Abstract—Airborne base stations (carried by drones) have a great potential to enhance coverage and capacity of cellular networks. Multiple scenarios and use cases will highly benefit from such technology such as (i) offloading terrestrial base stations (BSs) in dense and urban areas, and (ii) providing coverage for rural areas. However, one of the main challenges facing the deployment of airborne BSs is the limited available energy at the drone, which limits the flight time. In fact, most of the currently used unmanned aerial vehicles (UAVs) can only operate for one hour maximum. This limits the performance of the UAV-enabled cellular network due to the need to frequently visit the ground station to recharge, leaving the UAV’s coverage area temporarily out of service. In this article, we propose a new UAV-enabled cellular network setup based on tethered UAVs (TUA Vs). In the proposed setup, the TUAV is connected to a ground station (GS) through a tether, which provides the TUAV with both energy and data. This enables a flight that can stay for days. We describe in detail the components of the proposed system. Furthermore, we enlist the main advantages of a TUAV-enabled cellular network compared to typical untethered UAVs. Next, we discuss the potential applications and use cases for TUAVs. Finally, we discuss the challenges, design considerations, and future research directions to realize the proposed setup.

INTRODUCTION

It is widely believed that realizing a communication system where a base station (BS) is placed on top of a drone (airborne BS) will be beneficial for multiple scenarios. This is due to the inherent relocation flexibility of the drone and the higher probability to establish a line-of-sight (LoS) link with the ground users, because of the high altitude, which enables providing coverage for wider areas [1]. One of the scenarios that will highly benefit from airborne BSs is providing coverage for rural areas. Rural areas are commonly neglected or receive less interest from operators. According to [2], there are around two billion people around the world that lack internet coverage, mostly located in rural areas. Airborne BSs can be the solution for such problem due to its cost efficiency and faster deployment time, compared to the expensive and space consuming cell towers. Another potential application for airborne BSs is offloading terrestrial BSs in dense and urban areas. Deploying airborne BSs in such areas significantly enhances cellular coverage and capacity.

These potential advantages of airborne BSs have motivated the research community to study multiple aspects of UAV-enabled cellular networks such as the air-to-ground (A2G) channel characteristics [1], optimal placement of UAVs [3], and trajectory optimization [4]. In addition, there are two key design challenges in UAV-enabled systems that will be discussed in more details in this article. The first one is the limited energy resources available on board, which makes the flight time limited to less than one hour in most of the commercially available UAVs. The second key design challenge is the backhaul link.

Typically, the energy consumption of a UAV is two-fold: (i) propulsion energy, which is the energy consumed by the UAV for the purpose of flying and hovering and (ii) payload energy, which captures the energy consumption for communication and on-board processing. Many research works has been directed to designing energy efficient communication schemes for the UAVs in order to prolong their lifetimes [5]. However, since propulsion energy is significantly more than the payload energy [6], energy efficient communication will not highly affect the flight time. Such short flight times might not be an issue for some use cases, such as drone-based delivery between nearby locations or data dissemination and collection from sensor networks. However, when it comes to establishing a UAV-mounted BS, longer flight times are vital in order to ensure stable and uninterrupted cellular service. The problem of short flight times has motivated some work in the direction of relying on other resources of energy beside the on-board battery [7], [8]. One of the potential candidates for such purpose is solar energy. However, solar energy harvesting requires large solar panels in order to provide sufficient energy for the UAV. Unfortunately, the small size of UAVs makes it not possible to support large and heavy solar panels. In addition, heavy batteries are required in order to store the harvested energy and use it to ensure stable operation during the night. With that being said, it is worth mentioning that high altitude platforms (HAPs) are eligible for deploying solar panels. In fact, HAPs can stay in the air for months relying on solar energy harvesting. However, compared to HAPs, low altitude UAVs are faster to deploy, and have have better A2G communication channels due to the short-range LoS links. Other potential solutions to extend the flight time include laser-powered UAVs and battery hotswapping [7], [8]. Since recharging a battery takes quite a long time, battery swapping is a good alternative to avoid interrupting the UAV’s operation. However, this brings forth the challenge of developing mechanical systems that can handle autonomous battery exchange.

Unlike terrestrial BSs, which have wired backhaul links (typically using fiber cables), UAVs rely on wireless backhaul links. Compared to wired links, wireless backhaul links are susceptible to higher latency, interference, and lower achievable data rates. Hence, it is important to find the
best technology to establish a wireless backhaul link at the UAV \cite{9, 10}. Available solutions in the literature include: (i) satellite communication, (ii) millimeter wave (mmWave) communication, (iii) free space optical (FSO) communication, and (iv) in-band LTE backhaul communication. Each of these four solutions has its own pros and cons. For instance, satellite communication ensures a more reliable backhaul link, but suffers from higher latency. On the other hand, mmWave and FSO backhaul links ensure much higher data rates, compared to in-band LTE backhaul. However, both solutions suffer from high vulnerability to blockage and are reliable only over small distances. The solution of using in-band LTE for backhaul receives most of the attention in current literature. This solution has lower latency, compared to satellite backhaul. It does not require an LoS channel to communicate efficiently, like mmWave or FSO. However, due to the high altitude of the UAV, it suffers from higher levels of interference, which can reduce the achievable rate of the backhaul link significantly.

In this article, we propose a system setup that is based on tethered UAVs (TUAVs). The proposed technology solves the two technical challenges discussed earlier in this article: (i) short flight time due to limited onboard energy, and (ii) establishing a reliable/efficient backhaul link. Being connected to a stable resource of energy at the ground through the tether, TUAV can sustain much longer flight times. In addition, a TUAV has a wired data-link through the tether with the ground station (GS). This ensures reliable communication at high data rates between the TUAV and the GS. The great potential of TUAV to solve a lot of the current UAV challenges motivated many companies to start developing their own products of TUAV. The current commercially available TUAV products can stay in the air with uninterrupted operation for days. In addition, they can reach up to 150 meters (limited by the length of the tether). Furthermore, the data-link between the TUAV and the GS can achieve up to 200 Mbps, which ensures a fast and reliable backhaul link.

As explained earlier, we do not have today the technology to ensure long endurance of untethered UAV-mounted BSs. Hence, the TUAV can be seen as a bridge that will take us one step closer to the envisioned fully untethered UAV-enabled cellular network. On one hand, the TUAV unlocks the inherent benefits from the deployment at high altitudes. On the other hand, both the altitude and the UAV mobility are limited by the length of the tether. However, while the tether imposes some limitations on the mobility of the UAVs, it is a key-enabler for realizing a reliable UAV-mounted BS in the first place. In Fig. 1, we visualize the key differences between terrestrial BSs, UAVs, and TUAVs, in terms of main system advantages. It can be observed that TUAVs compromise some of the qualities of untethered UAVs in order to gain specific characteristics, that are necessary for reliable operation of an airborne BS. In particular, the TUAV sacrifices the mobility and relocation flexibility of UAVs in order to maintain the main requirements of a reliable cellular BS in terms of endurance and backhaul link quality. In the rest of this article, we will describe in detail the TUAV system. Next, we will discuss the main advantages of TUAVs and their potential applications and use cases. Finally, we will enlist the main challenges and design considerations that need to be carefully studied in future research works.

**System Setup**

The proposed system setup consists of three main components: (i) the UAV, (ii) the tether, and (iii) the GS. As shown in Fig. 2 the GS is placed at a carefully selected location and has a reliable connection to (i) the core network and (ii) a stable resource of energy. These two connections are extended to the UAV through the tether. Hence, the tether provides the UAV with uninterrupted energy supply, enabling it to stay in operation with significantly extended flight times. In addition, the tether also links the UAV to the core network through a wired connection providing it with a stable, reliable, and secure backhaul link.

The first and most important component of the TUAV system is the UAV. The UAV carries the antennas and some processing units. These processing units are connected to the GS through data-carrying optical fiber along the tether. While the antennas and the processing units are considered
heavy components for typical UAVs, current commercially available TUAU systems are prepared to carry up to 60 Kgs of additional payload [11]. The main job of the UAV is to hover within the possible range and find the optimal 3-dimensional (3D) placement given the tether length constraint, to provide maximum cellular coverage for ground users.

The UAV can only hover within a specific range, which mainly depends on the tether length. Assuming the ground station, which is the launching point of the UAV, is placed at a rooftop, the UAV can hover around the rooftop within a hemisphere of radius equivalent to the tether length and centered at the rooftop. The overall region within which the UAV can hover is limited mainly by the heights of the neighboring buildings, as well as the tether length. In the rest of this article, we will refer to this region as the hovering region.

It is clear from the above discussion that the smart selection of the rooftop locations is of high importance for the performance of the TUAU system. For instance, placing the GS at a rooftop surrounded by taller buildings from all sides would reduce its hovering region to almost only the area above its own rooftop. Smaller hovering region leads to a more constrained UAV 3D-placement problem and limits the mobility of the TUAU. The rooftop selection process should take multiple aspects into consideration such as the traffic demand spatial distribution, the rooftop’s height among its surrounding buildings, and its capabilities in terms of access to an energy resource and wired connection to the core network.

Note that the launching points of the UAV (the GSs) do not have to be placed at rooftops. Another choice would be placing the GS on a moving vehicle on the ground. This provides the TUAU system with an additional degree of freedom due to the ability of moving the launching point and changing it on demand. Placing the GS on a moving vehicle is a reasonable choice mainly in rural areas where there are no multiple tall buildings that might limit the hovering region of the UAV. However, in dense urban areas, it is more appropriate to place the GS on a rooftop to have a larger hovering region and to keep the tether away from public access to ensure its safety from malicious attacks or even accidental tangling.

**Main Advantages**

As discussed earlier, untethered UAVs are limited by the on-board battery as the sole resource of energy. Given that it typically takes less than an hour for battery depletion, the UAV operation itself is quite limited in many aspects. For instance, the payload of the UAV is typically kept low to reduce energy consumption during operation, the power dedicated for communication with ground stations or ground users is limited, and the relocation of the UAV should be minimized since it consumes most of the available energy on-board. Hence, untethered UAV’s energy limitations significantly affect its performance and reliability as a stable aerial BS. In this section, we will discuss in more detail the advantages of TUAUs compared to untethered UAVs or terrestrial BSs.

**Advantage 1.** The TUAU can stay in operation for days. It needs to land at the GS only for maintenance, which is a normal procedure even for terrestrial BSs. Prolonged flight times of the TUAUs makes them comparable to terrestrial BSs in terms of endurance. However, TUAU has the advantage of higher altitude and more mobility (within the hovering range), which can be exploited to optimally place and relocate the TUAU according to the traffic demands and the channel conditions with mobile users. Furthermore, compared to terrestrial BSs, a TUAU has much safer maintenance procedure, since it does not require climbing high towers. One more advantage for the TUAU over terrestrial BS is the reduced terrestrial footprint. The space required for the GS can be as small as the rooftop of a typical urban building. This space is only required to place some processing units and to establish the connections to the energy resource and the core network. In addition, unlike the deployment of terrestrial BSs, which is fixed and permanent, the GS of the TUAU (which is its launching point) can be relocated whenever necessary from one rooftop to another.

**Advantage 2.** The TUAU has the ability to sustain heavier payloads compared to untethered UAVs. This is due to the existence of a stable energy resource connected to the TUAU through the tether. In fact, current commercially available TUAU products can achieve up to 60 Kgs of payload. Thus, TUAUs can afford having more antennas and radio chains, which enables sectorization and/or MIMO. Hence, TUAUs offer more capacity and better interference management compared to untethered UAVs.

**Advantage 3.** Due to having a wired data-link with the GS through the tether, TUAU can delegate some of the processing units to the GS, such as the baseband unit. This reduces the used TUAU payload, which enables placing more antennas at the TUAU.

**Advantage 4.** As explained earlier, one of the main research challenges in establishing untethered UAV as an aerial BS is backhaul communication. According to recent studies, backhaul capacity imposes significant constraints on the achievable data rates between the UAV and the ground users [12]. In fact, there is a trade-off between placing the UAV close to the terrestrial BS to ensure strong and reliable backhaul link with high capacity, and placing the UAV close to the mobile users to enhance the quality of the channel between the UAV and mobile users. Hence, even in untethered UAV, free mobility and flexible placement is still constrained by the quality of the backhaul link and the distance to the terrestrial BS, which can be considered as virtual tether. On the other hand, TUAU has a stable wired connection to the GS with significantly higher capacity compared to a wireless backhaul link. Not only does this affect the achievable data rates, due to the high backhaul capacity, but also it frees more resource blocks for serving mobile users, that were reserved for wireless backhaul link in untethered UAV systems.

**Advantage 5.** One of the major concerns when using a UAV is the drone flyaway. During UAV operation, flyaway can be caused by many reasons such as software glitches, lost connection between the ground station and the UAV due to flying out of control range, hardware failure, interference in the communication channel leading to loss of control, or strong wind. In addition to the financial loss and the negative effect on
the performance of the UAV-enabled communication system, a drone flyaway imposes numerous public risks. It may crash into a pedestrian, a building, a highway, which might cause dangerous accidents. Many accidents caused by drone crashes or flying in improper areas were reported over the past few years, such as the Gatwick airport incident. The airport had to suspend flights in and out for several hours due to the sight of two drones near the runway. While untethered UAVs are susceptible to all these kinds of risks, TUA Vs are physically connected to the ground station through the tether. This limited length-tether can add another measure of controllability to the UAV, which is able to prevent the drone from straying away.

Advantage 6. One of the deployment challenges of terrestrial base stations is the fluctuations in the capacity utilization over the day. Mobile operators often observe that traffic demand peaks do not happen at the same time, even within a cluster of neighboring BSs. Hence, since each individual BS has to cater for the peak traffic demand it needs to serve, mobile operators end up procuring more area capacity than actually needed. The advantage of TUA Vs is that they can rearrange their physical locations and orientations to dynamically address spatial-temporal changes in the traffic demand. For a given spatial-temporal traffic pattern, the number of TUA Vs required would be less than their rigid terrestrial peers.

Capacity Enhancement and Traffic Offloading in Dense Urban Areas

TUA V’s main applications and use cases are those that require high endurance and prolonged flight time. For instance, untethered UAV with a flight time of one hour is eligible for applications like providing cellular coverage in emergency scenarios, or short-term events. However, traffic offloading in urban areas requires a more sustainable UAV operation, which is a perfect fit for the TUA capabilities. As shown in Fig. 3 GSs can be placed on multiple rooftops in dense urban areas. As noted earlier, the taller the rooftop, the larger the hovering region of the TUA gets. Having multiple TUA Vs with large hovering regions enables changing the constellation of the TUA Vs in the sky whenever needed, based on the traffic demands and the user locations. Reaching such flexibility in the spatial distribution of the TUAVs actually reduces the effect of the mobility restrictions induced by the tether, leading to a performance almost similar to that of untethered UAVs, in terms of mobility and relocation flexibility. Note that it is of great importance to smartly select the locations of the rooftops based on the statistics of the spatial distribution of traffic demands.

Coverage Enhancement in Rural Areas

Network operators are often not willing to invest in rural and low income areas, due to high costs of network deployment and low potential profits. As briefly discussed earlier, TUA Vs require much less time and money for deployment and operation compared to typical terrestrial BSs. As shown in Fig. 4 a TUAV communication system can be used to enhance cellular coverage in rural areas. Due to the nature of rural areas, where there are no much tall buildings, placing the GS on a moving vehicle can be enough to achieve large hovering regions. In addition, since traffic demands are significantly lower than urban counterparts, continuously changing the spatial location of the TUAV will not be necessary.

Network Densification: Terrestrial Small Cells vs. TUAVs

One of the top benefits of airborne BSs is the quality of A2G channel with mobile users. Due to the higher probability of establishing a LoS A2G channel, the coverage radius of an airborne BS is higher than that of a terrestrial BS. With the stable power supply carried through the tether, enabling long term operation of the UAV, TUAV can be used for network densification in areas with high traffic demand. Even though TUAV’s mobility is restricted compared to untethered UAV, it still brings the benefits of high altitude deployment. To investigate the potential of TUAVs in the context of network densification, in Fig. 5 we show the simulation results for coverage probability as a function of the deployment density for TUAVs compared to terrestrial small cells (SCs). Here we define the coverage probability as the probability that a randomly selected ground user has an average path-loss below a predefined threshold. The results show that we need around 75% less number of BSs to reach the same coverage probability when TUAVs are used instead of terrestrial SCs. For instance, to ensure a coverage probability of 0.9, we need
to deploy 5 TUAVs/km², while we need to deploy 20 terrestrial SCs/km² to achieve similar performance.

Note that here we are just assuming that each TUAV is hovering exactly above the rooftop where its GS is placed, which even underestimates the performance of the TUAV system. The TUAV can hover within its allowed hovering region in order to relocate itself closer to user hotspots. To give a general idea of how the hovering region should be exploited to locate the TUAV as close as possible to user-dense areas, we consider a system where the user locations are modeled by a Poisson cluster process [13]. The clusters in such a model represent the user hotspots, hence, the optimal deployment locations for the TUAVs are at the centers of the hotspots (clusters). However, the potential available rooftops for the deployment of the GS might be limited for many reasons. In that case, the GS should be placed at the closest possible rooftop to the cluster center. The next step is to find the closest point to the cluster center in the hovering region and locate the TUAV at this point. In Fig. 5, the results confirm that relocating the TUAV as close as possible towards the cluster center, within the hovering region, significantly improves the coverage probability, compared to just hovering the TUAV exactly above its own rooftop (case 2 versus case 3). Furthermore, when the distance between the rooftop and the cluster center is below a specific threshold, the coverage probability is almost similar to the case of deploying the GS at a rooftop located exactly at the cluster center (case 2 versus case 1).

**Challenges and Design Considerations**

**Challenge 1.** While airborne communication systems, in general, require new regulatory policies, TUAV systems might need some special considerations. For instance, new safety regulations should be implemented for the areas where tethers are allowed to extend. Safety margins around buildings and above ground have to be kept to avoid (i) any accidents because of tangling or (ii) any malicious attempts to mess with the tether. Given the high importance of the tether in the system, carrying data and providing power to the drone, its safety is vital to the safety of the drone. These restrictions impose some constraints on the potential deployment locations of the GS and the hovering regions. Hence, the TUAV optimal placement problem should take such safety regulations into consideration.

**Challenge 2.** As it can be noticed from Fig. 3, it makes more sense to place the GSs on tall rooftops when establishing TUAV systems in dense urban areas, due to the high density of obstructions (tall buildings). On the other hand, as observed from Fig. 4, rural areas are less-obstructed, hence, the altitude of the TUAV does not have to be very high, making it sufficient to place the GS on a moving vehicle. However, when deploying TUAV systems in urban or suburban areas, a trade-off comes to picture. On one hand, placing the GS on a moving vehicle has the advantage of mobility and, hence, the ability to relocate the GS, whenever needed, towards areas with more user density and higher traffic demand. In addition, it is less expensive than rooftops which require monthly/annual rents for building owners. On the other hand, rooftops have the advantage of higher altitude, which adds extra hovering region for the TUAV given the limited tether length. In addition, it keeps the tether away from public access, ensuring safer operation.

**Challenge 3.** Unlike typical untethered UAV placement optimization research work, TUAV placement problem is different. Each TUAV has to be physically connected to the GS on the rooftop through the tether during operation. Hence, the problem is more constrained and needs to be carefully studied. The rooftop selection problem can be solved using different approaches depending on the main objectives of the operator in terms of quality of service (QoS). In addition to cellular coverage-related considerations, cost efficiency should also be taken into consideration during the rooftop selection process. In fact, there is a trade-off between deploying less TUAVs at
tall rooftops located in the middle of user hotspots (probably higher rents), and deploying more TUAVs at shorter rooftops. This trade-off between capital expenses (number of TUAVs) and operational expenses (rooftop rents) adds another layer of complexity to the optimal rooftop selection problem.

**Challenge 4.** Given the location selected for placing the GS, it is important to know exactly how the hovering region looks like. Given the constraints of avoiding tangling upon neighboring buildings, ensuring being far enough from public access, and establishing safety margin above all surrounding buildings for safety, the hovering region of each rooftop is actually unique. In order to solve the 3D placement optimization problem of a TUAV, an analytical model for the hovering region needs to be derived first.

**Challenge 5.** The limited tether length imposes some challenges on the design of a TUAV-enabled communication system. Achievable tether lengths by commercially available TUAVs vary from 100 to 150 meters. These limitations usually result from the added weight of the tether. However, one of the main problems that UAVs, tethered and untethered alike, have to deal with, is suffering from high interference levels when deployed at high altitudes. Hence, TUAV will probably be flown at altitudes much less than its maximum tether length, to reduce the interference level [14]. The rest of the tether length, can be used to expand the hovering region in the azimuth space as much as possible, given the geometrical constraints posed by the building clutter.

**Conclusion**

In this article, we discussed the potential of TUAV for cellular coverage and capacity enhancement. The proposed setup can be thought of as a compromise that aims to replace the current untethered UAV performance constraints resulting from limited on-board energy with mobility constraints resulting from the tether connection. We showed that TUAV systems have some promising advantages compared to untethered UAVs, despite the mobility constraints resulting from the tether. We discussed some potential use cases and applications where TUAV-mounted BS will be of great benefit, such as capacity enhancement in urban areas, coverage enhancement in rural areas, and network densification. Finally, we discussed some open challenges and research problems that need to be well-investigated in order to understand better the performance limitations of the proposed setup.

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