ÉCOLE POLYTECHNIQUE
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Real-Time Control of Electrical Distribution Grids and Reliable Networking

Jean-Yves Le Boudec[1,2]
EPFL

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[1] https://people.epfl.ch/105633/research

[2] http://smartgrid.epfl.ch

Credits

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Contributors

Jagdish Achara
Andrey Bernstein
Niek Bouman
Andreas Kettner
Maaz Mohiuddin
Ehsan Mohammadpour
Mario Paolone
Marco Pignati
Lorenzo Reyes
Roman Rudnik
Erica Scolari
Wajeb Saab
Eleni Stai
Cong Wang

Contents

1. Real-time operation of electrical distribution grids (COMMELEC)

2. Deterministic Networking for real-time operation

1. Real-Time Operation of Microgrid: Motivation

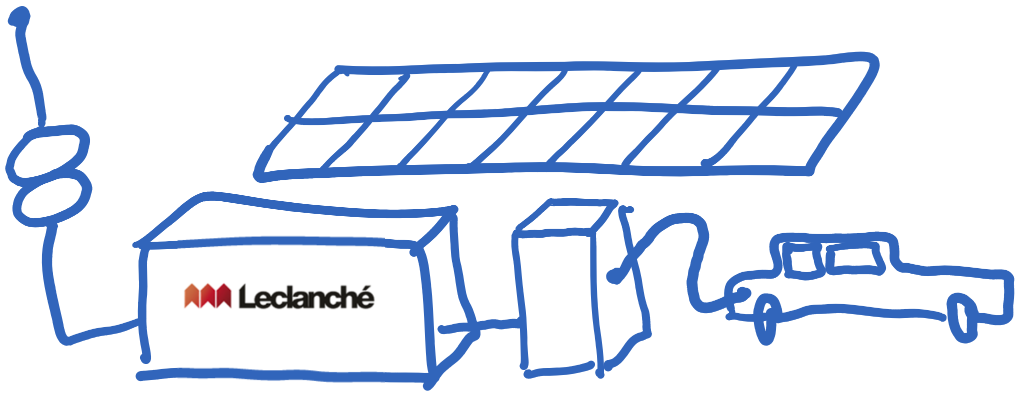
Absence of inertia (inverters)

Stochastic generation (PV)

Storage, demand response

Grid stress (charging stations, heat pumps)

Support main grid (primary and secondary frequency support)

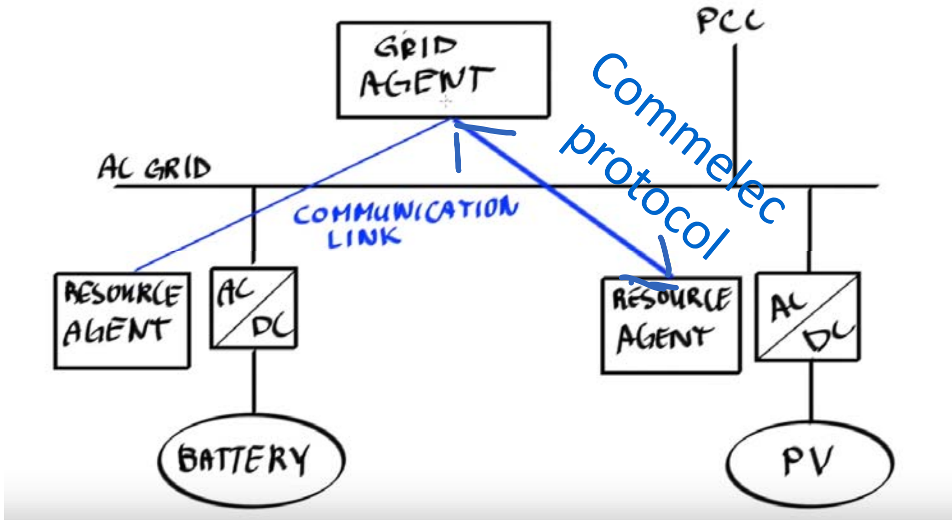


⇒ Agent based, real-time control of microgrid

COMMELEC Uses Explicit Power Setpoints

Every 100 msec

- Grid Agent monitors grid and sends power setpoints to Resource Agents
- Resource agent sends to grid agent: PQ profile, Virtual Cost and Belief Function



Goal: manage quality of service in grid; support main grid; use resources optimally.

[Bernstein et al 2015, Reyes et al 2015]
https://github.com/LCA2-EPFL/commelec-api

PQ profile = set of setpoints that this resource is willing to receive

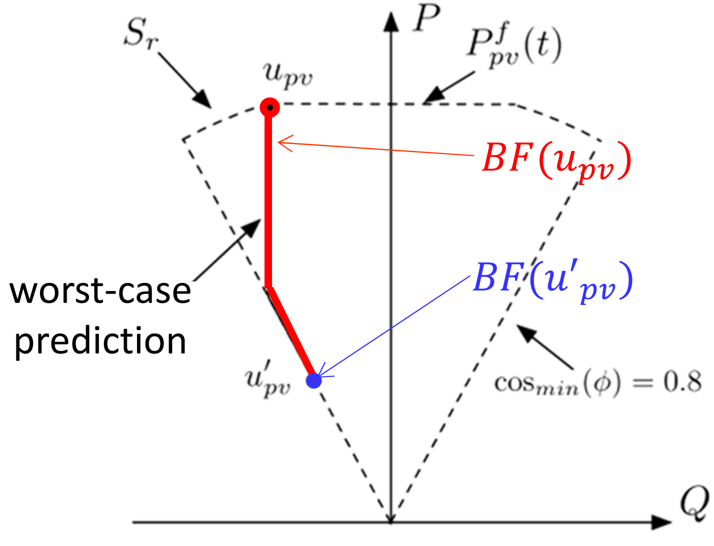
Belief Function

Say grid agent requests setpoint $(P_{\text{set}}, Q_{\text{set}})$ from a resource; actual setpoint (P, Q) will, in general, differ.

Belief function exported by resource agent means: the resource implements $(P, Q) \in BF(P_{\text{set}}, Q_{\text{set}})$

Quantifies uncertainty due to nature +
local inverter controller

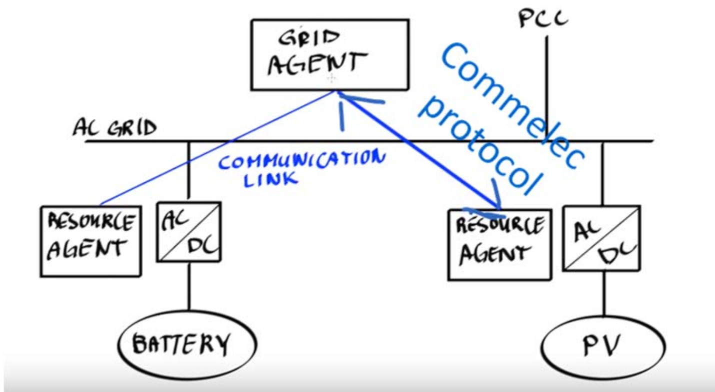
Essential for safe operation



Belief Function for a PV resource

Operation of Grid Agent

Grid agent computes a setpoint vector x that minimizes



Cost of power flow at point of common connection

$$J(x) = \sum_i w_i C_i(x_i) + W(z) + J_0(x_0)$$

Virtual cost of the resources

Penalty function of grid electrical state Z (e.g., voltages close to 1 p.u., line currents below the ampacity)

subject to admissibility.

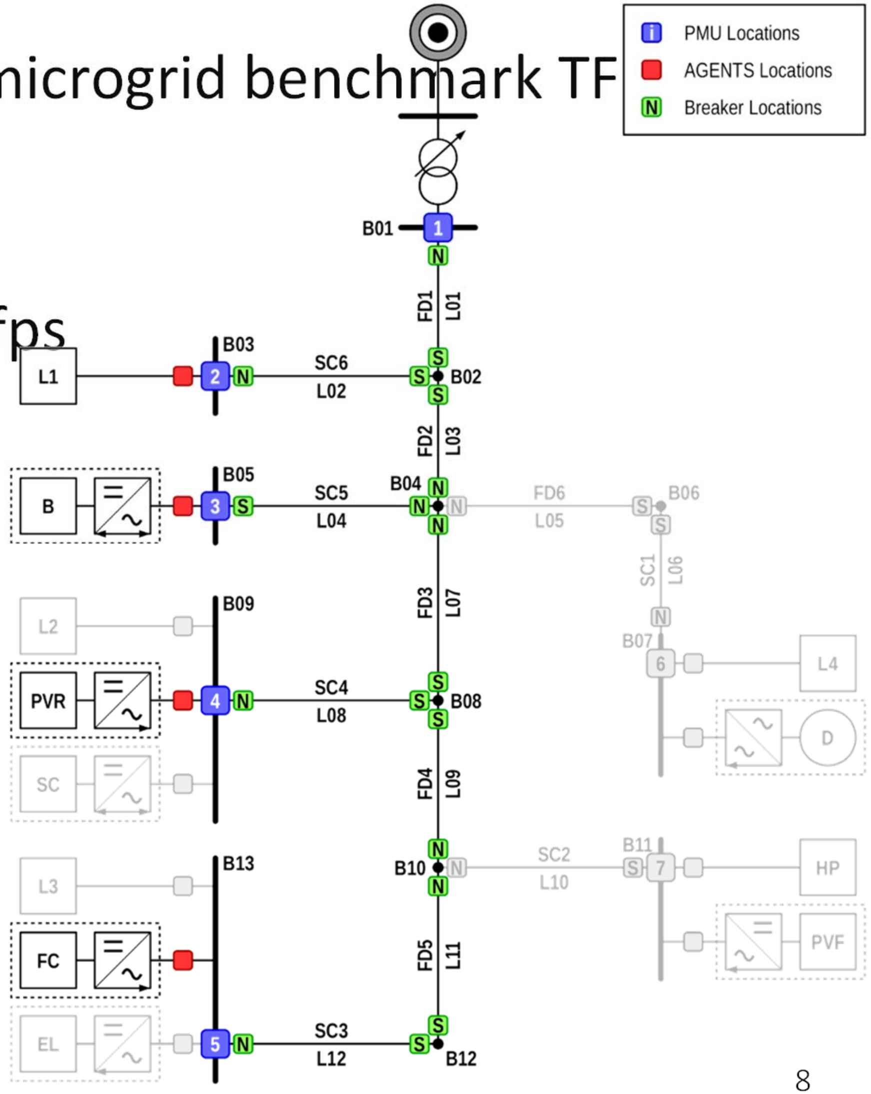
x is admissible $\Leftrightarrow$ ($\forall x' \in BF(x)$, x' satisfies security constraints)

requires solving a robust load flow; uses the theory of V-control [Wang et al 2016, 2017a, 2017b]

Implementation / EPFL Microgrid

Topology: 1:1 scale of the Cigré low-voltage microgrid benchmark TF C6.04.02 [Reyes et al, 2018]

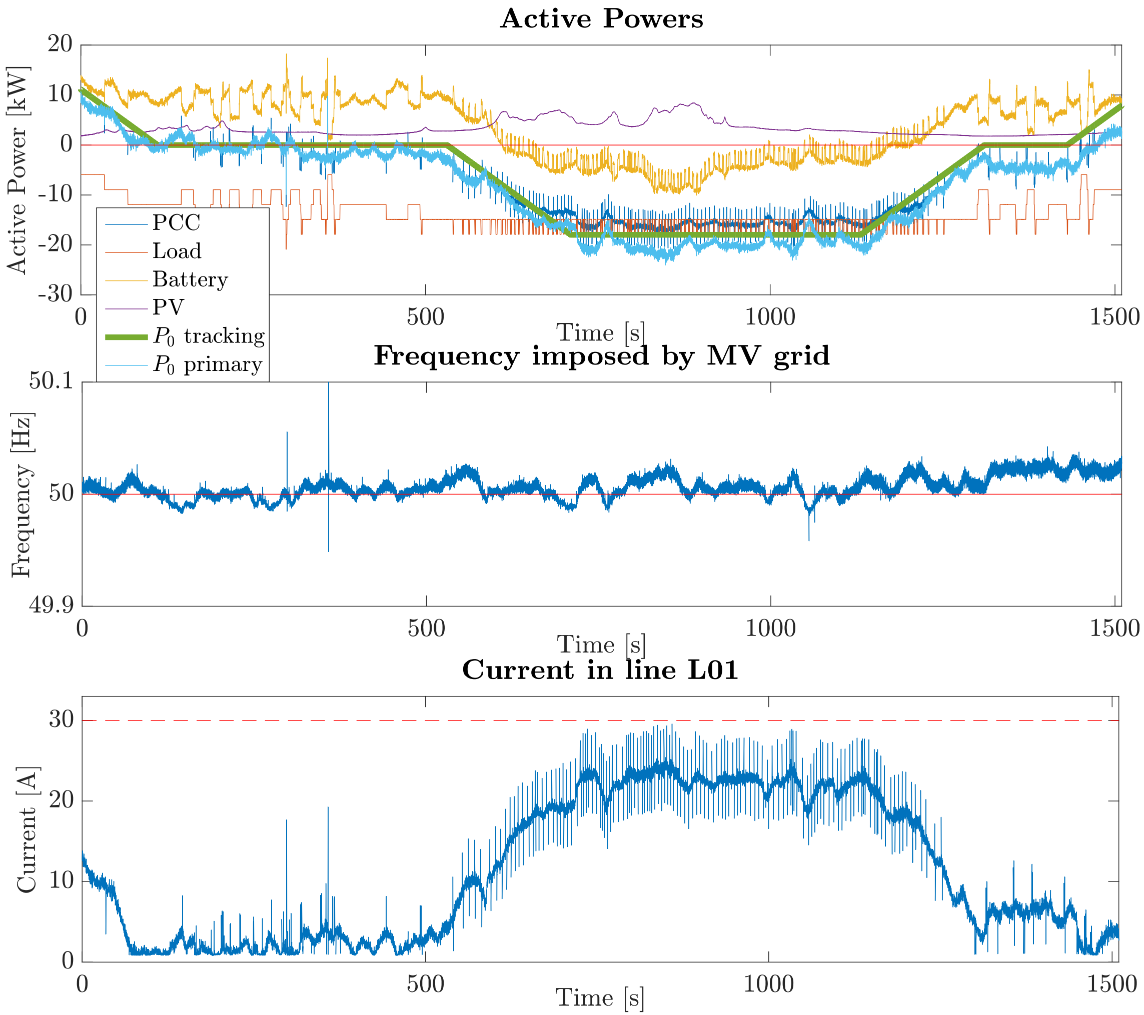
- Phasor Measurement Units:
  nodal voltage/current syncrophasors @50 fps
- Solar PVs on roof and fassade
- Battery
- Thermal Load (flex house)



Dispatch and Primary-Frequency Support

Superposition of dispatch and primary frequency control (i.e., primary droop control) with a max regulating energy of 200 kW/Hz

In parallel, keep the internal state of the local grid in a feasible operating condition.



2. Deterministic Networking

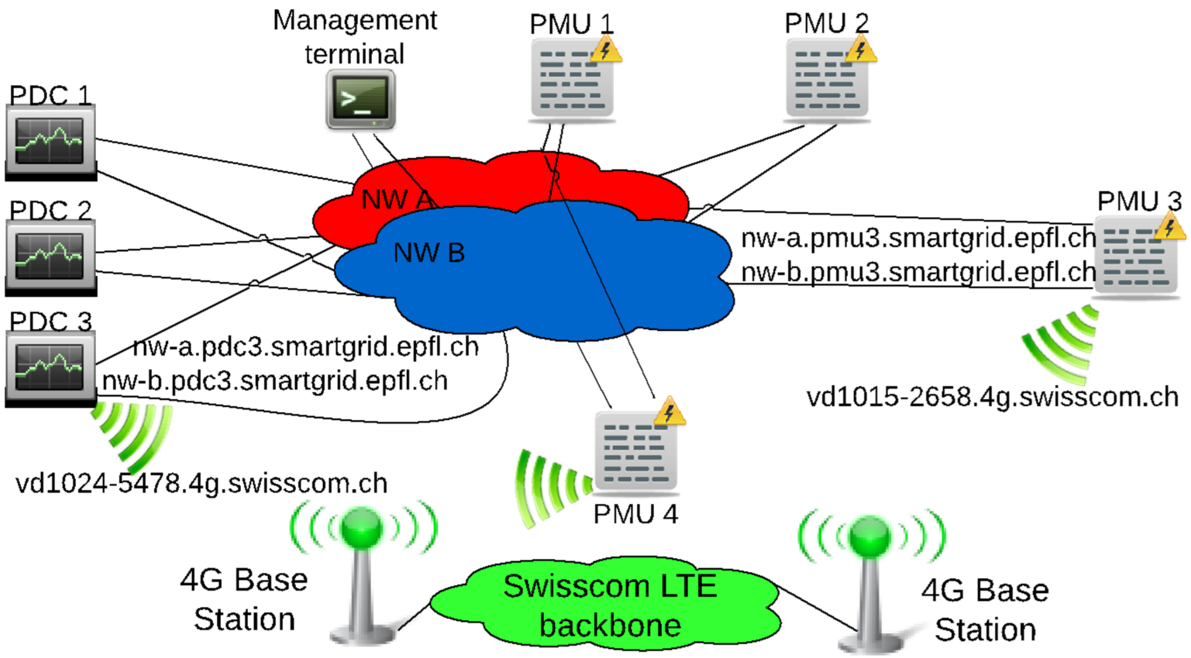
A real-time control such as COMMELEC is an example of cyber-physical infrastructure with real-time constraint.

- Deterministic Networking (IEEE 892.1 TSN, IETF Detnet)
    - Packet Duplication
    - Zero Congestion Loss
- Reliable computing

Network Reliability

Network reliability can be enhanced dramatically with packet duplication (IEEE TSN, HSR, PRP – on layer-2 networks only)

For layer-3 networks routers, we developed iPRP



iPRP (Parallel Redundancy Protocol for IP)

PDC, PMU, State Estimators are connected to 2 or more networks

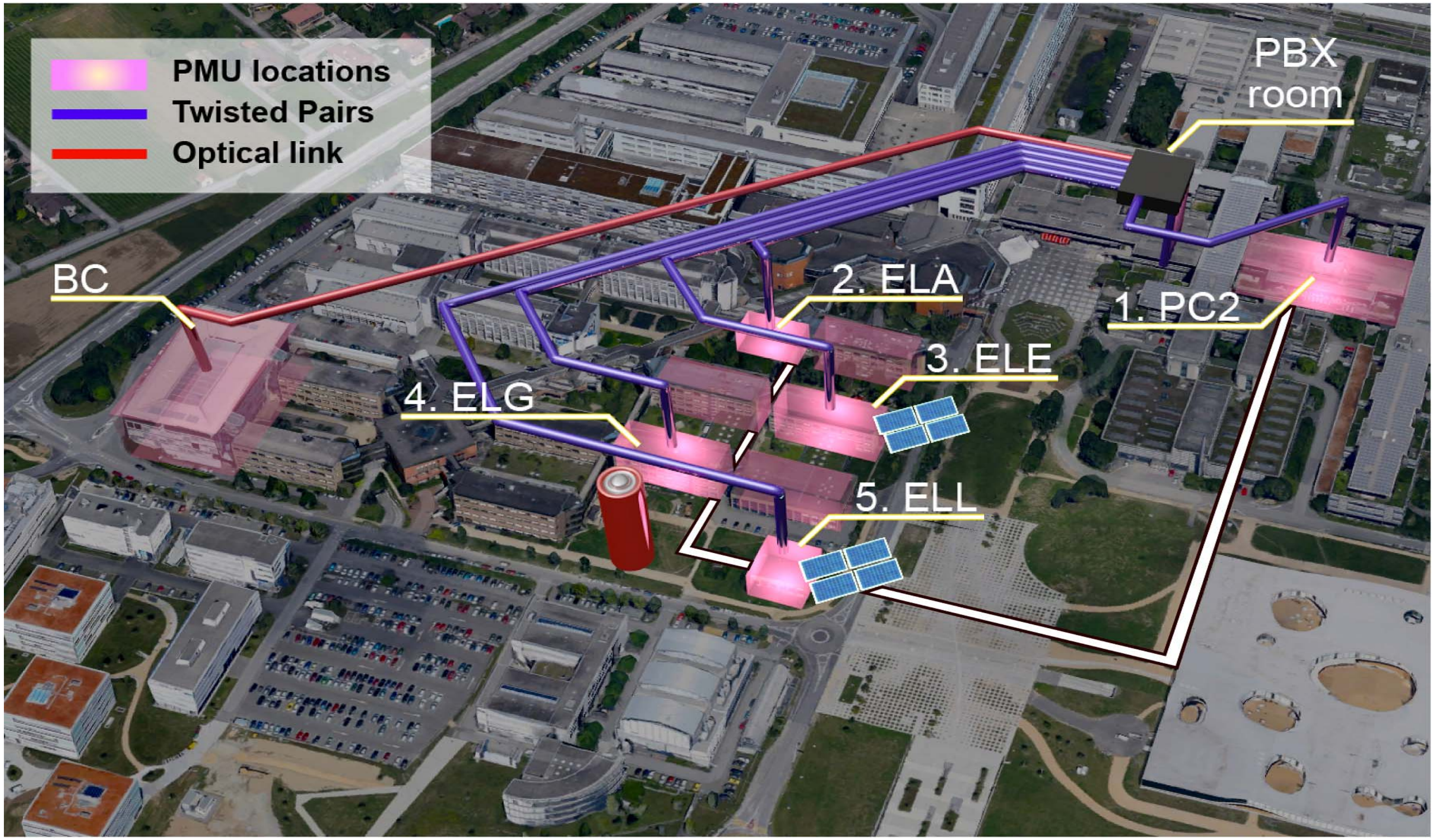
iPRP software duplicates UDP packets at source and removes duplicates at destination

fully transparent to application – works with any application that streams UDP packets over the socket interface

[Popovic et al 2015]

Open-source implementation: https://github.com/LCA2-EPFL/iprp

iPRP Deployment on MV Grid



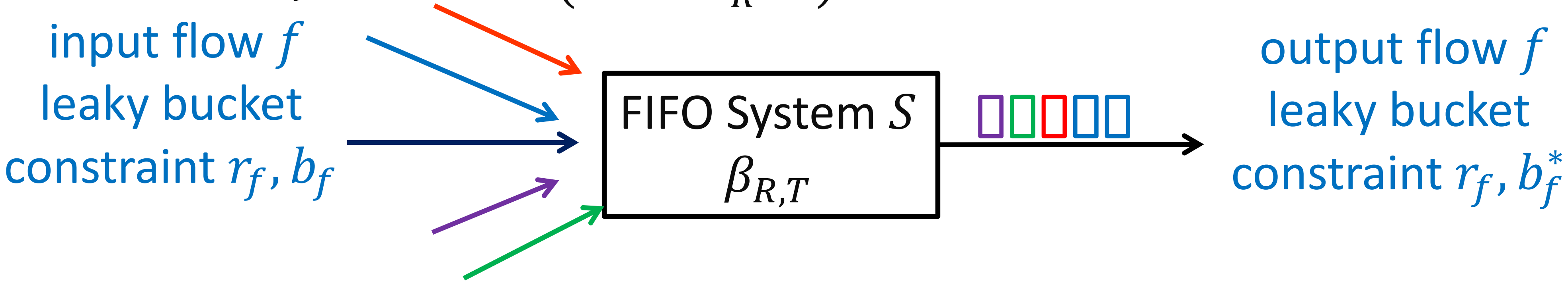
0 - Congestion Loss in FIFO Per-Class Networks

Time Sensitive Networking (IEEE 802.1 TSN, IETF Detnet) are FIFO per class

Computing backlog and delay bounds is hard due to burstiness cascade:

[LT 2001, Section 6.4] Increased burstiness causes increased burstiness

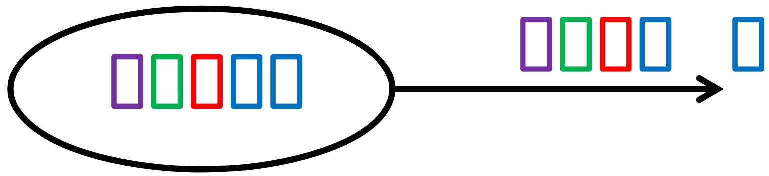
$$b_f^* = b_f + r_f \left(T + \frac{b_{tot} - b_f}{R}\right), \quad b_{tot} = \sum_i b_i$$



Delay bounds depend on topology and are generally bad except at low utilizations and small numbers of hop [Bennett et al 2002, Boyer et al 2012, Bouillard-Stea 2015, Bondorf et al 2017].

Avoiding Burstiness Cascade

Solution 1: re-shape every flow at every hop (per-flow shaping)
Solves the problem but defeats the purpose of per-class network.

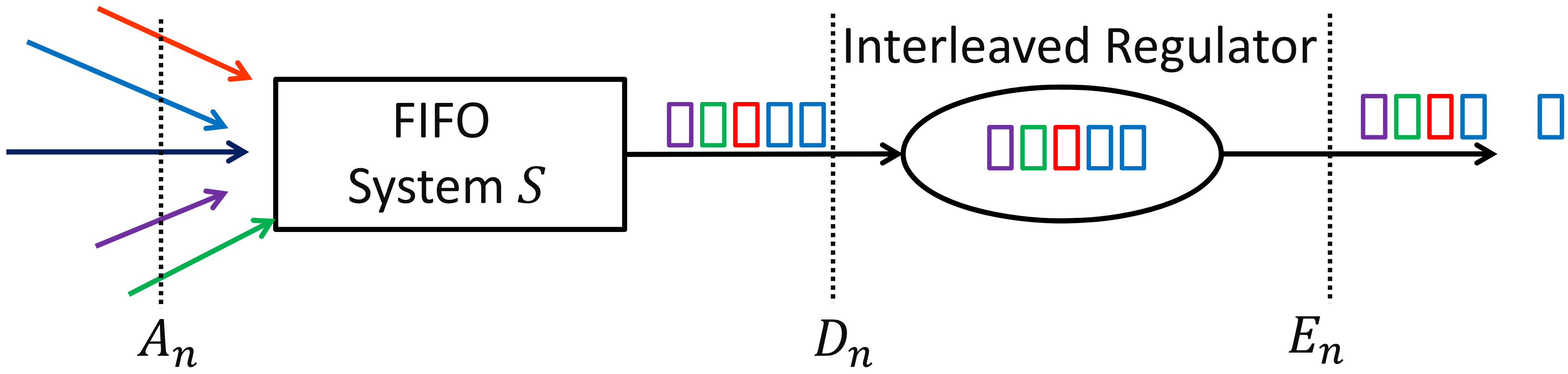


Solution 2: Interleaved Regulator

- FIFO queue of all packets of all flows in class
- packet at head of queue is examined versus traffic regulation of its flow; this packet is delayed if it came too early
- packets not at head of queue wait for their turn to come

[Specht-Samii 2016] “Urgency Based Scheduler”, now called “Asynchronous Traffic Shaping” at IEEE TSN

Interleaved Regulator Does Not Increase Worst Case Delay



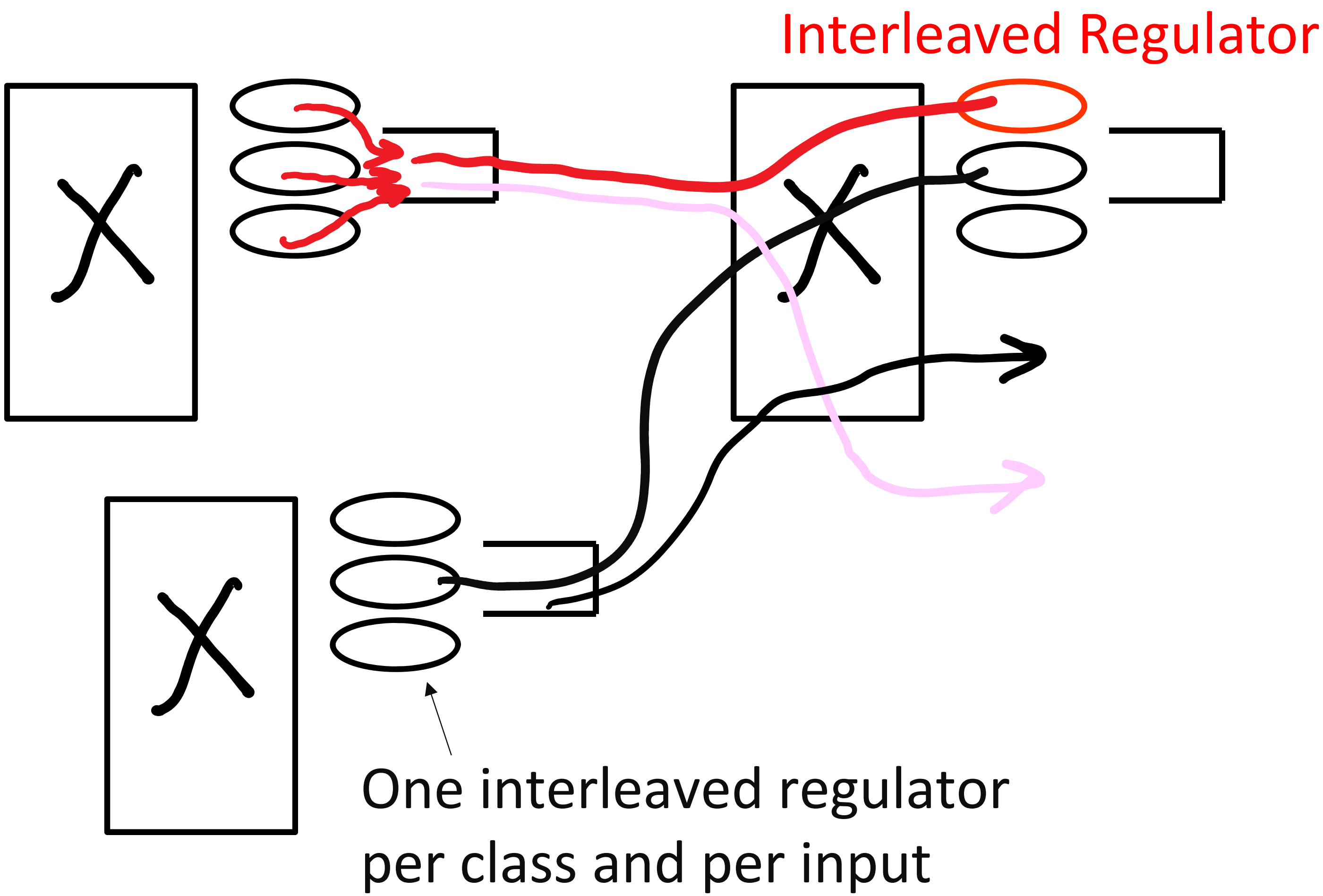
Every flow f is regulated before input to S

Output of S is fed to interleaved regulator with regulator Π^f for flow f

Theorem: [Le Boudec 2018] $\sup_n (D_n - A_n) = \sup_n (E_n - A_n)$

Reshaping flows with Interleaved Regulator is for free !

FIFO Network With Interleaved Regulators



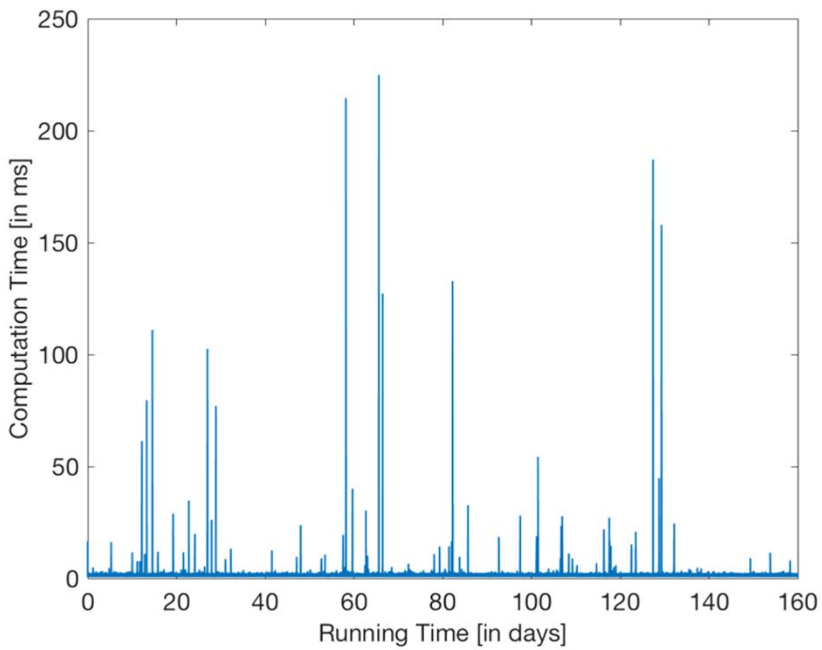
[Specht-Samii 2016] places one interleaved regulator per input port before output queue.

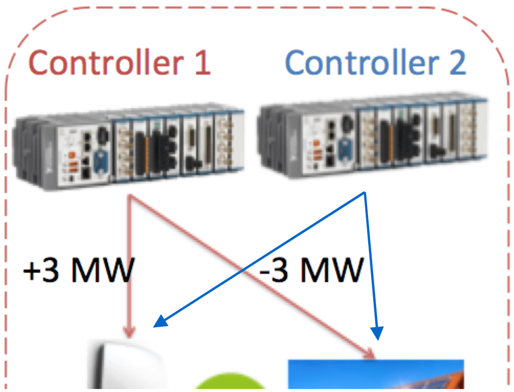
Output of interleaved regulator has known burstiness
⇒ no burstiness cascade
⇒ closed form delay and backlog bounds [Mohammadpour et al 2018]

Controller Delays and Crashes are Best Handled by Active Replication

Grid Agent's execution is susceptible to rare delay faults / crashes

Solution:
replication of GA





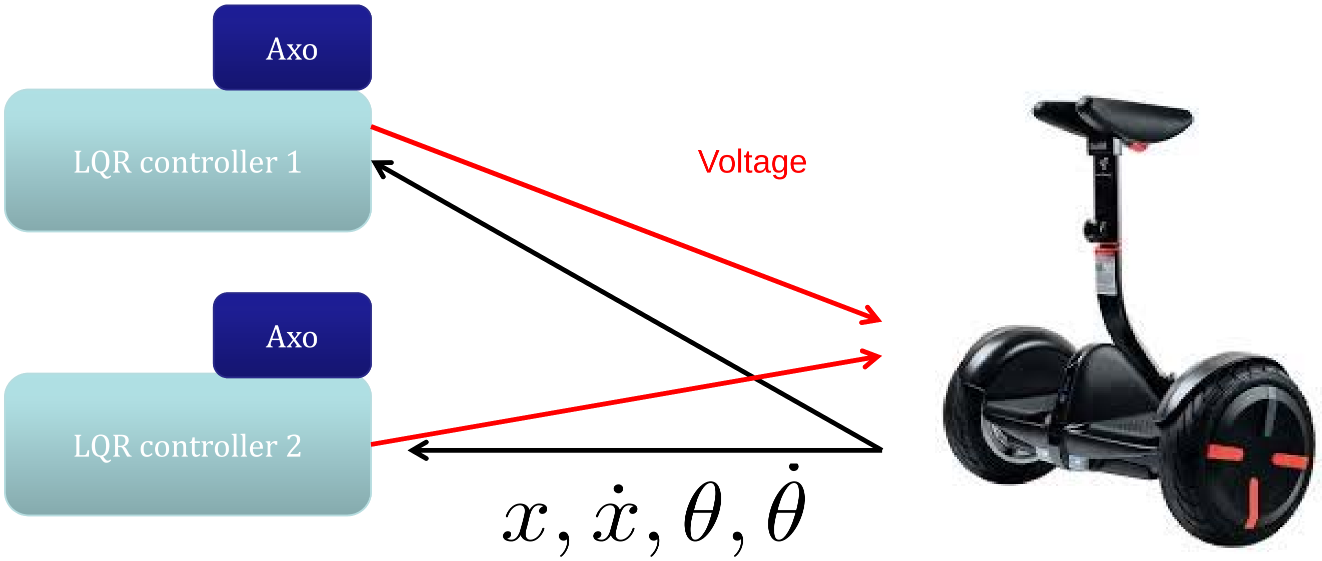
Issues with Active Replication: delayed setpoints

Toy example

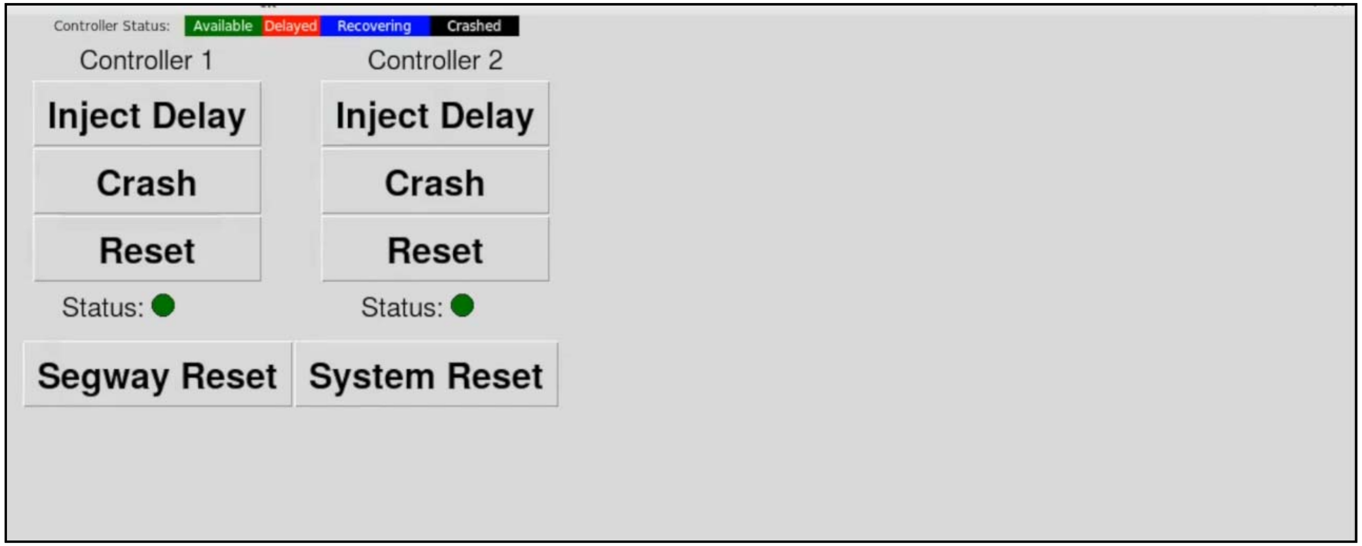
Duplicated controllers

Delayed setpoints

create instability



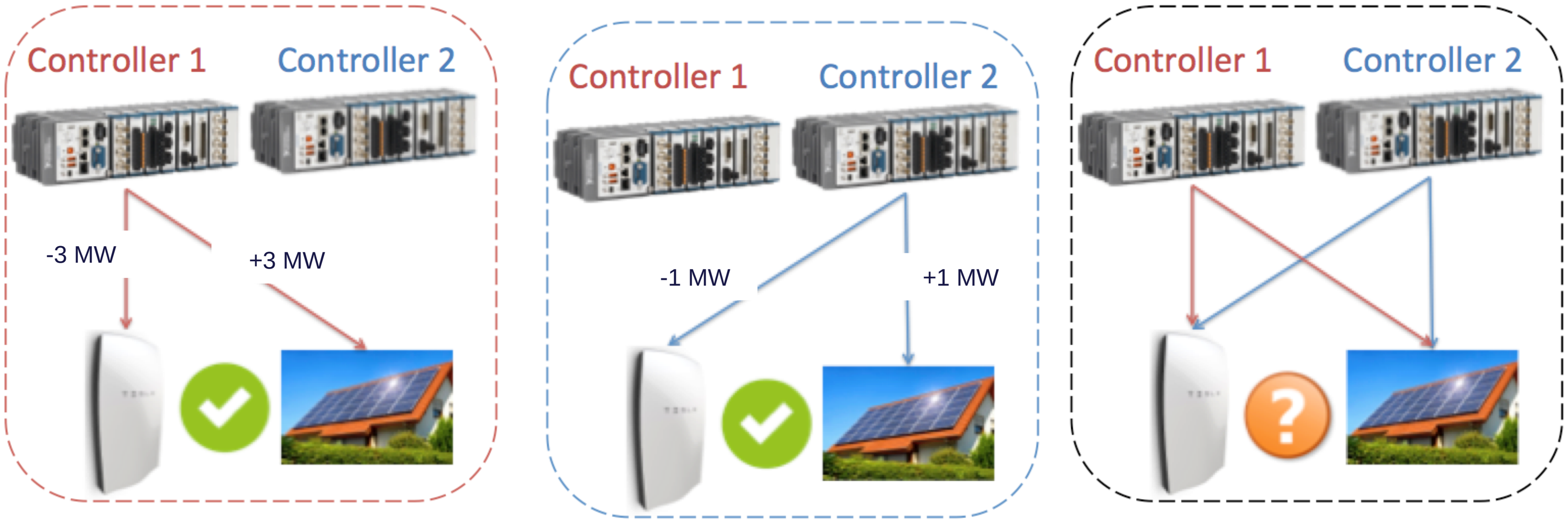
Controller Status: Available, Delayed, Recovering, Crashed



Without Axo

With Axo

Issues with Replication: interleaving is unsafe



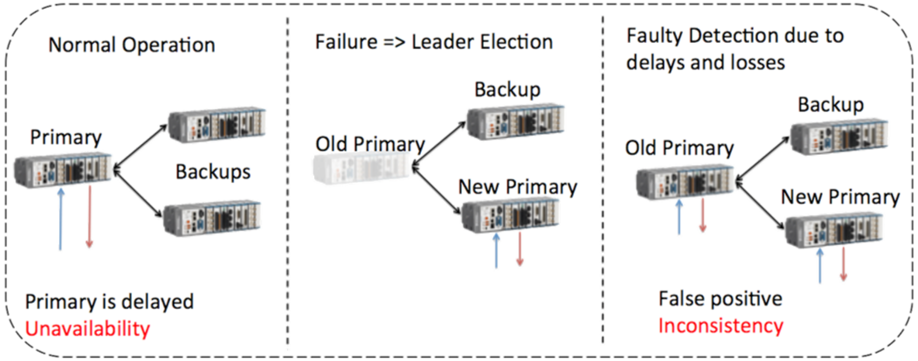
- Due to network losses or delays
  - Replicas compute with different measurements
  - Replicas issue correct but different setpoints

(-3 MW, +1 MW)
(-1 MW, +3 MW)

Existing solutions are

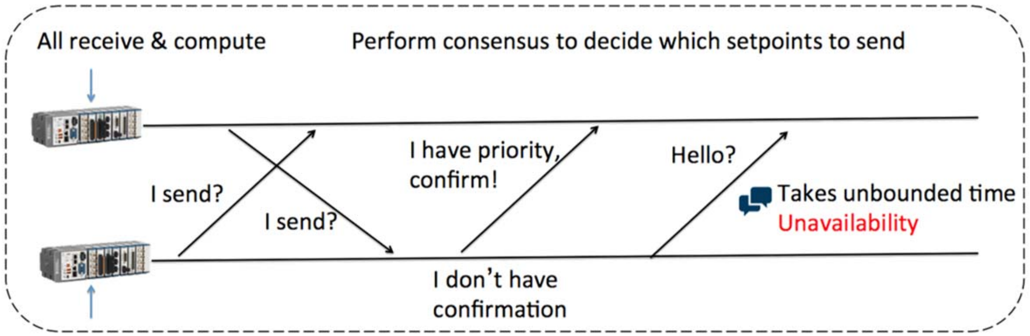
passive replication, hot or cold standby

→ does not work well with intermittent faults



active replication with consensus

→ unbounded delay

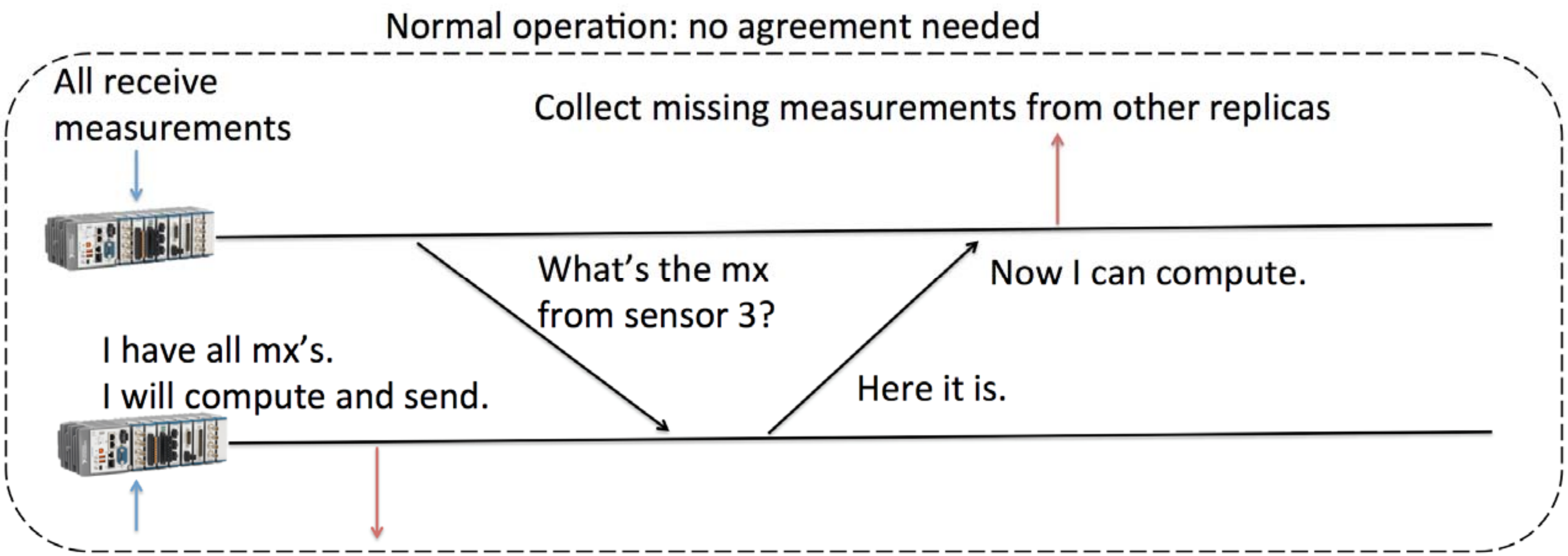


Active Replication with Axo + Quarts

Axo: makes sure delayed messages are not used

Quarts: GAs performs agreement on input, before starting computation
[Mohiuddin et al 2017, Saab et al 2017]

No delay in normal operation

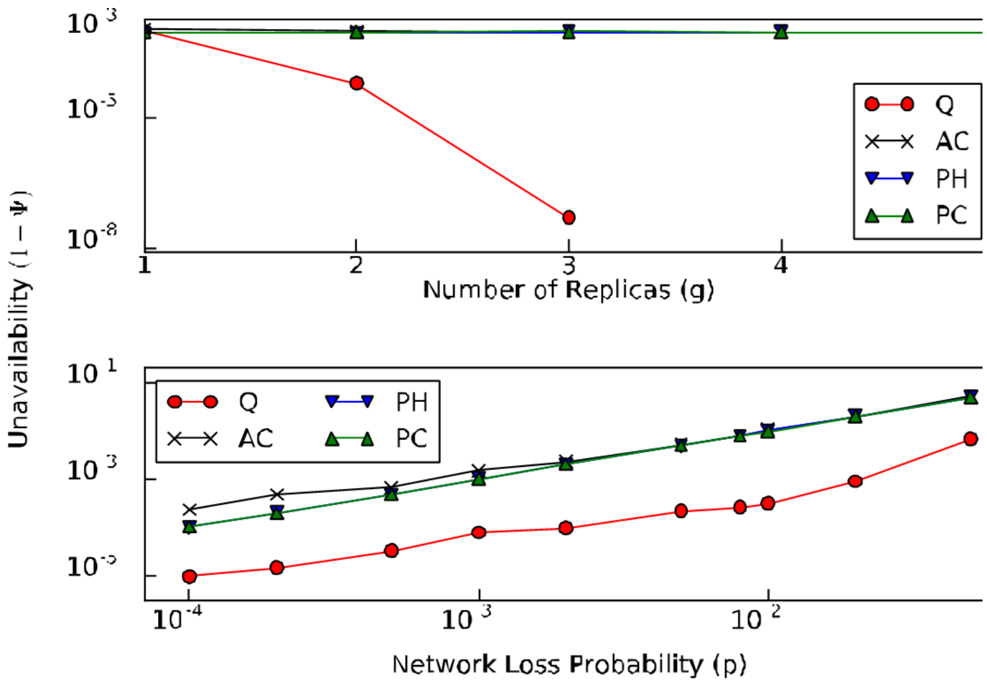


With Axo and Quarts, active replication provide high availability

Fast agreement even when some messages are lost

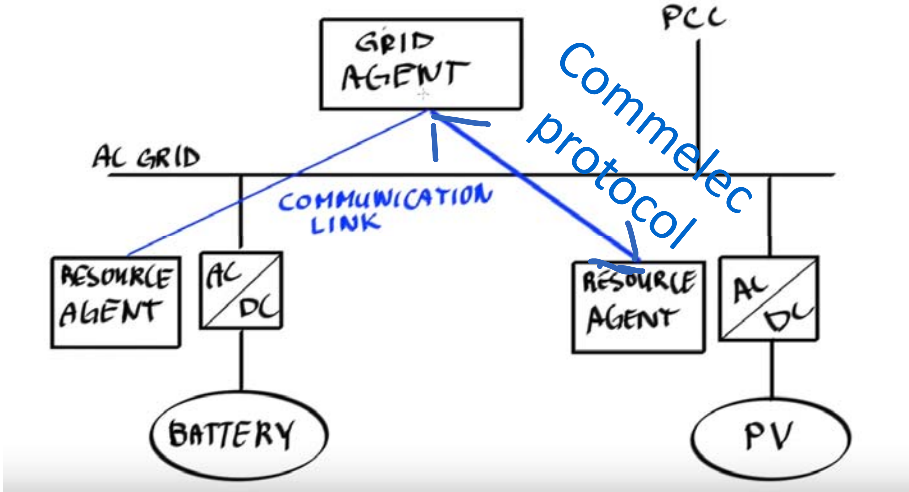
All GAs are always consistent

Highest availability



Delay and Cyber-Security

Most attacks follow taking control of some links (hosts) and modifying messages



We tested and ported
fast multicast message authentication
(ECDSA with precomputed tokens – real-time)
[Tesfay Le Boudec 2017]

Conclusion

Real-time control by software of electrical microgrids solves problems of distributed, stochastic generation

Real-time control requires deterministic networking and computing features

- packet duplication (iPRP),
- 0-congestion loss
- lightweight consensus (Axo, Quarts)

References

Control of Electrical Grids

- [Bernstein et al 2015, Reyes et al 2015a] Andrey Bernstein, Lorenzo Reyes-Chamorro, Jean-Yves Le Boudec , Mario Paolone, “A Composable Method for Real-Time Control of Active Distribution Networks with Explicit Power Setpoints, Part I and Part II”, in Electric Power Systems Research, vol. 125, num. August, p. 254-280, 2015.
- [Wang et al. 2016] Wang, C., Bernstein, A., Le Boudec, J.Y. and Paolone, M., 2016. Explicit conditions on existence and uniqueness of load-flow solutions in distribution networks. IEEE Transactions on Smart Grid.
- [Wang et al. 2017a] Wang, C., Bernstein, A., Le Boudec, J.Y. and Paolone, M., 2017. Existence and uniqueness of load-flow solutions in three-phase distribution networks. IEEE Transactions on Power Systems, 32(4), pp.3319-3320.
- [Wang et al. 2017b] Wang, C., Le Boudec, J.Y. and Paolone, M., 2017. Controlling the Electrical State via Uncertain Power Injections in Three-Phase Distribution Networks. IEEE Transactions on Smart Grid.

References

Deterministic Networking

- [Le Boudec 2018] Le Boudec, Jean-Yves, “A Theory of Traffic Regulators for Deterministic Networks with Application to Interleaved Regulators”, *arXiv preprint arXiv:1801.08477*.
- [Le Boudec-Thiran 2001] Le Boudec, Jean-Yves, and Patrick Thiran. *Network calculus: a theory of deterministic queuing systems for the internet*. Vol. 2050. Springer Science & Business Media, 2001, online at http://ica1www.epfl.ch/PS_files/NetCal.htm
- [Mohammadpour et al, 2018] Mohammadpour E., Stai, E. Mohiuddin, M., Le Boudec, J.-Y. “End-to-End Latency and Backlog Bounds in Time-Sensitive Networking with Credit Based Shapers and Asynchronous Traffic Shaping”, *arxiv:1804.10608*
- [Popovic et al 2015] Popovic, M., Mohiuddin, M., Tomozei, D.C. and Le Boudec, J.Y., 2015, May. iPRP: Parallel redundancy protocol for IP networks. In Factory Communication Systems (WFCS), 2
- [Specht-Samii 2016] Specht, J. and Samii, S., 2016, July. Urgency-based scheduler for time-sensitive switched ethernet networks. In *Real-Time Systems (ECRTS), 2016 28th Euromicro Conference on* (pp. 75-85). IEEE.
- [Tesfay Le Boudec 2017] T. T. Tesfay and J.-Y. Le Boudec. Experimental Comparison of Multicast Authentication for Wide Area Monitoring Systems, IEEE Transactions on Smart Grid, 2017

References

Deterministic Networking

- [Bennett et al 2002] Bennett, J.C., Benson, K., Charny, A., Courtney, W.F. and Le Boudec, J.Y., 2002. Delay jitter bounds and packet scale rate guarantee for expedited forwarding. *IEEE/ACM Transactions on Networking (TON)*, *10*(4), pp.529-540.
- [Bondorf et al 2017], Bondorf, Steffen, Paul Nikolaus, and Jens B. Schmitt. "Quality and Cost of Deterministic Network Calculus: Design and Evaluation of an Accurate and Fast Analysis." *Proceedings of the ACM on Measurement and Analysis of Computing Systems* 1.1 (2017) and arXiv:1603.02094v3
- [Bouillard-Stea 2015] Bouillard, A. and Stea, G., 2015. Exact worst-case delay in FIFO-multiplexing feed-forward networks. *IEEE/ACM Transactions on Networking (TON)*, *23*(5), pp.1387-1400.
- [Boyer et al 2012] Boyer, Marc, Nicolas Navet, and Marc Fumey. "Experimental assessment of timing verification techniques for AFDX." *6th European Congress on Embedded Real Time Software and Systems*. 2012.

References

Reliable Real-Time Computing

- [Mohiuddin et al 2017] Mohiuddin, M., Saab, W., Bliudze, S. and Le Boudec, J.Y., 2017. Axo: Detection and Recovery for Delay and Crash Faults in Real-Time Control Systems. IEEE Transactions on Industrial Informatics.
- [Saab et al 2017] W. Saab, M. M. Maaz, S. Bliudze and J.-Y. Le Boudec. Quarts: Quick Agreement for Real-Time Control Systems. 22nd IEEE International Conference on Emerging Technologies And Factory Automation (ETFA), Limassol, Cyprus, 2017.015 IEEE World Conference on (pp. 1-4). IEEE.