# Guest Editorial Special Issue on UAV Communications in 5G and Beyond Networks—Part I

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## I. Introduction

WIRELESS communication is an essential technology to unlock the full potential of unmanned aerial vehicles (UAVs) in numerous applications and has thus received unprecedented attention recently. Although technologies such as direct link, WiFi, and satellite communications are still useful in some remote scenarios where cellular services are unavailable, it is believed that exploiting the thriving 5G and beyond cellular networks to support UAV communications is the most promising and cost-effective approach, especially when the number of UAVs grows dramatically. On the one hand, to guarantee safe and efficient flight operations of multiple UAVs, it is of paramount importance to provide secure and ultra-reliable communication links between the UAVs and their ground pilots or control stations for conveying command and control signals, especially in beyond-visual-line-of-sight (BVLOS) scenarios. On the other hand, because of advances in communication equipment miniaturization as well as UAV manufacturing, mounting compact and lightweight base stations (BSs) or relays on UAVs becomes increasingly feasible. This has led to two promising research paradigms for UAV communications, namely, UAV-assisted cellular communications and cellular-connected UAVs, where UAVs are integrated into cellular networks as aerial communication platforms and aerial users, respectively. As such, integrating UAVs into cellular networks is believed to be a win-win technology for both UAV-related industries and cellular network operators, which not only creates plenty of new business opportunities but also benefits the communication performance of 3-D wireless networks. In addition, UAV related sensing and computing are also helpful for achieving efficient and reliable communication (e.g., in avoiding coverage holes) as well as smart UAV coordination, positioning, and trajectory design. However, 5G and beyond wireless networks with UAVs significantly differs from traditional communication systems, because of the high altitude and high maneuverability of UAVs, the unique UAV-ground channels, the diversified quality of service (QoS) requirements for downlink command and control (C&C) and uplink mission-related data transmission, the stringent constraints imposed by the size, weight, and power (SWAP) limitations of UAVs, as well as the new design degrees of freedom enabled by joint UAV mobility control and communication resource allocation.

This Special Issue (SI) aims to advance the research on UAV communications in 5G and beyond networks. It led to a strong response from the research community of UAV communications and attracted more than 130 high-quality submissions from researchers all over the world. Due to the space limitation, only 39 original contribution papers were eventually selected for publication in a double-issue. In addition, a tutorial paper from the Guest Editors was reviewed by the team of Senior Editors of IEEE Journal on Selected Areas in Communications. All submissions received at least three reviews, and the accepted papers went through at least one revision round.

The first part of the double issue starts with an article by the Guest Editors titled "A comprehensive overview on 5G-and-beyond networks with UAVs: From communications to sensing and intelligence." Specifically, this article provides a comprehensive overview of the latest research efforts on integrating UAVs into cellular networks, with an emphasis on how to exploit advanced techniques (e.g., intelligent reflecting surface, short packet transmission, energy

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Digital Object Identifier 10.1109/JSAC.2021.3090875

harvesting, joint communication and radar sensing, and edge intelligence) to meet the diversified service requirements of next-generation wireless systems. Moreover, important directions for further investigation in future work are also highlighted. The contributions of other articles are categorized as follows.

## II. UAV Channel Modelling

The article "Hovering UAV-based FSO communications: Channel modelling, performance analysis, and parameter optimization" investigates channel modelling and performance analysis of free-space optical links using hovering UAVs for extended high-throughput wireless connectivity. More specifically, a hovering UAV-based FSO serial relaying configuration is considered with decode-and-forward singling at the relay. Also, the accuracy of the presented analytical expressions (e.g., for the link outage probability) is investigated by numerical simulations.

The article "A non-stationary geometry-based MIMO channel model for millimeter-wave UAV networks" proposes a mm Wave channel model for UAV A2A communications, which takes the motion of the UAVs and clusters into account. Moreover, a two-state Markov model is introduced to model the dynamic evolution of clusters in the time domain, and the closed-expressions for the survival probability of clusters are derived. It also shows the significant impact of UAV movement and carrier frequency on channel characteristics.

The article "Empirical low-altitude air-to-ground spatial channel characterization for cellular networks connectivity" presents the results of an empirical low-altitude UAV spatial channel model for cellular networks. The CIRs have been extracted from the received data based on the SAGE-based method. Channel characteristics in cluster levels are investigated. The interesting results obtained in the article are important to enable advanced communications for both cellular-connected UAVs and the ground UEs in 5G and beyond networks.

The article "A novel non-stationary 6G UAV channel model for maritime communications" formulates a novel channel model for UAV communications in maritime scenarios. The model considers the Loss component, the single-bounce components resulting from the fluctuation of sea water, and multi-bounce components introduced by the wave-guide effect over the sea surface. The transmitter (Tx), receiver (Rx), and the clusters between the Tx and Rx are all set as moving with arbitrary speeds and directions. The fluctuation of seawater and the duct effect are also taken into account.

## III. UAV Meets Massive MIMO, IRS, and NOMA

The article "UAV swarm position optimization for high capacity MIMO backhaul" focuses on the downlink harvested energy and uplink spectral efficiency of cell-free massive MIMO taking into account the effects of both wireless power transfer and hardware impairments for UAV communications. The UAV harvests energy from downlink APs' energy symbols, which is used to support the uplink data and pilot transmission. In addition, the small cell and cellular massive MIMO systems are analyzed for comparison. Closed-form expressions for the downlink harvested energy and uplink spectral efficiency expressions are derived to quantify the impact of hardware impairments on the considered system. Furthermore, the authors propose an angle search trajectory design scheme and compare its performance with the AP search, and line path trajectory design schemes. Numerical results show that the cell-free massive MIMO system outperforms the cellular massive MIMO and the small cells systems.

The article "3-D deployment of UAV swarm for massive MIMO communications" designs a decentralized control strategy under the uplink transmission between a multi-antenna ground station and a UAV swarm. The local information is utilized to achieve optimal 3-D deployment. The optimization problem is first divided into several sub-problems with respect to the rank function, and then a capacity game is constructed with graph theory. The Nash equilibrium is achieved with proposed algorithms and simulation results has illustrated the performance of such deployment strategy.

The article "Reconfigurable intelligent surface-assisted aerial-terrestrial communications via multi-task learning" considers a RIS-assisted aerial–terrestrial multiuser communication system. In order to fully exploit the LoS transmissions, the flexible RIS elements partition, RIS configuration updating and the dynamic frame-structure were jointly optimized to improve the total throughput of the network. To solve the formulated mixed-integer non-linear programming, an iterative algorithm and a deep neural network (DNN)-based multi-task learning was proposed to reduce the problem-solving complexity.

The article "Intelligent reflecting surface enhanced multi-UAV NOMA networks" proposes an interesting multi-UAV transmission framework, where NOMA is employed for achieving flexible resource allocation and IRS is deployed to mitigate the inter-UAV interference. The authors formulate the sum-rate maximization problem for joint optimization of the 3-D placement and transmit power at UAVs, the reflection matrix at the IRS, and the NOMA decoding orders at each user group. A BCD-based algorithm is proposed to solve the formulated optimization problem. Extensive numerical results show that the proposed framework outperforms the OMA scheme and the scheme without IRS.

The article "Interference-aware NOMA for cellular-connected UAVs: Stochastic geometry analysis" explores the performance of downlink NOMA for cellular-connected UAVs and proposed a framework with the coexistence of cellular-connected UAVs and terminal users. With the proposed framework, the authors derive the coverage probability and average rate of each AU and TU, and explore the impact of various network setting and parameters. Also, an interference aware scheme which simply combines the maximum-SINR-based user association, directional antenna with fixed beamwidth, and ICIC is presented in the article.

## IV. UAV-Aided WPT and Backscatter Communications

The article "Joint design of UAV trajectory and directional antenna orientation in UAV-enabled wireless power transfer networks" investigates a UAV-enabled wireless power transfer network, where the minimum harvested energy among all the sensor nodes is maximized through the joint design of UAV trajectory and directional antenna orientation. The continuous time domain is quantized into equal time slots for further processing the optimization problem. Besides, through approximations of the antenna pattern and the harvested power, a modified cosine antenna pattern and a concave lower bound of the harvest power are constructed, which converts the non-convex problem into convex. Simulation results show that the proposed algorithm with the joint design of UAV trajectory and directional antenna orientation can achieve significant performance improvement as compared with the omnidirectional antenna case.

The article "UAV-aided wireless power transfer and data collection in Rician fading" studies a UAV-aided wireless power transfer and data collection network, where it is assumed that when the harvested energy at the sensor node (SN) cannot surpass its circuit activation threshold, or the received data rate at UAV falls below a minimum required rate threshold, the information outage occurs. The authors analyze the outage probability and optimize the UAV's elevation angle and system time splitting factor. As the formulated problem is non-convex, the alternating method is applied to sub-optimally solve it. Numerical results are presented as well for verification.

The article "UAV communications with WPT-aided cell-free massive MIMO systems" presents a cell-free UAV communication with wireless power transfer to support both uplink data and pilot transmission using HE from the downlink WPT. A novel closed-form downlink HE and uplink SE expressions are derived. Moreover, they propose an angle search trajectory design scheme to improve the per-slot spectral efficiency and design an access points search and line path trajectory schemes for comparison. Simulation results demonstrate that the proposed algorithm can achieve a large performance gain in terms of spectral efficiency.

The article "UAV-aided backscatter communications: Performance analysis and trajectory optimization" proposes a signal detection approach in UAV-aided backscatter communications and derives closed-form expressions for the error detection probability and bit error rate. The trajectory planning of multiple UAVs is optimized to minimize the energy consumption of UAVs. Theoretical and simulation results validate the derivations and show the importance of the optimized trajectory.

## V. UAV Communication Networks With Machine Learning

The article "Privacy-preserving federated learning for UAV-enabled networks: Learning-based joint scheduling and resource management" develops an asynchronous federated learning (AFL) framework for multi-UAV-enabled networks, which can provide asynchronous distributed computing by enabling model training locally without transmitting raw sensitive data to UAV servers. Moreover, the authors propose an asynchronous advantage actor-critic (A2C)-based joint device selection, UAVs placement, and resource management algorithm to enhance the federated convergence speed and accuracy. Simulation results are provided to evaluate the effectiveness of the proposed algorithm in UAV-enabled wireless networks.

The article "Deep reinforcement learning based three-dimensional area coverage with UAV swarm" addresses an area coverage problem by using a hierarchical UAV network. The authors build a 3-D model for an irregular terrain and project it to 2-D patches. A two-level UAV network is proposed to conduct the coverage tasks and a deep Q-learning algorithm is designed to select the patches. CNNs and the mean embedding method are used in SDQN to meet the communication constraints.

The article "Distributed multi-agent meta learning for trajectory design in wireless drone networks" investigates the trajectory design problem for the energy-constrained drones in dynamic wireless network environments. The proposed distributed multi-agent meta-learning method can dynamically learn drones' trajectories while generalizing their learning in unseen environments.

The article "Multi-UAV trajectory planning for energy-efficient content coverage: A decentralized learning-based approach" addresses the multi-UAV trajectory planning problem, aiming to provide ground users with content coverage. In particular, a decentralized learning-based approach has been proposed to maximize the energy efficiency of the UAV network. It shows that the proposed algorithm can achieve higher energy efficiency compared to the benchmarks.

The article "Multi-UAV trajectory and power optimization for cached UAV wireless networks with energy and content recharging-demand driven deep learning approach" considers exploiting UAVs equipped with cache and energy battery to serve users. Using a comprehensive dynamic optimization framework based on an infinite-horizon stochastic differential game, the authors investigate optimizing the UAVs' trajectory and radio resource allocation for minimizing a sum of several costs, including UAVs' average power consumption, users' request delay, and some penalty terms to mitigate UAV collision and avoid flying outside predefined space, and so on. The authors propose to solve the problem based on mean-field approximation and deep neural networks-based learning.

The article "Proactive UAV network slicing for URLLC and mobile broadband service multiplexing" formulates the UAV network slicing problem as a sequential decision problem to provide mobile broadband (MBB) services for ground mobile users, while satisfying ultra-reliable and low-latency requirements of UAV control and non-payload signal delivery. The authors exploit ADMM and echo state network to predict users' locations, construct accurate and analytically tractable channel gain models based on estimation results of DNNs, and develop a Lyapunov-based optimization framework to cope with the sequence-dependent problem.

## Acknowledgment

The Guest Editors would like to highly appreciate the strong support provided by Prof. Raouf Boutaba, Prof. Larry Milstein,

and Janine Bruttin, who are critical to the success of this Special Issue. The Guest Editors also give thanks to the authors and reviewers for their efforts to ensure that this is a high-quality and relevant Special Issue.

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