UAV Trajectory Optimization in Modern Communication Systems: Advances and Challenges

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***Abstract*—UAV trajectory optimization in modern communication systems is crucial as many research efforts are recorded in integration of 5G in UAVs. This has attracted significant attention from wireless communication research community around the world. With the rapid advancement in UAV-assisted communication systems, UAV's trajectory optimization has become important due to intrinsic constraints facing in modern communication systems. Notable research activities have been conducted in the direction of UAV trajectory optimization in different communication setups during last few years. Despite the importance of the topic, there are no extensive reviews available in open literature related to UAV trajectory optimization techniques used in 5G. Thus, this paper provide a comprehensive survey on UAV trajectory optimization techniques used in the open literature and advancement to date, with identified research issues and challenges. This provides a valuable reference and new avenues for the future research in this direction.**

***Index Terms*—Trajectory optimization UAV communication 5G**

I. INTRODUCTION

During the course of the last 20 years, the potential use of Unmanned Aerial Vehicles (UAVs) has attracted significant attention due to their practical applications in a wide variety of areas such as surveying and mapping, aerial imaging, inspection and monitoring, wireless communications, etc.. In the meanwhile, the fifth generation (5G) wireless network is going to boost the information traffic in next generation communications. In such a scenario, UAVs have been used as an effective solution to accommodate rapidly establishing wireless connections without fixed infrastructures [1]. Low cost and extreme deployment flexibility are the most highlighted features that characterizes UAVs within next generation communication systems, which also lend a hand to overcome some intrinsic limitations of the conventional communication infrastructure. In addition, UAVs can establish a line-of-site (LOS) connection with the user depend on the operational terrain and modify the coverage area whenever needed to maintain required quality-of-service (QoS) resulting in a significant increase in quality-of-experience (QoE). The use of UAVs as aerial base stations has attracted significant interest in past few years to meet the rapidly increasing data demand in temporary extremely crowded areas such as live concerts, football matches, etc... and to provide emergency cellular coverage during network failures due to natural disasters [2].

However, energy limitation in UAVs is a major drawback, which directly affects the time-of-flight (ToF). Energy con-

UAV	Unmanned aerial vehicle
5G	Fifth Generation
BS	Base Station
LoS	Line of Sight
NLoS	Non Line of Sight
ToF	Time of Flight
IoT	Internet of Things
QoS	Quality of service
QoE	Quality of experience
ESN	Echo State Network
URLLC	Ultra Reliable Low Latency Communication
mMtc	Massive Machine Type Communication
eMBB	Enhanced Mobile Broadband
RRT*	Rapidly exploring random tree star

TABLE I: List of abbreviations and acronyms used in the paper.

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sumption of the UAV is mainly depends on the UAV's overall weight, power consumption of the inbuilt electrical devices and the UAV's trajectory. UAV with longest battery endurance rotary wing available on the market nowadays has a ToF shorter than 30 minutes. Thus, UAV's trajectory optimization plays a crucial role in overall energy efficiency of the UAV, increasing the feasibility of using UAV to enhance wireless communication capabilities in next generation communication systems.

Trajectory optimization for UAVs is a newly born topic, which required further investigation with relevant to the specific application. Also it is noteworthy that there are only few survey papers available on the open literature related to different optimization techniques used in UAV's trajectory optimization. General overview of the basic principles of optimization techniques for a generalized trajectory without specific constraints is provided in [3]. In [4], the authors provide an overview of motion planning algorithms without defining specific constraints and considering atmospheric turbulence, uncertainty in the vehicle state and limited sensor capabilities. A recent survey paper [5] reviewed all the optimization techniques used to find an optimal route, which covers every important points located in a given area of interest. In [6], authors have focused more on the applications of UAV in cellular communications, considering trajectory optimization as a secondary goal. A detailed classification of all trajectory optimization techniques available in the open literature has been provided in [7]. However, the authors did not provide a insight about the effects of constraints on the overall trajectory optimization. In [8]authors have investigated optimal path planning techniques aiming at finding the shortest collision-free trajectory between a pre-defined start and end positions specially highlighting the RRT* algorithm. Even though the existing survey papers [3] - [8] presented in detail various optimization techniques used for general purpose UAV's trajectory optimization, they did not focus on UAV trajectory optimization techniques used in wireless communication systems. Thus, in this paper, we provide a comprehensive review of different optimization techniques used for UAV trajectory optimization in 5G communication systems.

Description	Reference
General overview, no specific constraints	[3]
General overview, no specific constraints	[4]
Optimal route search, given area coverage	[5]
Trajectory optimization secondary aspect	[6]
Small insight about constraints	[7]
No 5G constraint	[8]

TABLE II: A summary of all the optimization techniques summary available in open literature.

The structure of the paper is organized as follows. In section II, we provide a summary of UAV-assisted communication systems. Problem description and motivation related to UAV trajectory optimization is provided in Section III. Different optimization techniques used in UAV trajectory optimization are reviewed in Section IV. In section V, future directions and recommendations are given related to different application in 5G. Current UAV related research projects are presented in section VI. Finally, section VII concludes the paper.

II. UAV-AIDED COMMUNICATION AND NETWORK

UAVs have the potential to be used in many applications related to next generation wireless communications [9]. However, in depth investigation is required on the way UAVs can be used in communication systems to increase the overall system performance, while maintaining the QoS. In open literature, UAVs are used in three different ways in modern communication systems, i.e., mobile base stations, as a relay node in cooperative communication or as a caching device. Thus, it is required to formulate constraints for the UAV trajectory optimization by considering the role of the UAV within the wireless communication system. This section reviews existing research works in open literature on the ways of UAV exploitation in modern wireless communication systems.

A. Base station UAV trajectory optimization

In emergency and crisis scenarios, such as natural disasters, terrorist attacks and in extremely crowded places, must be assisted the existing communication infrastructure by additional wireless coverage within the serving area to provide uninterrupted service to the network users. To accommodate this additional coverage requirement, UAVs have been proposed to be used as aerial base stations(ABS) [2], [10]. This has several potential applications, e.g. to provide additional coverage during the time ground base station is offloading, due to extreme crowds at times such as public events, carnivals, live concerts, etc. Furthermore, the communication networks will benefit with the UAV deployment along the cell edges to increase area coverage [11]. Generally, UAV aerial base stations provide temporary coverage to assist ground base stations in extreme cases, where it is not reasonable investing money on fixed infrastructures [12], [13]. In addition, using UAVs as aerial base stations implies continuous connection with a ground gateway that provides access to the core network. UAV trajectory optimization research, when used as aerial base stations has been carried out in [14], [15], [16], extensively explained in section IV.

B. UAVs-aided relaying trajectory optimization

UAV use as a relay node in cooperative communication systems was first proposed in [17] for airborne military applications. Specifically, UAVs can serve to connect an isolated island of users with a base station [18]. Indeed, this is crucial during communication node failures, due to interference or when the line of sight is blocked, due to terrain constraints [9]. Thus, in order to work as a relay node in cooperative communication, UAVs must keep connected to the source and the destination in order to assist information transmission to the destination. Trajectory optimization considering UAVs as relay nodes has been carried out in [19], [20], [21], [22] and [23], as detailed in section IV.

C. Caching UAV trajectory optimization

UAVs as caches has been widely investigated in open literature [1], [24]. The most common information required by users are stored in the UAV memory, thus limiting the backhaul link and memory re-loading during recharging or off-peak hours. In general, due to the reduced required connectivity, caching brings a relaxation over the trajectory constraints during the optimization phase. Nevertheless, even if trajectory optimization is less constrained, the problem of optimizing the caching content of the UAV has also to be considered. As an example, neural networks have been used to optimize both trajectory and caching content of the UAV [25].

III. PROBLEM DESCRIPTION AND MOTIVATION

This section, provides a general formalization of the UAV's trajectory optimization problem. It is worth noting that each paper considers a slightly different communication system model. In particular, changes are due to the additional constraints or hypothesis used in each such system. Thereby, the one reported here is meant to be just a generalized problem formulation.

A. Dynamic UAV model

Many types of UAVs are considered in literature, whose choice it comes with different constraints on velocity, energy and ToF. The UAV position is characterized by the coordinates $x(t)$, $y(t)$, $z(t)$ that represent the time-dependant coordinates of the UAV in the 3D space being t the time. The start and destination location of the UAV denotes as x_s, y_s, z_s and x_f, y_f, z_f respectively. It is then considered a set of N users characterized by coordinates of the x_i, y_i, z_i, with $i \in \{1, 2, .., N\}$. As a consequence, The distance denoted as $d_i(t)$, between the i-th user and the UAV can be expressed as [15]

$$d_i(t) = \sqrt{(x(t) - x_i)^2 + (y(t) - y_i)^2 + (z(t) - z_i)^2}. \quad (1)$$

The height z also depend on the operational environment and municipal regulations of urban areas. Fixed operational UAV height has been used in [14], [15], [16], [19], [20], [21], [22], [23], [25], [26], [27], [28], [29], [30] and [31].

B. Telecommunication modeling

In several practical situation the communication model is a combination of LoS and NLoS with potential channel fading. Despite this, is commonly assumed that the UAV is capable of achieving LoS with the user, allowing the formulation of the channel gain accordingly to the freespace path loss model used in the great majority of the works [14], [15], [16], [19], [20], [21], [22], [23], [25], [26], [27], [28], [29], [30]. The channel gain is

$$G_{ch}(t) = \frac{\beta_0}{d_i(t)^{\alpha}}, \quad (2)$$

where α denotes the path loss exponent and β_0 denotes the signal-to-noise ratio (SNR) at the reference distance of $1\,m$.

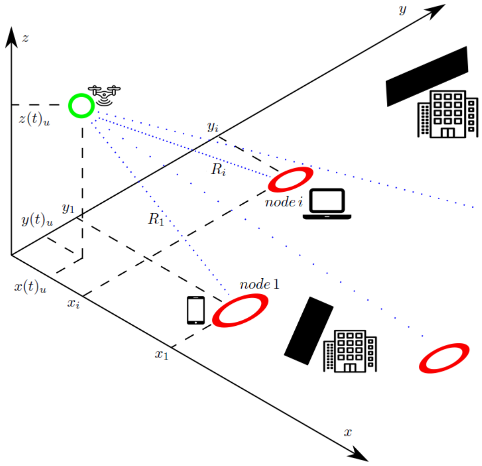

Fig. 1: Geometrical formulation of the UAV communication system. Red circles are the users and the green circle is the UAV. R_i is the transmission rate of the node i, characterized also by the coordinates x_i, y_i.

It is then possible to define the maximum transmission rate between the UAV to the user i as

$$R_i(t) = log_2(1 + \frac{P_t(t)\beta_0}{\sigma^2 d_i(t)^2}), \quad (3)$$

where $P_t(t)$ represents the transmission power and being σ^2 the noise power.

C. Trajectory Optimization

The UAV's trajectory optimization consist in maximizing the transmission rate $R(t)$ as

$$\max_{\substack{x(t),y(t)z(t)\\ P(t)}} R(t). \quad (4)$$

Once the optimization problem formulated, different optimization techniques can be used to solve it by evaluating the mathematical nature of its statement and the constraint functions.

IV. OPTIMIZATION APPROACHES

TABLE III: A summary of all the optimization techniques used to solve trajectory optimization problem in the analyzed works.

Method	Description	Work
Lagrangian approach	The problem is minimized linearly adding a constraint	[19] [21] [20]
Fractional programming	This methodology evaluate the efficiency of the system and provide the best trade off between different solutions	[30]
Sequential convex optimization technique	The problem of Power and Trajectory is decoupled and solved separately, requires a lower bound	[27] [15] [21] [21] [22] [23] [29]
Dynamic programming	An algorithm with a sequential update of the trajectory taking into account the constraints	[26] [16]
Q-learning	Advanced minimization technique based on a Q function that can be defined trough a table or neural networks	[14]
ESN	Recurrent neural network capable of carry out trajectory trough environment prediction	[29]

A summary of all the optimization techniques used is presented in Table III.

A. Lagrangian optimization approach

Lagrangian approach is used in [19], where the power consumption for a relay-UAV telecommunication is the objective function and movement considered as a constraint. After this formalization, the Lagrangian function is minimized in a time discrete domain. In general, once the derivability of the object function and of the constraint is proved, Lagrangian approach provides a sufficient condition for a stationary point to be a global minimum. Specifically, with this methodology it is possible to get to a local minimum or even to a maximum.

B. Fractional programming

Another optimization technique is presented in [30], where the x and y coordinates of the relay-UAV trajectory are fixed and the height z is used as a variable. Thus, a non-differentiable fractional objective function is obtained that describes power and height optimization. Fractional programming is than applied to optimize UAV height and power a methodology called.

C. Mixed Lagrangian and Sequential convex optimization technique

The so called sequential convex optimization technique is a frequently used minimization technique to solve this problem. It can be combined with the Lagrangian approach to develop new optimization algorithms. In [21] the transmission power of a relay-UAV is optimized through a Lagrangian approach. Subsequently, the trajectory is optimized trough a convex optimization technique with the optimal power profile imposed. The work [20] also combines a Lagrangian approach with the convex optimization technique. Specifically, it optimizes the UAV transmission power profile through a Lagrangian approach. Afterward, it applies the power profile found to the trajectory optimization, solving it trough sequential convex optimization technique for a relay-UAV.

D. Iterative algorithms based on sequential convex optimization technique

In [27], the problem has been divided in two sub-problems: the first concerns the UAV power profile, while the second one concerns UAV trajectory. In particular, the proposed algorithm in this work solves at every iteration the first problem thus finding the optimal power profile with a fixed trajectory found in the previous iteration. Afterwards, it solves the second problem, imposing the optimal power profile just found. These two phases are repeated until convergence. In [22] three different optimization problems for a UAV-relay node are presented. First, the UAV trajectory is optimized with a fixed power profile. Subsequently, the power profile is optimized fixing the UAV trajectory. Finally, both are jointly optimized. In all this cases, algorithms based on a successive convex optimization technique were used. Also the work [23] proposes an algorithm based on convex optimization techniques similar to [27] for a relay-UAV, with sequential optimization at every step, until convergence.

E. Cost function with sequential convex optimization technique

In [29], three problems are analyzed and three cost functions are defined. The first problem concerns trajectory optimization with fixed power profile. The second one concerns power profile optimization with fixed trajectory. Finally, the third cost function jointly optimizes trajectory and power profile. Specifically, the first two problems are used as a benchmark for the third one. All problems are non-convex, therefore, two algorithms based on sequential optimization technique are used. The result obtained for the third problem is proved to be a local minimum trough the use of the other two ones.

F. Sequential convex waypoint optimization

A slightly different approach is provided in [15], as applied to an UAV aerial base station. Here, it is investigated how to locate some waypoints called virtual base stations with the goal of optimizing the transmission power. therefore, sequential convex optimization technique is used to locate the waypoints and the trajectory is obtained connecting them.

G. Dynamic programming

In [16], a scenario is considered in which an UAV aerial base station is driven by a predetermined control law. This law is found through Bellman equations by moving backwards in time while taking into account power constraints. The work

[26] considers an algorithm that provides a path decision based on a reward function. In particular, the reward function considers the connectivity constraints between different users. The connectivity constraint implies that the UAV is not allowed to remain far from the user more than a predetermined amount of time.

H. *Q-learning*

Another optimization technique, called Q-learning, is shown in [14] for a UAV base station. Here, the so called Q-function is capable of understanding the environment and making real time decisions about the UAV direction. Specifically, the Q-learning is both table-based and neural-network based, depending on the environment dimension chosen. The inputs for the Q-function are created trough a reward function based on performance quality.

I. *Echo state network*

Finally, an optimization technique called Echo state network (ESN) is found in literature [25]. ESN is a recursive neural network applied on cashing UAV. ESN is used as a tool to predict the UAV cashing content and to determine the optimal UAV trajectory considering user mobility and characteristics. Moreover, at the end of the mission, the UAV could use the traffic data to improve the efficiency of its cashing content and trajectory.

V. RECOMMENDATIONS

Based on the analysis of the literature, it can be inferred that UAV trajectory optimization has the potential to enhance the performance of future wireless networks in several ways. Here, we identify future prospects and possibilities to improve the effectiveness of UAV trajectory optimization.

A. *Multiple UAVs trajectory optimization*

UAVs are subject to on-board power limitations. This is due both to flight constraints over a crowded area and the presence of power consuming hardware. Therefore, it is reasonable to think about a multiple UAV deployment scenario to reach the required data rate. A recommendation is to investigate how such a scenario affects the optimization phase. It must be inquired if a modification of the existing algorithms and techniques is still effective for the solution of this problem.

B. *UAVs dynamic trajectory optimization*

The majority of the existing works in the literature analyzed so far deal with an idealized environment. Specifically, perfect knowledge of user position and lack of environmental disturbances are assumed. This being the case, it is recommended to move towards a designing of algorithms that allow the UAVs to make decisions while interacting with a dynamic environment. Specifically, the dynamic environment might consist of moving users or a device that suddenly stops communicating for unknown reasons.

C. *UAVs stochastic trajectory optimization*

Another recommendation is to take into account a scenario in which users position is not perfectly known (due to GPS noise). In this scenario, an algorithm can be considered based on the user position probability distribution. To deal with this problem Kalman filters can be used.

D. *UAVs trajectory optimization in 5G communications systems*

5G technology will not only focus on people but also on things, forming the so called Internet of Things (IoT). Crucial characteristics of the IoT are Ultra Reliable Low Latency Communication (URLLC), Massive Machine Type Communication (mMTC) and Enhanced Mobile Broadband (eMBB). For all this three 5G aspects it is essential to investigate their combination with trajectory optimization. Concerning URLLC, it should be investigated how the development of NOMA, mmwaves, mMIMO and full-duplex could maximize user benefits when integrated with UAV trajectory optimization.

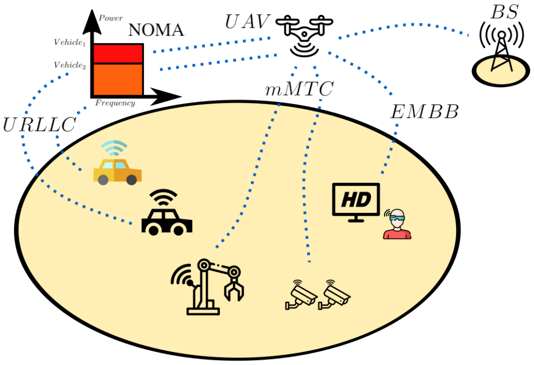

Fig. 2: 5G: this image gives an idea of the integration of the 5G technology in UAVs

E. *IoT and trajectory efficient UAVs*

IoT is essential in the already cited UAV telecommunication enhancer in a 5G scenario [32]. In particular, ways to exploit UAVs for IoT are related making them support a terrestrial network for disseminating or collecting information. Specifically, UAVs can act as users of the wireless infrastructure for surveillance, remote-sensing, virtual-reality cases and package-delivery applications. In such scenario, power consuming tasks are assigned to UAVs. Therefore, trajectory optimization and energy efficiency are of primary importance.

F. *Joint trajectory optimization and energy efficiency*

When discussing about UAVs applications, energy efficiency is a central topic. Trajectory optimization is not the only way to make an UAV energy efficient. Energy harvesting [33], co-operative communication and resource allocation are other candidate. Technologies combining these energy efficiency techniques with UAVs with an optimal trajectory allow the aforementioned UAVs application become more energy efficient in next generation communications systems.

G. Smart cities and effective UAV trajectory optimization

In recent years, the concept of smart cities is arising, aiming at designing efficient urban infrastructure and services at reduced costs. In particular, UAVs plays an important role in smart cities, since they can be used to carry objects, provide Internet connection and act as mobile sensor, enabling IoT [34]. This can be exploited for traffic management, natural disaster control, precision agriculture, urban security, big data processing and coordination between heterogeneous systems [35]. None of these power consuming tasks are possible using an energy inefficient UAV. Figure 3 represents the use of UAVs in cities.

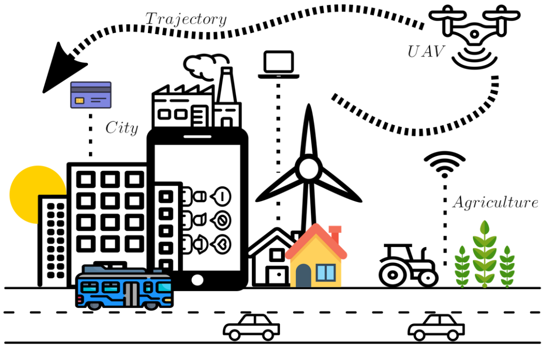

Fig. 3: Smart city: integrating UAV with IoT. All the elements of the city are connected and interact. The role of trajectory optimization is highlighted.

VI. CURRENT INTERNATIONAL RESEARCH PROJECTS RELATED TO UAV ASSISTED NEXT GENERATION COMMUNICATION SYSTEMS

All over the world 5G technology is attracting more and more investments by both government and private sectors. Some examples of current research projects are here provided to prove the importance of trajectory optimization on UAVs for 5G and for other applications.

A. 5GPPP program

A program worth mentioning is the European 5GPPP program, aiming at a private and public partnership to develop 5G in Europe. In particular, the 5G!drones project [36], aims at exploiting UAV potential for 5G deployment. This consortium will benefit from trajectory optimization in terms of hardware competitiveness.

B. Other projects involving UAVs

Other projects that would benefit from the development of trajectory optimization algorithms are the MultiDrone project [37] and the so called 'Creation of a geodetically accurate 3D model of a pilot region in the Russian Federation based on unmanned aerial survey data and GLONASS technologies' project, a partnership between Russian government and Geoscan [38].

The MultiDrone consortium consists in a development of a platform for media production to cover outdoor events. Multiple UAVs that film an event should communicate with the ground station (for video streaming) and with each other (for safety reasons e.g. collision collision avoidance), this happens in varying terrain, where obstacles (e.g. buildings) can obstruct communication. The best solution would be to have one UAV serving as a relay node, when QoS falls below a certain level. The Geoscan-driven project 'Creation of a geodetically accurate 3D model of a pilot region in the Russian Federation based on unmanned aerial survey data and GLONASS technologies' aims at creating 3D maps of cities, with Tomsk chosen as first city.

VII. CONCLUSIONS

In this article we provided an overview on most frequently used trajectory optimization techniques for UAV-aided communication and networking. Furthermore, it was shown that different minimization techniques for trajectory depends on the UAV application domain: relay-UAV, caching UAV and aerial base stations UAV. It was shown that algorithms based on the sequential convex optimization technique are very popular and that the trend is to move towards machine learning solutions. Future directions and recommendations on UAV's trajectory optimization are provided to help future researchers to design feasible and optimal UAV-enhanced wireless communication systems.

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