A Networks Perspective of Air Traffic Delays

Karthik Gopalakrishnan
Hamsa Balakrishnan, Richard Jordan
MIT

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Introduction: Air Transportation System

- Complex interconnected system
- Delays can spread through the entire system
- 22% of the flights in 2015 were delayed by more than 15 min
- 40% of these delays were due to late arrival of incoming aircraft
Motivation:
- Which airports have persistent delays?
- What is the susceptibility of an airport to delays from others?

Outline:
1. Representing the state of delay by a network
2. Identify characteristic patterns and model their evolution
3. Metrics for resilience
Delay Network

- Edge weights: Median delay on that link
- Total inbound delay at LAX = 10 + 10 + 35 = 55 min/flt
- Total outbound delay at LAX = 60 + 30 = 90 min/flt
Delay networks evolve in time

Data: Bureau of Transportation Statistics (2011-12)

- 158 airports
- \( \sim 1100 \) edges
- \( \sim 17,000 \) networks for 2 years
Insights from delay networks:
1. Community structure

Airports that form a community have high delay between them.

Example of community structure

Community structure for delay network (23 March 2011)
Insights from delay networks:
2. Characteristic delay states

- These are the typical delay patterns seen in the US airspace.
Model for evolution of airport delay

Features of airport delay:
- Delays at an airport tend to persist
- Delays at an airport depend on connectivity
Airport delay dynamics

Network structure

\[ A(t) = [a_{ij}(t)] \]

Persistence

\[
\begin{align*}
    d_{in}^i(t + 1) &= \alpha_{in}^i d_{in}^i(t) + \sum_j \beta_{ji}^{in} \bar{a}_{ji}(t) d_{out}^j(t) \\
    d_{out}^i(t + 1) &= \alpha_{out}^i d_{out}^i(t) + \sum_j \beta_{ij}^{out} \bar{a}_{ij}(t) d_{in}^j(t)
\end{align*}
\]

Network effect
Airport delay dynamics

Network structure

\[ A(t) = [a_{ij}(t)] \]

\[ d_{in}^i(t+1) = \alpha_{in}^i d_{in}^i(t) + \sum_j \beta_{ji}^i \bar{a}_{ji}(t) d_{out}^j(t) \]

\[ d_{out}^i(t+1) = \alpha_{out}^i d_{out}^i(t) + \sum_j \beta_{ij}^i \bar{a}_{ij}(t) d_{in}^j(t) \]

Persistence

Network effect
Delay propagation model

- Instead of $A(t)$, use the discrete networks from clustering

\[ x(t + 1) = \Gamma_1 x(t) \]
\[ x(t + 1) = \Gamma_2 x(t) \]

- Delay evolution within discrete mode: $\vec{x}(t + 1) = \Gamma_{m(t)} \vec{x}(t)$
- Discrete mode evolution: Markov transitions
Validation: Evolution of delays

- Learn $\alpha$ and $\beta$ from 2011 data
- Test data: 2012

![Graph showing total system delay from 10 am to 1 am]

- Atlanta ATL
- Chicago ORD
- Boston BOS
- Newark EWR

Karthik Gopalakrishnan (MIT)
**Resilience measure: Persistence of delays**

- High $\alpha \Rightarrow$ delays will persist longer
- Airports with demand close to capacity have high $\alpha$
Resilience measure: Influence of airports

- Inbound delay at an airport depends on outbound delay from other airports

Color and size both represent the induced delay per unit delay at other airport.
Conclusions

1. Network representation is useful to identify characteristic delay patterns

2. We quantify the tendency for delays to persist and the influence of network on delays at the top 30 US airports

3. Applications: Delay prediction and developing control strategies