iTUAVs: Intermittently Tethered UAVs for Future Wireless Networks

Nesrine Cherif, Wael Jaafar, Evgenii Vinogradov, Halim Yanikomeroglu, Sofie Pollin, and Abbas Yongacoglu

Abstract

We propose the intermittently tethered unmanned aerial vehicle (iTUAV) as a trade-off between the power availability of a tethered UAV (TUAV) and flexibility of an untethered UAV. An iTUAV can provide cellular connectivity to an area while being temporarily tethered to the most adequate ground anchor. Also, it can flexibly detach from one anchor, travel, and then attach to another one to maintain and improve the coverage quality for mobile terrestrial users. Hence, we discuss in this article the existing UAV-based cellular networking technologies, followed by a detailed description of the iTUAV system, its components, and mode of operation. Subsequently, we present a comparative study of the existing and proposed systems highlighting the differences of key features, such as mobility and energy availability. To emphasize the potential of the iTUAV systems, we conduct a case study, evaluate the iTUAV performance, and compare it to benchmark systems. Obtained results show that with only 10 anchors in the area, the iTUAV system can serve up to 90 percent of the users covered by the untethered UAV swapping system. Moreover, results for a small case study illustrate that the iTUAV system allows to balance performance and cost, as well as be implemented realistically. For instance, when user locations are clustered, the iTUAV system with only two active iTUAVs and four possible anchor locations, outperforms a system with three TUAVs, while when considering a single UAV on a 100 minutes mission, a system with only six anchors already outperforms a freely flying UAV as it combines location flexibility with increased mission time.

Introduction

What are the advantages of UAV-mounted wireless communications? It increases the chances of a stable Line-of-Sight (LoS) dominated channel to ground terminals [1]. UAVs can also move and optimize their locations to satisfy the dynamic service demand [2, 3]. These two features represent the core of all innovative wireless communication solutions enabled by Unmanned Aerial Vehicles (UAVs), including UAV base stations (UAV-BSs), also called on-board radio nodes (UxNBs) by the Third Generation Partnership Project (3GPP).

The limited battery capacity is the main challenge to fully unleash the UAV-BS potential. To overcome this issue, several solutions have been proposed, such as deploying recharging stations, battery or UAV swapping, and laser charging. Moreover, providing UAVs with permanent energy supply through a tether, also known as tethered UAV (TUAVs), has been proposed as an alternative to the aforementioned solutions. Nevertheless, this concept offers unlimited flight time at the expense of limited mobility due to its predetermined hovering region [4].

Consequently, we propose here a novel development to the operation mode of the TUAV system, which would make it more flexible and thus more attractive to industry. It consists on the introduction of an agile tether that can be attached/detached to/from existing infrastructures, called ground anchors, such as UAV and electric vehicle charging stations, as illustrated in Fig. 1. We call this novel system intermittently tethered UAV (iTUAV). It is noteworthy that “ground anchor” and “anchor” are used interchangeably throughout the article.

The rest of the article is organized as follows: We discuss state-of-the-art works aiming to overcome UAV-BS battery limitation. Then, we describe the iTUAV system components, operational mode, and provide a qualitative comparison to existing technologies. The potential of the iTUAV is presented next through a case study. Finally, we highlight a number of future research opportunities and conclude the article.

UAV-Based Communications: A Review

In recent years, the use of UAVs to provide cellular connectivity has attracted increasing attention and their potential for complementing terrestrial networks has been investigated extensively in the literature. Due to their agility and flexibility, UAV-BSs can handle temporary spikes in data demands during short-term events, such as large concerts and sporting events [5]. However, UAV-BS operations are hampered by limited flying times, typically ranging from 30 minutes to a few hours. To tackle this problem, numerous solutions have been investigated, including battery recharging and swapping, UAV swapping, laser charging, and TUAV systems. We provide an overview of the pros and cons of these solutions in Table 1 and describe them in the following subsections.
Battery Recharging and Swapping

To overcome the battery capacity limitation, one can design a system where a UAV-BS flies back to a dedicated charging station to either recharge its battery or exchange it for a filled one. In [6], the authors studied the coverage performance of a UAV-assisted cellular network supported by charging stations. They derived the coverage probability as a function of the battery size, density of charging stations, and charging time. In the analysis, they identified a trade-off between the deployment density of charging stations and their quality (i.e., charging time).

Critique: Since UAV-BSs have to spend time to travel and recharge at a dockstation or land for battery swapping, these solutions cause frequent service interruptions, which is not ideal for stringent connectivity services, such as safety applications.

UAV-BS Swapping

In order to eliminate service interruptions, several works have proposed continuous UAV-BS swapping. In [6], the authors discussed the swapping strategy that continuously sustains a predefined mission. Similarly, the authors of [7] proposed an automated UAV swapping for continuous cellular connectivity by monitoring UAV-BSs battery levels.

Critique: These approaches offer high UAV-BS deployment flexibility and sustained cellular services. However, their advantages come at the expense of higher capital and operational expenditures (CAPEX/OPEX), due to a larger UAV fleet.

Laser Charging

Another solution consists of recharging UAV-BSs on-the-fly through laser beaming. This technology can be implemented with a laser array oriented through a set of mirrors or diamonds aimed at the UAV-BS’s collecting lens. In spite of its great potential, laser beaming requires large collecting lenses and high laser power, two factors that limit its deployment, especially in urban areas. Alternatively, distributed laser charging (DLC) involves the use of photo-voltaic cells instead of a collecting lens, which is practical and cost-effective for small UAV-BSs [8]. Unlike laser beaming, DLC uses less than one kilowatt transmit power, thus favoring its deployment anywhere. Finally, efficient DLC requires LoS between the charging source and UAV-BS.

Critique: Due to health-related concerns, laser beaming with high power cannot be used in densely populated areas. In the meanwhile, DLC may perform poorly in non-LoS conditions. Moreover, due to its slow charging regime, DLC is only efficient when the UAV-BS is on stand-by [8].

TUAV Systems

TUAV does not suffer from short operation time. Its main idea involves linking the UAV to the ground using a tether that provides both power supply and high-capacity backhaul. Consequently, the limited TUAV mobility is compensated by a longer operation time and higher backhauling capacity. In [4], the authors described a TUAV-aided cellular network and evaluated its coverage probability. This research was extended in [9] to optimize the TUAV joint-placement and user-association for maximized coverage probability.

These works introduced specific constraints to TUAVs, such as limited tether length and safety considerations to avoid tangling the tether around surrounding buildings. Also, they assumed that the tether serves both as power cable and wired backhaul link. This assumption implies complex and high cost tether and anchor designs, since additional data equipment deployment/configuration are required. Alternatively, a simpler tether design can be used for power supply only, while relying on wireless backhauling through either radio or free-space optical communications [10].

| UAV-based solution       | Pros                                                                 | Cons                                                                 |
|--------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Battery swapping and recharging | • Operating a small UAV fleet compared to other systems | • Frequent service interruptions 
|                          | • Cost of charging stations deployment | • High CAPEX/OPEX for large UAV fleets |
| UAV swapping             | • Ubiquitous cellular coverage | • Practical and cost-effective DLC for small UAVs |
|                          | • Flexible cellular service | • Battery charging during missions |
|                          | | • No service interruptions |
| Laser charging           | • Battery charging during missions | • Restricted laser beaming in high dense areas |
|                          | • No service interruptions | • Mandatory LoS for efficient DLC charging |
| TUAV system              | • Unlimited mission time | • Long battery charging time |
|                          | • Good cellular coverage | • Limited hovering region |
|                          | • Reliable backhaul link | • Static/manual deployment and redeployment |

TABLE 1 Comparison of UAV-based cellular systems.
**Critique:** The main disadvantage of TUAVs is the reduced flexibility due to the highly restricted flying distance. Moreover, backhauling through a tether implies higher equipment cost. Thus, TUAVs may be considered a good alternative to terrestrial BSs (TBSs) and by far do not offer the large advantages of UAV-BSs.

**Intermittently Tethered UAVs**

Given the limited hovering areas of TUAVs and battery-limited operation of untethered UAVs, we propose here a compromise solution, called iTUAV, which offers both the flexibility of a UAV and the sustainable operation of a TUAV. In what follows, we present the iTUAV system components, operation mode, and a qualitative features comparison to existing technologies.

**System Components**

An iTUAV-aided communication system involves several components shown in Fig. 1 and described as follows:

**iTUAV:** An iTUAV is a small UAV equipped with a lightweight 5G New Radio (NR) UxNB for communication, for example, Ericsson’s network-on-a-drone. Specifically, the iTUAV has the following modularity.

**Access:** As specified in 3GPP TR 22.829, UxNB is able to connect to the 5G core network and operate as a BS, via a wireless backhaul link, and can bootstrap as a BS, from the core network’s perspective. The user experiences no difference between being served by a UxNB or by a TBS. To do so, we assume that the UxNB is equipped with multiple antennas enabling directional patterns toward users [11].

**Backhaul:** The backhaul can be provided by a wireless gateway (e.g., a nearby TBS, TUAV, or satellite) or through an associated anchor, if it provides backhauling services. In the case of a wireless backhaul, integrated access and backhaul (IAB) can be leveraged [10, 11]. Since 3GPP does not enforce any particular IAB implementation, radio access and backhauling can use different frequency bands (e.g., dual-band IAB: millimeter wave for backhaul and sub-6 GHz for access) or the same spectrum. The latter is possible since a UxNB supports directional antenna arrays to spatially separate the links. Although this technology is cost-effective and leverages the iTUAV’s payload, it provides a lower system capacity and requires more complex resource management than the dual-band IAB.

**Power:** To reduce costs, we assume that the iTUAV is equipped with a small battery that enables short flight times to reach anchors and reconnect through a tether. Moreover, each iTUAV is equipped with a socket that allows it to attach a retractable tether from the anchor and that can be used simultaneously to power the motors in-flight and to recharge the battery. This design suggests landing over the anchor to attach the iTUAV, thus causing service delays. Alternatively, the iTUAV can be equipped with a lightweight tether that is dropped vertically to the anchor rather than landing on it [12].

**Ground Anchors:** These are mainly power supply sources used to sustain iTUAV operations. A ground anchor may include one or several of the following components. First, it must have access to the power grid and be equipped with adequate power converters to support different types and sizes of UAVs and electric vehicles. Second, it may be provided with standardized sockets to plug UAVs and electric vehicles. Third, it may include power tethers dedicated for iTUAVs with power sockets. Fourth, it may have a battery swapping station, which may be used by UAV-BSs. Additionally, the anchor can offer backhauling through a wired link combined with on-site routing equipment. The versatility of the anchor role favors its business and practical interests as part of the smart city infrastructure. For instance, anchors can be easily and seamlessly integrated to lampposts, road signs, and lights.

**Gateway:** This is the entry-point of the iTUAV to the core network. It can be the routing equipment of an anchor, a TBS, a TUAV, or a satellite. Except for the anchor that allows a direct wired connection to the core network, the other alternatives require wireless links with the iTUAV. Although wireless transmissions are less efficient than wired ones, communicating with a TBS equipped with highly directional antenna arrays using IAB is an effective and cheap alternative.

**System Operation**

We assume a communication system deployed in an urban environment, for example, smart city, consisting of iTUAVs, TBSs, ground anchors, and mobile ground users. The main goal of an iTUAV-aided communication network is to meet the performance requirements related to ubiquitous coverage, for example, during temporary events, and to on-demand network densification due, for instance, to peak traffic demands. Figure 2 details the operational steps of this system, explained below:

- A TBS detects users that cannot be reliably served. These users are localized and clustered, then assigned to an iTUAV.
- To serve the cluster of users, the optimal loca-
tion of the iTUAV and its associated anchor are jointly determined. The formulation and solution of this problem may take into account practical limitations, such as the propagation environment, backhaul link quality, TBS radio resources, etc.

- The iTUAV flies to the anchor and connects to it through a retractable power tether. Next, it travels to its optimal location and hovers to serve the associated cluster of users.

- Since users are mobile, the optimal location of the iTUAV (determined in the previous steps) may become out of reach of the tether’s length. In this case, the new optimal location and associated anchor must be recalculated. Subsequently, the iTUAV detaches itself from the current anchor and re-executes step 3.

**iTUAV Systems Versus Existing Technologies**

The idea behind iTUAV emerges from the trade-off between mobility and power availability. In what follows, we compare the UAV-based cellular networks, namely iTUAV, UAV (i.e., untethered UAV-BS), TUBA, and TBS, from different perspectives.

**Mobility:** UAVs equipped with BSs gained popularity thanks to their exceptional 3D mobility. A typical UAV-BS configuration consists of providing connectivity for temporary events with high traffic demands. Such scenarios cannot be handled by terrestrial cellular networks due to the fixed nature of TBSs. In contrast, TUAVs and iTUAVs are much less constrained, and thus can leverage their partially limited mobility to better serve users. Nevertheless, a TUAV is permanently fixed to an anchor, which limits its region of activity, compared to an iTUAV, which is able to travel from one anchor to another. Consequently, iTUAVs cover wider areas than TUAVs.

**Re-deployment Flexibility:** UAVs are valued for their rapid deployment feature, due to their high flying speed. An iTUAV can be re-deployed almost as quickly, either by relocating within a hovering region, subject to the tether length, or by traveling to the closest anchor to the targeted location. Note that the inherent re-location flexibility of a TUAV is strongly linked to the length of the tether and thus to its hovering region. That means, if redeployment is required in an area outside the hovering region, the TUAV cannot satisfy the new requirement. Finally, TBSs lack this feature due to their fixed nature.

**Cellular Reliability:** A terrestrial network is considered reliable when its TBSs deployment is optimized and does not experience substantial coverage gaps. An aerial BS increases the probability of LoS to communicate with ground users and thus is capable of providing a similar performance as a TBS. However, untethered UAV-BSs rely on wireless backhauling, which is limited compared to a TBS wired backhaul. A TUAV system offers better reliability due to its wired backhaul; nevertheless, its limited motion prevents it from offering a highly reliable coverage. Finally, an iTUAV ensures a better reliability than UAV/TUAV systems due to its flexibility in connecting with different anchors to achieve better access/backhaul links. With enough available anchors, iTUAVs can achieve similar performance to TBSs.

**Backhaul Availability:** A terrestrial network provides a highly available backhaul through fiber links and point-to-point RF transmissions. Similarly, TUAV-based solutions assume that backhauling is carried through fiber links aggregated with the power supply within the tether. By contrast, iTUAVs are expected to operate opportunistically with both wireless and wired backhauling. Indeed, whenever the anchor provides a tether with a fiber optic data link, backhauling goes through it. However, if an anchor is exclusively a power source or when an iTUAV is traveling between anchors, then it has to rely on wireless links to most adequate TBSs, that is, with enough capacity to handle the iTUAV’s traffic, or to other wireless gateways. Wireless backhauling is significantly affected by the environment conditions, such as closeness of wireless gateways, obstacles, shadowing, and so on. Finally, untethered UAV-BSs rely solely on the wireless backhaul.

**Energy Availability:** Clearly, the untethered UAV-BSs has the lowest power capacity. By contrast, energy for TBSs and TUAVs is available continuously. iTUAVs, although occasionally traveling, enjoy a very high energy availability. When an iTUAV is attached to an anchor, it has unlimited access to power as TUAVs. This energy is used for both iTUAV operation and battery recharging. However, when it is traveling between different anchors, it relies exclusively on its on-board battery. Note that locations of anchors and battery capacity must be carefully and jointly designed in order to avoid draining the iTUAVs’s battery when traveling between anchors.

**Infrastructure Reuse:** Terrestrial cellular infrastructure suffers from a low usage rate due to users with sporadic traffic demands. In TUAV systems, the anchor is permanently powering a single or several TUAVs through tether(s), resulting in small or no opportunities to reuse the tether or the power supply of the anchor. By contrast, an iTUAV is only attached to an anchor for the time of its mission, then it releases the tether and flies to a different location. The low usage rate of anchors by iTUAVs favors their reuse for other applications such as recharging flying taxis, cargo UAVs, and electric vehicles. Moreover, the fleet of iTUAVs is much smaller than the one considered by UAV swapping. Infrastructure reuse substantially increases iTUAVs’ economic viability. Moreover, the additional generated revenue from anchors reuse can offset the investment of extensive anchor networks and the expenses thereafter (e.g., rental of rooftops).

**CAPEX:** One of the main concerns in setting up cellular services is the amount of initial investment needed. TBSs are usually costly. Locations for their deployment need to be purchased or leased, and they require expensive electrical and communications equipment. In contrast, UAVs are less expensive, but have limitations that need to be considered. This typically leads to purchasing a high number of UAVs, batteries, and recharging stations to enable UAV swapping, battery recharging/switching. In the case of TUAVs, the initial investment consists of buying UAVs with their tether anchors for power supply and communication. Due to the limited tether length, covering a large area would require the deployment of several TUAVs, which may rapidly increase costs. Like TUAVs, iTUAVs rely on anchors, but with lighter functionalities. Indeed, Compared to TUAV systems, a smaller
Authorized licensed use limited to the terms of the applicable license agreement with IEEE. Restrictions apply.
to maximize the average number of connected users to the mobile UAV. The average is calculated over multiple network topologies (i.e., different scenarios for users’ and anchors’ locations) and time. We assume different battery capacities for the UAV (w/o swap), ranging between 30 and 60 minutes of flying time, while the iTUAV relies on a number of anchors, between 3 and 10. We notice that the UAV (w/o swap) coverage performance is low with a small battery capacity (e.g., 8 users per min. with a battery of 30 min.), but it improves with a larger battery capacity (e.g., 16.8 users per min. with a battery of 60 min.). However, the TUAV can continuously serve 8 users per minute. The TUAV performance is mainly limited by the tether that prevents the UAV from hovering at a better location where it could serve more users. With more anchors, the iTUAV enjoys better performance over time as it can also serve more users owing to its mobility and stable power source, that is, through the tether and the on-board battery when traveling between anchors. Finally, considering UAV (w/ swap), this system is equivalent to having an unlimited battery capacity while enjoying full motion flexibility, thus it achieves the best performance, that is, around 26 users in average are covered through time. This performance, however, comes at the expense of an additional investment in a higher number of UAVs and more complex operations. In a nutshell, we conclude that, thanks to its unlimited power and flexible association to anchors, the iTUAV is able to sustain a reliable cellular service over time, which is better than the UAV (w/o swap) and TUAV systems, but slightly below that of the UAV (w/ swap) reference system. If a higher number and more adequate locations of anchors are available, iTUAV performance is expected to reach that of the UAV (w/ swap).

In Fig. 5, we illustrate the cellular coverage performance of iTUAV and TUAV systems with multiple UAVs as function of the CoV. When the users are very clustered, the iTUAV can outperform a system with two fixed TUAVs. A system with two iTUAVs and four anchor locations, clearly achieves the best performance in clustered users scenarios. This is due to the opportunistic iTUAV behavior to move freely between anchors and associate with the best one. In contrast, the TUAV system has less leverage on relocating due to its static deployment.

**CHALLENGES AND FUTURE DIRECTIONS**

As research of TUAV and iTUAV systems is in its infancy, several challenges remain to be addressed. In what follows, we discuss some key issues.

**NEW ANCHOR, UAV, AND TETHER DESIGNS**

Current TUAVs are built with the tether already attached at both anchor and UAV ends, such that attaching/detaching the tether must be executed manually. To achieve more flexibility to iTUAVs, two options can be considered:

- The tether is within the anchor and it provides an easy-clip attach/detach system, but would require landing over the anchor to connect.
- The tether is within the iTUAV.

The iTUAV drops the tether and the anchor “catches” it to establish the connection. The first option would require a longer power connection time than the second due to additional landing and taking-off, while the second option would require a careful “cable catching” mechanism to bypass environmental factors, such as strong winds and obstacles. The second option would also require a lightweight and inexpensive tether design to reduce impact on the UAV’s size, weight, power and cost. For this matter, industry players, such as VICOR, are proposing to transfer high voltage over thin and lightweight tethers and to use small fixed-ratio bus converters within UAVs. Moreover, depending on whether the iTUAV will be equipped with a very lightweight tether or not, the challenge is to design automatic hold/release mechanical or electromagnetic winches and sockets at the stations and/or UAVs. Currently, similar conductive automatic charging systems are being prototyped for electric vehicles, such as the DAZEplug, which can inspire equivalent systems for iTUAVs. In addition, EasyAerial is on the right track with its Raptor UAV, which is capable of detaching itself from the tether.

**MANAGEMENT OF iTUAV OPERATIONS**

The management of UAV operations is an active area of research in the context of unmanned aircraft system traffic management (UTM). For iTUAVs, operations are slightly different since they can “jump” from one anchor to another and thus induce unpredictable environmental changes. This aspect should be considered when integrating iTUAV operations within UTM systems. Also, iTUAV operations may be affected by the deployment strategy of anchors. For instance, vehicle-mounted anchors may change location, thus causing placement and trajectory updates for iTUAVs.

**INTEGRATION OF iTUAV WITH 5G AND BEYOND TECHNOLOGIES**

Although the proposed iTUAV system offers a trade-off between the flexibility of UAVs and the unlimited power of TUAVs, their performance is still suboptimal. To further enhance iTUAV communications, other technologies can be leveraged, such as reconfigurable smart surfaces (RISs) and device-to-device (D2D) communications. Specifically, RIS and D2D communications can...
extend the coverage area of an iTUAV and thus reduce the number of required anchors. Such approaches are expected to drastically reduce the deployment costs of iTUAV systems.

**Conclusion**

With the proliferation of UAV-based applications and the recent development of TUAVs, iTUAV systems are envisioned in this article as an intermediate solution that offers a trade-off between the continuous power supply of TUAVs and the mobility of UAVs. In this article, we first provided an overview of UAV-based communications, including UAV-BSs and TUAVs. Then, we proposed the iTUAV system and detailed its components, operation mode, and distinguishing features. Through a case study, we evaluated the coverage performance of the proposed iTUAV system and compared it to UAV-BS and TUAV counterparts. Preliminary results demonstrated the potential of iTUAV systems to sustain long and reliable cellular connectivity missions. However, several issues need to be addressed before their extensive deployment.

**Acknowledgments**

This work is funded by Natural Science and Engineering Research Council of Canada (NSERC) and Research Foundation Flanders (FWO), projects no. S003817N (OmniDrone) and G098020N.

**References**

[1] M. Abouada et al., “3-D Placement of an Unmanned Aerial Vehicle Base Station (UAV-BS) for Energy-efficient Maximal Coverage,” IEEE Wireless Commun. Lett., vol. 6, no. 4, Aug. 2017, pp. 434–37.

[2] Q. Wu, Y. Zeng, and R. Zhang, “Joint Trajectory and Communication Design for Multi-UAV Enabled Wireless Networks,” IEEE Trans. Wireless Commun., vol. 17, no. 3, Mar. 2018, pp. 2109–21.

[3] W. Jaafar et al., “On the Downlink Performance of RMSA-based UAV Communications,” IEEE Trans. Veh. Technol., vol. 69, no. 12, Dec. 2020, pp. 16,258–63.

[4] M. Kishk, A. Bader, and M.-S. Alouini, “Aerial Base Station Deployment in 6G Cellular Networks Using Tethered Drones: The Mobility and Endurance Tradeoff,” IEEE Veh. Technol. Mag., vol. 15, no. 4, Sept. 2020, pp. 103–11.

[5] I. Bor-Yaliniz and H. Yanikomeroglu, “The New Frontier in RAN Heterogeneity: Multi-Tier Drone-Cells,” IEEE Commun. Mag., vol. 54, no. 11, Nov. 2016, pp. 48–55.

[6] B. Galkin, J. Kihlida, and L. A. DaSilva, “UAVs as Mobile Infrastructure: Addressing Battery Lifetime,” IEEE Commun. Mag., vol. 57, no. 6, June 2019, pp. 132–37.

[7] M. Erdelj et al., “UAVs that Fly Forever: Uninterrupted Structural Inspection Through Automatic UAV Replacement,” Ad Hoc Netw., vol. 94, Nov. 2019, p. 101612.

[8] W. Jaafar and H. Yanikomeroglu, “Dynamics of Laser-Charged UAVs: A Battery Perspective,” IEEE Internet of Things J., vol. 8, no. 13, July 2021, pp. 10,573–82.

[9] M. A. Kishk, A. Bader, and M.-S. Alouini, “On the 3-D Placement of Aerial Base Stations Using Tethered UAVs,” IEEE Trans. Commun., vol. 68, no. 8, Aug. 2020, pp. 5202–15.

[10] N. Tafitsis et al., “Aerial Access and Backhaul in Millimeter Wave B5G Systems: Performance Dynamics and Optimization,” IEEE Commun. Mag., vol. 58, no. 2, Feb. 2020, pp. 93–99.

[11] G. Castellanos et al., “Evaluation of Beamsteering Performance in Multisensor MIMO Unmanned Aerial Base Stations Networks,” IEEE Access, vol. 10, 2022, pp. 62,565–80.

[12] A. L. Yingst and V. Marojevic, “Tethered UAV with High Gain Antenna for BVLOS CNPC: A Practical Design for Widespread Use,” Proc. IEEE Int. Symp. World Wireless Mob. Multim. Net., July 2021, pp. 323–28.

[13] A. AL-Hourani, S. Kandeepan, and S. Lardner, “Optimal LAP Altitude for Maximum Coverage,” IEEE Wireless Commun. Lett., vol. 3, no. 6, Dec. 2014, pp. 569–72.

[14] A. Mirahsan, R. Schoenen, and H. Yanikomeroglu, “Het-HetNets: Heterogeneous Traffic Distribution in Heterogeneous Wireless Cellular Networks,” IEEE JSAC, vol. 33, no. 10, Oct. 2015, pp. 2252–65.

[15] N. Cherif et al., “On the Optimal 3D Placement of a UAV Base Station for Maximal Coverage of UAV Users,” Proc. IEEE Glob. Commun. Conf., Taipei, Taiwan, Dec. 2020, pp. 1–6.

**Biographies**

**NESSINE CHIBIB** [S] (ncher082@uottawa.ca) is a Ph.D. student at uOttawa. Her research interests include non-terrestrial networks.

**WAEL JAFAAR** [SM] (wael.jaafar@etsmtl.ca) is a Professor at École de Technologie Supérieure (ÉTS), University of Quebec. His research interests include wireless communications, non-terrestrial networks, cloud/edge computing, and machine learning.

**EVGENI VINOGRADOV** [M] (evgenii.vinogradov@tii.ae) is a Lead Researcher at Technology Innovation Institute (TII), UAE. His research interests include wireless communication, non-terrestrial networks, cloud/edge computing, and machine learning.

**HALIM YANIKOMEROGLU** [F] (halim@se.ece.carleton.ca) is a Chancellor’s Professor at Carleton University, Canada. His research interests cover many aspects of 5G/6G wireless networks.

**SOFIE POLLIN** [SM] (sofi.pollin@kuleuven.be) is a Professor within the Electrical Engineering Department at KU Leuven. Her research interests include networked systems that require networks that are ever more dense, heterogeneous, battery powered, and spectrum constrained.

**ABBAS YONGACOGLU** [LM] (yongac@uottawa.ca) is Emeritus Professor at uOttawa. His research area is wireless communications.