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Can High Altitude Platforms Make 6G Sustainable?

Daniela Renga and Michela Meo

***Abstract*—The staggering growth of mobile traffic fostered by the spreading of 5G technology and massive Internet of Things applications is leading to the need for extensive Radio Access Network (RAN) densification. However, the entailed boost in energy consumption poses significant challenges for a sustainable transition towards 6G. High Altitude Platform Stations (HAPSs) equipped with aerial Base Stations (BSs) represent a promising and flexible solution to provide additional capacity that can be used in a flexible way to facilitate terrestrial BSs sleep modes and, ultimately, reduce energy consumption and make the network more sustainable.**

As a case study, we consider a portion of a urban RAN to investigate the potential benefits deriving from the integration of HAPSs in terrestrial RANs as a means to support joint energy and resource allocation strategies that will be needed in 6G networks. Our results show that offloading traffic to HAPS mounted BSs allows to reduce the grid energy demand of terrestrial nodes, still maintaining adequate Quality of Service.

***Index Terms*—Non-Terrestrial Networks, High Altitude Platform Stations, 6G Networks, Energy Efficiency, Green Networks**

INTRODUCTION

Radio Access Networks (RANs) are witnessing a staggering growth of mobile traffic demand due to the popularity of traditional communication services, especially those based on multimedia contents, as well as the penetration of massive Internet of Things communications in several fields. To satisfy this service demand, new mobile communication technologies require an extensive RAN densification, which will be further fostered by the upsurge of the number of connected machines that will lead 6G networks to support about ten million devices per square kilometer, ten fold more than the 5G connection density requirements.

In this scenario, two main challenges are emerging that might limit and compromise the deployment of innovative infrastructures. First, network densification can become critical, especially in urban environments, where physical, law and bureaucracy constraints limit the boundless installation of new network infrastructures. Second, the growth of energy consumption of the communication infrastructures is in contrast with the global efforts to guarantee sustainable development. In the design of 5G technologies, a significant effort was put to include energy as a key performance indicator, and energy efficiency has been largely improved. However, looking at consumption instead of efficiency, the overall power demand of 5G networks is estimated to be very large [1], at least 10 times larger than the demand of 4G, due to both network densification and high consuming BSs and users' equipment.

The design of 6G solutions cannot leave these two challenges aside. In order to tackle them, two technologies will play a fundamental role. On the one side, renewable energy (RE) sources will be integrated in the telecommunication infrastructure, with the purpose of reducing the energy consumption from the grid and the associated carbon emissions. On the other side, by leveraging on an unprecedented network flexibility that can operate across different technologies, new Resource on Demand (RoD) approaches will dynamically adapt the radio resource availability to the actual varying traffic demand, so as to reduce network consumption as much as possible and, at the same time, reduce the need to over-provision the network.

In this context, the integration of non-terrestrial networks may be strategic, since they provide supplementary capacity where and when it is more needed, without requiring additional energy consumption from the power grid. In particular, a High Altitude Platform Station (HAPSs)[1], which operates in the stratosphere at an altitude around 20 km [2], can be equipped with Super Macro BS (SMBS) and provide additional capacity over a wide geographical area of up to hundreds kilometers radius [3]. From Mobile Operators' perspective, moving towards a *Space-As-A-Service* paradigm means that HAPS mounted SMBSs can be exploited in support to energy and resource allocation strategies implemented by terrestrial nodes. Besides enabling coverage and capacity enhancement over the served region, SMBSs can also support data acquisition, computing, caching, and processing in manifold application domains [2].

So far HAPSs have been considered mainly as a mean to enhance the network service provisioning, and their usage was conventionally limited to rural and remote coverage and to disaster scenarios, where the terrestrial network may either

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[1]HAPS is also indicated as *IMT BS (HIBS)* according to ITU-R

not exist or be sparse. Few studies investigate the use of HAPS for Gigabit Mobile communication [4] or as a support to IoT applications in 6G framework [5], or as intermediate layer in Space-Air-Ground integrated networks [6]. The HAPS integration in populated areas characterized by dense terrestrial networks for reasons such as flexibility and sustainability is a less investigated aspect in the literature [2]. In this paper we aim at studying the potential benefits deriving from integrating HAPS mounted SMBSs in terrestrial RANs, as a mean to support joint energy and resource allocation strategies that will be needed in 6G networks. In particular, the novelty of our contribution consists in exploiting the HAPS capacity, which comes at no operational cost given the HAPS self-sustainability, to offload a limited portion of terrestrial traffic. Although this fraction may not be sufficient to cover the future generation network bandwidth demand, it allows to deactivate a high number of low loaded BSs to save energy during off-peak periods, providing an additional degree of freedom to pursue sustainability in future networks.

Finally, we aim at investigating the potential of flexibly allocating the HAPS bandwidth, that can be focused on specific areas or redirected from an area to another one depending on where it is more effective in improving energy efficiency and limiting the required on-ground RE supply.

The typical scenario is shown in Fig. 1. A portion of a urban mobile access network integrates a HAPS mounted SMBS that provides additional capacity over different areas and is incorporated in RoD strategies that target the reduction of energy consumption from the power grid. In each traffic area, several clusters consisting of heterogeneous cells coexist. The BSs are powered by the electric grid, and some of them can additionally be equipped with photovoltaic (PV) panels to locally generate RE that can be immediately used by the BSs or stored in some battery units for future usage. To optimize energy consumption, based on RE availability and the amount of traffic to carry, some BSs can be switched off and their traffic can be shifted to the aerial SMBS.

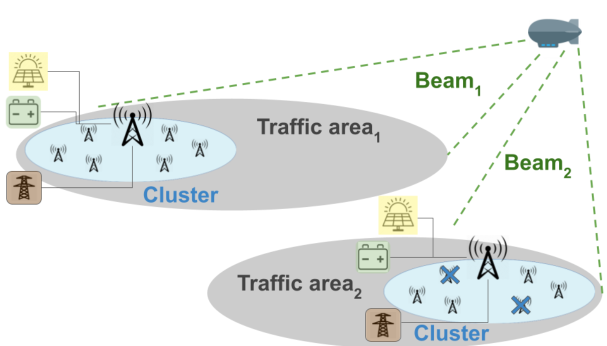

Fig. 1: HAPS integration in a terrestrial RAN.

By discussing the benefits that HAPSs can bring to joint energy and resource management, we claim that they can contribute in a substantial way to make future 6G networks greener and sustainable.

Integrating Non-Terrestrial Networks

The SMBS bandwidth capacity can be flexibly distributed in space. A single aerial BS can serve a wide geographical area and its coverage can be partitioned by means of multiple beams, whose signal can be dynamically steered and focused on desired spots, to form up to 100 cells over the entire served area [4], [7], [8]. Various partition schemes can be applied to build up differently shaped coverage cells featuring variable sizes that may shrink or expand over time to provide supplementary capacity to areas where it is needed [9].
These huge aerial platforms offer a wide surface to host photovoltaic panels, resulting quite effective to power HAPS with solar energy, given the abundance of unfiltered solar radiation at the typical operating altitudes. This primary energy source is coupled with electrical batteries or hydrogen fuel cells [2]. The high efficiency of today photovoltaic modules and high energy density batteries make HAPS fully self-sustainable.
The deployment of HAPSs is progressively becoming more and more economically feasible, thanks to the introduction of innovative and cost-effective technologies and materials, including light-weight building materials that enable high payload capacity, high density energy storage systems yielding 250 Wh/kg, and more efficient and cheap photovoltaic modules, featuring power exceeding 1.5 kW/kg, a record efficiency of almost 38% [2], and up to 50% CAPEX decrease expected in the decade 2018-2028 [10].
With a 4-fold power consumption increase for 5G BSs [1] and an expected 150% surge of operational cost for network operators in 5G scenarios, as reported by Vertiv and 451 Research the capacity provided by HAPSs at virtually no operational cost enabling BS deactivation makes aerial network nodes very attractive. Moreover, CAPEX for HAPS installation is compensated by the wide and flexible coverage offered by a single network node, whereas densified on-ground infrastructures requires several nodes and, hence, increased CAPEX.
The coverage range provided by HAPSs is in between terrestrial and satellite systems, making aerial BSs well suited as complementary network component. Aerial nodes can be rapidly installed (only a few hours are sufficient for a HAPS to become operative) and easily removed when they are no more needed. Despite this flexibility, they have the potential to remain operative for various years [11] and they can still be periodically brought down to the ground for reconfiguration, thus requiring lower upgrade cost with respect to

satellites [9], [12].
While in a first phase HAPSs have been considered to provide Internet access over remote and sparsely populated areas, it is now clear that they can play a crucial role also in Smart Urban ecosystems. A fully integrated three-layer Vertical Heterogeneous Network (VHetNet) is currently under discussion as a cornerstone in the 6G network architecture, consisting of (i) the satellites network, (ii) the aerial network, and (iii) the terrestrial network [9], [13]. In this picture, HAPSs can serve as distributed machine learning platforms and aerial data centers, support massive IoT communication services, and manage the mobility of swarms of Unmanned Aerial Vehicles (UAVs), deployed for large-scale monitoring purposes and cargo delivery tasks [2]. HAPSs can act as alternative backhaul for isolated BSs as well as to handle LEO satellites handoffs and provide seamless connectivity [2], [9]. Besides these interesting applications, that are summarized in Table I, little attention has been devoted to HAPSs as a fundamental technology to make future communications more sustainable. By adding flexibility to resource allocation and, at the same time, being self-sustainable, HAPSs can significantly improve energy consumption and efficiency of network operation.
In urban environments, the mobile access is provided by the overlapping of cells of different size, implemented by means of BSs possibly of different technologies. Since the network infrastructure is dimensioned to match the peak traffic demand, it results oversized most of the time. Hence, resources are dynamically activated and deactivated (put into sleep mode) based on the traffic. The traffic handled by deactivated micro BSs is moved to a macro BS, provided that it has still sufficient available capacity. In presence of a HAPS, a fraction of the on-ground mobile traffic from a cluster can be offloaded to the HAPS to reduce the cluster mobile load and allow additional BSs to be deactivated. The HAPS becomes a new knob to be used by the resource allocation strategies to reduce consumption and make the network more sustainable.

A CASE STUDY

To prove the concept discussed above, we consider a case study that takes inspiration from already deployed 4G technologies for which we have real traffic traces and consumption models. While actual traffic and consumption profiles will change in the future, the benefit of the use of HAPSs and the role they can play in the interplay between energy and resource management can already be proved in this scenario, which is realistic for today deployed technologies.
We consider a portion of a RAN in the city of Milan, Italy, where different traffic areas, as those sketched in Fig. 1, can be identified depending on the data traffic patterns. Real traffic data are extracted from a huge dataset provided by a large Italian mobile network operator, that reports the traffic demand volume of 1420 BSs for two months in 2015, with granularity of 15 minutes. To keep into account the growth of mobile traffic volume registered in the past years, the traffic traces are normalized and scaled up, assuming that the peak of each traffic pattern is equal to the maximum bandwidth capacity of a BS, i.e., 150 Mbps.
The BS energy consumption consists of a fixed component, corresponding to the energy that is consumed when the BS is active even with no traffic to transmit, and a variable component that is proportional to the load. Since no consumption model is available for future BSs, for our study we consider the consolidated and well known models for 4G technology [14]. While future BS consumption profiles will change, possibly becoming more load proportional, there is no evidence that they will be significantly lower or drastically different; and, in addition, the transition towards 6G will be based on a consistent use of current technology for quite some time. A negligible BS consumption is assumed in sleep mode.

On-ground node operation and powering

Considering that RANs are usually overdimensioned and given the little load proportionality of BS power consumption, RoD strategies allows the network to dynamically adapt to varying traffic load. In our study, a micro BS can be periodically put in sleep mode by a central controller if its traffic load is below a given threshold, denoted ρ_{min}, provided that the macro BS still has sufficient capacity to carry the traffic offloaded from the micro BS itself. The setting of ρ_{min}, whose values are in the range $[0,1]$ (1 corresponds to the maximum BS capacity), is decided so as to minimize the energy consumption per carried bit. When the traffic is below ρ_{min} it is convenient to carry the traffic on the macro BS and save the energy needed to keep the micro cell on. Conversely, when traffic is above ρ_{min}, it is more convenient to keep the micro cell BS on. The actual value of ρ_{min} depends on the consumption profiles; here, we take it to be equal to 0.37 as in [15], which is the optimal value in our setting. Note that although the future BS consumption models may be different, hence leading to different actual values of ρ_{min}, the general system behavior and the consequent benefits will remain similar.
Each cluster of BSs can be equipped with a set of PV panels and some units of lead-acid batteries to power BSs with locally produced solar energy. Assuming a PV panel efficiency of 19%, a physical area occupancy of about 5 m^2 per kWp is entailed [15], where kWp indicates the capacity of a PV module. The PV dimensioning aimed to contribute to sustainability rather than

TABLE I: HAPS applications in different scenarios

Remote regions	Smart Urban Ecosystems	Vertical Heterogeneous Network (6G)
• overcoming the digital divide • avoiding the installation of costly and underutilized terrestrial network infrastructures	• high speed Internet access in densely populated regions • enhancing URLLC and eMBB communications • supporting Intelligent Transport Systems • defeating coverage holes • covering unplanned user events	• edge intelligence • edge caching • supporting massive IoT communication • mobility management of swarms of UAVs • alternate backhauling for isolated BSs • handling LEO satellites handoffs • HAPS *mega-constellations*

entirely satisfy network demand.

Real RE generation profiles obtained from PVWatts are used to characterize the RE production in the city of Milan.The tool provides, on an hourly basis and for a given location, the average levels of RE power production obtained from a standard PV panel with capacity of 1 kWp during the typical meteorological year.

HAPS offloading

In the investigated scenario, a HAPS provides coverage over a wide geographical area by means of a SMBS installed on the platform itself. Thanks to the unique properties of the stratosphere, the HAPS can maintain a quasi-stationary position [2] and direct communication is enabled between end user devices and the SMBS. The coverage area is partitioned in a number of multiple spot cells, each focused on a defined traffic zone. Based on ITU-R recommendations, we assume that each HAPS cell can provide 2 Gbps bandwidth capacity in its covered area, where several clusters of on-ground BSs can be present. Our study investigates the operation of a single cluster per each traffic zone, consisting of a macro BS and a number of micro BSs, as representative of the behavior of the entire portion of RAN in that traffic area. We assume that the portion of additional capacity yielded by the HAPS cell that is actually made available to each cluster served by the same cell, and that we denote by C_h, is 150 Mbps in the baseline scenario, corresponding to a uniform bandwidth allocation among HAPS cells. Finally, the HAPS communication segment is powered by solar energy, by means of a set of PV panels and storage units that provide sufficient energy supply to satisfy the SMBS demand [2]. Although a consumption model of a SMBS is not yet available, considering a payload with 8 kW power rating for a renewable powered HAPS, the communication segment is reasonably assumed self-sustainable [2].

When a HAPS cell is available over a given traffic area, a fraction of the mobile traffic can be offloaded to the SMBS from the micro BSs, as long as enough residual capacity is available on the HAPS cell. Only when the HAPS cell capacity is fully utilized, additional traffic can be moved from the micro BSs to the on-ground macro BS, as is usually done when no HAPS is present. Note that in terms of grid energy demand it is always more convenient to carry any amount of traffic on the HAPS rather than on micro BS. Besides reducing the load proportional energy consumption, HAPS offloading enables the deactivation of unneeded BSs, further reducing the on-ground energy demand due to BS fixed consumption, either by carrying the entire traffic load of micro BSs or reducing it closer to ρ_{min}, so that macro BS offloading can be exploited to switch off the micro BSs.

Performance indicators

The system operation is evaluated by means of the following performance indicators:

- *Grid Energy Reduction (G_R)*; fraction of energy drawn from the grid that can be saved in the considered scenario with respect to baseline scenario, i.e., the case in which no HAPS is deployed, no on-ground RE is locally produced to power the BS cluster, and no RoD strategy is applied, so that all the cluster BSs are always active.
- *Capacity/Demand Ratio (R)*: average ratio between the overall offered capacity in a given traffic area (including both the on-ground BS cluster and the HAPS cell, when available) and the total traffic demand in the considered traffic area. This indicator assesses the effectiveness of allocating resources on demand.

HYBRID NETWORK PERFORMANCE

To investigate the effectiveness of the hybrid terrestrial/aerial access network to reduce energy consumption several combinations of the size of PV panels and battery are considered for the on-ground local RE generator, assuming commercial PV modules with capacity, denoted by S_P, of 2 kWp, 4 kWp and 8 kWp, and a battery size, denoted by S_B, of 2 kWh, 4 kWh and 8 kWh. For each traffic area, different values of the HAPS cell capacity are tested, corresponding to values of C_h ranging from 25% to 150% of the baseline considered capacity per cluster, i.e. 150 Mbps. Six micro BSs per cluster are assumed. All the simulations are run over a period of two months, with a time-step granularity of 1 hour.

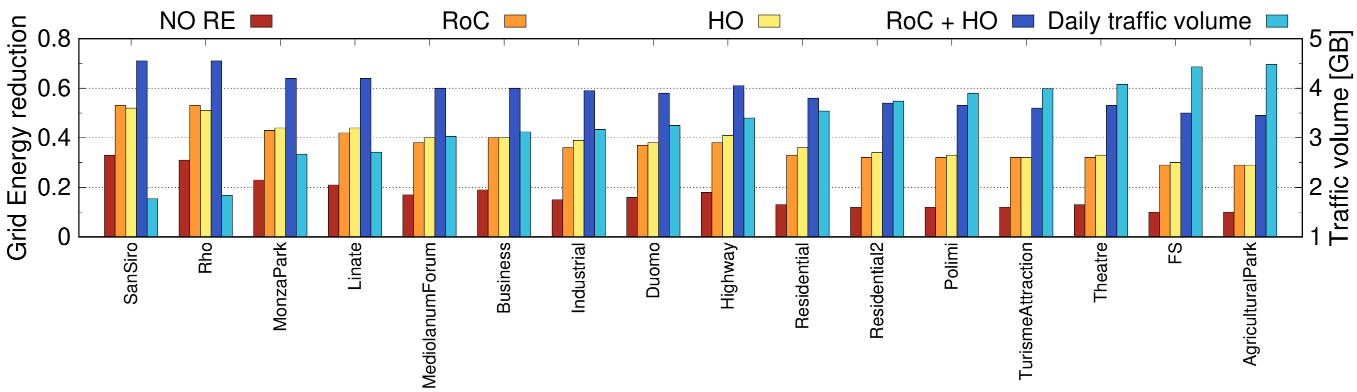

Fig. 2: Reduction of energy drawn from the grid, G_R, in different traffic areas.

Impact of HAPS offloading

We first analyse the effect of HAPS offloading on the system performance. Fig. 2 reports the grid energy reduction, G_R, for different traffic areas, along with daily traffic volume (azure bars), considering various configurations: i) *NO RE* (red bars): RoD is applied on the BS cluster, whereas neither RE is produced locally to power the BSs nor any HAPS is present; ii) *RE on Cluster* (RoC, orange bars): RE is locally produced to power the cluster, and RoD strategy is applied; iii) *HAPS offloading* (HO, yellow bars): HAPS offloading is active, combined with RoD strategy on the cluster; iv) *RoC + HO* (blue bars): HAPS offloading is active, combined with RoD strategy and local RE generation on the cluster. When C_h is set to 150 Mbps, HAPS offloading alone results mostly as effective as the presence of an on-ground RE generator in reducing the energy drawn from the grid, that is more than halved with respect to the baseline scenario. By combining the traffic offloading and RE at the terrestrial node, the system performance is further enhanced, achieving over 70% grid energy saving. Benefits are visible for all the considered traffic areas. However, absolute savings are lower in low traffic areas with respect to high demanding ones. Hence, when considering the overall grid energy reduction over different urban areas, it may be more convenient to allocate larger HAPS cell capacity over more loaded areas. The overall global allocation of HAPS capacity in space has to be carefully decided. These results confirm that for sustainability purposes several techniques need to be combined: accurate resource allocation, RE generation and aerial platform for offloading.

Fig. 3 shows how the system performance varies when the HAPS additional capacity, C_h, is reduced or increased by 50% in a sample traffic zone. Clearly, the effectiveness of HAPS offloading grows with capacity. This confirms that the role of HAPS in the considered scenario is crucial.

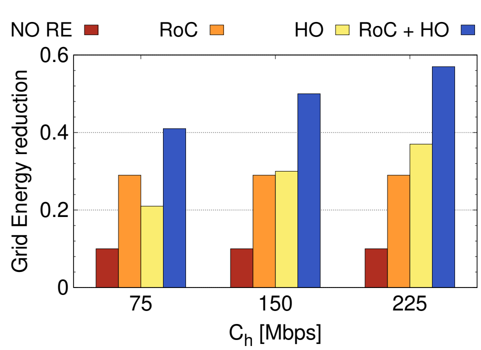

Fig. 3: Reduction of energy drawn from the grid, G_R, under different values of HAPS cell capacity per cluster, C_h.

Quality of Service under HAPS offloading

The values of the Capacity/Demand Ratio, R, are plotted in Fig. 4 under C_h=150 Mbps for all the considered traffic areas. The light blue bars represent the value of R in the baseline scenario, with all the BSs always active. Through RoD and HAPS offloading, R reduces, making the radio resource availability more proportional to the actual demand, still guaranteeing a reasonable Quality of Service level.

In areas with bursty or large traffic patterns, additional benefits in terms of bandwidth availability are achieved by exploiting HAPS offloading. These findings, together with those previously highlighted. offer interesting perspectives about the possibility of partitioning and distributing the HAPS capacity adapting it to the different traffic zones, to properly trade off grid energy saving and bandwidth availability. Based on the traffic zone characteristics, different values of capacity can be made available for each cluster, providing higher bandwidth where the traffic demand is larger and reducing it where it is not needed.

Allocating HAPS capacity based on traffic demand

We now investigate the impact of HAPS capacity and local on-ground RE supply on the system performance.

Fig. 5 shows the values of the performance in-

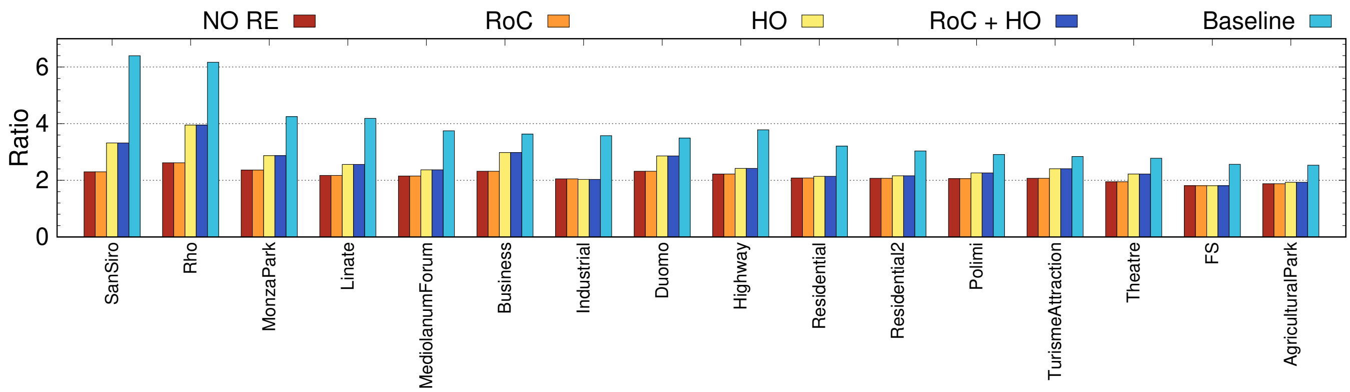

Fig. 4: Capacity/Demand ratio, R, in different traffic areas, sorted by icreasing traffic volume.

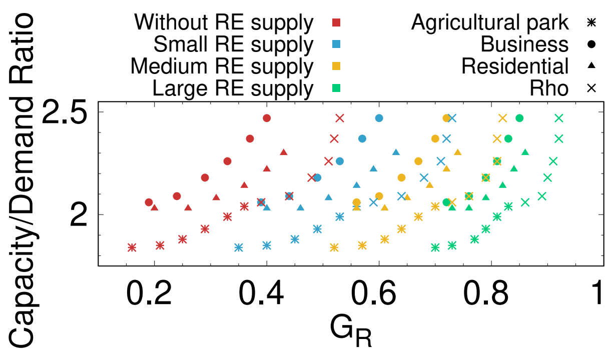

Fig. 5: Capacity/Demand ratio, R, versus reduction of energy drawn from the grid, G_R, under different values of C_h for different traffic areas, without RE and with differently dimensioned on-ground RE generators.

dicators R vs G_R in a subset of traffic areas, considering the case without any on-ground RE generator and the case with RE production at the cluster level, under different system size. For a given traffic area and a given RE supply, each dot in the graph represents a different value of the HAPS capacity C_h, ranging from 0.25x to 1.5x the default value of 150 Mbps, while colors correspond to different sizes of the RE generators with small, medium and large size being, respectively, $S_P = 2, 4, 8$ kWp, with battery capacity $S_B = 2, 4, 8$ kWh. As C_h grows, both R and G_R increase in all areas. However, when no RE supply is present, the grid energy saving can be reduced by about 50% at most even if the HAPS has large capacity. When a local RE supply is introduced in the cluster the curves tend to shift towards higher values of energy saving, with no impact on R and the gap between different traffic areas progressively reduces.

This analysis provides useful insights to tailor service provisioning based on the traffic area characteristics. For example, a larger RE generation system can be introduced to reduce the portion of HAPS capacity reserved to a cell covering a given traffic area, while making the saved capacity available in another cell that covers an area featuring higher traffic demand. Likewise, the value of the HAPS capacity can be set to higher values to obtain similar grid energy saving in those traffic areas where physical constraints do not allow the installation of properly sized RE generators.

Challenges and Future Directions

The proposed case study highlights the relevant potential of HAPS mounted BSs in dense mobile access networks to support a sustainable transition towards 6G.

There are, however, a number of key challenges. First, to gain the largest benefit from HAPS, new decision making approaches are needed for resource activation and allocation strategies, parameter and configuration setting. Given the size and complexity of the problem, machine learning approaches can provide a valuable support, but specific solutions must be designed. Second, for decision making to be effective, accurate predictions of demand for service are needed. Given that the advantages of HAPS are coming from their large coverage areas, and the effective interplay with terrestrial nodes whose coverage is smaller, predictions should explore also the space dimension, incorporating mobility models. Third, accurate analysis of CAPEX and OPEX are needed to define proper system dimensioning. These analysis are made particularly hard by the evolution of the energy market, which is influenced with the uncertainties related to technological advancements on energy sources, political situation and its evolution, effects of climate changes.

In addition to the sustainability perspective which is treated here, the HAPS role as complementary node for the terrestrial network is bound to become even more promising, since aerial BSs will be further enhanced by new pivotal features, including caching and computational capability as well as backhauling functionalities. Moreover, they will be able to cooperate with other types of aerial nodes, like UAVs and satellite networks. However, the orchestration of this variety of

nodes might become complex, introducing uncertainties and additional delays that are incompatible with some service provisioning.
While HAPS can be extremely useful in providing services in emerging countries, in case of natural disasters, emergency situations, or under temporary power outages, a key challenge is to design solutions to let HAPS operate when the power grid is unreliable or unavailable, and, hence, partially independently on the other nodes, and relying on limited information.

Conclusion

In the context of extensive mobile network densification in 5G scenarios and in view of the forthcoming transition towards 6G, the integration of HAPS mounted aerial BSs represents a promising solution to reduce the energy consumption from the grid, decrease the operational cost, and enable dynamic and flexible resource allocation.
Our results show that the integration of a HAPS mounted SMBS allows to reduce the grid energy consumption of terrestrial nodes, especially when combined with some local on-ground RE supply. A limited contribution in terms of HAPS bandwidth yields an additional degree of freedom to enhance sustainability. At no additional operational cost, HAPS offloading reduces the on-ground grid energy demand by (i) decreasing the energy consumption required to power terrestrial nodes, (ii) enabling the deactivation of low loaded micro BSs, and (iii) favoring terrestrial traffic offloading to macro BSs, further increasing the chance to put some BSs to sleep mode. The main benefits occur in highly loaded areas, a situation that is particularly relevant for future mobile networks. By properly adapting the HAPS cell capacity in time and space, based on the traffic load observed in the covered zones, the system performance can be further improved in terms of efficient bandwidth resource utilization.
To develop sustainable networks of the future, the integration of terrestrial and aerial technologies is needed. HAPSs become part of the access networks, enabling new cross-technology strategies that minimize energy consumption and exploit at best the presence of RE, while adapting in a very efficient and flexible way to the actual service demand. Our future work will be widened to include the multi-functionality potential of HAPS and its pivotal role as intermediate layer between terrestrial and satellite networks.

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Biographies

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Michela Meo is Full Professor in the Department of Electronics and Telecommunications at the Politecnico di Torino, Italy. She received the Laurea degree in Electronic Engineering in 1993, and the Ph.D. degree in Electronic and Telecommunications Engineering in 1997, both from the Politecnico di Torino.