Traffic Flow Analysis for Package Delivery Drones using a Queueing Model

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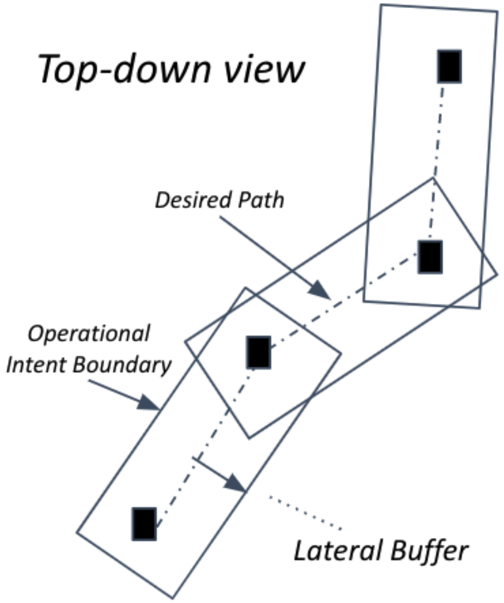
Trajectory Based OIV

Trajectory based Operational Intent Volumes (OIV)s are …

Trajectory-based operational intent



- Associated with a specific 4D path
- **Vertical** and **lateral** dimensions based on buffer from centerline
- **Time** buffer to account for time uncertainty

- a series of time-stamped cuboids
- cuboids that fully encompass the unmanned aircraft's (UA) flight path
- time-stamped such that the conforming flight always stays inside the OIV
- in conflict if two OIVs overlap both spatially and temporally

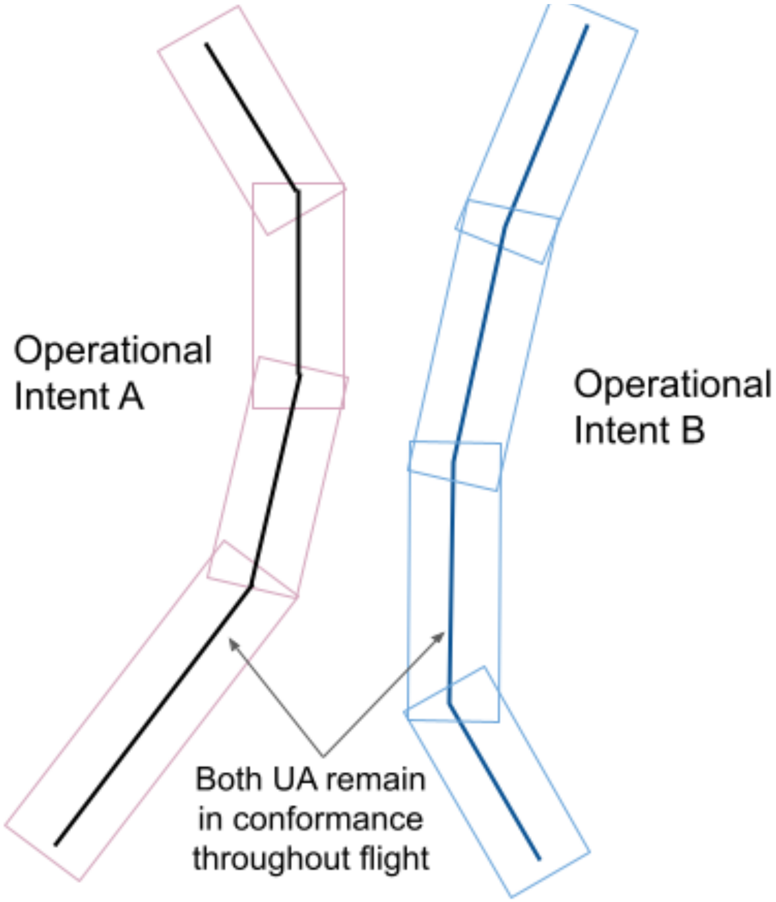


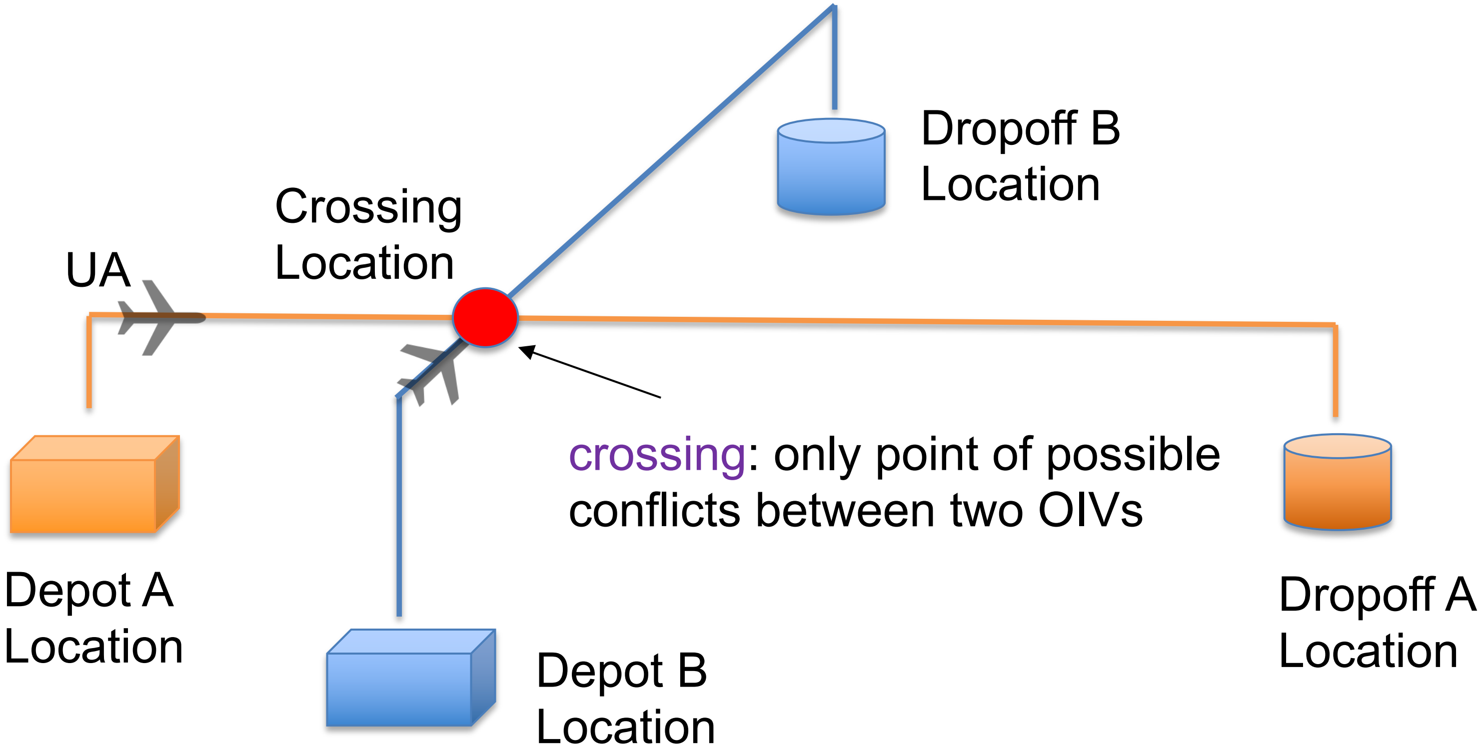
Figure 5. Nominal, Coordinated Operational Intents

Federal Aviation Administration NextGen Office, "UTM ConOps v2.0," Mar 2020

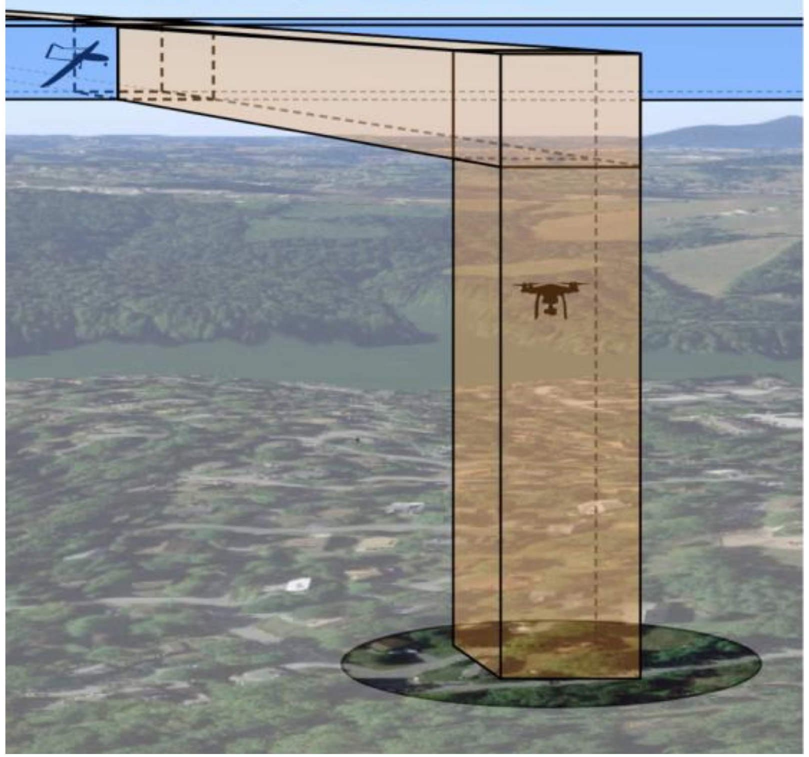
Related Works & Research Gap

- Air traffic management & traffic flow
  - MIT, NASA, others
    - Ground holding pattern
    - Air holding pattern
    - Sector-based capacity limits
- small UA deconfliction
  - Formulate optimization models
  - Heuristics
  - Deep reinforcement learning
- Very few work on planning and scheduling with OIVs

Prior Work: Single Crossing Deconfliction Problem



Temporal separation



NOTE: Actual flight plan might not be vertical climb and descent

P. Pradeep, A. A. Munishkin, K. M. Kalyanam, and H. Erzberger, "Strategic Deconfliction of Small Unmanned Aircraft Using Operational Volume Blocks at Crossing Waypoints," in AIAA SciTech Forum and Exposition, National Harbor, MD, 2023.

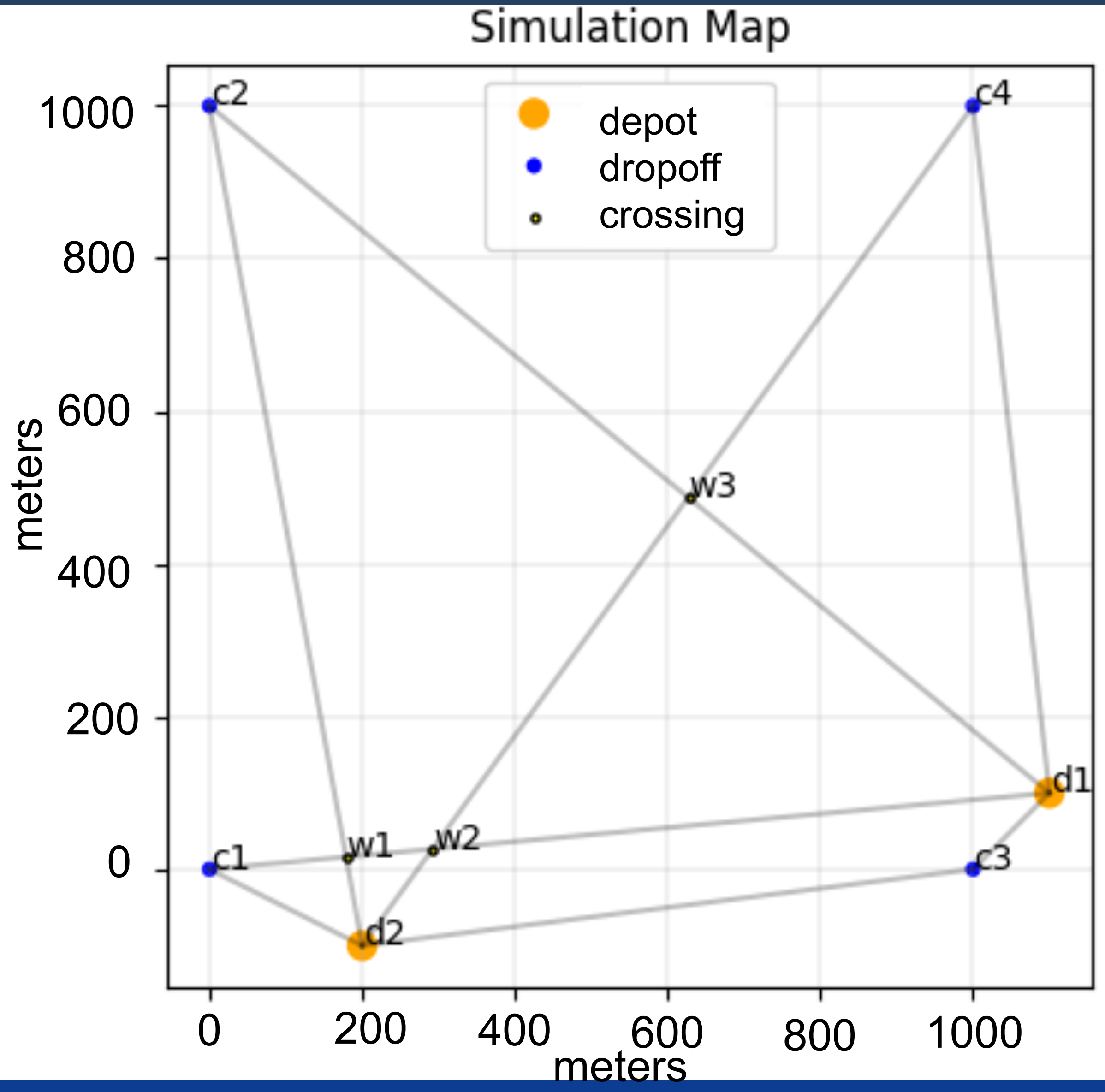
Multiple Crossing Deconfliction Problem

- One-way package delivery problem
  - Depots, dropoffs, and crossings
  - Routes: depots -> dropoffs

- Assumptions
  - A set of UA are waiting to depart at each depot
  - Each UA is associated with a depot and dropoff
  - Routes are fixed; ground speeds are fixed

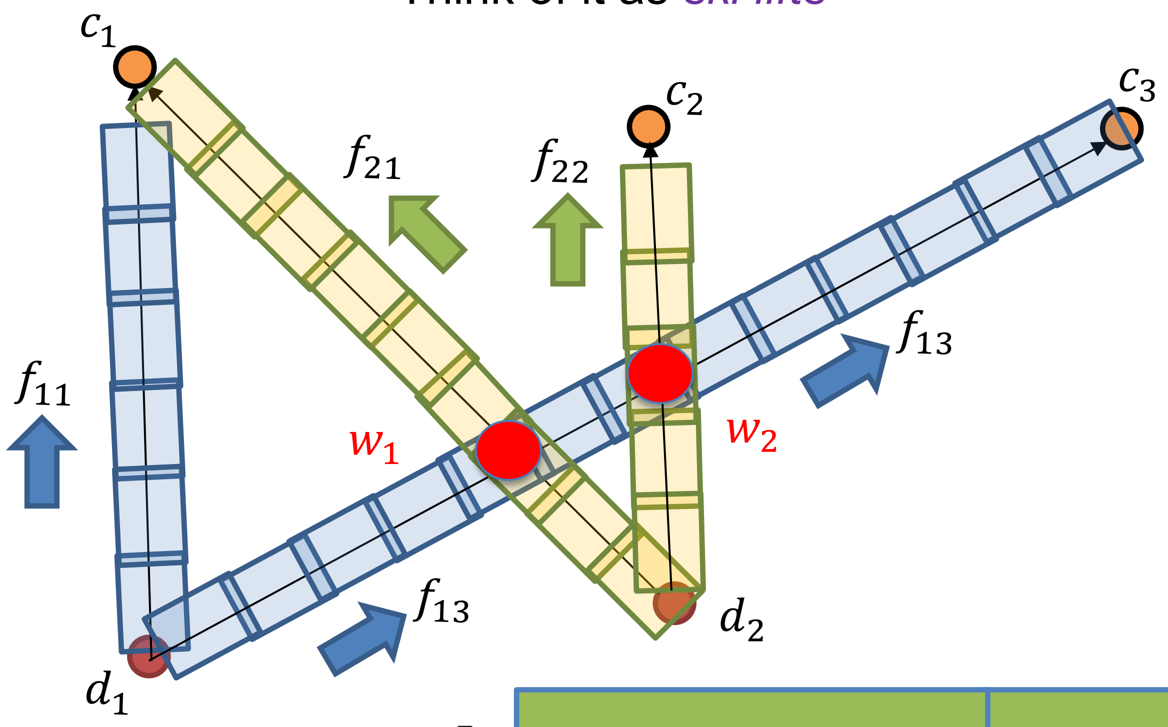
Objective

- Maximize network throughput while avoiding conflicts!



Basis of the Model: Traffic as Flow

Think of it as *ski lifts*



Model Assumptions:

1) The "flow" f_{ij} from depot d_i to customer dropoff location c_j is

$$flow = \frac{\#\ of\ flights}{unit\ time}$$

2) Uniform flows

3) Regular and predictable traffic conditions – think bus schedules or *ski lifts*

Variables, Metric, and Simulation Setup

What are the variables?

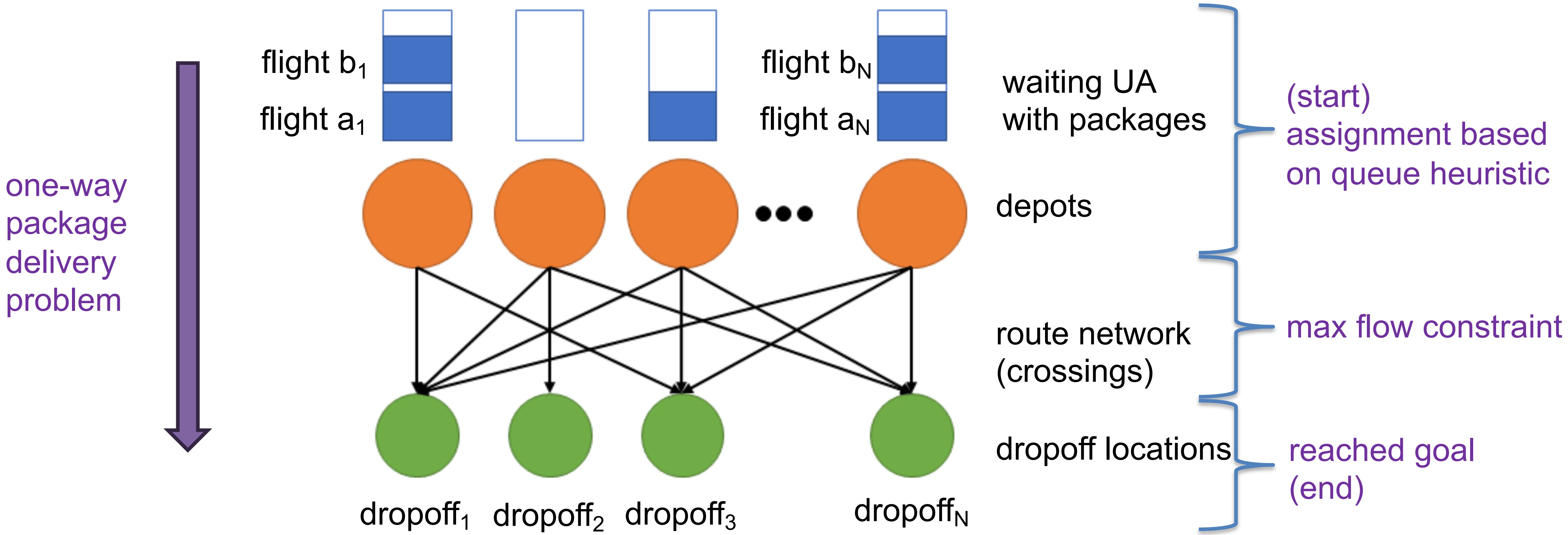
- input: on-demand customer request rate λ, OIV dimensions, route structure
- control: **UA assignment** per route based on queue processing
- output: **UA schedules** based on max flow and queue heuristics

$$\text{Throughput metric} = \frac{average\ arrival\ rate\ of\ deliveries}{\lambda}$$

Simulation

- is a simple agent-based simulator to test concept
- has as many flights as needed due to on-demand customer rate
- is stopped after time $\approx$ 3 simulation hours
- tests different queue heuristics for given route network

Structure of the Overall Model

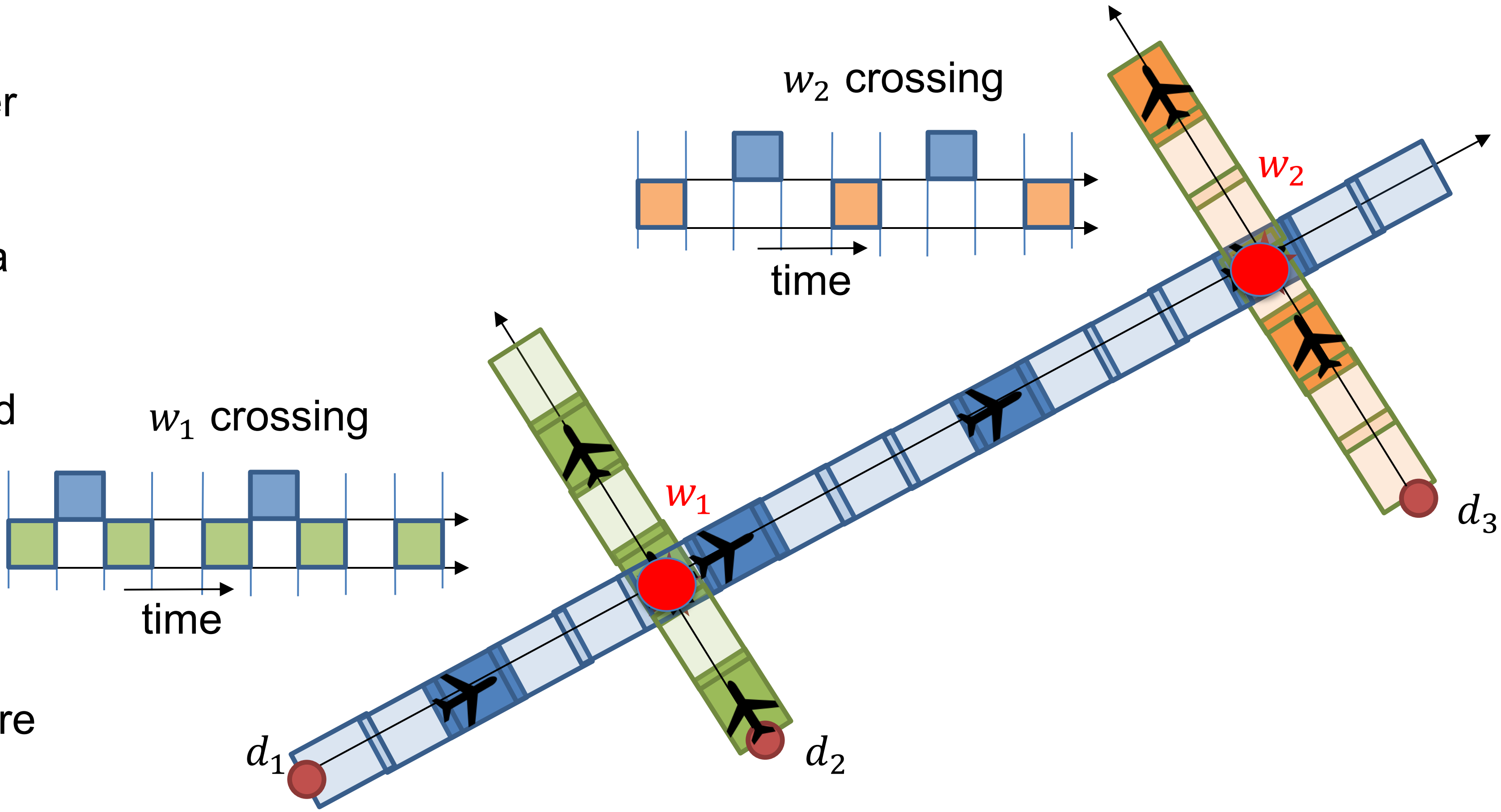


- 2D in space (ignoring altitude) Traffic Flow Analysis
- Route network has crossing waypoints, which creates temporal separation constraints
- Depots are assumed to have unlimited amount of UA

Multiple Crossings Using Traffic Flow and Queues

Idea of algorithm:

- Solve Max-Flow optimization per given UA route network
- Each depot $\{d_1, d_2, \ldots, d_n\}$ has a heuristic queue scheduler
- Iterate through set of depots and "simulate" flights
- If conflict occurs between two different depot flights, "shift"
- "Shift" as necessary until no more conflicts



Example of uniform flow with 2 crossings

Step 1: Solve Max-Flow Optimization

Step 1) Maximize flow on all routes

Constraints:

1. Satisfy input-output flow at crossings

2. Merging flows into a crossing is limited by temporal constraint at crossing

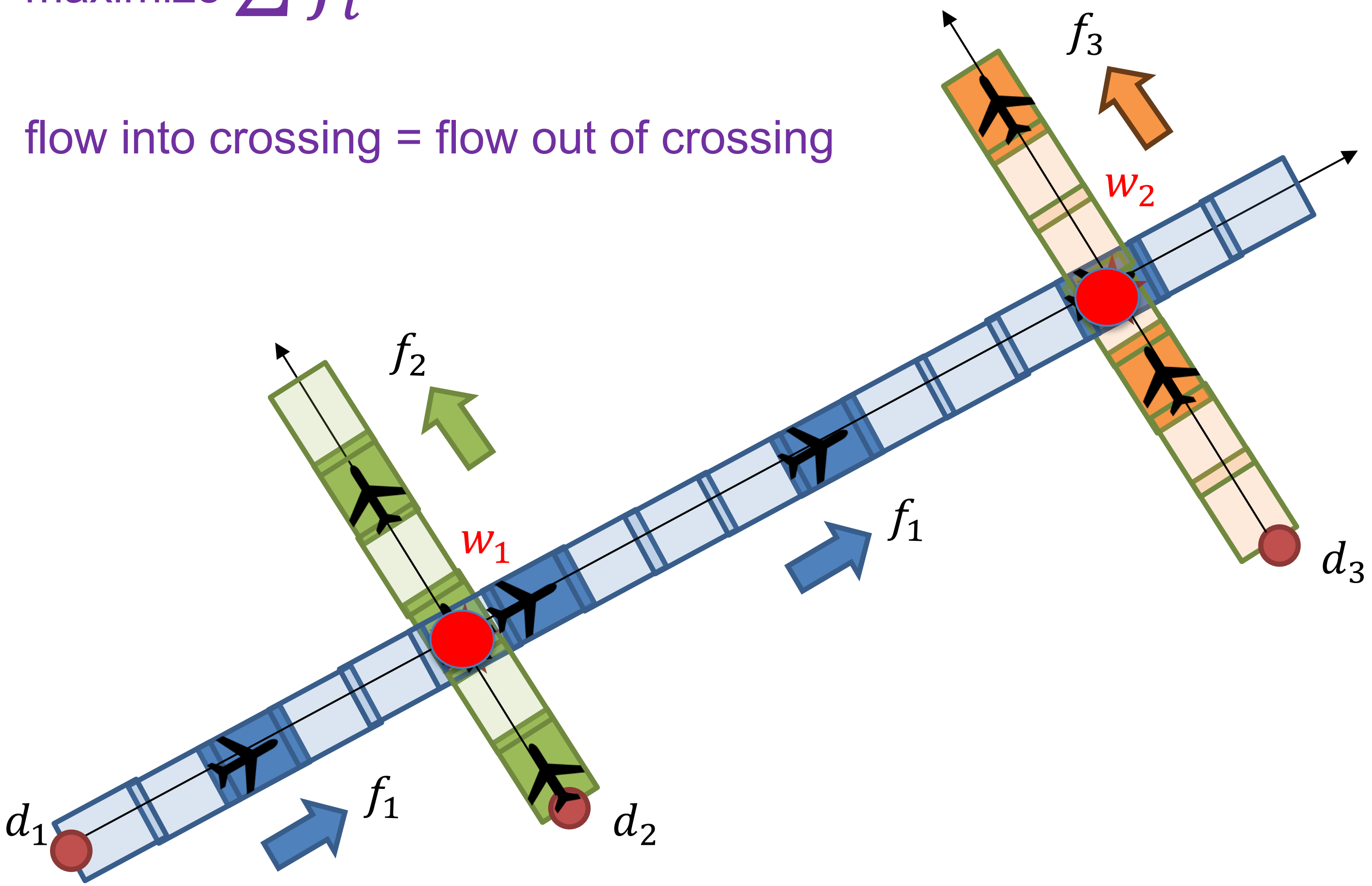
3. Flows are constant across one route

Linear program (LP) optimization

- FAST to solve
- scalable to very large route networks

maximize $\sum f_i$

flow into crossing = flow out of crossing

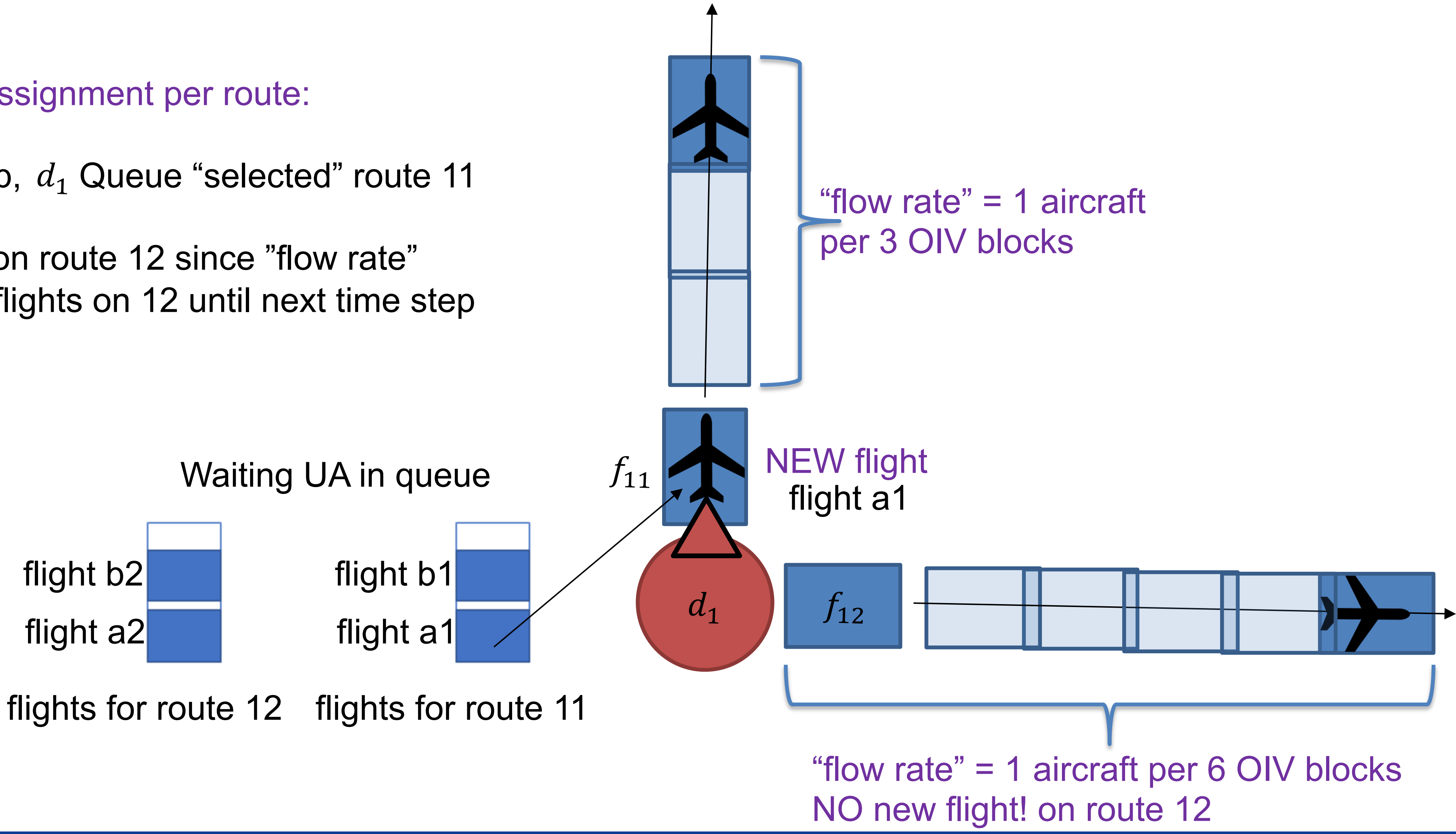


Step 2: Choose Queue Schedular

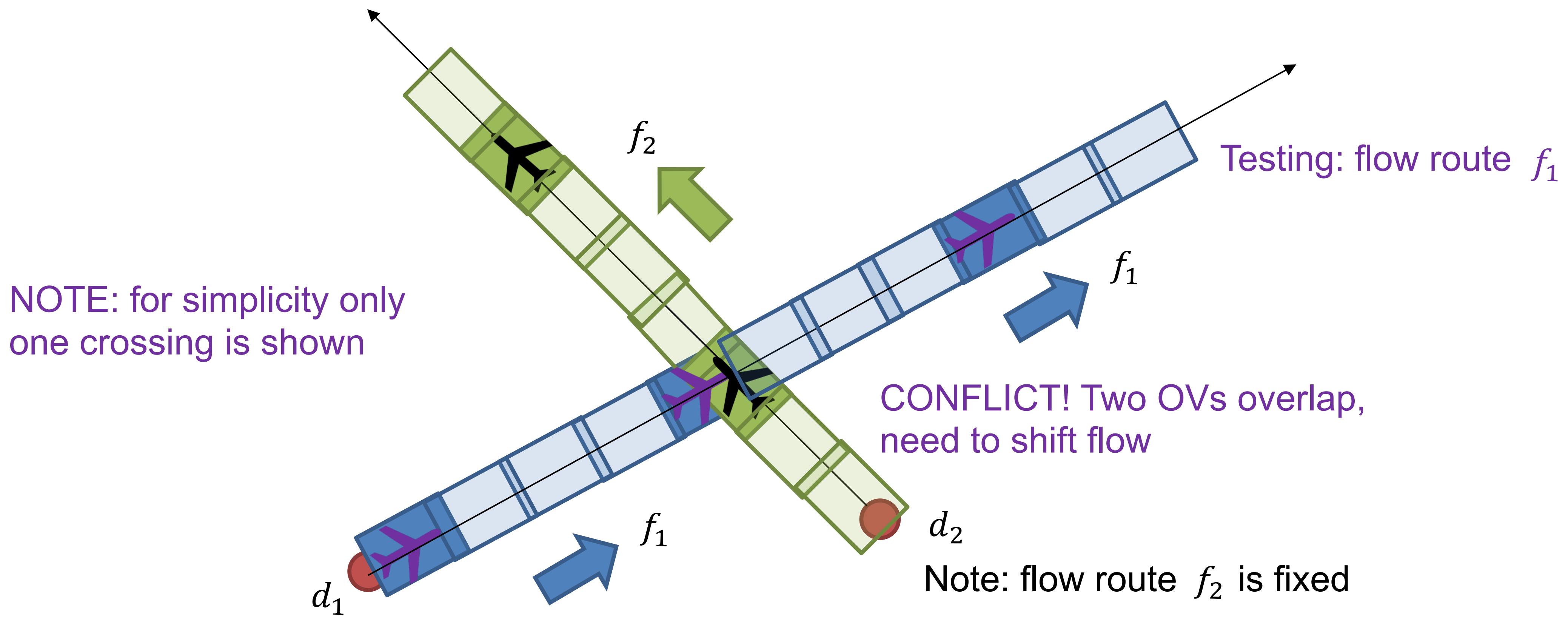
Pre-departure flight assignment per route:

Step 2) New time step, d_1 Queue “selected” route 11

NOTE: no new flight on route 12 since ”flow rate” constraints limit new flights on 12 until next time step



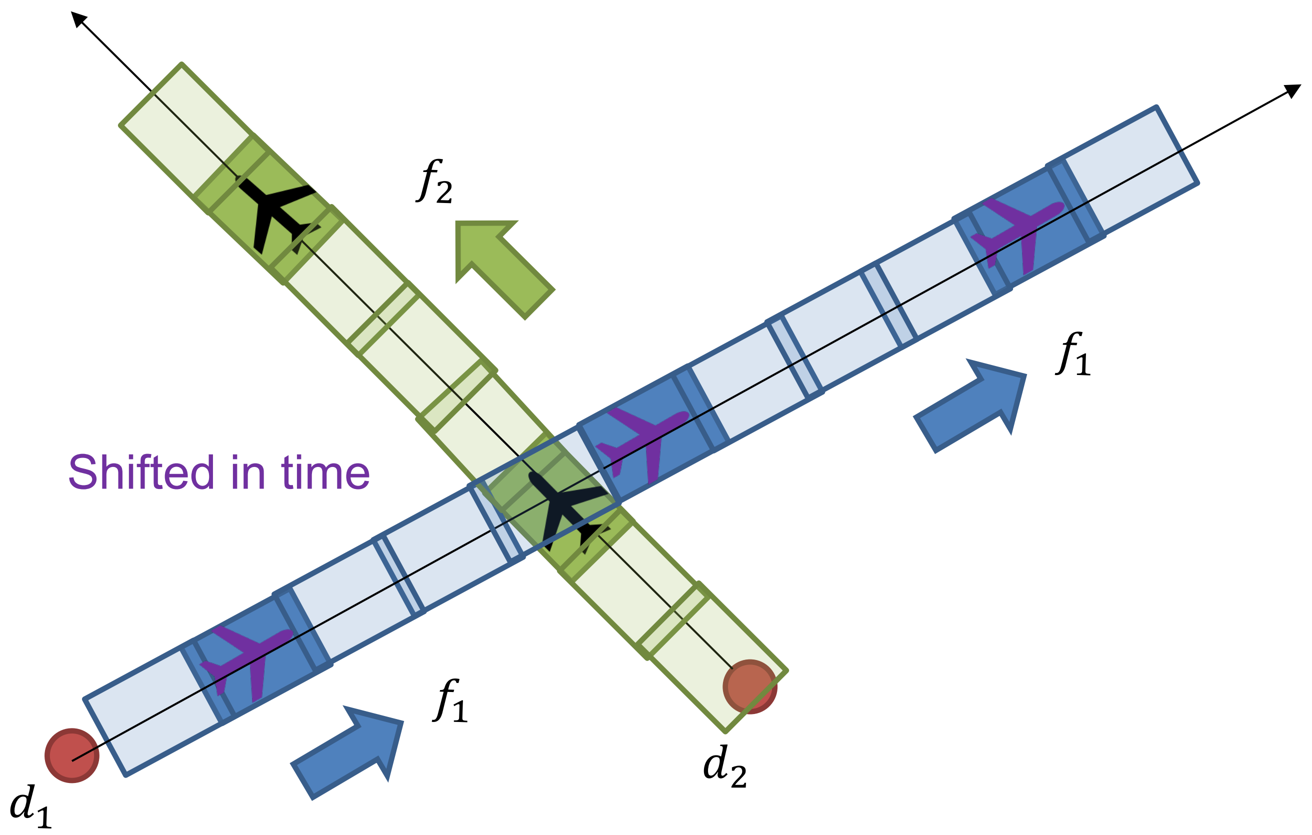
Step 3: Resolve Conflicts …



Step 3a) To resolve possible conflicts at crossings, “simulate” flights and “shift” as needed. “Simulation” here means to place vehicles at expected locations and see if there are conflicts

Step 3: Resolve Conflicts …

NOTE: for simplicity only one crossing is shown



Step 3b) "Shift": Time shifting the OIV blocks along route 12. De-conflicted at crossing between routes 1 and 2

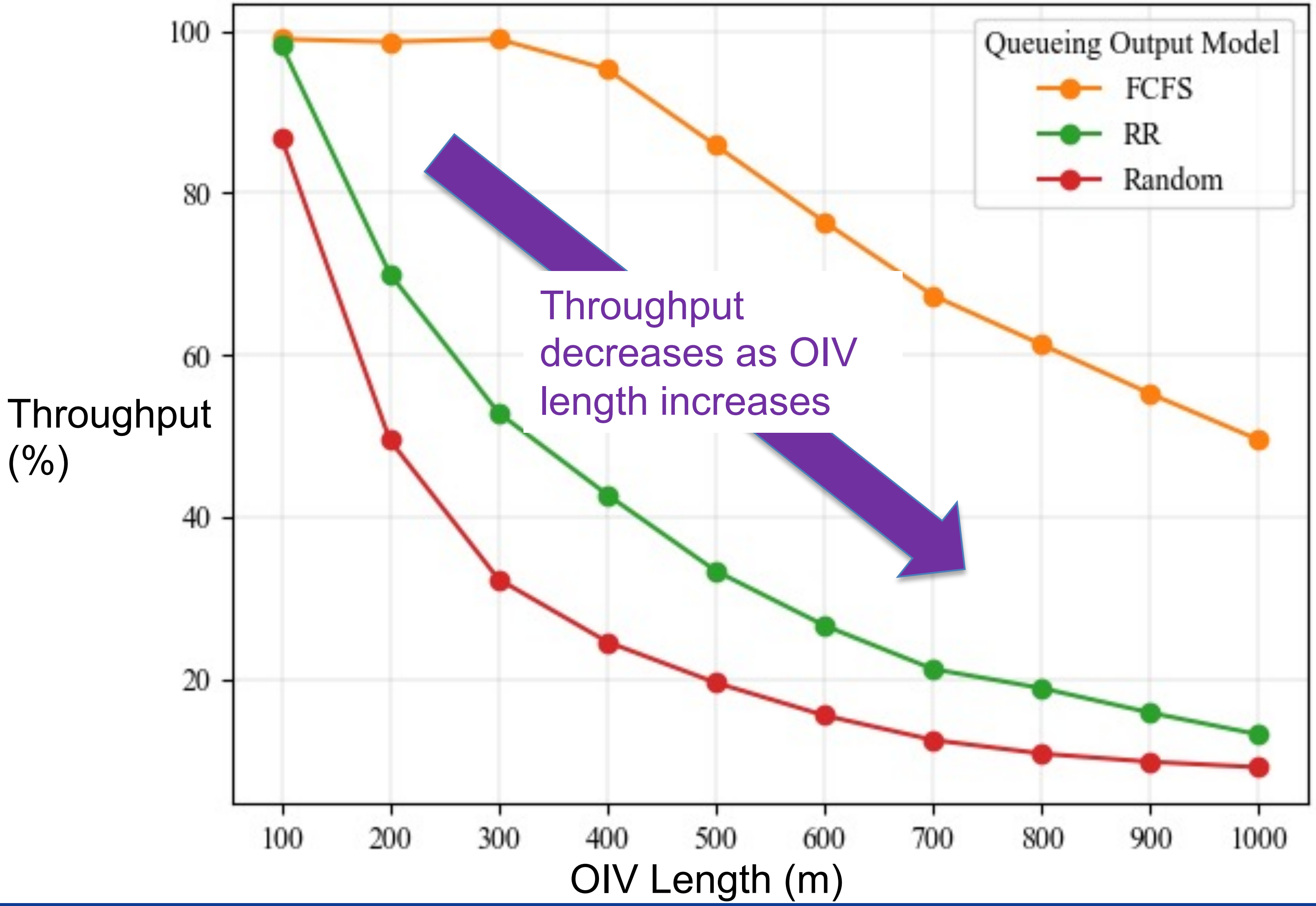
Case Study Results: 2 depots, 4 customers …

- Empirical results

- When throughput drops, other factors such as average ground delay, and average queue length remains constant

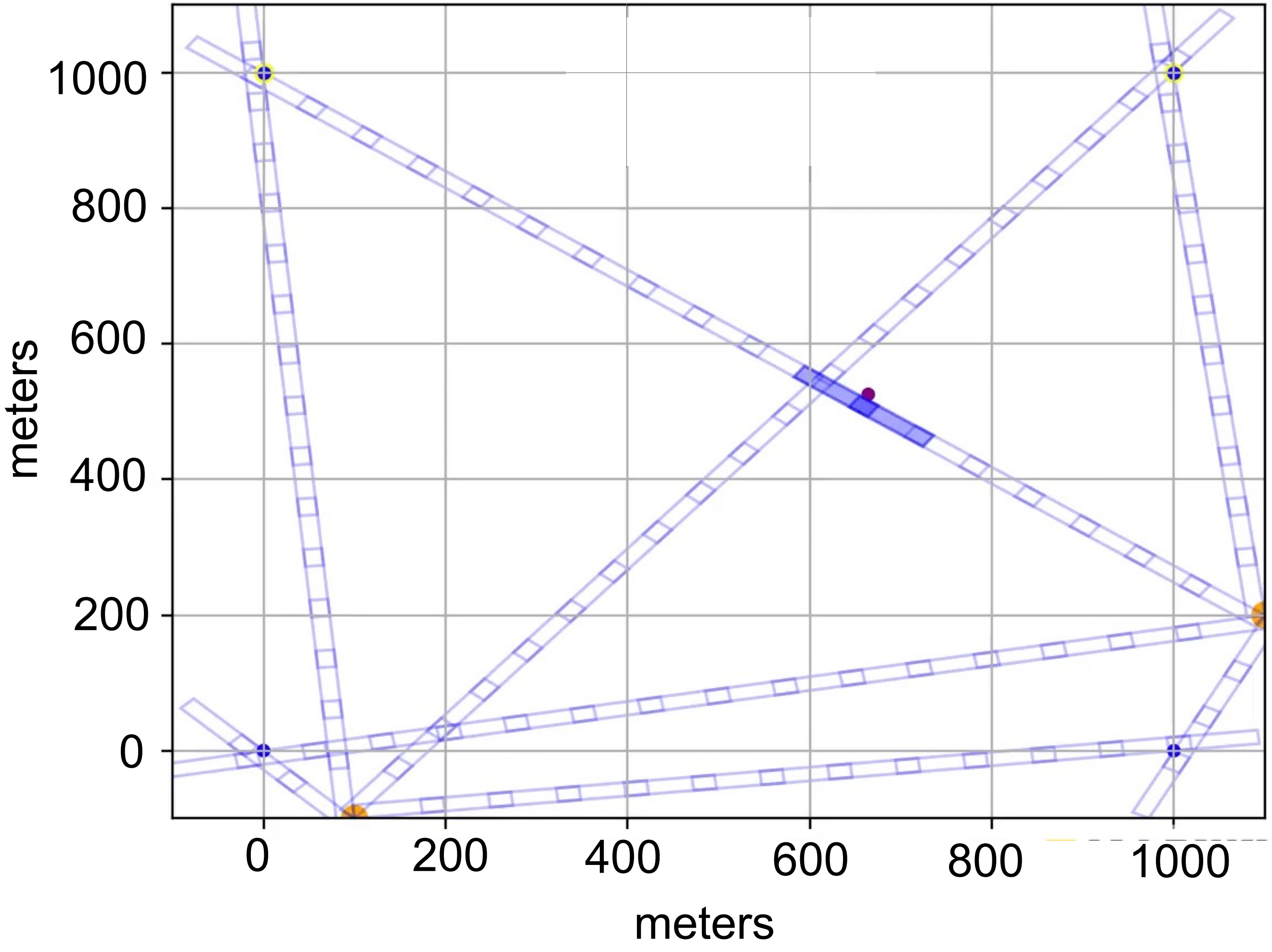
- FCFS (First-Come-First-Served) is the best

- Others are Round-Robin (RR), which is standard queue polling, and Random assignment of flights

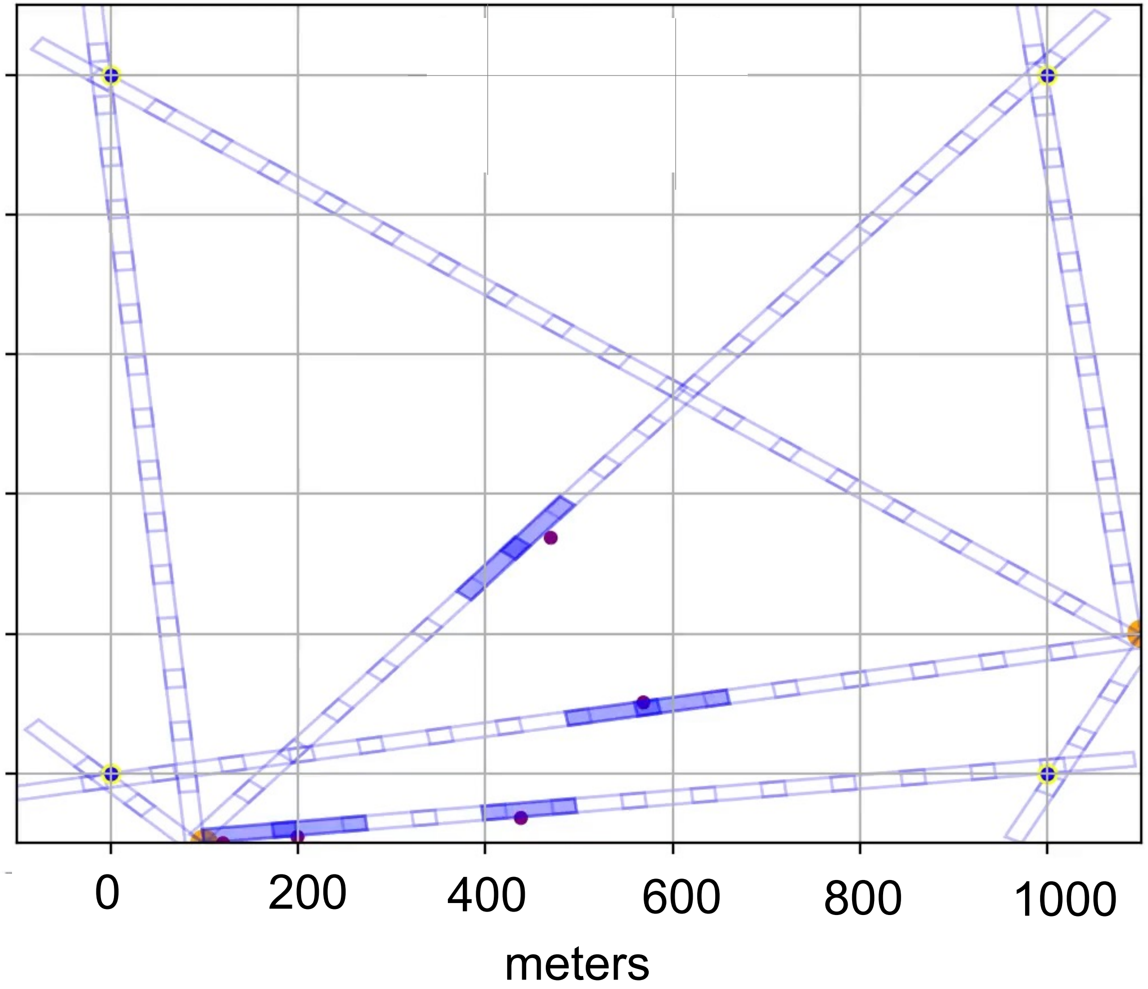


Case Study Movies: 2 depots, 4 customers …

294 flights (about 2 flights per minute)



2493 flights (about 15 flights per minute)



Conclusions / Possible Future Work

Max flow analysis for package delivery

- Flow-based optimization per UA route network
- Optimal in "steady-state" or higher density traffic flows otherwise inefficient, i.e., lower density has lots of missed opportunities for flights

Queue heuristics for pre-flight assignment per route

- FCFS Queue processing is the best heuristic so far
- Throughput for all methods greatly drops beyond 300 meters for OIV length (which is along the UA's heading direction)

Possible Future Work

- Varying UA ground speeds; including wind and other uncertainties
- Incorporate non-uniform flows (can investigate designing optimal flow configurations)
- Investigate different route networks

Questions?

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