Protocol-Based Congestion Management for Advanced Air Mobility

NASA ULI Mini-Symposium


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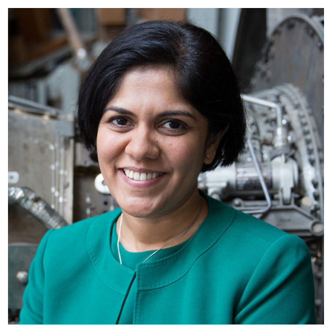
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Antony Evans


Maxim Egorov

Massachusetts Institute of Technology. USA

Airbus UTM, USA

Advanced air mobility operations are expected to increase

[Airbus UTM Blueprint for the Skies, 2018]

[FAA UTM Concept of Operations, 2020]

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Centralized traffic management may not be sufficient

- Less compatible with on-demand traffic
- Usually requires sharing of full trajectory information
- May not scale to meet forecasted demand

We explore protocol-based congestion management that determines the "**rules of the road**"

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Our protocol has four desired properties

Efficiency

Privacy

Scalability

Fairness

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Prior Work

- Air traffic flow management problem *(Bertsimas & Patterson 1998)*
- Fair congestion control *(Lu et al. 1999)*
- Distributed protocols *(Ribeiro et al. 2020, Hwang et al. 2007)*
- Fairness and efficiency trade-offs in centralized UTM *(Chin et al. 2020)*

Our contribution is the incorporation of **fairness** and **reduced information sharing** into a congestion management protocol

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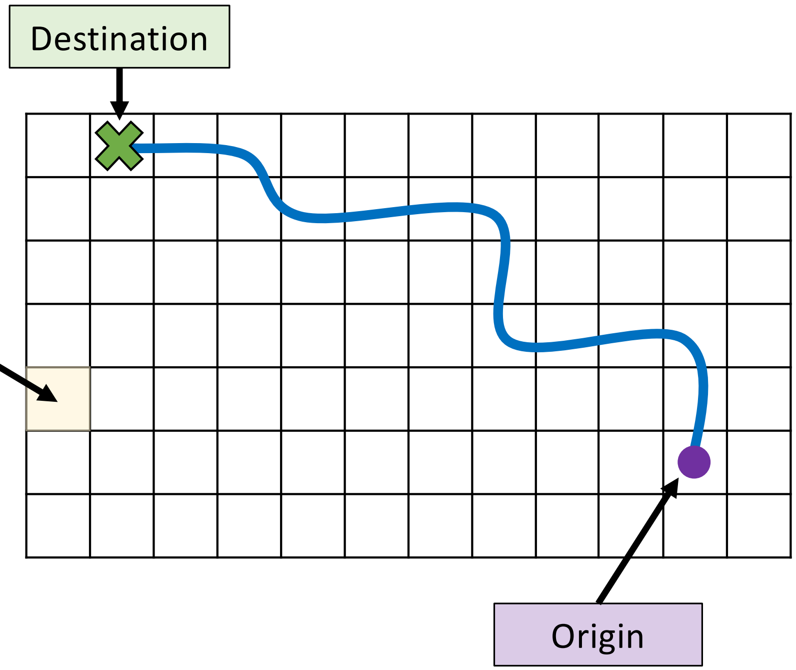
Outline

- **Problem Setup**
- A Protocol for Congestion Control
  - Preventing Gridlocks
  - Maximizing Efficiency
- Incorporating Fairness
- Experimental Evaluation

Problem Setup: Sectors and Vehicles

Space is discretized into sectors with capacity of 1



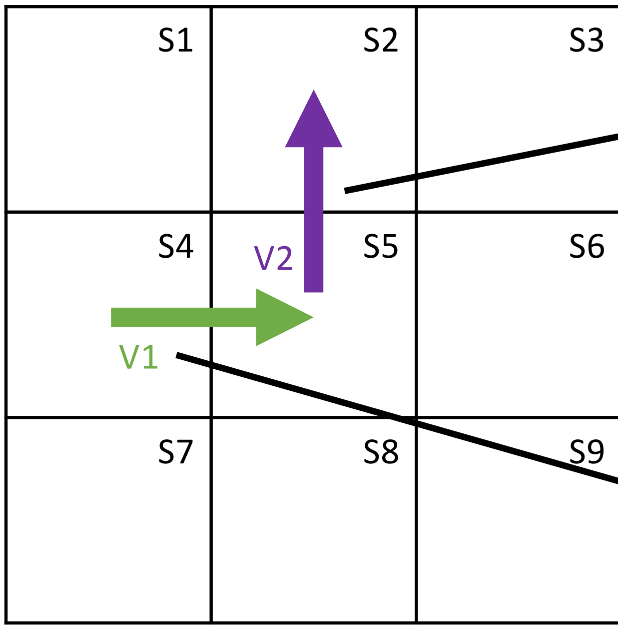
Vehicles have origins and destinations with scheduled times at each sector

Vehicles can be delayed on the ground or in the air, but their paths cannot change

Problem Setup: Time Discretization

Time is discretized into **time steps**

At each time step, each vehicle has its current sector and desired next sector



Example with Sectors S1-S9 and Vehicles V1, V2

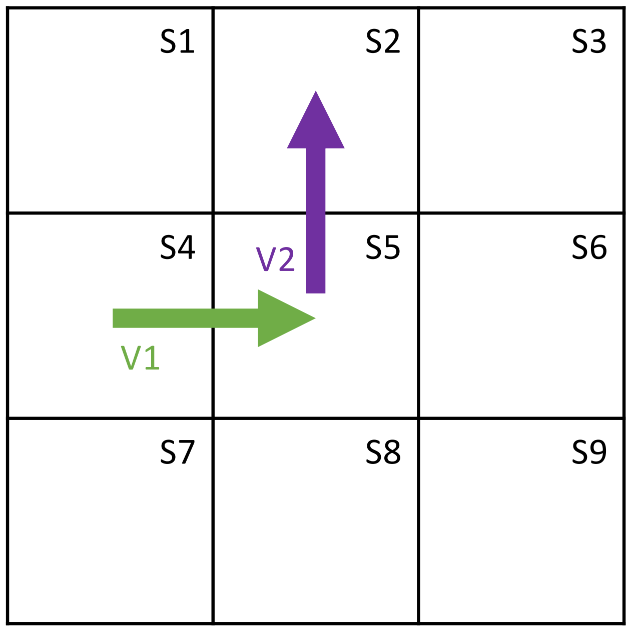
V2 currently occupies sector S5 and wants to move to S2 in the next time step

V1 currently occupies sector S4 and wants to move to S5 in the next time step

Problem Setup: Information Sharing

At each time step, each vehicle conveys its desired next sector to that sector

V1 (V2) tells S5 (S2) that it wants to use it in the next time step



Example with Sectors S1-S9 and Vehicles V1, V2

Each sector *i* can communicate two items to adjacent sectors

1) The identify—but not position—of vehicles that want to access sector *i*

S5 (S2) tells adjacent sectors that V1 (V2) wants to use it

2) The length of built-up queue

S5 (S2) tells adjacent sectors that it has a built-up queue of length 1 (2)

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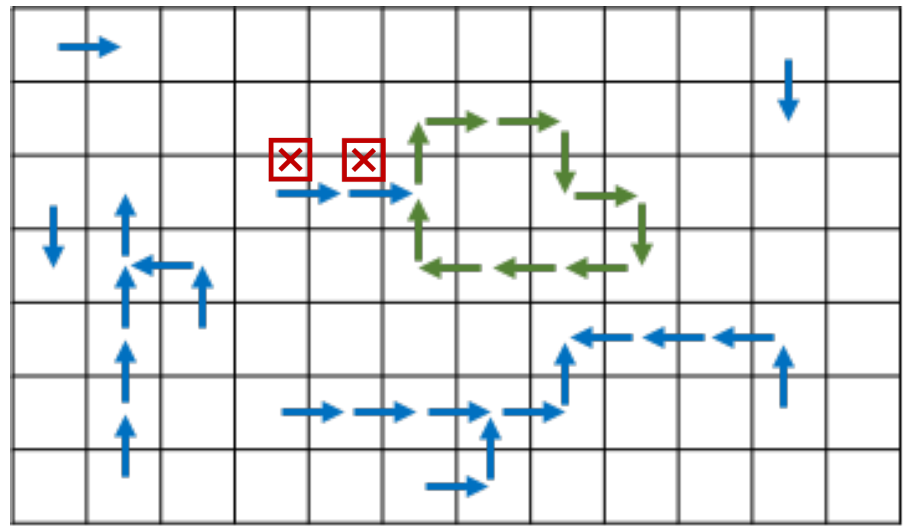
Protocol: Avoiding gridlock

Identify and prioritize **cycles**

↓

Hold flights incident on cycles

We identify cycles by adapting the standard distributed Roche-Thatte algorithm

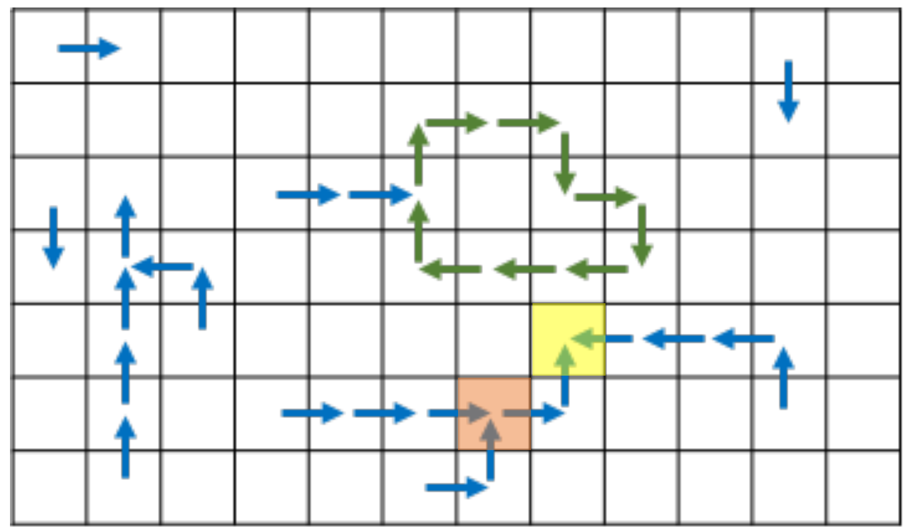


Flight trajectories that are part of a cycle

Flight trajectories that are not part of a cycle

Protocol: Computing sector prioritization

Deconfliction decisions at one sector can impact other sectors



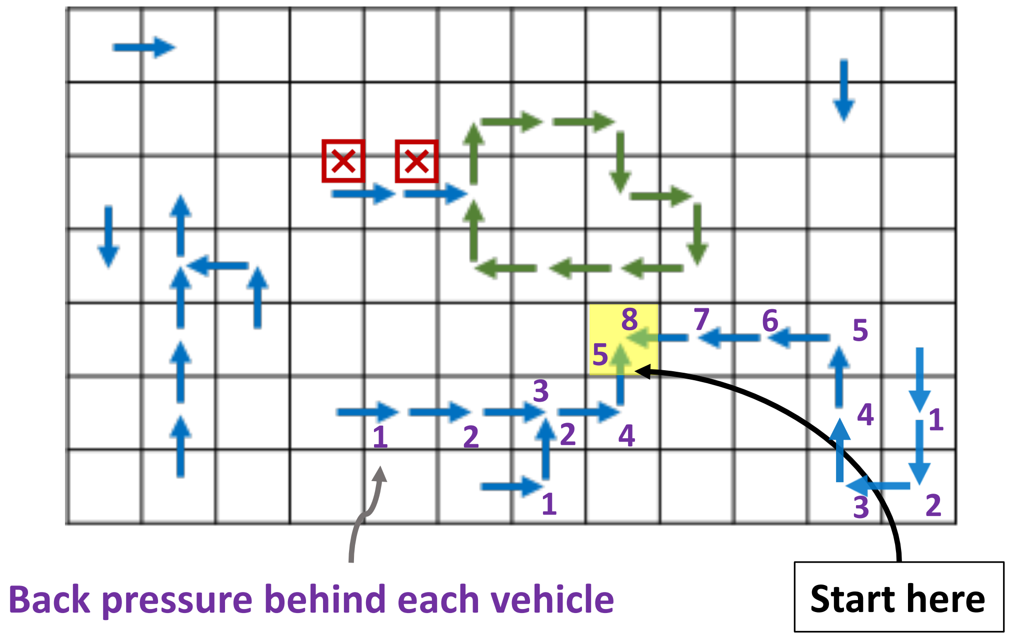
Key idea: Deconflict yellow sector before orange sector

Protocol: Compute sector prioritization

Deconflict sector with the highest **backpressure** first

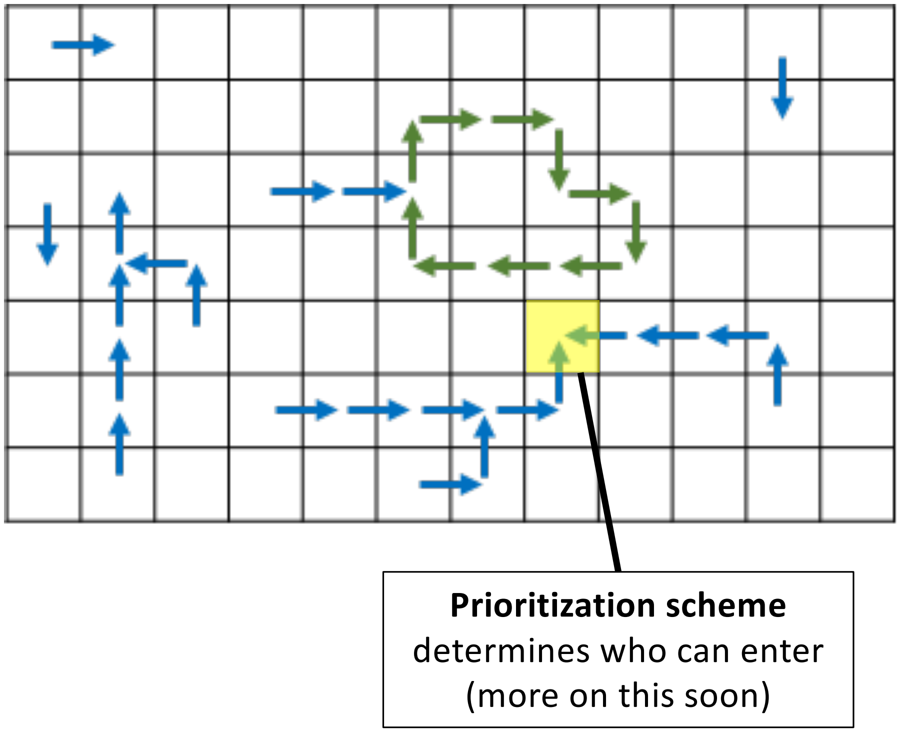
Backpressure = length of **longest** queue behind you

We can calculate backpressure even with our information sharing constraints



Protocol: Loop through sectors and decide

- If sufficient capacity for all inbound vehicles, allow them to proceed
- If insufficient capacity to allow all vehicles, use **prioritization scheme**



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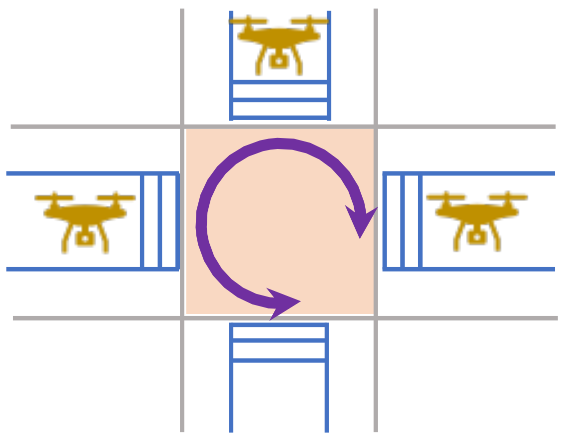
Baseline Prioritization Schemes

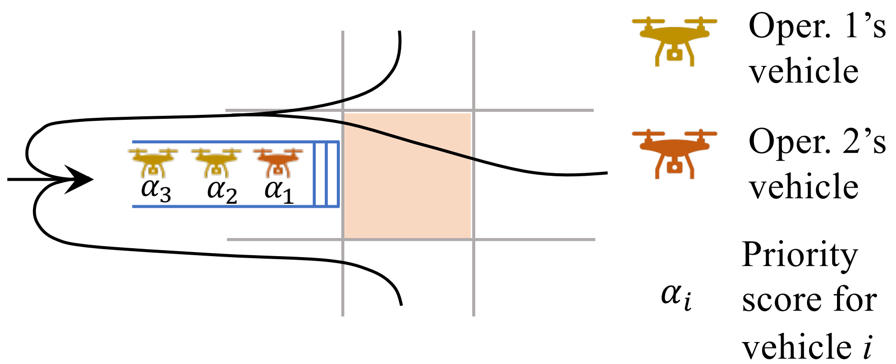
Two simple baselines:

1. Random prioritization
2. Round robin

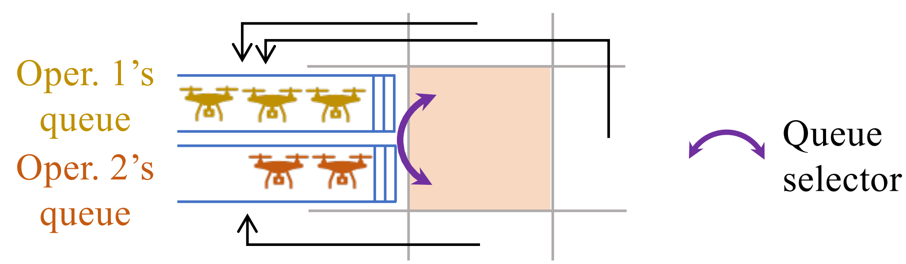


Flight-level vs. Operator-level Prioritization

Flight-level prioritization



Operator-level prioritization



Prioritize high backpressure

Flight-level ✅
Operator-level ✅

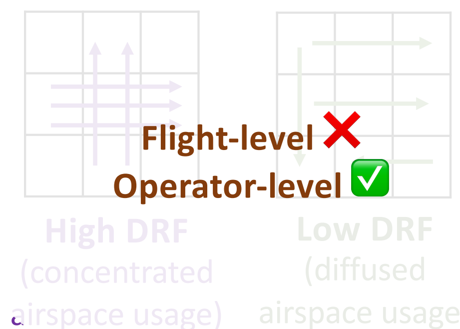
Prioritize high accrued delay

Flight-level ✅
Operator-level ✅

Prioritize high reversals

Flight-level ✅
Operator-level ✅

Prioritize low dominant resource fraction (DRF)



Flight-level ❌
Operator-level ✅

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- **Experimental Evaluation**

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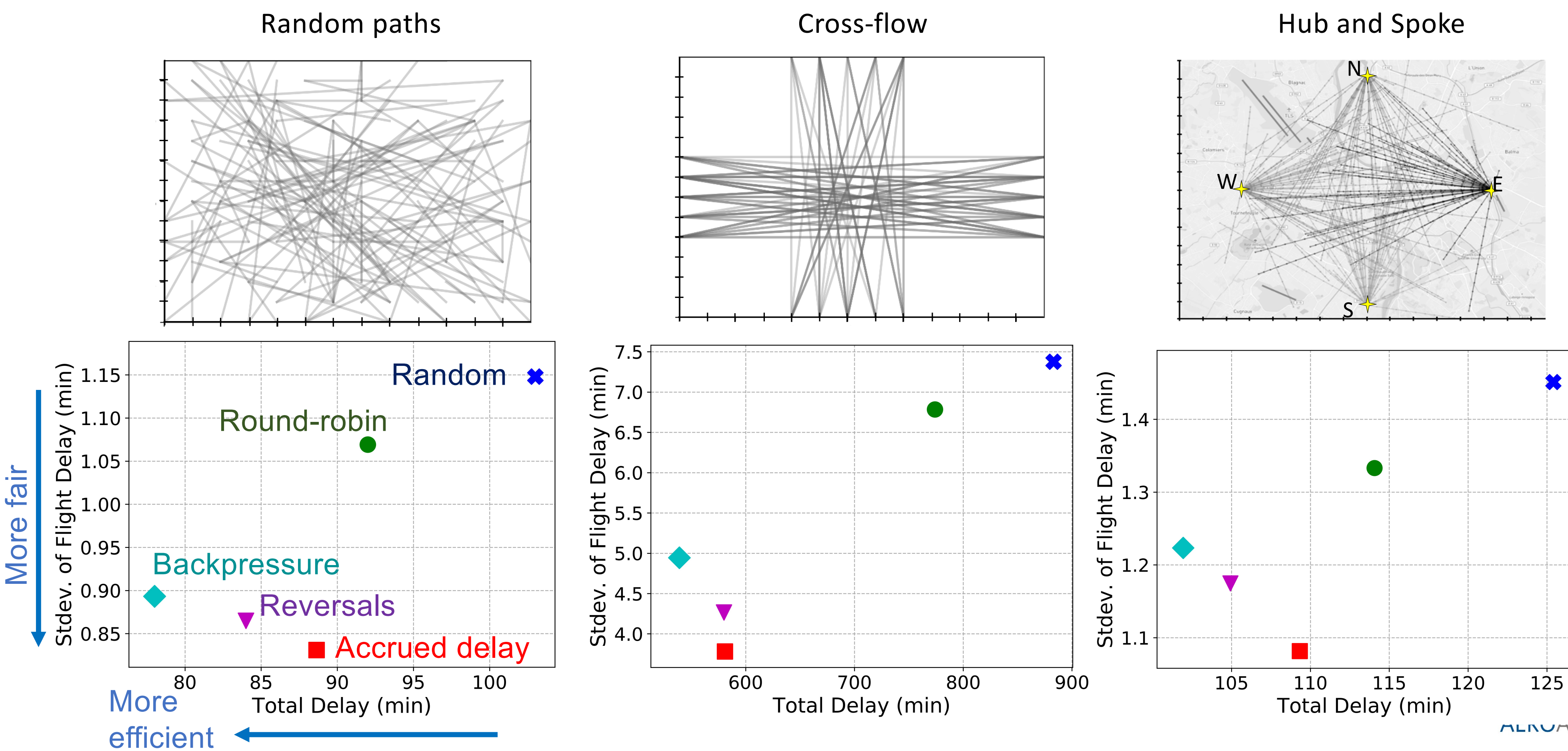
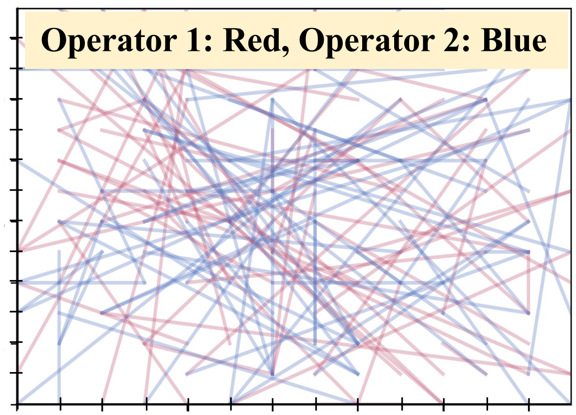
Results: Flight-level Prioritization

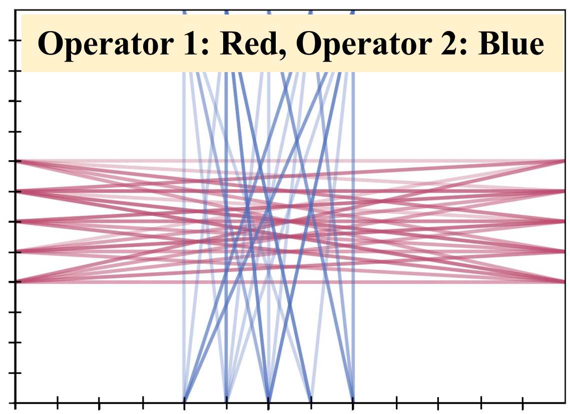


Results: Operator-level Prioritization

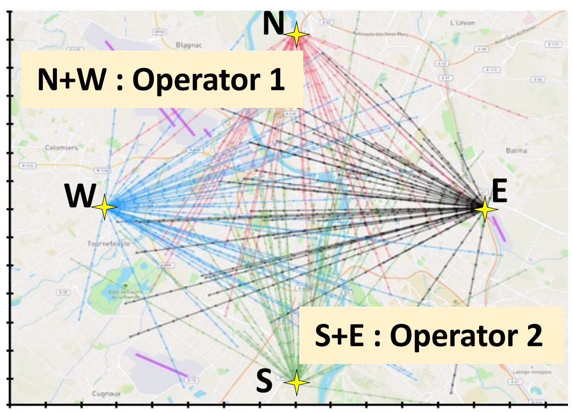
Random paths



Cross-flow



Hub and Spoke



Efficiency trends from flight-level prioritization hold (backpressure most efficient)

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Results: Operator-level Fairness

Considered three notions of fairness

1) Equal operator delay

2) Equal excess operator delay

3) Excess delay proportional to expected delay

Operator expected delay is the minimum amount of delay an operator would have incurred *if it were the only operator*

$$\overset{\text{“excess”}}{\mu_o^{exc}} = \overset{\text{“operator”}}{\mu_o^{oper}} - \overset{\text{“expected”}}{\mu_o^{exp}}$$

$$\frac{\mu_1^{exc}}{\mu_2^{exc}} = \alpha \frac{\mu_1^{exp}}{\mu_2^{exp}}$$

Want alpha to be close to 1

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Results: Operator-level Fairness

1) Equal operator delay

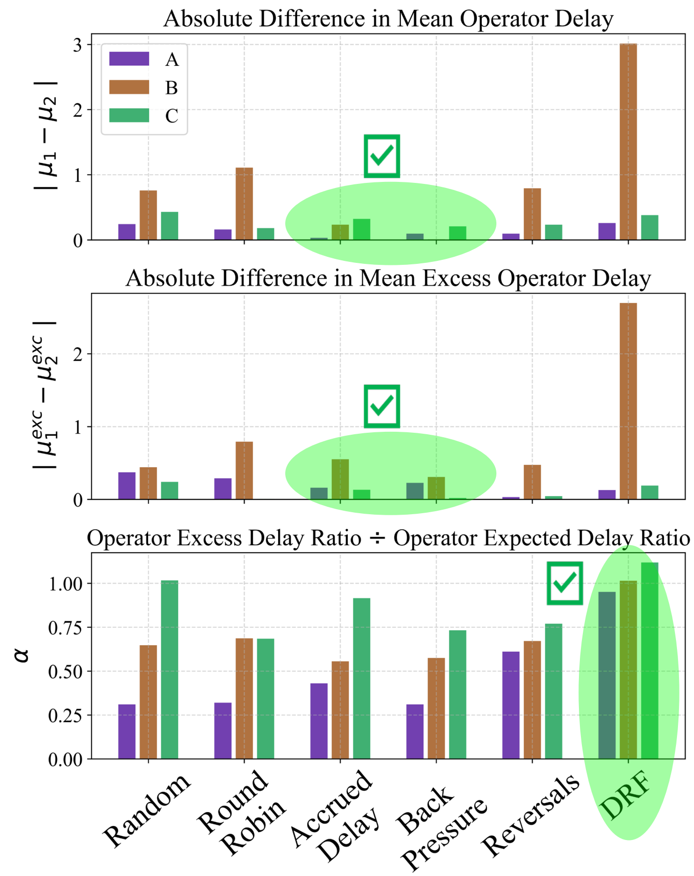
Backpressure/accrued delay are best

2) Equal excess operator delay

Backpressure/accrued delay are best

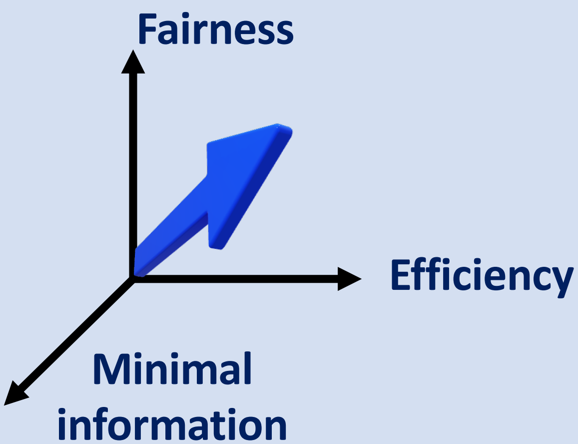
3) Excess delay proportional to expected delay

DRF has alpha closest to 1



Future Work

AAM Traffic Management introduces new objectives



We desire algorithms that lie on the pareto-frontier of this space

Practical considerations

- Dynamic
- 1 time-step
- Min. Info
- Fair

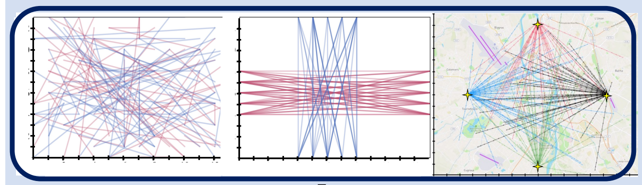
- Predictable
- Plan for hours
- Full flight plans
- Efficient

Reality:

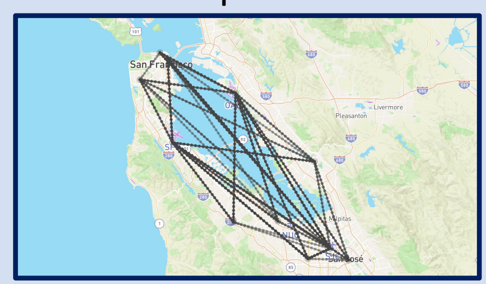
- Scheduled + on-demand flights
- No consensus on fairness
- Partial info. exchange

Theoretical properties

Will all our results and intuition from simulations..



.. hold true in this new traffic pattern?



Summary

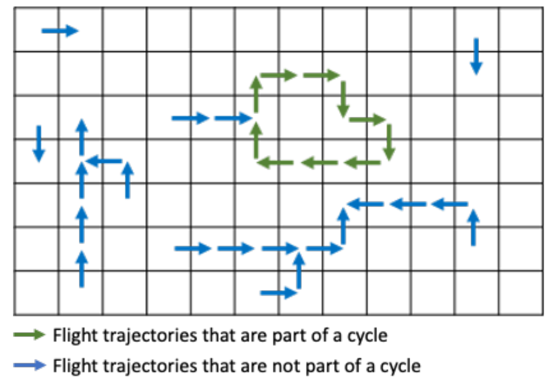
Feel free to contact me at chychin@mit.edu

Efficiency

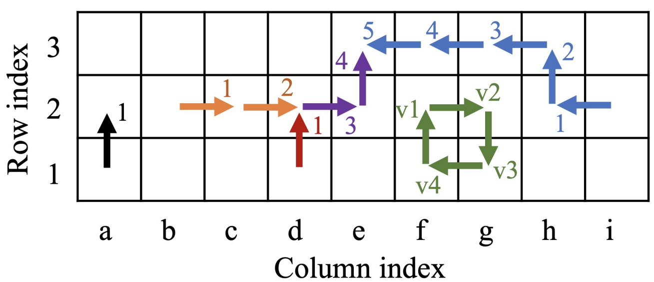
Privacy

Scalability

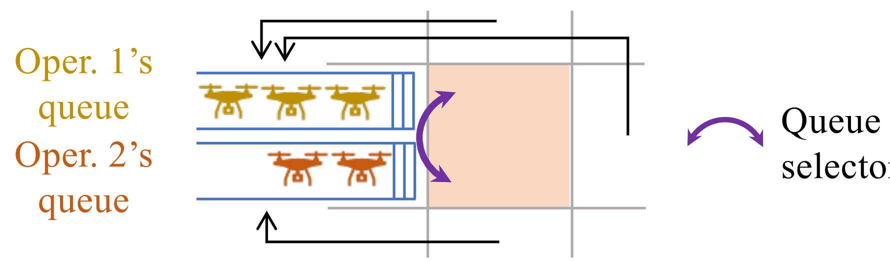
Fairness



Cycles



Backpressure



Prioritization Schemes