Resilience of Networked Cyber-Physical Systems

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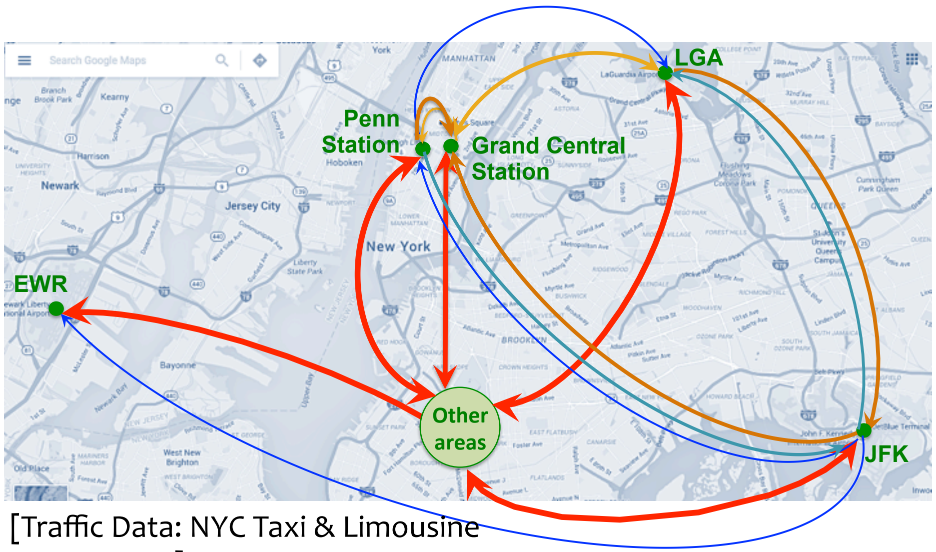
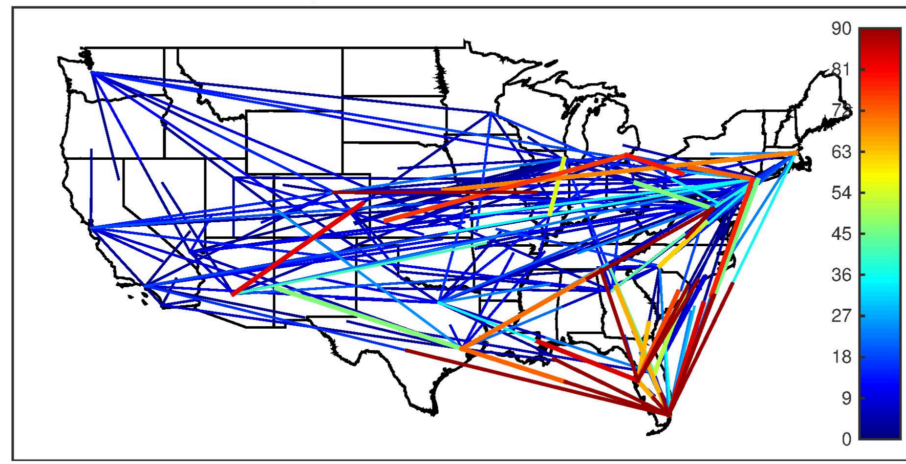
Some properties of infrastructure networks



[Traffic Data: NYC Taxi & Limousine Commission]



[Delay Data: Bureau of Transportation Statistics]

<table>
<tr><th>Traditional network theory</th><th>Properties of real-world infrastructures</th></tr>
<tr><td>Nodes and links in discrete states</td><td>States better modeled as continuous variables</td></tr>
<tr><td>Unweighted links</td><td rowspan="2">Interactions are weighted and directed
(Hub and Authority scores)</td></tr>
<tr><td>Undirected links (Eigenvector centrality)</td></tr>
<tr><td>Static network topology</td><td>Time-varying network topologies</td></tr>
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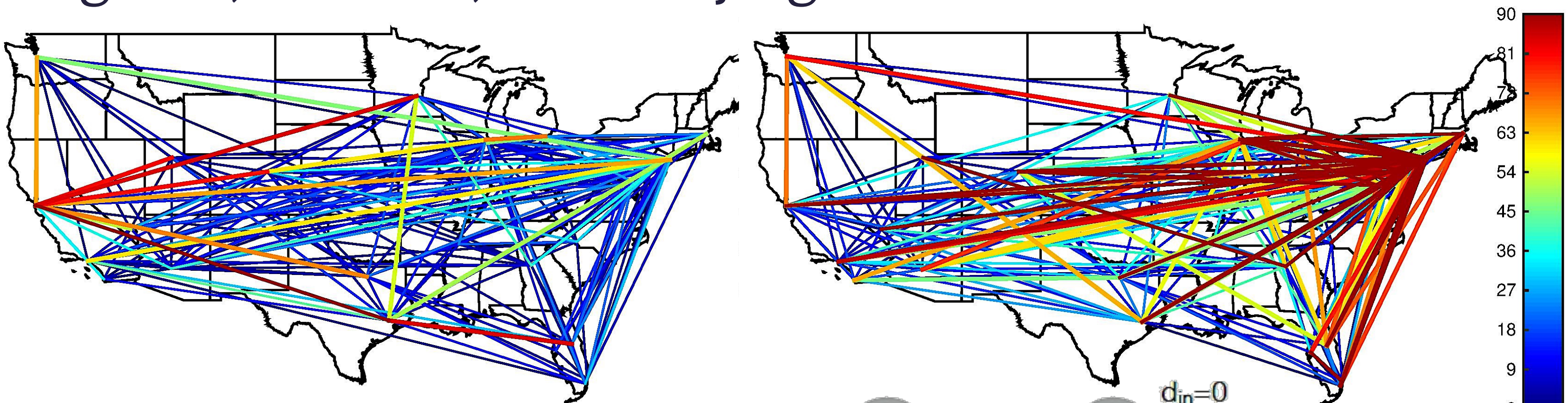
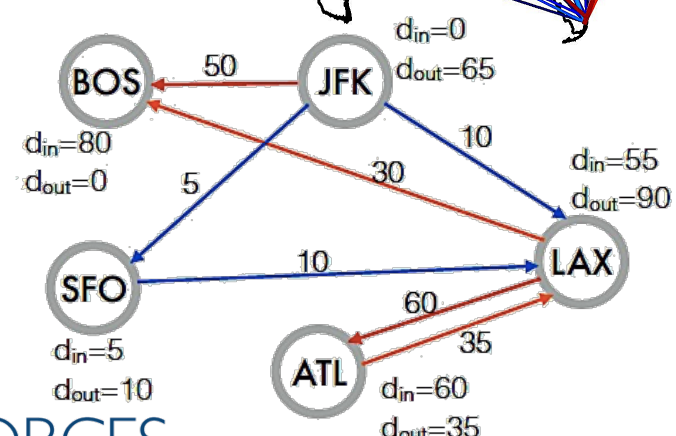
A network-centric view of air traffic delays

* For example, delay levels on edges between airports
* Weighted, directed, time-varying networks





Adjacency matrix, A:

$$a_{ij} = \begin{cases} w_{ij}, & \text{if } (i,j) \in \mathscr{E}, \\ 0, & \text{otherwise} \end{cases}$$

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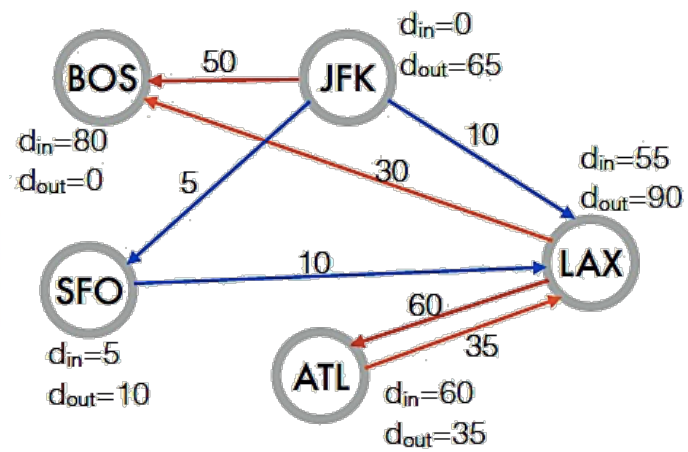
Simplistic model of delay dynamics

* Given an adjacency matrix, $A = [a_{ij}]$

$$d^i_{in}(t+1) = \alpha^i_{in} d^i_{in}(t) + \sum_j \beta^{in}_{ji} \bar{a}_{ji}(t) d^j_{out}(t)$$

$$d^i_{out}(t+1) = \alpha^i_{out} d^i_{out}(t) + \sum_j \beta^{out}_{ij} \bar{a}_{ij}(t) d^j_{in}(t)$$



* "State" of system: $\vec{x}(t) = \begin{bmatrix} \vec{d}^{\text{out}}(t) \\ \vec{d}^{\text{in}}(t) \end{bmatrix}$

* Therefore, for given network topology: $\vec{x}(t+1) = \Gamma(t)\vec{x}(t)$

where $\Gamma(t) = [\alpha] + [\beta] \begin{bmatrix} 0 & \bar{A}(t)^T \\ \bar{A}(t) & 0 \end{bmatrix}$

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[Gopalakrishnan et al. CDC 2016, sub.]

Effect of network topology on delay dynamics

* Let us consider two different networks, A_1 and A_2: How do we measure if they are similar or different?
  * **Comparison of state evolution (delay dynamics)**
    * Effect of network topology is of the form

$$\vec{x}(t+1) = \beta \mathcal{A} \vec{x}(t) \text{ where } \mathcal{A} = \begin{pmatrix} 0 & \bar{A} \\ \bar{A}^{\mathrm{T}} & 0 \end{pmatrix}$$

    * Principal eigenvector of $\mathcal{A}$ forms an invariant subspace
    * **Therefore, dynamics can be distinguished by the principal eigenvector and spectral radius of $\mathcal{A}$**

  * **Comparison of network-theoretic properties**

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Network centrality: Hub and Authority scores

* Strong **hubs point to** strong authorities; strong **authorities are pointed to** by strong hubs (Kleinberg 1997)
* Extension of eigenvector centrality to directed graphs
* Hub and authority scores can be calculated as the **principal eigenvector of** (Benzi et al. 2013)

$$\mathcal{A} = \begin{pmatrix} 0 & \bar{A} \\ \bar{A}^{\mathrm{T}} & 0 \end{pmatrix}$$

* Discrete modes determined by clustering based on:
  * Inbound and outbound delays at each airport
  * Hub and authority scores of each airport
  * System-wide delay trend (increasing/decreasing)

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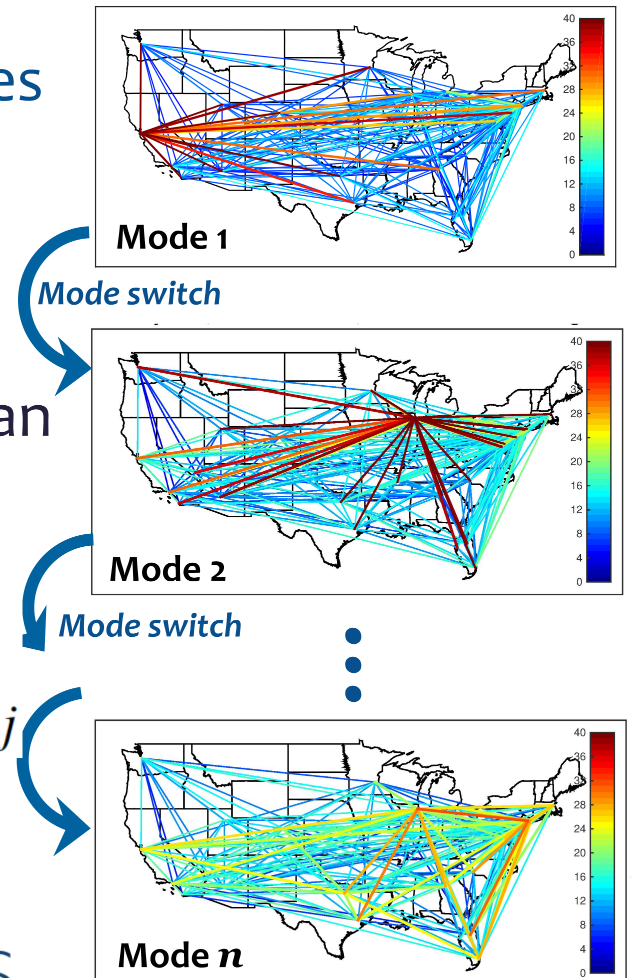
[Gopalakrishnan et al. ACC 2016]

Dynamics with switching network topologies

* Identify set of characteristic topologies ("discrete modes of operation")
* Determine linear continuous state dynamics under a fixed topology
* Switched linear system with Markovian transitions:

$$
\begin{aligned}
\vec{x}(t+1) &= \Gamma_{m(t)}\vec{x}(t) \\
\pi_{ij}(t) &= \Pr[m(t+1)=j|m(t)=i] \\
\vec{x}(t+1) &= J_{ij}\Gamma_i\vec{x}(t), \text{ if } m(t)=i \text{ and } m(t+1)=j
\end{aligned}
$$

* Markov Jump Linear System (MJLS)



System evolves under 1st topology

System evolves under 2nd topology

System evolves under n^{th} topology

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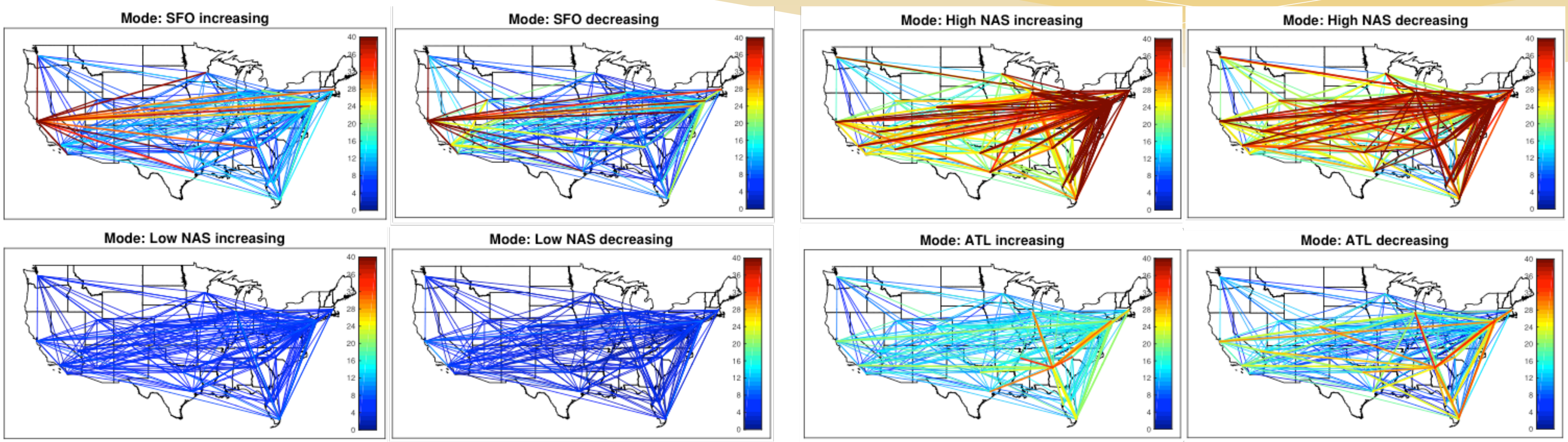
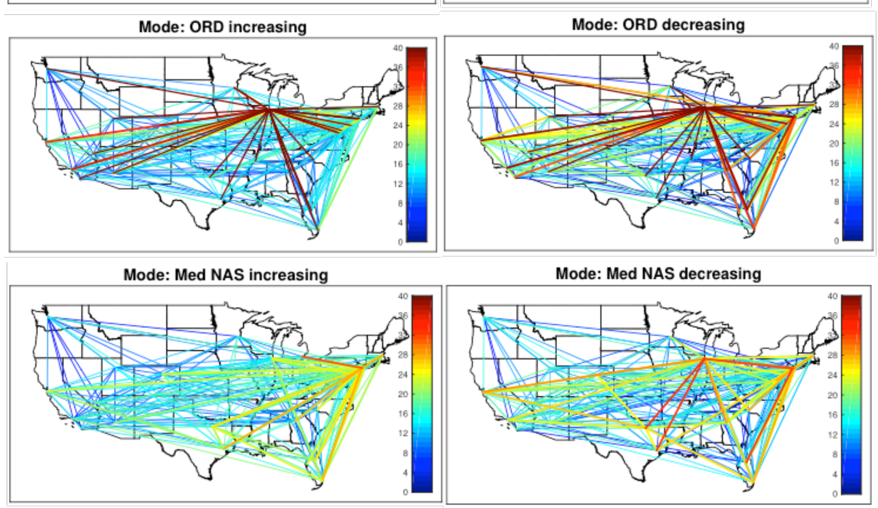
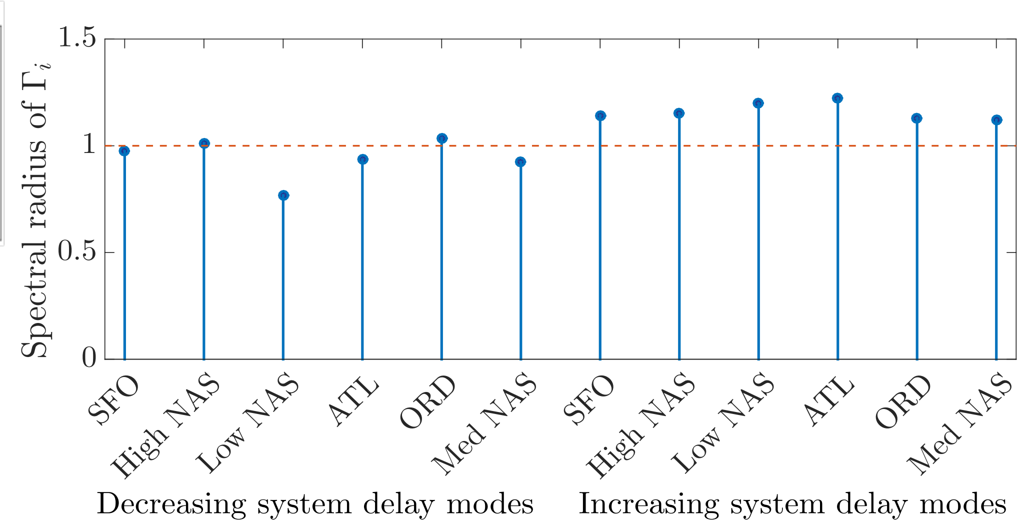
[Gopalakrishnan et al. CDC 2016, sub.] 6/4/16

Individual discrete modes







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[Gopalakrishnan et al. CDC 2016, sub.]

Stability of MJLS models

* "Physical interpretation": Will delays increase or decrease over time (e.g., over the course of a day)?
* **Almost-Sure Stability:** A system is said to be almost-surely stable if the state tends to zero as time tends to infinity with probability 1, that is,

$$\Pr[\lim_{k\to\infty} \|\vec{x}(k)\| = 0] = 1,$$

for any nonnegative initial condition $\vec{x}(0)$.

* Derive conditions for the stability of a discrete-time Markov Jump Linear System with time-varying transition matrices and continuous state resets (depends on Γ_i's, $\pi_{ij}(t)$ and J_{ij})

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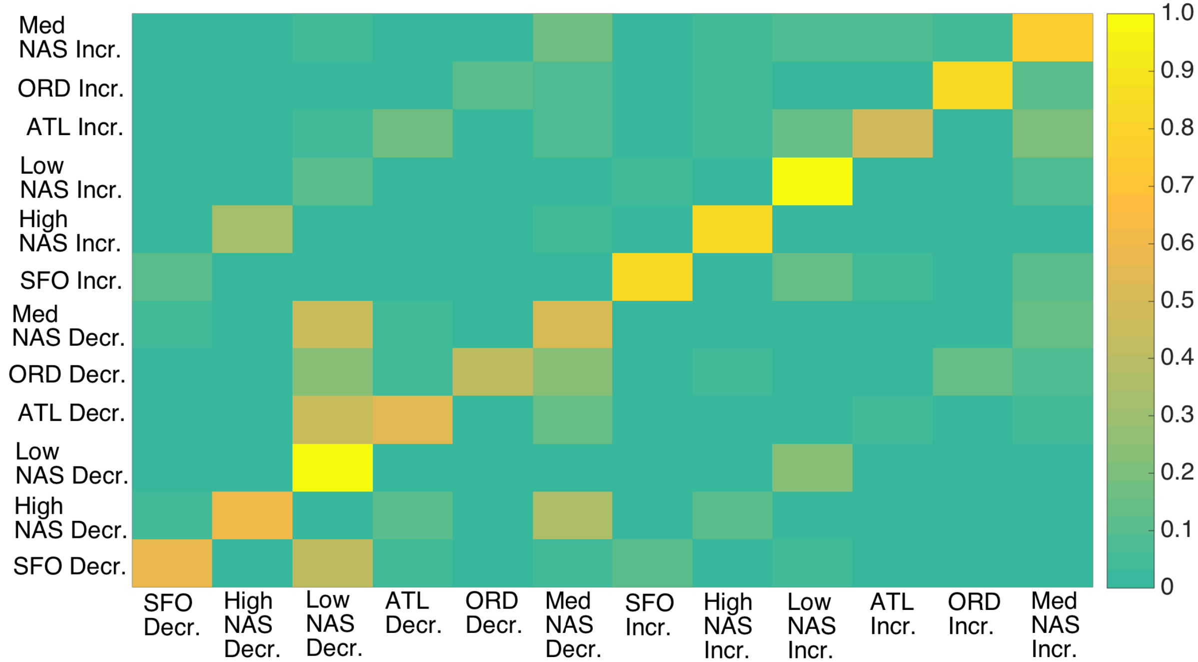
[Gopalakrishnan et al. CDC 2016, sub.]

Is the MJLS model of air traffic delays stable?

* **Check:** Data suggests answer is ***yes***, since delays dissipate overnight
* Suppose we consider an "average" mode transition matrix for each hour



* Resulting MJLS model is ***not*** stable

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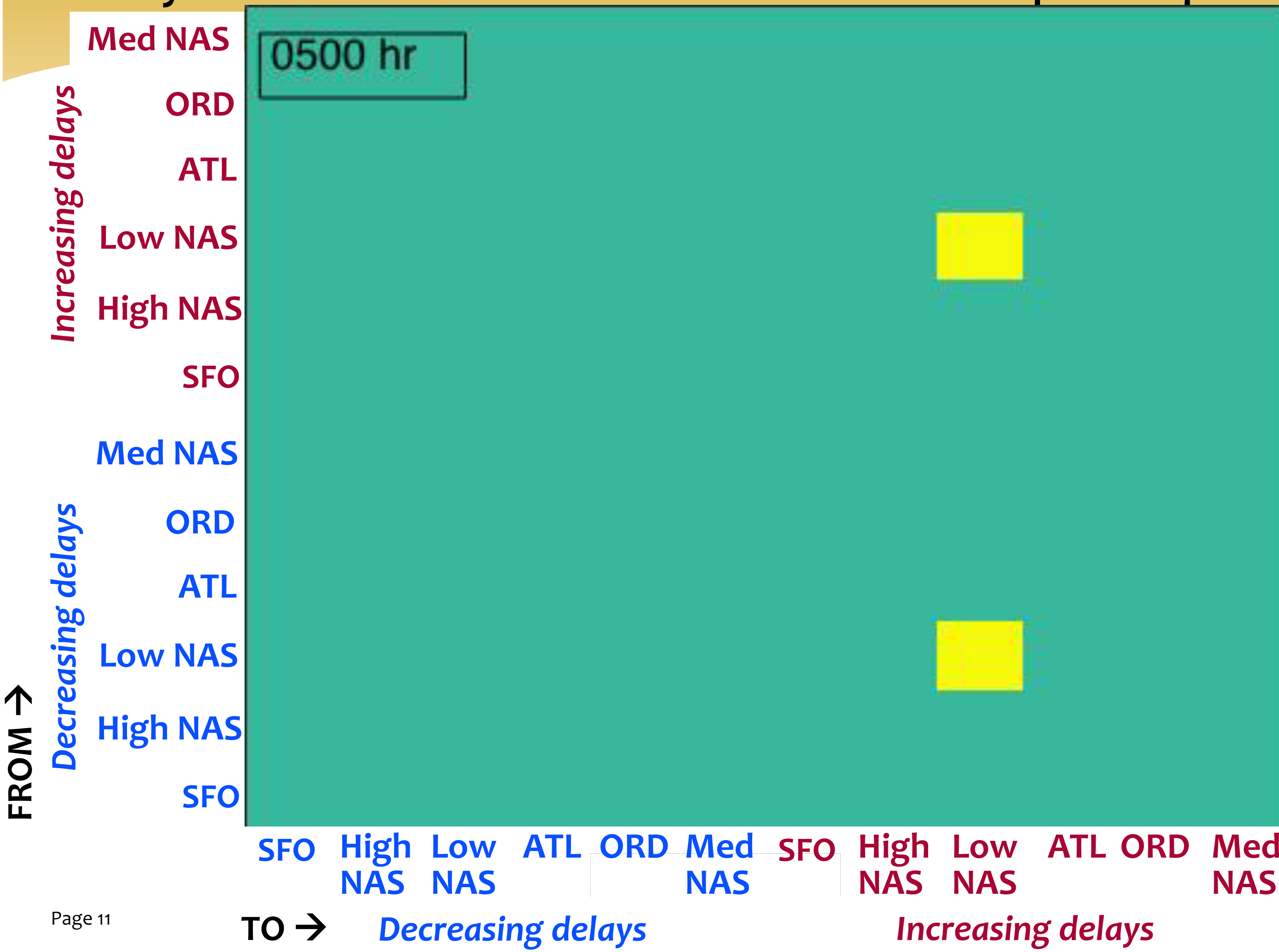
[Gopalakrishnan et al. CDC 2016, sub.] 6/4/16

Reality: Transition matrices exhibit temporal patterns



Stability of MJLS model

* Consider stability of MJLS model with periodic time-varying mode transition matrices (determined by hour of day)

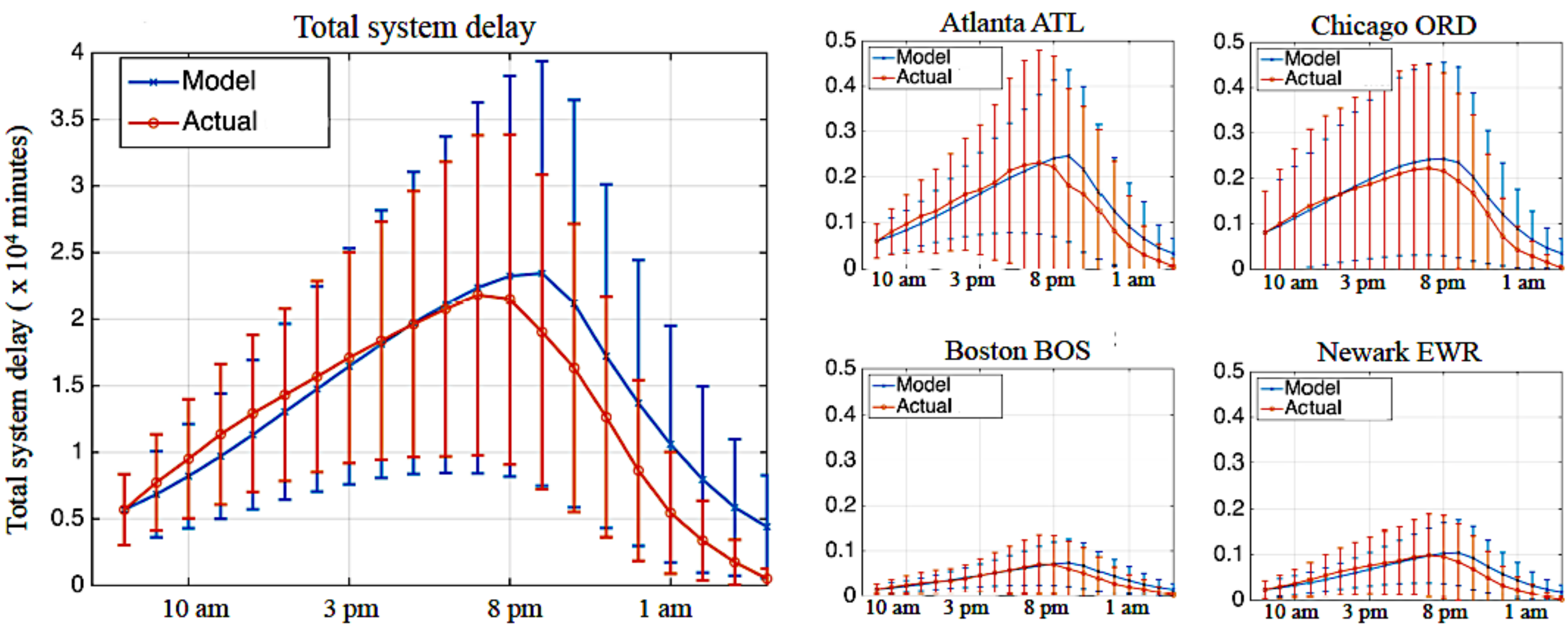
* Resulting MJLS model shown to be stable

* System appears to be stabilized by the temporal variations in the mode transition matrices

[Gopalakrishnan et al. CDC 2016, sub.]

MJLS model validation

* Model learned using 2011 data; validation using 2012 data



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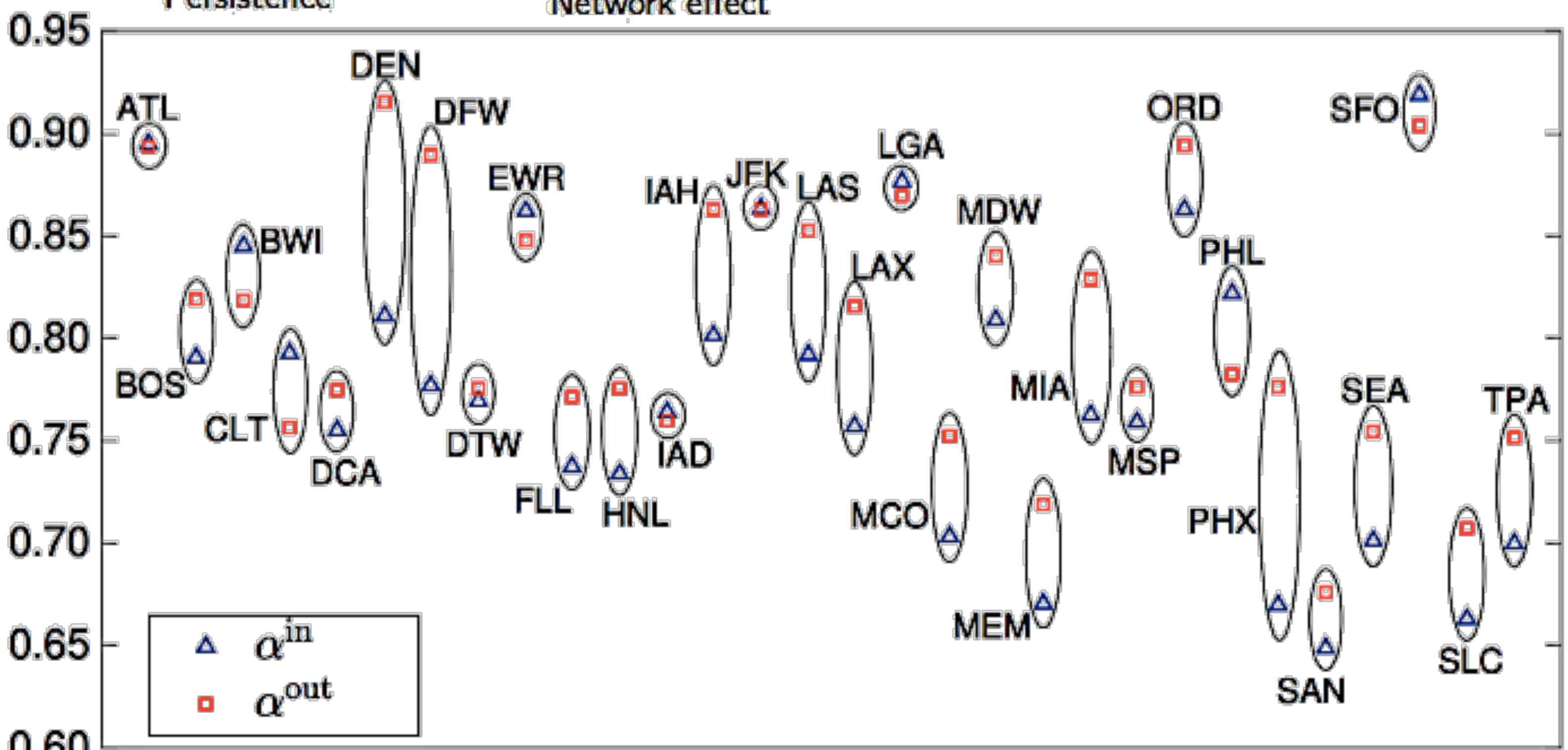
Measure of airport resilience: Delay persistence

$$d^i_{in}(t+1) = \underbrace{\alpha^i_{in} d^i_{in}(t)} + \sum_j \underbrace{\beta^{in}_{ji} \overline{a}_{ji}(t) d^j_{out}(t)}$$

$$d^i_{out}(t+1) = \underbrace{\alpha^i_{out} d^i_{out}(t)}_{\text{Persistence}} + \sum_j \underbrace{\beta^{out}_{ij} \overline{a}_{ij}(t) d^j_{in}(t)}_{\text{Network effect}}$$



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Next steps and open challenges

* Analysis of dwell times in each discrete mode
  * How long does a "delay state" tend to persist?
* Factors that trigger mode transitions
  * Weather impacts, Traffic Management Initiatives
* Prediction of future delays and delay states
* **Multi-layer, multi-timescale networks**
  * Cancellations, **operations**, capacity impact [ICRAT 2016]
  * Interactions between networks
* Post-disruption recovery
* and finally, revisiting an old problem…

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Revisiting an old problem: Interactions between NextGen and legacy infrastructures

FAA Worried About ADS-B, 1090 MHz Interference

Aviation Week & Space Technology
John Croft
Thu, 2016-05-12 04:00

Radio frequency congestion is a side effect of ADS-B the FAA is working to alleviate

With Automatic Dependent Surveillance-Broadcast (ADS-B) equipage on the rise and a wholesale mandate for the NextGen surveillance technology less than four years away, the FAA is getting serious about how to deal with a downside of the upgrade—radio frequency interference.

The issue involves the 1090 MHz frequency and the potential ill effects of too many signals occupying too small a volume of airspace. That frequency is used not only by ADS-B transmitters but also by FAA air traffic control radars, airborne traffic-alert and collision warning systems (TCAS) and military identification friend-or-foe systems.

Potential mitigations include replacing terminal radars (those typically covering a 60-nm radius around larger airports) with wide-area multilateration (WAM) systems, modifications to ground-based radars and adoption of hybrid TCAS variants.

"It is like being at a concert—the louder the music, the more 1090 MHz traffic, the harder it is to hear the person next to you," says Rob Strain, a senior principal engineer with The Mitre Corp.'s FAA-sponsored Center for Advanced Aviation System Development. Mitre, a not-for-profit organization, is part of an industry group tasked by the FAA with analyzing the issue and suggesting potential fixes.

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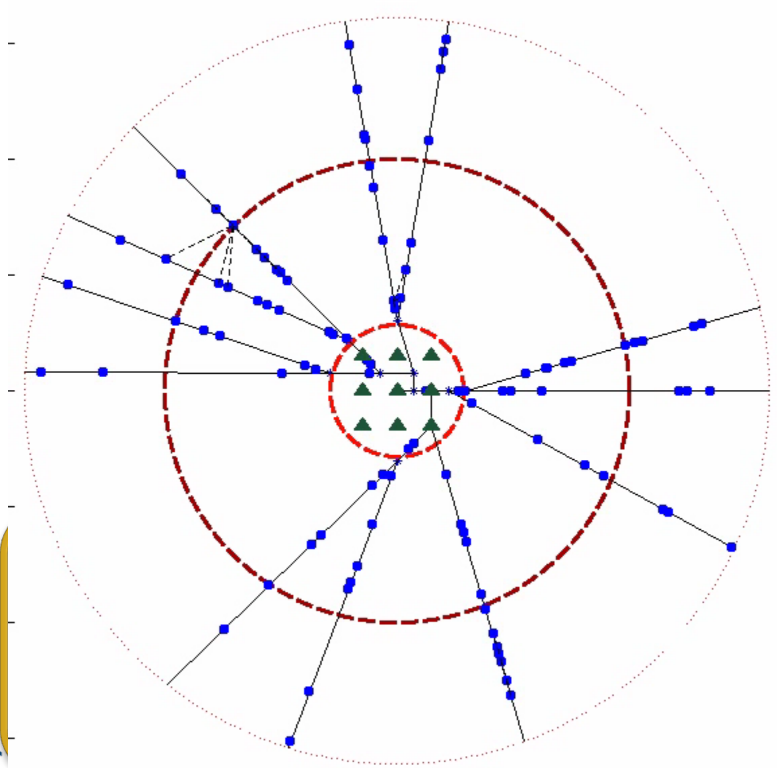
Hybrid Communication Protocols and Control Algorithms for NextGen Aircraft Arrivals

Pangun Park, Harshad Khadilkar, Hamsa Balakrishnan, and Claire Tomlin



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