CPS: Synergy: Distributed Coordination of Smart Devices to Mitigate Intermittency of Renewable Generation for a Smarter and Sustainable Power Grid

Prabir Barooah, Arturo Bretas, and Sean Meyn (UF)

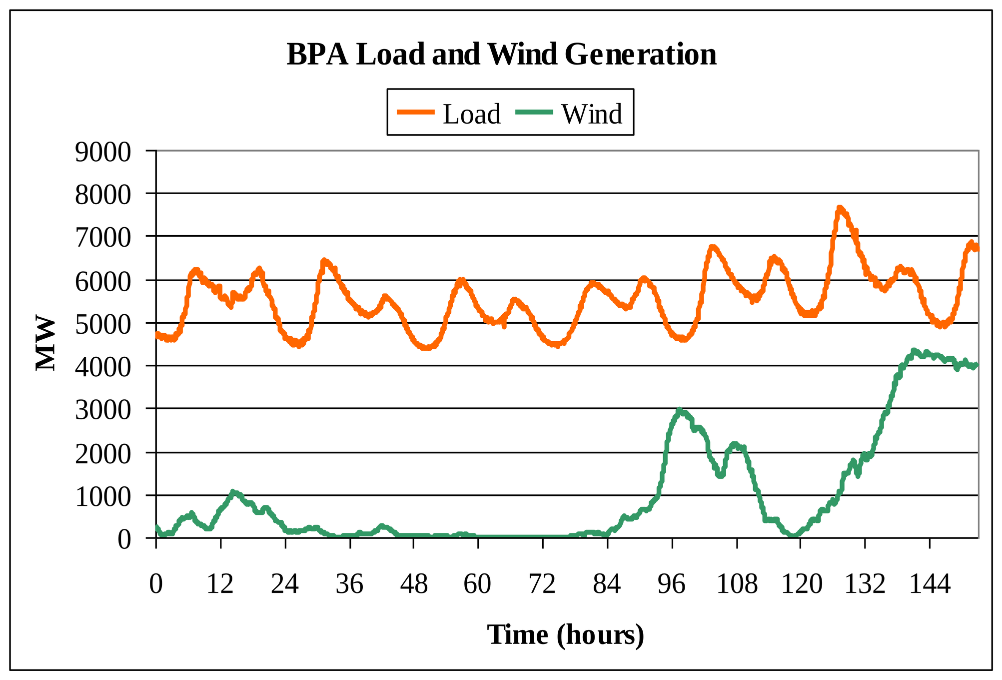
Managing volatility of renewable energy sources in the future power grid

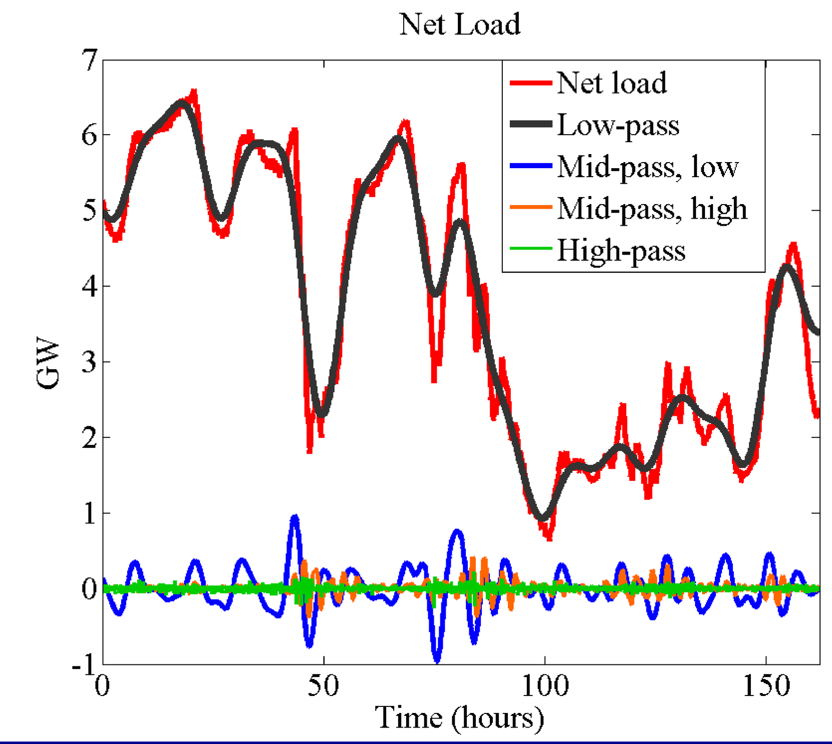
- Solar and wind energy are intermittent and uncontrollable, making balancing supply and demand challenging.
- Batteries can help, but they are expensive.
- Power demand of most loads is flexible and can be manipulated to provide "virtual energy storage" (VES).

Goal: Coordinate actions of many loads to provide robust and reliable VES

Concerns:
- Computational complexity
- Decentralized decision-making (communication, privacy)
- Consumers' quality of service (QoS)
- Robustness to uncertainty (weather, human behavior, etc.)

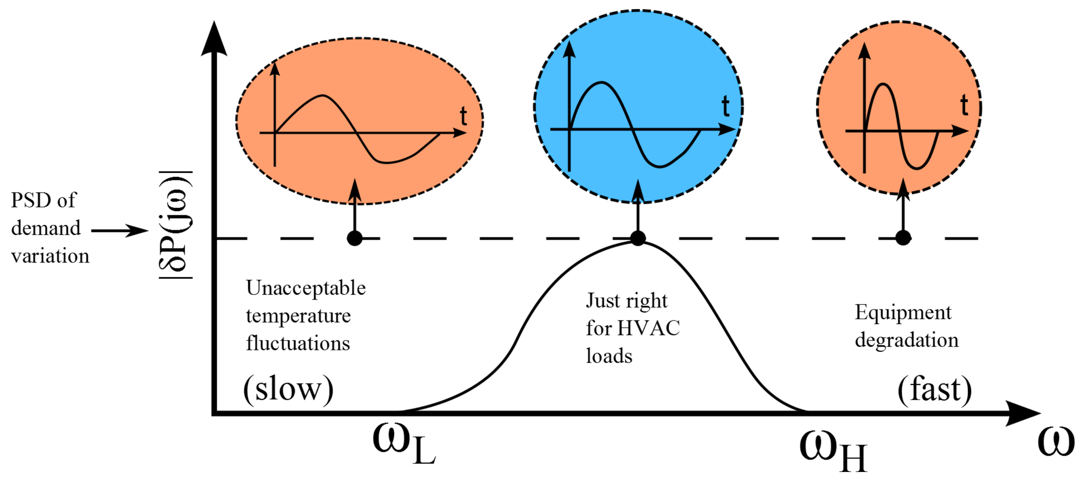
Key Innovations:
- Randomization to break the complexity barrier
- Global information from local measurements for coordination
- Spectral decomposition for resource allocation



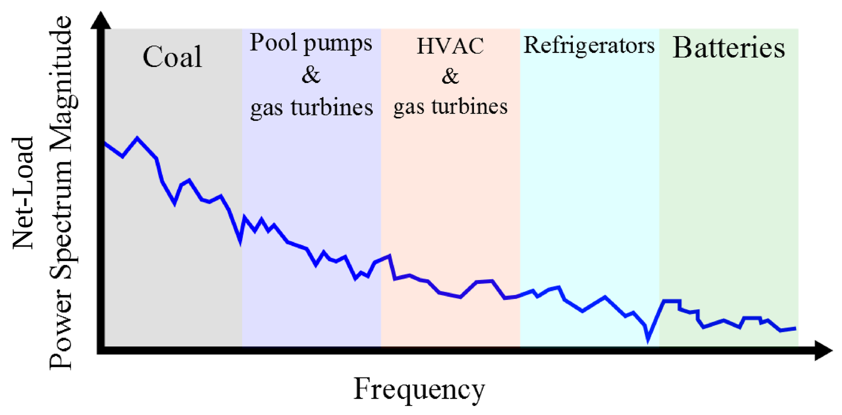


Distributed coordination using local measurements (aggregators and commercial HVAC)

Idea: Restrict loads' control actions to specific frequency bands.
- Provides strict bounds on QoS.
- Collectively, loads can negate fluctuations in net load.

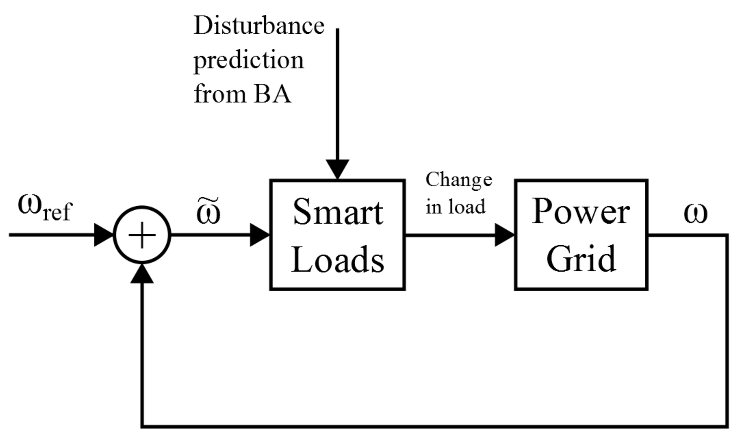


Each load type can account for a different frequency range



Question: How to coordinate loads without load-to-load communication?

Solution: Local feedback + predictions from BA.



BaLDuR-DMPC

$$\min_{\boldsymbol{u}_i[k]} \sum_{\ell=k}^{k+N-1} (\omega[\ell])^2$$

Subject to:

$$\omega[\ell] = g(u_i[\ell|k] + \hat{d}_i[\ell|k])$$

$$u_i[\ell|k] \in \mathcal{U}_i$$

$$|\text{DFT}(\boldsymbol{u}_i[k])| \le \alpha_i[m], \quad 0 \le m \le 2N-1$$

Enforces QoS

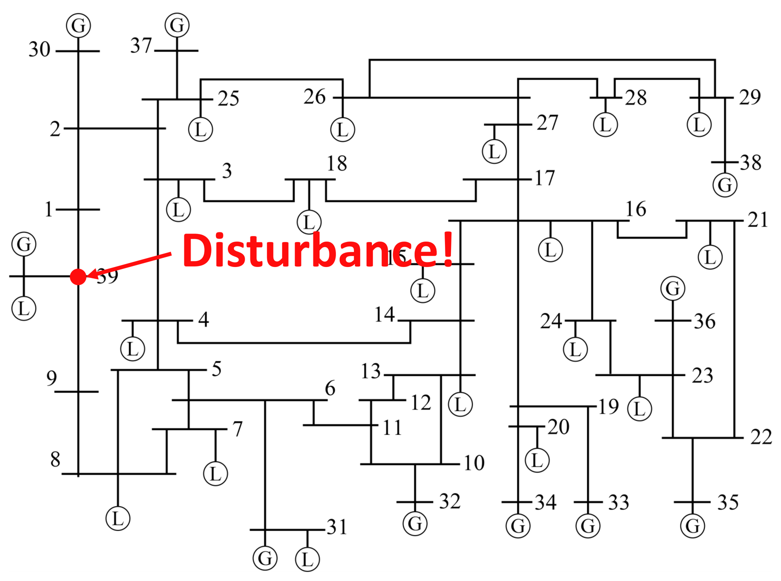
Use local frequency measurements to scale disturbance prediction: **Allows loads to coordinate without communication!**

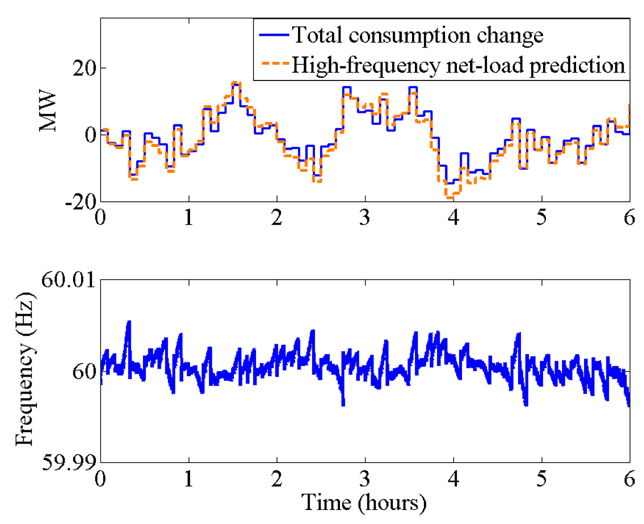
$$\hat{\boldsymbol{d}}_i[k] \triangleq \rho_i[k]\hat{\boldsymbol{d}}^{(BA)}[k]$$

$$\rho_i[k] = r_i[k]\rho_i[k-1]$$

$$r_i[k] = \min\left\{\max\left\{\left|\frac{\hat{d}[k]^{(BA)}}{\hat{\vartheta}_i[k_-]}\right|, \underline{r}\right\}, \bar{r}\right\}$$

$$\hat{\vartheta}[k_-] = \frac{\tilde{\omega}[k]}{g} - \hat{d}[k]$$





Problem: modeling quality of service
Solution: bandwidth constraints to enforce QoS constraints
Problem: coordinating many loads
Solution: frequency-based feedback at load level

Advantages:
- Decentralized
- Preserves privacy
- Low-bandwidth, one-way communication

Distributed coordination using randomization (on/off loads)

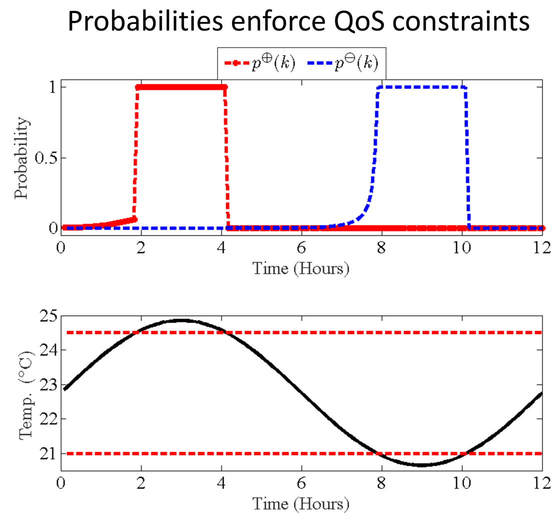
- 2 possible control commands for every load: on or off
- For 1 million loads: 2^{10^6} possible control commands AT EVERY INSTANT!

Idea: Use randomization to turn loads on and off to track net load in the aggregate while maintaining consumer QoS.

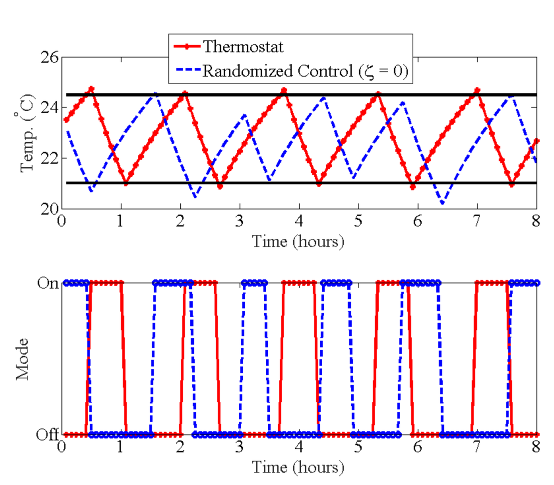
$p^{\oplus}(k) :=$ Probability of switching from off to on
$p^{\ominus}(k) :=$ Probability of switching from on to off

$R_0(x,1) =$ Probability of switching from "x" to on
$R_0(x,0) =$ Probability of switching from "x" to off

Probabilities enforce QoS constraints



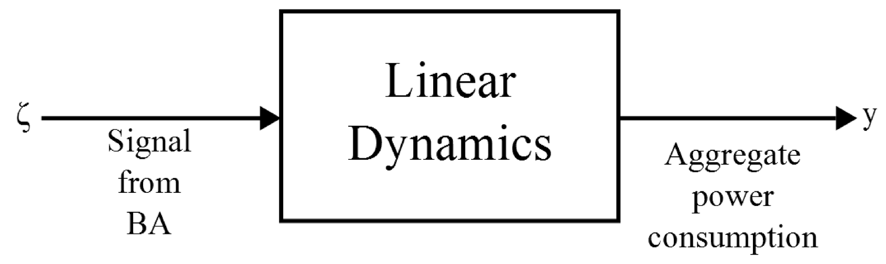
Rand. control mimics deterministic control



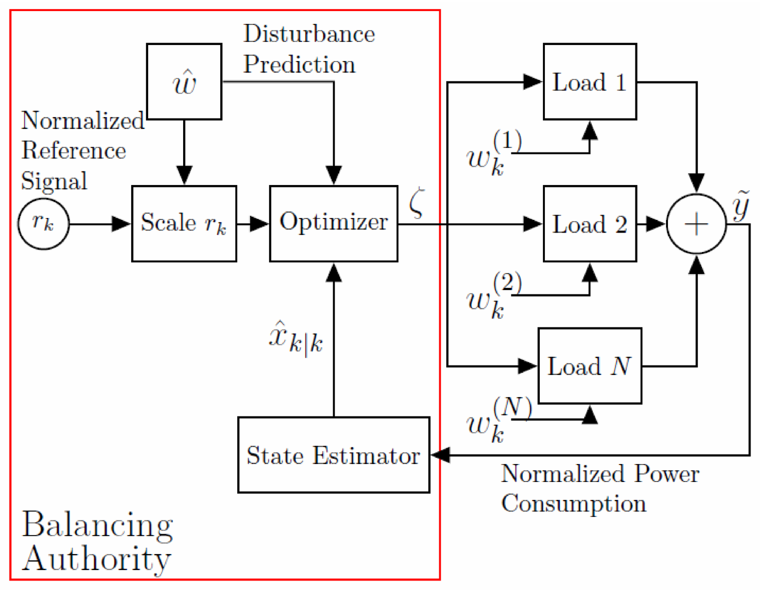
Define randomized local control law, parameterized by ζ:

$$R_\zeta(x, y^u) := R_0(x, y^u)\exp\left(\zeta\,\mathcal{U}(y^u) - \Lambda_\zeta(x)\right)$$

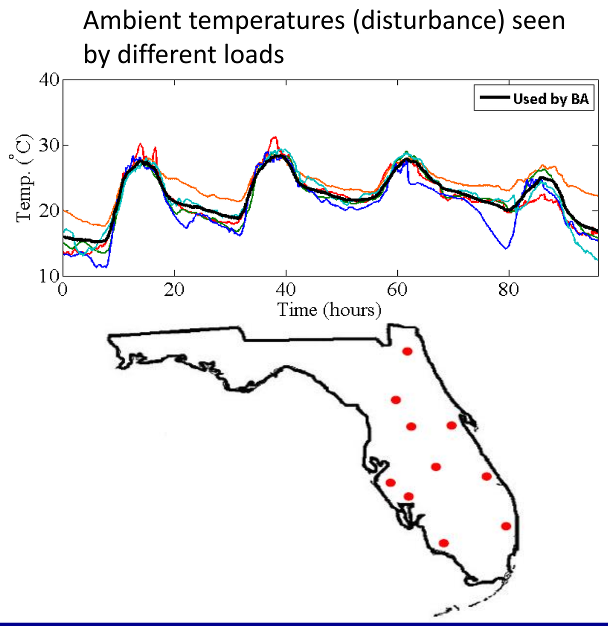
$$\mathcal{U}(y^u) = \begin{cases} 1, & y^u = \oplus \\ 0, & y^u = \ominus \end{cases}$$

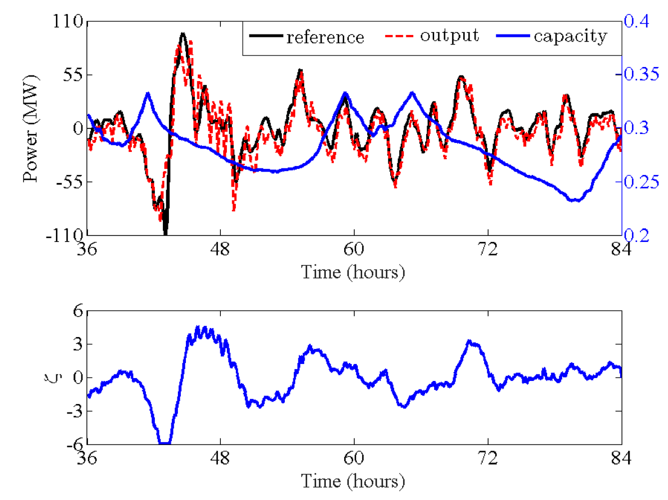


Design Architecture:
- Balancing authority (BA) sends signal ζ to the loads to adjust probabilities of turning on and off.
- Loads turn on and off randomly, accordingly.
- QoS constraints are maintained for each load.
- Aggregate power consumption tracks a desired reference.



Ambient temperatures (disturbance) seen by different loads

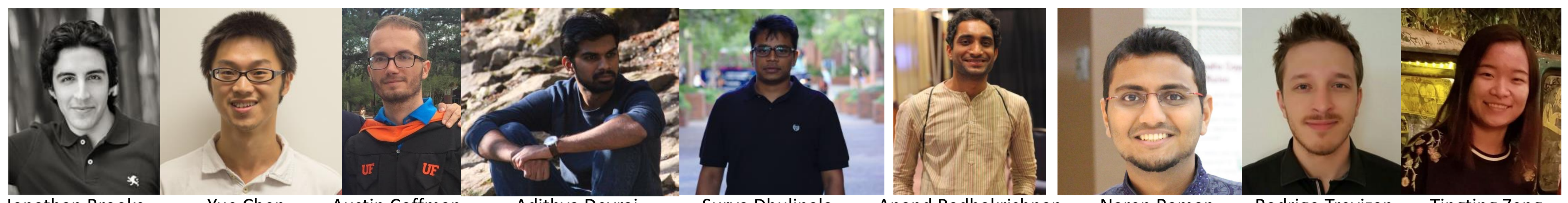




Problems: Computational complexity and coordinating many on/off loads
Solution: Randomized control architecture

Advantages:
- Mimics deterministic control
- Decentralized
- Preserves privacy

Barooah, P. "Virtual energy storage from flexible loads: distributed control with QoS constraints," in Smart Grid Control: An Overview and Research Opportunities, *under review*.
Chen, Y., Hashmi, U., Mathias, J., Busic, A., and Meyn, S. "Distributed control design for balancing the grid using flexible loads," in IMA Volume on the Control of Energy Markets and Grids, *accepted*.
Austin Coffman and Prabir Barooah. "Simultaneous identification of building dynamic model and occupant-induced disturbance," in Energy and Buildings, *accepted*.
Brooks, J., Trevizan, R., Barooah, P., and Bretas, A. "Analysis and Evaluation of an Optimal Load Control Algorithm for Contingency Service," *under review*.
Brooks, J. and Barooah, P. "Consumer-aware load control to provide contingency reserves using frequency measurements and inter-load communication," in American Control Conference, 2017.
Busic, A., Hashmi, U., and Meyn, S. "Distributed control of a fleet of batteries," in American Control Conference, 2017.
Brooks, J., Trevizan, R., Barooah, P., and Bretas, A. "Performance assessment of an optimal load control algorithm for providing contingency service," in North American Power Symposium, 2017.
Brooks, J., and Barooah, P. "Virtual energy storage through decentralized load control with quality of service bounds," in American Control Conference, 2017.
Weije, P., Dhulipala, S., and Bretas, A. "DG integration and power quality management in railway power systems: a distributed approach," in Bulk Power Systems Dynamics and Control Symposium, 2017.
Busic, A., and Meyn, S. "Distributed randomized control for demand dispatch," in IEEE Conference on Decision and Control, 2016.
Radhakrishnan, A., and Meyn, S. "Feedback particle filter design using a differential-loss reproducing kernel Hilbert space," in American Control Conference, *under review*.
Radhakrishnan, A., Devraj, A., and Meyn, S. "Learning techniques for feedback particle filter design," in IEEE Conference on Decision and Control, 2016.
Chen, Y. "Markovian demand dispatch design for virtual energy storage to support renewable energy integration," PhD dissertation, 2016.



Jonathan Brooks | Yue Chen | Austin Coffman | Adithya Devraj | Surya Dhulipala | Anand Radhakrishnan | Naren Raman | Rodrigo Trevizan | Tingting Zeng