Multiscale Adaptive Scheduling and Path-Planning for Power-Constrained UAV-Relays via SMDPs

Bharath Keshavamurthy and Nicolò Michelusi

I. Extended Summary

With sustained device proliferation, enterprises across sectors have stepped-up their adoption of Unmanned Aerial Vehicles (UAVs) to gather data, survey infrastructure, monitor operations, and automate logistics. Inevitably, this has fostered varied academic research and industrial R&D on drone-augmented beyond line-of-sight connectivity and traffic offloading in cellular networks: the coverage and service capabilities of an extant terrestrial radio access network are enhanced by the mobility and maneuverability of these autonomous aerial relays.

Unsurprisingly, the pervasive potential of such hybrid networks brings along a plethora of challenges in real-world deployments: specifically, on-board energy constraints of these aerial platforms impacting mission times, stringent Quality-of-Service (QoS) mandates for reliable connectivity, channel characteristics of Air-to-Ground (A2G) links in highly-mobile settings, and computational feasibility challenges in trajectory design brought on by the inherently large state and action spaces. Ergo, several works in the state-of-the-art have tried to tackle these challenges using tools from optimization theory, machine learning, and reinforcement learning—however, various problems remain unsolved and various challenges are left unaddressed.

Several single UAV-relay formulations in the state-of-the-art consider non-adaptive schemes designed for primarily for data harvesting applications wherein the ground users generate deterministic traffic. Yet, practical deployments involve dynamically-generated traffic from miscellaneous sets of users, each with varying degrees of QoS mandates and technological prowess. Unlike these works, we consider dynamic traffic generation from random deployments of ground users, thereby constructing a control strategy that is receptive to uncertain system dynamics.

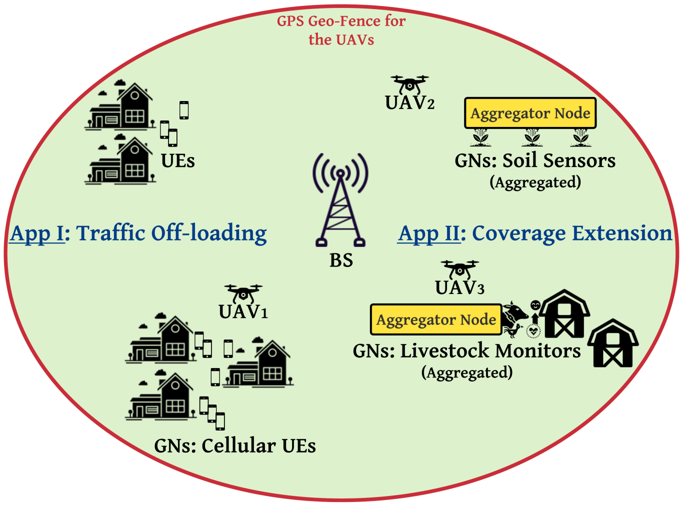
Furthermore, these works solve for the optimal service schedules and associated trajectories via Successive Convex Approximation (SCA), which apart from being computationally infeasible to accommodate dynamic traffic due to prohibitively large convergence times, relies on first-order Taylor approximations of the optimization problem to enforce convexity, thereby introducing inaccuracies into the model. On another note, these works employ Free Space Path-Loss (FSPL) models that fail to account for the A2G channel characteristics inherent in UAV-assisted wireless networks; moreover, their approximations in the traffic delivery constraint preclude the adoption of rate adaptation which allows the transmitters in the network to leverage channel stochastics to maximize throughput. In this paper, in addition to accurately modeling A2G channel characteristics and employing rate adaptation at all the transmitters to efficiently exploit said characteristics, there are no such underlying approximations.

Pivoting to the path-planning problem for a single relay, a Competitive Swarm Optimization (CSO) approach is proposed in this paper to bypass the computational infeasibility seen in SCA-oriented designs. Unlike SCA, which employs approximations to enforce convexity, CSO does not depend on the specific problem structure to work effectively. Contrary to the limited update scope of Particle Swarm Optimization (PSO), CSO exhibits superior performance on large-scale optimization benchmarks, since it involves more efficient updates wherein pair-wise competition is invoked between particles—permitting the winners to advance and the loser particles to learn from the winners. Unreasonably, works that employ PSO, either optimize static hovering positions only, or impose impractical path and velocity restrictions.

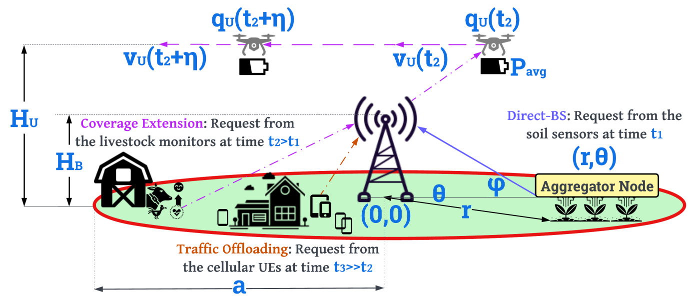
Next, shifting our attention to swarm orchestration frameworks, we find inefficient solutions such as centralized deployments in which an aggregation center coordinates the operations of the UAV-relays; or either joint multi-relay optimization methods or model-free formulations consisting of combined state and action spaces. Centralized swarm deployments bring in the need for additional capital and operational expenditure; and joint multi-UAV constructions lead to prohibitively large solution spaces resulting in unnecessary overhead in policy convergence times, which when scaled to larger swarms result in intractability. To mitigate these drawbacks, we present an orchestration framework suitable for decentralized UAV-relay swarms by embedding our single UAV-relay policy with multi-agent heuristics and replicating it across the swarm.

In this paper, with rate adaptation to exploit A2G channel stochastics, we first constrain our study to single relay settings, wherein the problem of minimizing the time-average service delay subject to an average UAV power constraint, is formulated as a Semi-Markov Decision Process (SMDP). We derive a multiscale decomposition to this formulation: optimizing the long-term delay-power costs yields outer decisions on radial wait velocities and service positions (via value iteration); consequently, greedily minimizing the instantaneous delay-power costs yields inner actions on angular wait velocities (via exhaustive search) and service trajectories (via competitive swarm optimization). Post single relay policy convergence, with an overlaid command-and-control network, we supplement this control strategy with multi-agent heuristics—namely, spread maximization and consensus-driven conflict resolution—and replicate it across the swarm.

Future developments to this research include M/G/x queue management heuristics for link-layer prescient scheduling, a hierarchical variant of CSO to facilitate efficient scalability to higher-dimensional trajectory design, and viability analyses via emulations and real-world flight-tests on NSF AERPAW (OFDM PHY radio + MAVLink vehicle control).

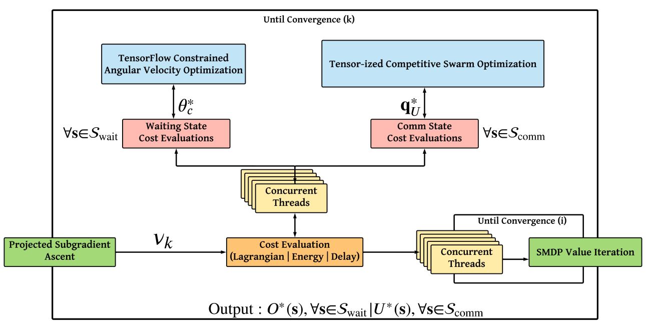


(a) Our generalized deployment model

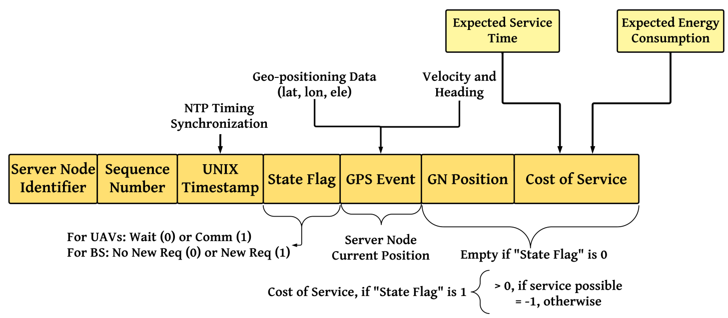


(b) Our single UAV-relay specialization

Fig. 1: (a) *(Not to scale)* A terrestrial base station aided by 3 UAVs serving as cellular relays for a diverse set of GNs: traffic offloading for cellular UEs, and coverage extensions for livestock monitors and soil sensors; (b) The single-agent specialization of our generalized deployment depicted in Fig. 1a: a rotary-wing UAV serving as a cellular relay to a random distribution of GNs in precision agricultural applications.

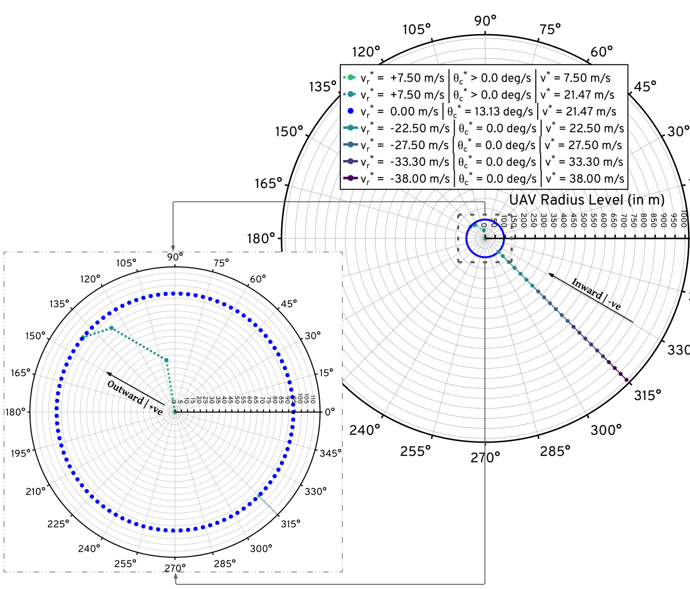


(a) Single UAV-relay: our policy optimization process

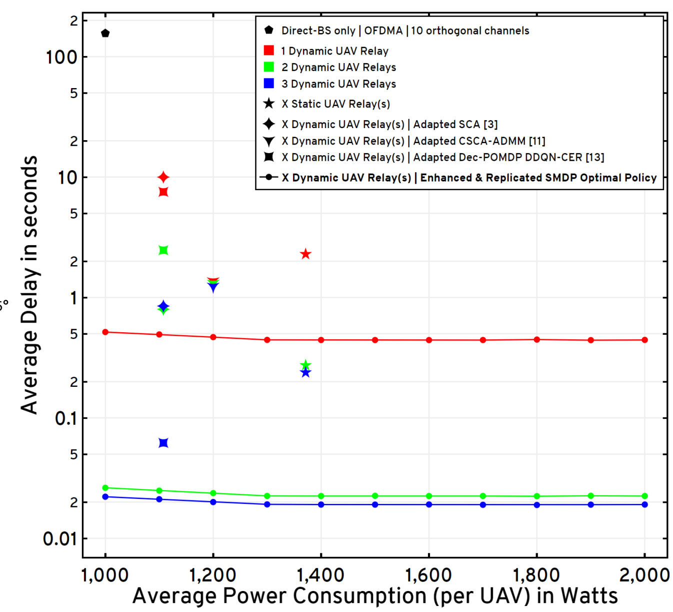


(b) Swarm extensions via multi-agent heuristics: our control frame design

Fig. 2: (a) Algorithmic flow inherent in our single UAV policy optimization; (b) Structure of the control frames exchanged among the BS and the UAVs.



(a) Optimal Wait Policy



(b) Optimal Delay-Power Trade-off Performance

Fig. 3: (a) Optimal waiting state policy for L=1 Mb with P_{avg}=1.2 kW; (b) Average service latencies vs average power constraints for L=1 Mb.