A DDDAS Protocol for Real-Time Large-Scale UAS Flight Coordination

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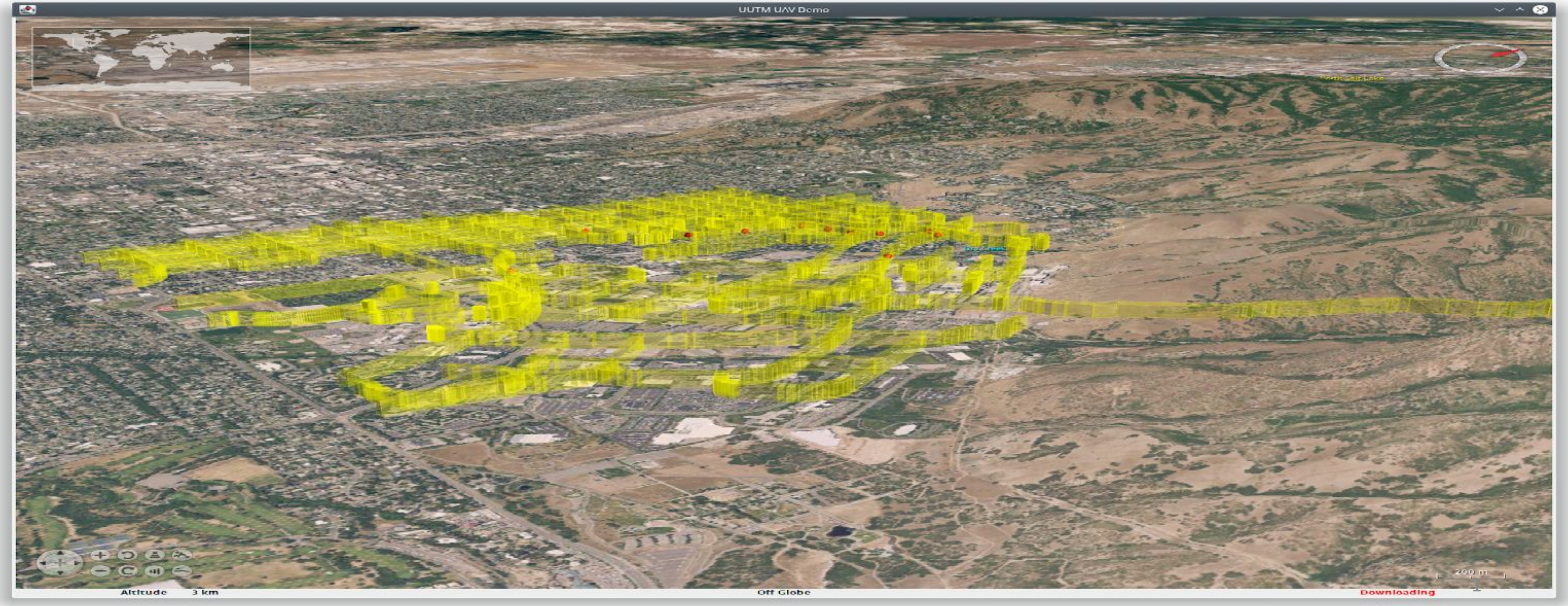


Problem:

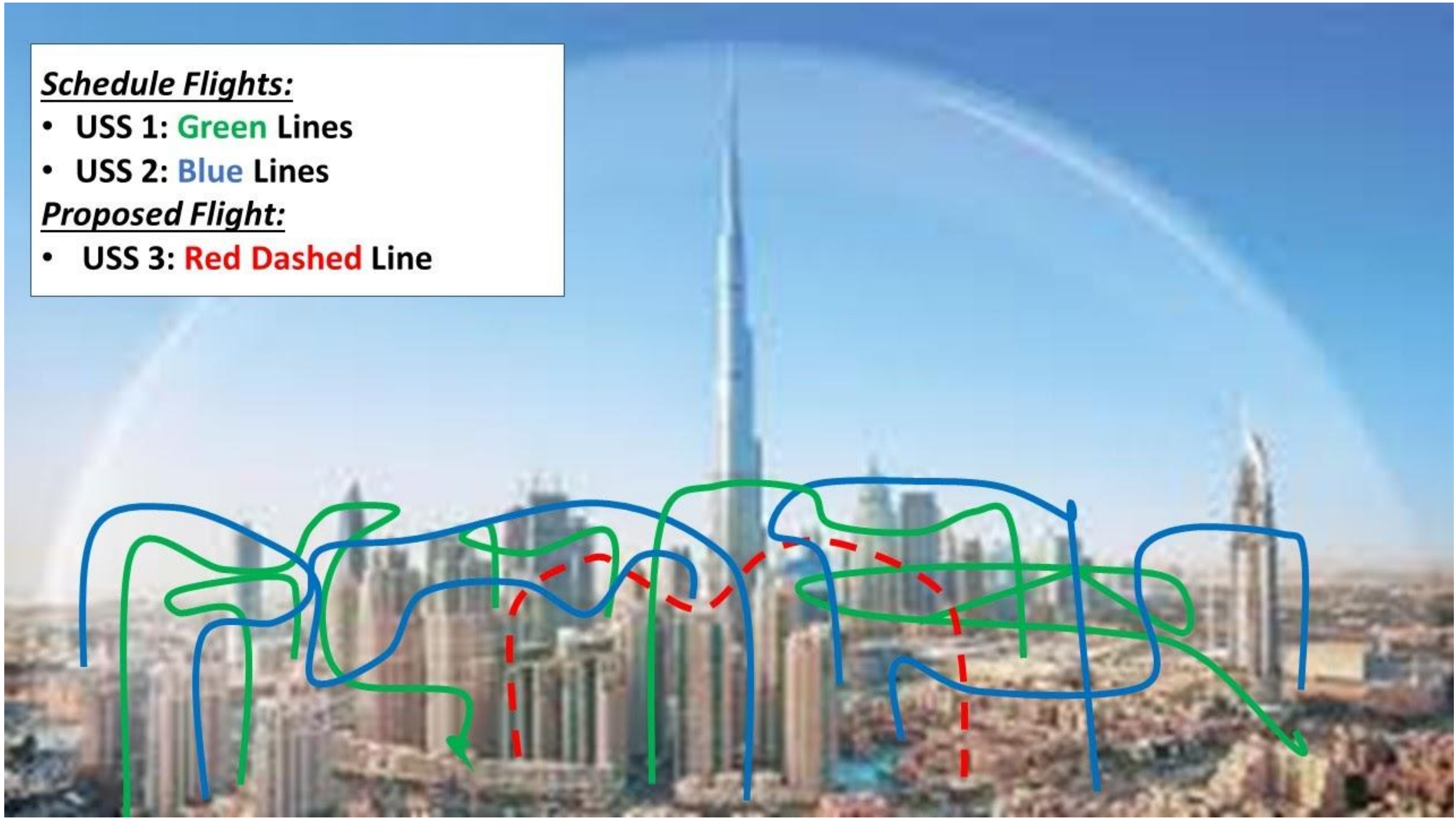
Coming soon everywhere! 1000's of drones

How to Manage all these Flights?

FAA-NASA:

Pairwise deconfliction of all flights in common space-time

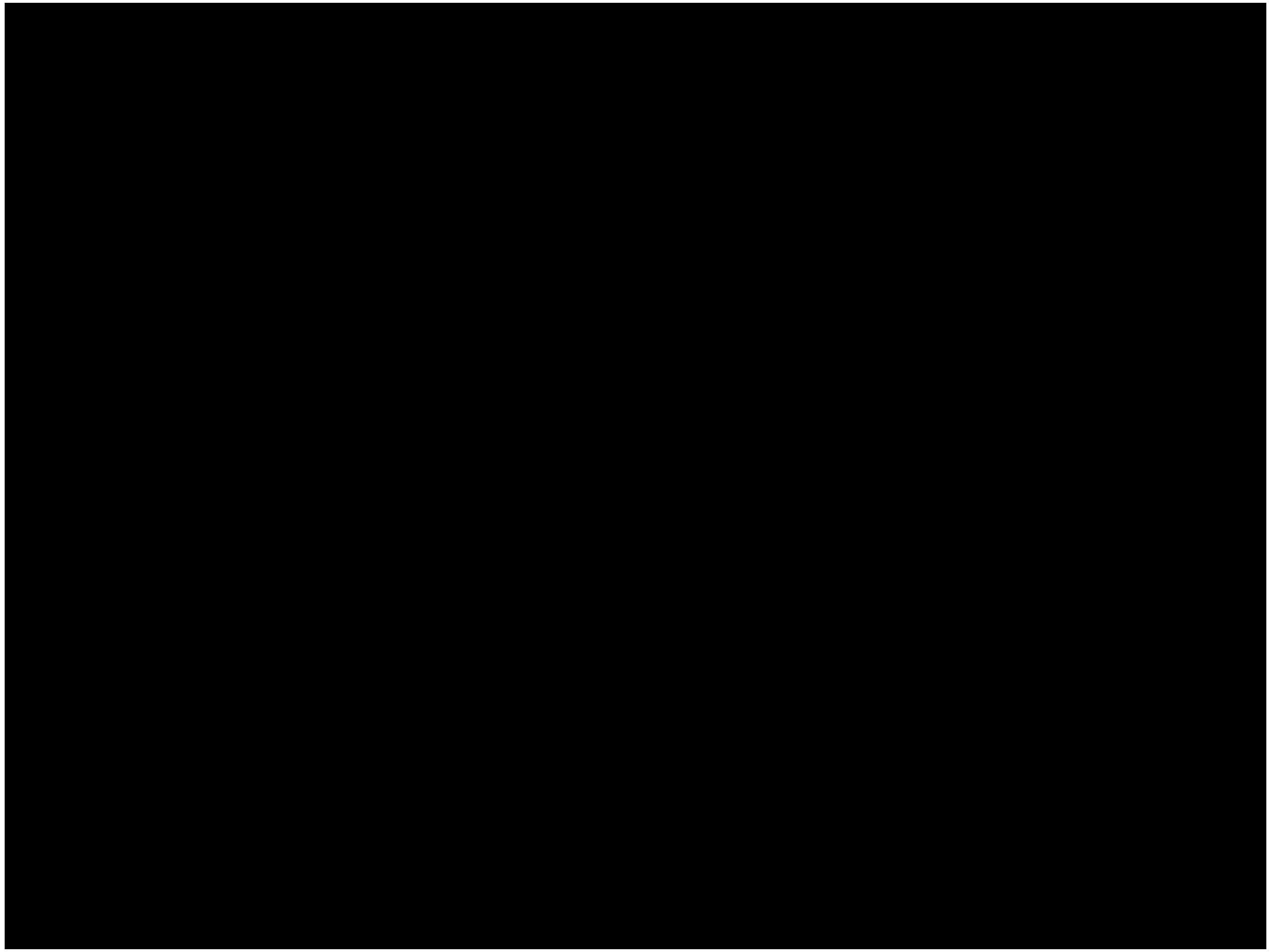
The
<u>UAS Traffic Management</u>
(UTM) Problem



How to Manage all these Flights?

Our Proposal:

Lane-based
Strategic Deconfliction
(lanes defined by Air
Management Authorities)

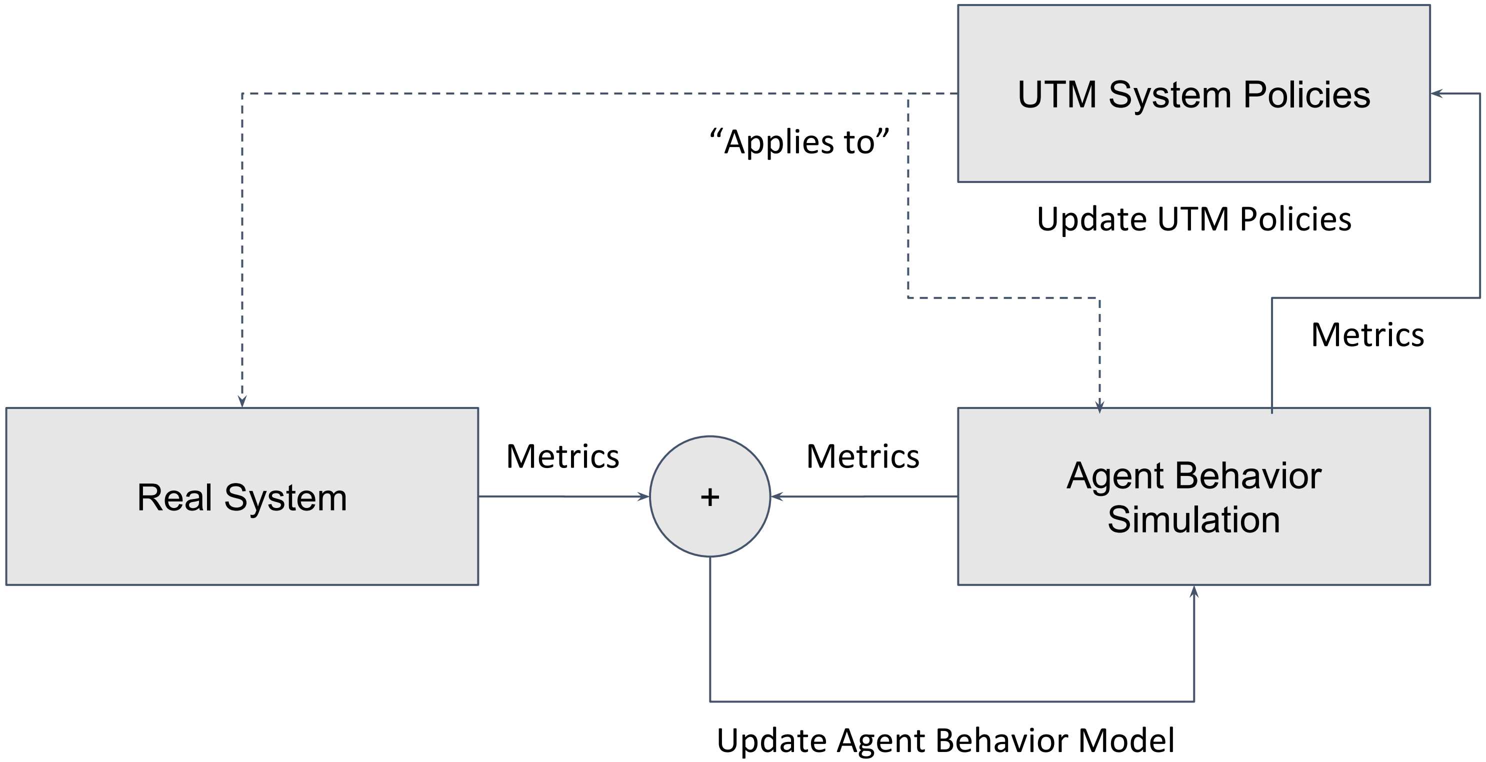


UTM and the DDDAS Paradigm

Model:
- **Lane-Based UTM (System Policies and Structure)**
- **UAS Behaviors (Onboard and Real-Time Algorithms)**

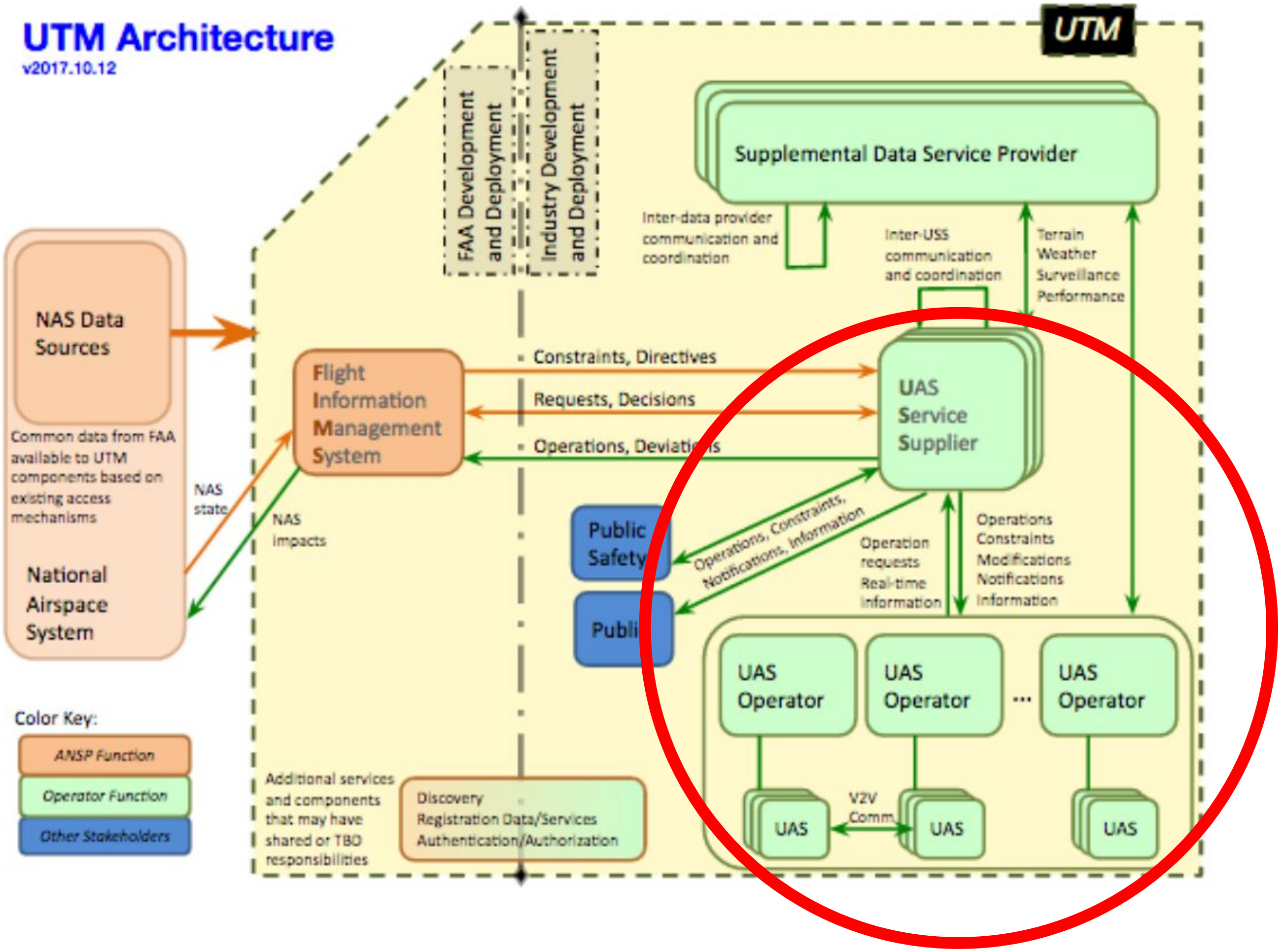
Data:
- **Schedules**
- **Contingencies**

Metrics:
- **Average Speed**
- **Average Delay**
- **Failed Schedules**



UAS Traffic Management

FAA-NASA Approach



USS-UAS

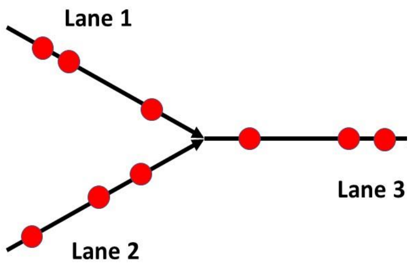
- Nominal behaviors
- Contingency behaviors

UTM: structure and rules of airways

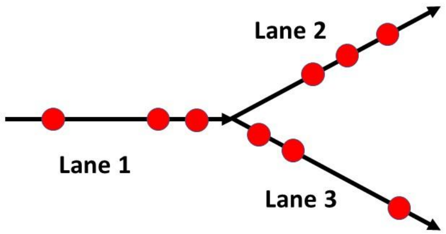
- Deconfliction rules
- Airway structure
- Contingency handling

UTM Structure & Policies

- Lanes
  - One-way
  - Linear (skeleton)
  - Virtual volume (e.g., circular tube along skeleton)
  - Speed constraints
  - Headway constraints
- Roundabouts
  - Defined at intersections
  - Basic units
    - 3-Merge
    - 3-Diverge



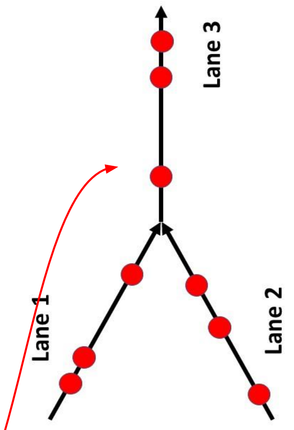
3-Merge



3-Diverge

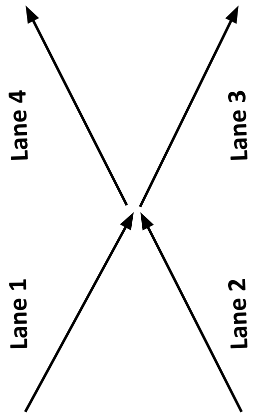
UTM Structure & Policies

- 3-Merge/Diverge v. Cross Conflict
  - SD Constraint: Trajectories must not violate headway (separation) distance



Expanded Constraints
Lane 3 is SD

Strategic bottleneck – can be designed to maintain correct separation

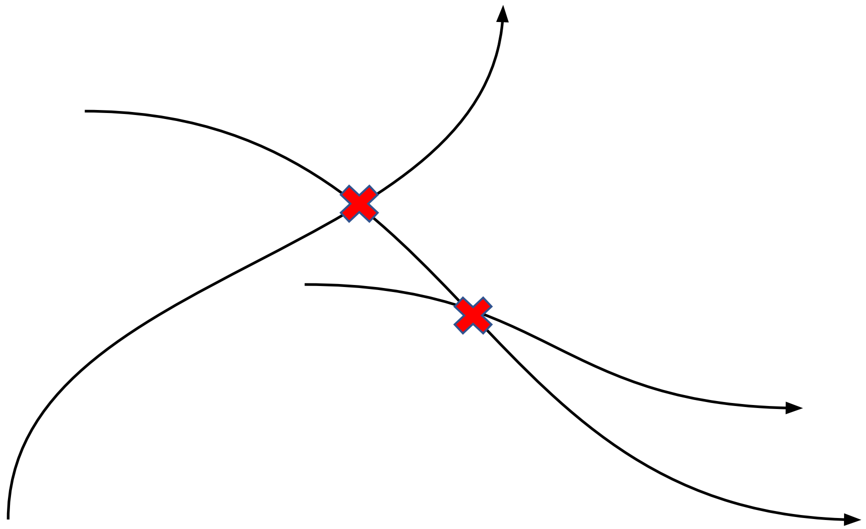


Expanded Constraints
Lane 3 is SD
Lane 4 is SD
Intersection is SD

Requires zone constraints to ensure separation at intersection

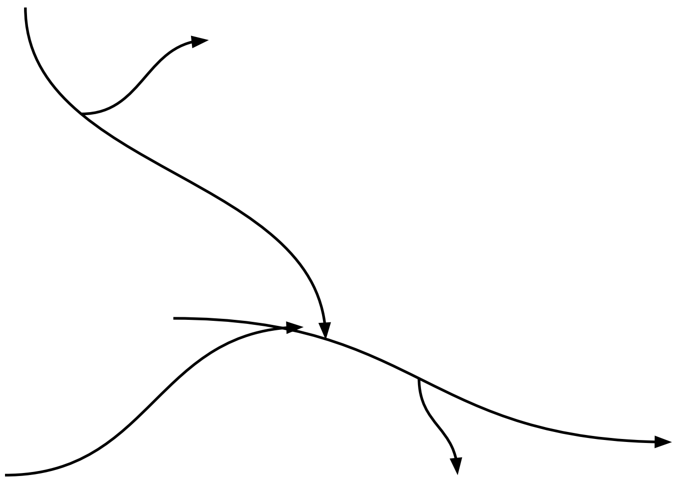
UTM Structure & Policies

- Lanes versus Free-Flight



Free-Flight

Each Aircraft Must Perform a Search in 4D Space



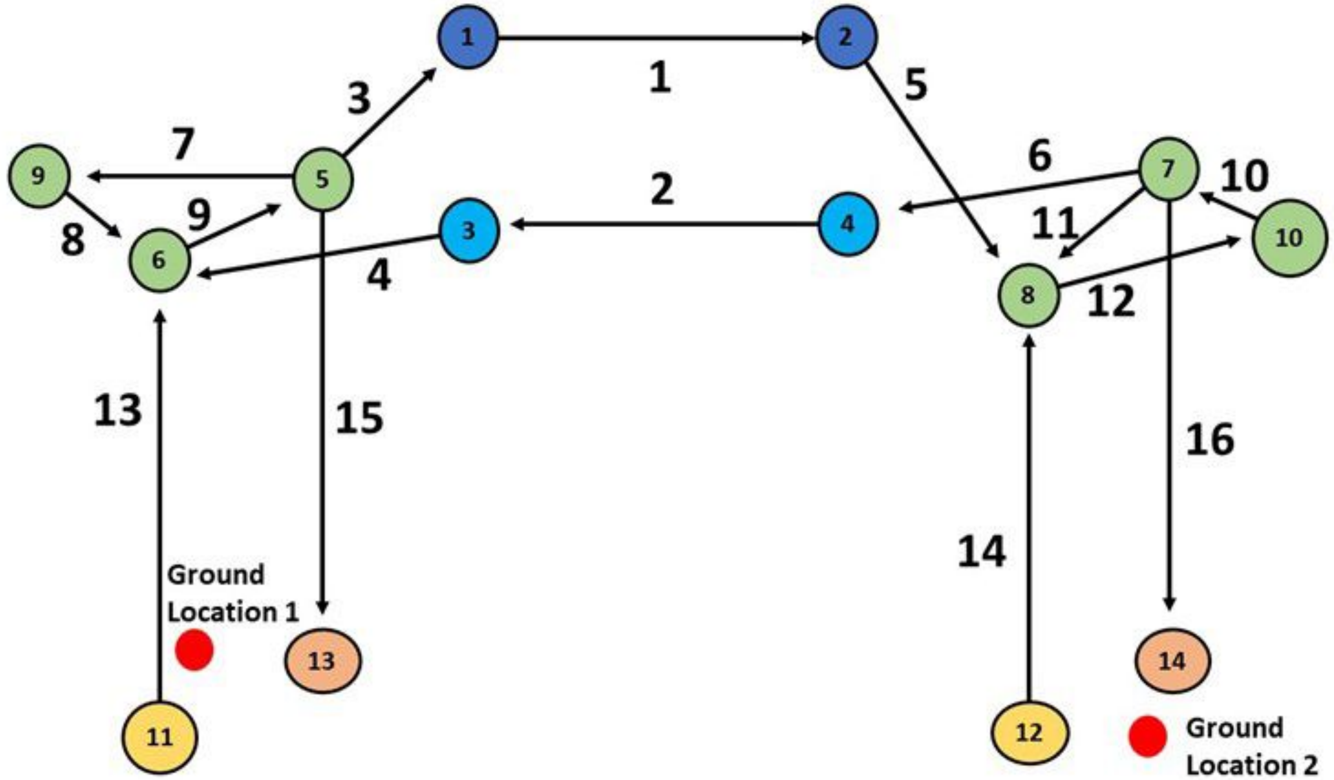
Lanes

Reusable Paths – Each aircraft only searches in 1D time

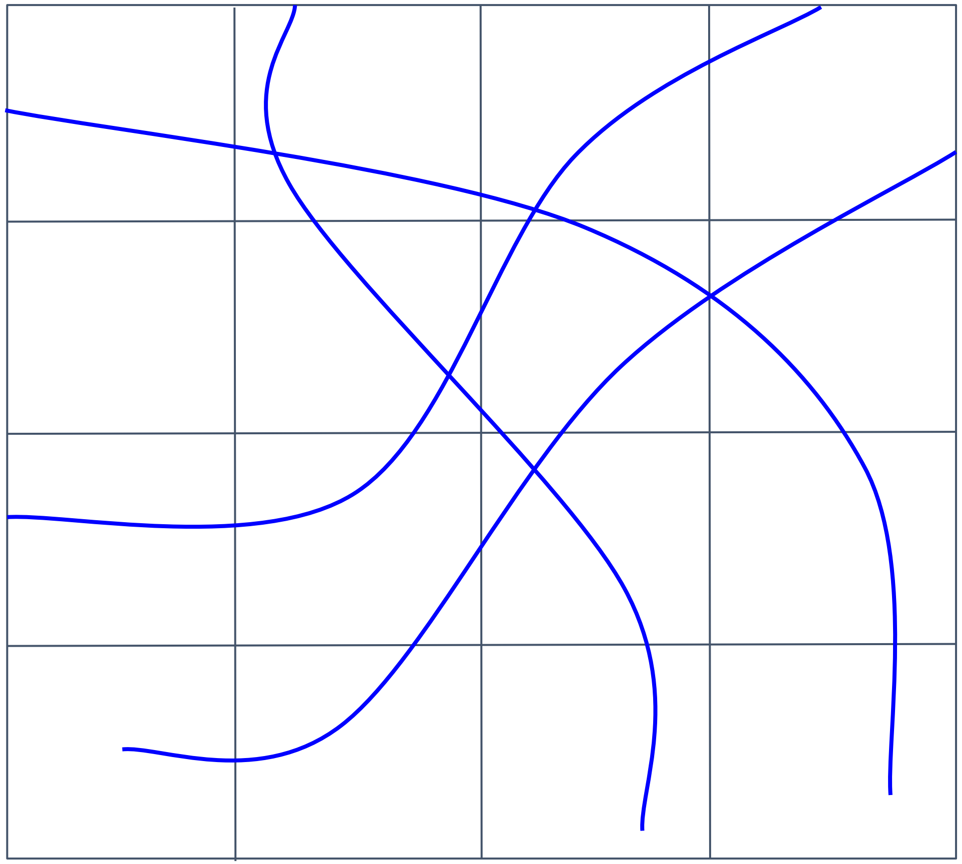
UTM Structure & Policies

- Emergency Protocols
- Contingency Handling
- Lane Creation/Deletion/Modification
- Flight Authorization
- Aircraft Certification
- Strategic Deconfliction

Lane-Based UTM

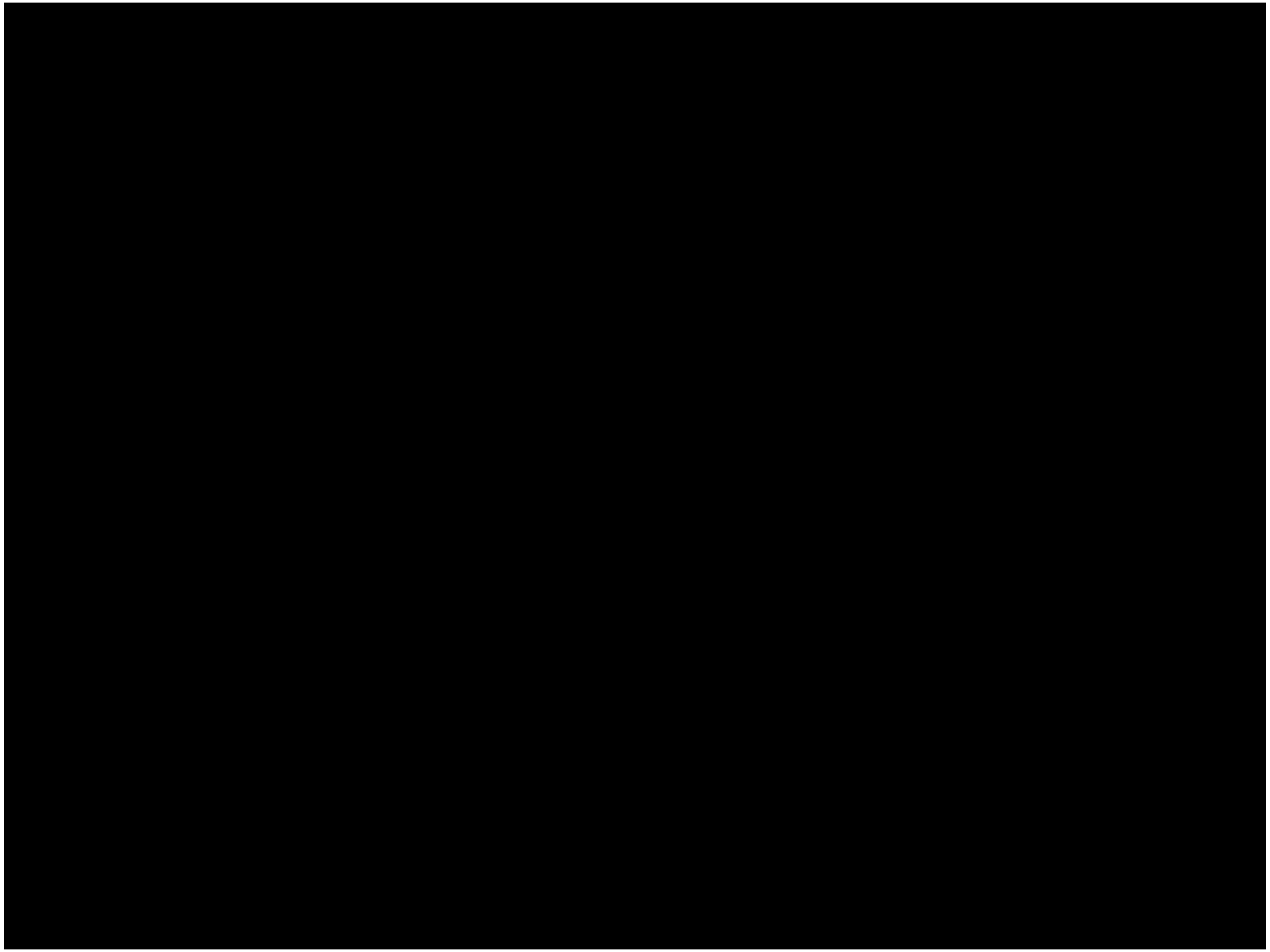


Proposed Lane System

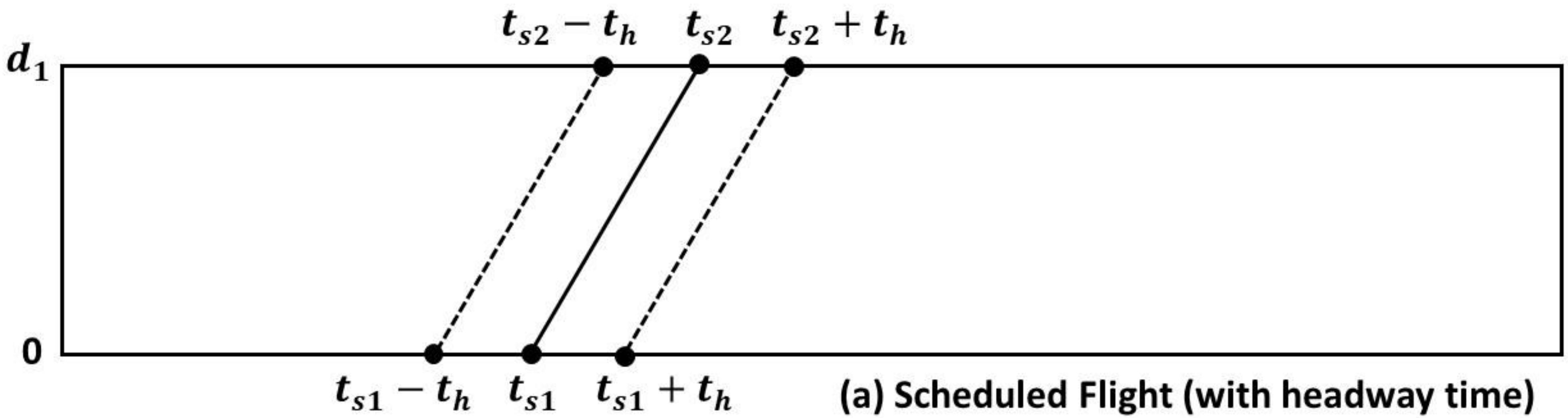


NASA-FAA Grid System

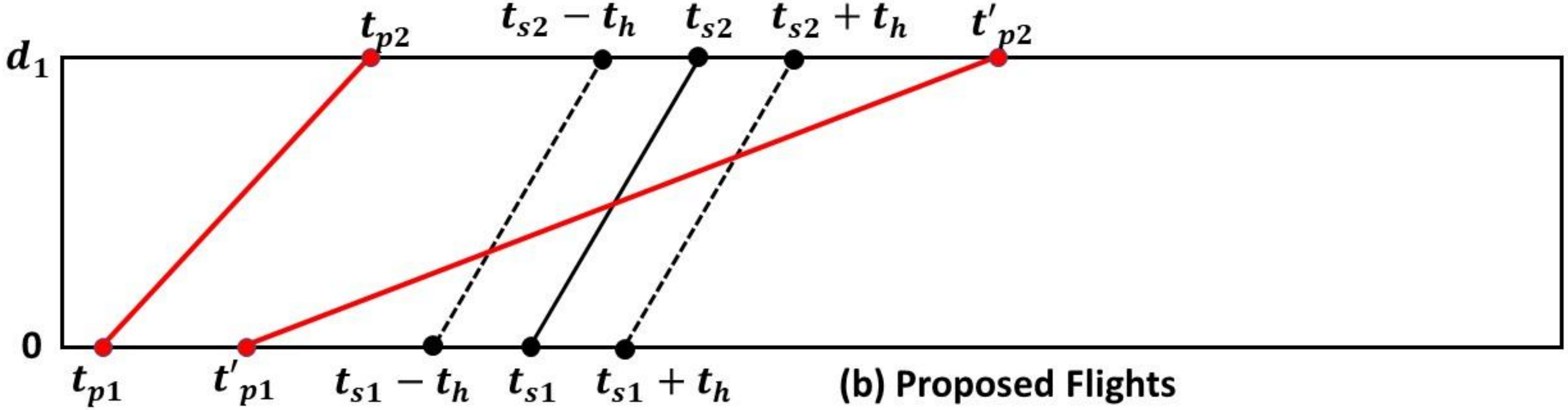
Lane Creation
e.g., SLC (above roads)



Strategic Deconfliction: Space-Time Lane Diagram

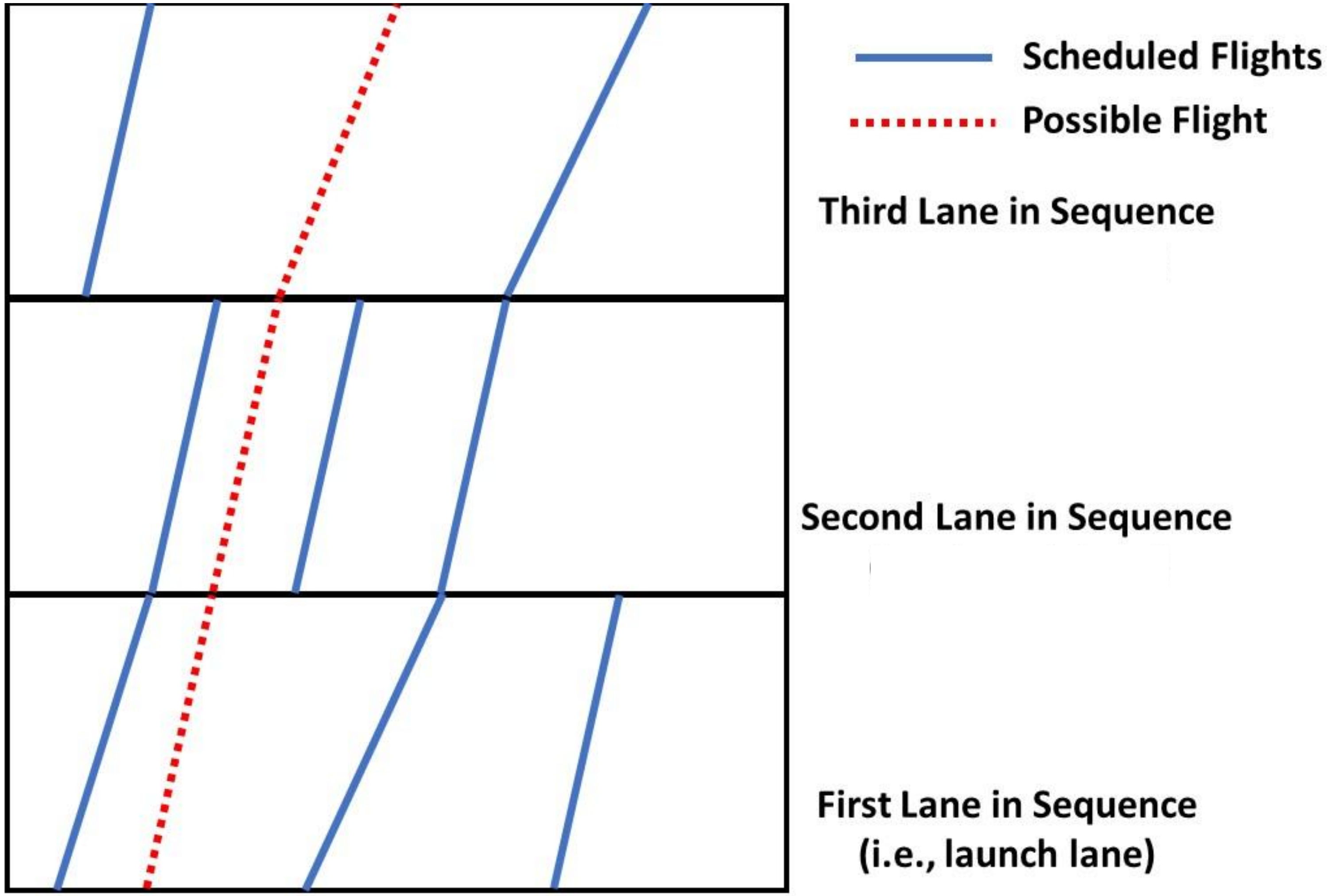


(a) Scheduled Flight (with headway time)

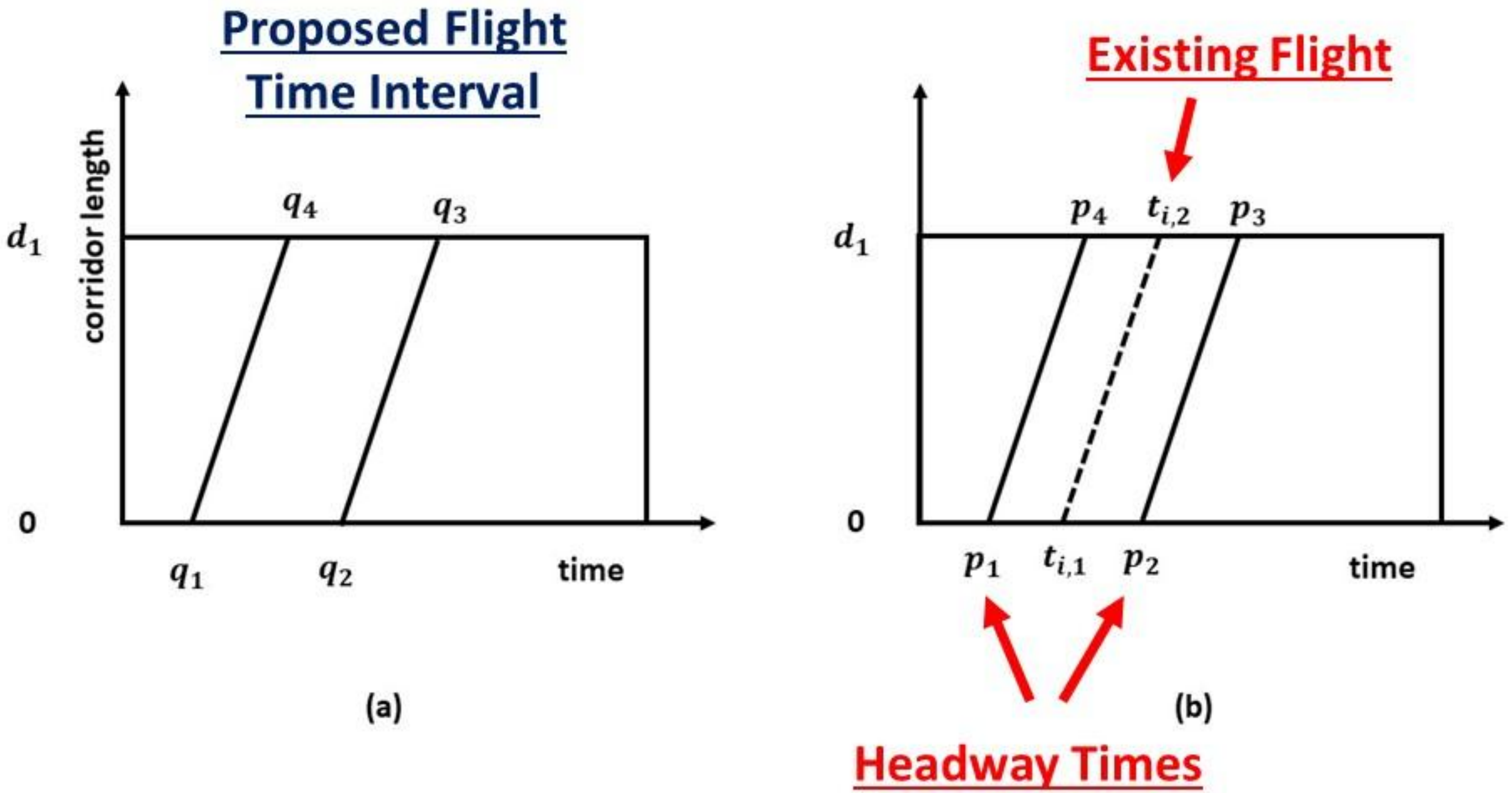


(b) Proposed Flights

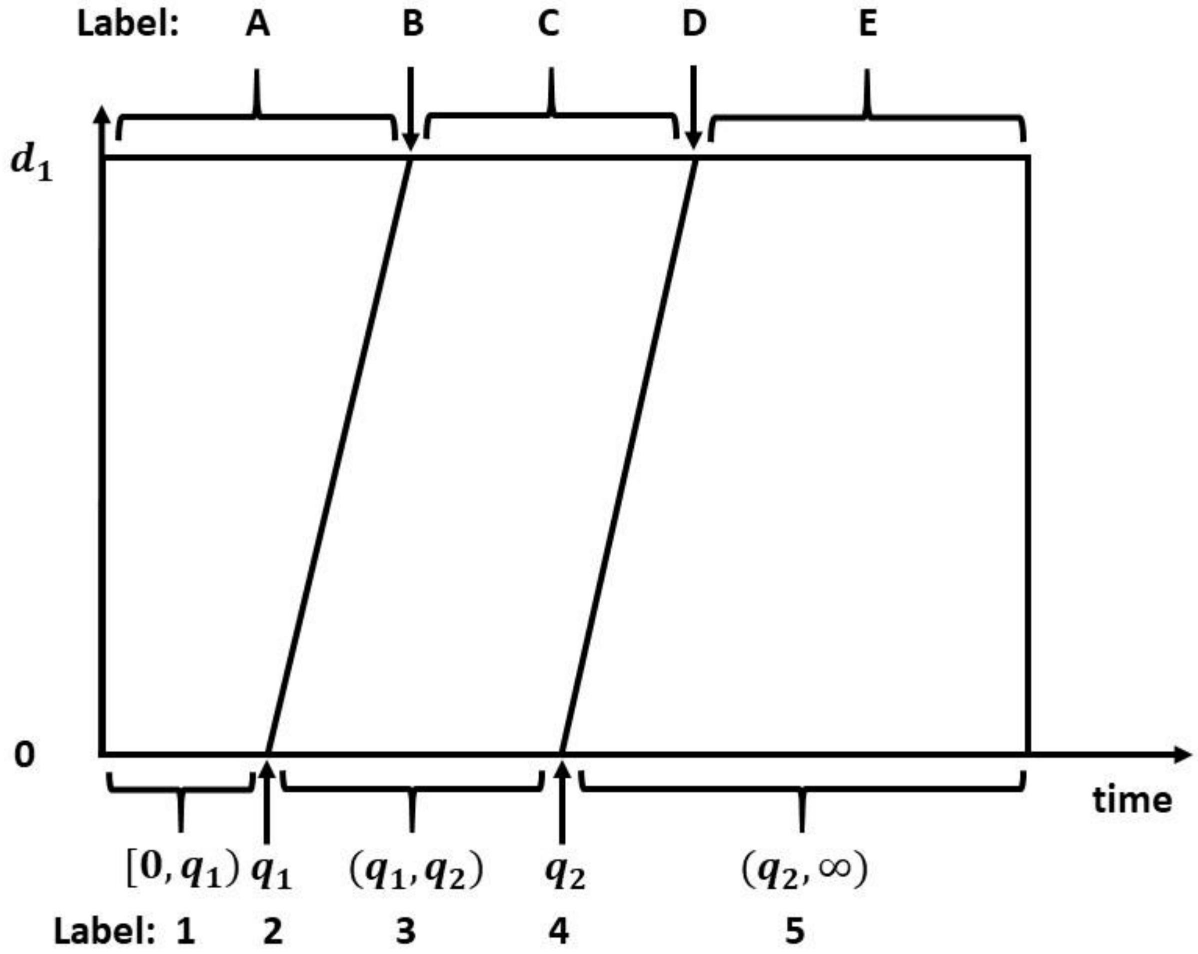
Lane-Based Reservation System



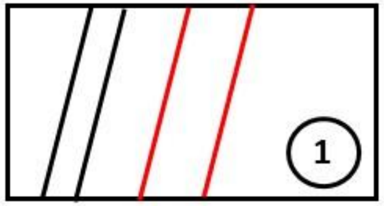
Space Time Lane Diagram



Strategic Deconfliction: Labels

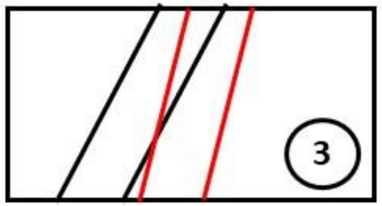


Examples



1A,1A
$[q_1, q_2]$

1A,1B
$[q_1, q_2]$



1A,1C
$[p_3 - ts, q_2]$

1A,1D
$[q_2, q_2]$

1A,1E
[ ]

1A,2A
$[q_1, q_2]$

1A,2B
$[q_1, q_2]$

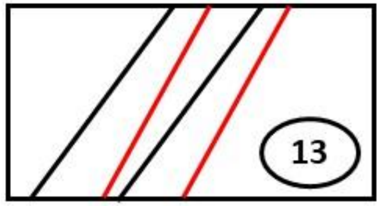
1A,2C
$[p_3 - ts, q_2]$

1A,2D
$[q_2, q_2]$

1A,2E
[ ]

1A,3A
$[p_2, q_2]$

1A,3B
$[p_2, q_2]$



1A,3C
$[p_3 - ts, q_2]$
s_s < s_r

1A,3C
$[p_2, q_2]$
s_s=s_r

1A,3C
$[p_2, q_2]$

TABLE II

ENUMERATION OF ALL POSSIBLE SCHEDULED FLIGHTS VS REQUESTED LAUNCH TIMES INTERACTIONS.

Labels	Intervals	*Labels*	*Intervals*	*Labels*	*Intervals*
1A,1A	$[q_1, q_2]$	1C,5E	$\emptyset$	3B,4C	$[q_1, q_1;$
				3B,4C	$q_2, q_2]$
1A,1B	$[q_1, q_2]$	1D,1E	$\emptyset$	3B,5C	$[q_1, q_1]$
1A,1C	$[p_3 - t_s, q_2]$	1D,2E	$\emptyset$	3B,5D	$[q_1, q_1]$
1A,1D	$[q_2, q_2]$	1D,3E	$\emptyset$	3B,5E	$[q_1, q_1]$
1A,1E	$\emptyset$	1D,4E	$\emptyset$	3C,3C	$[q_1, p_1, <;$
				3C,3C	$p_3 - t_s, q_2, <]$
				3C,3C	$[q_1, p_1, =;$
				3C,3C	$p_2, q_2, =]$
				3C,3C	$[q_1, p_4 - t_s, >;$
				3C,3C	$p_2, q_2, >]$
1A,2A	$[q_1, q_2]$	1D,5E	$\emptyset$	3C,3D	$[q_1, p_1;$
				3C,3D	$q_2, q_2]$
1A,2B	$[q_1, q_2]$	1E,1E	$\emptyset$	3C,3E	$[q_1, p_1]$
1A,2C	$[p_3 - t_s, q_2]$	1E,2E	$\emptyset$	3C,4C	$[p_1, p_4 - t_s;$
				3C,4C	$q_2, q_2]$
1A,2D	$[q_2, q_2]$	1E,3E	$\emptyset$	3C,4D	$[q_1, p_1;$
				3C,4D	$q_2, q_2]$
1A,2E	$\emptyset$	1E,4E	$\emptyset$	3C,4E	$[q_1, p_1]$
1A,3A	$[p_2, q_2]$	1E,5E	$\emptyset$	3C,5C	$[q_1, p_4 - t_s]$
1A,3B	$[p_2, q_2]$	2A,3A	$[p_2, q_2]$	3C,5D	$[q_1, p_4 - t_s]$
1A,3C	$[p_3 - t_s, q_2, <$	2A,3B	$[p_2, q_2]$	3C,5E	$[q_1, p_1, \leq;$
1A,3C	$[p_2, q_2, \geq]$			3C,5E	$q_1, p_4 - t_s, >];$
1A,3D	$[q_2, q_2]$	2A,3C	$[p_2, q_2]$	3D,3E	$[q_1, p_1]$
1A,3E	$\emptyset$	2A,4A	$[q_2, q_2]$	3D,4E	$[q_1, p_1]$
1A,4A	$[q_2, q_2]$	2A,4B	$[q_2, q_2]$	3D,5E	$[q_1, p_1]$
1A,4B	$[q_2, q_2]$	2A,4C	$[q_2, q_2]$	3E,3E	$[q_1, p_1]$
1A,4C	$[q_2, q_2]$	2A,5A	$\emptyset$	3E,4E	$[q_1, p_1]$
1A,4D	$[q_2, q_2]$	2A,5B	$\emptyset$	3E,5E	$[q_1, p_1]$
1A,4E	$\emptyset$	2A,5C	$\emptyset$	4A,5A	$\emptyset$
1A,5A	$\emptyset$	2A,5D	$\emptyset$	4A,5B	$\emptyset$
1A,5B	$\emptyset$	2A,5E	$\emptyset$	4A,5C	$\emptyset$
1A,5C	$\emptyset$	2B,3C	$[p_1, q1;$	4A,5D	$\emptyset$
		2B,3C	$p_2, q_2]$		
1A,5D	$\emptyset$	2B,4D	$[p_1, q_1;$	4A,5E	$\emptyset$
		2B,4D	$q_2, q_2]$		
1A,5E	$\emptyset$	2B,5E	$[p_1, q_1]$	4B,5C	$[q_1, q_1]$
1B,1C	$[p_3 - t_s, q_2]$	2C,3C	$[p_1, q_1;$	4B,5D	$[q_1, q_1]$
		2C,3C	$p_3 - t_s, q_2]$		
1B,1D	$[q_2, q_2]$	2C,3D	$[p_1, q_1;$	4B,5E	$[q_1, q_1]$
		2C,3D	$q_2, q_2]$		
1B,1E	$\emptyset$	2C,3E	$[p_1, q_1]$	4C,5C	$[q_1, p_4 - t_s]$
1B,2C	$[p_3 - t_s, q_2]$	2C,4E	$[p_1, q_1]$	4C,5D	$[q_1, p_4 - t_s]$
1B,2D	$[q_2, q_2]$	2C,5E	$[p_1, q_1]$	4C,5E	$[q_1, p_4 - t_s]$
1B,2E	$\emptyset$	2D,3E	$[p_1, q_1]$	4D,5E	$[q_1, q_2]$
1B,3C	$[p_3 - t_s, q_2]$	2D,4E	$[p_1, q_1]$	4E,5E	$[q_1, q_2]$
1B,3D	$[q_2, q_2]$	2D,5E	$[p_1, q_1]$	5A,5A	$\emptyset$
1B,3E	$\emptyset$	2E,3E	$[p_1, q_1]$	5A,5B	$\emptyset$
1B,4E	$\emptyset$	2E,4E	$[p_1, q_1]$	5A,5C	$\emptyset$
1B,5E	$\emptyset$	2E,5E	$[p_1, q_1]$	5A,5D	$\emptyset$
1C,1C	$[p_3 - t_s, q_2]$	3A,3A	$[p_2, q_2]$	5A,5E	$\emptyset$
1C,1D	$[q_2, q_2]$	3A,3B	$[p_2, q_2]$	5B,5C	$[q_1, q_1]$
1C,1E	$\emptyset$	3A,3C	$[p_2, q_2]$	5B,5D	$[q_1, q_1]$
1C,2C	$[p_3 - t_s, q_2]$	3A,4A	$[q_2, q_2]$	5B,5E	$[q_1, q_1]$
1C,2D	$[q_2, q_2]$	3A,4B	$[q_2, q_2]$	5C,5C	$[q_1, p_4 - t_s]$
1C,2E	$\emptyset$	3A,4C	$[q_2, q_2]$	5C,5D	$[q_1, p_4 - t_s]$
1C,3C	$[p_3 - t_s, q_2]$	3A,5A	$\emptyset$	5C,5E	$[q_1, p_4 - t_s]$
1C,3D	$[q_2, q_2]$	3A,5B	$\emptyset$	5D,5E	$[q_1, q_2]$
1C,3E	$\emptyset$	3A,5C	$\emptyset$	5E,5E	$[q_1, q_2]$
1C,4E	$\emptyset$	3B,3C	$[q_1, q_1;$		
		3B,3C	$p_2, q_2]$		

This is a complete table of all possible proposed flight versus scheduled flights with resulting intervals.

Algorithm SD

Computational Complexity:
(in terms of interval operator, I)

$$\# \text{ of I ops} \leq \sum_{k=1}^{n} f_k + \sum_{i \neq j} f_i f_j$$

Big O: O(f^2 ***)***
where $f = \sum_{k=1}^{n} f_k$

Algorithm SD (Strategic Deconfliction)
On input:
lanes: lane sequence for requested flight
$[q_1, q_2]$: requested launch interval
n_c: number of lanes
flights: flights per lane
h_t: maximum required headway time
On output:
Safe time intervals to launch
begin
possible_intervals ← $[q_1, q_2]$
for each lane $c \in$ lanes
time_offset ← time to get to lane c
possible_intervals ← possible_intervals + time_offset
for each flight, f, in lane c
new_intervals ← $\emptyset$
for each interval in possible_intervals
$[t_1, t_2]$ ← interval i
label ← get_label($t_{f,1}, t_{f,2}, s_f, t_1, t_2, s, h_t$)
f_int ← get_interval(label,$t_{f,1}, t_{f,2}, s_f, t_1, t_2, s, h_t$)
new_intervals ← merge(new_intervals,f_int)
end
end
possible_intervals ← new_intervals
end
possible_intervals ← possible_intervals - time to last lane

Beyond SD: Contingencies!

If every UAS follows its nominal flight plan:

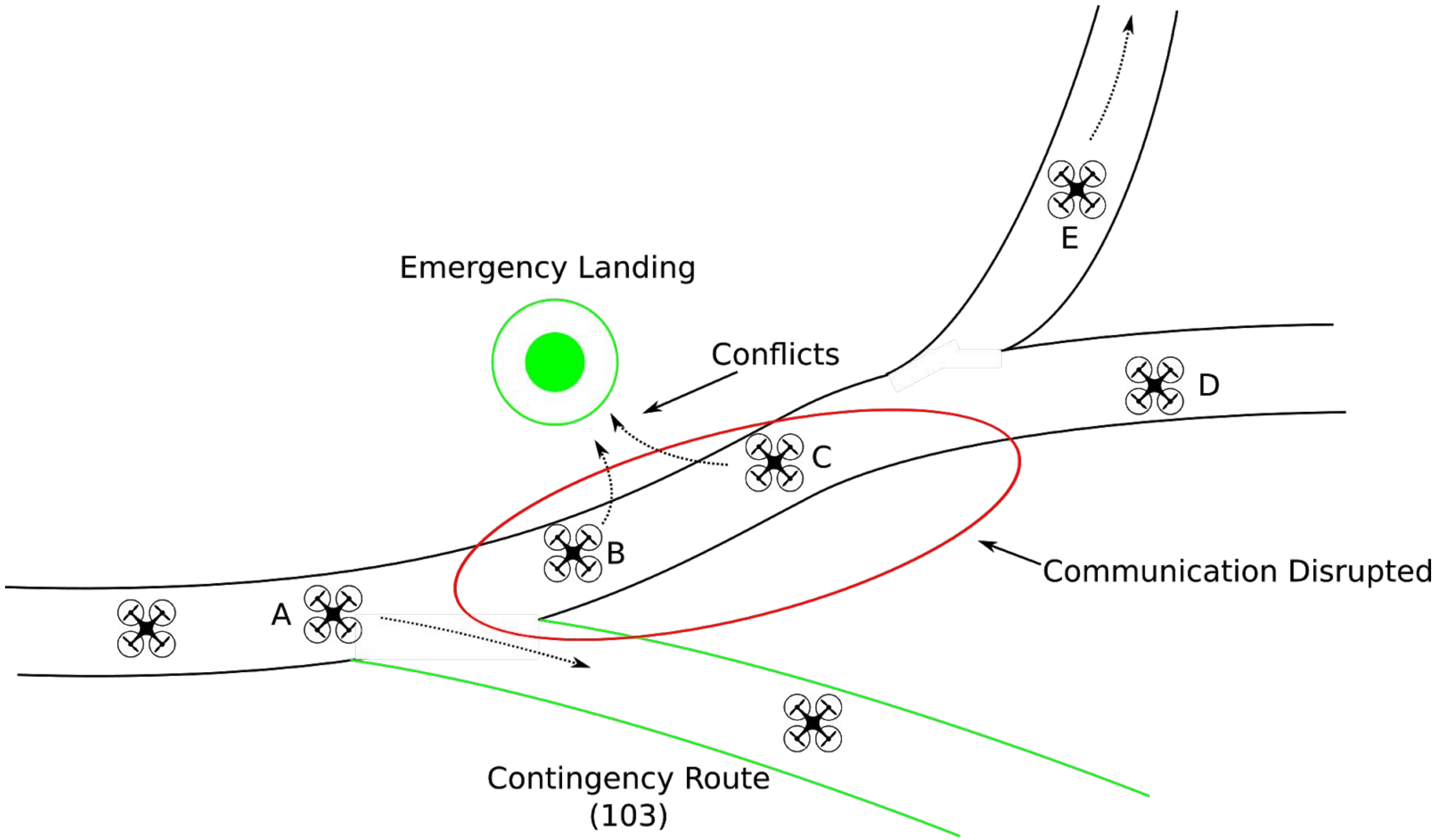
➔ there are no problems!

But, there are contingencies:

"something that might possibly happen in the future, usually causing problems or making further plans and arrangements necessary"
(Cambridge Dictionary)

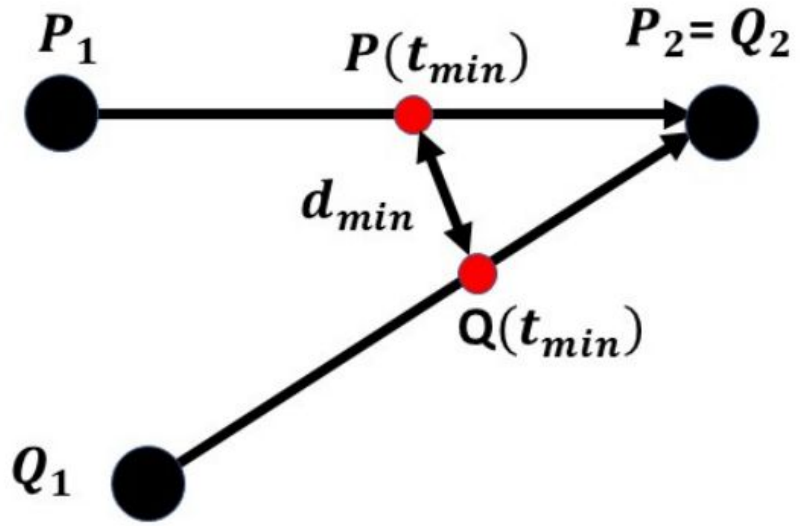
Example - Communication Outage

Lanes give us the ability to deal with contingencies in a deterministic way



Real-Time Tactical Deconfliction (UAS Behavior)

- Uses the Closest Point of Approach (CPA) method
- “In-between” strategic deconfliction and sensor-based methods



If a flight, f_1, has a conflict with flight f_2, then the two flights can be deconflicted as follows:

Deconflict_Pair

while conflict(f_1,f_2)
  reduce speed, s_1, of f_1
  if $s_1 < s_{min}$
  then flight f_1 fails

This allows the definition of the Closest Point of Approach Deconfliction (CPAD) algorithm:

Algorithm 1: Closest Point of Approach

∀ active flight, f
if f enters a new lane
  OR a neighboring flight has slowed
  OR f has reduced speed on its own
then call Deconflict_Pair for all flights in neighboring lanes
if f has reduced speed
then f broadcasts this information.

Real-Time Tactical Deconfliction (UAS Behavior)

- Uses the Closest Point of Approach (CPA) method
- "In-between" strategic deconfliction and sensor-based methods

- **Communications are not required**
- **The Lane Based network enables efficient storage of local lane maps**
- **Sensors provide a fallback option and a second opinion on the state of the system**
- **More options to handle nefarious contingencies**

If a flight, f_1, has a conflict with flight f_2, then the two flights can be deconflicted as follows:

Deconflict_Pair

while conflict(f_1,f_2)
    reduce speed, s_1, of f_1
    if $s_1 < s_{min}$
    then flight f_1 fails

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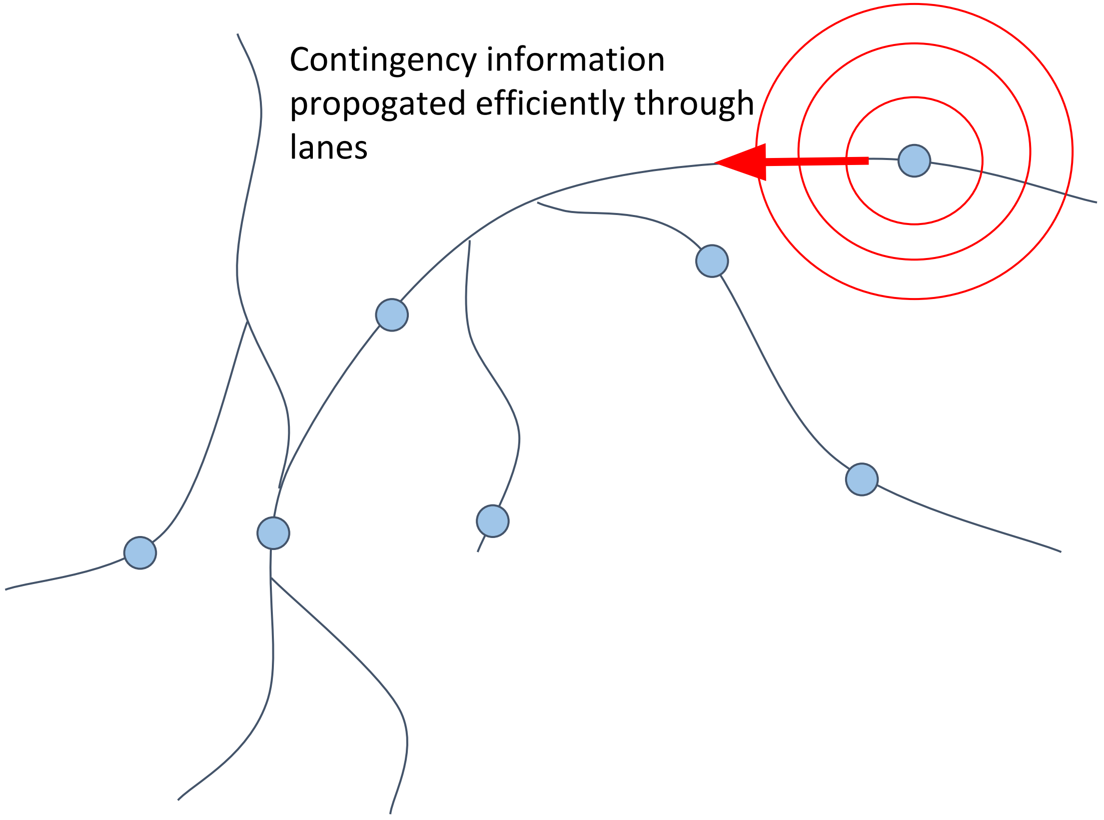
Algorithm 1: Closest Point of Approach

```
∀ active flight, f
if f enters a new lane
        OR a neighboring flight has slowed
        OR f has reduced speed on its own
then call Deconflict_Pair for all flights in neighboring lanes
if f has reduced speed
then f broadcasts this information.
```

Approximate Global Deconfliction

- Global deconfliction achieved by each UAS running the CPAD algorithm
- Limited data exhanged between vehicles
- Violations of safe separation only possible in certain contingency scenarios like communication issues
  - Agents can fallback to sensor based tactical deconfliction
  - Contingency information propagates throughout network in affected lanes



Experiments - Discrete Event Simulation

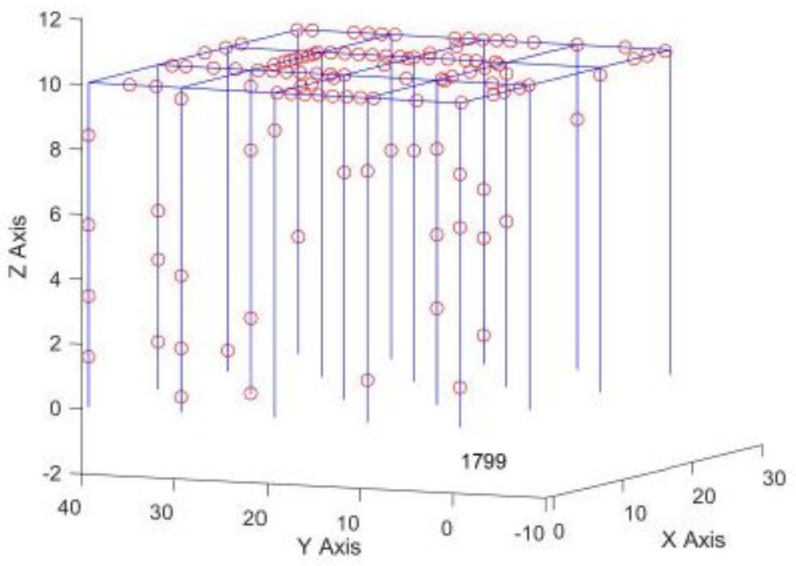


Fig. 1: Set of UAS on Airways during Discrete Event Simulation. Red dots represent UAS in Flight; blue lanes are launch lanes.

- Simulation Parameters:
  - tmax - simulation time
  - nf - number of flights
  - smax - maximum speed allowed
- Simulation process
  - Each new flight selects a sequence of lanes
  - Event triggered by time-of-arrival for each lane
  - Flights advanced in position and speed
- Performance Metrics
  - Total delay (in simulation units)
  - Average Speed
  - Failures to schedule (due to safe-separation constraint)

Simulation Results

Table 1: Delays and Failures in Experimental Simulations

t_{max}	n_f	s_{max}	Wait	Fly	Done	Fail	Avg Speed	Delays
100	100	5	1	18	81	0	4.98	2
			2	12	86	0	4.98	2
			0	15	85	0	4.99	1
			0	11	89	0	4.98	2
			1	18	81	0	4.96	4
means			0.8	14.8	84.4	0	4.98	2.2
100	100	9	0	11	89	0	8.98	1
			1	8	91	0	8.94	2
			0	12	88	0	8.99	0
			0	6	94	0	8.99	0
			0	11	88	1	8.98	0
means			0.2	9.6	90	0.2	8.98	0.6
200	200	5	0	14	186	0	4.96	6
			0	11	189	0	4.97	8
			0	17	183	0	4.98	6
			1	13	186	0	4.99	10
			0	6	194	0	4.96	9
means			0.2	12.2	187.6	0	4.97	8.6
200	200	9	0	7	193	0	8.96	4
			1	6	193	0	8.97	2
			0	8	192	0	8.97	4
			0	7	193	0	8.98	3
			0	4	196	0	8.97	2
means			0.2	6.4	193.4	0	8.97	3

- Two aspects simulated:
  - tmax:{100,200}, smax:{5,9}
  - nf chosen to launch approximately one flight per minute on average
- Five runs of simulation for each parameter
- Only one flight failed to schedule due to separation constraints
- Average speed near max indicates efficient absorption of contingent events (new flights entering the network)

Contributions

- DDDAS Paradigm for Unmanned Air Traffic Control
- Real-time conflict/contingency management protocol
- Lane-based model for airspace structure

Future Work

- Broader experiments that explore lane-configuration
- Sensitivity analysis
- Experiments with real vehicles in flight
- Characterize communication requirements for CPAD protocol