Resilient UAVs Traffic Operation Using Fluid Queueing Models

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Background and Motivation

- **Background**
  - Increasing amount of activities of UAVs in the civil aviation domain.
    - Over one million UAVs have been registered.
    - 7 million UAVs will be registered as estimated and 2 million for commercial use.
  - Large companies have initiated projects on UAVs delivery and transportation service.
    - Amazon: Prime Air
    - Uber: Uber Elevate
Motivations

Motivation

- Recent transportation research has been focused on UAVs assisted traffic, but UAVs themselves can cause traffic congestions with increasing volume.
- UAVs are sensitive to weather uncertainty. Congestion control under weather uncertainty brings more challenges.
- Models that capture the characteristics of UAVs traffic is needed. Tools need to be developed to analyze the congestion of the UAVs traffic under uncertainties.
Goals

- Develop realistic and tractable models for UAV traffic under weather uncertainty
  - the system level model of UAV traffic: aggregated flow
  - the change of the weather conditions
  - the impact of weather change
- Analyze the system level of performance of UAV traffic in the merits of resilience
  - define resilience for UAV traffic
  - derive conditions for the UAV traffic to be resilient
  - improve the traffic efficiency
Fluid Queueing model for UAV traffic:

\[
\dot{Q}(i, q, t) = r(i, q, t) - f(i, q, t),
\]

\[
f(i, q, t) = \min(s(i, q, t), c_i).
\]

States:
- \( Q \): stochastic queue length,
- \( q \): realization of queue length,
- \( I \): stochastic mode,
- \( i \): realization of mode,
- \( r \): receiving flow
- \( s \): sending flow
- \( f \): outflow
- \( c_i \): saturation rate(capacity)

Weather Uncertainty:
Continuous Markov Process with governing transition matrix: \( \Lambda \)
Assume: process is irreducible and ergodic:
steady state distribution: \( p\Lambda = 0, \ |p| = 1 \)
More Models

\[ r_1 = a, \]
\[ s_1(i, q) = \min(vq_1, c_{1i}), \]
\[ r_2(q) = w(\theta - q_2), \]
\[ f_{12}(i, q) = \min(s_1, r_2), \]
\[ f_2(i, q) = \min(vq_2, c_{2i}). \]

Observation (fundamental diagram):

▶ More traffic flow can be sent to downstream if there is more traffic in upstream.
▶ Less traffic flow can be sent to downstream if there is more traffic in downstream.
▶ No flow can be sent to downstream if downstream is congested.

\[ r_1 = a_1, \]
\[ r_2 = a_2, \]
\[ s_{13}(i, q) = \min\{vq_1, c_{1i}\}, \]
\[ r_{13}(i, q) = \frac{q_1}{q_1 + q_2} w(\theta - q_3), \]
\[ f_{13}(iq) = \min\{s_{13}, r_{13}\}, \]
\[ s_{23}(i, q) = \min\{vq_2, c_{2i}\}, \]
\[ r_{23}(i, q) = \frac{q_2}{q_1 + q_2} w(\theta - q_3), \]
\[ f_{23}(iq) = \min\{s_{23}, r_{23}\} \]
\[ f_3(i, q) = \min\{vq_3, c_{3i}\}. \]
Resilience Definition

- Quantity of Interest
  - Stability: the long run boundedness of the queueing system
    - Mathematical Definition:
      \[
      \limsup_{t \to \infty} \frac{1}{t} \int_0^t \mathbb{E}[\exp(|Q(\tau)|)]d\tau \leq C. \tag{1}
      \]
  - Efficiency: maximum throughput of the queueing system
    - \[
    \max_{a} |a|, \tag{2}
    \] subject to (1).
Some intuitive results:

*If the tandem queue is stable, then* \( a \leq \sum_{i=1}^{m} c_{ji} p_i, \ j = 1, 2. \)

*If the merge queue is stable, then* \( a_j \leq \sum_{i=1}^{m} c_{ji} p_i, \) for \( j = 1, 2, \) and \( a_1 + a_2 \leq \sum_{i=1}^{m} c_{3i} p_i. \)

Some not so intuitive result:

*If there exist positive constants \( \alpha_1, \alpha_2 \ldots \alpha_m \) and \( \beta \) such that:

\[
\forall i \in \mathcal{I}, \alpha_i \beta (2a_1 + 2a_2 - \tilde{F}_m(i)) + \sum_{j \in \mathcal{I}} \lambda_{ij} (\alpha_j - \alpha_i) \leq -1
\]

*merge queue system is stable.*\(^1\)

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\(^1\) See details at: "Resilient UAV Traffic Congestion Control using Fluid Queuing Models" (Under Review)
Numerical Experiments

**Figure:** Effect of Transitional Intensity

**Figure:** Effect of Capacity Fluctuation
Stochastic fluid queueing models can also be applied to other types of traffic.
Discrete version of the results can also be derived.
Feedback control policies can be developed for more models.