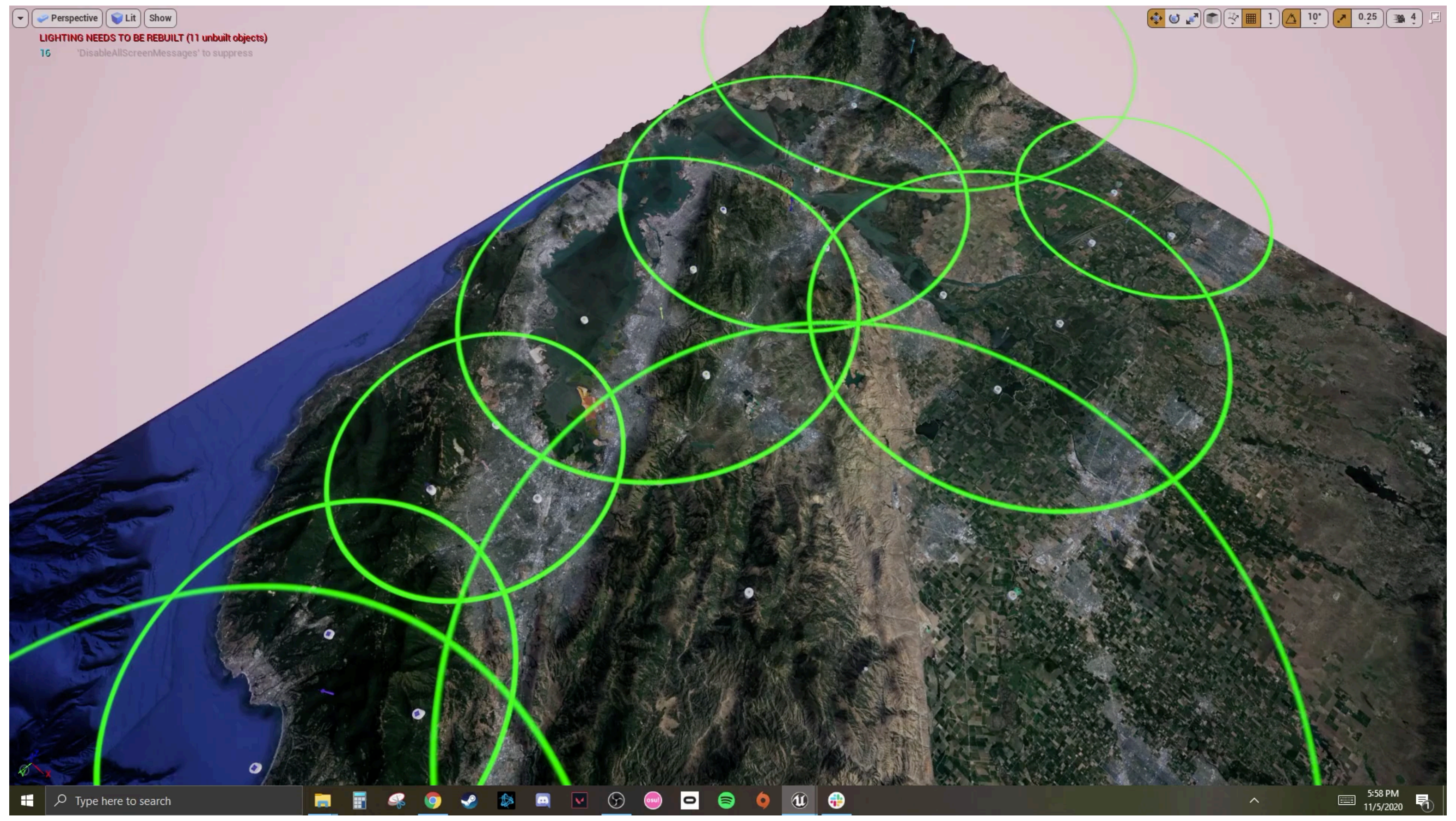
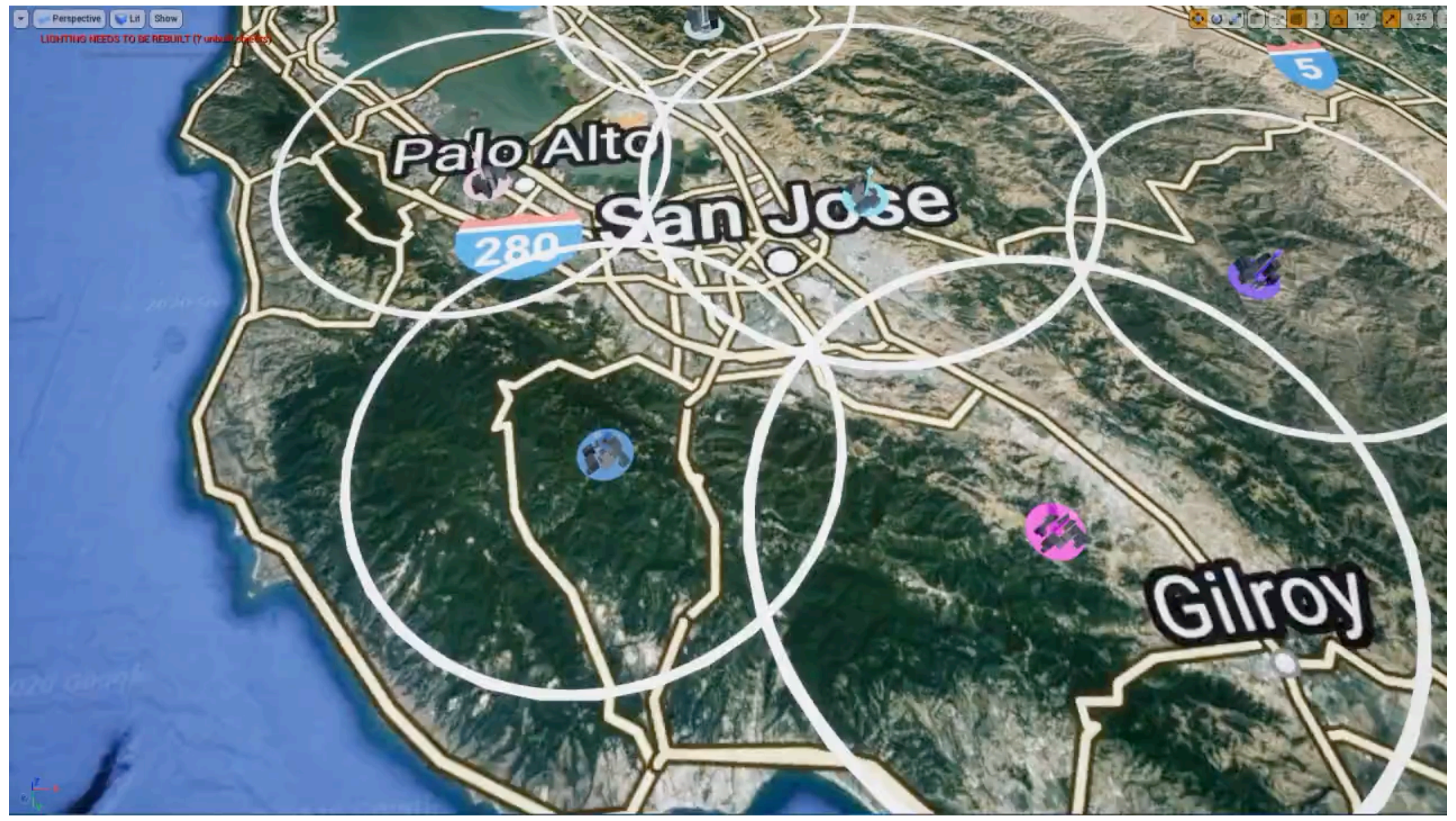
Verifiable Decentralized Traffic Management for UAM

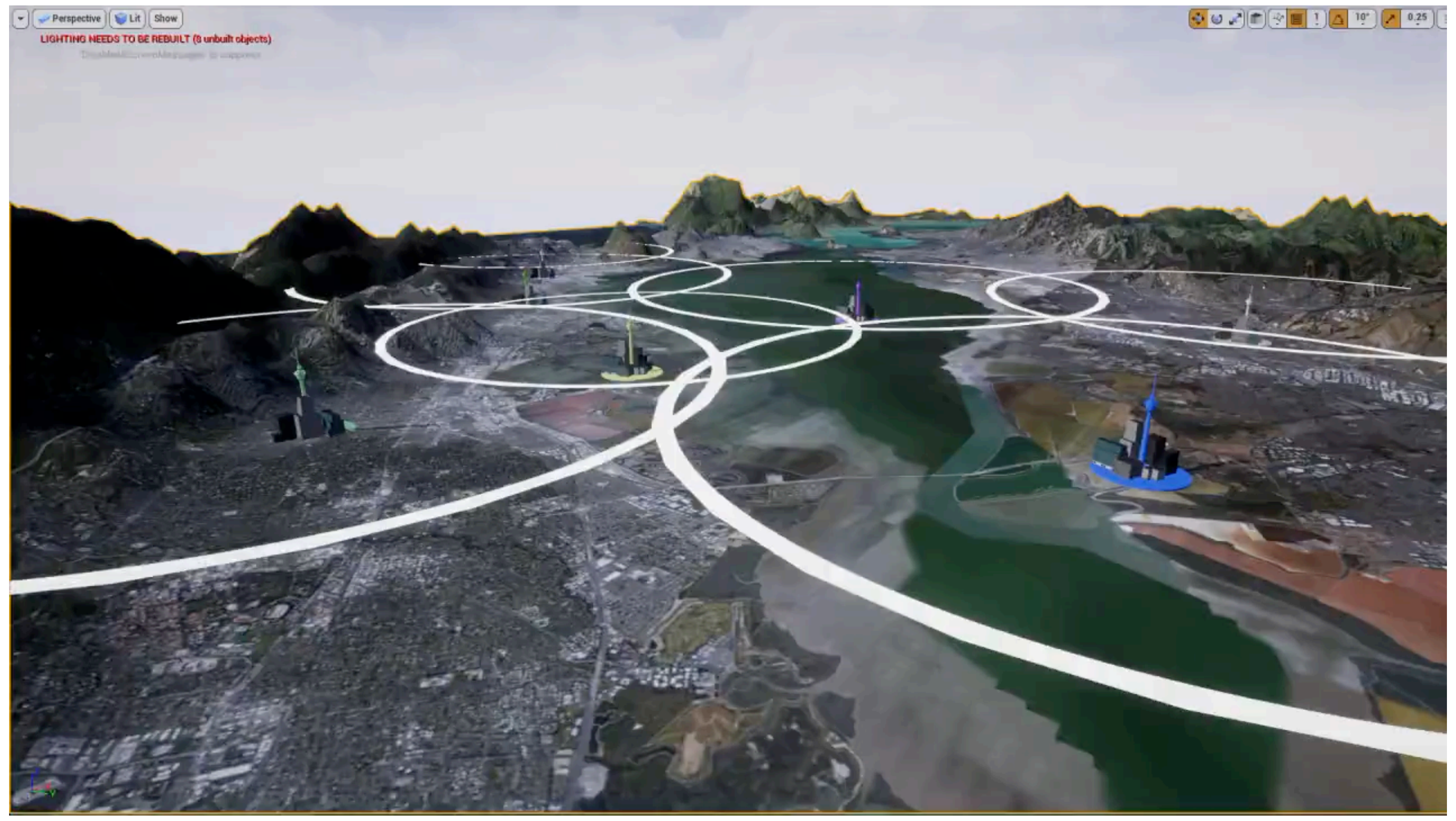
NASA ULI Kickoff

04 October 2021

Suda Bharadwaj

Overview



Approach:

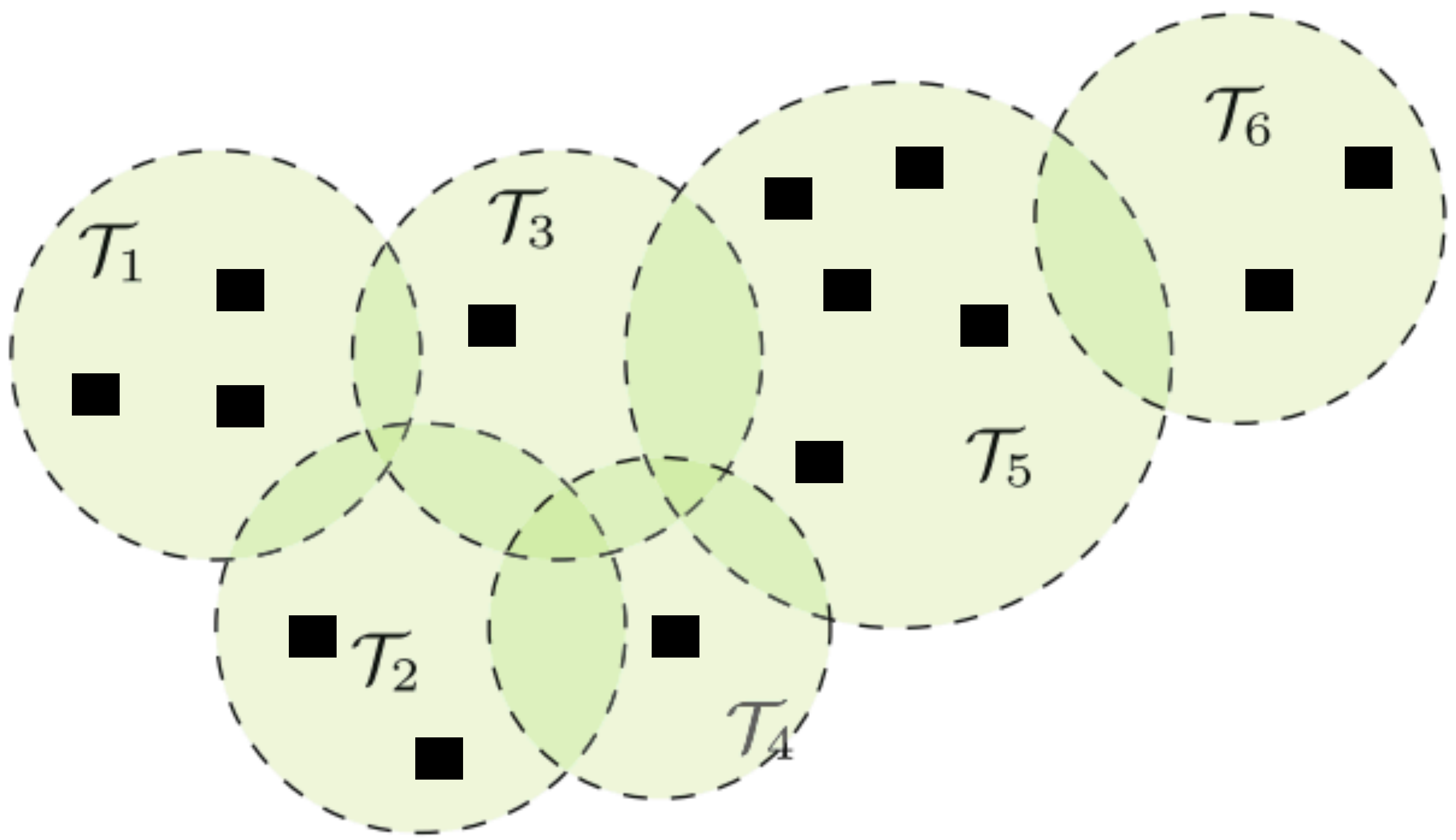
- Developed a decentralized and hierarchical architecture for UAM air traffic management.
- Represent requirements as temporal logic specifications
- Introduced a contract-based synthesis approach to extract strategies with correctness guarantees.

Key Idea #1

Hierarchical and decentralized ATM architecture

Why? Allows **scalability** and **separation of concerns**

- **Vertiport/Vertihub/Vehicle model**
  - *Vertiport controller:* Manage take/off and landing
  - *Vertihub controller:* Composed of vertiports and manages airspace
  - *Vehicle*: issues *requests* to vertiport and vertihub controllers
- **Requests**: $O = (r, T, c)$
  - $r \in \mathscr{R}$ is the request class - landing, take-off, pass-through,
  - $T \in \mathbb{N}$ is the amount of time left for request to be granted - analogue for fuel reserves
  - $c \in C$ class of vehicle



Key Idea #2

Formally represent precise requirements over requests

Why? Formal requirements are ***actionable*** *and* ***verifiable***

Natural language requirements

- Cap wait times on emergency vehicles.
- All requests must be eventually granted.
- Maximum number of vehicles allowed in airspace

Temporal logic

Formal language requirements

- $\square(\text{vehicle\_class} = \text{emergency}) \implies (\text{wait\_time} \leq \text{T})$
- $\square \Diamond \text{request}$
- $\square(|\text{vehicles}| \leq N)$

Key Idea #3

Contracts between controllers

Why? Enforce **coordination** amongst controllers

- Contracts between controllers help each other satisfy requirements.
    - “Vehicle will guarantee minimum separation of X between other vehicles if vertihub controller guarantees maximum number of vehicles less than N.”
    - Can represent using temporal logic.
    - Guarantee properties across the whole network with *decentralized synthesis.*

Main Results

- Theorem #1:
    - **Correctness**: if all satisfiable controllers exist, then global composition is guaranteed be **correct** with respect to all requirements.
- Theorem #2:
    - **Fairness**: all vehicles are guaranteed to **make progress** towards their goals.
- Theorem #3:
    - All vehicles are **minimally interfered** with by controllers.


Perspective
Lit
Show
LIGHTING NEEDS TO BE REBUILT (11 unbuilt objects)
16 'DisableAllScreenMessages' to suppress
10°
0.25
4
Type here to search
5:58 PM
11/5/2020


Shift+F1 for Mouse Cursor
LIGHTING NEEDS TO BE REBUILT (11 unbuilt objects)
15 'DisableAllScreenMessages' to suppress
Type here to search
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What if specifications are not satisfiable?

Minimum-violation planning

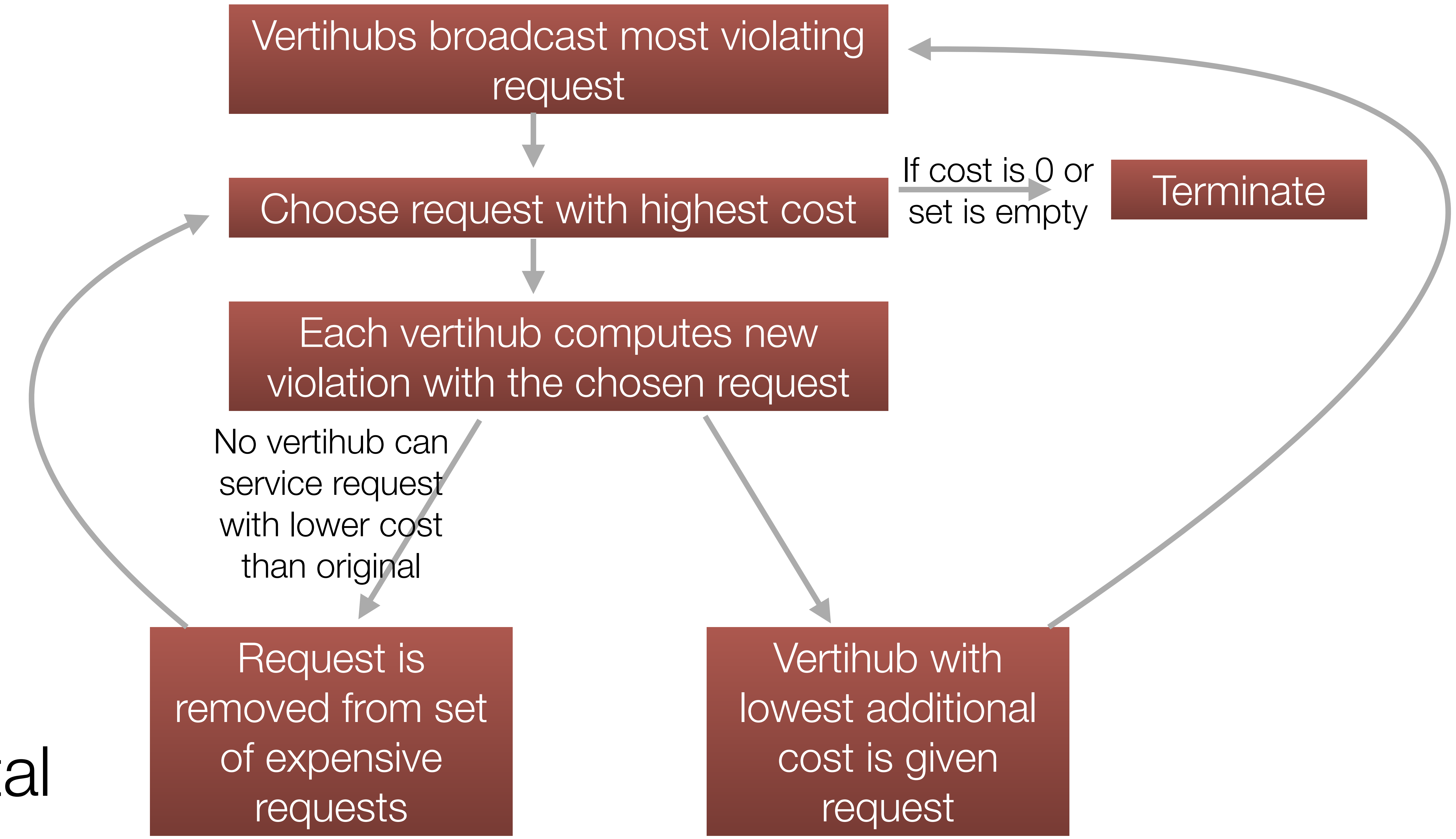
Why? Contingencies, poorly defined requirements etc.

- Prioritized safety specification: $\Psi = \{\Psi_1, \Psi_2\}$
    - $\Psi_1 = \{\psi_{1,1}\}$
    - $\Psi_2 = \{\psi_{2,1}, \psi_{2,2}, \psi_{2,3}\}$
- Priority function: $\overline{\varpi}$
- Accept requests to **minimize** prioritized violation cost.

How to decentralize the planning?

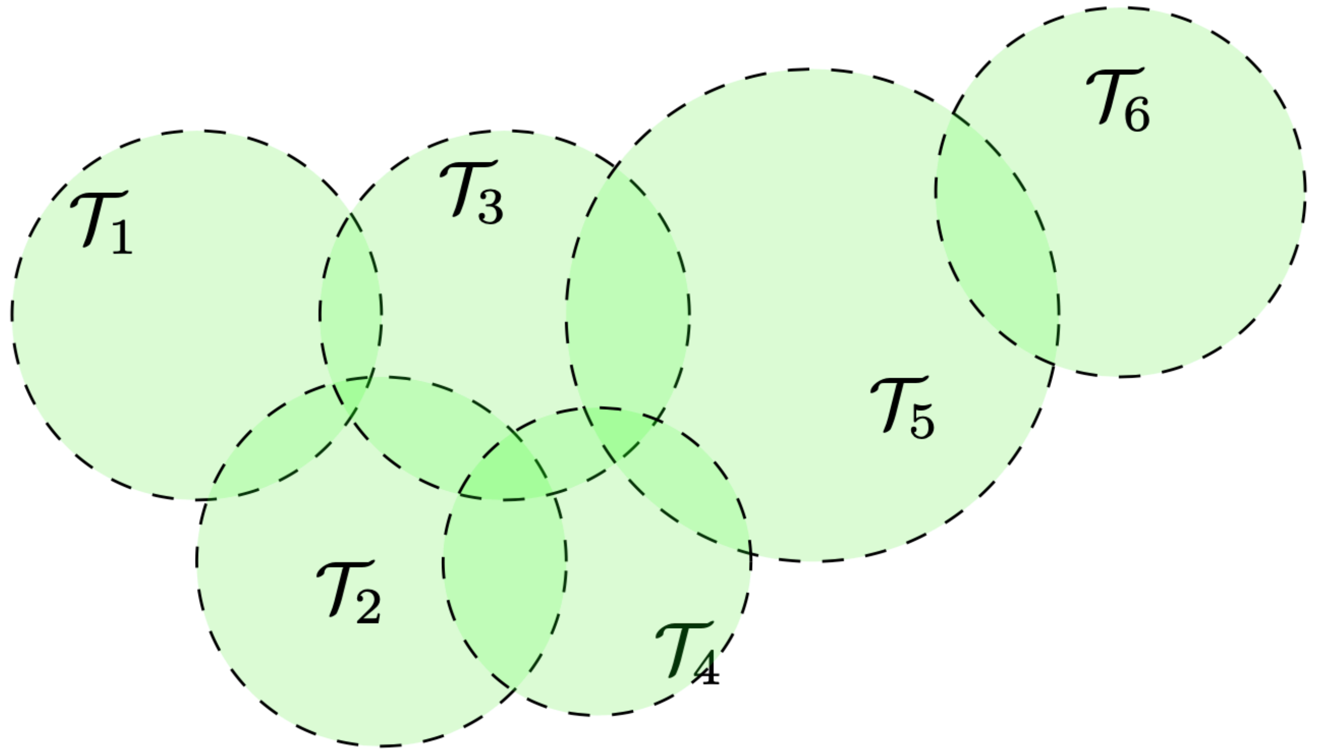
Why? For scalability

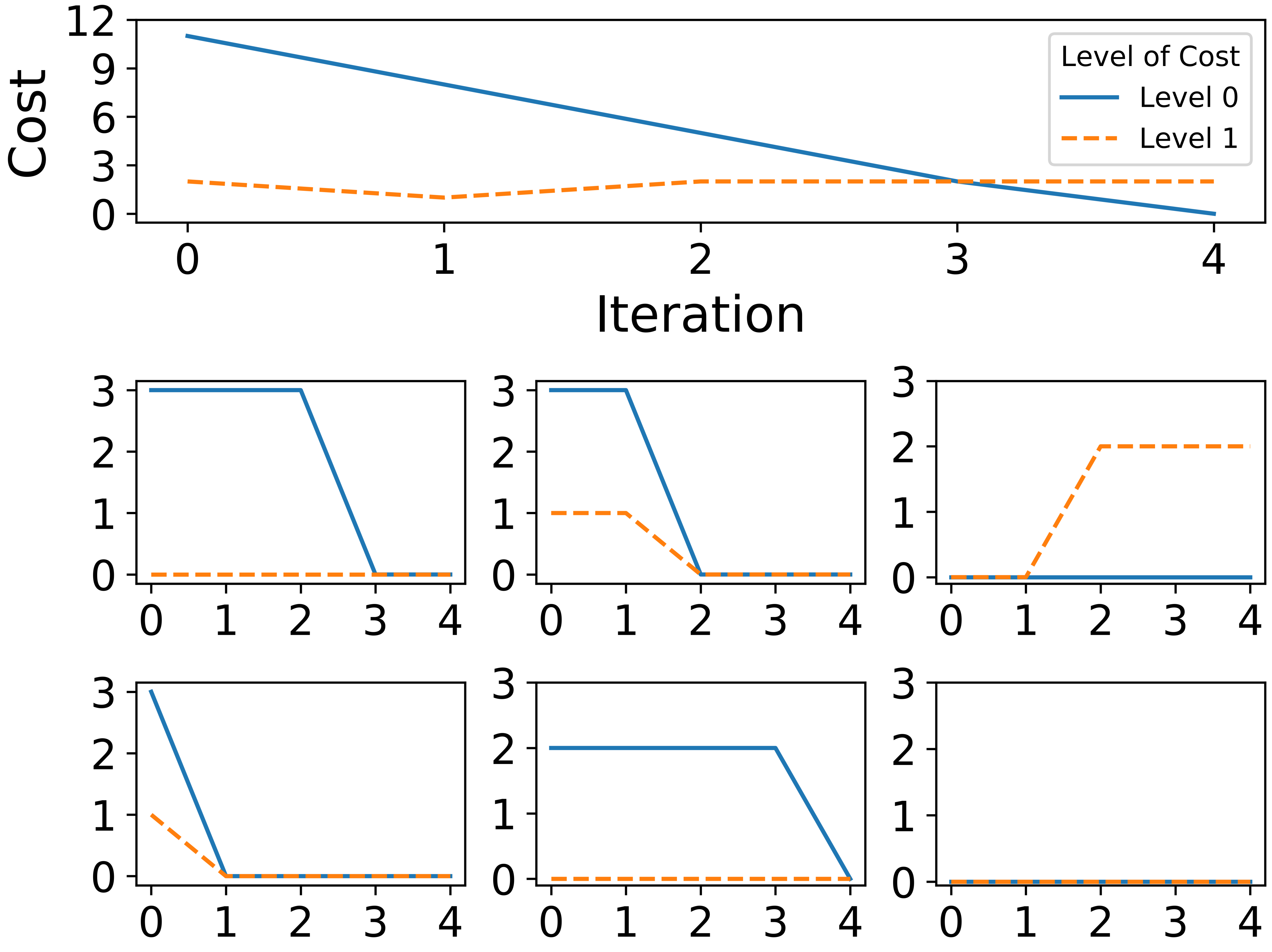
- Want to minimize the total unsafety across all vertihubs.
- We propose an iterative round-based approach.
- Main result:
    - Every iteration reduces the total violation cost of the global network.



Example results

- $\Psi_1 = \{\psi_{1,1}\}$
  - $\psi_{1,1}$ = Never allow request timer to expire
- $\Psi_2 = \{\psi_{2,1}, \psi_{2,2}, \psi_{2,3}\}$
  - $\psi_{2,1}$ = Do not land vehicles past vertiport's capacity
  - $\psi_{2,2}$ = Do not allow too many vehicles in the airspace
  - $\psi_{2,3}$ = Land vehicles at desired vertiport





Relevant Papers

Decentralized Control Synthesis for Air Traffic Management in Urban Air Mobility

Suda Bharadwaj, Steven Carr, Natasha Neogi and Ufuk Topcu

Abstract—Urban air mobility (UAM
tion services within an urban area,
fashion. We study air traffic managem
a UAM fleet, while guaranteeing systen
as traffic separation. Existing ATM me
systems such as UTM utilize alternativ
provide strict safety guarantees. No
exists for providing ATM at scale
decentralized, hierarchical approach f
for scalability to high traffic densit
theoretical guarantees of correctness wi
safety specifications. Our main contrib
we propose a novel UAM ATM archit
authority between *vertihubs* that are e
vehicles in their local airspace. Eac
a number of *vertiports* that are in
takeoffs and landings. The resulting ar
and hierarchical, which not only en
robustness in the event of any indivi
no longer being operational. Second, w
correct-by-construction reactive synthe
guarantees safety properties with resp
specifications in linear temporal lo
approach on large-volume UAM air t

Traffic Management for Urban Air Mobility

Suda Bharadwaj[1(✉)], Steven Carr[1], Natasha Neogi[2], Hasan Poonawala[3], Alejandro Barberia Chueca[1], and Ufuk Topcu[1]

[1] The Universit
{suda.
[2] NASA-Lan

[3] University

Abstract. Urban ai
portation services w
planning for vehicles
requirements such as

Online Synthesis for Runtime Enforcement of Safety in Multi-Agent Systems

Dhananjay Raju, Suda Bharadwaj, Ufuk Topcu, and Franck Djeumou

Abstract—We study the problem of enforcing safety in multi
agent systems at runtime by modifying the system behavio
if a potential safety violation is detected. Traditional runtim
enforcement methods that solve a reactive synthesis problen
at design time have two significant drawbacks. Firstly, thes
techniques do not scale as one has to take into account al
possible behaviors from every agent, and this is computationall
prohibitive. Second, these approaches require every agent t
know the state of every other agent. We address these limitation
through a new approach where online modifications to behavio
are synthesized onboard every agent. There is an *enforce*
onboard every agent, which can modify the behavior of onl

Minimum-Violation Traffic Management for Urban Air Mobility

Suda Bharadwaj[1(✉)], Tichakorn Wongpiromsarn[2], Natasha Neogi[3], Joseph Muffoletto[1], and Ufuk Topcu[1]

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Future directions

- Integrate learning-based methods:
  - Parameterize specifications and utilize learning-based methods to optimize contracts between controllers.
  - Observe delay times for more optimal route-planning for vehicles.
- Planning under **intermittent communication**