FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Clusters and Communities in Air Traffic Delay Networks

Karthik Gopalakrishnan
Prof. Hamsa Balakrishnan
MIT

Berkeley UNIVERSITY OF CALIFORNIA
Massachusetts Institute of Technology
NSF
MICHIGAN
VANDERBII UNIVERSIT

Motivation

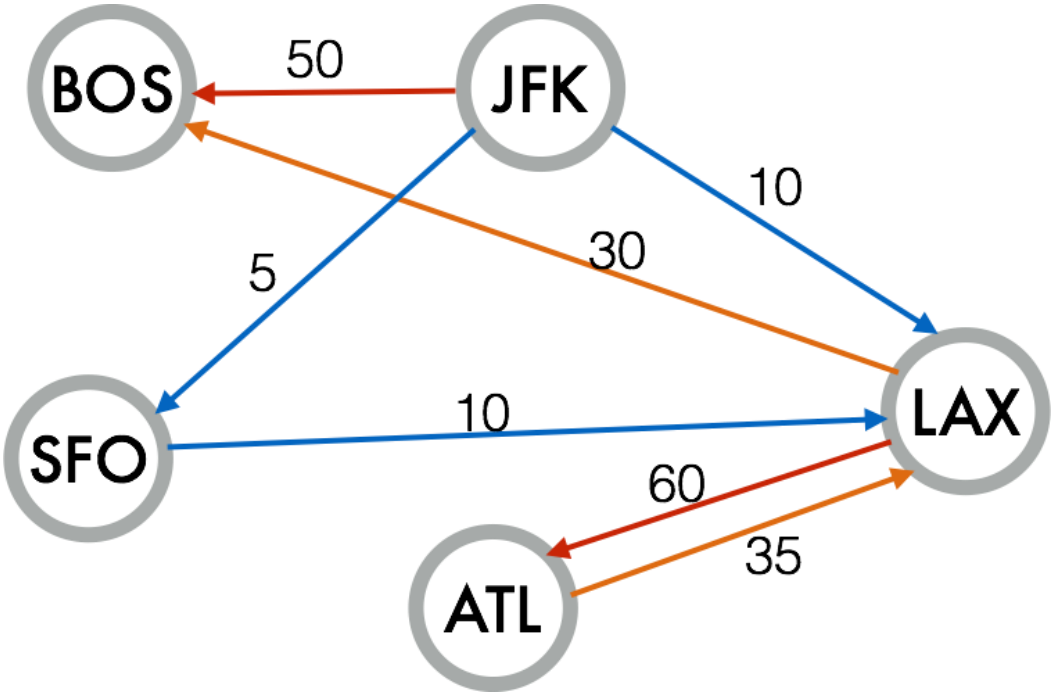
* 22% of flights were delayed by more than 15 minutes in 2015
* Cost of delays: 31-40 billion dollars annually

* Important questions:
  * When can we say that the delay levels in the system are similar ?
  * What are the common delay patterns ?
  * When do these delay patterns occur ?

* Broad objective: Delay prediction and mitigation

Delay network

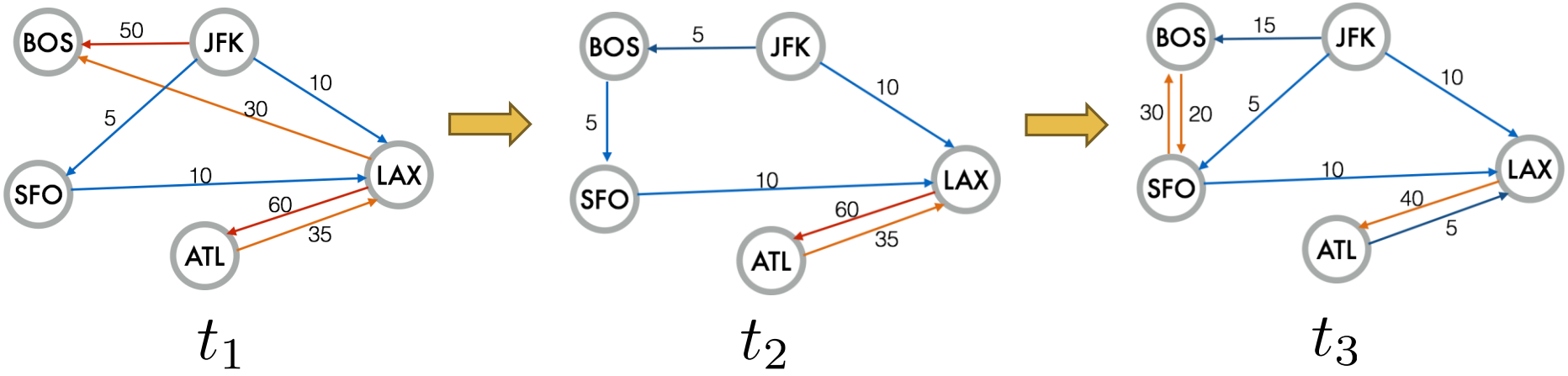
The delay state of the air transportation system at any time can be represented using a *weighted-directed graph*



* Nodes: airports
* Edge weights: median delay (min)

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Time series of delay networks



* Given: Time series of networks $G_1, G_2, ..., G_N$
* Objective: To find characteristic delay networks

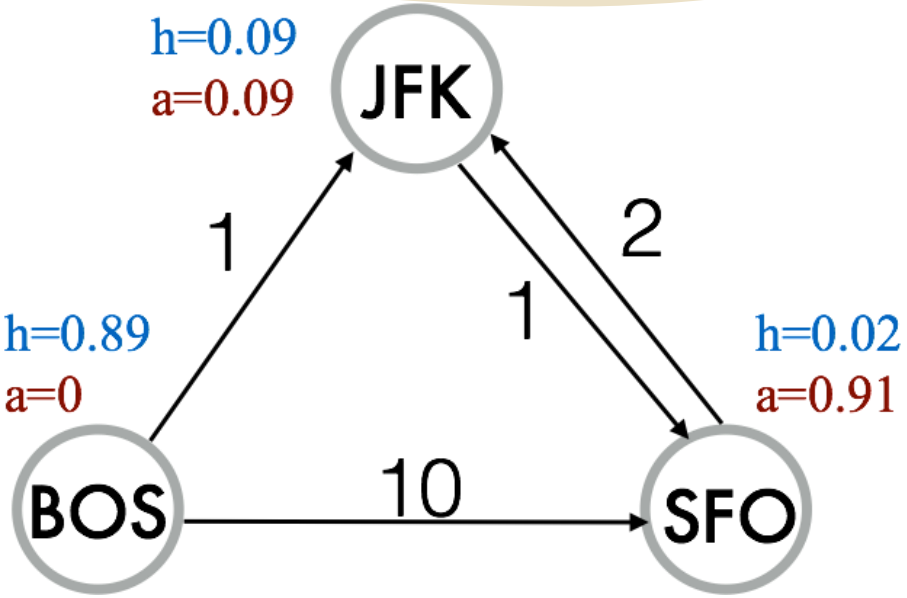
FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Clustering delay networks

* To find characteristic delay networks, we identify clusters
  * Cluster the delay networks based on feature vectors
* For every network G_i , we construct a feature vector f_i
* The feature vector f_i should capture
  * Delay connectivity
  * Magnitude of delays

Features for comparing networks

* The hub and authority score of a network is a measure of node centrality
  * Good hub points to good authorities
  * Good authority points to good hubs



$$f_i = (\text{Total delay})_i \times \begin{bmatrix} \vec{h} \\ \vec{a} \end{bmatrix}$$

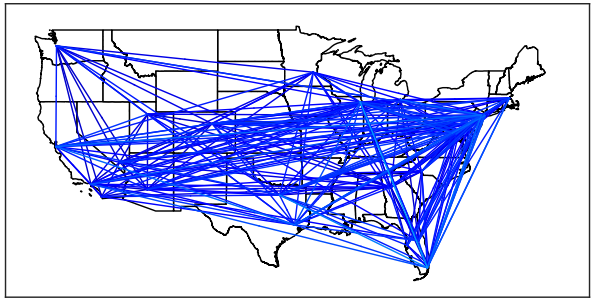
FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

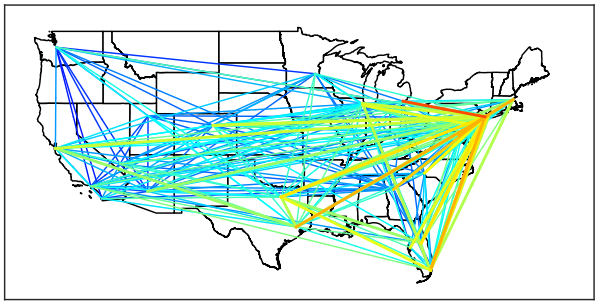
The characteristic delay states

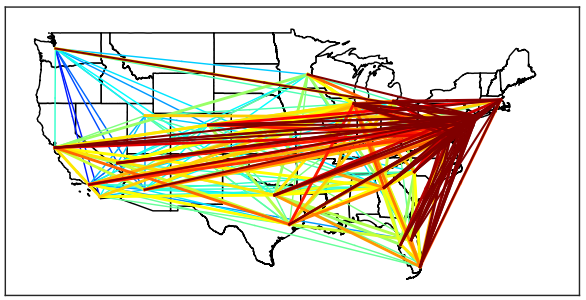
(1) Low delay state

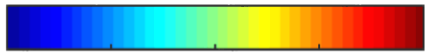
(2) Medium delay state

(3) High delay state







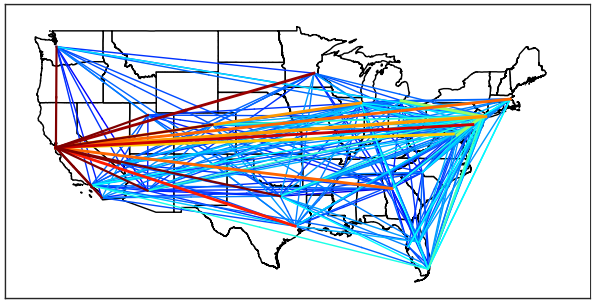


0 90 min

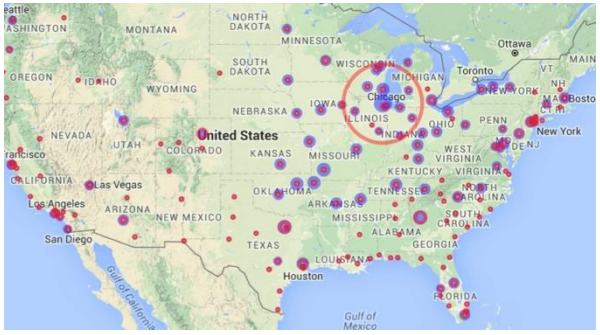
FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

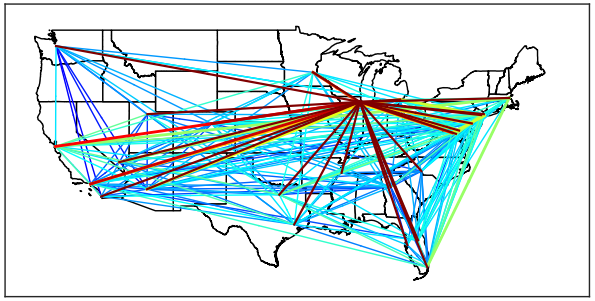
The characteristic delay states

(4) SFO delay state

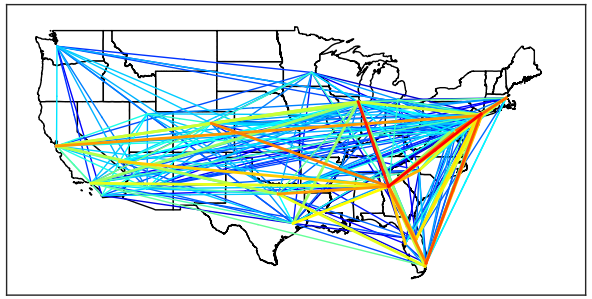


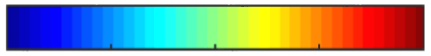
(5) Chicago delay state





(6) Atlanta delay state

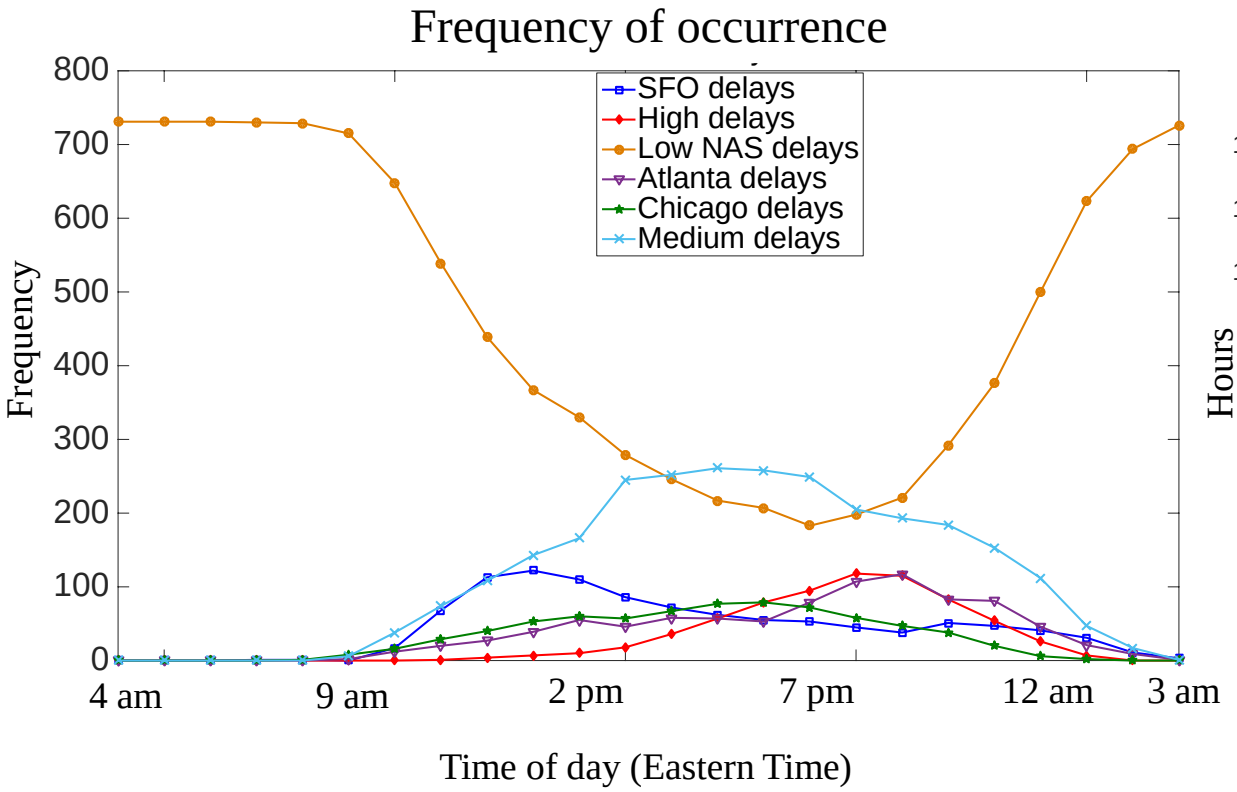


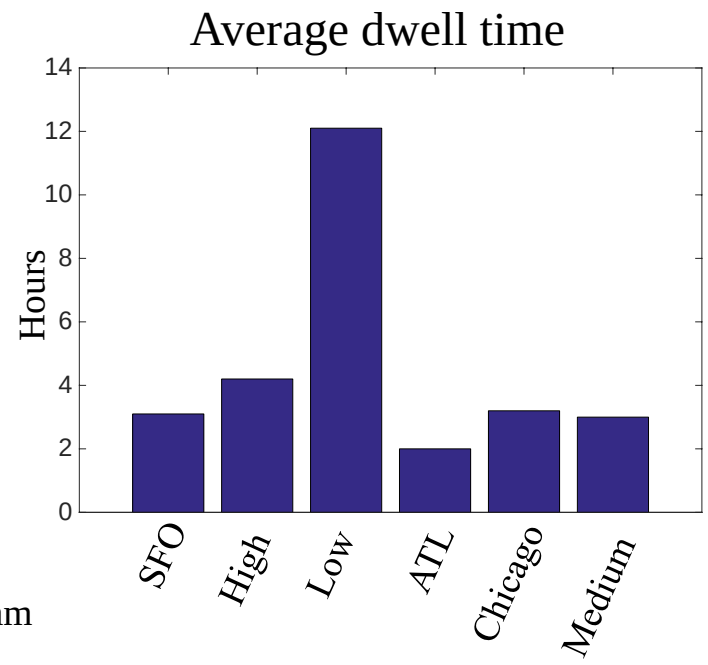


0 90 min

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Temporal characteristics of delay states

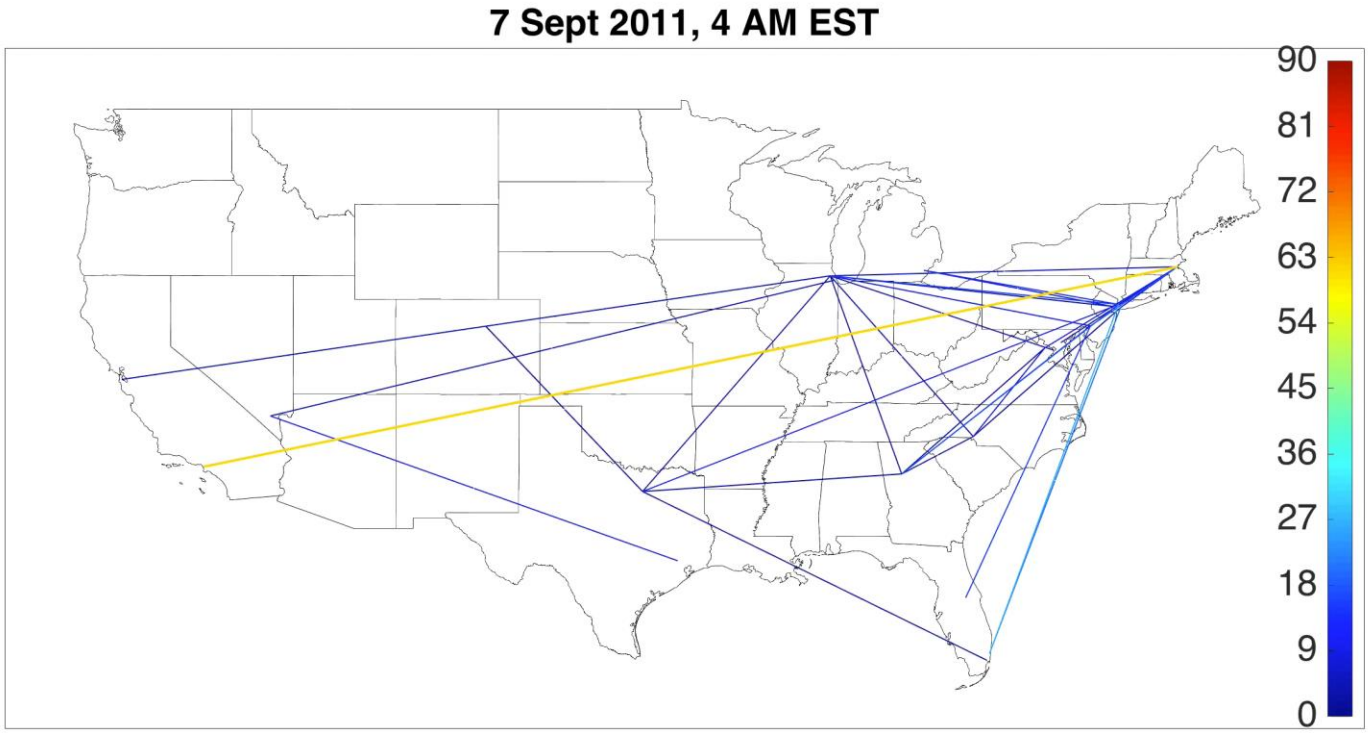




FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Extension to types-of-days

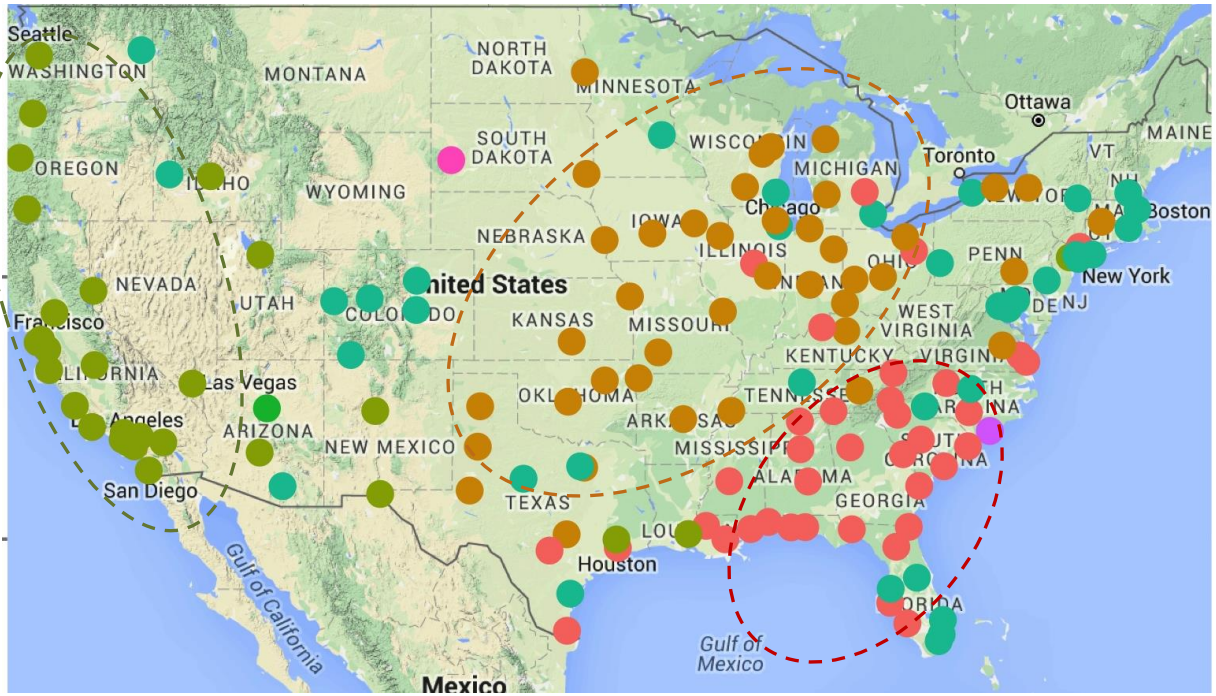
Example: High delay type-of-day



FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Community detection in delay networks

Airports with similar delay levels between them form a community



The structure of communities varies with delay state!

FORCES
FOUNDATIONS OF RESILIENT CYBER-PHYSICAL SYSTEMS

Summary

* Identifying characteristic delay patterns is important for
  * Developing predictive models
  * Planning mitigation strategies

* Identified characteristic delay states and types of days
  * Describes the spatial and temporal delay patterns

* Extensions:
  * Correlations of delay states with control actions, weather disruptions
  * Models for delay dynamics