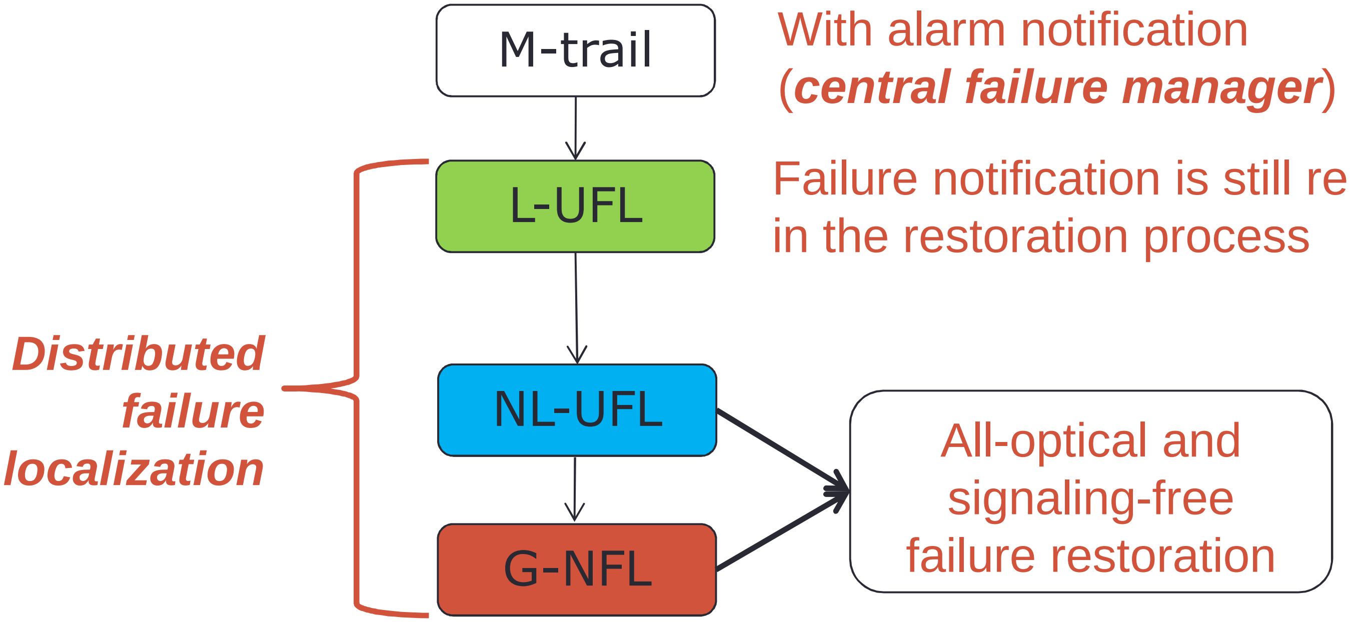


SRLG	Derived code $a(f_1, f_2)$	Alarm code matrix
$\{(0,2)\}$	$\underline{a}^T_{(0,2)}$	1 0 0 0 0
$\{(0,1)\}$	$\underline{a}^T_{(0,1)}$	0 1 0 0 0
$\{(0,3)\}$	$\underline{a}^T_{(0,3)}$	0 0 1 0 0
$\{(1,2)\}$	$\underline{a}^T_{(1,2)}$	0 0 0 1 0
$\{(1,3)\}$	$\underline{a}^T_{(1,3)}$	0 0 0 0 1
$\{(2,3)\}$	$\underline{a}^T_{(2,3)}$	1 0 0 0 1
$\{(0,2), (2,3)\}$	$\underline{a}^T_{(0,2)}$ OR $\underline{a}^T_{(2,3)}$	1 0 0 0 1
$\{(1,3), (2,3)\}$	$\underline{a}^T_{(1,3)}$ OR $\underline{a}^T_{(2,3)}$	1 0 0 0 1
$\{(1,2), (2,3)\}$	$\underline{a}^T_{(1,2)}$ OR $\underline{a}^T_{(2,3)}$	1 0 0 1 1
. . .	. . .	. . .
$\{(0,3), (1,3), (2,3)\}$	$\underline{a}^T_{(0,3)}$ OR $\underline{a}^T_{(1,3)}$ OR $\underline{a}^T_{(2,3)}$	1 0 1 0 1

Péter Babarczi, János Tapolcai, and Pin-Han Ho, *Adjacent Link Failure Localization with Monitoring Trails in All-Optical Mesh Networks*, **IEEE/ACM Transactions on Networking (ToN)**, vol. 19, no. 3, pp. 907-920, impact factor 2.033, 2011.

All-optical failure localization

Using S-LPs in failure restoration (e.g., Failure Dependent Protection, FDP)


M-trail
L-UFL
NL-UFL
G-NFL
Distributed failure localization
All-optical and signaling-free failure restoration

With alarm notification (***central failure manager***)

Failure notification is still required in the restoration process

- ***L-UFL:*** Local UFL – a single node performs UFL based on the status of the traversing S-LPs
- ***NL-UFL:*** Network-wide L-UFL – each node in the network is L-UFL capable
- ***G-NFL:*** neighborhood failure localization – localize only links relevant for FDP

János Tapolcai, Pin-Han Ho, Péter Babarczi, and Lajos Rónyai, *On Signaling-Free Failure Dependent Restoration in All-Optical Mesh Networks*, **IEEE/ACM Transactions on Networking (ToN)**, vol. 22, no. 4, pp. 1067-1078, impact factor 1.986, 2014.

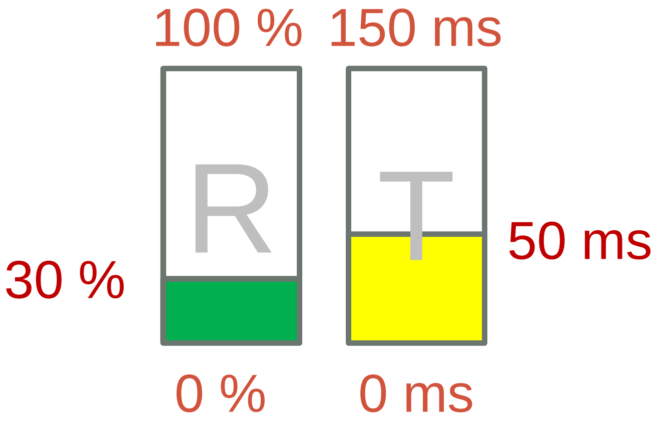
IEEE INFOCOM

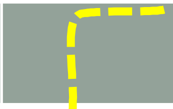
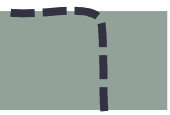
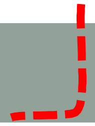
April 14-19, 2013 - Turin, Italy

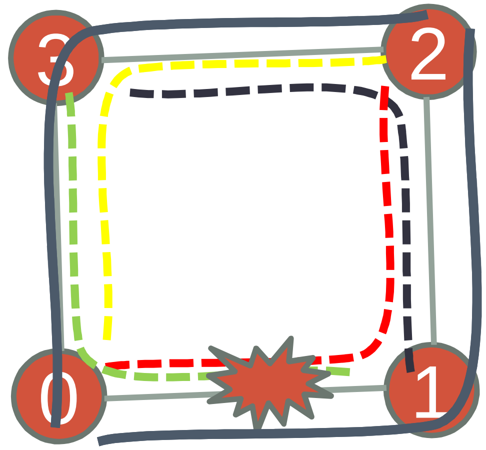
All-optical failure localization

Completely eliminating control plane signaling

- Each (switching) node can recover the disrupted connections ***without any control plane signaling***
  - After the failure localized, the node can immediately start switching matrix configuration (sub 50 ms recovery)
  - The number of alarms is no longer a concern (goal: ***minimize the total length of m-trails***)



Node 2				Action
0-1	0	0	1	SW 1->3
1-2	0	1	1	
2-3	1	1	0	
3-0	1	0	0	



János Tapolcai, Pin-Han Ho, Péter Babarczi, and Lajos Rónyai, *On Achieving All-Optical Failure Restoration via Monitoring Trails*, in Proceedings of the **32nd IEEE International Conference on Computer Communications (INFOCOM),** pp. 380-384, Turin, Italy, 2013.

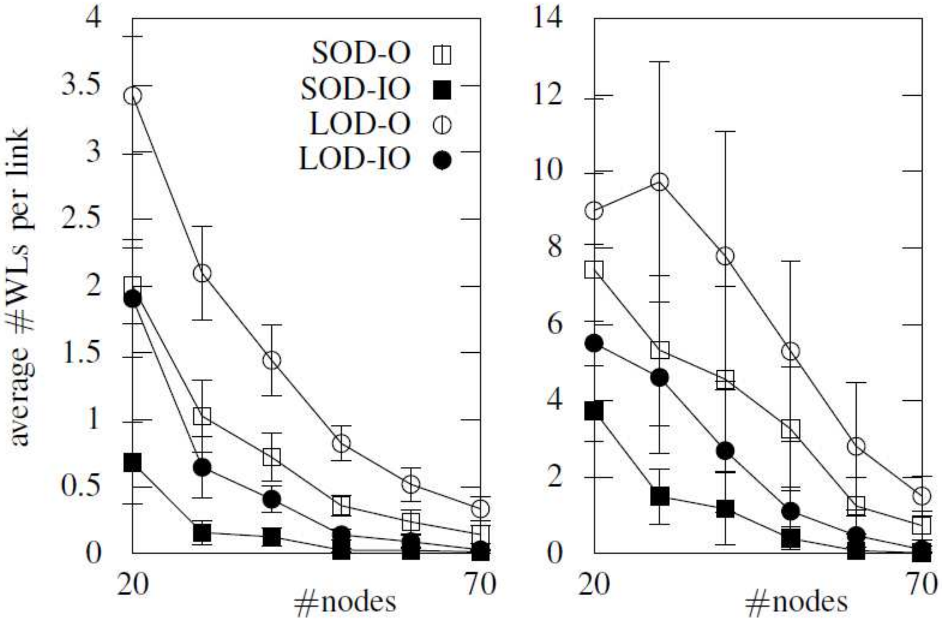
All-optical failure localization

Protection resources „hide" the S-LP capacity

- What is the price we have to pay for fast recovery?
  - The additional S-LP capacity is negligible even in lightly loaded networks

W-LP is established between 30% of *s-t* paris

-O: only S-LPs are tapped
-IO: data plane (W-LPs) are tapped as well -> reconfiguration



(a) Dense networks (b) Sparse networks

Fig. 6. Monitoring overhead that cannot be hidden by the spare capacity.

János Tapolcai, Pin-Han Ho, Péter Babarczi, and Lajos Rónyai, *Neighborhood Failure Localization in All-Optical Networks via Monitoring Trails*, accepted to **IEEE/ACM Transactions on Networking (ToN)**, impact factor 1.986, 2015.

MTA-BME FUTURE INTERNET RESEARCH GROUP

- Internet routing – Compressing IP forwarding tables
- Bloom filter based future Internet addressing
- ESCAPE - SDN prototyping framework

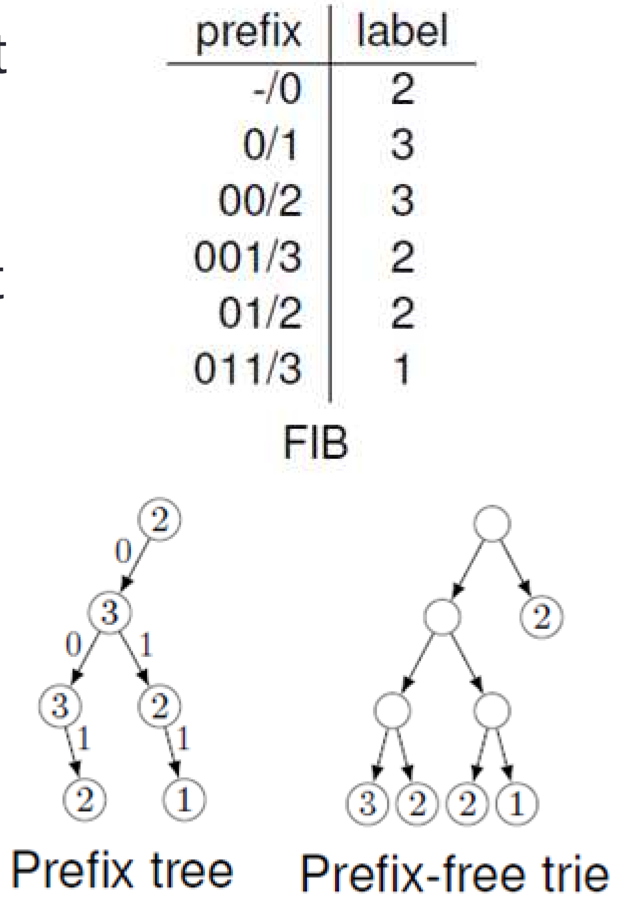
Group leader: Dr. János Tapolcai http://lendulet.tmit.bme.hu/

Compressing IP forwarding tables

Compressed data structures

SIGCOMM 2013 Hong Kong

- Compression not necessarily sacrifices fast access!
- Store information in entropy-bounded space and provide fast in-place access to it
  - take advantage of regularity, if any, to ***compress data drifts closer to the CPU in the cache hierarchy*** operations are even faster than on the original uncompressed form
- No space-time trade-off!
- Goal: advocate compressed data structures to the networking community
- ***IP forwarding table compression as a use case***



prefix	label
-/0	2
0/1	3
00/2	3
001/3	2
01/2	2
011/3	1

FIB

Prefix tree

Prefix-free trie

Gábor Rétvári, János Tapolcai, Attila Kőrösi, András Majdán, and Zalán Heszberger, *Compressing IP forwarding tables: towards entropy bounds and beyond*. In *Proceedings of the* **ACM SIGCOMM,** pp. 111-122, ACM, New York, NY, USA, 2013.

Compressing IP forwarding tables

IP Forwarding Information Base

- The fundamental data structure used by IP routers to make forwarding decisions
- Stores more than 440K IP-prefix-to-nexthop mappings as of January, 2013
  - consulted on a packet-by-packet basis at line speed
  - queries are complex: longest prefix match
  - ***updated couple of hundred times per second***
  - takes several MBytes of fast line card memory and counting
- May or may not become an ***Internet scalability barrier***
- With the proposed compressed IP FIB in Linux kernel prototype
  - Several million lookups per sec both in HW and SW
  - faster than the uncompressed form
  - Size of 100-400 KB
  - tolerates more than 100, 000 updates per sec

Gábor Rétvári, János Tapolcai, Attila Kőrösi, András Majdán, and Zalán Heszberger, *Compressing IP forwarding tables: towards entropy bounds and beyond*. In *Proceedings of the* **ACM SIGCOMM,** pp. 111-122, ACM, New York, NY, USA, 2013.

Future Internet addressing and forwarding

Information Centric Networks (ICNs)

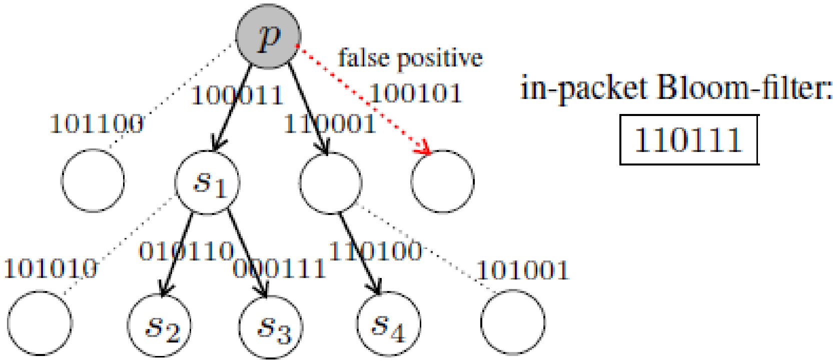
- Publish/subscribe service model
  - Spatially and Temporally Decouple Communicating Parties
    - producer of information (publisher) does not need to coexist in time with the consumers (subscribers)
  - Clearly Separate Network Functions
    - ***rendezvous*** matches demand for and supply of information
    - ***topology management*** and formation, to determine a suitable forwarding architecture (e.g., multicast tree)
    - this transfer being executed by the third function, ***forwarding***.
- The ICN paradigm shifts communication goal: ***what*** information required is more important than ***where*** it is in the network
  - Traditional IP forwarding mechanisms (based on end-point addresses) does not work (**architectural change required**)
  - Typically point-multipoint communication, but naturally support multipath routing for unicast connections as well.

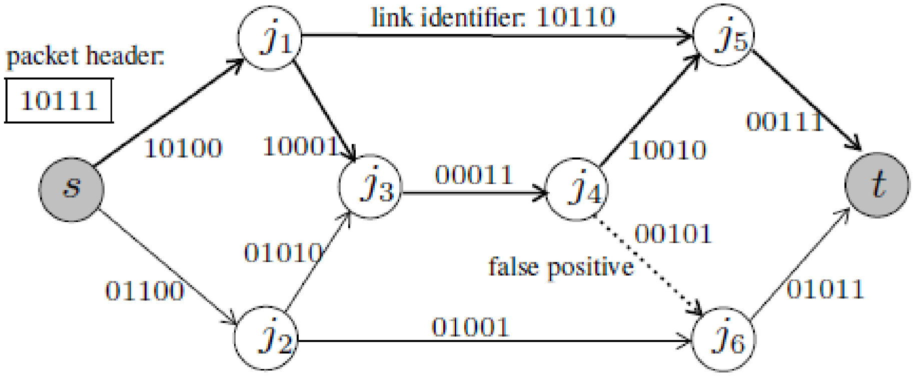
János Tapolcai, József Bíró, Péter Babarczi, András Gulyás, Zalán Heszberger, and Dirk Trossen, *Optimal False-Positive-Free Bloom Filter Design for Scalable Multicast Forwarding*, accepted to **IEEE/ACM Transactions on Networking (ToN)**, impact factor 1.986, 2015.

Future Internet addressing and forwarding

Forwarding based on in-packet Bloom filters

- Computation of in-packet Bloom filters
  - Each link is assigned by a binary link address (consisting of bits of which at most ***k*** are set to 1).
  - The topology manager computes the packet header by bitwise OR-ing the addresses of the links in the corresponding ***multicast tree / routing DAG***
  - ***SDN prototype*** implementation
  - In ToN: how to design „short" in-packet filters resulting (statistically) zero false-positive forwarding





János Tapolcai, József Bíró, Péter Babarczi, András Gulyás, Zalán Heszberger, and Dirk Trossen, *Optimal False-Positive-Free Bloom Filter Design for Scalable Multicast Forwarding*, accepted to **IEEE/ACM Transactions on Networking (ToN)**, impact factor 1.986, 2015.

ESCAPE

Extensible Service ChAin Prototyping Environment using Mininet, Click, NETCONF and POX

SIGCOMM CHICAGO 2014

- ***Service Chaining with SDN/NFV***
  - Dynamic service creation for infrastructure/service providers
  - Service is described as a graph of service components
  - Service components operates as Virtual Network Functions
    - simple packet manipulation: header rewrite, network coding
    - more complex tasks: Firewall, NAT
  - Network is programmed (SDN) to steer traffic to VNFs

- **SDN:** Remote Controller programs the forwarding behavior of switches
- **NFV:** Middleboxes run in virtual machines

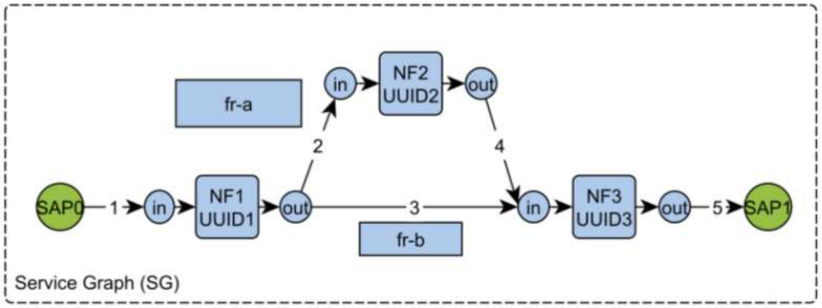


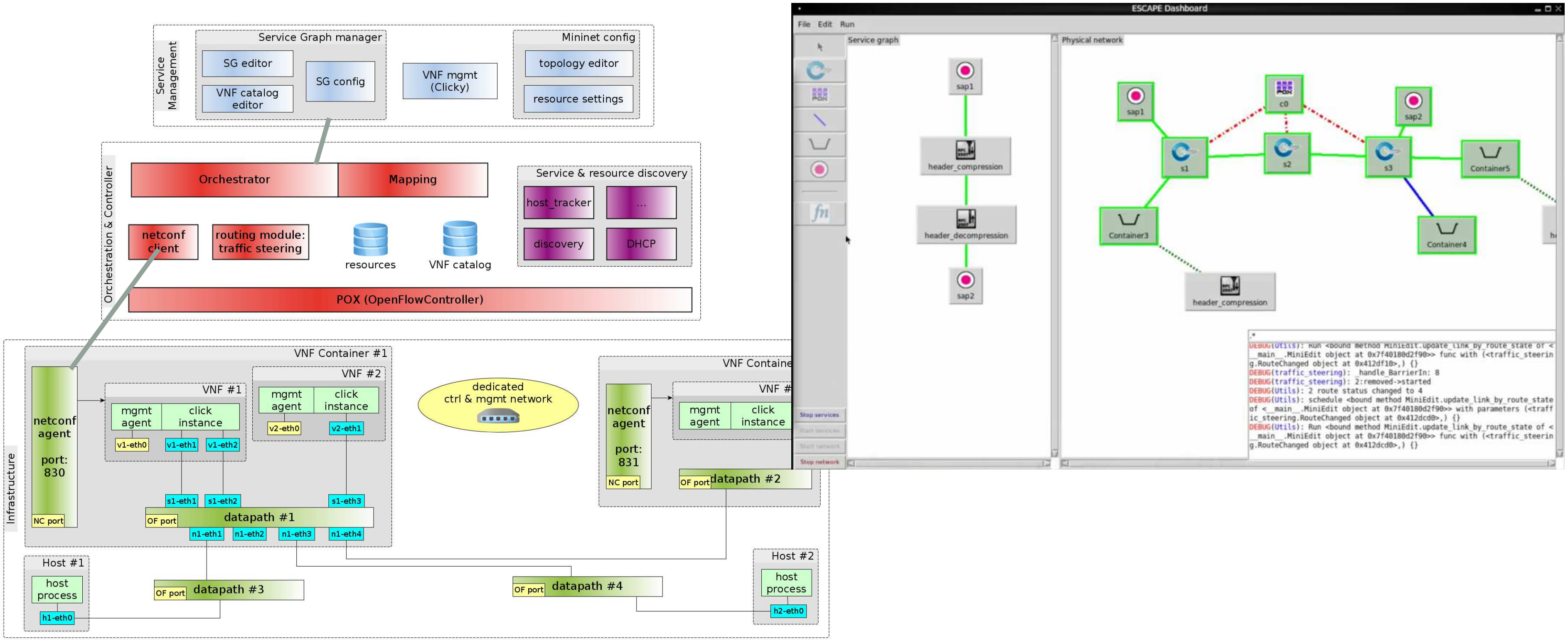
Figure 5: An illustrative example of a Service Graph (SG)

A. Csoma, B. Sonkoly, L. Csikor, F. Németh, A. Gulyás, W. Tavernier, and S. Sahhaf, *Escape: extensible service chain prototyping environment using mininet, click, netconf and pox*, in **ACM SIGCOMM (Demo)**, pp. 125-126. 2014.

ESCAPE

Extensible Service ChAin Prototyping Environment using Mininet, Click, NETCONF and POX

SIGCOMM CHICAGO 2014



```
.*
DEBUG(Utils): Run <bound method MiniEdit.update_link_by_route_state of <
__main__.MiniEdit object at 0x7f40180d2f90>> func with (<traffic_steerin
g.RouteChanged object at 0x412df10>,) {}
DEBUG(traffic_steering): _handle_BarrierIn: 8
DEBUG(traffic_steering): 2:removed->started
DEBUG(Utils): 2 route status changed to 4
DEBUG(Utils): schedule <bound method MiniEdit.update_link_by_route_state
of <__main__.MiniEdit object at 0x7f40180d2f90>> with parameters (<traff
ic_steering.RouteChanged object at 0x412dcd0>,) {}
DEBUG(Utils): Run <bound method MiniEdit.update_link_by_route_state of <
__main__.MiniEdit object at 0x7f40180d2f90>> func with (<traffic_steerin
g.RouteChanged object at 0x412dcd0>,) {}
```

https://sb.tmit.bme.hu/mediawiki/index.php/ESCAPE

A. Csoma, B. Sonkoly, L. Csikor, F. Németh, A. Gulyás, W. Tavernier, and S. Sahhaf, *Escape: extensible service chain prototyping environment using mininet, click, netconf and pox*, in **ACM SIGCOMM (Demo)**, pp. 125-126. 2014.

THANK YOU!

QUESTIONS?

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