Constrained-Sensors Data Collection with Unmanned Aerial Vehicle

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The role of Unmanned Aerial Vehicles (UAVs) as active components in telecommunications is increasing. Due to their capabilities, such as flexibility of movement and adaptability to different wireless technologies, UAVs are especially suitable for scenarios with inadequate networking infrastructure, constrained or impervious environments, and specific operational needs. At the same time, the Internet of Things (IoT) and related technologies enable tasks such as remote data collection. IoT sensors, although they are constrained in terms of computational power and energy, perform these tasks through ad hoc communication networks and protocols. Real-world applications of UAV-assisted IoT data collection span diverse domains, including precision agriculture for crop monitoring, environmental sensing in remote areas, post-disaster infrastructure assessment, and wildlife tracking. In these scenarios, energy efficiency is critical due to the limited battery capacity of both UAVs and IoT end-devices [3]. If, on the one hand, ad hoc networks and protocols are capable of enabling low-energy and long-range transmissions, on the other they impose peculiar limitations on gateways, end-devices, and their transmissions [2]. In practice, these restrictions translate into novel spatial and temporal constraints on drone-device interactions, which, if omitted, would lead to inefficient routing or data-collection decisions.

The problem we aim to solve is the following: a single drone must gather data from a set of sensors spread across an area. The area, an inherently continuous space, is represented as a set of discretized points where the drone can hover during a single flight to achieve complete data collection from nearby end-devices. Similar problems have been studied in the literature, such as the vehicle routing problem (VRP) with drones [6] and UAV routing with data-collection peculiarities [7]. However, many of the existing formulations are tailored to logistics applications, such as drone-aided parcel delivery [4], or, while addressing data collection [5], they typically remain at a high level of abstraction and do not capture the wireless technology-specific attributes that are critical for realistic IoT deployments.

In this work, we start from an Integer Linear Programming (ILP) model for UAV-assisted data collection that accounts for the peculiarities of IoT protocols. To address the features and constraints imposed by LoRa and LoRaWAN [1], the formulation uses binary decision variables that indicate whether data collection occurs from a sensor to UAV at a hovering point, and also selects the configuration of spreading factor, transmission power, channel and bandwidth to be used during each transmission, by selecting each of them among a discrete set defined by the protocols. Constraints properly model the UAV's ability to collect data simultaneously from multiple sensors, reflecting the limitations of LoRa chipsets in demodulating parallel signals. Further constraints enforce LoRaWAN duty-cycle compliance. Such a detailed representation of LoRa/LoRaWAN protocol constraints is typically not considered in existing UAV-assisted IoT data collection models, which either omit these constraints or consider only a subset of them. Although we focus on two technologies, the mathematical formulation readily generalizes to other IoT protocols through straightforward adaptation of the protocol-specific parameters and constraints. The objective function minimizes the overall energy consumption and is defined as the sum of three components. The first component captures the energy consumed by the UAV during flight. The second component takes into account the energy consumed during hovering, as the UAV must hover at each selected location to perform data collection. The third component sums up the energy consumed by the end-devices for data transmission. We remark that the impact on the objective function of the hovering operations depends not only on the data gathered, but also on the hovering position (hence the distance from IoT devices as determined by the chosen points to visit in the area) and on the transmission parameters (power level, spreading factor, bandwidth). The latter also directly affects the time-on-air of the transmitted payload and the energy consumed by the end-device to perform uplink communication, as accounted for by the last objective function component. Therefore the model provides optimal least energy-demanding UAV and IoT operations, by jointly defining the UAV path, and when and with which parameters each end-device should transmit along this path.

Preliminary numerical experiments with off-the-shelf mixed-integer programming solvers (namely, Gurobi) empirically demonstrate that the model, composed of hundreds of thousands of constraints for realistic instance size, is impractical to solve within a reasonable amount of time. While we derive problem-specific valid inequalities to strengthen the formulation, the model remains computationally challenging for large-scale instances composed of hundreds of sensors distributed across vast areas.

We propose an Adaptive Large Neighborhood Search (ALNS) to overcome these computational challenges. The metaheuristic starts with a greedy initial solution generated by a nearest-neighbor procedure for both UAV movements and sensor-to-UAV transmission assignments. Moreover, we employ carefully designed destroy and repair operators: the former use random or an arc-length-based heuristic strategy to eliminate single nodes or subpaths from the tour; the latter reconstruct solutions through greedy insertion, random placement, or fast local-search-guided heuristics based on 2-opt moves. The frequency of operator usage is proportional to the weights updated during the search, based on their local performance [8]. The degree of destruction of the destroy operators is parametrized, and the acceptance criterion for repaired solutions follows a simulated annealing mechanism (i.e., an approach with a gradually decreasing acceptance probability for non-improving solutions). Additionally, we design ad hoc greedy assignment operators that couple sensors to UAV locations and an exact procedure for optimally determining the transmission configurations. A preliminary implementation of the proposed ALNS algorithm exploits the framework in [8] and outperforms off-the-shelf solvers with a two-hour time limit, by finding higher-quality solutions on large-scale instances.

Ongoing work focuses on extending the ALNS with additional operators and exploring hybrid approaches that combine it with exact methods. Another aspect currently under development is the implementation of further adaptive mechanisms that, during the optimization process, adjust parameters that now are fixed by preliminary tuning. Future research will also investigate alternative ILP formulations, model extensions for multi-UAV and periodic routing scenarios, as well as incorporating quality of service and age of information as optimization objectives.

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