Decentralized Path Planning For Air Traffic Management

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Outline

- Background
  - National Aviation System
  - Needs for Next Generation Air Traffic Management Systems
  - Air traffic control system from a control perspective
- Hierarchical Decentralized Flight Planning
  - Problem Formulation
  - Solution Procedure
  - Advantages Over the Current Planning Procedure
  - Simulation Results
- Conclusions

Motivations

National Aviation System is a large-scale Cyber-Physical System

14,500 traffic controllers, 4,500 safety inspectors, 5,800 technicians,

19,000 airports, 600 traffic control facilities, 50,000 flights each day

Physical components: large number of aircrafts, equipment and human agents

Cyber components: traffic & weather measurements, computation, prediction and communications.

Research Perspectives: FAA, traffic controllers, airline companies

My focus: System-level modeling and optimization methods for en-route traffic management and terminal area operations

The Needs for Next Generation ATM

Air traffic delays in 2007 has cost US economy $41 billion

- fuel: 740 million gallons, carbon dioxide : 7.1 million tons

Staffing Emergency in major ATC facilities across the nation

As of 2008:

- 11,077 certified controller s–lowest level in 15 years
- 10,000 are expected to retire before 2015
- Oakland Center: training ratio: 2-1 vs 12-1 in 2005
  operational error: 30 vs 14 in FY07
- planning to hire 12,000 before 2018

Jan, 2010

- Certified TRACONs controllers plummeted more than 25% in the last six years
- New York reaches post-1981 low

Situation gets much worse due to the expected two- to three-fold increase in air traffic

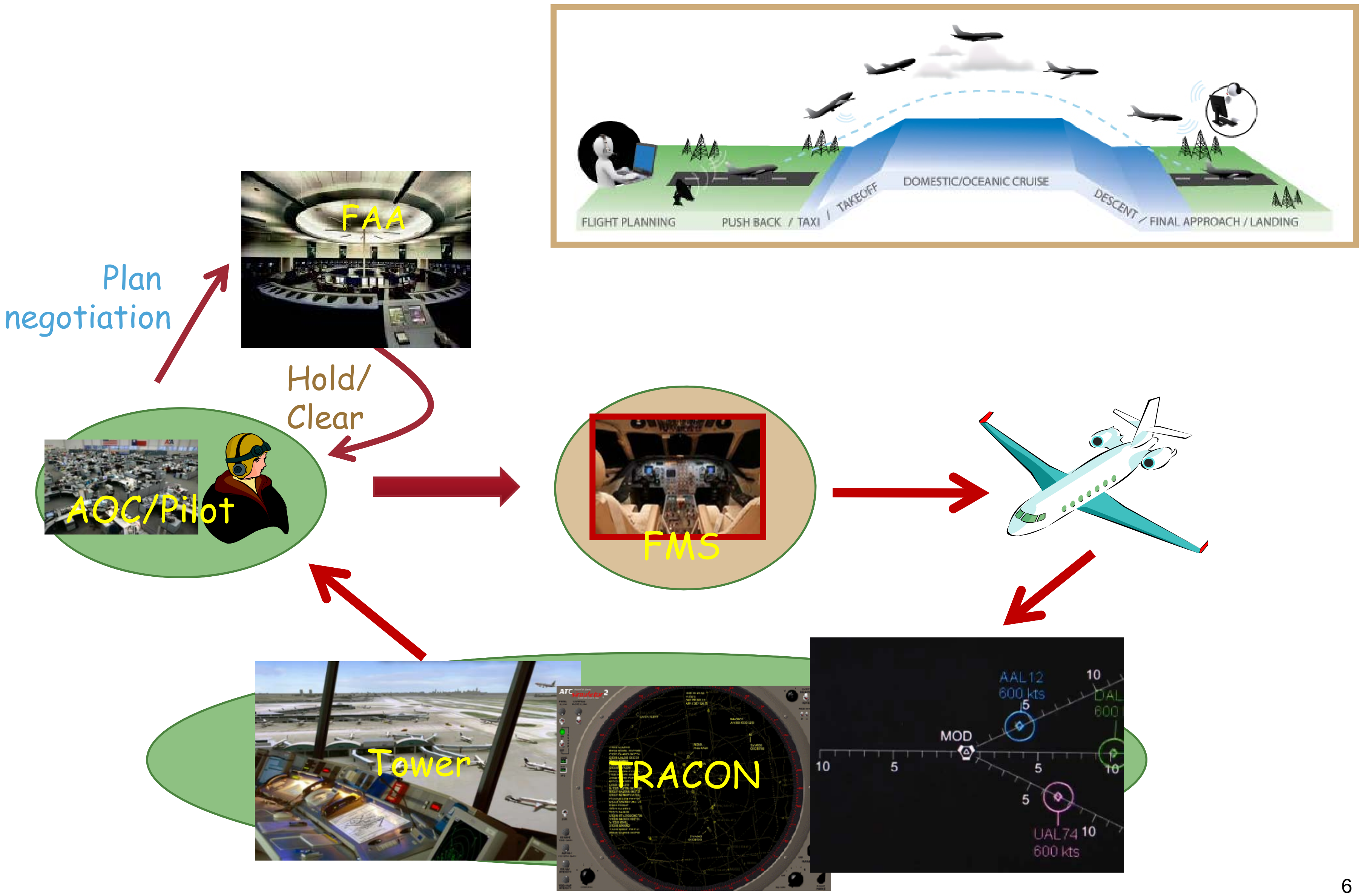
Need to modernize, (semi)-automate the ATC system NOW

Challenges

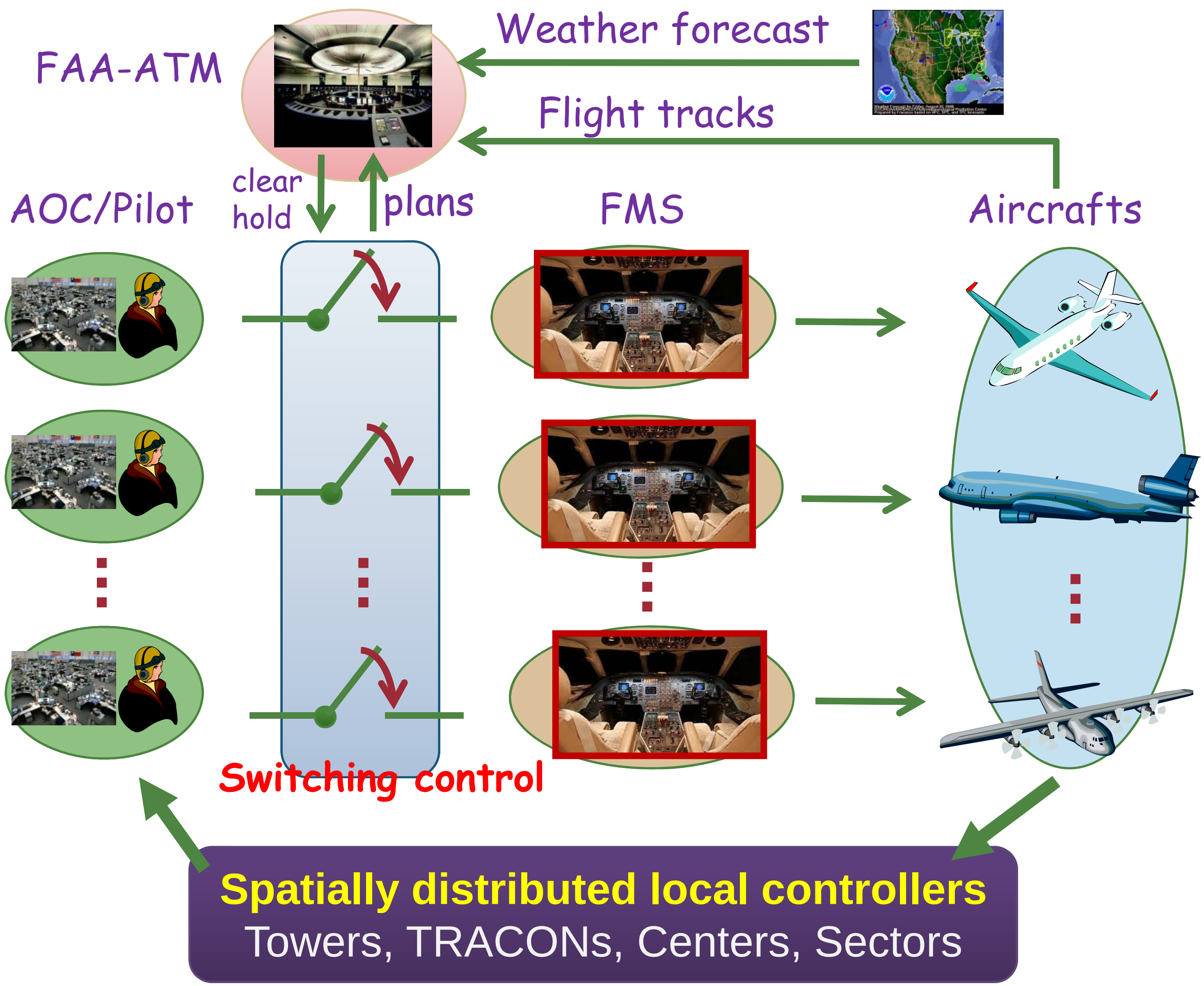
- Legacy systems
  - require continuous operations
- Critical Safety Standards
- Large number of competing users
- Human in the loop
  - fear of new working conditions
  - TRACON controllers are still using the same Radar system as they did in 1960s.

- Gradual change
- Respective the structure of the system

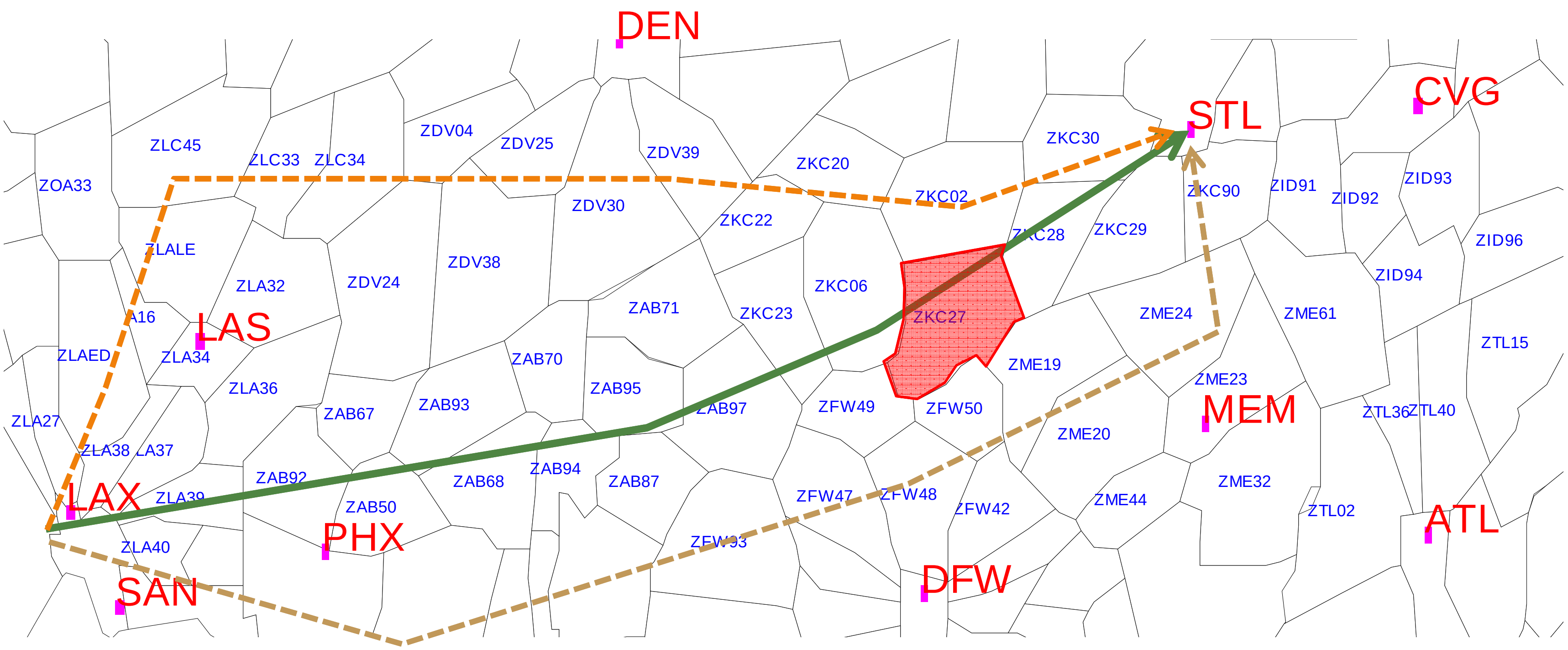
Background of ATM



Hierarchical Control Structure of ATM



Lack of Collaborative Information Exchange

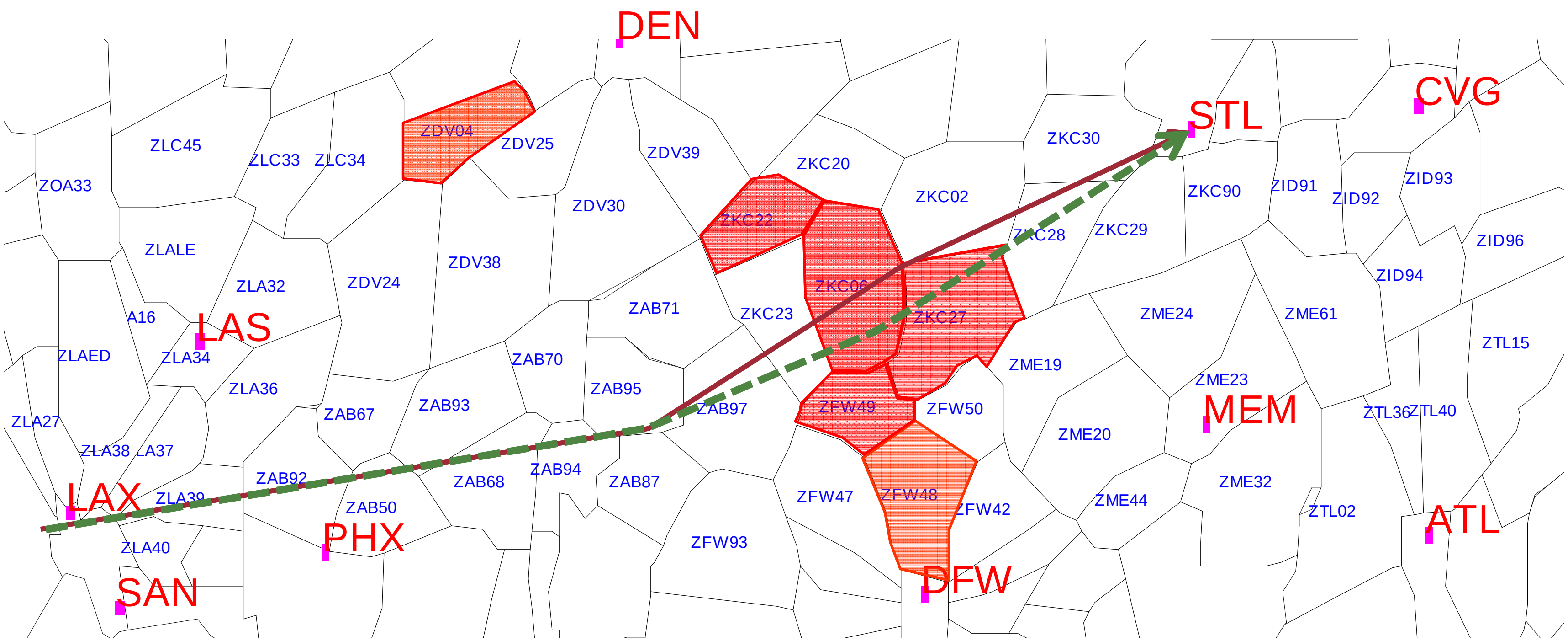


A major problem: lack of information exchange

- User does not know the traffic information
- only weather briefing is available before taking off
- FAA/ATM does not know users' preferences

Consistent situation awareness is needed

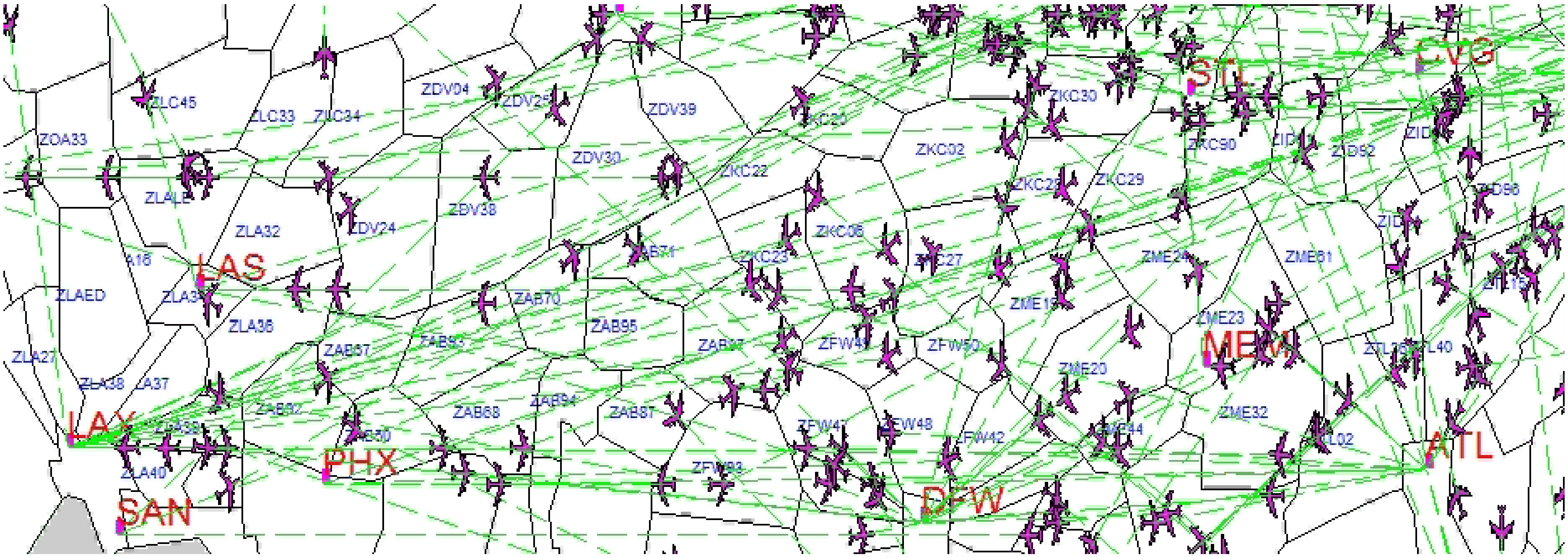
Benefit of Information Sharing



With the traffic information

- User can find the best path (according to its specific preference) to avoid traffic according
- Decide whether to delay the flight or take the best available detour

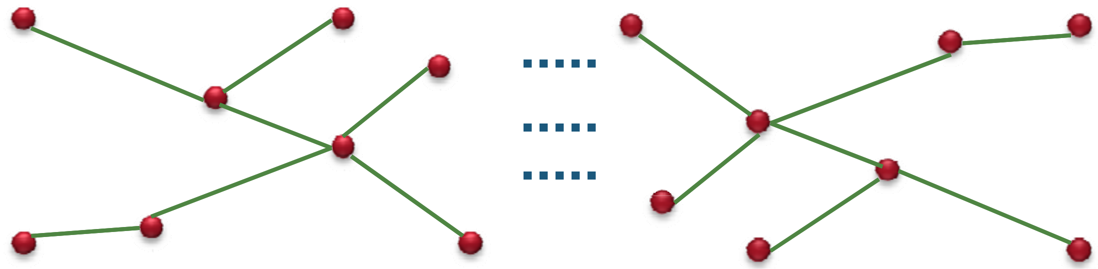
Towards a New Flight Planning Framework



A framework with planning algorithm

- deal with large number of aircrafts in real time
- consider both weather and traffic restrictions, guaranteed safety with certain “optimality” for the nominal trajectories
- 4D trajectory (3D + time)
- practically feasible

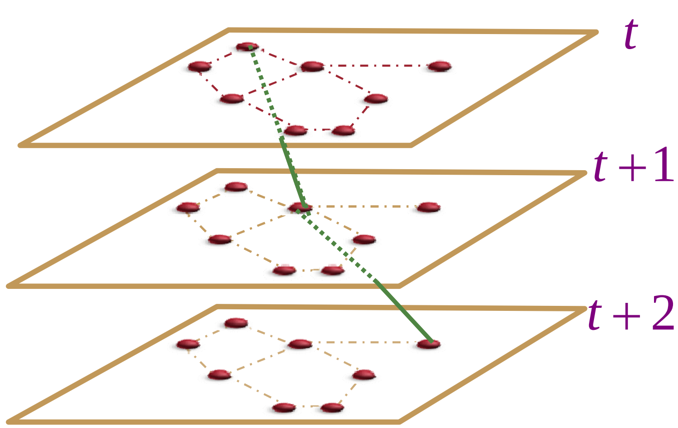
Graph of Airways



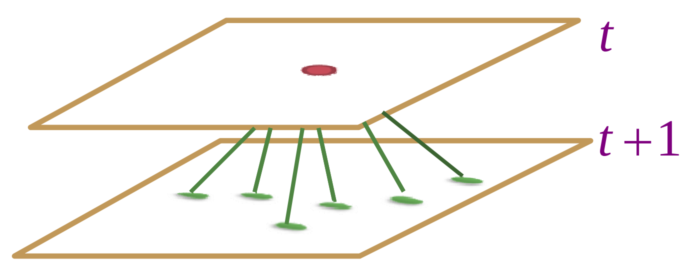
- Spacial graph $\mathcal{G}_s = (\mathcal{V}_s, \mathcal{E}_s)$
  - vertices (nodes): waypoints (Navigation aids, airports, "virtual" waypoint)
  - Edges: airways of jetways

Space-Time Graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$

$$\mathcal{V} = \{(x,t) : x \in \mathcal{V}, t = 1, \ldots, N\}$$



- Nodes are disconnected within the same layer
- Edges between layers determined by the dynamics of the aircraft

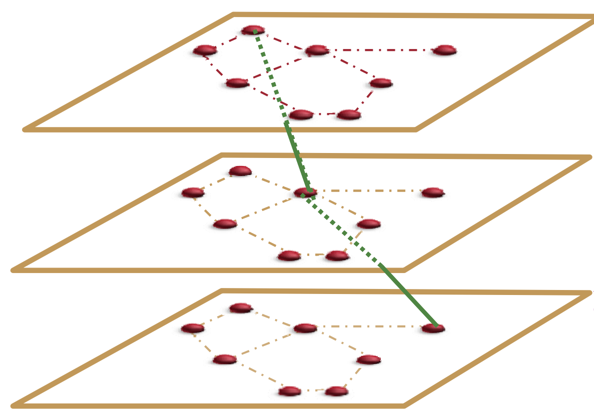


Planning Under Weather Uncertainty

Link weight ("length"):

$l(v_i, v_j)$

- Fuel cost;
- expected turbulence based on weather forecast;
- infinite when crossing forbidden weather zone



Single aircraft path planning with weather data is a shortest path problem

Departure nodes
Departure time

$$z_0 = \begin{bmatrix} x_0 \\ t_0 \end{bmatrix} \dashrightarrow z_f = \begin{bmatrix} x_f \\ t_f \end{bmatrix}$$

Destination
Latest arrival time

$$J(z_0, u; \lambda) = \phi(z_{t_f}) + \sum_t^{t_f - 1} l(z_t, u_t)$$

Need to handle sector capacity constraints

$$\sum_i \mathbf{1}_{S_j}(x_t^i) \leq \text{max sector counts } \forall t, j$$

Planning with Traffic Restrictions

- Current way for Traffic control:
  - speed variation, ground delay program, holding pattern, vector for spacing, redirecting
- Traffic Regulation Function: $\lambda(j,t)$

$$\lambda(j,t) = \begin{cases} 0 & \text{sector j open over } [t, t+1] \\ \infty & \text{otherwise} \end{cases}$$

- Each aircraft tries to minimize its own cost subject to the traffic rules specified by FAA

$$J_i\left(z_0^i, u^i; \lambda\right) = \phi\left(z_{t_f^i}^i\right) + \sum_t \left[l\left(z_t^i, u_t^i\right) + \sum_j \lambda_{j,t} \cdot \mathbf{1}_{S_j}\left(z_t^i\right) \right]$$

infinite link cost if crossing forbidden weather zone
infinite price if sector “sold out” over certain time period

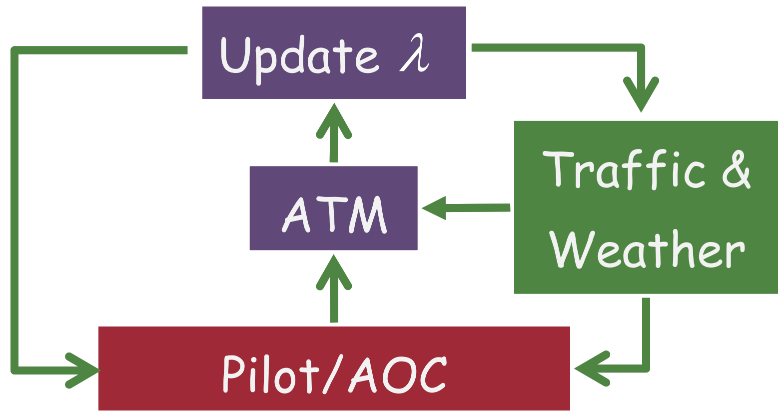
↓

Safety and satisfy all sector constraints

Decentralized Path Planning Algo

Planning /Rerouting Algorithm

1. Get weather data and traffic restrictions λ
2. Solve the shortest path problem
3. File the plan
   - ATM approve and update traffic rules λ



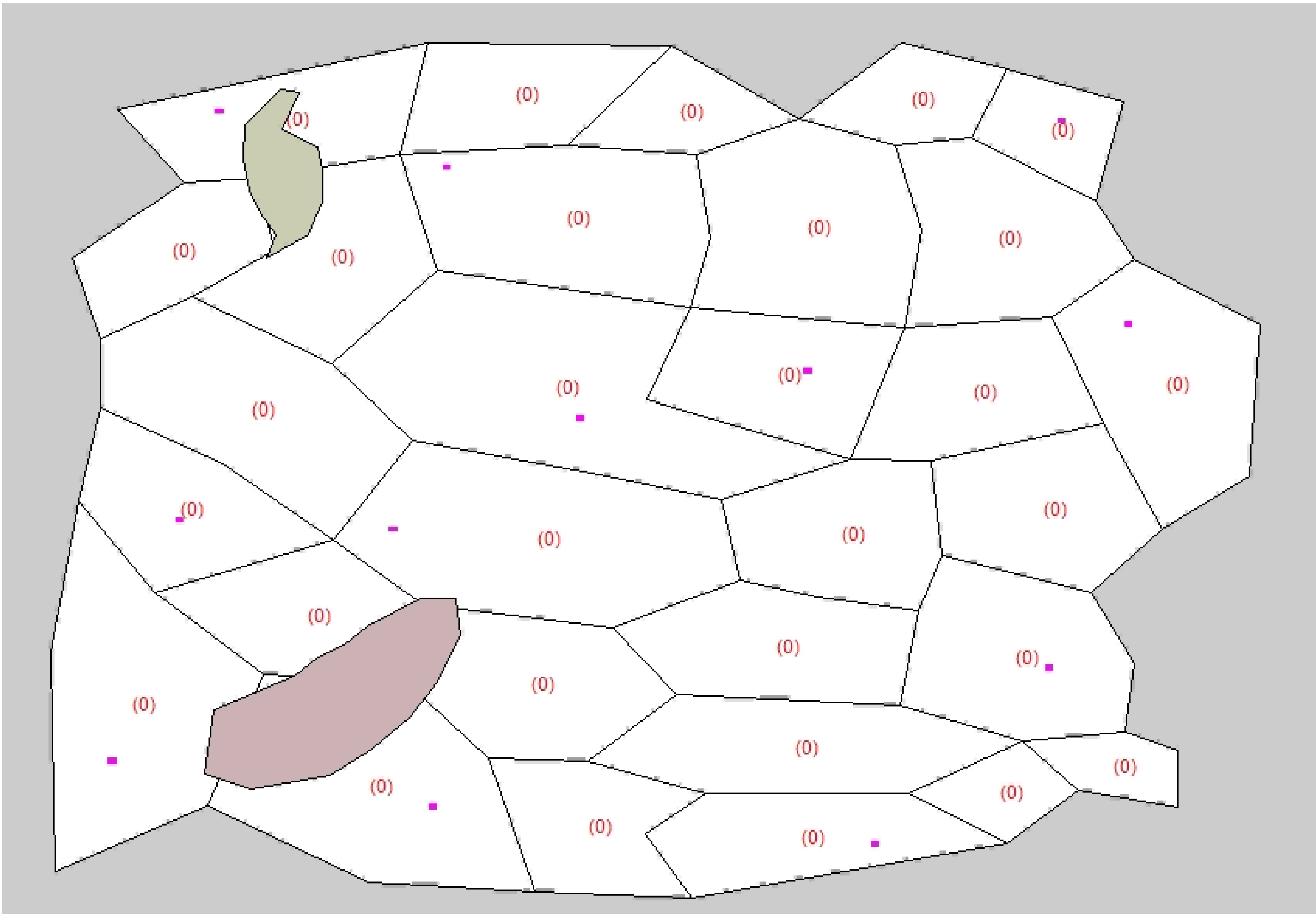
- $\lambda(j,t)$ is a tool for the ATM to regulate traffic
  - the above is First-Come-First-Serve rule
  - can achieve certain "fairness " by using the historical data
  - nominal plans are safe but capacity buffer is needed to cope with uncertainty

Distinctions and Advantages

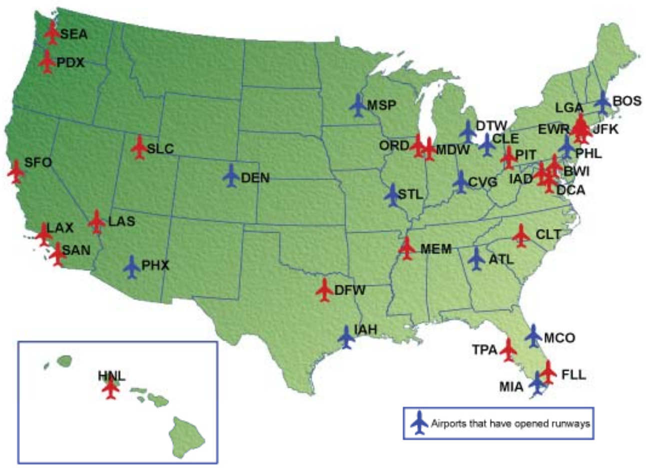
- Traffic Flow Management
  - Bertsimas 98', Waslander 08'
- Path Planning with Weather Uncertainty
  - Nilim (ACC03), Pannequin (GNC07), Kamgarpour (CDC10)
  - mostly centralized and only works for a small number of aircrafts
  - require same taking off time
  - does not consider traffic information
- Distinctions of our methods
  - decentralized
    - used for the entire NAS or different subregions of NAS
  - planning considering weather and traffic
  - 4D trajectory (3D + time)
  - guaranteed safety with certain "optimality"
  - respect current planning procedure, practically feasible in the near future

Simulation Results I

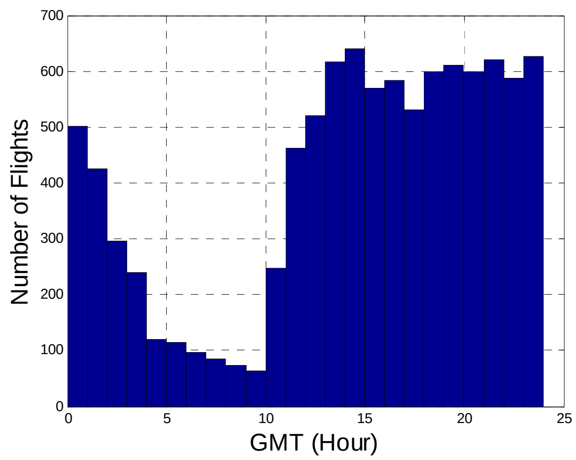
- 30 sectors, 2 deterministic weather zones, 12 airports, 100 flights
- randomly select departure and arrival airports, random departure time
- plans are made and filed in the order of departure time



Simulation Results II



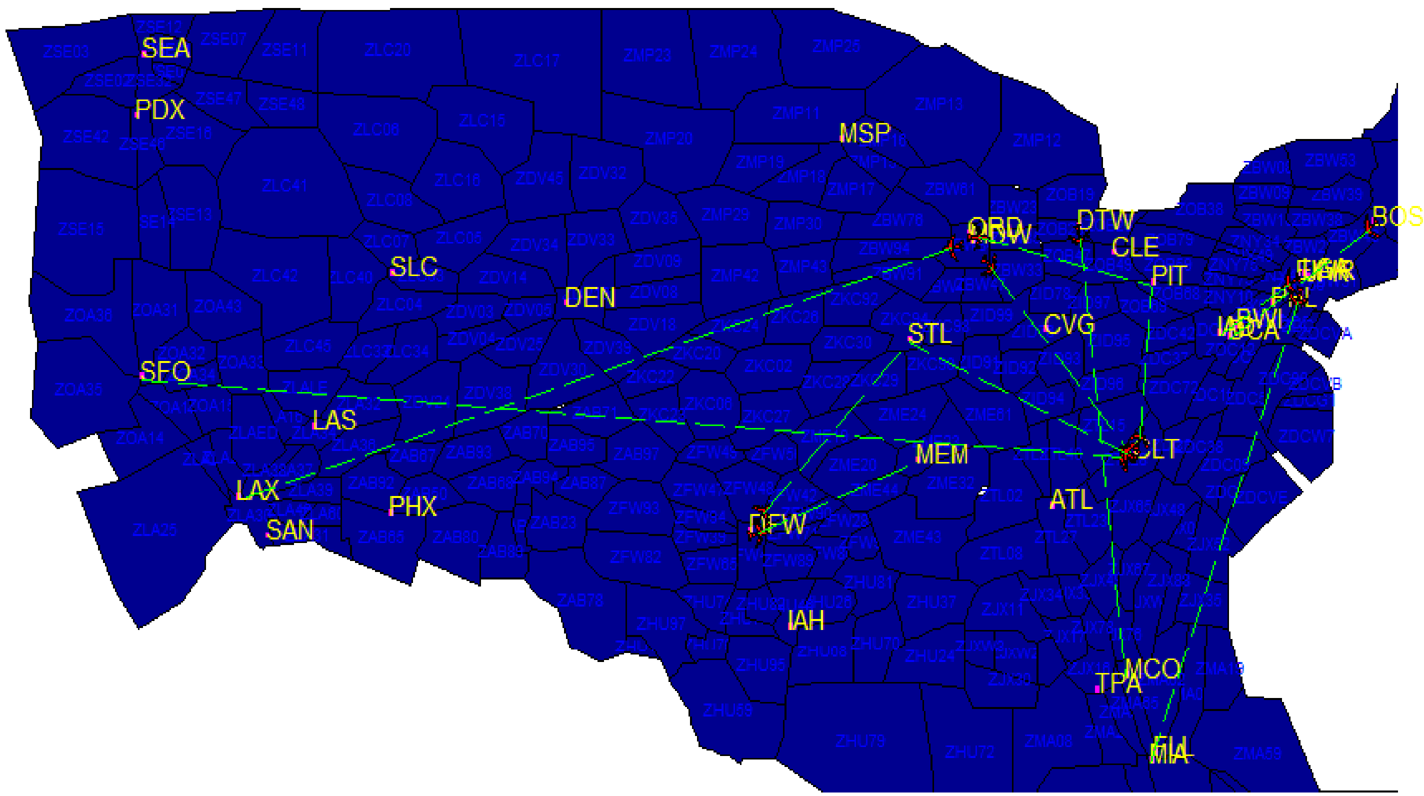
Operational Evolution Plan (OEP) Airports
-- about 74% passengers and 69% operations



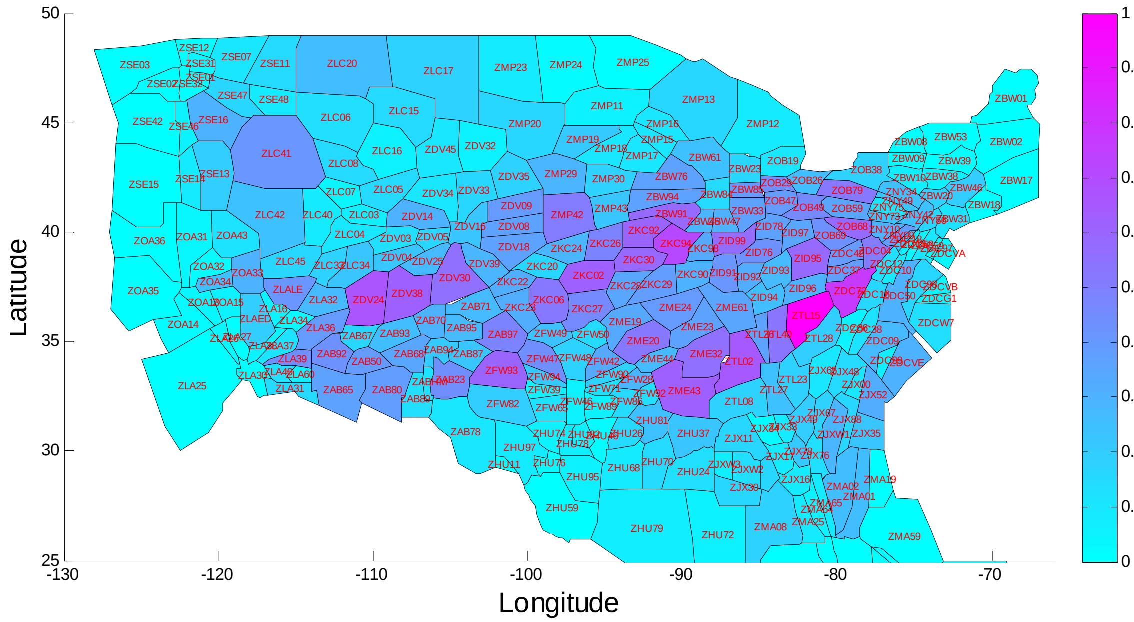
Flight schedules among OEP airports
-- Aug. 24, 2005

- We consider 34 OEP airports (except HNL)
- Consider flights depart between 7am EST and 5pm EST
- Proof of concept: the framework works for realistic traffic patterns and realistic number of flights
  - no weather data and no comparison with real flight tracts
  - assume all flights try to minimize travelling distance
  - uniform grids corresponding to roughly 3 minutes flight time

Unconstrained Flight Plans

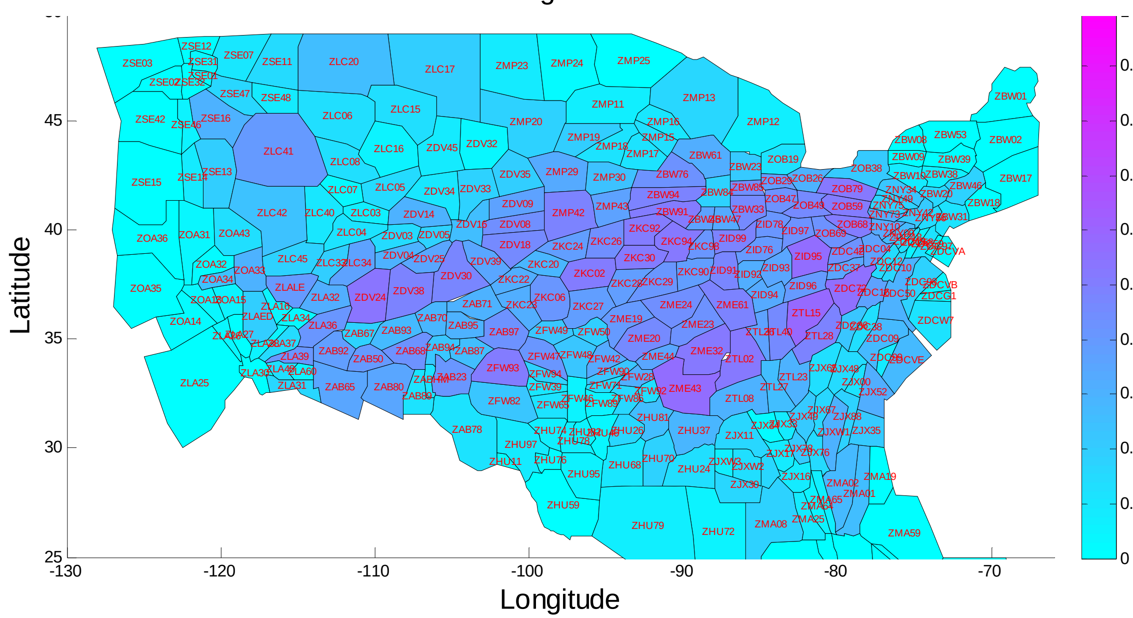


Traffic Regulation Results



Without constraints,

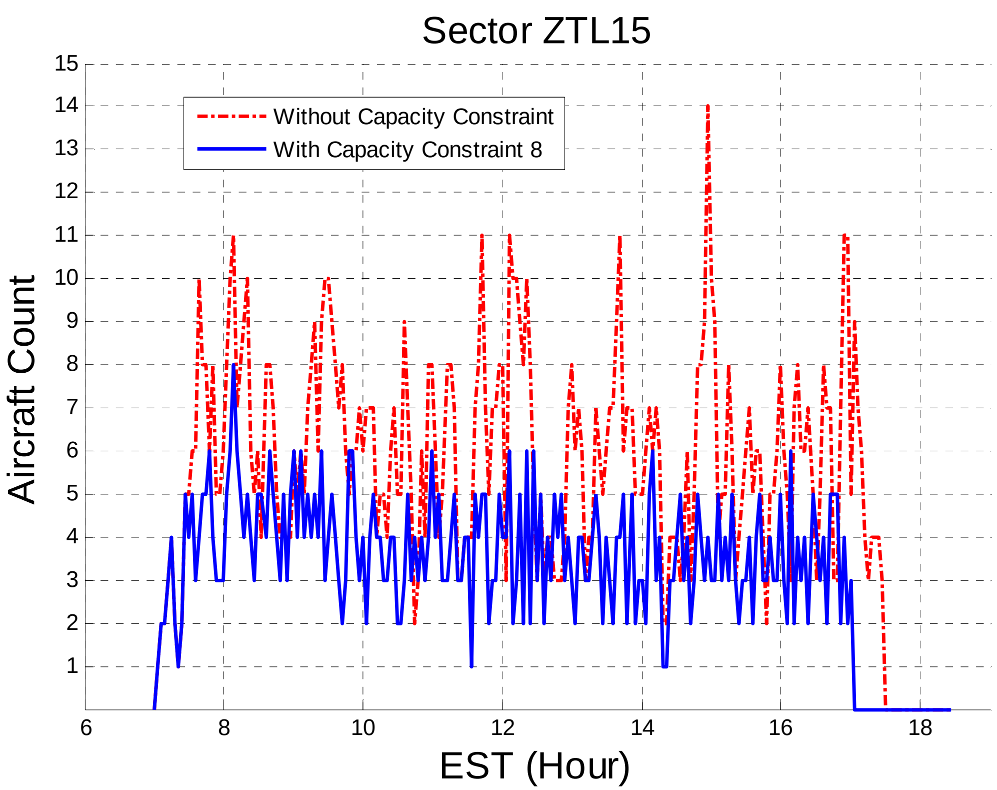
- traffic concentrates on a few sectors
- the majority of the rest under-utilized
- 40 sectors have counts above 8 at some time



With traffic control

- meet capacity constraints at all time
- traffic in congested sectors diffused into neighbors
- increase 0.71% travel time

Result for Sector ZTL15



Satisfy capacity at all time

The new sector count does not always stay below the old one

Conclusion

- Proposed a Hierarchical Decentralized Flight Planning Framework
- Respect user’s preference and has potential to reduce delay and energy
- Future Work
  - Further validating the framework using realistic weather data
  - compare the fuel savings as compared with the real flight plans

Thank you very much!