Improving Unmanned Aerial Vehicle Traffic Flow at a Crossroads by Splitting Demand into Parallel Streams

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1 INTRODUCTION

Goods delivery is one of a number of emerging applications for unmanned aerial vehicles (UAVs), see (Shakhatreh *et al.*, 2019) for a review. While predictions of future demand are highly uncertain, some authors predict dramatic growth in the sector, e.g., Oosedo *et al.* (2021) forecast that 32,887 deliveries a day in Sendai (Japan) will be targeted for UAV delivery. Current proposals for unmanned traffic management (UTM) to facilitate such operations, e.g., (European Union Aviation Safety Agency, 2020, Federal Aviation Administration, 2020), are based on a centralized approach where flight plans are deconflicted prior to take off. In our opinion, this centralized approach is likely to become both computationally infeasible for such large numbers of UAVs, and potentially vulnerable to brittle failures.

An alternative approach (Sedov & Polishchuk, 2018) is to adopt decentralized methods for traffic management where UAVs instead autonomously resolve future conflicts as they arise by implementing a sense and avoid (S&A) scheme. In (Bonnell & Wilson, 2021) we developed a simple pairwise S&A scheme using velocity obstacle (VO) methods (Fiorini & Shiller, 1998) in which UAVs modify their velocities to ensure a safe separation S is maintained. Inspired by current rules of the air (ICAO, 2005), UAVs will, by default, turn to the right to avoid each other. Furthermore, an optimal velocity model (Bando *et al.*, 1995) is employed to modify each UAV's velocity such that in the absence of S&A maneuvers, it steers towards a given destination.

Inspired by UAV delivery applications, we also developed a simple scenario to test our decentralized S&A scheme where UAVs fly between fixed points, e.g., warehouses, and thus naturally form streams of traffic in the airspace, which we model as a 2D plane to reflect current flight ceilings (120 m in UK and EU) and the desire to maximize vertical separation with pedestrians or property. An example is shown in Figure 1(a), where two uni-directional streams of traffic intersect at a point to form a sort of 'crossroads' at which UAVs will need to avoid each other. We have shown how the performance of such a system deteriorates as the demand at the crossroads increases and this paper will therefore explore a higher level design solution, inspired by (Mao *et al.*, 2000), where a traffic stream is split in to two streams and the demand shared between them, see Figure 1(b). Thus the total number of crossroads is increased, but the contention at each is decreased.

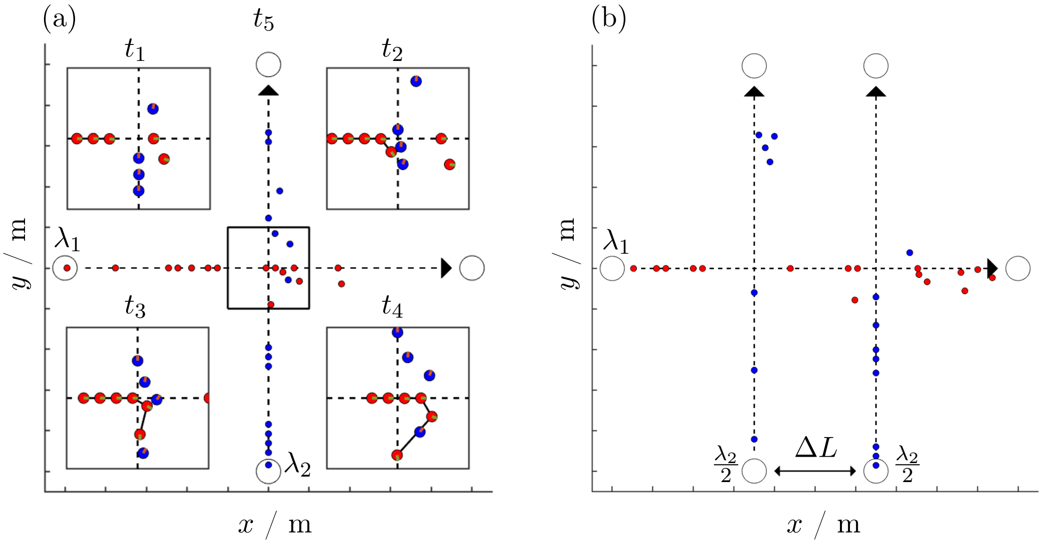

Figure 1 – *(a) Two streams of autonomous UAV traffic, described by take off rates λ_1 and λ_2 from the origin ports, form a crossroads and use a S&A method to resolve future conflicts. (b) The vertical traffic stream (as viewed on the page) in (a) has been split in to two parallel streams, ΔL apart, that equally share the demand of the single stream. Thus the number of crossings has increased but the contention at each is reduced.*

2 EXPERIMENTAL SETUP

We employ a simple conceptual model of UAV traffic between fixed points in which we assume that all UAVs are of the same multi-rotor type, with a common desired cruising speed v_{CS} that represents some regulatory speed limit. In order to simplify the complexity of the distributed control we restrict the horizon of S&A maneuvers to those in which the time-to-conflict (i.e., the time remaining until two UAVs breach the safe separation distance based on their current displacements and velocities) is less than the natural time scale $\tau := 2v_{\mathrm{CS}}/a_{\max}$, where $a_{\max}$ is the maximum achievable acceleration. Note τ is the time it takes for a UAV travelling at the cruising speed to reverse its direction.

For this paper, the base case is the simplest possible crossroads setup, used to produce the simulation snapshot in Figure 1(a), in which UAVs fly between four 'ports' at positions $(\pm L/2, 0)$ and $(0, \pm L/2)$ which form two sets of origin-destination pairs. UAVs are generated at the origin ports at $(-L/2, 0)$ and $(0, -L/2)$, with initial velocities $v_{\mathrm{CS}}(1, 0)$ and $v_{\mathrm{CS}}(0, 1)$, according to independent Poisson processes. There are thus two traffic streams, a 'horizontal' stream (as viewed on the page) and a 'vertical' stream (as viewed on the page) with Poisson rates λ_1 and λ_2 respectively. When a UAV is generated, it is added to a queue for take-off, which is served deterministically to maintain a minimum spatial separation $S_{\mathrm{takeoff}} := 3S/2$ that ensures UAVs do not come into conflict in the early stages of their flight. UAVs are removed from the simulation when they enter a 'landing zone' disk of radius $R_{\mathrm{LZ}} \ll L$ centred upon their destination. We therefore measure the performance of a given setup by comparing the flight time between takeoff and entering the landing zone, to the time $(L - R_{\mathrm{LZ}})/v_{\mathrm{CS}}$ that each UAV would have taken in the absence of interactions with any other UAVs.

In Figure 1(b) the vertical stream has been split in two. In our simulations, this is achieved by replacing one of the origin-destination pairs with new ports at positions $(\pm\Delta L/2, \pm L/2)$ to produce two parallel streams of traffic distance ΔL apart. The demand at the new origin ports is set to $\lambda_2/2$, to ensure that the total demand is the same as the base case. Later we will also consider setups in which the horizontal stream of traffic is split instead. Due to the right-handedness of the default S&A maneuvers, the system performance is different in this case.

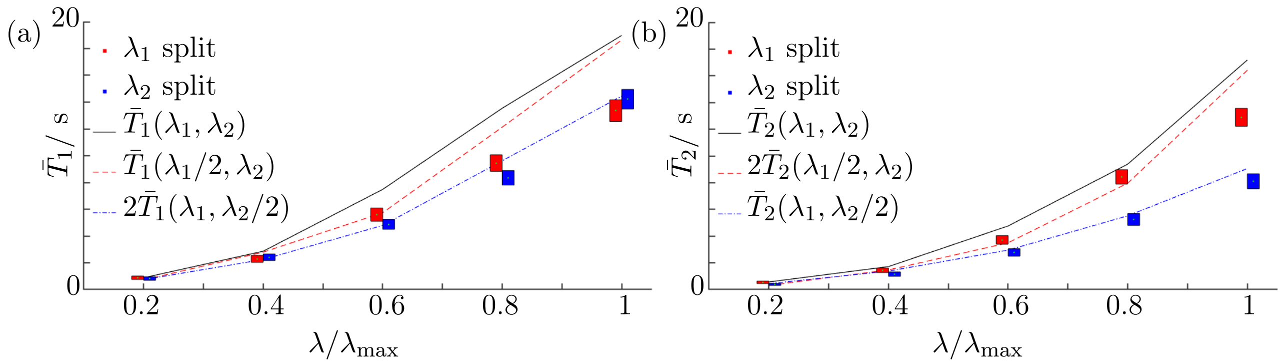

Figure 2 – *Bootstrapped estimates (inter-quartile range) of mean time delay experienced by UAVs in the (a) horizontal and (b) vertical streams. We also show the base case delay (black lines) and the predicted mean delay when the horizontal stream (red dashed line) or the vertical stream (blue dashed line) is split, which can be compared to the estimated mean delays of the same color. In (a) we see that there is a larger than expected reduction in the mean delay when the horizontal stream is split but all split traffic scenarios improve upon the base case when demand is high.*

3 RESULTS

For both the base case and split stream setups, we sweep through generation rates $\lambda_1 = \lambda_2$, from small values where UAV interactions are rare and delays are small, up to a theoretical maximum rate $\lambda_{\max} := v_{\mathrm{CS}}/(2\sqrt{2}S)$ that the crossroads could sustain, without interaction between the UAVs, if the traffic streams were evenly spaced and perfectly phased with each other. Each simulation is run until 1,000 UAVs have taken off from each origin port, corresponding typically to $4,000$–$40,000$ s of simulated time, of which the first 200 s of departures are discarded as simulation 'run-up' (where delays are anomalously short). The flight times of the remaining UAVs are bootstrapped to estimate a confidence interval for the mean delays $\bar{T}_1$ and $\bar{T}_2$ experienced by individuals in the horizontal and vertical streams respectively.

From Figure 2, splitting the vertical stream provides a marked reduction in delays, while splitting either stream provides some benefits to both streams. A key modelling idea is to explain the total delays that result in terms of the delays incurred at each individual crossing. For example, when the vertical stream is split, two crossroads result, which might each be modelled by the demand combination $(\lambda_1, \lambda_2/2)$ from the base case setup. The two vertical streams experience just one of these crossroads each, whereas the unsplit horizontal stream experiences both crossroads, so its delay should be double the $(\lambda_1, \lambda_2/2)$ base case. Figure 2 shows that this approach to modelling delay is accurate for almost all of the setups tested, with the exception of the delay $\bar{T}_1$ incurred by the horizontal stream when it is split, which is less than that predicted, when demand is sufficiently high. In fact, close inspection of the data (not shown here) reveals that the two 'branches' of the horizontal stream incur quite different delays.

The greater than expected reduction in $\bar{T}_1$ when the horizontal stream is split can be explained by the default S&A rule where UAVs turn to the right. UAVs are thus displaced from their linear flight path and are dispersed laterally, see Figure3(a), and since the UAVs' destinations are distant from the first crossing, the traffic stream stays dispersed which in turn lowers the effective contention at the second crossing. Note that the dispersion effect is still present when the vertical stream is split, see Figure 3(b), but its impact is small compared with the splitting effect.

4 DISCUSSION

In this paper we have shown that splitting UAV traffic into parallel streams can significantly reduce the delays experienced at 'crossroads' where streams cross. Furthermore, analysis of resulting UAV trajectories shows a variety of non-local effects where one crossroads is affected

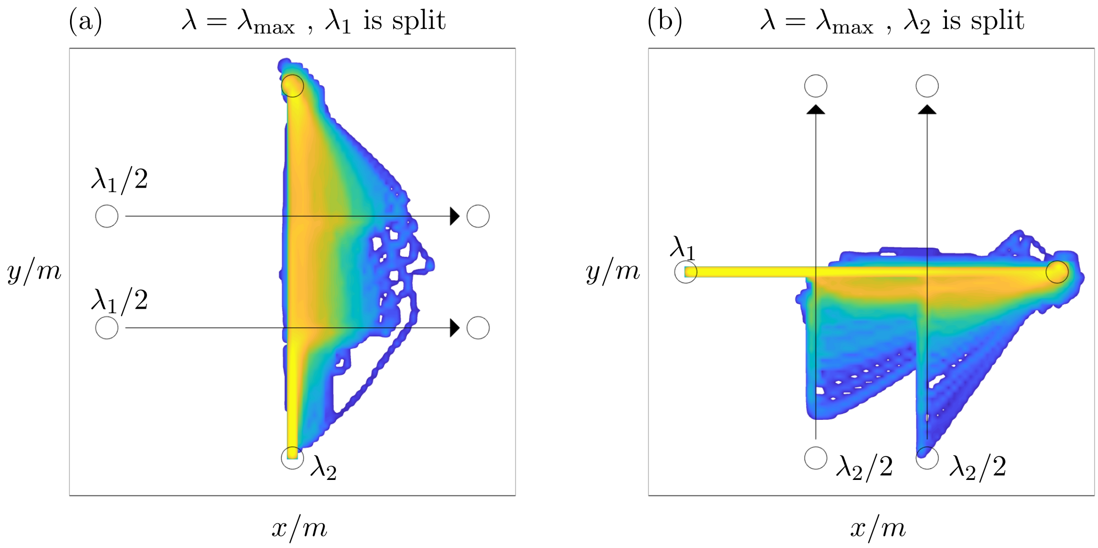

Figure 3 – *Time aggregated density plots for traffic in the (a) vertical stream when the horizontal stream is split and (b) horizontal stream when the vertical stream is split. In both scenarios the traffic in the un-plit stream is dispersed laterally so that the contention at the second crossroads it encounters is reduced.*

by another, in particular, each crossroads has the effect of spreading traffic laterally which can deliver further benefits at downstream crossroads.

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