Integrating the Skies for 6G: Techno-Economic Considerations of LEO, HAPS, and UAV Technologies

Laszlo Toka, Mark Konrad, Adrian Pekar, and Gergely Biczók

The authors conduct a techno-economic analysis of the non-terrestrial enabling technologies of combined airspace and non-terrestrial networks.

Abstract

The combination of airspace and non-terrestrial networks (combined ASN), leveraging low Earth orbit (LEO) satellites, high-altitude platform stations (HAPSs), and unmanned aerial vehicles (UAVs), creates a transformative 6G connectivity infrastructure. The envisioned architecture combines the strengths of these technologies in a hierarchical network, addressing coverage, especially in remote areas not served today. In this article, we conduct a techno-economic analysis of the non-terrestrial enabling technologies of combined ASN. First, we identify and categorize a set of use cases ranging from rural connectivity through maritime scenarios to augmenting terrestrial networks, which could be implemented with different combinations of LEO satellites, HAPSs, and UAVs. Second, we provide a detailed total cost of ownership (TCO) analysis for these technologies, and find that a LEO constellation plus well-controlled UAVs are fit to provide global connectivity (TCO of a LEO satellite is 1.5 million USD) and on-demand network augmentation (10 million USD of TCO to serve a densely populated city), while a HAPS is best suited for regionally focused services with a TCO figure of 4.4 million USD. Finally, we provide an overview of the technological, regulatory, and economic challenges of HAPS, and outline specialized use cases where HAPS might be a good alternative.

Introduction

The concept of Space-Air-Ground Integrated Network (SAGIN) [1] has emerged as a comprehensive solution to address the increasing demand for ubiquitous and resilient communication networks. Encompassing the integration of space, air, and terrestrial networks, SAGIN addresses the emergent need for a resilient network infrastructure that can ensure uninterrupted communication services. This architecture is particularly relevant for extending coverage in remote and traditionally underserved areas, which are beyond the scope of conventional ground-based networks.

At the forefront of this integrated approach is the combined Airspace and NTN (non-terrestrial network), abbreviated as combined ASN [2], which leverages the synergistic capabilities of unmanned aerial vehicles (UAVs), high-altitude platform stations (HAPSs), and low Earth orbit (LEO) satellite networks, as illustrated in Fig. 1. At the apex of this architecture, LEO satellites offer expansive coverage through a space-based mesh network designed for global communication. These satellites also establish connections with terrestrial networks through satellite backhaul, merging space-based and earthbound operations. The intermediate layer, populated by HAPSs stationed in the stratosphere, delivers localized coverage with lower latency, higher data rates, and targeted service delivery [3]. Moreover, HAPSs facilitate a high-capacity bridge between LEO satellites and UAVs, ensuring a smooth transfer of information between various strata. The most accessible layer, comprised of versatile UAVs, facilitates immediate deployment for emergencies and on-demand coverage, reconnaissance, and sensor-based data acquisition [4].

This integrated system delivers superior throughput, resilience, and extended coverage, serving rural and remote areas, augmenting ground stations, and enabling smart urban infrastructure. The system's scalable design adapts to evolving communication demands, positioning the combined ASN as a cornerstone for future global connectivity enhancements. Nevertheless, a techno-economic assessment of the proposed architecture focusing on its enabling aerial technologies is essential to assess its real-world feasibility.

Our study aims to enhance the techno-economic understanding of SAGIN by building on existing methodologies in the field. Previous works by Osoro *et al.* [5] presented an open-source model for assessing the engineering-economics of satellite broadband, evaluating coverage, capacity, and cost for major LEO constellations such as Starlink, OneWeb, and Kuiper. Lin *et al.* [3] introduced a techno-economic assessment framework for LEO satellite constellations, focusing on the cost-per-capacity performance of low-complexity satellites. Li *et al.* [6] further complemented these studies by exploring the integration of LEO satellites with terrestrial networks for 6G. Additionally, the analyses in [7, 8] highlight critical aspects of integrating engineering and corporate finance techniques within a techno-economic framework for 5G networks, the methodologies developed therein are pertinent to our work.

Digital Object Identifier: 10.1109/MCOM.003.2400120

The authors are with the Budapest University of Technology and Economics and HUN-REN, Hungary; Laszlo Toka (corresponding author) and Gergely Biczók are also with AITIA, Hungary; Gergely Biczók is also with the University of Michigan, USA.

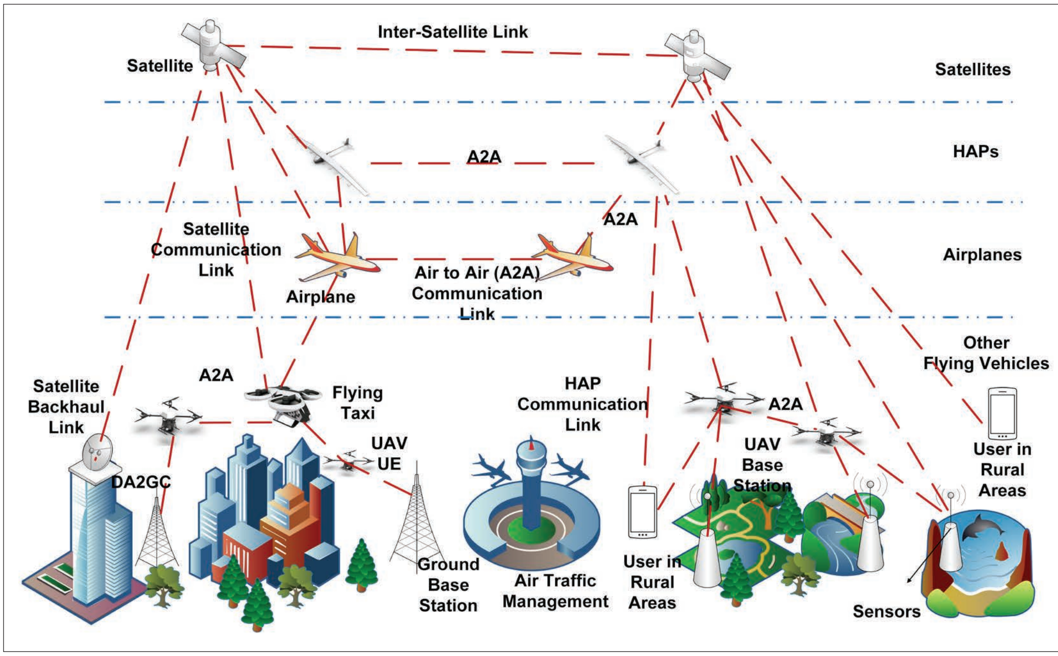

FIGURE 1. The combined ASN architecture proposed in [2] for 6G.

In this article, we contribute to this body of work by conducting a total cost of ownership (TCO) analysis for LEO, HAPS, and UAV technologies within the combined ASN. Our contribution encompasses three main aspects:

- We define a range of use cases, spanning from rural connectivity to network augmentation that can be realized through various combinations of LEO satellites, HAPSs, and UAVs.
- We conduct TCO analysis, concluding that a LEO constellation coupled with UAVs can deliver global connectivity and on-demand network augmentation.
- We outline challenges associated with HAPS and discuss HAPS-specific use cases.

The remainder of this article is structured as follows: We first explore the capabilities of LEO, HAPS, and UAV technologies, detailing key use cases and techno-economic factors of the ASN architecture. Then we analyze the costs associated with these technologies. Following that, we present a quantitative analysis assessing the viability of integrating LEO satellites, HAPS units, and UAVs for network augmentation. We then examine HAPS-specific challenges and use cases. The final section concludes the article.

Background

Technology Characteristics

Each component of the combined ASN has unique strengths and limitations. LEO satellite constellations offer continuous global coverage, adequate latency for real-time applications owing to their proximity to Earth, and resilience against service interruptions. Satellites have a long lifespan and tolerate weather effects well but have fixed orbits and substantial setup times due to launches. HAPS excels in providing spatiotemporally focused, semi-permanent communications services catering for large regional events and sustained emergency response situations; however, both their coverage, mobility, and longevity are moderate. UAVs add responsiveness, facilitating rapid deployment for temporary service gaps and disaster recovery. Flying at low altitudes and equipped with sensors, they are able to provide real-time data for environmental monitoring and infrastructure inspection, thereby instantiating the joint communication and sensing vision of 6G networks. On the other hand, large-scale UAV deployments pose complex fleet and air traffic management challenges.

A comparison of these technologies, highlighting their coverage, longevity, and technical capabilities, is given in Table 1. Although limited on their own, integrating LEO satellites, HAPSs, and UAVs into the combined ASN architecture creates a dynamic network capable of adjusting to a wide range of spatial and temporal demands [2]. LEO satellites form the backbone for widespread coverage, HAPSs enhance localized connectivity, and UAVs offer precise, on-demand support. This layered approach maximizes network coverage, bandwidth, and resilience, ensuring reliable communications even under challenging conditions.

Use Cases

6G connectivity services provided by non-terrestrial components in the combined ASN are categorized based on their spatial characteristics into two main types. The first focuses on airspace communication as part of initiatives like the digital Single European Sky (SES) [2], linking flying endpoints to the 6G infrastructure through air-to-ground and air-to-air links [2]. Applications include connectivity for airline passengers, urban air mobility, safety services in smart cities, and integrating digital airspace with terrestrial networks for air traffic and national security management. The second category aims to connect terrestrial users, enhancing either capacity or coverage. This includes extending mobile connectivity to remote areas, boosting ground communication capacity as needed, supporting non-3GPP traffic like Earth observation and disaster management, and enhancing IoT

Capability	LEO	HAPS	UAV
Coverage area	Hundreds of thousands of km^2 per satellite	Hundreds of km^2	Tens of km^2
Operational longevity	5–8 years	Several months to years	Hours to days
Data throughput	Up to Gb/s	Tens to hundreds of Mb/s	Mb/s to Gb/s
Communication latency	10–50 ms	< 1 ms locally, up to tens of ms globally	< 1 ms
Orbital/operational altitude	350–2000 km	17–22 km	< 0.5 km
Deployment time	Months to years	Weeks to months	Minutes to hours
Mission flexibility	Low (fixed orbits)	Moderate (geo-stationary)	High (fully maneuverable)
Resilience to adverse weather	High	Moderate	Low
Platform stability	Fixed (orbital path)	Quasi-stationary	Variable
Scalability	Moderate (requires satellite launches, stable once established)	Moderate	Moderate (high flexibility but needs fleet/air traffic management capability)

TABLE 1. Comparison of key ASN components: LEO satellites, HAPSs, and UAVs.

Use Case	Technology		
	LEO	HAPS	UAV
Global Coverage	Low-medium data rates, medium latency		
Rural/Remote Coverage	Feasible with strategic ground stations	Location-specific	
Aeronautical Connectivity	Medium data rates, medium latency globally	High data rates, low latency in dense areas	Relay capability
Maritime Connectivity	Low-medium data rates, medium latency globally	High data rates, low latency in dense areas	Relay capability
Network Augmentation	Variable rates/latency	Minimal changes with dynamic deployment	Effective with coordinated deployments

TABLE 2. Use cases vs. non-terrestrial access technologies: LEO, HAPS, and UAV.

connectivity through extended coverage.

The different scenarios are grouped into use cases with varying requirements, see Table 2.

Coverage Extension on Land: LEO satellite constellations, supported by GEO satellites [9], offer extended coverage for IoT devices without the need for high data rates or real-time operations. They provide medium latency connections anywhere, aided by space-to-ground and space-to-space links and ground stations in remote locations. HAPS also supports connectivity in remote areas, though their deployment requires careful planning due to their limitations.

Improved Connectivity for Aerial and Maritime Use: LEO satellites can connect vehicles anywhere on Earth, including planes and ships. Alternatively, HAPS units positioned over busy air corridors and shipping lanes could facilitate low-latency maritime communications. In both cases, UAVs can serve as relays for simpler devices without antennas that are capable of connecting to satellites or HAPSs directly [10]. Note that strict regulatory measures in aviation pose an additional challenge as they are being expanded to unmanned aircraft, here serving as part of the network infrastructure. Additionally, UAV fleets will likely be under an integrated air traffic management system [2], creating strict requirements for their control functionality.

Network aUgmentation — Capacity Extension in Terrestrial Edge Networks: LEO satellites can alleviate temporary congestion in edge networks by rerouting traffic, while HAPS can provide additional regional capacity, offering temporary relief without permanently expanding the terrestrial infrastructure and ensuring low-delay, high-speed connectivity.

TCO of LEO Satellite, HAPS, and UAV Technologies

Examining the techno-economic aspects of LEO constellations, HAPS units, and UAV-based solutions in the combined ASN ecosystem is crucial, given the delicate balance between their technological capabilities and financial viability. In a context where judicious management of capital expenditure (CAPEX) and operational expenditure (OPEX) is paramount, ensuring both technical performance and economic sustainability becomes pivotal. To assess differences between these technologies, highlighting potential use cases and general usability, a service provider's perspective on deployment and maintenance costs is needed. Table 3 contains the details of the deployment and operational costs of the respective technologies. LEO satellite data is based on [6], HAPS data is sourced from [11] and [12], while UAV parameters are based on a heavy-duty drone capable of lifting ^{a} 30 kg, such as the Draganfly Heavy Lift Drone

Examples	LEO Satellite	HAPS	UAV
	Starlink, OneWeb, Kuiper	Zephyr, Sunglider, Blimp	Draganfly, JOUAV CW-80E
CAPEX Manufacturing [USD] Launch [USD] Lifetime Total [annual in USD]	0.7M 0.5M (60 satellites per launch) 5 years 0.24M	4M — 20 years 0.2M	0.05M — 1000 hours 0.006M
OPEX Maintenance Charging [USD] Total [annual in USD]	10 % Solar 0.02M	15 % Solar 0.03M	10 % 0.26 per hour (0.13 per kWh) 0.003M
Total [annual in USD]	0.26M	0.23M	0.009M
PV of OPEX with 5 % discount rate	0.086M	0.371M	0.0029M
TCO (CAPEX + PV of OPEX)	1.46M	4.371M	0.0089M
Coverage Diameter	500 km	100 km	10 km
Ground Station	0.5M	Existing base stations	Existing base stations

TABLE 3. LEO, HAPS, UAV: TCO.

[13]. As a brief market overview, we list a few available products for cost baseline in Table 3.

Manufacturing Costs

The manufacturing of satellites, HAPSs, and UAVs is influenced by several cost factors, including design complexity, materials used, electronics, and communications equipment required for 6G compatibility. As of early 2024, the cost of manufacturing a standard commercial UAV ranges from 10,000 to 100,000 USD, depending on its capabilities and the technology involved. For a complex HAPS unit, remaining airborne for extended periods of time, the costs are significantly higher, starting at approximately 1 million and potentially reaching tens of millions of USD for advanced models with extensive payloads. LEO satellites fall in between the two ranges: the cost of a single satellite is in the order of hundreds of thousands of USD. Economies of scale play a significant role in driving down costs: if a company were to order a fleet of 100 UAVs, the per-unit cost would decrease due to bulk ordering of materials and streamlined production.

We refer the reader to [6] for a detailed cost estimation on LEO satellite constellations. In the realm of HAPS, the market growth is attributed to several factors, including the advancements in photovoltaic technology, which is essential for powering these platforms, and the development of new generation engines, which will likely enhance HAPS capabilities and operational efficiency. HAPS aircraft, like Airbus' Zephyr, utilize solar panels for daytime flight at high altitudes and battery power for nighttime operations. Besides the world-record-breaking Zephyr, capable of flying continuously for months, BAE Systems also completed a successful test flight of its solar-powered PHASA-35 in 2023, reaching altitudes over 20,100 meters. Moreover, Softbank Corp. presented its HAPS solution Sunglider in 2020, then acquired 200 HAPS-related patents from Google Loon in 2021, indicating a strategic move into the telecommunications platform space from the stratosphere [11]. Despite these positive developments, one of the significant challenges the HAPS market faces is the high cost associated with developing these systems, particularly for communications purposes. Additionally, maintaining such networks can drive operational expenses higher. We assume 4M USD for the manufacturing cost of a HAPS aircraft based on [11] (page 27), instead of the outdated estimation of 40M USD in [12]; the decreasing manufacturing cost points to a maturing technology.

In the current market of large drones, the Bayraktar (5M USD), MQ-9 Reaper (30M USD), and Global Hawk (100M USD) are prominent UAV models used for various application domains. As their prices are comparable to HAPS aircraft, we argue that such drones are not competitive for telecommunications purposes. However, the market segment of small UAVs (including mini-, micro-, and nano-) is rapidly growing, offering economical solutions for a wide range of applications, from search and rescue to agricultural monitoring. We estimate the manufacturing cost at 50k USD for a heavy lift (but small) UAV for telecommunications purposes.

Deployment Costs

An important aspect of CAPEX is the lifetime of the devices; for example, LEO satellites are rated for 5 years of service, so all devices must be replaced periodically to keep the constellation healthy. A 5-year expenditure for a 5400-satellite LEO constellation is therefore calculated as (5400·0.7M USD + 5400·0.5M USD)·1.5 = 9.7B USD. Note that we assume disposable launch vehicles (no recovery cost). Furthermore, an assumed collection of 150 ground stations at 0.5M each USD, as in the Starlink network, would cost an extra 75M USD. The lifetime of UAVs is estimated as the industry average of 1,000 flight hours, while a HAPS's lifetime is based on the standard lifetime of an airliner. For these two

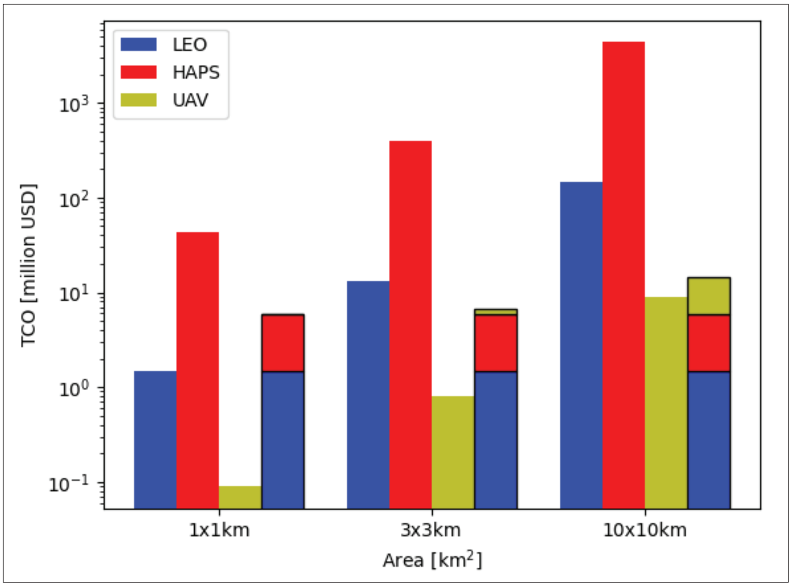

FIGURE 2. Network augmentation costs in small scale scenarios.

latter technologies, their integration with existing terrestrial network equipment is assumed (as opposed to the procurement of new ground stations/gateways).

Maintenance Costs

These include repairs, part replacements, software updates, and battery or fuel cell replacements. HAPS and UAV units can be effectively maintained in specialized ground-based facilities if needed. Nevertheless, with the implied logistical costs this can reach up to 15 percent of the manufacturing costs annually in case of HAPS [11].

Operating Costs

Operating costs for UAVs and HAPSs are multifaceted and include energy consumption, personnel, airspace usage fees, insurance, and regulatory compliance. UAVs typically operate on battery power; assuming an average cost of electricity at 0.13 USD per kWh and a UAV requiring 2 kWh for a one-hour flight, the cost of energy per flight hour is approximately 0.26 USD. Note that such costs can increase steeply for larger UAVs or those with greater power demands. HAPS, on the other hand, uses solar power, which has minimal direct operating costs but requires a large upfront investment for high-efficiency solar cells and energy storage systems.

TCO

This is calculated by summing the CAPEX and the present value (PV) of OPEX over the asset's lifetime [5]. To calculate the PV of OPEX, a 5 percent discount rate is applied, reflecting industry standards for telecommunications projects [5]. Based on this model, we estimate the TCO for LEO satellites to be 1.46M USD with a PV of 0.086M USD over 5 years, for HAPS to be 4.371M USD with a PV of 0.371M USD over 20 years, and for UAVs to be 0.0089M USD with a PV of 0.0029M USD over approximately 0.34 years (calculated based on the assumption of 8 operational hours per day, translating 1000 hours into about 0.34 years).

Opting for HAPS within cities or smaller countries can be cost-effective for service providers; even a few HAPS units can provide coverage for a large area. However, if a provider aims to expand its services to a continent or a global scale, the significant investment cost of a LEO constellation (i.e., thousands of satellites) may be justifiable due to their extensive coverage capabilities. In network augmentation scenarios, HAPS excel over LEO satellites in applications requiring near-real-time latency and high data rates due to their proximity to the ground and user equipment. However, for smaller, localized coverage areas, UAV-based solutions offer a more economical alternative, provided they effectively cover the designated area. The comparison in Table 3 reveals that while the TCO for HAPS is significantly higher than for LEO satellites, considering HAPS's 20-year lifespan compared to the 5-year lifespan of LEO satellites, the difference becomes less pronounced on an annualized basis, that is, when CAPEX is evenly distributed over the lifespan. In contrast, the UAV-based solution is two orders of magnitude cheaper than LEO satellites and HAPS; however, a UAV covers a two orders of magnitude smaller area.

Network Augmentation: Quantitative Analysis

This section presents a quantitative analysis assessing the viability of integrating LEO satellites, HAPS, and UAVs for network augmentation, weighing in technical factors like throughput alongside TCO.

The analysis considers various area sizes ranging from 1 × 1 km to 300 × 300 km (small-scale scenarios represent events in stadiums, festivals, and cities, and large-scale scenarios stand for cities, metropolises, and regions), with a single user demand throughput of 1 Mb/s and client density of 10,000 users per square kilometer. As a reference, the population density in New York City is 11,300 people per square kilometer. In each scenario, LEO satellites, HAPS, and UAVs are deployed to fulfill the outstanding throughput demand, either alone (e.g., only UAVs), or combined. Figures 2 and 3 illustrate the numerical results of the analysis for small and large-scale scenarios, respectively. The *x*-axis of the grouped bar charts represents the serving area; the *y*-axis represents TCO in US dollars. Each bar group comprises three monolith bars, representing LEO, HAPS, and UAV deployments separately, and the rightmost stacked bar (emphasized with thick edge) that stands for the combined ASN solution. In the combined scenario, the throughput demand is assumed to be fulfilled by deploying technologies in this order: leveraging LEO satellites, followed by on-demand deployment of HAPSs, and finally by a swarm of UAVs.

In contrast to the homogeneous cases where we ignore radio beam size and interference, essentially allowing any number of LEO satellites and HAPS to serve an area of arbitrary size, in the combined ASN case we assume a LEO satellite constellation similar to Starlink, comprising 5400 satellites orbiting at an altitude of 550 km. The satellites operate in the Ku-band with a bandwidth of 2 × 500 MHz. Additionally, HAPSs are considered as large macrocells in terrestrial networks, operating in the 3GPP-designated FR1 band with a bandwidth allocation of 2 × 40 MHz. We also assume that HAPSs can be placed geographically to the cross points of a rectangular grid if needed.

Similarly, UAVs are assumed to operate in the L or S band with a bandwidth of 40 MHz. One LEO satellite serves the designated area with as many beams as the size of the area allows. The diameter of a typical LEO satellite cell on the Earth's surface covered by a beam is 25 km; the throughput capacity of each beam is assumed to be 1/8 of the total LEO capacity. For small-scale scenarios, one HAPS is assumed, while for large-scale scenarios, a grid of HAPSs (e.g., 2 × 2, 6 × 6) is deployed, focusing the coverage area diameter of each HAPS down to 50 km, or even more. The remaining throughput demand is covered by UAVs, leveraging efficient spectrum re-usage due to their limited radio transmission power and low altitude position. For interference and spectral efficiency, we make simplifying assumptions regarding line of sight propagation, MIMO configurations, and beamforming antenna technologies. Spectral efficiency varies based on off-nadir angles and beam directions, but in our scenarios, we focus on high-demand areas served by many flying units (particularly UAVs). Therefore, close-to-vertical directions are assumed. Furthermore, MU-MIMO and beamhopping techniques can be employed to enhance system-level spectral efficiency and mitigate interference. With peak spectral efficiency at 8 bps/Hz and 10 bps/Hz for LEO and HAPS/UAV, we assume a cell capacity of 10 Gb/s and 1 Gb/s for LEO and HAPS/UAV, respectively (with MU-MIMO).

The results shown in Figs. 2 and 3 offer valuable perspectives on integrating LEO satellites, HAPS, and UAVs for enhancing network capacity in various deployment contexts. In regions with intense demand for high throughput, UAVs emerge as the economically preferred option. Expanding a LEO constellation permanently to meet such demand would be astronomically expensive, even more so in case of HAPS, although the latter can be relocated and reused easily. Additionally, augmenting terrestrial networks with aerial devices in large areas, that is, larger than a city, is prohibitively expensive. The TCO of the combined ASN in scenarios of 1 × 1 km and 3 × 3 km is significantly higher than a purely UAV-based network augmentation solution, which means that in those cases leveraging LEO and HAPS capacities costs more than substituting them with UAVs.

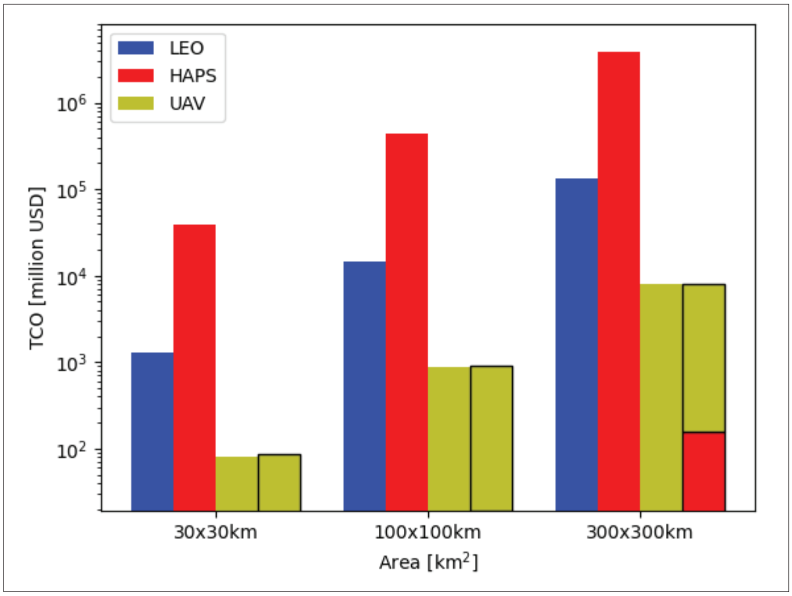

FIGURE 3. Network augmentation costs in large scale scenarios.

HAPS: Challenges and Considerations

The analysis above has revealed that a combination of a LEO constellation and well-controlled UAVs is suitable for enabling most mentioned use cases in a cost-efficient manner. HAPS, albeit a unique novel technology in telecommunications infrastructure, suffers from many technological, regulatory, and economic issues.

Technological Challenges

There are multiple engineering challenges concerning the efficient operations of HAPS. These include:

- The need for lightweight but high-performance solar panels
- Adapting to dynamic weather conditions with limited human intervention
- Physical design constraints regarding payload weight and environmental robustness, and, last but foremost
- The establishment of high-capacity feeder links to ground gateways, other HAPS, and satellites. There is reason for optimism that the first three challenges are going to be overcome in the next few years; however, spectrum issues may be tougher to manage (see below).

Regulatory Challenges

The unique characteristics of the combined ASN and HAPS specifically invoke stubborn regulatory obstacles. These include:

- The inherently complex combined ASN architecture potentially spurring lengthy debates within and across standardization bodies
- The airspace utilization of HAPS requiring joint regulatory practices across the telecommunications, aviation, and space sectors
- The envisioned combined ASN (being both critical infrastructure and a cyber-physical system of systems) having to satisfy stringent cybersecurity *and* safety requirements [2] regarding users, flying user equipment (UE) , and aerial platforms
- The need for novel dynamic spectrum management with respect to the now three-dimensional networks.

Although the first three obstacles can slow down the adoption of HAPS and combined ASN technology, spectrum management might be the most challenging to tackle.

Spectrum Challenges

Two types of communication links are required for HAPS: service link and feeder link. The service link is a one-to-multiple communication between HAPS and the UEs, while the feeder link is a one-to-one communication between HAPS and the ground station (connecting to the 5G/6G core system). The feeder link "binds" the HAPS to a ground station, limiting its mobility; therefore, an inter-HAPS mesh and satellite feeder links might be applied to maintain flexibility (and potentially save on ground station CapEx). During the last two ITU World Radio Conferences, the 700-900 MHz, 1.7 GHz, 2GHz, Military/national security operations constitute another type of specialized use case. In such a scenario, the capabilities of HAPS (better image resolution than LEO satellites, longer endurance than UAVs) are in the sweet spot for remote surveillance of larger regions.

and 2.6 GHz mobile spectrum bands were designated to (directional) HAPS service links, and the 6.5 GHz, 27/31 GHz, 38 GHZ, and 47/48 GHz regions were allocated to HAPS feeder links [14]. While the frequency band above these (E-band) is assigned to satellite usage, studies show that the achievable throughput is much higher here also for HAPS; it is expected that some sub-bands will also be reserved for HAPS feeder links. In fact, in order to achieve higher data rates, be less dependent on weather effects, and deal with the scarcity of millimeter wave spectrum, researchers have already proposed THz and optical wireless solutions for HAPS/satellite feeder and inter-HAPS/inter-satellite links. These, however, are in their infancy, facing their own techno-economical challenges before reaching an adequate maturity level. Furthermore, to utilize the spectrum efficiently, dynamic spectrum-sharing mechanisms are also potentially required (both in the above licensed and unlicensed bands), adding an extra layer of complexity.

Economic Challenges

As shown in previous sections, HAPS currently has high initial and operational costs and competes against established technologies such as satellites and UAVs. Adding to the usual struggles around technology adoption, HAPS is facing potentially steep compliance expenses owing to strict equipment certification in the aviation and space sectors. Nevertheless, the defining economic difficulty lies within the uncertainty of the return on investment (ROI), as evidenced by the recent financial failure of Project Loon. Our scenario analyses reinforced the reality that (under the current cost regime) there is no profitable general and/or global use case for HAPS. While technology maturation and shifting economic priorities may offset this situation in the long run [12], presently, we see only two specialized scenarios where the use of HAPS is advantageous.

Specialized Use Cases

We argue that only in very specific scenarios, can HAPS be the preferred technology. There is a strong willingness and an already launched project in Japan (launched by NICT and spearheaded by NTT, DoCoMo, and JSAT) [11], where a whole HAPS-based communications architecture is developed and deployed, including ground stations, advanced feeder links, and a satellite backhaul. Here, the enabling factors are threefold. First, Japan is in a tectonic hot spot, which calls for permanent emergency preparedness. Second, this invites an IoT network deployment focusing on seismic activities dispersed geographically to hundreds of islands, where HAPS is a natural fit. Third, Japan's geolocation eases the burden of advanced spectrum management. Although it is built primarily for natural disaster recovery, this future infrastructure might also dedicate some capacity to general public use (such as rural coverage or network augmentation), recovering some of its costs in the long run.

Military/national security operations constitute another type of specialized use case. In such a scenario, the capabilities of HAPS (better image resolution than LEO satellites, longer endurance than UAVs) are in the sweet spot for remote surveillance of larger regions. In addition to functional advantages, military operations are generally less cost-sensitive. Specifically, the US Navy proposed the use of Airbus Zephyr-like HAPS for the persistent coverage of the South China Sea, citing the mobility, endurance, and lower price compared to the Navy-developed alternative [15]. As for the vulnerability of HAPS to enemy attacks, the consensus is that it is both out of range for mobile shoulder-launched surface-to-ground missiles and interceptor fighter jets, making it suitable for deployment over areas without advanced air-defense systems. Alas, HAPS might also be utilized in case of civil unrest as a quickly deployable temporary coverage solution in the event of successful anti-satellite attacks and other "deep sensing" scenarios; this is likely to happen in the near future.

Conclusion

In conclusion, this research explores the complex field of non-terrestrial technologies — specifically LEO satellites, HAPS, and UAVs — within the combined ASN architecture, demonstrating their potential to revolutionize ubiquitous connectivity. The integration of these technologies meets diverse geographical and operational needs. Our techno-economic analysis identified the combination of LEO satellites and UAVs as optimal for global coverage and on-demand terrestrial network augmentation services: the TCO of a LEO satellite is 1.5 million USD and covers 500 km in diameter, while UAVs worth 10 million USD in TCO can serve a densely populated city. HAPS faces significant technological, regulatory, and economic challenges (TCO of a HAPS is 4.4 million USD) and is currently only favorable in selected specialized use cases.

Acknowledgments

This work was supported by the Ministry for Culture and Innovation from the National Research, Development and Innovation Fund through projects no. 135074 under the FK_20 and no. 138903 under the FK_21 funding schemes, ÚNKP-23-5-BME-436 and ÚNKP-23-5-BME-461 New National Excellence Program. L. Toka and A. Pekar were supported by János Bolyai Research Scholarships of the Hungarian Academy of Sciences. G. Biczók was supported by the Fulbright Visiting Scholar program. This research was partially funded by the Hungarian National Research, Development, and Innovation Office, under the agreement no. 2020-1.2.3-EUREKA-2021-000006.

References

[1] J. Liu *et al.*, "Space-Air-Ground Integrated Network: A Survey," *IEEE Commun. Surveys & Tutorials*, vol. 20, no. 4, 2018, pp. 2714–41, DOI: 10.1109/comst.2018.2841996.

[2] M. Ozger *et al.*, "6G for Connected Sky: A Vision for Integrating Terrestrial and Non-Terrestrial Networks," *Proc. 2023 Joint European Conf. Networks and Commun. 6G Summit*, 2023, DOI: 10.1109/eucnc/6gsummit58263.2023.10188330.

[3] X. Lin *et al.*, "On the Path to 6G: Embracing the Next Wave of Low Earth Orbit Satellite Access," *IEEE Commun. Mag.*, vol. 59, no. 12, 2021, pp. 36–42, DOI: 10.1109/mcom.001.2100298.

[4] M. Mozaffari *et al.*, "Toward 6G with Connected Sky: UAVs and Beyond," *IEEE Commun. Mag.*, vol. 59, no. 12, 2021, pp. 74–80, DOI: 10.1109/mcom.005.2100142.

[5] O. B. Osoro and E. J. Oughton, "A Techno-Economic Framework for Satellite Networks Applied to Low Earth Orbit Constellations: Assessing Starlink, Oneweb and Kuiper," *IEEE Access*, vol. 9, 2021, pp. 141,611–25, DOI: 10.1109/access.2021.3119634.

[6] K. T. Li *et al.*, "A Techno-Economic Assessment and Tradespace Exploration of Low Earth Orbit Mega-Constellations," IEEE Commun. Mag., vol. 61, no. 2, 2023, pp. 24–30, DOI: 10.1109/MCOM. 001.2200312.
[7] E. J. Oughton *et al.*, "An Open-Source Techno-Economic Assessment Framework for 5G Deployment," *IEEE Access*, vol. 7, 2019, pp. 155,930–40, DOI: 10.1109/ACCESS.2019.2949460.
[8] E. J. Oughton and W. Lehr, "Surveying 5G Techno-Economic Research to Inform the Evaluation of 6g Wireless Technologies," *IEEE Access*, vol. 10, 2022, pp. 25,237–57, DOI: 10.1109/ACCESS.2022.3153046.
[9] O. Liberg *et al.*, "Narrowband Internet of Things for Non-Terrestrial Networks," *IEEE Commun. Standards Mag.*, vol. 4, no. 4, 2020, pp. 49–55, DOI: 10.1109/MCOMSTD.001.2000004.
[10] S. S. Hassan *et al.*, "Seamless and Energy-Efficient Maritime Coverage in Coordinated 6G Space–Air–Sea Non-Terrestrial Networks," *IEEE Internet of Things J.*, vol. 10, no. 6, 2023, pp. 4749–69, DOI: 10.1109/jiot.2022.3220631.
[11] FRONTEX, HAPS market report, https://www. frontex.europa.eu/ assets/EUresearchprojects/2023/FX HAPS WP1 — Market Report V4.pdf, 2023.
[12] J. Kim *et al.*, "Is HAPS Viable for the Next-Generation Telecommunication Platform in Korea?" *EURASIP J. on Wireless Communications and Networking*, vol. 2008, no. 1, 2008, DOI: 10.1155/2008/ 596383.
[13] Draganfly, *Heavy Lift Drone*, https://draganfly.com/products/heavylift/, 2024.
[14] *Proc. World Radiocommunication Conf.2023 – Provisional Final Acts*, International Telecommunication Union, http://handle.itu.int/11.1002/pub/8225d4fb-en, 2023.
[15] E. A. Karlik, *Bring Flexibility to FONOPs with HAPS*, https://www.usni.org/magazines/proceedings/2020/december/bring-flexibility-fonops-haps, 2020.

Biographies

Laszlo Toka received his Ph.D. degree from Telecom ParisTech in 2011. His research focus is on cloud computing and artificial intelligence. He is currently an Associate Professor with the Budapest University of Technology and Economics (BME) and a member of the HUN-REN-BME Cloud Applications RG.

Mark Konrad is a Master's student at BME, Hungary, where he received his BSc degree in 2022. His current research focuses on federated learning and 6G technologies.

Adrian Pekar earned his PhD from the Technical University of Kosice, Slovakia, in 2014. He presently holds the position of Associate Professor at the Department of Networked Systems and Services at BME, Hungary. His research interests encompass network and service management and data science.

Gergely Biczók is an associate professor in the CrySyS Lab at BME, a Senior Researcher in the BME-HUN-REN Information Systems RG, and a Fulbright Visiting Researcher at the University of Michigan. His research focuses on the economics of networked systems.