On Cyclic Dependencies and Regulators in Time-Sensitive Networks

40th IEEE Real-Time Systems Symposium (RTSS)
3rd-6th December 2019, Hong Kong

Ludovic Thomas (EPFL),
Jean-Yves Le Boudec (EPFL) and
Ahlem Mifdaoui (ISAE-SUPAERO)

April 30th, 2020

Introduction

- In time-sensitive networks, delays at network elements have to be bounded in worst case, not in average.

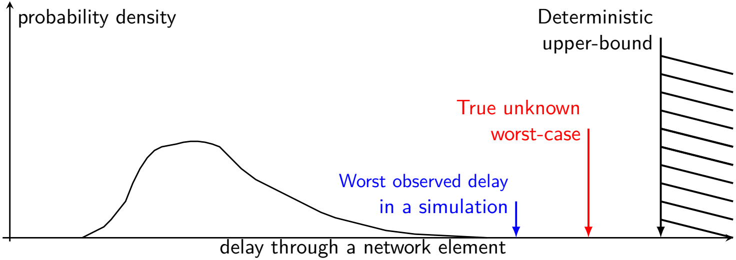


Figure: Distribution of suffered delay through a network element

- Upper-bounding is challenging when we have **cyclic dependencies**.

What is a cyclic dependency ?

When **directed path of flows** form a cycle.
= When the **directed graph** of **contention points** has a cycle.

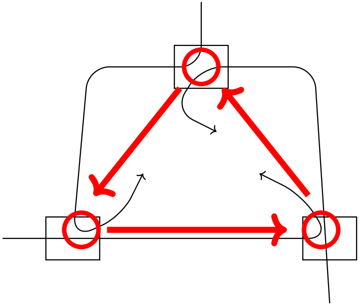


Figure: A cyclic dependency

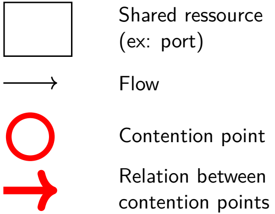
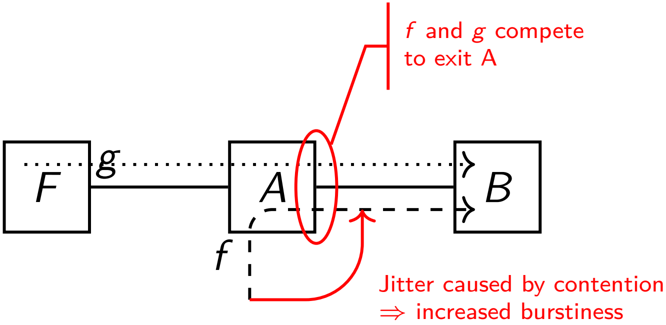


Figure: Legend

Why are cyclic dependencies an issue ?

- In **class-based** asynchronous networks (FIFO-per-class policy).



Why are cyclic dependencies an issue ?

- In **class-based** asynchronous networks (FIFO-per-class policy).

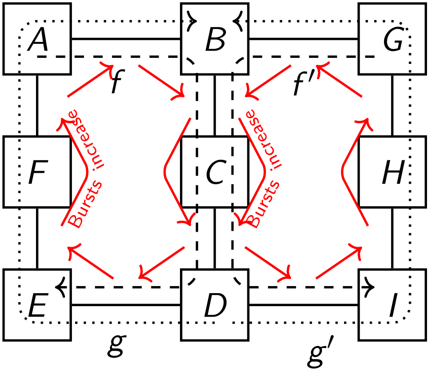


Figure: Cascades of burst increase

For some networks,
cascade of **always increasing** bursts:

[Andrews, 2009]:

For any $\epsilon > 0$, there exists a network with FIFO scheduling and load ϵ that is unstable ($=$ **unbounded bursts, unbounded latencies**)

Objectives

For any network with cyclic dependencies:

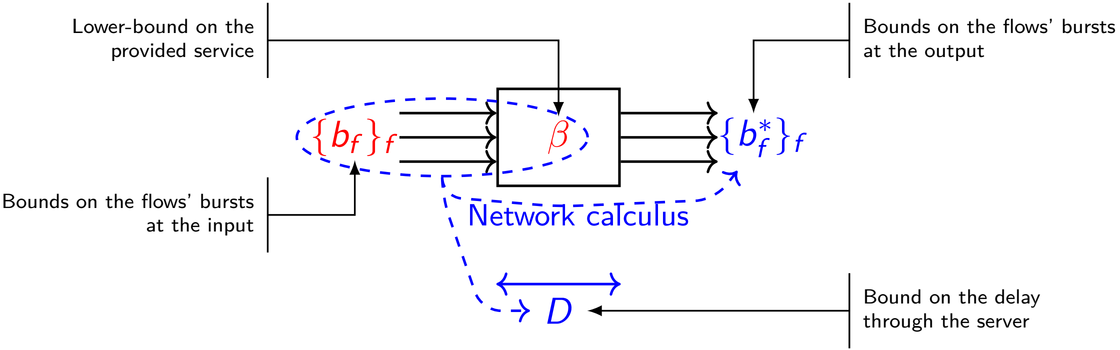
- **Guarantee** worst-case delays.
- Minimize **deployment cost** of the network.
- Keep **high-scalability** architectures.

Network Calculus

Can be used:

- to compute **delay bounds**.
- to provide **sufficient** conditions for the **stability** of networks with **cyclic dependencies**.

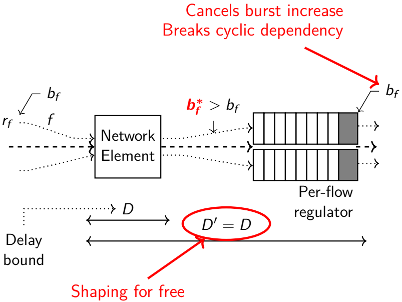
Inputs, **transfer function** and **outputs**.



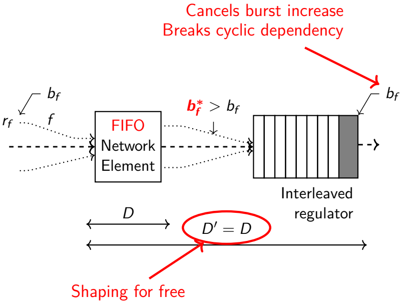
Traffic re-shaping breaks burst cascade

Reshaping in the network using traffic **regulators**.

- **Per-Flow Regulator**
  [Le Boudec and Thiran, 2001, Ayed et al., 2014]



- **Interleaved Regulator**
  [Le Boudec, 2018]



- Radical solution: **reshape at every node** $\Rightarrow$ bursts never increase.

Contributions

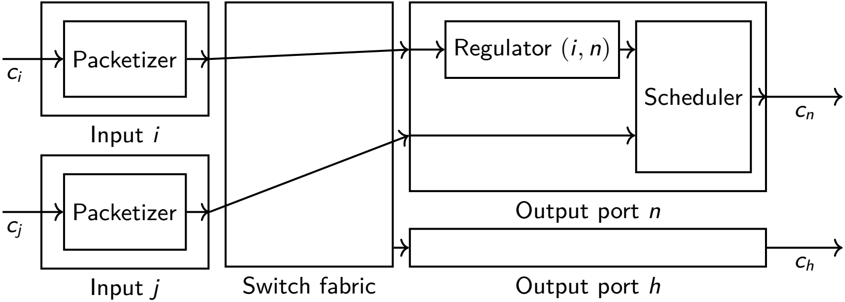
- Reshape **only on a subset** of nodes → **partial deployment**.
  - Performances compared to full deployment at every node ?
  - How to **select the positions** ?

    Low-Cost Acyclic Network (LCAN): { removes all cyclic dependencies with minimum regulators

- Performances of **full** and **partial** deployment vs **no deployment** at all ?

  Fixed-Point Total Flow Analysis (FP-TFA): { computes delay bounds on general topologies with or without regulators

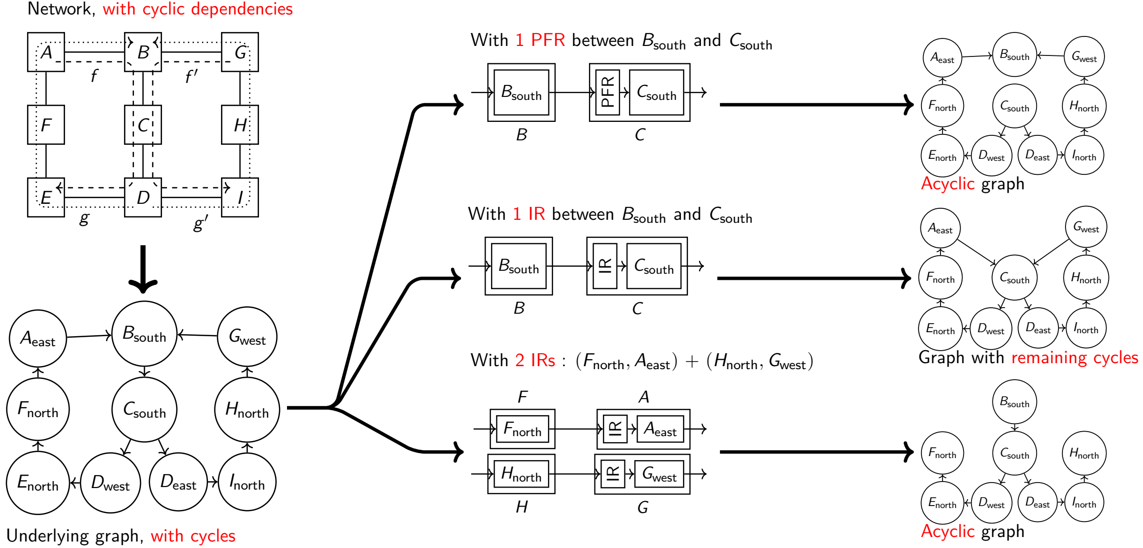
Network model



Content

1. Low-Cost Acyclic Network (LCAN)
   - Modeling the effect of regulators on cyclic dependencies
   - Obtaining minimum positions
2. Fixed-Point Total Flow Analysis (FP-TFA)
   - Delay bound in a node
   - Fixed-point
   - FP-TFA overview
3. Analysis
   - A parametric topology
   - Industrial case

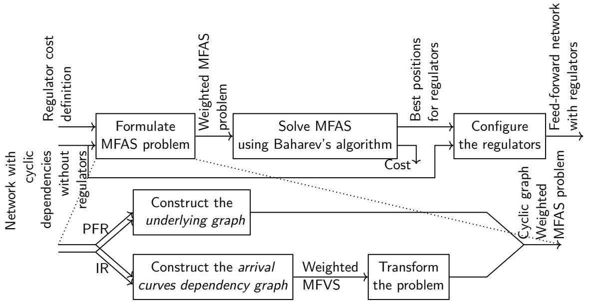
Modeling the effect of regulators on cyclic dependencies



Obtaining minimum positions

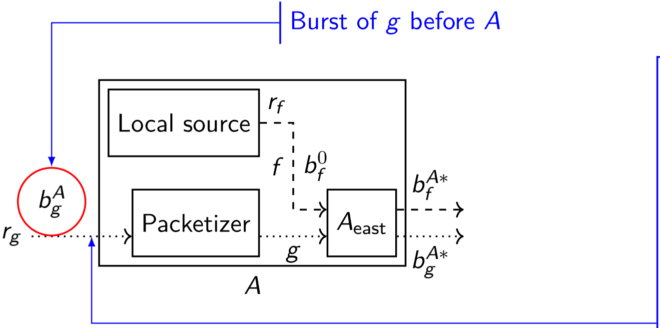
- With PFRs: *Minimum Feedback Arc Set* (MFAS)
- With IRs: *Minimum Feedback Vertex Set* (MFVS)

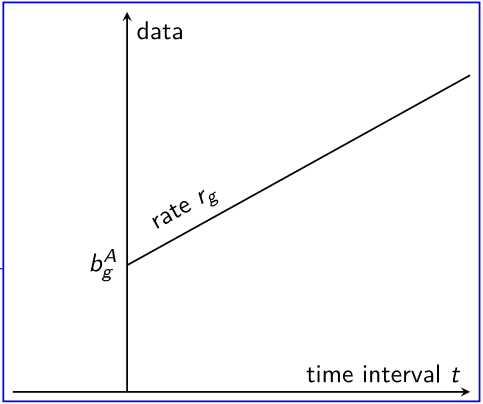
- Both are **equivalents**.
- Solved using a state-of-the-art optimal algorithm [Baharev et al., 2015].



Content

Example:

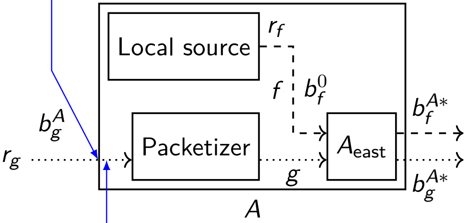




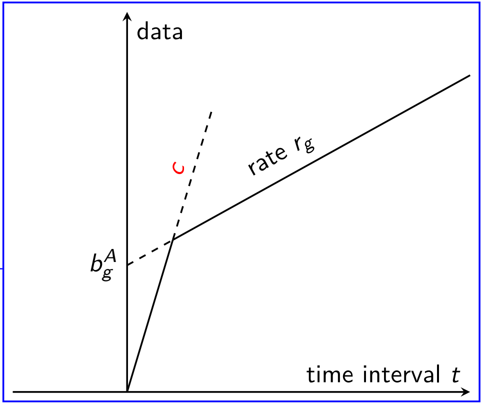
Traffic upper-bound (*Arrival Curve*)

Example:

Line rate c
Maximum speed of incoming bits

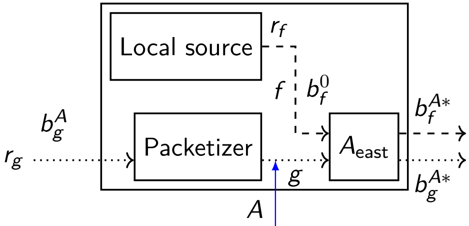


Line shaping

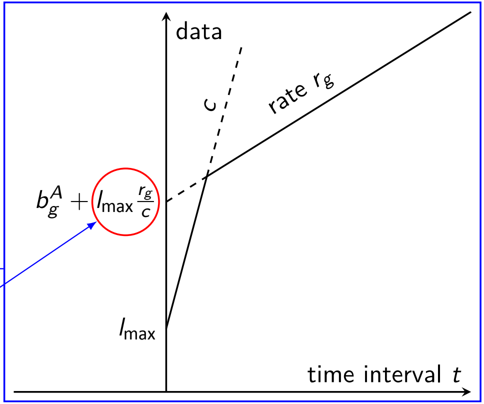


Traffic upper-bound (*Arrival Curve*)

Example:

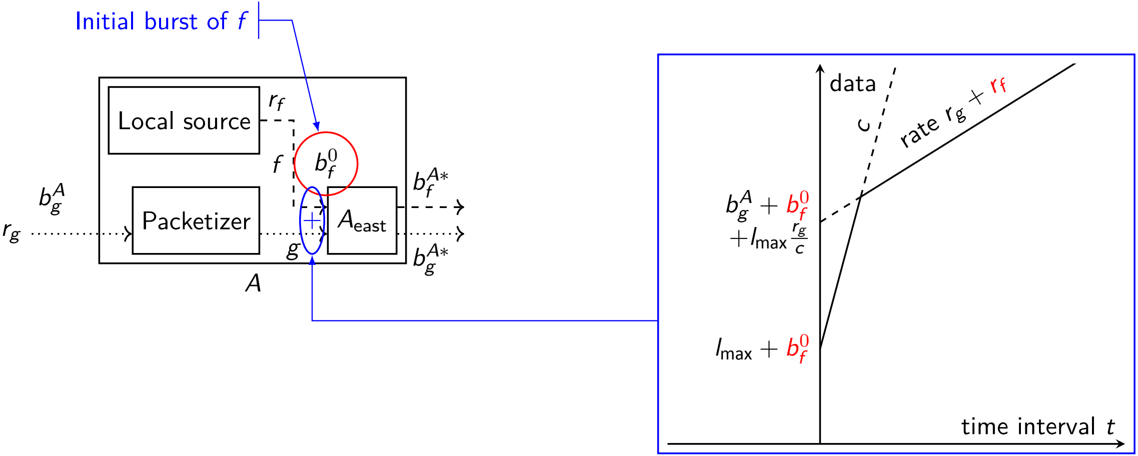


- Previous result: $+l_{\max}$
- New result: $+l_{\max}\frac{r}{c}$



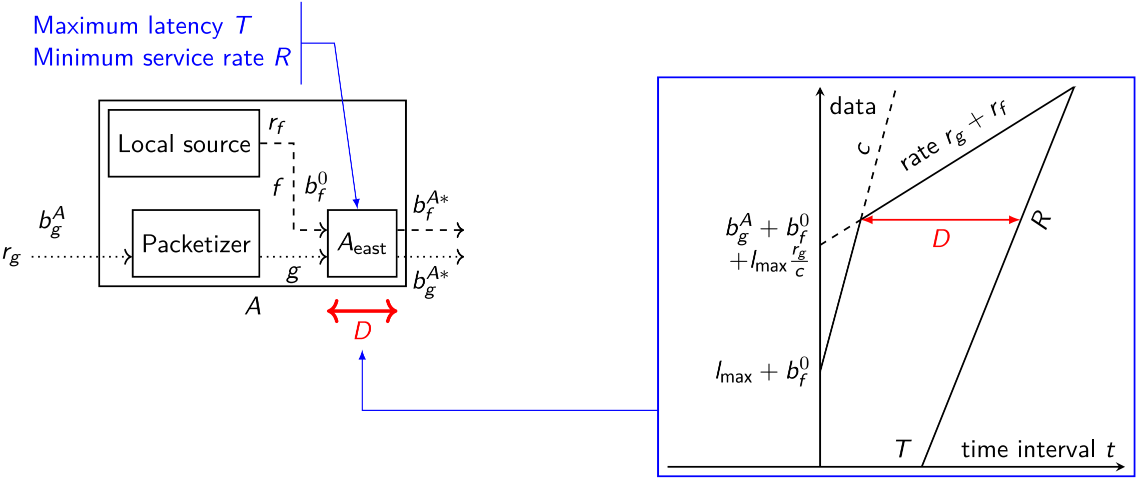
Traffic upper-bound (*Arrival Curve*)

Example:



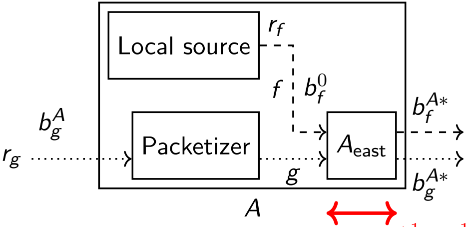
Traffic upper-bound (*Arrival Curve*)

Example:



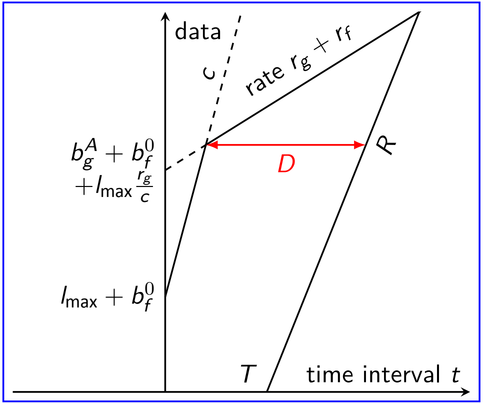
Delay computation

Example:



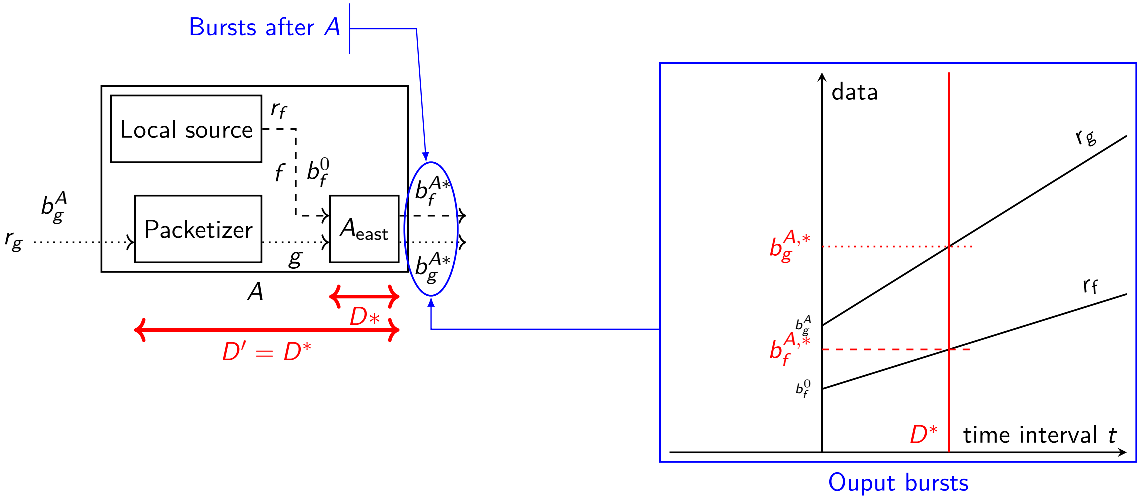
$D^* = D - l_{\min}(\frac{1}{R} - \frac{1}{c})$

Improvement by [Mohammadpour et al., 2019]

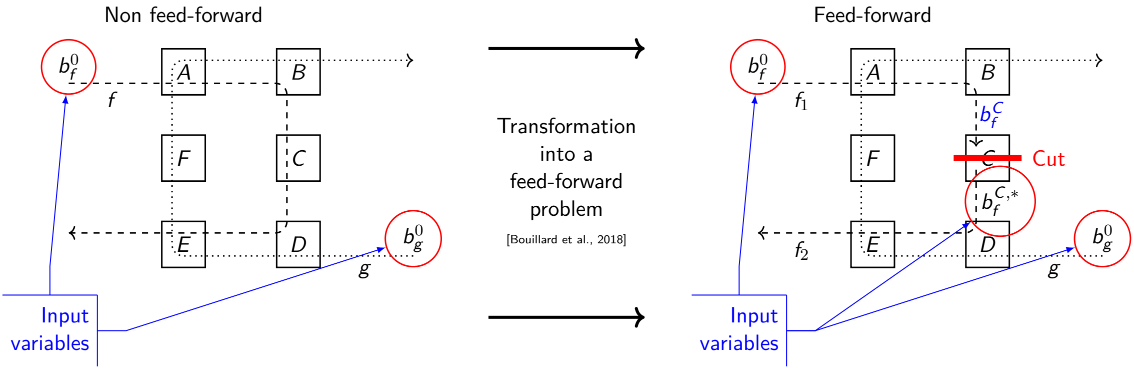


Delay computation

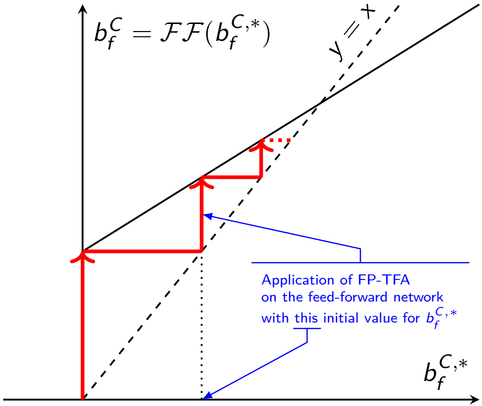
Example:

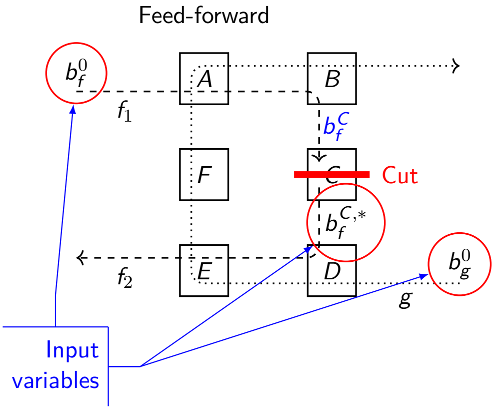

Bursts after A
Local source
r_f
f
b_f^0
Packetizer
A_{east}
b_g^A
r_g
g
b_f^{A*}
b_g^{A*}
A
$D*$
$D' = D^*$
data
r_g
r_f
$b_g^{A,*}$
b_g^A
$b_f^{A,*}$
b_f^0
D^*
time interval t
Ouput bursts

Networks with cyclic dependencies



Networks with cyclic dependencies





Improved result on the fixed-point

Time-stopping proof, in [Bouillard et al., 2018]

The **highest** fixed-point of $\mathcal{FF}$ is a valid burst bound at the cuts.

In our paper

If the network is empty at $t = 0$, then **any** fixed-point of $\mathcal{FF}$ is a valid burst bound at the cuts.

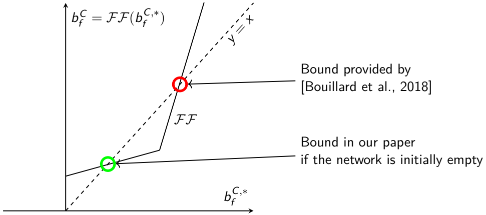
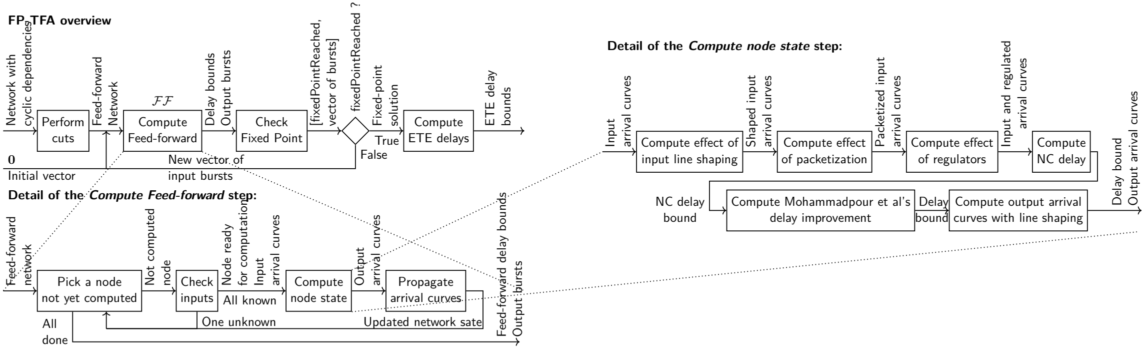


Figure: Schematic representation of $\mathcal{FF}$ with several fixed-points

FP-TFA algorithm

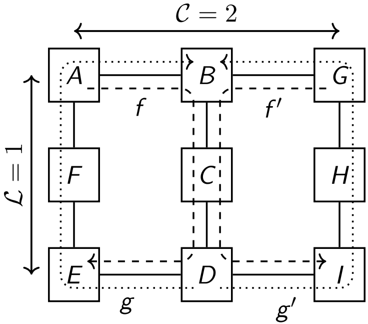


Content

1. Low-Cost Acyclic Network (LCAN)
   - Modeling the effect of regulators on cyclic dependencies
   - Obtaining minimum positions
2. Fixed-Point Total Flow Analysis (FP-TFA)
   - Delay bound in a node
   - Fixed-point
   - FP-TFA overview
3. Analysis
   - A parametric topology
   - Industrial case

A parametric grid topology

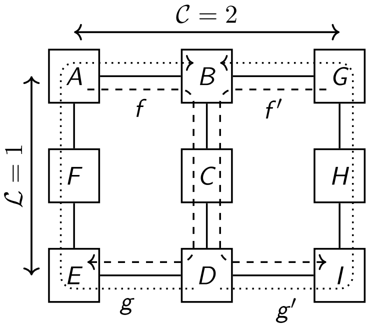
Symmetries (G, I), (E, I) $\rightarrow$ control of the network size.



Number of placed regulators

Partial deployments with LCAN require **81%**[1] to **89%**[2] fewer regulators than the **total**-deployment scheme.

Cyclic dependencies can be removed from this network with very few regulators.

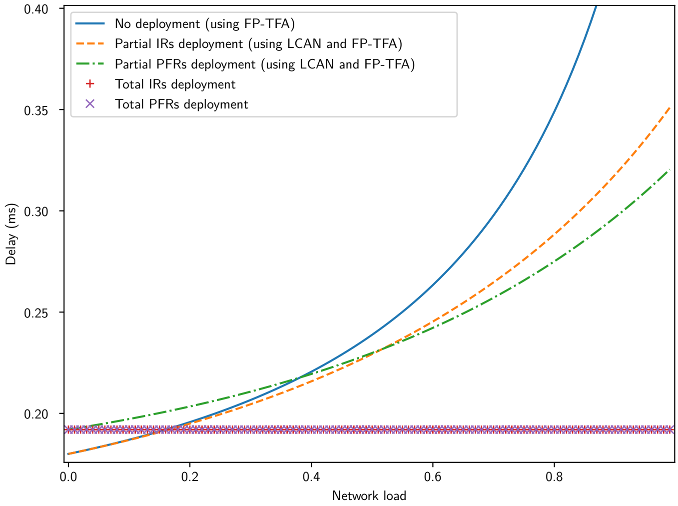


[1] When using Interleaved Regulators (IRs)
[2] When using Per-Flow Regulators (PFRs)

Latency bounds with respect to network load

Figure: End-to-end delay bound of the flows on the grid versus the network utilization.

- Full-deployment: penalty at low load compared to no deployment, but benefit at high load.
- **Partial deployment**: never the best performance but **good compromise**.

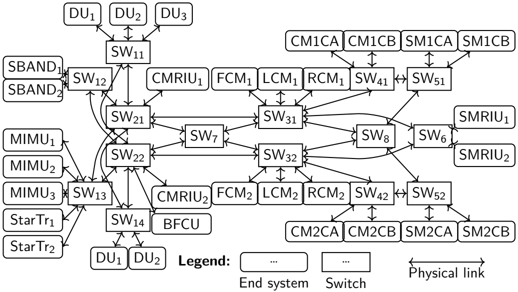


A representative industrial case

Orion spacecraft [Obermaisser, 2011, Zhao et al., 2018].
119 arbitrary multicast high-priority flows
>293'000 cyclic dependencies.

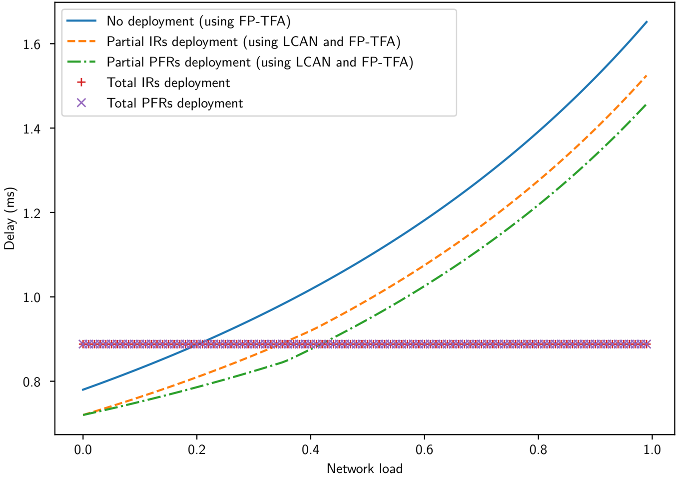
- Total deployment: 249 regulators.
- Partial deployment: 14 IRs or 9 PFRs.

Substantial cost savings can be achieved in industrial cases.



Performance evaluation on the industrial case

Figure: Highest ETE delay bound of the flows within Orion versus the network load.



- No-deployment scheme no longer the best approach at low load.
- Benefit of regulators (even partially) in heterogeneous networks.

Conclusion

- **FP-TFA** computes **latency bounds** in networks **with** *cyclic dependencies*.
- **LCAN** **removes** the *cyclic dependencies* using *traffic shaping*, with the **minimum** number of PFRs/IRs.

- Analysis on parametric/industrial topologies:
  - Low load ⇒ significant effect of ***line shaping***.
  - At medium to large load ⇒ benefit of regulators becomes apparent.
  - Partial deployment of Per-Flow Regulators (PFRs) offers a **good compromise** between performances and deployment cost.
  - Interleaved regulators (IRs) **need to be placed everywhere** to provide noticeable improvement.

Bibliography I

Andrews, M. (2009).
Instability of FIFO in the Permanent Sessions Model at Arbitrarily Small Network Loads.
ACM Trans. Algorithms, 5(3):33:1–33:29.
http://doi.acm.org/10.1145/1541885.1541894.

Ayed, H., Mifdaoui, A., and Fraboul, C. (2014).
Hierarchical traffic shaping and frame packing to reduce bandwidth utilization in the AFDX.
In *Proceedings of the 9th IEEE International Symposium on Industrial Embedded Systems (SIES 2014)*, pages 77–86.
http://doi.org/10.1109/SIES.2014.6871190.

Bibliography II

Baharev, A., Schichl, H., and Neumaier, A. (2015).
An exact method for the minimum feedback arc set problem.
Fakultät für Mathematik, Universität Wien.
https://www.mat.univie.ac.at/~neum/papers.html.

Bouillard, A., Boyer, M., and Corronc, E. (2018).
Deterministic Network Calculus: From Theory to Practical Implementation.
Networks and Telecommunications. Wiley.
http://doi.org/10.1002/9781119440284.

Le Boudec, J.-Y. (2018).
A Theory of Traffic Regulators for Deterministic Networks With Application to Interleaved Regulators.
IEEE/ACM Transactions on Networking, 26(6):2721–2733.
http://doi.org/10.1109/TNET.2018.2875191.

Bibliography III

Le Boudec, J.-Y. and Thiran, P. (2001).
Network Calculus: A Theory of Deterministic Queuing Systems for the Internet.
Lecture Notes in Computer Science, Lect.Notes Computer. Tutorial. Springer-Verlag, Berlin Heidelberg.
https://www.springer.com/us/book/9783540421849.

Mohammadpour, E., Stai, E., and Boudec, J. L. (2019).
Improved Delay Bound for a Service Curve Element with Known Transmission Rate.
IEEE Networking Letters, pages 1–1.
http://doi.org/10.1109/LNET.2019.2927143.

Obermaisser, R. (2011).
Time-Triggered Communication.
CRC Press, Inc., Boca Raton, FL, USA, 1st edition.

Bibliography IV

Zhao, L., Pop, P., Zheng, Z., and Li, Q. (2018).
Timing Analysis of AVB Traffic in TSN Networks Using Network Calculus.
In *2018 IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS)*, pages 25–36.
http://doi.org/10.1109/RTAS.2018.00009.