Unleashing the Potential of Tethered Networked Flying Platforms: Prospects, Challenges, and Applications

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Abstract

Researchers are currently speculating about what the six generation (6G) of wireless systems will be. Several applications are proposed ranging from enhancing the conventional mobile communications to holographic and tactile communications. However, a crucial and pivotal aspect of 6G is worldwide connectivity. In fact, nearly 4 billion people do not have internet connection. Hence, 6G intends to bridge the digital divide and connecting the unconnected. For that purpose, 6G relies on terrestrial communications, satellite communications, and airborne communications. Terrestrial and satellite communications are expensive and take time to deploy. Airborne communications overcome these limitations and have shown promising success, such as, unmanned aerial vehicles (UAVs) and high altitude platforms (HAPS). However, even though these free flying platforms are a promising solution, they have issues with endurance and backhaul capacity. Tethered flying platforms overcome these limitations by providing continuous supply of power and data via the tether. They are also cost efficient and have good green credential. Not limited to communications, tether platforms have a wide range of applications, such as, energy harvesting, entertainment, science, research, public safety, disaster relief, Government, and defence. In this survey, we intend to provide an extensive and comprehensive overview of tethered platforms. We provide all the types of tethered platforms, their components, applications, advantages as well as their challenges. We also show several case studies in various fields and applications. Finally, we present the start of art of tethered platforms from a wireless communications perspective.

Index Terms
Tethered Networked Flying Platforms, tethered balloons, tethered blimps, Helikites, Unmanned Aerial Vehicles (UAVs), tethered UAVs, High Altitude Platform (HAPS), tethered HAPs, lighter-than-air platforms, heavier-than-air platforms, aerostats platforms, aerostatic, aerodynamic platforms, Buoyant Airborne Turbines (BATs), hybrid airship, wireless communications.

I. INTRODUCTION

In 1980s, the first generation (1G) of wireless communications was launched allowing voice communication. After, nearly 40 years, the world is ready to launch the fifth generation (5G) if wireless communications. An evolution of standards have been witnessed through this saga of communications generations resulting in an increase of data rates and a decreases in latency form each each generation to another. Now, the researchers are speculating on what the six generation (6G) will be, or more exactly, what 6G should be [1]. Researchers start to investigate the perspectives of 6G [2]–[7]. Some argue that we should be less concerned about high data rate, but rather focused on the classes of services provided by the 6G as well as the it will be this and this and this longevity of the mobile battery [2]. Other propose new type of communication scenarios such as, tactile Internet, teleoperated driving, flying networks, and holographic calls [4]. The paper [1] presents some of the applications that the 6G can offers, such as, enhancing the conventional mobile communications, increasing the accuracy of indoor positioning, providing holographic and tactile communications, and worldwide connectivity and integrated networking.

Worldwide connectivity is major concern, especially since the number of unconnected people it the end of 2018 was 3.9 Billion [8]. Indeed, a large proportion of people around the word do not have access to internet connection, especially and rural, sparse, and poor areas. The services that are lacking in these areas, and can be further facilitated by the internet connection include, but not limited to, eHealth, eEducation, farming, eCommerence, and eGovernment. That is why 6G intend to bridge this digital divide and connect the unconnected [9], [10].

For that purpose, 6G intends to rely on the following trifecta: terrestrial communications, satellite communications, and airborne communications. Terrestrial communications and tower mast are expensive to erect. Which is not a lucrative business model form telecommunications company in poor or rural areas. Plus, it takes time to construct terrestrial communications. Also, terrestrial communications only are suitable for two-dimensional scenarios, that is the height of the users are relatively negligible. For instance, terrestrial communications are ill-suited to connect the upcoming flying cars [11].
On the other hand, satellite communications are extremely expensive, they take time to deploy and have low delay due to the distance between the satellite and the users. Also, satellite communications need satellite phones, which are bulky ones, and they require global subscription for global coverage. At the time of writing this paper, there are two companies that are working on solutions to connect regular phones with satellites, namely Lynk Global [12] and AST & Science [13]. The test carried out of these two companies are at early stages, they offer global communications via regular phone in a decade or two.

The last type of communications aforementioned are airborne communications. Recently this type of communications is facing a great interest from researchers due to their intrinsic flying properties which allow them a large coverage. These airborne communications include different type of flying platforms. Some of them flying at lower altitude such unmanned aerial vehicles (UAVs) [14]. Others fly at higher altitude such as high altitude platforms (HAPs) [15]. These flying platforms overcome some of the satellite and terrestrial communications’ limitations, such as higher cost, low delay, and slow deployment.

However, the main limitations of these flying platforms are persistence, endurance, and backhaul connection. To deal with these limitations, other types of flying platforms are currently used and used by government, military, and telecommunications companies: tethered platforms.

Tethered platforms, as their name suggest, are tethered with a ground unit. The tether supplies continuously the flying platforms with data and power. Tethered platforms are cost efficient and have overall low operation cost compared to other free flying platforms.Also, in terms of wireless communications perspective, they are cost efficient compared to other communication infrastructure such as bases stations and satellites. Another aspect that make tethered platforms a great solution compared to free flying platforms is endurance and persistence. This aspect is crucial in telecommunication and surveillance mission. They are also quick and relatively easy to deploy. But, the most relevant properties of tethered platforms are their backhaul capacity and constant supply. Not limited to communications, tethered platforms have applications, such as, energy harvesting, entertainment, science, research, public safety, disaster relief, Government, and defence. Tether platforms can also carry out several applications at the time, acting as “Swiss army knife”.

To the best of our knowledge, there are no survey papers about to tethered platforms in the literature. Although there are some papers dealing with tethered aerostats from a design and manufacturing perspective, such as, [16]. No prior works have considered comprehensive
overview of tethered platforms, and we hope that this survey fills this gap.

The organization of this paper is as follows: Section II gives an extensive overview of tethered platforms. Use cases, projects and companies related to tethered platforms are presented in Section III. In Section IV explores tethered platforms from wireless communications perspective. Finally, we conclude this paper in Section V.

II. OVERVIEW OF TETHERED PLATFORMS

A. Type of Tethered Platforms

Airborne platforms are vehicles that can fly in the air by opposing the force of gravity either using a static lift or a dynamic lift. For instance, balloons and blimps use static lift and they belong to the lighter-than-air (LTA) category, whereas airplanes and UAVs use dynamic lift and they belong to the heavier-than-air (HTA) category. However, there is also a hybrid category that use both static lift and dynamic lift. In this survey, we are only interested in tethered platforms, hence free flying platforms are out the scope of this paper.

1) LTA Tethered Platforms: The LTA platforms that use static lift or aerostatic lift are called aerostats. They are filled with an LTA gas with low density such as helium. The difference between the density of the air outside the envelope of the aerostat and the density of LTA gas produces buoyancy according to Archimedes’ principle. The most popular tethered LTA are balloons and blimps.

   a) Balloons: Balloons were the most used shape (spherical shape) for tethered platforms, or more precisely, tethered aerostats Fig.1. They are easy to design and manufactured with less cost than the other tethered aerostats. They are also easy to deploy. The maximum altitude that tethered balloon can research is around 600 m to 700m, and the maximum payload that they can carry is around 50 Kg. However, they are designed to sustain high speed wind since their shape is not designed to cope with high speed wind. Tethered balloons can sustain wind speed around 20km/h up to 40 Km/h.

   b) Blimps: Blimps, or also known as streamlined aerostat, are high performance platforms since they can sustain high speed wind, carry heavy payloads, and stay aloft at high altitudes Fig.2. There are several categories of blimps, and they differ in sizes, altitudes and payloads [17]. For instance, TCOM categorizes their blimps into three classes, tactical class, operational class, and strategic class, as depicted in Fig.3.
• Tactical Class: tactical class blimps are compact and can be deployed rapidly. Their envelope size range from 12m and 17m. They are suitable for surveillance missions with tactical needs. They have been used in Iraq and Afghanistan by the U.S army, and for border surveillance between U.S and Mexico. They can carry 27 Kg of payload and research altitude of 300m. Also, they can stay aloft for 7 days and sustain a wind speed of 100 Km/h (see Fig.2a).

• Operational Class: operational class blimps have a medium sized envelope that ranges between 22m and 28m. They combine portability and flexibility for quick deployment and retrieval. They can carry a payload up to 200 kg, and they can research altitude of 1Km. This class of blimps are suitable for surveillance and monitoring operations where land-based surveillance in unfeasible. Also, they are suitable for maritime surveillance and border surveillance. Operational Class blimps can stay aloft for two weeks and they can sustain a wind speed of a 130 Km/h (see Fig.2b).

• Strategic Class: strategic class blimps have arguably the largest tethered platforms in market. Their envelope size ranges from 71m to 74m and they can carry a large payload of 2300 kg. They are ideal for long surveillance and monitoring mission since they can stay in the air for 30 days and can sustain a wind speed of 166 km/h. They can also reach an altitude of 4,6 Km allowing them to cover a large area. They are also used to detect low flying aircraft or cruise missiles (see Fig.2c and Fig.2d).

c) Buoyant Airborne Turbines (BATs): Buoyant Airborne Turbines (BATs) are wind turbine manufactured by Altaeros [18]. They can reach an attitude of 600 m since wind speeds are higher than at the ground. They can harvest twice the energy compared to land-based tower turbines.
Fig. 2: The different types of TCOM blimps [17].

[19]–[22]. BATs envelope is filled with helium and have a tether that keeps them in place while transmitting the harvested power to the ground station (see Fig.4).

2) HTA Tethered Platforms: The HTA platforms that use dynamic lift or aerodynamic lift are called aerodynes. Their lift is produced by the relative motion between the HTA platform and the air, hence pushing the platform upwards (Bernoulli’s principle). The most popular tethered HTA are tethered UAVs and airborne turbine kite.

a) UAVs: tethered UAVs are UAVs with a physical link called tethered that supply them with power and data, and they can reach altitude of 200 m and can carry a payload up to 15 Kg (Fig.5). They usually have a battery back in case the tether damaged or if there is a cut in power. Since, the tethered UAVs have a constant supply of power, their can, in theory, stay up in the air for an unlimited period of time. However, the main limiting factor is the motor of the UAV which starts to heat up and get hot. But they can still stay aloft for 2 to 4 days.
| Altitude | Flight Duration | Payload | Wind Speeds |
|----------|----------------|---------|-------------|
| 5 Km     | 7 days         | 27 Kg   | 74 Km/h – 100 Km/h |
| 1 Km     | 14 days        | 200 Kg  | 92 Km/h – 130 Km/h |
| 300 m    | 30 days        | 2300 Kg | 130 Km/h – 166 Km/h |
|          |                |         |             |

Fig. 3: TCOM blimps and their type of missions.

Fig. 4: Altaeros BATs.

(a) [Image]

(b) [Image]
b) Airborne Turbine Kite: Airborne Turbine Kite are wind turbine used to harvest wind power in the air since wind speed is higher at higher altitudes (see Fig. 6). Thus, they can harvest more energy than a tower, with less cost compared to tower construction. Their electrical generator can be land-based (on the ground), or airborne (in the air). The tether is issued to transmit the harvested energy to the ground. They can be held aloft at lower altitude or higher altitude, and they can reach an altitude of 4600 m [24]–[26].

3) Hybrid Tethered Platforms: As mentioned before, hybrid platforms use both static lift and dynamic lift. The static lift is produced by buoyancy (Archimedes’ principle), and the dynamic lift is produced by the relative motion between the aircraft and the air, hence pushing the aircraft upwards (Bernoulli’s principle). The most used hybrid tethered platforms are Helikite. Also,
hybrid airships can also be tethered to the ground.

a) Helikites: Helikites are hybrid aerostats that benefit from static lift and dynamic lift. Helikite is a portmanteau of helium and kite, and it has been designed and patented by the company Sandy Allsopp in 1993 (see Fig.7). The Helikite is composed of an oblate-spheroid shaped balloon that is filled with helium to provide the static lift, and a kite structure to provide dynamic lift. The combination of these two lifts require less amount of helium compared to the other comparably sized aerostats, and they can fly at much higher altitudes compared to aerostats of the same size. Helikites offer several advantages compared to the other tethered platforms: 1) Their compact design allows them to be deployed with low number of personal. 2) They do not get down by high speed winds since winds force them to go upward. 3) They are smaller; thus, they have very problems with helium leakage, and they use less helium because they benefit form dynamic lift. Helikites can stay in the air for two weeks at an attitude of 1.5Km and carrying a payload of 23Kg. Allsopp claims that their Desert Star Helikites can carry a payload of 220Kg at an altitude of 3.4 Km, but they mention that these are estimated performance [29].

b) Buoyant Airborne Turbines (BATs): Hybrid airships are hybrid aircraft which means 60% of their lift comes from buoyant lift (aerostatic lift), and the remaining 40% comes for aerodynamic lift (see Fig.8). Hybrid airships do not need airports since they can take off and land anywhere as long as there is a large open and flat field. They can reach an altitude of 6000 m and carry a payload of 60.000 Kg [30], [31]. Although the main usage of hybrid airships is to transport passenger and delivering heavy cargo, they can still be used for other purposes.
Fig. 8: Airlander hybrid airship by Hybrid Air Vehicles [30].

Fig. 9: Different tethered platforms and their components (from left to right: TCOM blimp [17], Drone Aviation Corp. balloon [34], Helikite [29], and Elistair tethered drone [23].

They can also be tethered to the ground, and when needed take off and be deployed elsewhere if needed. They are expected to be in service by 2024 [32], [33].

B. Components of Tethered Platforms

We detail in this section, the different components of tethered platforms, which can be summarized in Fig.9 and Fig.11.

1) Envelope/Shell: The envelope of tethered platforms contains the gas that allows the platforms to soar and stay aloft. Some envelopes have a spherical forms (balloons) as shown in Fig.12a, other have a fish shaped or streamlined form (blimps) in Fig.12b. The lifts of those envelopes rely solely on buoyant gas. Other envelopes have kites attached to them, which provide an aerodynamic lift to improve their performance in the presence of winds, such as Helikites in Fig.12c. Envelopes are usually made from synthetic material, such as polyester, polyurethane,
Fig. 10: Components of tethered platforms.

Fig. 11: Components Altaeros SuperTower System [35].
(a) Balloon envelope [34].

(b) Blimp envelope [17].

(c) Helikite envelope [29].

(d) UAV shell [23].

Fig. 12: Illustration of various images

and polyvinyl. Envelopes can also contain materials such as laminates, to prevent degradation from ultraviolet light exposure, or materials to prevent the envelope from abrasions.

On the other hand, tethered UAVs have shells or frames instead of envelopes as shown in Fig. 12d. The shell defines the shape and the look of the UAV, and have the necessary components of the drones within, such as, the motor, blades, the protection cover, landing gears, etc. The motors provide the force and lift to the tethered UAVs. Generally, UAVs have 4-8 motors. An UAV with 4 motors are called quadcopter, an UAV with 6 motors are called hexacopter, and an UAV with 8 motors are called octacopter. The number of motors used depends on the type of missions. Also, landing gear are used for UAVs that require larger ground clearance.

2) Lifting Gas: The lifting gas, or also called LTA gas, is a gas that has a lower density than the air (atmospheric gas), hence it permits to lift the envelope of the aerostat by creating buoyancy according to Bernoulli’s principle. Hydrogen and Helium are the most used and lightest
gases used for aerostats. However, each gas has its pros and cons as shown in Table I.

The main advantages of hydrogen are that it is the lightest existing gas, and can be easily produced. However, its main disadvantage is that it is highly flammable, and some countries are prohibiting its use, especially after the Hindenburg incidents [36], [37]. Helium, on the other hand, is the second lightest gas, and contrary to hydrogen, is a nonflammable gas. However, helium is expensive, very scarce, and is a non-renewable resource. Although helium is most used gas for tethered platforms, its aforementioned disadvantages are leading researchers and manufacturers to reconsider the hydrogen usage and coping with its related safety issues. Also, some vendors are designing aerostats that use both hydrogen and helium.

| TABLE I: Comparisons between Hydrogen and Helium. |
|--------------------------------------------------|
| **Gas** | **Hydrogen** | **Helium** |
| **Advantages** | - Lightest existing gas | - Second lightest gas |
| | - Easily produced in large quantities | - Non-combustible |
| **Disadvantages** | - Highly flammable | - Expensive |
| | | - Scarce |
| | | - Non-renewable resource |

3) **Payload:** The payload is the weight that the tethered platform can carry while being in the air (Fig.13). The payload differs from a tethered platform to another as shown in Table IV. To be more specific, we denote by the total capacity payload, the total weight the platform can lift excluding its own weight and its tether’s at the desired altitude. The total capacity payload is divided into:

- The supporting system payload: includes all the necessary equipment to operate the platform, such as, power system, communication repeaters, backup batteries, lights, etc.
- The operational payload: includes equipment related to the mission, such as, high definition camera, telescope, electronics, panchromatic imaging camera, electro-optical/infra-red sensors, acoustic detectors. Note that the type equipment varies from one mission to another.

4) **Tether:** The tether is rolled up around the winch in one extremity, and is attached to the envelope/shell in the other. Fig.14 shows pictures of a tether cable. The materiel from which tethers are made from are usually synthetic fibers, and depending one the type and the size of the tethered platforms, the tether’s length, diameter, resistance and weight differ from one platform
(a) Payload of 22M TCOM blimp [17].

(b) Payload of Elistair tethered drone [23].

c) Payload of tethered balloon [38].

(d) Payload of Allsopp Helikite [29].

Fig. 13: Payload of different tethered platforms.

to another. It is worth noting that depending on the size of the platform, one to several tethers can be used. The tether has the following purposes:

- it maintains and stabilizes the platform to the ground when it floats in the air;
- it provides power to the platform through a power line;
- it provides data to the platform through optical fibers.

Also, the tether has to be weather-proof to withstand high and low temperatures, humidity, rain, snow, lightning, and other weather conditions.

5) **Mooring Stations and Anchor Units:**

a) **Mooring stations:** The mooring station is the system that holds the envelope of the aerostat, while being inflated before the launching process, while being deflated after the flight, and during the maintenance. The moorings stations differ in size, from, and complexity from tethered platform to another as depicted in Fig. [15] For instance large blimps require large
and heavy mooring stations, while smaller platforms, such as Helikites, require lighter and simpler mooring stations. The mooring stations depend on the environment in which the tethered platforms will be used in. For instance, tethered platforms can be deployed in the sea or the ocean, therefore, they must have mooring stations designed for maritime applications as depicted in Fig 16.

b) Anchor points: The anchor point or anchor unit is the unit that the platforms is anchored into, and it maintains the platforms in place while aloft. There are different types and sizes of anchor units, which we will present in more details in section II-C. Note that, the mooring stations can also serve as anchor points.

6) Winches: The winch is the device used to let out the tether during the launching process, adjust its tension while the platform is aloft, or pull it in during the recovery process. The tether is wound around a drum called the winch drum. The size and type of winches varies between
Fig. 15: Mooring stations for different types of tethered platforms.

Fig. 16: Maritime mooring station and anchor unit.
different platforms. For instance, smaller tethered platforms can be used manually using a crank, whereas larger tethered platforms require a power or motored winch. Winch can be attached to the mooring station, or mounted on a trailer, such as a flat bed or a truck bed. The Fig[17] shows different types of winches.

7) *Ground Control Station:* Ground control stations serve as operation base for the tethered platforms as shown in Fig[18] They can be used to:

- Control the altitude of the platforms
- Monitor and control the platforms and the equipment they carry
- Store, and in some cases process, the data related to the mission, such as, videos, images.

The types of ground control stations differ according to the missions, they can a building, a tent, a vehicle a container or any place that serves as a shelter.

8) *Transportation:* Tethered platforms components (mooring stations, winch, envelope, etc.) have to be carried to the deployment location by transportation. The type and the size of the transportation methods used depend on the tethered platform and the deployment site. For instance trucks are used to transport tethered platforms on the ground, whereas for maritime applications, ships are used as transportation. Fig[19] depicts the ground and sea transportation of tethered platforms.

C. *Type of Anchor Units*

1) *Ground Anchor Unit:*

- Mooring stations: tethered platforms can be anchored on the mooring station which is usually the case for blimps.
- Building: tethered platforms can be anchored on rooftop of buildings, such tethered UAVs. This is because UAVs can reach a maximum altitude of 150 m, hence gaining more altitude when placed on top of building [49]–[51].
- Vehicles: tethered platforms can be anchored to vehicles such as truck, thus, benefiting from the mobility of the vehicles [52].
- Ground: since tethered UAVs are very compact, they can be placed on the ground since they do not require any additional infrastructure unlike other tethered platforms such as blimps or balloons [53].

2) *Sea Anchor Unit:*
Fig. 17: Winches of tethered platform (a) [44], (b) [45], (c) [23].
(a) Tethered UAV ground control station \cite{46}, \cite{47}.

(b) TCOM blimp ground control station \cite{17}.

Fig. 18: Ground control stations of tethered UAV and blimp.

(a) Transportation on sea \cite{48}.

(b) Transportation on land \cite{29}.

Fig. 19: Transportation of tethered platforms on sea and land.
- Ship: when tethered platforms are used in maritime context, they use the ship or offshore floating structures as an anchor unit. However, the anchor point must be designed in order to satisfy the requirements needed in maritime applications [54], [55].
- Buoy: when deployed in the sea or the ocean, tethered platforms can be anchored to oceanographic buoys [56].
- Drag Sail: Drag sails can be used as an anchor unit for tethered platforms. For instance, the authors in [57] proposed a configuration where the platforms (balloon) is launched with tether wound into a reel. The tether has a drag sail at its end, so after reaching the desired altitude, the tether is reeled out which anchors the platforms into the sea. After completing the mission, the tethered platform cuts the tethered in return to a free flying state.

3) Air Anchor Unit: Although it was never tested before, the authors in [58] proposed an interesting setup to cope with the winds that blow in different directions at different part of stratosphere. The idea is to tether the platform to HTA glider tug aircraft at a lower altitude than the tethered platforms.

D. Altitudes

1) U-LAP (50m-150m): Generally, tethered UAVs, balloons, Helikites, and BATs fly at this altitude. These altitudes are suitable for quick operations such as disaster relief by rapidly deploying tethered platforms with decent range and coverage [23], [50].

2) LAP (200m-600m): Tethered UAVs do not reach this altitude, but balloons, Helikites and blimps can fly in these range of altitude, although balloons usually do not fly higher than 400 m. At this altitude, tethered platforms have higher coverage compared to ultra-Low altitudes which is suitable for missions that last between 3 to 7 days [17], [18], [29].

3) MAP (0.7km-5km): Only Helikites and blimps can reach this altitude. Although Helikites usually do not fly beyond 1.5 Km, they can reach attitudes around 3 Km according to estimation available on their website [29]. However, blimps can reach attitudes around 4.6 Km. These altitudes are for long-duration operations and surveillance missions. At these altitudes, tethered platforms benefit higher range and coverage [17], [29].

4) HAP (15km-22km): To this day no tethered platform has researched these high altitudes. However, there are several studies that show and demonstrate the feasibility of high altitude tethered platforms [57]–[66].
Fig. 20: The different categories and types of tethered platforms.

5) **U-HAP (45km-50km):** Although these altitudes seem extreme and unreachable by tethered platforms, there is one paper that study the feasibility of tethered platforms flying at ultra-high altitude [67].

**TABLE II: Comparisons between different tethered platforms.**

| Properties      | UAVs       | Balloons   | Helikite  | Blimps     | BATs      |
|-----------------|------------|------------|-----------|------------|-----------|
| Payload         | 1Kg-15Kg   | 5Kg-50Kg   | 2Kg-25Kg  | 16Kg-2600Kg| NA        |
| Altitude        | 150m-200m  | 150m-700m  | 100m-1.5Km| 100m-5Km   | 150m-600m |
| Wind Speed      | 40Km/h-55Km/h | 20Km/h-40Km/h | 90Km/h  | 75Km/h-165Km/h | 160Km/h  |
| Flight Duration | 2-4 days   | 1 day-7 days| 2-4 days  | 1 day-30 days| NA        |
| Deployment Time | Fast       | Moderate   | Fast      | Slow       | Fast      |
| Cost            | Low/Moderate| Low/Moderate| Low/Moderate| Moderate/High | NA        |
Fig. 21: Comparisons between Helikites, balloons, UAVs, and larger blimps.

Fig. 22: Altitudes and anchor unit of tethered platforms.
E. Applications of Tethered Platforms

1) Government & Defence:

a) Tactical Operations: Tethered platforms helps military to conduct tactical operation with accurate environment perception allowing real-time imaging [17], [68]–[70].

b) Observation and Surveillance: Tethered platforms offers continuous aerial surveillance and reconnaissance by day or by night (up to several days), enabling target tracking for enemies and reduced exposure of allies [17], [69]–[73].

c) Telecommunications: Tethered platforms turn out to play a crucial role during military operations as it allows the extension of the communication in areas where the cellular coverage is lacking [68], [74].

d) Border Surveillance: Tethered platforms are used to track illegal aliens, unauthorized personnel, arms smugglers, narcotics traffickers, or detecting and preventing enemy force to cross the borders [17], [69], [70], [72].

e) Surveillance of Sensitive Sites: Tethered platforms allow the aerial surveillance of sensitive site such as, military bases, nuclear plant, industrial sites, offshore platforms, harbors, and airports [17], [69], [72], [73].
f) Detection of aircraft: Depending on their altitude, tethered platforms are capable, within its area of coverage, of detecting low flying aircraft \cite{17}, \cite{70}.

2) Public Safety and Disaster Relief:

a) Search and Rescue Missions: For search and rescue missions, tethered platforms help increasing the search coverage. Also, they provide a cellular coverage in areas lacking coverage such as desert or mountain \cite{69}, \cite{75}–\cite{78}.

b) Firefighting Missions and Wildfire Monitoring: During firefighting missions, tethered platforms not only bring coverage to the area, but can take remote-sensing aerial infrared (IR) images to draw a temperature map in order to detect and identify critical hot spot. This will help managers to give precise directions and decisions to the crew \cite{69}, \cite{79}.

c) Emergency Communications: Cellphone connectivity and coverage are Paramount in aftermath of natural disasters. Earthquake, tsunami, hurricanes and floods can destroy cell phone towers. Bring cellphone coverage via tethered platforms can help the rescue crew to communicate and take decisions. This also will help the crew to identify and prioritize the most affected areas by the disaster \cite{75}–\cite{78}, \cite{80}, \cite{81}.
**d) First Operations:** During rescue operations, first responders need to communicate with each other in order to coordinate their tasks to find and help the victims. Tethered platforms help the first responders by providing communication coverage, and by helping the rescue team assessing the situation by providing large visual coverage [75]–[77], [81].

**e) Crowd Control and Management:** Tethered platforms are very useful when it comes to crowd management and riot Control [69], [73].

**f) Aerial Observations:** For aerial observations and surveillance tasks, height is a huge advantage. Hence, tethered platforms can be used for surveillance purpose such as control of illegal fishing activities or for homeland security such as anti-terrorism activities [69], [72], [73], [82].

**g) Traffic Regulation, Accidents Management and Vehicles Surveillance:** Tethered platforms can be useful for traffic regulations since they have great view. They can also help anticipating traffic jam, and alerting vehicles about accident happening in their vicinity or a given area. Finally, they can used to locate suspect vehicles or track vehicle during car chases.

3) **Communications:**

**a) Cellular Coverage:** Tethered platforms overcome the limitations of terrestrial communication towers. Due to their higher altitude, they have a larger coverage area and better LOS. Plus, their are less costly that cell towers and satellites [45], [50], [83]–[85].

**b) Coverage in Rural and Remote Areas:** Almost half of the global population lives in remote or rural areas. And it is not economical nor profitable for phone operators to erect cell towers in these areas, consequently, most of the people living in these areas do not have access to internet connection. Tethered platforms permit to bridge this gap by providing internet connection to these peoples and still being economically profitable for phone operators [44], [45], [77], [83], [86].

**c) Temporary Communications:** In certain situations, there is a need for temporary communications. Tethered platforms comes come in handy since they can be used as temporary transmitters or acting as relays [68], [75]–[78], [80], [81].

**d) Remote Sea and Ocean Area Coverage:** seas and oceans are lacking coverage, which makes tethered platforms even more useful in those areas. This can benefit sailors, fishermen, personal on floating structures to have access to internet connection [51], [55], [56].

4) **Entertainment:**
Fig. 25: Diagram of tethered platform applications.

a) **Coverage of Major Sport Events**: Major sport events, such as football, baseball, rugby, etc. gather a massive number of people, making tethered platforms an excellent choice to cover and broadcast those events, and bring coverage to these areas.

b) **Surveillance of Large Public Events**: The surveillance of large public events cannot be overstated. Tethered platforms permit to have a wide view of those events [69], [72], [73].

c) **Aerial Recording and Photography**: Tethered platforms can be used to take aerial photos and take advantage of their altitude to offer photos from a perspective that is hard to access from a regular height. They can also be used to record videos or used in movies recording [69].

d) **Advertisement**: Tethered balloons are also used for advertisement purposes. The tethered platforms can have a written sign on it, or it can lift an advertisement sign. The tethered platforms can be illuminated at night for a better visibility of the advertisement. They can be for instance during major sport events to attract people’s attention.

5) **Science, Research and Environments**:

a) **Remote Sensing**: Tethered platforms can be equipped with remote sensing sensors can be deployed and collected data for various applications, such as detecting landslides and habitat destruction [54], [87]–[92].
b) Education: In education, tethered platforms can be used as educational tool, to show students phenomenon that can only be see from certain altitude.

c) Meteorological data recording and Aerial Seismology: Tethered platforms are used to gather meteorological data such as atmospheric temperature, wind speed, air pressure and humidity [93]–[95]. They are also used in aerial seismology to detect earthquakes [96], [97].

d) Telescopes: Since they have a better view at higher altitude, tethered platforms are used as aerial telescopes [98]–[101].

e) Agriculture and Farming: Tethered platforms are helping farmers do identify several types of plants via aerial images, and also they help to prevent farming frauds [89], [102], [103].

f) Deforestation and Vegetation Mapping: Taking aerial images from high altitude, tethered platforms are used to detect and prevent deforestation. These aerial images can also be used to understand biodiversity through time [89], [104].

g) Pollution: Tethered platforms are used to detect oil-spills and floating debris. They are also used to detect and monitor light pollution [105].

6) Energy Harvesting:

a) Solar Energy: The power harvested by the ground photovoltaic panels depends heavily on the weather. Thus, their power collected by these photovoltaic panels decreases drastically in countries such as the united kingdom with lower hours of solar exposure. However, tethered platforms can fly at higher altitude, and get more solar exposure [52], [59], [106]–[108].

b) Wind Energy: Wind speed is much higher at 150 meters than at the ground. Hence, tethered platforms can harness more powerful winds at these altitudes and can generate twice the energy of a similarly ground based turbines [22], [24], [25].

F. Advantages of using Tethered platforms

1) Cost-Efficient: Tethered platforms are cost efficient compared to free flying platforms. They are also cost efficient compared to other communication infrastructure such as bases stations and satellites.

Tethered platforms have overall low operation cost compared to free flying platforms. For instance, they have low purchase, maintenance and service compared to their counterparts to free flying platforms. Also, they also require less training of operators and a smaller number of operators. When we compared them with tower masts, the fist aspect is that tethered platforms allow a cost saving of nearly ten time the cost of erecting a tower mast. The second aspect is
that coverage of tethered platforms equals the coverage of multiple tower masts. The last aspect is that the consumption of tower mast in terms energy and fuel (off-grid BSs) is large, whereas tethered platforms consume less energy that BSs and require no fuel. Finally, the cost of satellites and their launching to orbit is extremely high. Especially considering that their life operations is approximately ten years. Tethered platforms offer a great alternative to satellites with a lower cost compared to satellites.

2) **Endurance & Persistence:** One key advantage that tethered platforms have over free flying platforms is endurance and persistence. This is more pertinent in surveillance missions and telecommunications when the flying platform must stay aloft during a prolonged period (from days to weeks) and/or in stationary position, whereas the persistence of free flying platforms is several hours, and it is very hard for free flying platforms to keep a stationary position.

3) **Green Credentials:** Another advantage that tethered platforms have is their great green credentials and low consumption of fuel and power compared to other free flying platforms. Regarding tower masts, the consumption of fuel is exceptionally large. In India for instance, nearly 2 billion liters of diesel are burnt each year by tower masts to be operated [45]. This number will increase to reach 15 billion to cover rural and remote areas in India which will
dramatically increase the carbon footprint and hence the pollution in the atmosphere.

4) **Coverage & Backhaul Link:** Tethered platforms have a wide coverage compared to tower masts, which is due to their altitudes, which allow them to cover a large area. When compared with satellites and terrestrial networks, tethered platforms have a higher and stronger LOS than terrestrial networks and Lower propagation delay than satellite. Also, tethered platforms have great backhaul link capacity compared to free flying platforms since wireless backhaul is more prone to interference and higher latency (which is the case of free flying platforms). In the contrary, wired (tethered) backhaul have a wired data-link via the tether with the tower mast allowing reliable and high data rates communications between the two aforementioned entities.

5) **Quick Deployment:** One of tethered platforms biggest asset is their fast deployment, which make them suitable for safety mission and disaster relief operations. In addition, tethered platforms can be moved and relocated to areas of interest. This is not the case of tower masts, because one erected, they cannot be moved elsewhere. Tethered platforms can also be used to areas where it is not feasible to erect a tower mast. This can be a disaster situation where the communications infrastructures are severely damaged or destroyed. Or it can be that the land of interest is not favorable to erect a tower mast on it. In summary, tethered platforms can be quickly deployed, easily reconfigurable and rapidly relocated.

6) **Constant Supply:** The role of the tethered is to supply the platforms with power so they stay aloft from days to weeks, whereas free flying platforms have limited power supply. Also, the power supply allows tethered platforms to carry more payloads compared to their counterparts free flying platforms. In addition to power, the tether offers data and connections to the ground station via fiber for high data rate connections and increasing the backhaul link capacity compared to free flying platforms.

**G. Disadvantages of tethered platforms**

1) **Mobility:** Although tethered platforms are rapid to deploy, and have a better mobility compared to ground stations, they are still limited in their movement. This is due to the physical constraint imposed by the tether. The tether offers continuous power and data supply to the platforms, but it comes with the price of mobility. Compared to the free flying platforms, tethered platforms cannot move beyond the radius of the tether’s length.

2) **Tether Constraints:** Although the tether has great benefits in terms of constant power and data supply to the platforms, several constraints come with it. One constraint that we
mentioned before is the limited mobility imposed by the tether. Also, the tether itself can be an issue if it sustains damages (intentionally or unintentionally), preventing the supply of data and communications which can hinder the ongoing operation, especially critical operations, such as military missions and disaster relief operations. Hence, it is always recommended to protect the tether, and not let it unattended, and having several tethers attached to the platform for redundancy.

3) Optimal Placement: This contains stems for the fact of having a tether. Indeed, free flying platforms can hover or fly freely in the air. Hence, they can move to optimize their positions. However, tether platforms are constrained by the tether preventing them to optimizing their position.

4) Intervention Operations: Tethered platforms are not made for intervention operations since they cannot move freely and quickly in the air compared to aircrafts. But tethered platforms are not designed for such operations, hence the usage of tethered platforms must match the requirements of the mission.

Fig. 27 summarizes the advantages and disadvantages of using tethered platforms. We see the comparison between tethered platforms, satellites and tower masts regarding the communications aspect in Fig. 27a. We can clearly see that tethered platforms have most of advantages of other communications aspects without suffering burden of their disadvantages. For instance, if we
compared tethered platforms with satellites, we notice that satellite have a more coverage and endurance than tethered platforms, but this comes with a far greater cost, lower delay, and longer time to deploy. Also, if we compare tethered platforms with tower masts, we can see that tethered platforms outperform tower masts in terms of mobility (tower masts are static); coverage due to their altitude, lower cost, LOS probability.

From Fig 27b we see the comparison between tethered platforms and free flying platforms. We can clearly see that free flying platforms outperforms tethered platforms only in mobility and LOS probability. On the other hand, tethered platforms have lower cost, better backhaul link capacity, better endurance and persistence, constant power and data supply, and lower rate of pollution.

H. Regulations

1) Socio-Technical Concerns of Tethered platforms: Although tethered platforms offer several advantage and applications, there are several concerns that have to be taken into account regarding theses platforms such as privacy, data protection and public safety. Before we explain the regulations related to tethered platforms, we describe the socio-technical concerns related to these platforms [109]:

- Privacy: since tethered platforms have a great coverage on the area of interest, they can be unintentionally (or intentionally) a threat to individuals and businesses privacy. Therefore, legislation and regulations have to be established to protect individuals as well as businesses’ privacy.
- Data Protection: due to their coverage, tethered platforms can collect massive data of the public such as images, videos, and personal data. Hence, these data has to protected from abuse according to data protection laws, and operations of tethered platforms have to be subject to regulation in order to protect personal information. [110].
- Public Safety: another critical issue of tethered platforms is public safety. Although tethered platforms present less safety issues to the public compared to untethered platforms, regulations must still be issued to protect the public. An example of issue that can happens with tethered platforms are: a tethered platforms falling on the public, a cut in the power supply, procedure of landing the platforms when the tether is cut, preventing collision with flying aircraft, etc.
As non-tethered platforms, tethered platforms are subject to regulations. However, tethered UAVs and tethered LTA aerostats are not subject to the same regulations. Tethered LTA aerostats and Helikites are fall under part 101 of aeronautics and space regulations, whereas tethered UAVs fall under part 107 of aeronautics and space regulations [111].

We will outline the the regulations tethered UAVs and tethered LTA aerostats, and highlighting the main difference between tethered and non-tethered regulations.

2) **Tethered UAVs**: Although there are debates whether tethered UAVs should be considered as kites or balloons, the the Federal Aviation Administration (FAA) states that tethered UAVs fall under the same category as UAVs when it comes to regulations. However, some countries do not classify tethered UAVs as UAVs since they are tethered to anchor point. Hence, the classification of tethered UAVs depends on the aviation laws of each country [112].

Table III shows the main requirements related to UAVs.

| Requirements                                         | UAV              | Tethered UAV |
|-------------------------------------------------------|------------------|--------------|
| Captive system                                       | Not Required     | Compulsory   |
| Max. Altitude                                        | Compulsory       | Compulsory   |
| Loss of data link                                    | Compulsory       | Not Required |
| Identification                                       | Compulsory       | Not Required |
| Registration                                         | Compulsory       | Compulsory   |
| Geo-fencing                                          | Compulsory       | Compulsory   |
| Security                                             | Compulsory       | Not Required |
| Endurance                                            | Compulsory       | Compulsory   |
| Visibility                                           | Compulsory       | Compulsory   |

We can see from Table III that tethered UAVs are not with the same constraints safety-wise, making tethered UAVs easier to deploy. We can also see that from the set of requirements presented in Table III three of them have no impact on the tethered UAVs:
• Loss of data links: in this situation, a free-flying UAVs can fly away with all the risks and safety issue involved. However, when it comes to tethered UAVs, they cannot fly away since there are attached with a tethered to the ground station. Therefore, there is no need to restore the lost data link or abort the flight.

• Identification: free-flying UAVs have a remote direct identification systems that allow the UAV to be identified in the case of a flyaway situations. However, tethered UAVs are exempted from this requirements since their flying perimeter is limited by the tether length (between 90m and 160m).

• Security: in the case of free flying UAVs, the data are transmitted though the air, which makes them vulnerable to eavesdroppers and can also be subject to interference. In the contrary, tethered UAVs transmit the data via the tether, hence decreasing the signal loss, the signal attenuation, and interference. However, the tether has to be protected from physical harm and hijacking.

Another aspect that is worth-noting is the piloting skills of the tethered UAVs. In fact, free flying UAVs impose that the pilot is qualified and has a flying certificate. But in the case of tethered UAVs, the pilot does not need to posses piloting skills to fly the tethered UAV. Plus, the tether makes it easier to stabilize the UAVs its movements [this remark falls into the category of advantages].

Also, when there is a ground power cut, this will set off a safety mechanism that activate a battery to keep the UAVs in the air. This mechanism also trigger a alarm to alert the pilot of the situation, hence the pilot can land the UAV.

| Country    | Max Altitude | Min distance to people |
|------------|--------------|------------------------|
| Canada     | 90 m         | 150 m                  |
| Germany    | 10 0m        | not over crowds        |
| Spain      | 12 0m        | not over groups        |
| United States | 122 m    | N/A                    |
| Chile      | 130 m        | 30 m                   |
| Japan      | 150 m        | 30 m                   |
| Colombia   | 152 m        | N/A                    |

TABLE IV: Regulations regarding UAVs heights for commercial purposes [113].
3) **Tethered LTA platforms and Helikites:** These regulations related to tethered platforms can be divided into three types: regulations related to the flight and aviation aspect, regulation relation to the communication aspect, and regulations related to the equipment that the platform is tethered with.

- **Flight and Aviation Regulations:** The FAA requires that all tethered aerostats a rapid deflation device that will automatically and rapidly deflate the aerostat if the tether is cut. If the device does not respond or do not function properly, the nearest air traffic control has to be notified about the the location and the time of the escape of the aerostat. The devices are units that are activated when the tethered aerostat exceed a predetermined distance from a given location (using a global positioning system (GPS)), or when the aerostat has exceeded a predetermined altitude (using a barometric pressure sensor). The aerostat has to be lightened and illuminated if it is flying from sunset to sunrise. For further information about the regulations concerning tethered aerostats, the reader is advised to read the electronic code of federal regulation website [111].

- **Communications Regulations:** The missions or operations that require communications via tethered aerostats are regulated by Federal Communications Commission (FCC). For further information about the regulations concerning tethered aerostats, the reader is advised to read the electronic code of federal regulation website [114].

- **Transportation Regulations:** The regulations may also be applied to the transportation to which the aerostat is attached to.

### III. USE CASES, PROJECTS AND COMPANIES RELATED TO TETHERED PLATFORMS

In this section, we explore the numerous applications of tethered platforms. In that regard, we will present projects and case studies used in real-life scenarios involving tethered platforms. Also, for the sake of completeness, we present the major companies that manufacture and sell tethered platforms worldwide.

#### A. Project and Case Studies

1) **Paris Airport Maintenance:** The Precision Approach Path Indicator (PAPI) is a system with four lights (two white lights and two red lights) placed beside the landing runways, that helps pilots assessing their landing slope (as shown in Fig. 28a). Basically, if the PAPI displays two white lights and two red lights, it means that the airplane has the correct slope. Other than
that, the slope is either too high (three white lights or more), or too low (three red lights or more) as shown in Fig. 29a.

To calibrate the precision of this system, maintenance has to be carried out by using elevating work platforms which block the access to the runway. Hence, the airport will close the runway, causing time loss, complicated maintenance logistics, and risks taken by the ground operators in the runways and the operators in the air on the elevating work platforms.

To solve this problem, the French airport authority Groupe ADP used a tUAV at Paris airport Charles-de-Gaulle. An Elistair hexacopter was used to perform the maintenance task and calibrate the PAPI. The tUAV allows a precise air-view on the Paris airport runways. The advantage of using a tUAV to perform this task are: 1) it can stay in a stationary position for a prolonged period of time, 2) the tUAV can take off and land in very small surfaces (1.2m diameter), 3) the tUAV can detect precisely the threshold and boundary between each color, which is depicted in pink (a mix of white and red) as shown in Fig. 29c. To further increase the accuracy of the PAPI, two tUAVs are placed at different distances, hence, by using the required threshold angle $\alpha_A$, the threshold can be verified by checking the accurate altitude of the pink color detected by the tUAVS at the distance $d1_A$ and $d2_A$ as shown in Fig. 29b.

The use of a tUAV prevents the operators from any risk, such as falling down from the elevated task platforms. Since the UAV is tethered, it is directly linked to the control tower, which permits secure and interference-free communications. Also, the tUAV can be deployed in the runway with the necessary safety measures, while the rest of the airport continues running without interruption. Finally, the tUAV calibrates all the thresholds in one hour.
2) Road Traffic Monitoring in Lyon: To monitor the traffic road in Lyon, Elistair proposed a solution using their tUAV to continuously monitor the roundabout. Lyon, which is the second largest urban area of France, has a big concentration of traffic flow, especially in the suburb areas.

The tUAV was equipped with a Full HD camera, and the operation last 3 hours during rush hours. The tUAV was placed 110 meters away for the roundabout. For security reasons, the tUAV was in 50 meter secured radius to ensure that the operation will not be interrupted or jeopardized as depicted in Fig.30b.

Using the tUAV offers several advantages, such as maintaining a steady position to control the setting of the camera thanks to the tether cable. Also, the tether allows safe data transfer and can be displayed at a real-time. To analyze the data collected from the tUAV, the cloud-based platforms DataFromSky was used to as it proves AI and ML tools to process and analyze the road traffic data [117].
(a) A snapshot of the traffic video after DataFromSky processing. 

(b) The configuration of the tUAV placement.

Fig. 30: The aerial view of the roundabout and the placement configuration of the tUAV [116].

Fig. 31: DataFromSky uses Artificial intelligence (AI) and machine learning (ML) to analysis traffic form videos. [117].

The process is as follows: the tUAV records the traffic flow in the roundabout, then the videos are uploaded in the DataFromSky platforms. DataFromSky then processes and analyzes the data, and it sends a video and the data metrics required, such as speed, acceleration, and trajectory of the vehicles as shown in Fig. 30a. It also provide the numbers, categories, and the types of the vehicles: cars, motorcycles, trucks bus.

This shows how using tUAV allows traffic monitoring with an easy configuration and fast deployment. Using tUAVs for monitoring outperforms the traditional traffic monitoring method in terms of mobility, and coverage. Additionally, by using a tether cable: 1) the UAV maintains a persistent and steady position to record the traffic; 2) the communications and data are secured;
3) the tUAV can stay aloft for several hours (days if needed) thanks to the constant supply in power.

3) Border Security in Southern Texas: Rio Grande Valley, located in southern Texas with the Mexican borders, has accounted for the highest number of apprehended illegal immigrants since 2016 in the U.S [118]. The U.S. Department of Homeland Security (DHS) and Customs and Border Protection (CBP) are facing a huge challenge due to the long stretch of the borders between the U.S and Mexico. Also, the type of terrains in these areas are challenging, and the ground-based surveillance systems are limited, which pushed the DHS and CBP to seek for an elevated or aerial solution.

To deal with this, the DHS and CBP used TCOM tethered blimps. The tethered blimps provided a large coverage and continuous surveillance of the areas to the border authorities. The advantage of tether blimps is that, they can stay aloft for several weeks while providing real-time videos and monitoring, which helps the authorities to make better decisions. Also, the blimps have high degree of mobility, the cab be rapidly deployed, are battle-proven, and low-cost.

After using the tethered blimps, the border authorities have witnessed a decrease in illegal immigrant crossings, thanks to the tethered blimps’ wide coverage and long persistence.

4) Oil-spill Detection in Arctic Ocean, Norway: The Norwegian Clean Seas Association for Operating Companies (NOFO) is a oil spill response organization. NOFO works with 30 offshore operators, providing and managing oil-spill preparedness plans. To detect oil spills an areal
solution is more suitable since oil spills detection is hard form a sea level. Using an aerial camera offers a wide coverage to assess the extend as well as the thickness of the oil spill. Although aircraft and UAV can be a solution, they lack persistence and steadiness in the air, especially for long oil sweeping missions.

To overcome these limitations, NOFO used Helikite to detect oil spilling., and the system was called "The Ocean Eye". Helikites have the advantage of being small and compact, can be easily handled, deployed easily, and can sustain harsh sea weather. The Helikite can be anchored to the cleaning ship or nearby boats as shown in Fig. 33. The Helikite provides real-time video on the oil spill helping the cleaning boat to have accurate positioning information on the oil spill, which consequently help them extracted more oil in shorter time for the sea.

5) Aerial Photographic Survey of Armarna in Egypt: A Cambridge University researcher group wanted to conduct an archaeological photography of the ancient site of Armarna in Egypt, where the famous Tutankhamen was born. They wanted to take still stereo-images of the site. Hence, they used Helikites equipped with two 35mm single-lens reflex (SLR) cameras. The Helikite had the advantage of being low cost solution, allowing closeness to the site with low vibration, and maintaining a steady position to take still images. Additionally, the Helikite was weather-proof since it performed very well under the challenging hot conditions in Egypt.

6) Aerostats All Australia (AAA) Mobile Coverage: According to [121], nearly 70% of Australia lands do not have mobile coverage. To deal with problem, a project named AAA offers
a plan to extend the coverage in Australia, including lands as well as surrounding sea areas. In order to do so, AAA project proposes the use of tethered platforms to bring wide coverage with lower cost compared to the other alternative solutions. The AAA envisions offering mobile coverage with low latency and real-time applications for all mobile users in remote areas. In the short term, AAA propose to double the Australian coverage from one-third to two-thirds of the total land areas. Over the long term, AAA aims to provide mobile coverage to all Australia.

7) Altaeros SuperTower: The Altaeros SuperTower is a solution proposed and developed by Altaeros to provide cellular coverage in rural areas (Fig. 34). Standard infrastructure solutions have the disadvantage of being expensive and not lucrative in areas with few subscribers. SuperTowers are tethered blimps that fly at 240 m of altitude. The coverage gained by this altitude allows one SuperTower to replace 15 cell towers, allowing 60% of lower cost. Hence, using this solution can accelerate the implementation of network more quickly and efficiently that standard cell towers, with significantly less cost [122].
B. Companies Related Tethered Platforms

We present the major companies that manufacture and sell tethered platforms. Table V shows the companies that manufacture LTA platforms, that is, blimps, balloon, and BATs.

TABLE V: LTA tethered platform companies.

| Type     | Company                      | Contact                  |
|----------|------------------------------|--------------------------|
| Blimps   | • TCOM [17]                  | • NA                     |
|          | • Lindstrand Technologies [123] | • sales@lindstrandtech.com |
|          | • CNIM Air Space [124]       | • +33 5 34 43 04 09     |
|          | • ADASI [125]                | • NA                     |
|          | • Altaeros [18]              | • info@altaeros.com      |
| Balloons | • Vigilance [126]            | • +31 402 340 600        |
|          | • Drone Aviation Corp [127]  | • info@droneaviationcorp.com |
|          | • SkyDoc [128]               | • charlie@skydoc.com     |
| BATs     | • Altaeros [18]              | • info@altaeros.com      |

Table VI shows the companies that manufacture HTA platforms, such as, tUAV and airwind turbine.

TABLE VI: HTA tethered platform companies.

| Type                               | Company                        | Contact                                      |
|------------------------------------|--------------------------------|----------------------------------------------|
| tUAVs                              | • Elistair [23]                | • +33 9 83 57 06 39                         |
|                                    | • Equinox Innovative Systems [129] | • NA                                          |
|                                    | • Tethered Drone Systems [130] | • info@tethereddronesystems.co.uk          |
|                                    | • Hoverfly tech [131]          | • info@hoverflytech.com                      |
|                                    | • Drone Aviation Corp [127]    | • info@droneaviationcorp.com                |
|                                    | • Fotokite Sigma [132]         | • contact@fotokite.com                       |
| Air Wind Turbines                  | • Makani [28]                 | • NA                                         |
|                                    | • Airborne Wind Europe [133]   | • +32 27396212                               |

Finally, Table VII shows the companies that manufacture hybrid platforms, such as Helikites and Hybrid airship. We recall that, hybrid airship have the possibility to be tethered, but are not systematically tethered platforms.

Finally, we present two companies that propose solutions for UAV, namely, Spooky Action and AeroMana. These companies propose a tether configuration that can be plugged into existing
TABLE VII: Hybrid tethered platform companies.

| Type                | Company            | Contact                  |
|---------------------|--------------------|--------------------------|
| Helikite            | • Allsopp Helikite | • info@helikites.com     |
| Hybrid Airship      | • Hybrid Air Vehicles | • +44 (0) 1234 336400   |
|                     | • Lockheed Martin  | • NA                     |

UAVs without any modifications. This will give an additional degree of freedom to the untethered UAVs, by allowing them to be tethered when needed.

TABLE VIII: tUAV solution companies.

| Company          | Contact                  |
|------------------|--------------------------|
| Spooky Action    | + 952-649-1637           |
| [134]            |                          |
| AeroMana         | info@aeromana.com        |
| [135]            |                          |

IV. TETHERED PLATFORMS FROM A WIRELESS COMMUNICATIONS PERSPECTIVE

A. Geometric Analysis

In order to evaluate the performance of tethered platforms, we have to investigate geometrical aspect between a given tethered platform (e.g., blimp) and the earth. This can be carried out following a similar approach used for low earth orbiting (LEO) satellites [136], [137]. Fig.35 shows the geometrical aspect and the coverage surface between a blimp and a given user located on the ground. In Fig.35, \( R_e = 6378 \) Km denotes the earth radius at sea level, \( h \) is the height of the blimp above the earth, \( d \) is the distance from the blimp and the ground user, also know as, slant-range, \( \alpha \) is nadir angle, that is, the angle under which the blimp views the ground user, \( \beta \) is is central angle, that is, the geocentric angle between the user and blimp nadir, and \( \theta \) is elevation angle, that is, the angle between the slant range and the horizon plane.

Following the same approach in [136], [137], we obtain the following equations

\[
\alpha + \beta + \theta = \frac{\pi}{2},
\]

(1)
Fig. 35: Coverage of the tethered platforms from a geometric perspective.

\[ d \cos(\theta) = (h + R_e) \sin(\beta), \tag{2} \]

and

\[ d \sin(\alpha) = R_e \sin(\beta). \tag{3} \]

When distance \( d \) is required, for instance, to compute path loss, we apply the cosines law for the triangle in Fig.35 which yields

\[ (h + R_e)^2 = r^2 = R_e^2 + d^2 + 2R_e d \cos \left( \frac{\pi}{2} + \theta \right), \tag{4} \]

Solving the equation (4) with respect to \( d \) yields the following solution

\[ d = R_e \left[ \sqrt{\left( \frac{R_e + h}{R_e} \right)^2 - \cos^2(\theta) - \sin(\theta)} \right]. \tag{5} \]

Hence, \( d \) reaches its maximum value when \( \theta = 0 \), which is given by

\[ d_{\text{max}} = d \left( \theta = 0 \right) = \sqrt{h^2 + 2hR_e}. \tag{6} \]

Also, from applying the sinus law in Fig.35 we get
(a) Surface coverage as a function of $h$ for several values of $\theta$. (b) Surface coverage as a function of $\theta$ for several values of $h$.

Fig. 36: Surface coverage as a function of $\theta$ and $h$.

\[
\frac{\sin(\alpha)}{R_e} = \frac{\sin\left(\frac{\pi}{2} + \theta\right)}{R_e + h} \tag{7}
\]

Then we have

\[
\sin(\alpha) = \frac{R_e \cos(\theta)}{R_e + h}. \tag{8}
\]

Finally, the angle $\alpha$ is given by

\[
\alpha = \sin^{-1}\left(\frac{R_e \cos(\theta)}{R_e + h}\right). \tag{9}
\]

To calculate $\beta$, we use the equation (2)

\[
\beta = \sin^{-1}\left(\frac{d}{R_e + h} \cos(\theta)\right). \tag{10}
\]

Also, we can use the equation (1) and (9) to calculate $\beta$, hence

\[
\beta = \frac{\pi}{2} - \theta - \sin^{-1}\left(\frac{R}{R_e + h} \cos(\theta)\right). \tag{11}
\]

Finally, to calculate the surface coverage by the blimp can be computed as follows

\[
S_{\text{cov}} = 2\pi R_e^2 \left(1 - \cos(\beta)\right). \tag{12}
\]
To better assess the impact of $h$ and $\theta$ on different metrics, such as surface coverage and the range $d$, we plot different curves in Fig. 36 and Fig. 37.

In Fig. 36a, we plot the surface coverage as a function of $h$ for several values of $\theta$. We can see that, as the altitude of the blimp increases ($h$ increases), the surface coverage increases as well. This remark is intuitive, because as altitude of the blimps increase, the blimp can cover a greater surface. We can also notice that, the difference between surface coverage when $h = 100$ m and $h = 40$ Km is four order of magnitude.

Fig. 37b plots the range $d$ as a function of the elevation angle $\theta$ for several values of $h$. We can see that the range $d$ decrease as the elevation increases. For instance, when $\theta = 90$, the user is exactly blow the blimps, which corresponds to the shortest distance possible between the blimp and the user. Inversely, when $\theta = 0$, the user is the farthest from the blimp, which corresponds to $d_{\text{max}}$.

B. Performance Analysis

Very few works investigated the performance of tether platforms in wireless communications. Most of works in literature focus on freee flying platforms such as HAPs and UAVs. For example, in the absence of terrestrial infrastructure, the UAVs are used to assist cellular networks. For instance, in a post-disaster scenarios, most communication infrastructures are destroyed or
damaged. But one major issue limiting the connection between UAVs and the core network are the backhaul constraints and limited energy.

Few works have addressed this issue, for instance the work in [138] proposed a multihop connection thought several UAVs to alleviate backhaul constraint. However, by increasing the hops, the latency is increased and the spectral efficiency of a communications is reduced.

Hence, the authors in [139] proposed a configuration with a tethered balloon connected to the core network via fiber showed in Fig. 38. The tethered balloon acts as a “flying base station” located at higher altitude than the UAVs allowing a strong LOS backhaul connection. The proposed configuration showed an increase in the achievable end to end data rate of the users. Plus, they proposed an optimization framework that optimizes the transmit power, the placement and the association of the UAVs.

Regarding the use of tUAVs, the authors in [140] proposed a hybrid solution to overcome these challenges. The solution consists of using three different types of UAVs: the first one are UAVs that acts as communications drone. The second type are tUAVs that provides backhaul connection to the communications drone via FSO/RF hybrid link [141], [142]. The last one are UAVs that power the communications UAVs by proving on the fly battery charging. The authors showed that unlimited cellular communications can be provided and guarantying a minimum rate for all the users.

tUAVs as airborne base stations have also a huge potential to extend the network capacity
and coverage for the 6G \[143\]. In \[53\], investigated the optimal placement of tUAV placed on a rooftop to minimize the path loss between the tUAV and a ground user with the constrains that the tether has a limited length, and the inclination angle of the tUAV for safety issues. The authors in \[144\] compared the performance of UAVs and tUAVs under a heavy traffic conditions, Their results showed that tUAVs outperformed UAVs.

But tether platforms are not limited to cellular networks assisting ground users, the are also a relevant solution to connect other flying platforms with the core network, especially with the upcoming development of flying cars. Indeed, flying cars require reliable aerial wireless communications network, since communications technologies used in vehicular communications \[145\] are ill-suited for flying cars due to they lack of aerial coverage \[11\].

Finally, tether platforms can be user as a relay between airborne platforms and ground stations. For instance, in \[146\], the authors considered communications between untethered HAPs and ground based stations. To maximize the sum-rate, they implemented interference alignment scheme. However, in this case, CSI was hard to obtain due to the high altitude and the mobility of HAPs. Thus, without CSI knowledge, the performance in terms of sum-rate can be degraded significantly. To overcome the absence of CSI, the authors proposed an interference alignment scheme by using a tethered balloon as relay between the HAPs and ground based stations. The proposed scheme achieved maximum sum rate without CSI. Additionally, they showed that there is an optimal altitude of the tethered balloon that maximize the achievable sum-rate.

V. Conclusion

In this survey, we provided an extensive and comprehensive overview of tethered platforms. We showed the types of tethered platforms, their components, applications, advantages as well as their challenges. We also showed several case studies in various fields and applications. Finally, we present the start of art of tethered platforms from a wireless communications perspective.

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