Learning-based Second Price Auction for Distributed Delivery Scheduling in Smart and Autonomous Urban Air Mobility

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***Abstract*—This paper proposes a novel service-oriented and learning-based autonomous control in urban air mobility (UAM). In this paper, we consider drone-taxi services which is one of major applications of UAM networks. The proposed algorithm designs joint truthful and distributed aerial drone-taxi scheduling which is based on second price auction (SPA). Furthermore, the SPA procedure is improved via deep learning framework for revenue-optimality. After the truthful and distributed scheduling, the passengers in the drone-taxi can utilize video streaming services where the services are under delay constraints. Therefore, in order to maximize video streaming quality under the delay constraints, the proposed algorithm is designed based on Lyapunov optimization framework. Simulation results verifies that the proposed algorithm achieves desired performance improvements.**

***Index Terms*—Drone-taxi, autonomous aerial mobility, scheduling, video streaming, optimization**

I. Introduction

A. Background

In modern research trends and industry applications, the Information and Communication Technology (ICT) convergence has been actively and widely discussed in order to enable intelligent and autonomous smart city scenarios [1]. Among various technologies, unmanned aerial vehicle (UAV) networks are also in major interests for smart city applications [2]–[4]. The reasons why the UAV networks can be widely used for smart city applications are they can be easily deployable and flexible, and thus, the UAV networks are able to be used in various applications, e.g., unmanned artificial intelligence (AI)-based autonomous surveillance [5]–[7] and intelligent logistics for smart cities such as drone-taxi [8]–[12].

B. Methods

For the drone-taxi application in smart city applications, as illustrated in Fig. 1, every single passenger who wants to enjoy aerial transportation from one location (i.e., source point) to the other location (i.e., destination point) should take a drone-taxi among candidates. For the procedure (i.e., drone-taxi service reservation procedure), the used algorithm should work in a distributed manner for scalability. Therefore, this paper proposes an algorithm which is fully distributed without full knowledge across the drone-taxi service networks. In this case, various econometric methods can be utilized because they are useful for strategic decision making under uncertainty (i.e., without full knowledge). Among various econometric methods0 (such as game theory [13]–[15], auction mechanisms [16]–[18], and stable marriages [19]–[21]), the proposed algorithm is designed based on auction for distributed resource allocation and scheduling. Furthermore, the performance can be improved further based on deep learning methodologies. More details are in Sec. II-A.

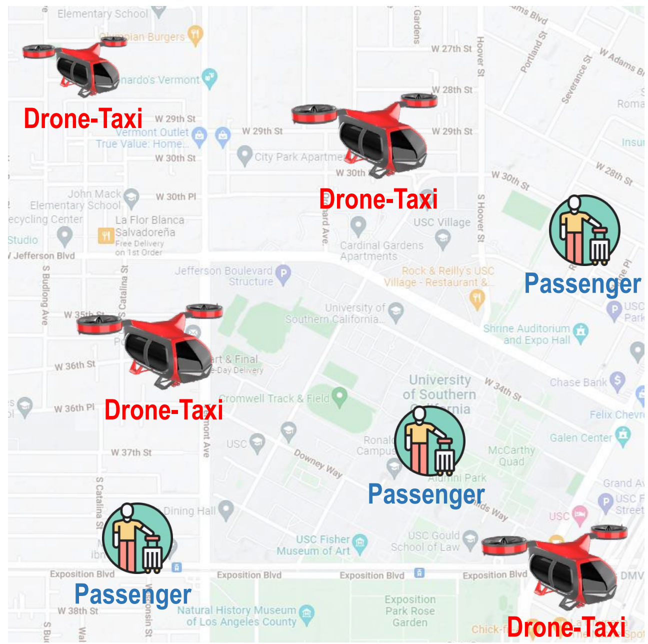

Fig. 1. Reference drone-taxi network model.

After the drone-taxi logistic service reservation, individual passengers who are under the services should be able to enjoy multimedia services such as Youtube, Zoom, and Google meeting. For these types of multimedia services, delay constraints are very important for user service satisfaction. For the purpose, i.e., delay minimization, each video chunk can be compressed a lot for minimizing the size as much as possible. However, it is not good for high quality services. Therefore, we can observe the tradeoff between quality and delay. In order to design an algorithm for control the quality of each chunk for time-average video streaming quality maximization subject to delay constraints, a novel Lyapunov optimization based method is considered because it has been proved that its time-average performance is optimal [22].

C. Contributions

The major contributions of this research can be summarized as follows.

- For the drone-taxi service reservation by individual passengers, a novel distributed and scalable resource allocation algorithm is required as proposed in this paper. Based on auction-based algorithm design in this paper, the proposed algorithm is additionally beneficial in terms of truthfulness.
- Furthermore, the performance of our proposed truthful, distributed, and scalable drone-taxi service reservation algorithm can be additionally improved based on deep learning framework.
- Lastly, this paper also proposes an algorithm that is essentially required for multimedia services for the drone-taxi passengers. For the multimedia services, the proposed algorithm pursues time-average video streaming quality maximization subject to delay constraints. Note that the algorithm is designed inspired by Lyapunov optimization framework for mathematical optimality.

D. Organization

The rest of this paper is organized as follows. Sec. II explains our proposed algorithm for drone-taxi service reservation (refer to Sec. II-A) and high-quality video services for drone-taxi passengers (refer to Sec. II-B). Lastly, Sec. III concludes this paper and presents future research directions.

II. Algorithm

Our proposed algorithm in this paper consists of two sequential parts, i.e., drone-taxi service reservation (refer to Sec. II-A) and high-quality video services for drone-taxi passengers (refer to Sec. II-B).

A. Drone-Taxi Service Reservation

Suppose that multiple drone-taxi devices and passengers are existing. Then, it is impossible to make centralized scheduling/matching between drone-taxi devices and passengers. Therefore, distributed algorithms under uncertainty are required. Furthermore, for the robust and autonomous operations, truthful mechanisms are essentially required. Among various algorithms for the purposes, auction-based algorithms are generally used as shown in the literature [2].

The most well-known first-price auction (FPA) is a general type of auction mechanisms that the bidder who submits the highest bid value to auctioneer is awarded and pays its bid value to the auctioneer. Here, we suppose that N bidders, i.e.,

$$b_1, \cdots, b_N, \tag{1}$$

and only one auctioneer exist, where the bid values are

$$v_1, \cdots, v_N. \tag{2}$$

Then, the auctioneer selects one bid value v^* with

$$v^* = \max\{v_1, \cdots, v_N\}; \tag{3}$$

and the winner bidder b^* is the bidder who submitted bid value as v^*. In addition, we consider that the second highest bid value is $v^\dagger$. In this case, the winner bidder b^* does not need to pay v^* of bid values because slightly higher bid value than $v^\dagger$ can guarantee the game winning. Therefore, individual bidders need to be strategic in our considering FPA.

The other type of auction mechanisms is second price auction (SPA). With this SPA, the mechanism for selecting a single winner is same to FPA, where the payment by the winner is not same with the winner's highest bid value. Note that the payment by the winner is same with the second highest bid value. In the literature, it has been proved that this SPA is truthful [2]. Therefore, this SPA is widely and actively used for various truthful resource allocation algorithms in distributed computing applications [23], [24]. However, one remarkable disadvantage of this SPA is that this SPA does not guarantee revenue-optimality, i.e., the auctioneer is not able to achieve maximum benefits because the second bid value will be given to the auctioneer.

Here, we can conclude that the FPA is good for revenue optimaliy whereas it is not truthful. On the other hand, the SPA is good for truthfulness whereas it is not revenue-optimal. Therefore, it should be the best if the SPA can be improved for revenue-optimality.

To achieve revenue-optimality in the conventional SPA, various approaches have been actively studied in the literature. Among them, the Myerson auction mechanism with the concept of virtual valuation is one of the well-known and actively/widely used approaches [2], [25]. For numerically formulating the virtual valuation, monotonic increasing functions are generally considered [2], [25]. Due to the advances in deep learning research [26], the Myerson auction mechanism computation procedure can be approximated with the form of deep learning framework.

B. High Quality Video Streaming Service

1) Algorithm Design: With the explosive growth of multimedia service utilization in any places even in the sky, the planing and management of video streaming services is essentially required for autonomous mobility platforms. Our main objective in this paper aims at video quality level selection algorithm design subject to delay constraints. The corresponding mathematical optimization problem can be formulated as follows [27],

$$\max : \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} R[f[\tau]], \tag{4}$$

subject to queue stability, i.e.,

$$\lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} Q[\tau] < \infty \text{ (stability)}, \tag{5}$$

where R represents the function of video quality performance which can be numerically identified as the ratio of peak-signal-to-noise (i.e., peak-signal-to-noise-ratio (PSNR)), therefore, $R[f[\tau]]$ is the video quality depending on quality level selection over video frames $f[t]$ in each unit time t. In addition, $Q[t]$ stands for the delay at t.

If the quality level increases in each video frame, it is obvious that the video quality in the frame will be increased. However, enlarging the quality level also extends delays due to the increased video frame file size. Therefore, there exists a tradeoff between our objective (video quality) and delay. In this system model, Lyapunov optimization theory [22], [27]–[30] can be used to pursue time-average utility maximization subject to stability.

Our proposed optimal control for dynamic video frame rate selection can be designed as follows. In each unit time, current delay at t, i.e., $Q[t]$, is observed and the proposed Lyapunov optimization-based algorithm calculates $\alpha^*[t]$, which is an time-average optimal action at t, as follows,

$$\alpha^*[t] \leftarrow \max : V \cdot R[f[t]] + Q[t] \cdot b[f[t]]. \quad (6)$$

Here, if the proposed system pursues more aggressive stability (i.e., more aggressive delay requirements) with smaller V, it can be obviously argued that the system operates to minimize system delay for safe and stabilized multimedia services.

In order to verify whether the (6) works well, we provide the following two example cases.

- *The case for $Q[t] \approx \infty$:* In this case, (6) tries to maximize $b(\alpha[t])$, thus the processing should be accelerated for satisfying the stability, and the video frame quality level at t ($\alpha[t]$) is selected, which is the fastest one.
- *The case for $Q[t] = 0$:* In this case, (6) tries to maximize $R(\alpha[t])$, i.e., the proposed algorithm pursues the video frame quality maximization, and the frame rate selection at t ($\alpha[t]$) is conducted, which is the highest-quality one.

III. Conclusions and Future Work

This paper basically proposes a novel learning-based control algorithm for autonomous aerial mobility. In this paper, we consider drone-taxi services which is one of widely considered applications in UAM network researches. The proposed algorithm designs joint truthful and distributed aerial drone-taxi scheduling which is based on second price auction (SPA). Based on this SPA, the proposed algorithm can be truthful, distributed, and scalable. Furthermore, the SPA procedure is improved via deep learning framework for revenue-optimality. After the learning-based SPA scheduling between drone-taxi devices and passengers, the passengers in the drone-taxi can utilize video streaming services where the multimedia services are under delay constraints. Therefore, for maximizing video streaming quality under the delay constraints, the proposed algorithm is designed based on Lyapunov optimization.

As future research directions, data-intensive performance evaluation will be conducted under the consideration of various conditions. pecific wireless channels for video streaming into drone-taxi can be discussed. Note that millimeter-wave and tera-hertz wireless communications can be considered for real-time large-scale massive video streaming [31]–[34].

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