

A Stackelberg-GNE Framework for Heterogeneous UAV Task Scheduling in Shared Low-Altitude Airspace

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Abstract

The surge of low-altitude logistics has intensified competition for vertiport landing slots during peak demand periods, leading to conflicts between time-critical emergency landings and heterogeneous commercial delivery operations. This paper models these interactions via a bi-level Stackelberg-GNE framework in which the upper level is an emergency scheduling agent (leader) that reserves or sets priority intensities for landing slots to guarantee timely emergency service, while the lower level comprises self-interested commercial unmanned aerial vehicle (UAV) operators (followers) who non-cooperatively select landing slots under coupled capacity constraints. We explicitly model follower heterogeneity via agent-specific revenue and delay-sensitivity parameters, and we discuss an optional tiered priority extension for policy comparison. The followers' Generalized Nash Equilibrium (GNE) is formulated as a variational inequality (VI) and embedded as an equilibrium constraint in the leader's problem. For computation, we propose a leader-follower iterative scheme coupling an extragradient VI solver with projected gradient updates for the leader; for small-scale validation we also employ single-level reformulation solved by mixed-integer programming. Numerical experiments under peak/off-peak scenarios demonstrate boundary and interior Stackelberg equilibria, a crowding-out effect of commercial traffic under aggressive reservation, and trade-offs between emergency response timeliness and aggregate system efficiency, with heterogeneous follower parameters significantly shaping allocation outcomes.

Keywords

Stackelberg leadership model, Generalized Nash equilibrium, Peak demand, Heterogeneous UAV task, Landing slot allocation.

