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Analysis of High Altitude Platform Stations for network reliability improvement

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Dedicato a nonna Anna,
che mi ha visto iniziare questo percorso
ed ora, dovunque lei sia, so che mi vede
portarlo a termine.

Dedicato alla mia famiglia,
perché in ogni mio pensiero, in ogni mia
azione, c'è e ci sarà sempre qualcosa di
ognuno di voi.

Spero di essere, a modo mio, il figlio, il
fratello, il nipote che meritate di avere.

Summary

Over the last decade, the global volume of data exchanged through Radio Access Networks (RANs) has grown significantly. This trend, along with an increase in blackouts and power grid failures, has highlighted the importance of reliability and resilience in modern wireless networks. Typically, the Base Stations (BSs) in RANs are powered by the electricity grid, and in the event of an outage, they rely on expensive backup batteries. Once these batteries are depleted, the service they provide is interrupted. To address the potential interruption of RAN services due to power loss at BSs, we propose using a revolutionary and disruptive technology: High Altitude Platform Stations (HAPSs). HAPS can be equipped with solar panels and batteries to ensure energy autonomy, as well as networking hardware to operate as aerial RAN Base Stations (BSs). In the event of power grid shortages, we offload part of the traffic normally handled by terrestrial BSs to the HAPS. Our work presents the results of a study conducted by simulating an urban RAN that includes several terrestrial BSs and a HAPS. The simulated RAN provides both Long Term Evolution (LTE) and New Radio (NR) connectivity, using real traffic data provided by an Italian network operator. We investigate different HAPS offloading strategies aimed at improving the energy autonomy of terrestrial BSs. The results demonstrate that integrating HAPS into modern urban RANs, along with the use of targeted offloading strategies, significantly improves the energy autonomy of terrestrial BSs and enhances the overall reliability of the network.

Acknowledgements

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Last but not least, I want to thank my family. I know I am not easy to deal with, but I want you to know, in my way, that I love you all. Thank you for always standing by my side, I promise I will always stand by yours.

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Acronyms

3GPP

Third Generation Partnership Project

BLE

Bluetooth Low Energy

BP

Bent-Pipe

BS

Base Station

BW

Bandwidth

CAPEX

Capital Expenditure

CAV

Connected and Autonomous Vehicle

DL

Download

EMC

Emergency Management Center

ENISA

European Union Agency for Cybersecurity

ESA

European Space Agency

EU

European Union

GBS

Geostationary Balloon Satellite

GEO

Geosynchronous Equatorial Orbit

gNB

Next Generation Node B

HALE

High Altitude Long Endurance

HAPS

High Altitude Platform Station

HO

HAPS Offloading

ICT

Information and Communication Technology

IoT

Internet of Things

IPL

Inter-Platform Link

ISL

Inter-Satellite Link

ISTAT

Italian National Institute of Statistics

IT

Information Technology

ITU

International Telecommunication Union

KPI

Key Performance Indicator

LEO

Low Earth Orbit

LoRa

Long Range

LTE

Long Term Evolution

MIMO

Multiple Input Multiple Output

M-MIMO

Massive-MIMO

NaN

Not-a-Number

NASA

National Aeronautics and Space Administration

NB-IoT

Narrowband IoT

NICT

National Institute of Information and Communications Technology

NR

New Radio

NTN

Non-Terrestrial Network

OR

Offloading Ratio

PA

Power Amplifier

PPDR

Public Protection and Disaster Relief

PV

Photovoltaic

QoS

Quality of Service

RAN

Radio Access Network

RB

Resource Block

RE

Renewable Energy

RES

Renewable Energy Source

RF

Radio Frequency

RG

Regenerative

RoD

Resource on Demand

RR

Radio Regulation

RTT

Round Trip Time

SMBS

Super Macro Base Station

SNR

Signal-to-Noise Ratio

TSO

Transmission System Operator

UAV

Unmanned Aerial Vehicle

UE

User Equipment

UL

Upload

URLLC

Ultra-Reliable and Low Latency Communications

USAF

United States Air Force

VHetNet

Vertical Heterogeneous Network

VLEO

Very Low Earth Orbit

WAN

Wireless Access Network

Chapter 1

Introduction

Within the last decade, the world has known a considerable growth for what concerns the exchange of data through Radio Access Networks (RAN). Indeed, the proliferation of smartphones and other mobile devices, together with the advent of cellular technologies such as LTE, 5G connectivity and massive IoT applications, have led the global mobile traffic demand to reach unmatched peaks.

Among other factors, this surge is mostly driven by the rapid expansion of mobile broadband networks, in addition to the ever-growing consumption of data-intensive applications such as video streaming, online gaming, and social media platforms. As mobile traffic continues to escalate, it exerts significant pressure on the underlying infrastructure, particularly in terms of electricity consumption. It comes without saying that such growth of demand would require large-scale networks densification and enhanced power grid systems in order to keep up with the general need, both in terms of connectivity and energy.

Looking at the general picture, with particular regard towards the power consumption aspects, fundamental importance is acquired by the factors related to **network reliability**. A reliable network, in fact, may always be able to assure radio access to the users at any time in any situation, even the most critical ones. In particular, some of the main characteristics of a proper reliable network are reported as follows [1].

- **Fault tolerance**, indicating the capability of a network to limit the impact of a failure on its correct functioning, in such a way that the fewest number of devices are affected. Another crucial feature of a fault tolerant network is a quick recovery from any type of failure.
- **Scalability**. A scalable network is able to rapidly expand in order to provide service to new users without affecting the performance of the service delivered to already existing users. One important factor that enables scalability is network compliance to accepted standards and protocols.

- **Security**. A secure network always assures two types of security, namely:
    - network infrastructure security;
    - information security.

  In particular, proper network security is achieved through the satisfaction of three well defined requirements [2], reported as follows:
    - confidentiality;
    - integrity;
    - availability.
- **Quality of service**. In the communication domain, QoS often indicates the capability of a network to reliably deliver services to the end user with a certain quality standard, even under critical circumstances such as congestion. The definition of clear and effective QoS policies is a fundamental step to carry out in order to assure the reliability of a network.

Among all, particular relevance is assumed by the first aspect exposed, related to situations in which electricity can be unavailable due to power grid faults or other major accidental causes. In such sense, particularly indicative is a report by the European Union Agency for Cybersecurity (ENISA) about telecommunication security incidents in 2022 [3]. The report highlights a worrying trend in the growth of such incidents gravity. As depicted in figure 1.1, in fact, in 2022 a total number of 155 incidents were registered by European National authorities, for a general loss of 11209 million user hours, compared to the 5106 million reported in 2021.

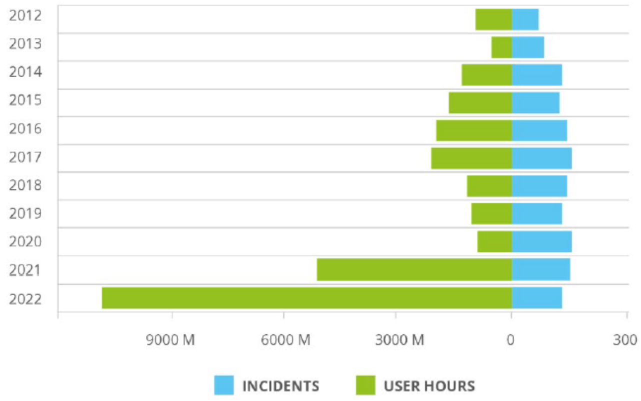


Figure 1.1: Number of telecom incidents and user hours lost every year (2012-2022) [3].

Figure 1.1 indeed shows a sensitive increase in the number of total user hours lost, and this information can help understand the real entity of the problem and the reason why it needs to be urgently tackled by modern and effective solutions. Surely, one important network characteristic that must be enhanced in order to achieve a higher level of reliability is the so called **robustness**, defined in [4] as "the inherent strength or resistance in a system to withstand external demands without degradation or loss of functionality". In that sense, in order to always ensure sufficient radio traffic provisioning to users, network robustness to power unavailability could be reached through the integration of revolutionary and disruptive systems, namely **High Altitude Platform Stations** (HAPS). Figure 1.2 depicts a conceptual representation of such platforms.

Figure 1.2: High Altitude Platform Station - concept. Source: ATLAS LTA.

HAPSs are characterized by a strong versatility and they can be easily equipped with **networking hardware** in order to act as operational **Base Stations (BS)** in a typical radio access network. It must be underlined that similar applications have already been experimented and tested worldwide in many situations. As an example, [5] describes the feasibility of the application of aerial platforms to deliver 4G/LTE and 5G NR connectivity to users in under served areas, such as remote locations. The scenario of application is represented in figure 1.3 and the airplane-based station is intended to fly over the coverage zone while providing a service link to users and assuring the connection to one or more ground gateways. According to this paradigm, the aerial platform operates as a traditional BS and supports Internet connectivity over the covered area, reducing the traffic load handled by the terrestrial communication infrastructure.

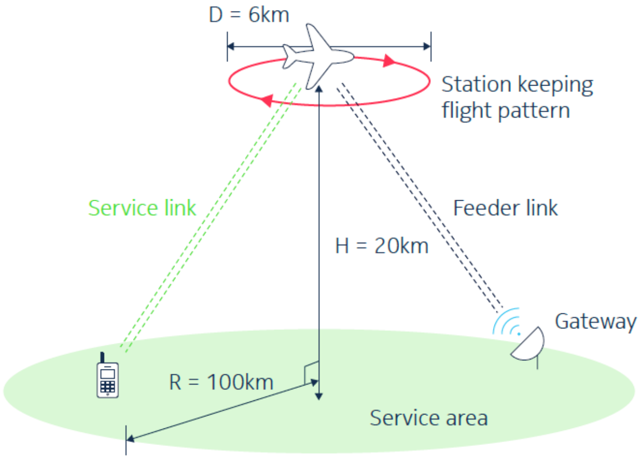


Figure 1.3: Typical HAPS operating scenario [5].

Whilst a radio access network experiences any kind of failure or power shortage, the base stations operation is undermined by such lack of power, since they are not able to gather the needed energy directly from the power grid, as they normally would. Given the absence of power available directly from the grid, the only option BSs have to continue their normal operation is to utilize their **back-up batteries** as power supply. Nonetheless, the energy available using a battery is rather limited when considering the huge power consumption of a traditional RAN covering a densely populated urban area. For these reasons, it is fundamental to implement an effective solution in order to reduce the power consumption of BSs in the period of power shortage or absence.

Indeed, by offloading part of the traffic to a HAPS, network operators can, in fact, enhance reliability, while also addressing issues such as latency and congestion, especially in critical situations such as **blackouts**.

1.1 The role of resilience in network reliability

On December 23, 2015, a group of Russian hackers, namely "Sandworm", managed to shut down a power plant in western Ukraine, represented in figure 1.4 [6]. This operation resulted in power outages for roughly 230,000 consumers in Ukraine for 1-6 hours. In total, it is estimated that around 73 MWh of electricity were not supplied due to the attack [7].

This incident highlighted the vulnerability of interconnected systems and the devastating impact of compromised network security and resilience. The attack served as a wake-up call, emphasizing the need for robust fault tolerance mechanisms, advanced cybersecurity measures, and comprehensive contingency planning to protect critical infrastructure from similar threats. Ensuring resilience in networks is not only crucial for maintaining uninterrupted service but also for safeguarding **national security**.

Figure 1.4: Western Ukraine's Prykarpattyaoblenergo utility [6].

Since that episode, several similar cases have occurred all around the world, as it has become very clear to criminal and terrorist organizations that electricity shortage can successfully be exploited as a large scale weapon to assault the public safety of a Nation.
In particular, during the Russian-Ukrainian War, many hostile operations targeted at neutralizing power generation utilities such as nuclear power plants: a famous case among the others is the one occurred in 2022 at the Ukrainian nuclear power plant based in Zaporizhzhia [8].
Nevertheless, terrorist attacks and acts of asymmetric war are not the only causes that can lead to a loss of electric energy on a large geographic scale.
Particularly significant is a study published by Stankovski et al. in 2023, showing the occurrences and consequent impact of **blackouts** in the European continent [9]. The article starts from the premise that in 2021 alone, there were three significant events that affected with catastrophic effects the efficiency of large scale power systems, namely the Texas blackout and two separations of the European synchronous area. Each one of these events had a disruptive impact on the lives of millions of people. and this first information alone can help the reader understand the real entity of the issue.
The study then proceeds to analyze a wide dataset comprehending a total of 478 continental-scale events registered over a time span of 30 years, and 14577 national-scale events, registered within 10 years and published by Italian transmission system

operator (TSO) Terna. In particular, the events are labeled as "severe" whenever they have resulted in a system performance loss of at least $10^3 MWh$.

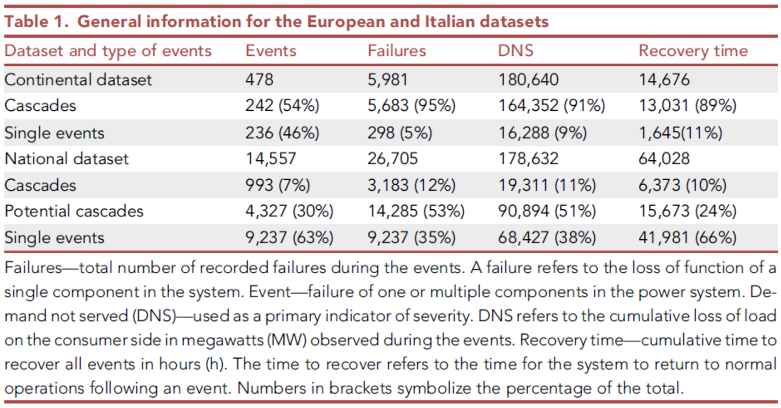


Table 1. General information for the European and Italian datasets

Dataset and type of events	Events	Failures	DNS	Recovery time
Continental dataset	478	5,981	180,640	14,676
Cascades	242 (54%)	5,683 (95%)	164,352 (91%)	13,031 (89%)
Single events	236 (46%)	298 (5%)	16,288 (9%)	1,645(11%)
National dataset	14,557	26,705	178,632	64,028
Cascades	993 (7%)	3,183 (12%)	19,311 (11%)	6,373 (10%)
Potential cascades	4,327 (30%)	14,285 (53%)	90,894 (51%)	15,673 (24%)
Single events	9,237 (63%)	9,237 (35%)	68,427 (38%)	41,981 (66%)

Failures—total number of recorded failures during the events. A failure refers to the loss of function of a single component in the system. Event—failure of one or multiple components in the power system. Demand not served (DNS)—used as a primary indicator of severity. DNS refers to the cumulative loss of load on the consumer side in megawatts (MW) observed during the events. Recovery time—cumulative time to recover all events in hours (h). The time to recover refers to the time for the system to return to normal operations following an event. Numbers in brackets symbolize the percentage of the total.

Figure 1.5: Blackout occurrences in Europe and Italy [9].

Figure 1.5 depicts the dataset of interest, while figure 1.6 provides a detailed overview of the distribution of system performance loss and recovery time for the registered events.

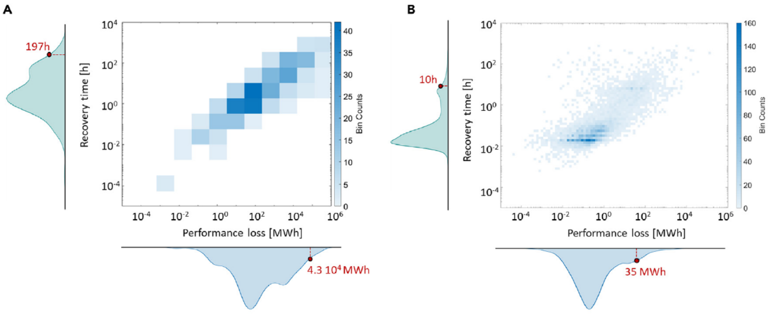


Figure 1.6: Distribution of system performance loss and recovery time for blackouts [9].

One important factor to underline is the percentage of events occurred due to severe weather conditions. 32% of all blackouts in the continental dataset and 46% of all events in the Italian national dataset are reported to have occurred because of adverse and severe weather conditions [9].

The data yet exposed depict a concerning picture. Indeed, with the frequency of blackout occurrences constantly growing and the impact on social and economical life becoming more and more significant, it must be highlighted that the importance of robustness and resilience in networks reliability has never looked as crucial as now.

One common and thus critical issue all the scenarios previously described can cause is related to **IT infrastructures**. Absent or, in best case scenarios, limited power supply to IT infrastructures can have, in fact, severe and far-reaching effects on businesses, economies, and societies. Firstly, it disrupts business operations, leading to downtime, lost productivity, and financial losses. Critical services such as banking, healthcare, and communication can be severely impacted, compromising service delivery and potentially endangering lives. Data centers, which are the backbone of modern digital services, can face significant disruptions, risking data loss and undermining data integrity. The lack of reliable power can also damage hardware, shorten equipment lifespan, and increase maintenance costs. Modern societies of civilized States are indeed deeply integrated with telecommunication technologies, therefore to have long-lasting electricity shortages, leading to **radio access unavailability**, is not an affordable scenario anymore, both in terms of economy and, most important, **security**.

Focusing on this last concept, it must be highlighted that major accidental consequences may eventually follow the absence of connectivity, even for limited periods of time. As an example, it can be thought of a generalized humanitarian crisis or a natural disaster, such as a volcanic eruption or a large scale earthquake. Both these situations would require a huge cooperation among the whole system that would be activated, namely rescuers and humanitarian aid organizations. Indeed, it would be completely impossible for such entities to manage the entire spectrum of rescue operations without relying on a robust and resilient Radio Access Network. Therefore, in the broader context, increasing networks robustness and resilience to power shortages, attacks and faults is a challenge of major importance for humanity, and HAPSs can undoubtedly play a crucial role in pursuing that purpose.

1.2 Document purpose and structure

The ultimate objective of the present document is to explore and analyze the revolutionary impact that HAPSs can have on the telecommunication domain, while providing a complete overview on the possibility of integrating such aerial platforms into already existing RANs, with the aim of increasing their reliability and **resilience**.

In order to pursue this purpose, a **simulator** is exploited in order to investigate the benefits a conventional RAN can achieve by **offloading** part of the traffic to a HAPS, trying to tackle the over demand issues typically caused by blackouts.

The document's structure is characterized by multiple chapters, briefly described as follows.

- **Chapter 2** presents the basic concepts about HAPSs and reports an exhaustive description of the **state of the art**, followed by a more in-depth review of technical literature. Furthermore, the chapter exposes a pool of HAPS usages, such as connectivity provision and crises and emergency management.

- **Chapter 3** illustrates the main aspects related to the **methodology** of the performed study. The considered scenario is defined, together with explanations referred to the used dataset and the modelling of known elements such as BSs and HAPSs.
- **Chapter 4** aims at exposing the principal and most indicative **results** of the carried out analysis.
- **Chapter 5**, finally, outlines the **conclusions**.

Chapter 2

State of the art

2.1 Introduction to High Altitude Platform Stations

A High Altitude Platform Station (HAPS), also referred to as High Altitude Pseudo-Satellite or High Altitude Platform System, is a particular type of aircraft, specifically designed to provide long-enduring observation or communication services, similarly to common artificial satellites [10].

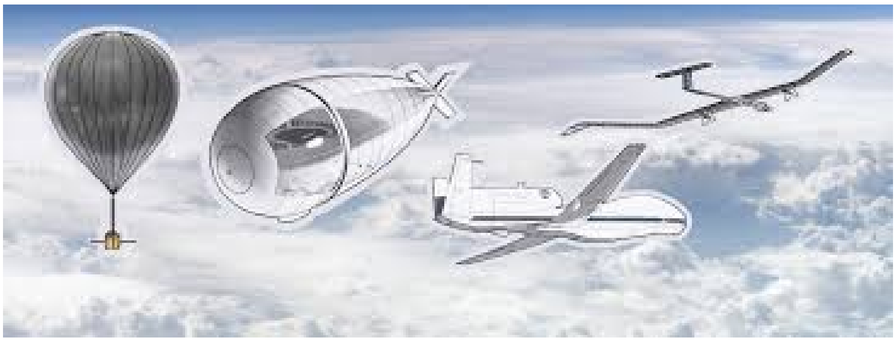


Figure 2.1: Different types of HAPS [11].

HAPSs are generally positioned above **20 km altitude**, in that part of the Earth atmosphere called Stratosphere, for long-duration flights lasting months or even years. This peculiar kind of unmanned aircraft may be airplanes, airships or balloons. The usage of HAPSs can be correlated to a wide spectrum of applications, such as telecommunications, emergency and public safety communications, transportation systems, maritime surveillance, environmental monitoring, land border control and many others [12].

As already mentioned, HAPSs are generally **Unmanned Aerial Vehicles (UAV)**, and their high-altitude, long endurance flights have been studied since 1983, with demonstrator programs being set up since 1994. Having as their most peculiar aspect the capability of remaining airborne for long-lasting periods of time, many alternative solutions to conventional engines were investigated over time, with hydrogen, solar power and, more in general **Renewable Energy Sources (RES)**, as the most significant options.
One important aspect to highlight is the difference between High Altitude Platform Stations and High Altitude Long Endurance (HALE) aircraft; these differences are standardized and regulated by international organizations as follows.

- **High Altitude Long Endurance (HALE)** aircraft are non-weaponized military drones that are able of flying at 60,000 ft for over 32 hours.
- A **High Altitude Platform Station (HAPS)** is "a station on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth" [10] [13].

In particular, the definition given to HAPSs was standardized by the International Telecommunication Union (ITU) in one of the Radio Regulations (RR). Among the wide set of HAPSs applications, this document is going to focus mostly on the one related to **radiocommunication services**. In fact, within the last two decades, many experiments, mostly carried out in Europe, have highlighted the possibility of exploiting High Altitude Platform Stations to bring **Internet connectivity** to the 5 billion people lacking it.

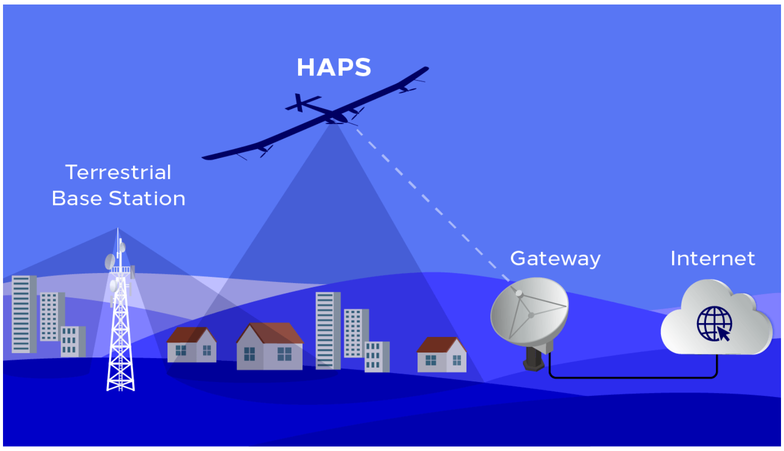


Figure 2.2: Schematized HAPS connectivity provision. Source: Saudi Arabia CST Commission

In particular, a HAPS could potentially deliver high-speed connectivity to users, over areas of up to 400 km. Furthermore, HAPSs could deliver bandwidth (BW) and capacity similar to a broadband Wireless Access Network (WAN), providing coverage over an area similar to the one of a traditional geostationary artificial satellite [10].

This possibility, conceptually represented in figure 2.2, opens the door for new scenarios and revolutionary solutions in the domain of radiocommunication, mostly important for what concerns the aspects related to robustness and resilience of the networks.

2.1.1 Evolution over time

The concept of HAPS can be traced back to the early 20th century when visionaries first imagined using high-altitude balloons for communication purposes. However, significant advancements in HAPS technology began in the 1980s and 1990s, marking a fundamental era for the development of these platforms. In 1983, in fact, Lockheed produced a preliminary study of solar powered aircraft for NASA. The following year, they published a report about *Design of Long Endurance Unmanned Airplanes Incorporating Solar and fuel cell propulsion.* Finally, in 1989, a document namely *Design and experimental results for a high-altitude, long-endurance airfoil* was drafted and published, marking a turning point in HAPSs history [10].

One of the earliest pioneering initiatives was the *Stratospheric Platform Project* by the National Institute of Information and Communications Technology (NICT) in Japan. Launched in the 1990s, this project aimed at developing a stratospheric airship capable of providing wireless communications over large areas [14].

Figure 2.3: Japan Stratospheric Platform poster. Source: University of York.

Meanwhile, NASA introduced the well-known Pathfinder series, a set of solar-powered UAVs designed to prove the feasibility of sustained flight at high altitudes. The Pathfinder Plus, a key part of this series, successfully flew at an altitude of 24,445 meters in 1998, setting the stage for future HAPS developments [15].

Figure 2.4: NASA Pathfinder-Plus [15].

Throughout the early years of 2000, various countries and organizations continued to explore the potential of HAPSs. The European Union (EU) initiated revolutionary projects such as the € 5 million worth CAPANINA project [16], focusing on high-altitude platforms for broadband communications, and HeliNet, coordinated by the Politecnico di Torino, which aimed at developing a network of stratospheric platforms for diverse applications, including disaster management and environmental monitoring [17]. These projects underscored the versatility of HAPSs, highlighting their capability to provide wide-area coverage and rapid deployment in emergencies.
In more recent years, advancements in solar power and lightweight materials have propelled HAPS technology further. Alphabet's Loon project, one of the most high-profile examples in this field, utilized high-altitude balloons to provide with internet access remote and underserved areas.

Figure 2.5: Loon balloon [18].

Launched in 2011, Loon balloons operated in the stratosphere, creating a network of floating cell towers that could be re positioned as needed. Despite its termination in 2021 due to financial sustainability challenges, the Loon project demonstrated the practical potential of HAPS for bridging the digital divide [18]. Facebook's Aquila project also made significant contributions to the rapid evolution of HAPSs. Initiated in 2014, Aquila's main objective was to use solar-powered drones to provide internet connectivity to remote regions. The Aquila drone had a wingspan comparable to a Boeing 737 aircraft but weighed only 400 kg, enabling it to stay airborne for extended periods. Although Facebook shut down the project in 2018, Aquila's technological advancements continue to influence ongoing HAPSs research and development [19].

Figure 2.6: Facebook Aquila [19].

Throughout their history and evolution, HAPSs have been designed in various forms and shapes, each one with its peculiarities and operational and functional features. Nowadays, with hundreds of experiments performed, firms interested in the aerospace domain and, more in detail, the NTN domain, typically design and deploy HAPSs exploiting a set of well-known concepts. The most widespread examples of HAPS are reported as follow.

- **Airplanes**, mostly used for military reconnaissance and surveillance. An example of Airplane-shaped HAPS is the Northrop Grumman RQ-4 Global Hawk (depicted in figure 2.7), developed and deployed by the United States Air Force (USAF) in 2001 [20]. Another example, undoubtedly more revolutionary for what concerns the design, is the already described NASA Pathfinder.

Figure 2.7: Northrop Grumman RQ-4 Global Hawk [10].

- **Airships**, designed to operate at high altitudes (between 18.3 and 22.9 km above the ground). Given the operational altitudes they are deployed at, such air platforms are subject to ultraviolet damage and ozone corrosion [10]. One example of airship HAPS is the Thales Alenia Stratobus, shown in figure 2.8

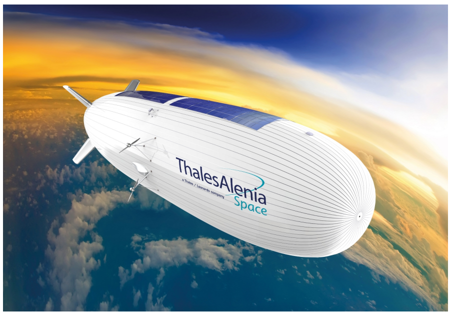


Figure 2.8: Thales Alenia Stratobus. Source: Thales Alenia Space.

- **Balloons**, also referred to as geostationary balloon satellites (GBS). This particular type of HAPS is able to maintain a fixed position with respect to ground level and for this reason is one of the designs that best adapts to the usage in the RAN domain. One illustrious example of GBS is the yet mentioned Google's Project Loon (figure 2.5).

- **Rotorcraft**. An easily recognizable example of such type of design is the Boeing A160 Hummingbird (represented in figure 2.9), jointly developed by the US Army and the US Navy in 2003 [21].

Figure 2.9: Boeing A160 Hummingbird [21].

Despite the termination of some high-profile projects, the promise of HAPSs remains strong. The technology continues to evolve, driven by advancements in solar energy, battery storage, together with the growing exploitation of RES and lightweight materials. Companies and governments worldwide are investing in HAPSs to provide cost-effective, wide-area coverage, especially in regions where traditional ground-based infrastructure is impractical. Furthermore, HAPSs can play a crucial role in disaster response, environmental monitoring, and extending internet connectivity to remote areas, thereby contributing to development goals of global interest.

The future of HAPSs has never looked as promising as now, since the enabling technologies are maturing and thus becoming more and more cost-effective, in addition to the growing interest towards Non-Terrestrial Networks based on HAPSs instead of low earth orbit (LEO) satellites. Ongoing research and development efforts aim to address the challenges of operating in the stratosphere, such as extreme weather conditions and regulatory hurdles. With continued innovation and collaboration among industry, government, and academia, High Altitude Platform Stations have the potential to revolutionize global communications and surveillance, offering a flexible and scalable solution to some of the world's most pressing challenges, both in terms of radio connectivity and power consumption management.

2.1.2 Key design aspects

Given their airborne nature and the peculiar capability to remain in flight for very long periods of time, High Altitude Platform Stations require, in order to be fully operational and efficient, a meticulous design phase. It comes as a consequence that such design process is of critical importance for the general outcome of the projects and thus the final performance of the platforms.

One of the most crucial aspects to be taken into account throughout the entire design phase is **power**. Relying on fossil fuels or traditional propellants would be, in fact, a strong limitation to the flight endurance of the HAPS, as it would cause the

platform to be grounded periodically for refueling. Therefore, several alternative solutions were investigated and experimented over time, mostly involving RESs and alternative ways of power generation. Nowadays, one the most accredited solutions is undoubtedly **solar power**, often exploited in combination with a set of electric batteries or fuel cells, capable of storing electric energy generated throughout the day and usable during the night [10].
Another crucial aspect to consider is undoubtedly **altitude**. As already mentioned, HAPSs are typically deployed in the Earth's stratosphere (i.e. between 17 and 22 km above the ground) [10]. This feature makes them particularly efficient for what concerns radio frequency (RF) communications as they usually experience very low propagation delays (i.e. between 1 and 2 ms); as a consequence traffic data packets sent to and received by HAPSs will be subject to lower round trip times (RTT) with respect to the ones managed by LEO and GEO satellites [10] [22]. Furthermore, another important advantage of being deployed at such altitude, is the negligible Doppler shift, in addition to a less complicated and more cost effective launch and consequent deployment with respect to conventional LEO satellites [22].
However, the technical aspects yet described are not the only reason why it is generally chosen to deploy HAPSs in the stratosphere. Indeed, another crucial factor that must be taken into consideration throughout the design phase is the **wind and turbulence management**. It would be completely impossible to deploy a UAV-based HAPS in the high troposphere because of the high-velocity winds and also the intense air traffic that occurs at any time at those altitudes. On the contrary, the stratosphere offers a perfect operational environment for HAPSs, since it is subject to relatively moderate winds and turbulence, and its altitude is also located above the commercial air transport [10].

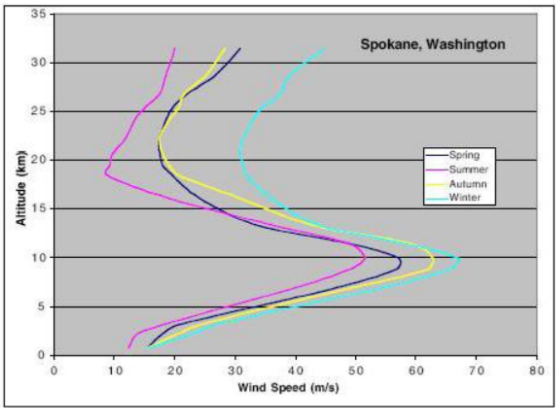
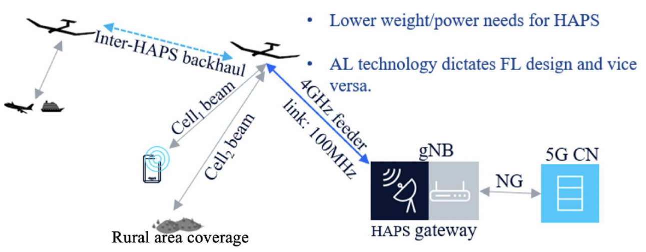


Figure 2.10: Wind velocity in relation to altitude. Source: NASA [10].

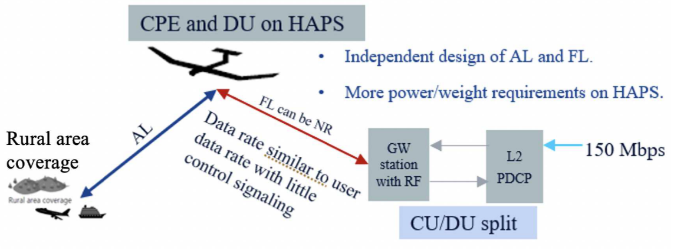
Figure 2.10 depicts the variation of wind intensity at different altitudes located above the city of Spokane (Washington, USA). The data, collected and processed by NASA clearly show lower values of wind velocity for altitudes between 17 km and 22 km above the ground, in correspondence of the stratosphere. Therefore, it will be much easier for a UAV to maintain a fixed position with respect to the ground, having to contrast lower intensity winds and turbulence.

Up to this point, only technical and functional aspects correlated to the airborne capacity of HAPSs have been analyzed and discussed. Nonetheless, the peculiar feature of interest of this document is the **usage of such platforms as base stations (BS)** for providing radio access and internet connectivity to users on the ground. It is clear that a sufficiently detailed design process is required for HAPSs to accomplish such complicated and technical tasks. In particular, the architecture of the chosen radio technologies must be fully and coherently integrated with the chosen UAV infrastructure. In order to deliver to the reader a general context as clear as possible, a particular case study can be analyzed. Indeed, Xing et al., in an article published in March 2021, investigate two different architectures for a innovative HAPS solution.

The first considered architecture is indicated as **Bent-Pipe (BP)**, and it consists of a HAPS station working as a RF repeater or relay station. On the other hand, the second architecture of interest is labeled as **Regenerative (RG)** and in this second case the HAPS is supposed to work as a normal BS. The two architectures are represented in figures 2.11a and 2.11b.



(a) Bent-pipe (BP) architecture.



(b) Regenerative (RG) architecture.

Figure 2.11: HAPS architectures analyzed by Xing et al [22].

In terms of costs, the BP architecture is for sure cheaper than the RG solution, given its low weight and low power consumption. At the end of the study, utilizing a high-gain repeater on top of the BP architecture, the HAPS showed performance similar to the RG solution (or in some cases, even better) both for what concerns spectral efficiency and hardware complexity [22]. This outcome goes to prove and highlight the importance of investigating many different combinations of technologies while designing a HAPS, with the ultimate aim of finding the more efficient and effective trade off. In applications such as HAPSs, where efficiency, power management and reliability are all features of crucial importance, it goes without saying that analyzing each possible variable in the design phase is not optional, but a proper requirement.

2.2 High Altitude Platform Stations for connectivity: motivation

In the previous paragraphs, it was provided a clear overview of the main aspects related to HAPS for what concerns concept, design and main applications. It is ultimate intent of this section to deliver to the reader a concise yet comprehensive description of the motivations that drive the usage of HAPS to accomplish specific

tasks related to connectivity.
Firstly, it must be underlined that the general trend for global bandwidth demand is the one of a general growth. As shown in figure 2.12, in only 6 years between 2017 and 2022 the global demand for bandwidth has almost quadrupled, and this particular data is rather indicative of the general trend the world is going to meet during the next decade.

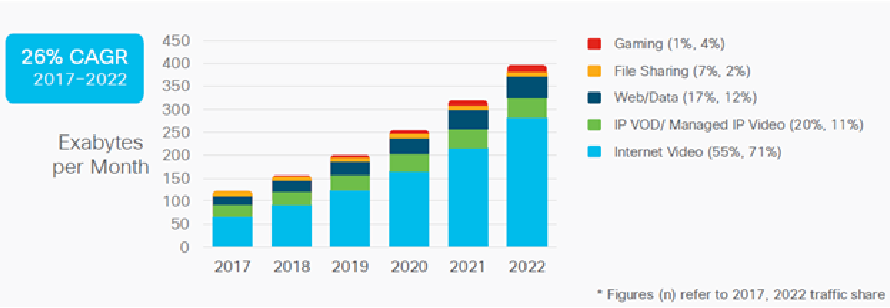


Figure 2.12: Global bandwidth demand in 2017-2022. Source: Cisco.

One of the most accredited solutions which have been largely exploited by connectivity providers on a global scale so far is the network infrastructures densification. Nevertheless, this method appears not to be sufficiently effective anymore and, most of all, it could soon become unaffordable from the point of view of cost effectiveness. Analyzing these information, it is clear that one of the biggest challenges in the future of communication systems is going to be the development and implementation of alternative and flexible solutions for wireless connectivity. One promising technology which has demonstrated to be valid and trustworth during the last years is the so called vertical heterogeneous network (VHetNets), represented in figure 2.13. In particular, the usage of non-terrestrial platforms for wireless connectivity has already been discussed in Release 17 by 3GPP [23], which goes to prove once again the great attention that telecommunication organizations are directing at this kind of innovative solutions.

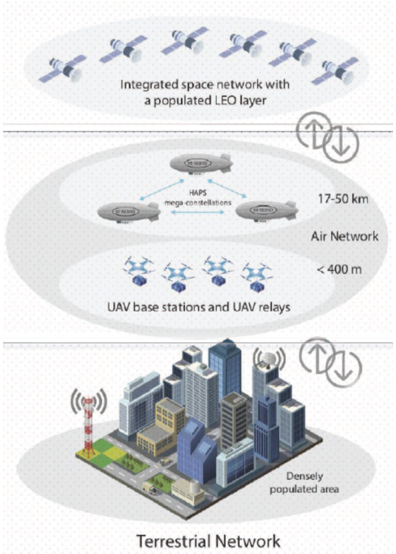


Figure 2.13: Vertical Heterogeneous Network [24].

2.2.1 HAPS Super Macro BS and relative advantages

In the broader context of VHetNets, HAPS certainly cover a role of particular importance, as they can provide connectivity services exploiting some of their most peculiar technical feature, which are going to be exposed in detail further in this section.
A rather relevant hypothesis of HAPS application, analyzed and exposed in [25], is the **HAPS Super Macro BS (HAPS-SMBS)**. In this operational scenario, the HAPS is considered as a SMBS because of its wide area of coverage and the provision of technical features as data acquisition, computing, caching and processing [25]. The use of a HAPS, especially if deployed in densely populated areas, indubitably can enhance RANs from the point of view of flexibility. Indeed, it would provide an alternative to problems such as the deployment of terrestrial BSs or LEO or Very Low Earth Orbit (VLEO) satellites. [25], in particular, mentions two different roles which can be covered by HAPS in a VHetNet scenario, namely:

- **UAV Base Station (BS)**, capable of handling the traffic offloaded by terrestrial BSs;
- **UAV User Equipment (UE)**, such as autonomous drones for package carrying.

Such implementation is not only desirable from the point of view of flexibility, as already mentioned, but also for what concerns a wide list of advantages shown by HAPSs with respect to conventional wireless communication means such as terrestrial BSs and LEO satellites. These advantages are clearly listed in [25] and the most relevant ones are reported as follows.

- **Channel conditions**, in fact HAPSs typically show lower values of channel attenuation with respect to LEO and VLEO satellites, together with a generally higher value of Signal-to-Noise Ratio (SNR). Both these features are partly due to the lower operational altitude of HAPSs.

- **Static position**. Given this particular feature, signals sent by and to HAPSs tend to be less subject to Doppler shift effects, as already mentioned in section 2.1.2. In addition to this aspect, given the geostationary nature of HAPSs, device tracking can be avoided since their position is practically known at any time instant.

- **Size of platforms**. In section 2.1.1 it was presented, together with many others, a particular type of HAPS design, namely Airship. Airship HAPSs are typically of bigger size than the average urban building, and this characteristic can be exploited for integrating useful technical equipment on board of the HAPS itself. Big surfaces allow, in fact, to mount more solar panels and bigger energy storage systems on the platforms. Furthermore, larger dimensions make HAPSs suitable for Multiple Input Multiple Output (MIMO) and massive-MIMO (M-MIMO).

- **Latency**. Since the aerial platforms are deployed at lower altitude than artificial satellites, as a consequence signals to and from such platforms will generally experience lower values of latency. As a matter of fact, a 40 km distance with the ground will take to a signal a RTT of just 0.13 ms, on average, to be covered.

Given the importance of each one of the characteristics yet exposed, HAPSs are meant to cover progressively more important roles in modern RANs and, more in general, in the telecommunication domain. As a matter of fact, thanks to their flexibility, versatility and disruptive nature they appear as the perfect tool to overcome some of the major challenges of future wireless communication networks, mostly regarding traffic overload and bandwidth distribution.

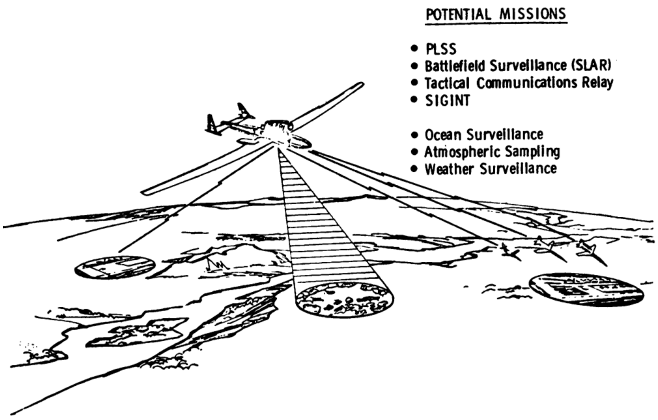


Figure 2.14: HAPS potential military tasks spectrum [10].

2.2.2 Potential HAPS applications in modern scenarios

A detailed list of HAPS applications in modern wireless communication scenarios is reported in [25]; a reduced set of such applications is going to be exposed as shown below.

- **IoT applications**. Aerial platforms are, in fact, able to provide connectivity for a massive number of low power and low bandwidth devices such as the ones used in Internet of Things applications. For microcontrollers, sensors and even small gateways, similar to the ones exploited in LoRa applications [26], it would be undoubtedly effective to rely on an aerial BS instead of a terrestrial infrastructure for wireless communication.

- **Handling of computational offloading**. In such scenario, the background concept is similar to the one of edge computing [27]. Future applications, and even present ones, require, indeed, enormous amounts of data to be gathered and processed. In similar contexts, it is fundamental for users to offload part of the whole computational burden on powerful and reliable devices, such as HAPSs.

- **Flying data centers**. Aerial platform could enable flying and therefore mobile data centers, capable of providing computational power as a back-up in case of unpredictable critical events or generalized emergencies [25].

- **Services provision in coverage holes**. In particular, such solution could be rather effective in those areas where terrestrial BSs are not capable of delivering a sufficient quality of service (QoS) in terms of signal strength.

- **Smart transportation systems**. Indeed, HAPSs can support the activity of coordination of connected and autonomous vehicles (CAV).

- **Support of extensive groups of aerial UE**. As already mentioned in section 2.2.1, HAPSs can cover a crucial role in the cooperation and consequent coordination of fleets of UAVs for commercial use (figure 2.15). The fact that one entire city could be potentially covered by a single operational aerial platform [25] can provide a clear idea of the efficiency of the idealized solution in future scenarios.

Figure 2.15: Example of commercial drone for package carrying. Source: Amazon.

- **Intermediate communication nodes for reaching LEO and VLEO satellites**. Given the typical high velocity at which artificial satellites usually move, high altitude stations can exploit their large coverage ranges to provide to the users a more efficient interface to communicate with LEO satellites, without encountering losses of connection, handover to terrestrial gateways and other similar issues [25].

- **Coverage of temporary failures**.

This last task is meant to be the ultimate focus of the present document. As mentioned earlier, high altitude platform stations have the functional and technical capabilities to provide service whenever the terrestrial telecommunication infrastructure is subject to any kind of failure or shortage. The key point of this logic is the so called **traffic offloading**, being the management by HAPSs of part of the traffic normally handled by conventional BSs only.
In that sense, HAPSs can surely contribute to ensure service continuity for users even during critical events like acts of war, terrorist attacks, blackouts, severe weather conditions and other similar emergency scenarios.

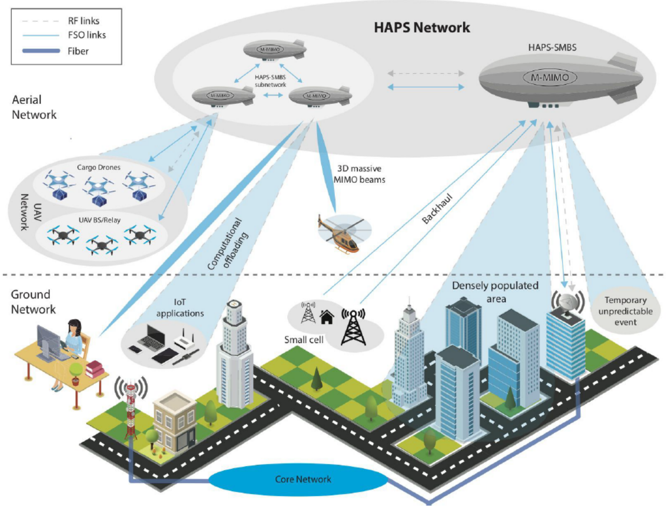


Figure 2.16: Hypothetical HAPS mixed application scenario [25].

A comprehensive representation of the applications yet discussed is coherently depicted in figure 2.16.

2.3 Studies on HAPS usage in literature

So far, the reader was presented a general overview of High Altitude Platform Stations for what concerns the basic concepts, a brief review of their evolution in time, the main design aspects, the advantages they show with respect to conventional devices and, finally, a pool of their principal applications in modern scenarios.
Objective of the present section is to depict an even clearer picture about potential benefits and enhancements that modern RANs could achieve through the integration of aerial platforms into their architectures.
Since the great attention HAPSs have been given during the last two decades up to nowadays, it is not rare to find in the **technical literature** examples of articles, books and publications whose main focus is to study and analyze the application of such technology to tackle real world problems. Those pieces of literature typically aim at finding alternative and revolutionary solutions to large-scale and widespread issues of modern wireless communication networks, such as congestion avoidance and handling, bandwidth distribution, quality of service preservation and, most important, power consumption management. Therefore, it is precious for whatsoever study about HAPSs to rely on the huge pool of technical literature about the subject that is commonly available for the community to consult.

Throughout this section, several HAPS use cases (either real or simulated) reported in the literature are going to be exposed and analyzed.

2.3.1 HAPS for networks sustainability

As mentioned earlier, one of the most crucial aspects to deal with when talking about modern radio access networks is **power consumption**. In fact, within the last years, in order to keep the general networks capacity in line with the upsurging mobile traffic demand, one solution that was largely exploited is network densification. Nonetheless, such densification does not come without some negative implications, one of which is the huge growth of power required by terrestrial communication infrastructures (e.g. BSs).
Starting from such premises, one study of particular interest, published by Renga and Meo in 2022 [28], takes the chance of analyzing more in depth the potential outcomes of exploiting high altitude platform stations in RANs in order to decrease the general power consumption while still being able to assure connectivity with sufficient QoS levels. Even though the study pursuits the purpose of investigating future applications involving 6G connectivity, it can still be rather indicative for what concerns sustainability of RANs in general. Furthermore, it depicts a much clear picture of what an enhanced wireless network with integrated HAPS would appear like.
The central problem, object of the analysis, is described as composed of two components, reported as follows.

- **Network densification** will soon become unsustainable from the point of view of physical and legal constraints.
- The constantly increasing **power demand** of communication infrastructures undermines compliance with the international agreements for sustainable policy, first of all the Paris Agreement [29].

Given a clear problem statement, two precious tools are indicated as crucial for future solutions, namely:

- **Renewable Energy Sources (RES)**;
- New **Resource on Demand (RoD)** approaches.

In particular, RoD strategies aim at dynamically adapting the radio capacity of the infrastructure to the actual demand requested by users at a given time instant. This logic comes with the aim of avoiding over-provision of bandwidth and consequently reducing network consumption. Considering these information, it is clear that HAPS integration in existing RANs could achieve some disruptive effects in terms of efficiency goals. HAPSs are able, in fact, of delivering additional capacity to the general architecture whenever it is needed, and this feature can potentially provide several benefits to the overall networks operation:

- additional capacity whenever the network experiences congestion at any level;
- traffic can be handled by the HAPS without the need to increase the total power drawn from the power grid;
- SMBSs can support focal activities such as data gathering, caching and processing [25].

With all the considerations above being explained, a further aspect that needs to be highlighted is the architecture affordability from a financial cost perspective. In [28], in fact, it is reported that even though the integration of a RAN architecture with a HAPS may be a costly operation in the short term, there is another factor to consider. Indeed, with the advent of new enabling technologies, such as light-weight materials, new generation PV panels and high efficiency energy storage systems, the CAPEX for the deployment of a high altitude platform station is expected to decrease by a solid 50% in the decade 2018-2028. It goes without saying that in the next years the integration of HAPSs in existing RANs will progressively become more financially effective, especially if considered that aerial platforms are typically characterized by a rather long operational life, which is meant to compensate, in the long term, the cost of their initial set up.

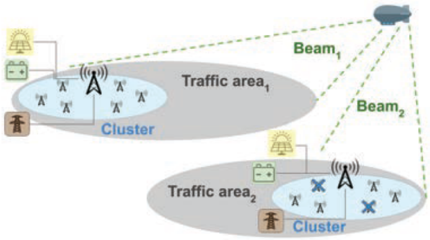


Figure 2.17: Scenario under examination [28].

The study carried out by Renga and Meo analyzes a well described scenario, reported in figure 2.17, comprehensive of a set of terrestrial BSs, which can be powered by grid or, in some cases, through additional energy, locally generated by groups of photovoltaic (PV) panels. In order to create an optimal power consumption management strategy, the terrestrial BSs have the possibility to turn power off (i.e. **sleep mode**), in order to save energy in off-peak periods of time. The crucial aspect that must be underlined while describing the scenario is the total **energy autonomy** of the HAPS. The aerial platform, indeed, is equipped

with solar panels and works at an altitude such that sun rays can reach the panels unfiltered, resulting in a rather efficient and sustainable power supply for the station itself. In addition to this factor, the HAPS is provided with high-efficiency power storage systems, namely high-density batteries which can store electricity produced during the day in order for it to be exploited throughout the night. Given the aspects yet described, the HAPS in this specific scenario is to be considered completely energy independent.
The environment under analysis is part of an existing RAN in the city of Milan, Italy, and a dataset of real traffic data is utilized for simulation purposes.
Since networks capacity is typically designed to be aligned with traffic demand at its peak, **oversized** RANs come as a consequence. Thus, a great number of BSs are often turned on when their action is not necessary, resulting in avoidable energy wastes. The solution proposed by Renga and Meo, as mentioned earlier, is the peculiar BS sleep mode, which can be triggered at any time whenever the traffic load of the base station is smaller than a threshold, namely ρ_{min}.
The second strategy, already described, is the **HAPS offloading (HO)**. The aerial station is, in fact, capable of managing traffic from more than one BSs cluster in the same cell, allocating a specific value of capacity for each cluster, indicated as C_h. In order to apply a smart and efficient offloading strategy and to achieve a sensitive power demand reduction, traffic offloading to the aerial SMBS is performed whenever possible, and only when HAPS's channel is saturated, micro BS can offload traffic to the relative terrestrial macro BS.
For this study, two different key performance indicators (KPIs) are taken into account, namely:

- **Grid Energy Reduction** (G_R);
- **Capacity/Demand Ratio** (R).

Finally, several simulations are run, varying parameters regarding both the RE generation for terrestrial BSs and the RoD strategy.
As a result, the cases in which RE generation on terrestrial BSs is turned on and HO is performed present in all zones smaller values of R. This result is of critical importance, since is indicates that a joint usage of RE and HO can surely support network providers in avoiding the problem of network capacity oversize. Indeed, a dynamical adaptation of capacity to the actual traffic demand can be a key factor in reducing the energy footprint of the whole network, while still preserving a decent QoS provision to the end user.

On second hand, for what concerns grid energy reduction, higher values of G_R are reported for the cases when HO and RoC are applied. As a consequence, lower values of total network energy consumption will be registered whenever a RoD strategy is applied in combination with RE generation on terrestrial nodes.

Finally, a last analysis is carried out by varying the value of C_h. The article reports that, for growing values of C_h, both R and G_R tend to show higher values in all the analyzed areas. These information demonstrate once again the huge impact HAPSs can have on the performance of RANs, while supporting the reduction of power consumption. Even when no RE is generated by terrestrial BSs, indeed, total energy consumption can sensitively be reduced by up to 50%, exploiting HO [28].

The outcomes of the study carried out by Renga and Meo are of critical importance for future implementations of HAPSs in modern wireless communication networks. Indeed, the analysis has effectively demonstrated the great benefits the community could achieve by exploiting a disruptive technology such as HAPSs, both in terms of networks performance and reduction of the energy footprint.
Considering that the best results obtained through simulations, were achieved combining HO and RE generation on terrestrial nodes, it is clear that both of these factors will be of critical relevance while designing future RANs, especially considering that HAPS operation has the greatest impact on zones characterized by high levels of traffic demand. From this point of view, HAPSs can surely provide a solid support in solving problems such as QoS assurance, reducing power consumption and avoiding excessive network densification.

2.3.2 HAPS for energy efficiency of networks

As already specified in section 2.3.1, one particular use case which undoubtedly provides a clear overview of the sensitive impact HAPSs usage can have on modern and future wireless networks is the one which analyzes the use of aerial platforms as enablers for energy efficiency.
From this point of view, one article of particular interest is one published by Song et al. in 2023 [30], which, in line with other similar studies [28], investigates the potential use of HAPS in reducing the power consumption of a RAN, in order to discuss the sustainability of future 6G networks from an energetic point of view.
The study takes into consideration a specific scenario, represented in figure 2.18, where a HAPS is integrated onto a urban zone with a total number of 960 terrestrial BSs. As in [28], the HAPS is equipped with a SMBS, to which traffic can be offloaded in order to make data handling smoother and more energy efficient.

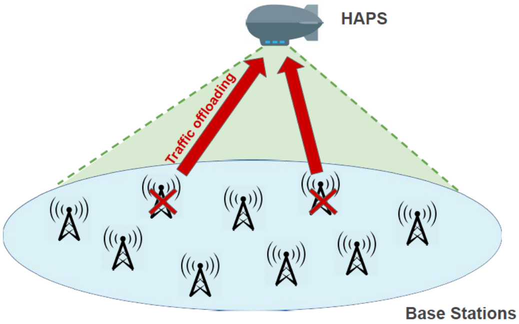


Figure 2.18: Scenario under investigation [30].

Terrestrial BSs can be put into **sleep mode** whenever they have no traffic to manage. This condition, however, is subject to two basic constraints which are described in the article as follows:

- In order to assure basic QoS, the number of BSs put into sleep mode cannot exceed a fraction l_B of the total;
- the total offloaded volume cannot exceed the capacity of the HAPS.

With these constraints being clearly specified, the general problem is thus stated as the **minimization of an element $\mathbf{E_{total}}$**, being the general power consumption of the whole analyzed network.
Aiming to perform a simulation as close as possible to a real world scenario, a set of elements are modeled. The simulation elements subject to **modelling** are reported as follows.

- **Traffic**. The traffic traces, gathered by a common connectivity provider in the city of Milan are scaled up through an effective algorithm in order to make them as close as possible to the volumes registered in a Chinese modern urban zone.
- **BS consumption**. The formulated model takes into account more than one contribution to the total energy consumption. In fact, Song at. al propose an equation based on the following elements:
    - baseline consumption;
    - baseband processing;
    - RF chains;
    - power amplifier (PA);
    - data transmission.

- **HAPS capacity**. This factor is computed exploiting the well known Shannon-Hartley theorem [31], based on two crucial elements, namely:
    - bandwidth (B);
    - SNR (γ).

In addition to the considerations yet exposed, the article also presents a coherent **HO strategy**, based on the offloading of traffic relative to BSs showing the smallest volumes of data.
A further measure that is adopted in order for the simulation to be as realistic as possible is the implementation of three peculiar parameters, namely:

- **Elevation angle** of the HAPS with respect to its coverage area.
- **Building type**, exploited to coherently estimate hypothetical signal losses.
- **Indoor UE**, indicating whether user equipment is positioned indoor or outdoor, with the aim of determining whether the users are subject to entry losses or not.

In the end, one thousand simulations are run with various values for each one of the parameters yet listed.

From the point of view of energy reduction, the general trend is the one of a sensitive **power demand reduction**, as the article reports a peak of 29% during week days and a solid maximum value of 41% throughout the nights. These outstanding results are achieved thank to a smart and dynamical utilization of HO.

Furthermore, another relevant indication is related to the percentage of offloaded traffic with respect to the total traffic demand. Indeed, even though the results never reach values of percentage greater than 15% throughout the day, the obtained performance is still sufficient to achieve a sufficient reduction in power demand.

Ultimately, HAPS capacity utilization is investigated. This last metric, expressed in % of total capacity, can be very indicative especially when trying to consider the adopted solution from the perspective of QoS. In fact, with the article reporting values of HAPS capacity utilization comprised between 30% and 50% during the day, it comes as a consequence that the users will experience higher values of BW per traffic unit, which, theoretically, results into **higher QoS standards**.

The analysis yet described assumes great importance in the domain of present and future application of high altitude stations, since it manages to demonstrate the potential expressed by such revolutionary devices in the domain of **sustainability and QoS** of wireless networks.

2.3.3 HAPS for crises management

One application of particular relevance which can be described as rather disruptive when analyzing HAPS usage in modern scenarios, is the one correlated to **disaster and crisis management**.
During natural disasters (e.g. storms, earthquakes, sever weather conditions, etc.) and human-driven catastrophes (e.g. acts of war, terrorist attacks, etc.) the conventional terrestrial cellular network infrastructure can suddenly become unavailable for users, leaving a large number of basic and fundamental services uncovered. In addition to this aspect, every potential activity of post-disaster management, such as rescue operations and situation monitoring, requires an efficient and fully reliable telecommunication structure, critical for a successful outcome of the operations.

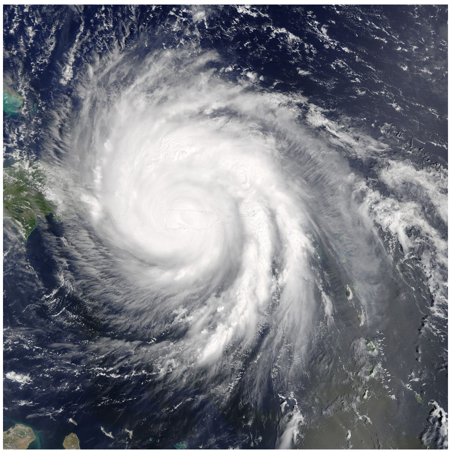


Figure 2.19: Hurricane Maria over Puerto Rico. Source: Wikipedia.

Due to their versatility, flexibility and other peculiar characteristics, high altitude platform stations fit particularly well the application in such emergency scenarios, as they enable the deployment of **on-demand networks** whenever needed and they are easily integrable with the terrestrial infrastructure not damaged by catastrophic events.
In fact, HAPS usage in similar scenarios is stated in a list drawn up by the European Space Agency (ESA) about the services enabled by HAPSs. In the list, it is clearly specified that aerial stations can be exploited in "emergency activities such as maritime search and rescue, fight against illegal activities, industrial site monitoring, crisis management and disaster relief" [32].
It must be underlined, as described by ITU [33], that similar applications have already been experimented in the past. In particular, balloon-based high-altitude systems were utilized in Puerto Rico during the 2017 hurricane Maria emergency

and in Peru during 2019 earthquake post-disaster management. In both cases the HAPSs were exploited to partly restore mobile communications, showing good overall results in accomplishing their tasks.
An analysis of particular interest, consultable in literature, about such applications is the one carried out by Gharbi et al. and published in 2019 [34], which aims at investigating the potential benefits HAPS usage can provide to overcome disasters and crises.
As already described in section 2.2.1, HAPSs show smaller values of latency with respect to conventional satellites while still providing great connectivity in terms of coverage area. Starting from these premises, Gharbi et al. perform a preliminary study with the objective of designing a heterogeneous architecture based on a combined use of aerial platforms, satellites and terrestrial infrastructures in order to deliver efficient and effective communication services to tackle emergency scenarios. In particular, the study introduces three different segments in which a satellite network architecture can be divided, namely:

- **space**;
- **ground**;
- **control and management**.

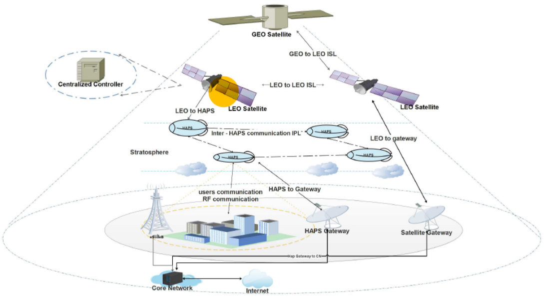


Figure 2.20: Types of link in the heterogeneous architecture [34].

Based on the three segments yet listed, three different types of link (represented in figure 2.20) can be designed as follows:

- HAPS-to-satellite, or **Inter-Satellite Link (ISL)**;
- **Inter-Platform Link (IPL)**;
- **HAPS-to-ground link**.

Given the flexible nature of a HAPS, it can behave as a normal BS in addition to the conventional terrestrial ones. In order to manage as effectively as possible cases of overloading, the study proposes the introduction of a **centralized controller**, with the aim of managing network and radio functionalities. Such controller is integrated into a LEO satellite and it supports load balancing functions internal to the architecture.
The analysis by Gharbi et al. divides the possible crisis scenarios in two hypothetical categories, namely:

- events involving major geographical areas;
- events involving minor geographical areas.

In the first scenario, a single HAPS can be used to cover an area of up to 200 km^2, where it can act as an intermediate node between UE and the closest Internet gateways. This application is exhaustively depicted in figure 2.21.

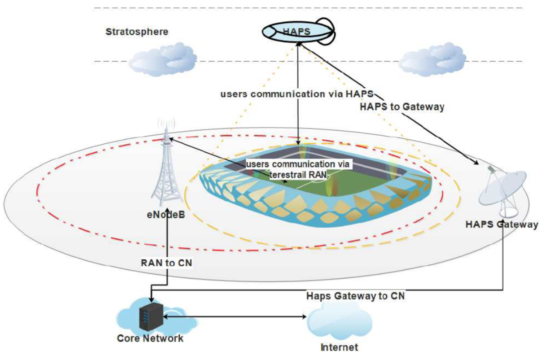


Figure 2.21: First analyzed scenario [34].

On the other hand, in the second scenario, the proposed solution consists of a **backbone of HAPS**. In this specific case, the preferred links to be used are the one of IPL type, and three particular metrics are evaluated in order to make communications as efficient as possible:

- shortest physical distance;
- link availability;
- link stability.

The second application described is coherently represented in figure 2.22.

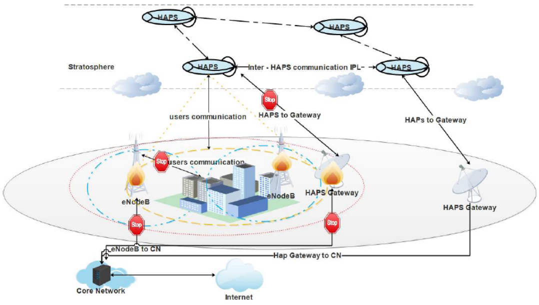
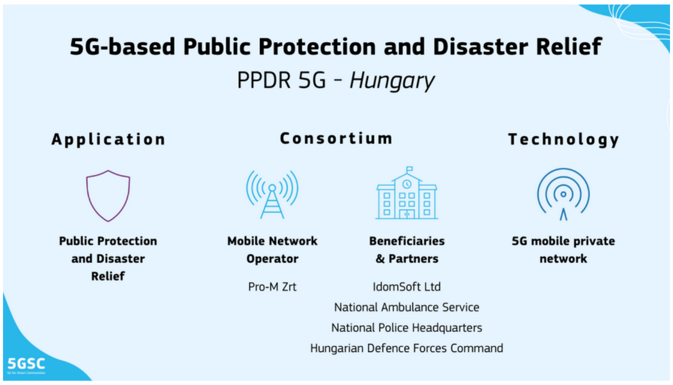


Figure 2.22: Second analyzed scenario [34].

The article by Gharbi et al. is particularly precious when talking about HAPS usage in emergency or crisis scenarios, since it exposes a clear and detailed overview of a possible heterogeneous architecture involving a multi-layered structure which integrates HAPSs, satellites and terrestrial nodes. For the reasons yet indicated, it can surely be exploited as a significant starting point for further research and simulation studies.

2.3.4 HAPS and UAV joint usage for disaster management

In section 2.3.3 a peculiar application of HAPSs in emergency monitoring and management was exposed. However, several different architectures were investigated over time, aiming to elaborate an aerial platform-based architecture which could support disaster monitoring activities in the most efficient way as possible.
One option of particular interest involves the combined use of two disruptive aerial technologies, namely UAVs and HAPSs. While [35] provides an exhaustive study about a solution merely exploiting UAVs, a very detailed overview of HAPS-UAV combined usage for disaster monitoring is exposed in [36].
The article underlines the impact that aerial devices such as HAPSs and UAVs can have on the wide spectrum of crises management activities, especially in compliance with the newest 5G-based **Public Protection and Disaster Relief** (PPDR 5G) (figure 2.23) [37].



5G-based Public Protection and Disaster Relief

PPDR 5G - *Hungary*

Application

Public Protection and Disaster Relief

Consortium

Mobile Network Operator

Pro-M Zrt

Beneficiaries & Partners

IdomSoft Ltd

National Ambulance Service

National Police Headquarters

Hungarian Defence Forces Command

Technology

5G mobile private network

Figure 2.23: PPDR 5G, Hungarian case study [37].

PPDR 5G is, in fact, a €5.3 million worth project, largely financed by EU with the aim of creating a revolutionary solution to "ensure high quality, secure and disaster resilient communications for police, border guards and ambulance services" [37].
Within this context, Unmanned Aerial Vehicles can surely support the deployed personnel on the ground by providing a backhaul to connect to the Internet while exploiting a HAPS umbrella coverage. Furthermore, UAV-HAPS integrated architectures can use **Ultra-Reliable and Low Latency Communications (URLLC)** [38] to assure complete reliability for lifeline telecommunications.
In [36] it is specified that both UAVs and HAPSs are able to maintain connection with sensors and other monitoring devices on the ground, and this feature makes them perfectly suitable for collecting data of crucial importance to be processed and transmitted to the closest Emergency Management Center (EMC). To accomplish this task, the UAV can either host a IoT gateway or a more effective 5G gNB (i.e. 5G Next Generation BS which supports the 5G New Radio [39]).

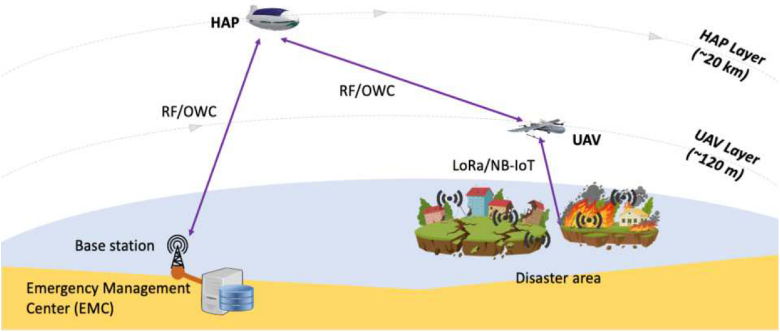


Figure 2.24: UAV-HAPS architecture for PPDR [36].

Figure 2.24 shows a comprehensive representation of the emergency management architecture described in [36]. The characteristics that must be highlighted in this case is the connection between terrestrial devices, UAVs, HAPSs and EMC. The overall system is specifically designed to fit its application, thus it is able to assure short reaction times and very high levels of reliability and robustness, in compliance with the URLLC paradigm.
Consistently with the concepts already exposed in section 2.1.1, the yet mentioned article describes three types of HAPS suitable for the task, namely:

- **airplanes**;
- **balloons**;
- **airships**.

These HAPSs can coherently be combined in their use with an equal number of UAV types, namely:

- **fixed-wing**;
- **rotary-wing**;
- **hybrid**.

Furthermore, [36] describes two different types of architecture which can be exploited in a disaster management scenario. The two types of system, coherently with what was exposed in section 2.1.2 [22], are the well known:

- **Bent-pipe (BP)** architecture, where the HAPS acts as a RF repeater or a relay station;
- **Regenerative (RG)** architecture, designed for the HAPS to operate as a gNB.

Another crucial aspect to take into account while designing an emergency management communication architecture is the choice of **communication protocols**. Some of the most widely spread radio technologies are reported as follows:

- **Bluetooth Low Energy (BLE)**;
- **WiFi**;
- **ZigBee**;
- **LTE-M**;

- **Narrowband IoT (NB-IoT)**;
- **Sigfox**;
- **LoRa**.

[36] exhaustively describes pros and cons for each described technology, as reported in figure 2.25, where the different solutions are compared according to throughput, range, power consumption, infrastructure and device costs.

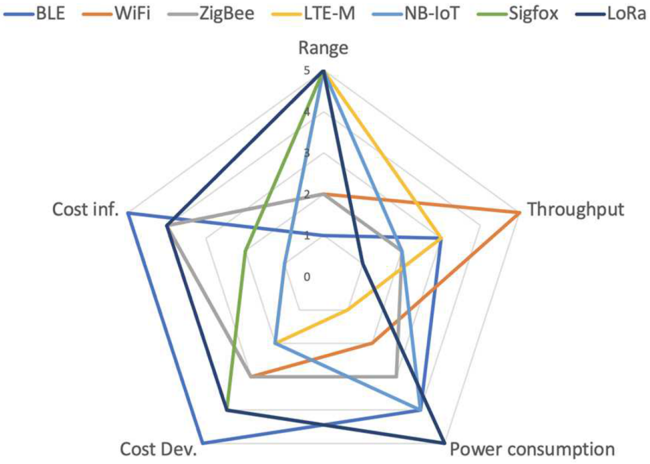


Figure 2.25: Communication technologies comparison [36].

Finally, two technologies are selected as the most suitable for UAV-HAPS-based emergency monitoring systems, namely **LoRa** [26] and **NB-IoT** [40]. This selection comes as the result of a trade off between many aspects, related to the efficiency and the costs of every technology.
In conclusion, it can be undoubtedly stated that system architectures involving the combined use of HAPSs and UAVs will play a fundamental role in the future evolution of emergency management and disasters monitoring. The peculiar characteristics of HAPSs, in particular their extended coverage area, in addition to the flexibility and versatility of UAVs can surely support the forces deployed on-the-ground by providing telecommunications with a high level of reliability and robustness. These features in particular are of crucial importance in all those situations where terrestrial communication infrastructures are severely damaged and public safety needs to be preserved.

Chapter 3

Methodology

This chapter comes with the aim of describing in detail the **methodology** adopted in order to efficiently carry out the analysis object of the present document.
As already described in chapter 1, the study has the objective of investigating the potential benefits modern RANs can achieve from the point of view of **network reliability** by implementing the usage of **HAPSs** into their design. In particular, the analysis is mainly focused on investigating networks performance from the perspective of **resilience**.

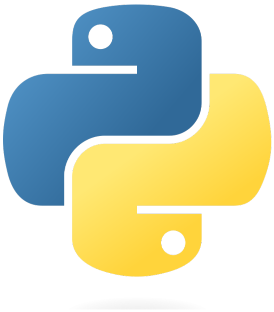


Figure 3.1: Python programming language [41].

The principal tool exploited to perform the general study and analysis is a **ad-hoc simulator**. The simulator was almost entirely programmed using the **Python** programming language (figure 3.1), which supports multiple programming paradigms, including object-oriented and functional programming [42]. For the reasons yet exposed, Python perfectly fits the applications related to data analysis and simulation, specifically object of the study described in this document.
The basic scenarios under investigation aim at emulating the case of a modern RAN equipped with multiple BSs, supported in their operation by a high altitude

platform, capable of managing the offloaded traffic demand in case of failures or power shortages experienced by the terrestrial communication infrastructures. In other words, the ultimate objective of the HAPS in the simulated scenario is to support the network in assuring service provision in the case of critical circumstances such as blackouts or similar critical events.

In order to make the simulation as loyal as possible to real world cases, the **real traffic demand** is used, confidentially provided by an Italian network operator. This comes with the aim of emulating real traffic demand data and thus simulating the RAN behaviour in a much more realistic manner.

Moreover, the RAN is realistically modelled from the point of view of **energy management**, since power consumption data for every considered BS are provided in the mentioned dataset, and the behaviour of reserve batteries is modelled by the simulator as well. These features make it possible for the user to analyze in an effective way the network performance not only in terms of QoS but, additionally, from the point of view of **energy efficiency**, **sustainability** and, most of all, **resilience**.

Further in this chapter, every aspect of the general analysis will be taken into account and described, starting from the considered scenario and following up with the most technical features and details, such as modelling and used traffic traces.

3.1 General scenario description

Within this section, the reader will be provided with a clear overview of the considered general scenario, object of the analysis.

As mentioned in the chapter introduction, the simulator aims at modelling a typical **Radio Access Network** composed of several BSs, each one individually characterized from the point of view of traffic and power demand. The RAN is designed to support multiple technologies, namely **Long Term Evolution (LTE)** and **New Radio 5G (NR)**, covering more than one frequency.

The coverage area is meant to be a densely populated area, and thus it is characterized by a statistically high traffic demand, which needs to be efficiently managed by the operational BSs on the ground.

A conceptual representation of the general scenario under analysis is reported in figure 3.2 [25].

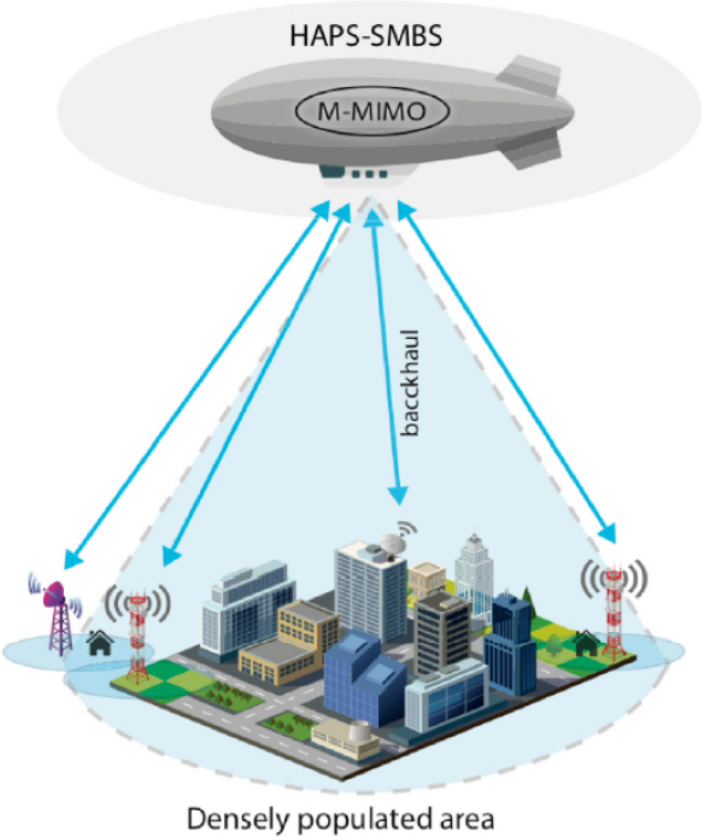


Figure 3.2: Considered scenario [25].

The number of BSs operating in the urban RAN can vary from 1 up to a maximum number of 7.
In addition to the capacity provided by the terrestrial infrastructure, the service provision of the networks is further enhanced by the presence of a **High Altitude Platform Station**, depicted in figure 3.2, which is capable of managing traffic offloaded by ground BSs both in:

- normal operational conditions;
- **emergency circumstances**.

The HAPS is equipped with mMIMO capacity and has a dedicated channel to manage traffic demand coming from the whole coverage area.

The considered hypothesis for what concerns HAPS's energy management, is a **total autonomy** from the point of view of power supply. The platform is indeed equipped with a set of high efficiency **solar panels** and a set of **batteries**,

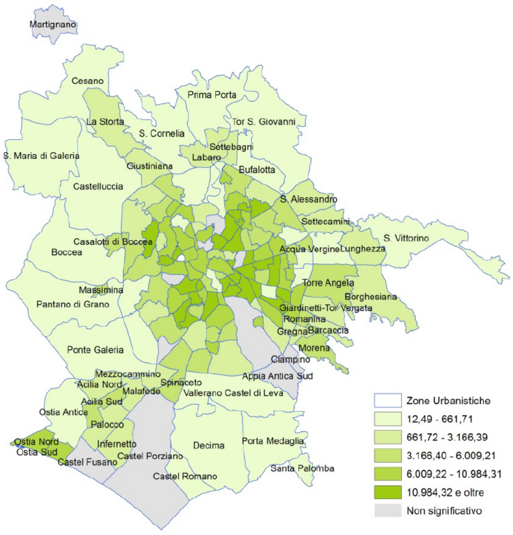
which ensure the generation and storage of a quantity of energy which is sufficient to supply the HAPS in all its operations either during the day and the night. Therefore, given these premises, the aerial platform is to be considered completely autonomous from the perspective of energy supply, and thus it is able to operate without any external power supply.
For what concerns the terrestrial BSs, a fundamental role in their normal operation is played by the **power grid**. Indeed, the ground BSs, while performing their operations in normal conditions, are meant to get the entire needed quantity of energy from the grid. In addition, similarly to the HAPS, they are mounted **back-up batteries**, in order to assure continuity in the services provision even in critical conditions when the power grid may be unavailable.
Since the ultimate objective of the analysis is to assess the actual impact the usage of aerial stations can have in the enhancement of a network's **resilience**, the scenario is designed to simulate the occurrence of one or several **blackouts**.

Figure 3.3: Satellite view of Italian blackout, September 2003. Source: Rai News.

During such events, the power grid is intended to be totally unavailable for ground BSs, and the only power that can thus be exploited is the one stored in the BS back-up batteries. Nonetheless, such batteries provide only a limited amount of energy to be used. Therefore, **HAPS Offloading (HO)** will be used in a smart way, through a set of well designed **offloading strategies**, with the aim of maximizing the battery duration in case of a blackout, and ensuring the services keep being delivered to the users for the time required to make the power grid available again.

3.2 Dataset

In order to render the whole simulation realistic and adherent to real world scenarios, a **dataset** was exploited in such a manner that the simulations could be coherently characterized from the point of view of **traffic demand** and **power consumption**.



(a) Rome metropolitan area.

(b) Downtown Rome area.

Figure 3.4: Population density in Rome (inhabitants/km^2). Source: ISTAT.

The data in the dataset were collected and confidentially shared by a famous network operator, providing connectivity services in Italy.
The dataset contains information about **10 sites** located in **Rome, Italy**, and according to the network operator the reciprocal distance between the different sites is around 420 meters. According to the Italian National Institute of Statistics (ISTAT) the metropolitan area of Rome is the typical example of high densely populated urban area, as coherently shown in figure 3.4. Therefore, the data concerning traffic demand in such area are intended to provide a clear and realistic overview of what traffic volumes may be managed in the analyzed scenario.
The data were collected over a span of **32 days** between December 12^{th}, 2023 and January 12^{th}, 2024. The samples were collected with a **1-hour** time granularity.
Since severe problems concerning anomalies and missing values were encountered while pre-processing data referring to Sites 2, 5 and 10, only the remaining **7 sites** were retained utilizable for simulation purposes.
According to the information shared by the network provider, every site in the dataset is composed of multiple layers, and each layer contains a number of 3 sectors. As a consequence, in the dataset it is possible to find **multi-frequency** sites, as well as **multi-technology** sites.
The possible **technology-frequency combinations** which are included in the considered dataset are thus exposed as follows.

- LTE (800 MHz);
- LTE (800, 900 MHz);
- LTE (700, 800, 900 MHz);
- LTE (1800, 2100 MHz);
- LTE (2600 MHz);
- NR (3700 MHz);
- NR (2100 MHz).

Every record in the dataset reports the following data:

- **timestamp** in Unix time format [43];
- **site**;
- **sector**, stated as a combination of technology, frequency and cell;
- **load in DL/UL**, expressed as % of resource blocks (RB) utilized;

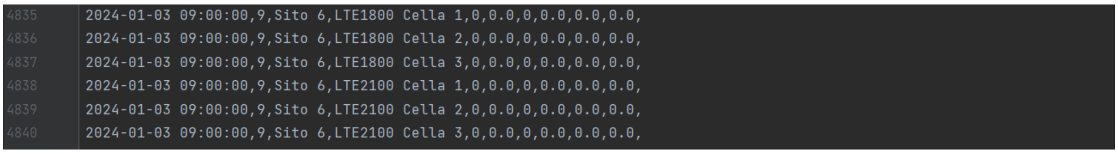
- **available RBs**, expressed as the number of RB that can be employed;
- **traffic volume in DL/UL**, expressed in kByte;
- **energy consumption**, expressed in kWh.

Together with the traffic traces yet described, the network provider shared two more additional files concerning:

1. **maximum transmission power** for every sector of each frequency at each site. The TX powers are expressed in dBm.
2. **Attenuation** along the power cables for each sector of each frequency at each site. The attenuation data are expressed in dB.

3.2.1 Faulty samples management

Whilst sites 2, 5 and 10 were retained undoubtedly unusable for simulation due to the gravity of the issues encountered during the analysis of their collected data, **site 6** was indeed accounted as utilizable. Nevertheless, a small pool of missing and anomalous samples were identified and thus had to be managed in such a way that would render the dataset fully operational.
Such anomalies are probably due to a temporary failure of the data collection system, which could potentially be related to an electricity shortage or similar issues.
Figure 3.5 depicts the group of anomalous samples that were detected in the site 6 dataset.



```
2024-01-03 09:00:00,9,Sito 6,LTE1800 Cella 1,0,0.0,0,0.0,0.0,0.0,
2024-01-03 09:00:00,9,Sito 6,LTE1800 Cella 2,0,0.0,0,0.0,0.0,0.0,
2024-01-03 09:00:00,9,Sito 6,LTE1800 Cella 3,0,0.0,0,0.0,0.0,0.0,
2024-01-03 09:00:00,9,Sito 6,LTE2100 Cella 1,0,0.0,0,0.0,0.0,0.0,
2024-01-03 09:00:00,9,Sito 6,LTE2100 Cella 2,0,0.0,0,0.0,0.0,0.0,
2024-01-03 09:00:00,9,Sito 6,LTE2100 Cella 3,0,0.0,0,0.0,0.0,0.0,
```

Figure 3.5: Missing values in Site 6 trace.

The faulty samples presented issues of different nature, described as follows.

- **Null values** in the fields of:
  - traffic volume in DL/UL;
  - load in DL/UL (in terms of used RBs);
  - available RBs;

- **Missing values** in the field of energy consumption, which would be interpreted by software as *not-a-number* (NaN) values.

During the early stages of the activity, the temporarily adopted solution was to operate a basic management of the NaN values, which would be substituted by **null** values.
Nonetheless, with the progression of the simulations, such solution would present issues related to a lack of continuity and adherence to real world behaviours.
Therefore, the definitive chosen solution reckoned on the use of a **linear interpolation** technique.
Considering a single traffic trace with missing values between hours h and k, then the value of traffic volume at hour $h + n$ can be interpolated as follows:

$$t_{h+n} = t_h + (n \times \frac{(t_k - t_h)}{k - h}) \tag{3.1}$$

Having, for instance, a group of missing value between hours 07:00 and 12:00, then it is possible to retrieve the traffic volume at hour 09:00 as:

$$t_9 = t_7 + (2 \times \frac{(t_{12} - t_7)}{5}) \tag{3.2}$$

Exploiting the same scheme for every hour from 08:00 to 11:00, it is possible to reconstruct the entire time series starting from the known values and using interpolation to retrieve the missing ones.
The interpolation technique yet described was successfully exploited to manage the faulty samples detected in site 6 dataset, and it was specifically utilized to substitute both **null** and **NaN** values with data more coherent to reality.
Finally, using linear interpolation, it was possible to tackle the issue of faulty and missing data, either they were traffic volume, load or energy consumption data.
Subsequently to the interpolation, all the fields previously affected by anomalies were fully restored. Therefore, the dataset was consequently operational and fit for simulation use.

3.2.2 Dataset analysis

The present section comes with the aim of providing the reader with a more detailed overview of the dataset already described in previous paragraphs. Indeed, a preliminary analysis was performed, in order to observe the data in a clear and exhaustive manner and spot interesting patterns and trends in the samples.
First of all, one of the most important parameters to take into account for the simulations of interest is undoubtedly the **traffic volume**.
Every BS provides coverage for different **sectors**, as already illustrated in the

introduction of section 3.2.
Each sector is a combination of a **cell** and a **frequency**, and the dataset reports the value of traffic volume in **download** and in **upload** for every single sector at every time instant.
For simulation purposes, it was retained useful to calculate, in addition to the sector-specific traffic volumes, also the total traffic volumes managed by each BS over time. Therefore, the whole volume of traffic in DL (V_{DL}) managed by a BS at time instant t was computed as:

$$V_{DL}(t) = \sum_{s=1}^{N_s} V_{DL}^{s}(t) \tag{3.3}$$

where s indicates the sector and N_s the number of sectors covered by the BS. Similarly, the total volume of traffic in UL (V_{UL}) managed by a BS at a certain time instant is given by:

$$V_{UL}(t) = \sum_{s=1}^{N_s} V_{UL}^{s}(t) \tag{3.4}$$

Consequently, the overall traffic volume (V_{tot}) managed by a single BS at a certain time instant t is computed as follows:

$$V_{tot}(t) = V_{DL}(t) + V_{UL}(t) \tag{3.5}$$

Figure 3.6 depicts the trend of total traffic volume (V_{tot}) managed by every BS over a span of 48 hours. The analyzed time period starts at 00:00 on December 12^{th} 2023 and ends at the same hour on December 14^{th}. The shown time series were **normalized**.

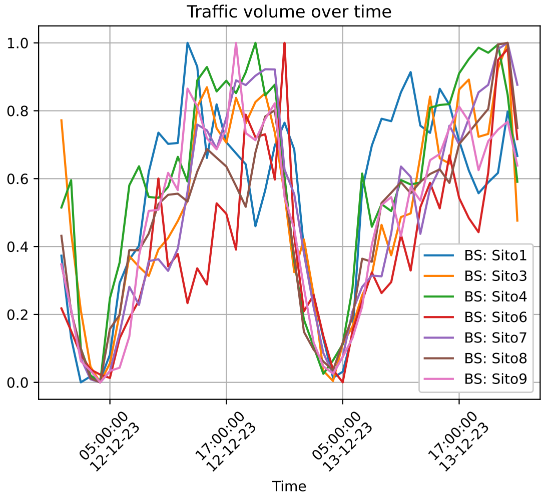
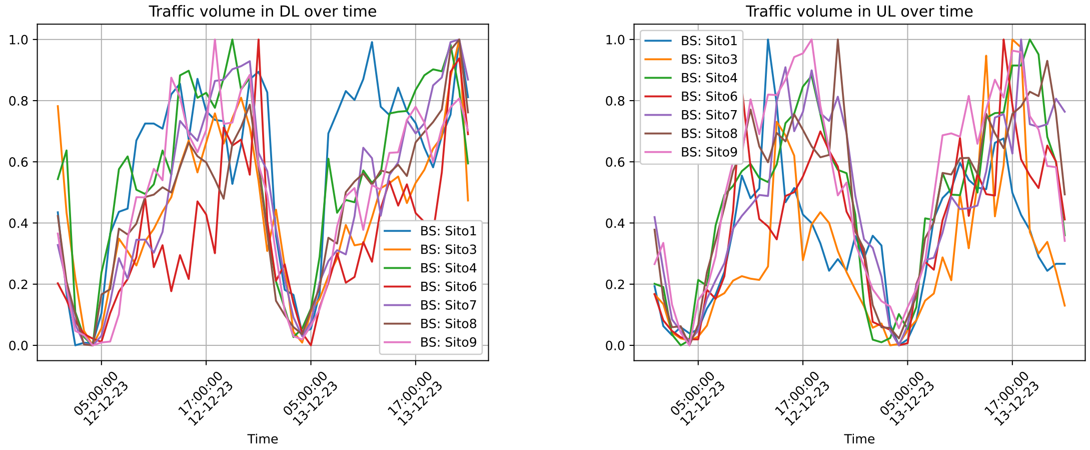


Figure 3.6: Total traffic volume for all BSs over time.

Figure 3.6 clearly shows an interesting trend in the data concerning traffic volume, indeed it must be underlined that the greatest peaks in such parameter are encountered during daytime, when the Internet traffic demand is typically higher. As a consequence, the traffic volume managed by BSs knows a sensitive decrease during the nighttime.
Such pattern is similar for all the BSs and it can be also spotted in the individual trend of traffic volumes in DL and UL, whose time series were coherently normalized and depicted in figures 3.7a and 3.7b.

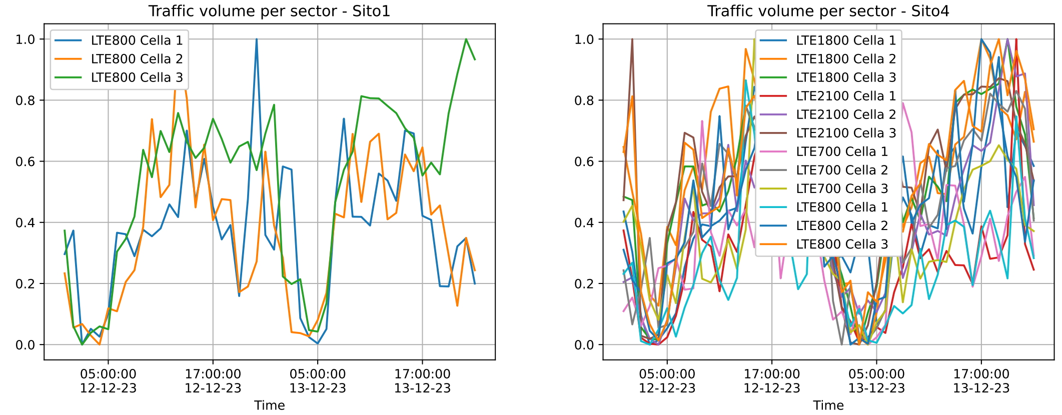


(a) Download.

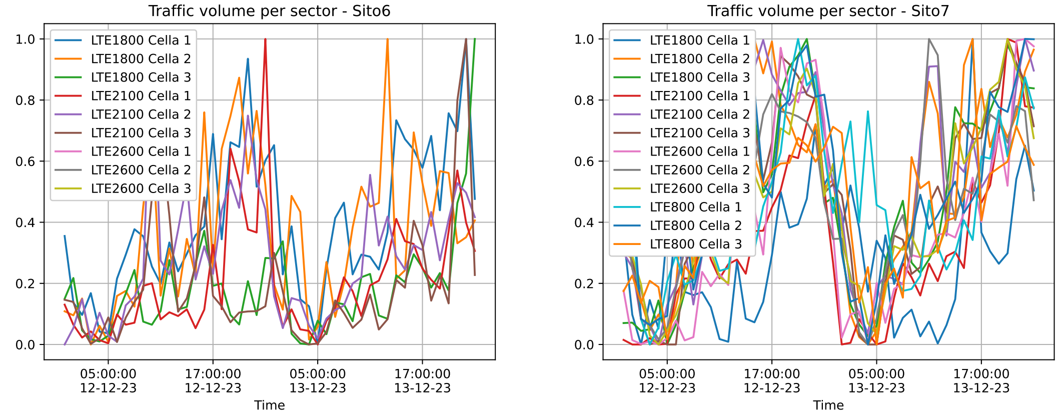
(b) Upload.

Figure 3.7: Traffic volume over time in DL and UL.

Despite the trend of total traffic volumes, a fundamental notion to point out is that the distribution of sectors among the BSs is heterogeneous. As a consequence, every BS will be tasked to cover sectors that vary in terms of number and type.
In order to clarify this last concept, in figure 3.8 is reported the trend of **sector-specific** traffic volumes for 4 out of the 7 analyzed BSs. The considered time period is the same as figures 3.6 and 3.7 (i.e. 48 hours) and it must be highlighted that each sector is characterized by a unique trend, especially in terms of peak demand and hours of the day with the highest volumes of traffic. In this case the data were also normalized.



(a) Site 1. **(b)** Site 4.



(c) Site 6. **(d)** Site 7.

Figure 3.8: Traffic volume over time divided per sector.

In addition to the volume of traffic, another crucial parameter to take into account is the BSs **energy consumption**. Such data are also provided by the dataset and they are divided by sector.
Similarly to the operation performed for traffic volume (exposed in equations 3.3

and 3.4), the total BS power consumption (PC_{tot}) at time instant t was computed as a sum of every sector-specific consumption.

$$PC_{tot}(t) = \sum_{s=1}^{N_s} PC^s(t) \tag{3.6}$$

Figure 3.9 shows the trend of power consumption for all the 7 BSs over a time period of 48 hours. The data were normalized for plotting purposes.

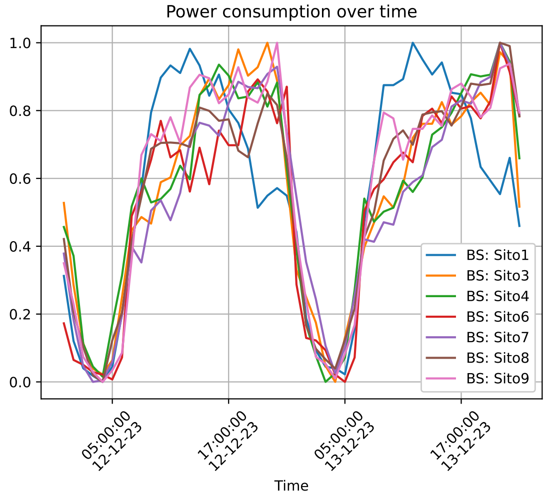


Figure 3.9: Power consumption for all BSs over time.

Comparing figures 3.6 and 3.9, it appears clear that higher volumes of traffic do not necessarily correspond to greater energy consumption. Such information assumes a particular relevance and thus it had to be taken into account in all further simulation stages, especially while developing efficient HAPS offloading strategies.

Finally, tables 3.1 and 3.2 report the **mean** value and **standard deviation** of total traffic volume and total energy consumption per each site of the dataset.

	Site 1	**Site 3**	**Site 4**	**Site 6**	**Site 7**	**Site 8**	**Site 9**
Mean (μ)	59.98	235.25	408.20	57.03	927.29	359.38	219.20
Std. Dev. (σ)	25.93	106.64	155.31	31.68	355.87	158.71	105.15

Table 3.1: Mean and std. dev. of total traffic volume (Gbit).

	Site 1	**Site 3**	**Site 4**	**Site 6**	**Site 7**	**Site 8**	**Site 9**
Mean (μ)	780.28	905.69	1368.58	464.83	1739.52	1933.13	1338.42
Std. Dev. (σ)	92.44	116.21	229.03	46.71	250.73	258.01	165.81

Table 3.2: Mean and std. dev. of total energy consumption (Wh).

The tables confirm the trend depicted in figures 3.6 and 3.9, showing relevant values of standard deviation for traffic volumes, this is due to the sensitive fluctuations of such parameter between night and day.
Analyzing the tables, it is confirmed that base stations with greater traffic volumes do not always correspond to the ones with the highest power consumption.

3.3 HAPS modelling

A crucial component of the scenario described in section 3.1 is the **High Altitude Platform Station**. The HAPS had to be correctly modeled and set up in order to perform simulations in a coherent and plausible manner.
The aerial platform is equipped with a full set of high-efficiency **PV panels**, which constantly ensure the satisfaction of the station's energy demand. Therefore, from the energetic point of view, the aerial station is to be retained completely **autonomous**, and thus it does not require any sort of additional power supply.

On second hand, it was necessary to implement a realistic and coherent model to compute the HAPS's **total capacity**. Such model was retrieved from [30], therefore the overall HAPS capacity was calculated according to the following scheme.
As partly described in section 2.3.2, the capacity model exposed in [30] exploits the well known Shannon-Hartley theorem, according to which the capacity C of **one HAPS-mounted BS** can be computed as:

$$C = B\log_2(1 + SNR) \tag{3.7}$$

where B is the **bandwidth** and SNR is the Signal-to-Noise Ratio.
The SNR can be retrieved as:

$$SNR = \frac{P_{RX}}{N_P} \tag{3.8}$$

with P_{RX} representing the received power and N_P the noise power.
Furthermore, P_{RX} can be found through the following expression:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - PL \tag{3.9}$$

where P_{TX} is the transmitted power, G_{TX} and G_{RX} are the transmitter and receiver antenna gains respectively and PL represents the total path loss.
The trasmitter gain G_{TX} is assumed to be computable as:

$$G_{TX} = G_{element} + 10\log(n \times m) \tag{3.10}$$

where $G_{element}$ is the gain of a single element of the antenna array, while n and m are, respectively, the number of rows and columns of the array.
The total path loss PL is then found through the following equation:

$$PL = PL_B + PL_E \tag{3.11}$$

where PL_B is the basic path loss and PL_E is the building entry loss.
PL_B is thus computed through a set of random variables also depending on the distance between HAPS and the ground, the BS operational frequency and the elevation angle. On the other hand, PL_E strictly depends on building type, the building location and the user movement within the building. An important point to specify is that in the modelling process, two types of building are considered, namely:

- thermally efficient buildings;
- traditional buildings.

With the second type causing higher entry loss with respect to the first one.
Finally, the **total HAPS capacity** is computed taking into account the number of BSs (N_{BS}) the HAPS is equipped with, according to the following expression:

$$C_{tot} = N_{BS} \times C \tag{3.12}$$

Since the final overall capacity is expressed in *bit/s*, unit of measurement of **data rates**, thus the total volume of traffic that can be offloaded to the HAPS within an hour of time is computed as follows:

$$V_{offload}^{max} = 3600 \times C_{tot} \tag{3.13}$$

where 3600 is the number of seconds per hour.
For our study, the number of BSs aboard the HAPS (N_{BS}) was set equal to 3, resulting in a **total HAPS offloading capacity** of **2.26 Tbit**.

3.4 Ground BS battery model

In order to correctly simulate the BSs behaviour in terms of energy management, it was necessary to develop an efficient **back-up battery model** and coherently integrate it into the simulator.
In the analyzed scenario, **lead-acid batteries** were considered for energy storage. Such type of battery is rechargeable and, despite its relatively low energy density, is able of supplying high surge currents [45]. These characteristics, together with their relatively low cost, make lead-acid batteries an undoubtedly valid solution when it comes to provide a back-up power supply for terrestrial base stations.

Figure 3.10: Lead-acid battery.

The parameters used to model the battery units were set according to [46], and are reported as follows:

- **Capacity**: 200 Ah
- **Voltage**: 12 V

The battery as a whole was modeled through the following parameters of interest:

- **Storage capacity** (i.e. number of battery units): 6
- **Depth of Discharge (DoD)**: 70% (i.e. 0.7)
- **Loss** due to discharging process: 15% (i.e. 0.15)

The battery model was developed to correctly manage **discharging** operations coherently with the time-varying energy consumption. In particular, it is designed to update its charge level every hour, using as input the **energy consumed** (E_c).

As previously mentioned, the discharging process is affected by a **loss** (L). As a consequence, the battery level at hour t ($BL(t)$) is computed as follows:

$$BL(t) = \max(0, BL(t-1) - \frac{E_c(t)}{(1-L)}) \tag{3.14}$$

The **consumed energy** (E_c) is computed with a time granularity of 1 hour according to expression 3.6. In normal operational conditions, such energy demand is always satisfied by the **power grid**, which continuously provides energy supply to every ground BS.
As already described in section 3.1, the back-up batteries are exploited in emergency scenarios, when the power grid is not available. The objective of such energy storage systems is to make it possible for ground BSs to keep ensuring sufficient QoS to the users during critical situations.

3.5 Key Performance Indicators

A crucial step of every simulation-related study is certainly the definition of **Key Performance Indicators (KPIs)**.
KPIs are defined as indicators expressly designed to evaluate the success of an activity, such as projects and analyses. They are meant to provide help to the operators in the decision-making process and also in the evaluation of an activity's outcomes.
The KPI should always be determined according to the so-called SMART criteria. The acronym SMART is described as follows [44]:

- The measure described by the KPI must have a **S**pecific purpose.
- The considered data should be **M**easurable.
- The defined norms should be **A**chievable.
- The improvement of a KPI should be **R**elevant for the success of the study.
- The measure has to be **T**ime phased, resulting in the outcomes being shown for a predefined and relevant period.

For the analysis described in the present document, three main KPIs were computed and exploited to evaluate the performance of the developed HO strategies. As the ultimate aim of the project was to develop smart algorithms to enhance the autonomy of ground BS during power shortages, the KPIs had to be eventually related to both traffic demand and power consumption.
The defined Key Performance Indicators are thus described as follows:

1. **Battery duration**.
   This parameter is of particular relevance because of its close correlation with the objective of the study. The battery duration is intended as the time period of autonomy of a BS's back-up battery during a period of power shortage. Such parameter can be enhanced (i.e. increased) through a smart utilization of HAPS Offloading.

2. **Traffic volume** managed by the HAPS and the ground BSs.
   Such parameter is rather relevant, and its importance is given by the fact that it provides a clear indication of the Quality of Service delivered to the users during the emergency period. In other words, making sure that the entire traffic demand is correctly managed by either the HAPS and the ground BSs is a crucial step to assure a satisfying QoS level to the end-users.

3. **Offloading ratio**.

   The Offloading Ratio (OR) for base station i at time t is defined as:

   $$OR^i(t) = \frac{V^i_{offloaded}(t)}{V^i_{tot}(t)} \tag{3.15}$$

   where $V^i_{offloaded}(t)$ is the volume of traffic offloaded by base station i to the HAPS at time t and $V^i_{tot}(t)$ is the total traffic demand of BS i at such time instant.
   The OR parameter is always comprised in a 0 to 1 range and it is fundamental in evaluating the impact of HAPS Offloading in the satisfaction of traffic demand during the period of emergency. For instance, a OR value of 0 indicates that no traffic was offloaded to the HAPS, while a OR of 1 corresponds to the offloading of the entire traffic demand to the HAPS, with the ground BS consequently standing by.

Chapter 4

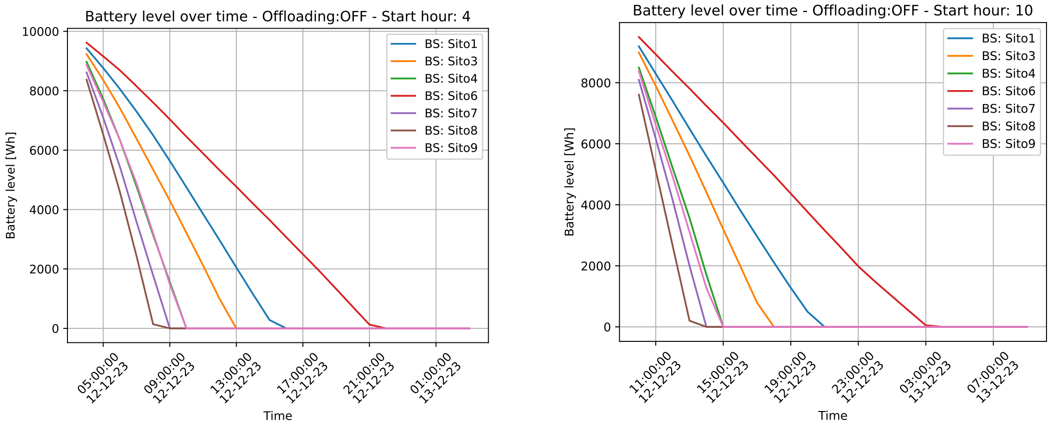
Results

The present chapter is going to expose in a detailed way the most significant results achieved during the study and the outcomes of the most relevant tests that were performed.
As already exposed in chapter 3, the core of the study was to explore a set of different and variegate **traffic offloading strategies** with the aim of mitigating the traffic load on terrestrial BSs during emergency power grid outages. As previously exposed, in the case of such power outages, the BSs can only rely on their **back-up batteries**, thus having limited energetic autonomy. In such conditions, traffic is meant to be partly offloaded on the aerial platform to reduce the ground BSs' energy consumption and therefore increasing their autonomy while still delivering a satisfying QoS level to the users.
Within the following sections, several offloading strategies are going to be described, along with the results achieved through their implementation.
In order to correctly evaluate the obtained outcomes, however, it was necessary to perform a first crucial step, determining a **baseline** for what concerns the autonomy of ground BSs **without any type of HAPS offloading**. Indeed, only relying on back-up batteries for emergency autonomy is the method currently applied in modern RANs.

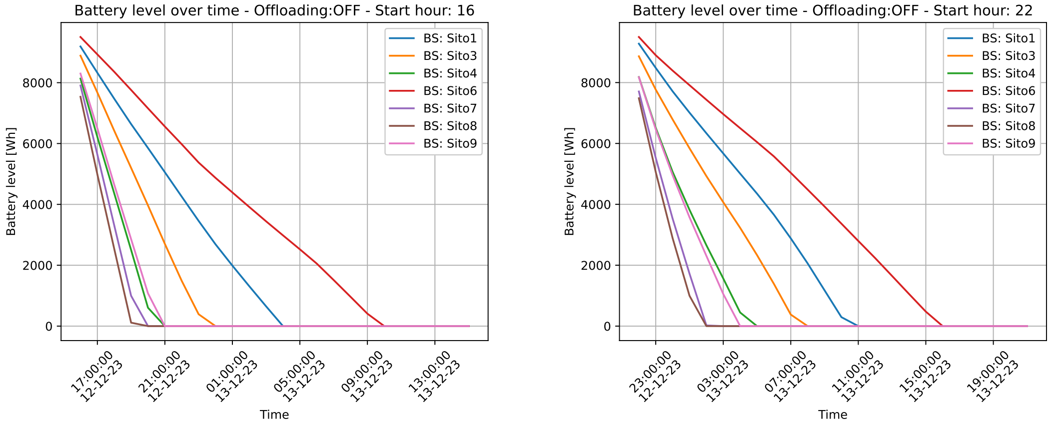
4.1 Baseline

In the case of our study, the baseline is represented by the time duration of terrestrial BSs' back-up batteries in the case of a critical scenario such as a blackout. Such time duration need to be first computed in absence of any kind of traffic offloading strategy, thus leaving the entire volume of traffic demand to be entirely handled by the Base Stations.
Since the traffic demand is subject to sensitive variations and fluctuations over

different hours of the day, as depicted in figure 3.6, the baseline autonomy of each ground BSs needed to be determined in several periods of the day.
Figure 4.1 shows the battery level of all 7 BSs over a time period of 24 hours. The simulations were performed considering a continuous 1-day long blackout, and during such period of time the terrestrial BSs were tasked to operate without the exploitation of HAPS offloading. The four simulations were performed starting at different hours, at 04:00, 10:00, 16:00 and 22:00. Four plots are coherently used to show the results for every starting hour.
Given these premises, such plots provide a clear indication of the **autonomy** of each ground BS in critical circumstances and without reckoning on any offloading strategy.



(a) 04:00 **(b)** 10:00



(c) 16:00 **(d)** 22:00

Figure 4.1: Battery levels over time without HAPS Offloading. Different starting hours.

Table 4.1 reports the battery duration (expressed in hours) for each one of the considered ground BSs and for every starting hour of the day. Therefore, these results need to be taken into account as a valid starting point for further enhancements involving the usage of HAPS offloading.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
04:00	12	9	6	18	5	5	6
10:00	11	8	5	18	4	4	5
16:00	12	8	5	18	4	4	5
22:00	13	10	7	18	5	4	6

Table 4.1: Back-up batteries autonomy (hours) without HAPS offloading.

Analyzing both figure 4.1 and table 4.1, it appears clear that the autonomy of ground BSs is closely correlated with the hour at which the blackout begins. Indeed, the overall best autonomy values are obtained in the case of a blackout starting at 22:00 (figure 4.1d), since the traffic demand during the nighttime is generally smaller than during the day hours (as confirmed by the trend depicted in figure 3.6). As a logical consequence, the autonomy data measured in the case of a blackout starting at 10:00 (figure 4.1b) are reported to be the least satisfying, due to the sensitive increase of demand registered during the day.

The results so far illustrated and described are going to be exploited in following sections as a solid and accountable baseline to perform a valid evaluation on the performance of single offloading strategies.

4.2 Technology-wise strategies

As described in section 3.2, the dataset entries concerning traffic volumes always specify the **technology** and **cell** of reference. Those two factors, combined together, provide the considered **sector**. It comes as a consequence that all the strategies need to operate a wise exploitation of sectors and technologies while implementing efficient schemes of offloading traffic to the HAPS.
The strategies about to be exposed concentrate on dividing and offloading traffic according to the different technologies, and thus they can be labeled as **technology-wise**.

4.2.1 Strategy n.1

Strategy n.1 manages traffic offloading timestep by timestep, with a time granularity of **1 hour**, in line with the samples from the considered dataset (section 3.2).

In this peculiar case, ground BSs perform HO one by one in a **round-robin** fashion. The order followed by the BSs is arbitrarily set by the user.
The terrestrial BSs only offload the traffic relative to just **one technology**, and the technologies that every BS must offload are specified and fixed *a priori* by the user.
For the tests whose results are about to be exposed, the technologies to offload are reported in table 4.2.

Site	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
Technology	LTE800	LTE2100	LTE700	LTE2100	LTE2100	LTE2100	NR3700

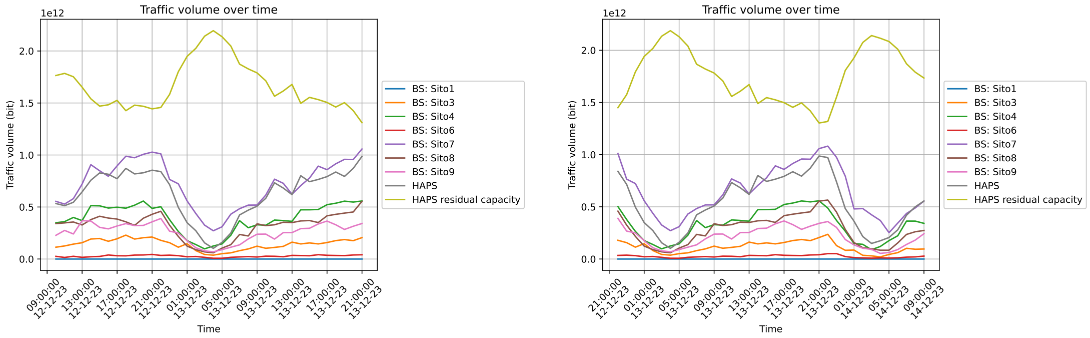
Table 4.2: Strategy n.1: technology offloaded per ground BSs.

In addition, the BSs priority order was arbitrarily set to the one reported in table 4.3.

Site	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
Position	1	2	3	4	5	6	7

Table 4.3: Strategy n.1: BSs priority order.

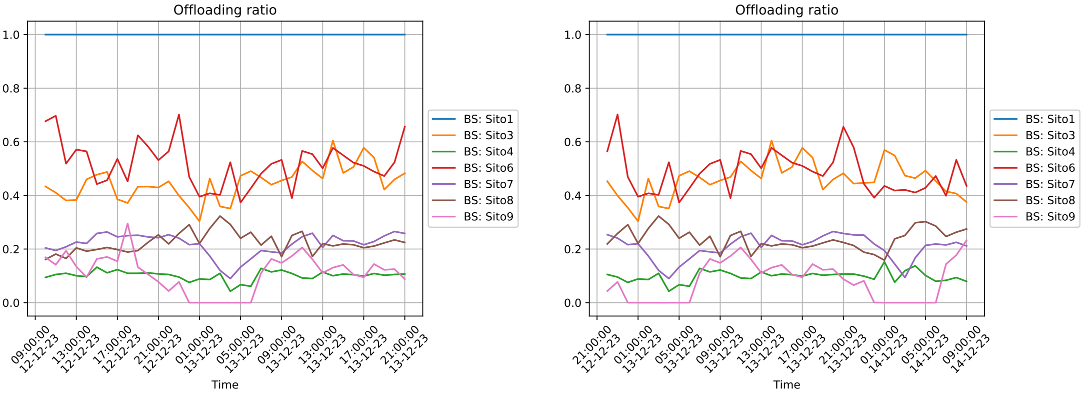
Two **36-hour long** simulations were run, one starting at hour 10:00, the other at 22:00. The achieved results are reported in figures 4.2, 4.3 and 4.4. In particular, figure 4.2 depicts the **traffic volumes** handled by the ground BSs and the HAPS at any time instant, in addition to the HAPS channel's residual capacity. Figure 4.3 shows the trend of the **offloading ratio** over time. In conclusion, figure 4.4 reports the battery level of every ground BS over the simulation time.



(a) 10:00.

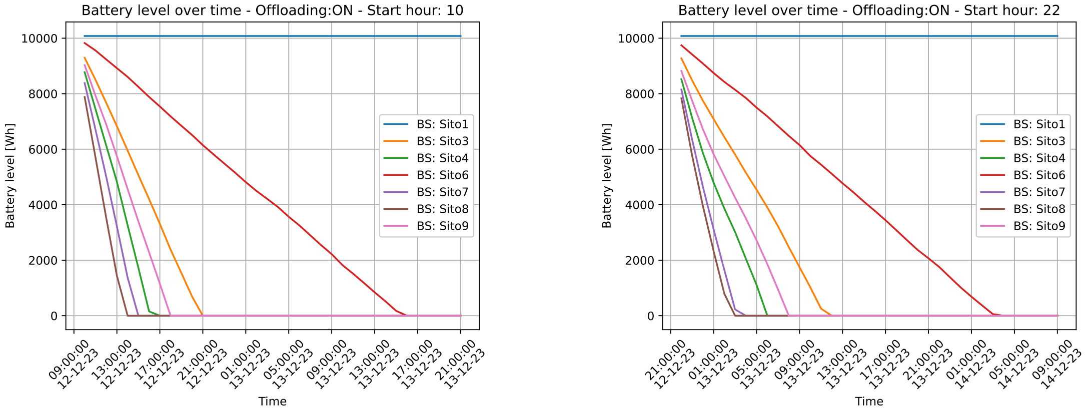
(b) 22:00

Figure 4.2: Strategy n.1: traffic volume managed by HAPS and ground BSs over time.



(a) 10:00. **(b)** 22:00

Figure 4.3: Strategy n.1: offloading ratios over time.



(a) 10:00. **(b)** 22:00

Figure 4.4: Strategy n.1: ground BSs battery level over time.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	36	11	7	30	5	4	8
22:00	36	14	8	30	6	5	10

Table 4.4: Strategy n.1: back-up batteries autonomy (hours).

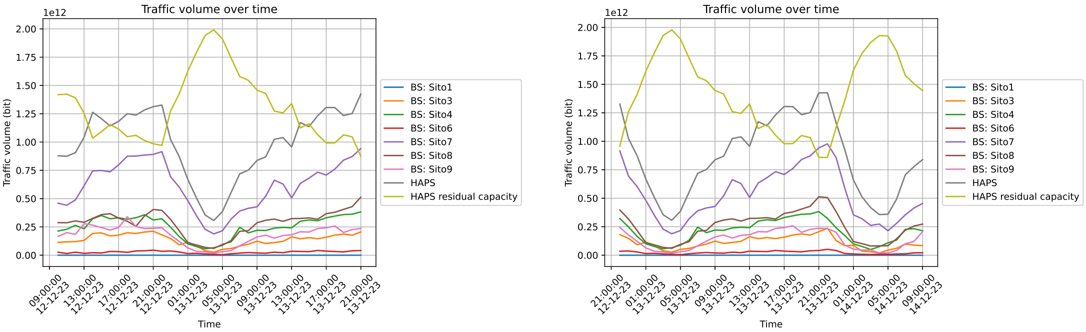
Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	25	3	2	12	0	1	3
22:00	23	4	1	12	1	1	4

Table 4.5: Strategy n.1: autonomy enhancement w.r.t. baseline (hours).

Finally, the terrestrial BSs autonomy is reported in table 4.4, and the autonomy enhancements measured in hours are reported in table 4.5. Although strategy n.1 assures sensitively increased autonomy up to 25 hours (table 4.5) for the ground BSs, it still highlights some critical problems to tackle. The most relevant encountered issue are the heterogeneous benefits that the different BSs obtain by applying the strategy. Indeed, *Site 1*, only having one technology to handle (i.e. LTE 800 MHz, as shown in figure 3.8a), always results in offloading the entire amount of traffic to the HAPS, preserving its batteries from whatsoever power consumption.
In conclusion, strategy n.1 tends to favor BSs with a smaller number of technologies to manage, as they also typically have smaller quantities of traffic to handle.

4.2.2 Strategy n.2

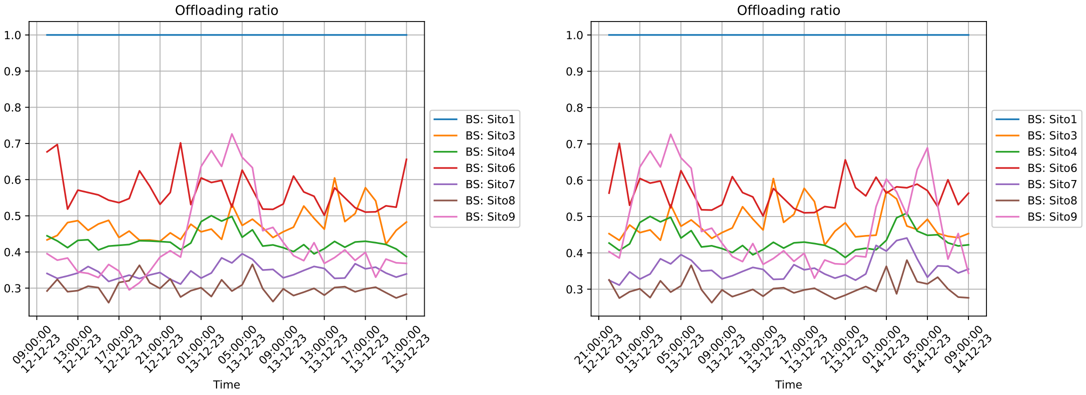
Strategy n.2 aims at improving the previous technology-wise strategy by taking into account the traffic volumes referred to each technology at any time instant.
In particular, strategy n.2 implements the same round-robin scheme as the previous strategy, as well as the BSs offloading priority order. Nevertheless, at any timestep, each BS performs the offloading of the technology showing the **greatest traffic volume** at that timestep. Therefore, in this case, the technologies to offload are not fixed anymore, but **dynamically selected**.
Similarly to what has been described in section 4.2.1, two 36-hour long simulations were run, starting at 10:00 and 22:00. The BSs priority order was also arbitrarily set according to table 4.3.
The results achieved by strategy n.2 are reported in figures 4.5, 4.6 and 4.7.



(a) 10:00.

(b) 22:00

Figure 4.5: Strategy n.2: traffic volume managed by HAPS and ground BSs over time.



(a) 10:00.

(b) 22:00

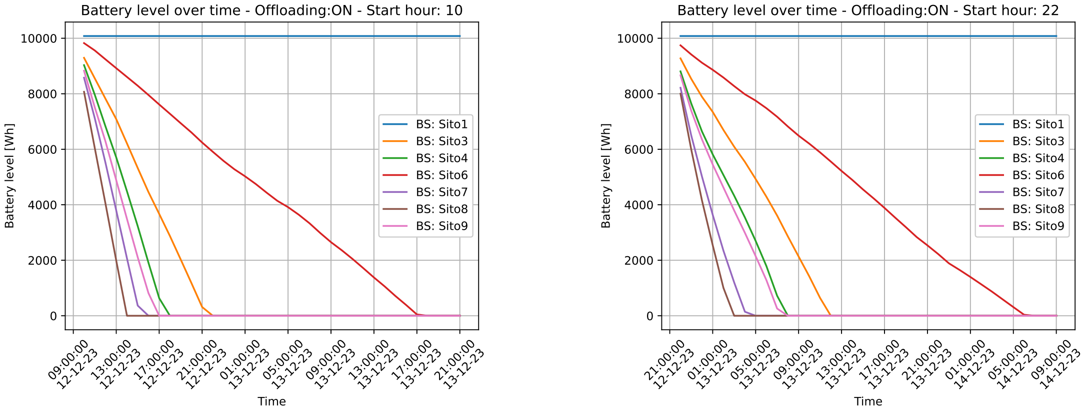
Figure 4.6: Strategy n.2: offloading ratios over time.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	36	12	8	32	6	4	7
22:00	36	14	10	33	7	5	10

Table 4.6: Strategy n.2: back-up batteries autonomy (hours).

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	25	4	3	14	2	0	2
22:00	23	4	3	15	2	1	4

Table 4.7: Strategy n.2: autonomy enhancement w.r.t. baseline (hours).



(a) 10:00. **(b)** 22:00

Figure 4.7: Strategy n.2: ground BSs battery level over time.

The terrestrial BSs autonomy is reported in table 4.6, while the autonomy enhancements are shown in table 4.7.
Overall, strategy n.2 achieves a slightly better performance with respect to strategy n.1. Figure 4.5 clearly depicts a smarter exploitation of HAPS capacity with respect to the one shown in figure 4.2. Indeed, a sensitively smaller portion of the HAPS channel's capacity is left unexploited at any hour.
Table 4.6 reports autonomy data which highlight a limited enhancement of the ones achieved by strategy n.2.
Nonetheless, the results still appear to be affected by some issues, reported as follows.

- Ground BSs managing a smaller number of technologies are still advantaged with respect to the others.
- A big portion of the total HAPS offloading capacity is still remaining unused.
- Greater volumes of traffic do not always correspond to greater power consumption.

In conclusion, the considerations yet exposed underline the need for smarter strategies, able to provide greater power savings and saturation of the HAPS channel.

4.3 Sector-wise strategies

In contrast to technology-wise strategies, sector-wise strategies focus on dividing and offloading traffic volumes based on their belonging **sectors**.
Since traffic volumes are sensitively smaller when aggregated by sector instead of technology, the main advantage of sector-wise strategies consist in the fact that each turn in a round-robin scheme allows the current BS to only offload a limited part of the overall traffic. The resulting round-robin scheme is more **dynamic** and it eventually allows a better exploitation of the HAPS channel capacity.

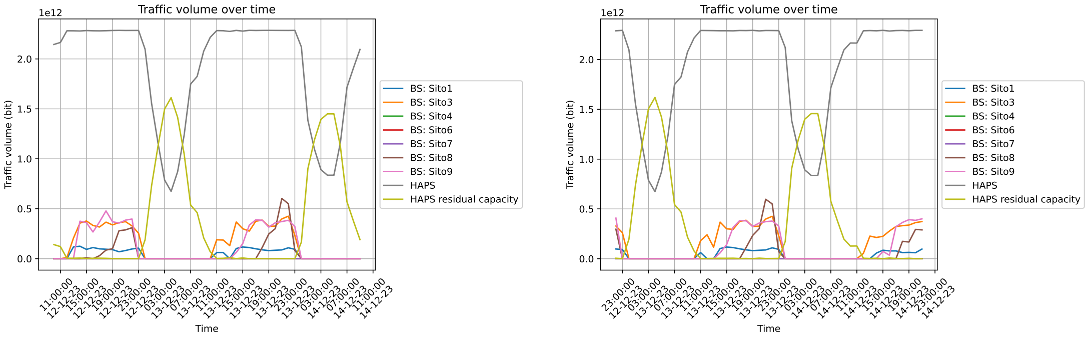
4.3.1 Strategy n.3

Applying strategy n.3, the terrestrial BSs operate offloading in a **round-robin** scheme, according to a priority order previously set by the user.
Each BS offloads the traffic relative to one sector at the time, before passing the turn to the next BS in the priority order.
The offloading procedure is operated at every timestep, and it comes to an end whenever the HAPS total capacity is **saturated**, and thus there is not sufficient capacity to offload any other amount of traffic.
In order to assess the performance achieved by this strategy, two 48-hour long simulations were run, one starting and 10:00 and the other at 22:00. The BSs priority order was arbitrarily set according to table 4.8.

Site	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
Position	3	4	5	6	7	1	2

Table 4.8: Strategy n.3: BSs priority order.

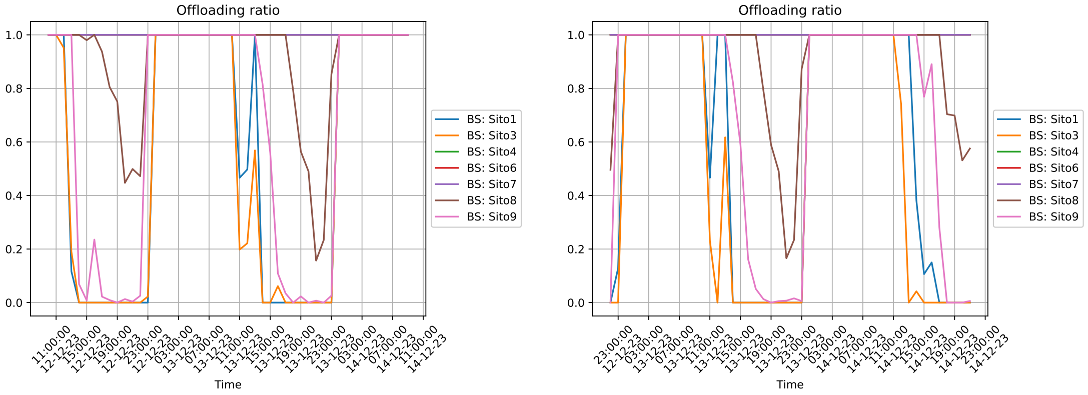
The achieved results are coherently depicted in figures 4.8, 4.9 and 4.10. Finally, the ground BSs autonomy data are shown in tables 4.9 and 4.10.



(a) 10:00.

(b) 22:00

Figure 4.8: Strategy n.3: traffic volume managed by HAPS and ground BSs over time.

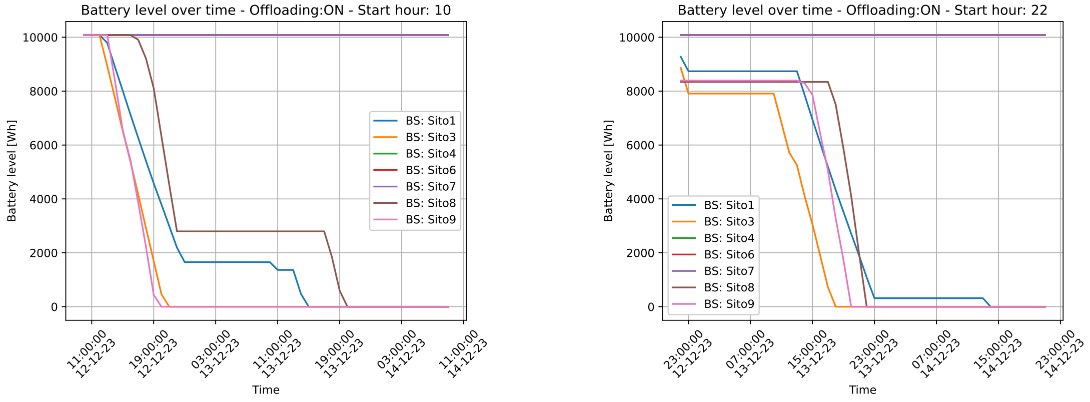


(a) 10:00.

(b) 22:00

Figure 4.9: Strategy n.3: offloading ratios over time.

Figure 4.8, in particular, clearly highlights a better exploitation of the whole HAPS channel's capacity, with respect to the previously discussed technology-wise offloading strategies (section 4.2). Indeed, the HAPS residual capacity reaches the zero value during the hours of the day characterized by greater traffic demand. This trend is coherently confirmed by the offloading ratio values reported in figure 4.9, showing values of OR equal to 1 over a considerable time span for some of the BSs.



(a) 10:00.

(b) 22:00

Figure 4.10: Strategy n.3: ground BSs battery level over time.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	29	11	48	48	48	34	10
22:00	40	20	48	48	48	24	22

Table 4.9: Strategy n.3: back-up batteries autonomy (hours).

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	18	3	43	30	44	30	5
22:00	27	10	41	30	43	20	16

Table 4.10: Strategy n.3: autonomy enhancement w.r.t. baseline (hours).

The autonomy data reported in figure 4.10 and table 4.9 are undoubtedly satisfying, with great part of the ground BSs managing to completely offload their traffic to the HAPS, thus preserving their back-up batteries from any loss.
Nevertheless, these results highlight a critical issue, namely the impact that the BSs priority order has on the autonomy of the BSs themselves. The last BSs in the order are, in fact, strongly disadvantaged with respect to the first ones, since they can only rely on smaller values of residual HAPS capacity. In fact, the first BS in the priority order (i.e. *Site 3*), at the beginning of every timestep, can exploit the entire HAPS channel's capacity, equal to 2.26 Tbit (see section 3.3), while the residual capacity exploitable by the last BS in the order (i.e. *Site 2*) can reach minimum values of only 60.41 Mbit.
This phenomenon results in the strategy's performance being highly conditioned by

the BSs priority order, which therefore needs to be set according to a **well defined criterion**, instead of being arbitrarily chosen *a priori*.

4.3.2 Strategy n.3 with optimized BSs priority order

As specified in the previous section, one fundamental factor, which affects the performance of sector-wise strategies, is the **BSs priority order**. The results previously exposed have, in fact, highlighted the need to define such order on the base of a smart and efficient criterion.
In order to further improve the results achieved by strategy n.3, the adopted solution was to take into account the **maximum transmission power** of each ground BS.
Indeed, as already specified in section 3.2, in addition to the main dataset concerning traffic data, we also had at our disposal for the study a specific file containing the data of maximum transmission power for each cell and technology of every individual BSs.
Therefore, the developed idea was to compute the total maximum transmission power (P_{tot}^{TX}) for every BS according to equation 4.1.

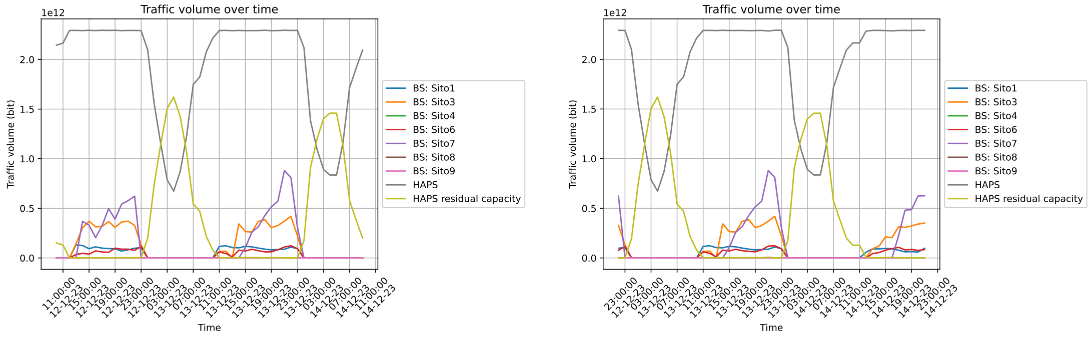
$$P_{tot}^{TX} = \sum_{s=1}^{N_s} P_s^{TX} \tag{4.1}$$

where P_s^{TX} is the maximum transmission power referred to sector s, and N_s is the number of sectors covered by the considered BS.
The BSs were then placed in order of decreasing P_{tot}^{TX}. The final result was the **optimized BSs priority order** reported in table 4.11.

Site	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
Position	7	3	6	5	2	4	1

Table 4.11: Optimized BSs priority order.

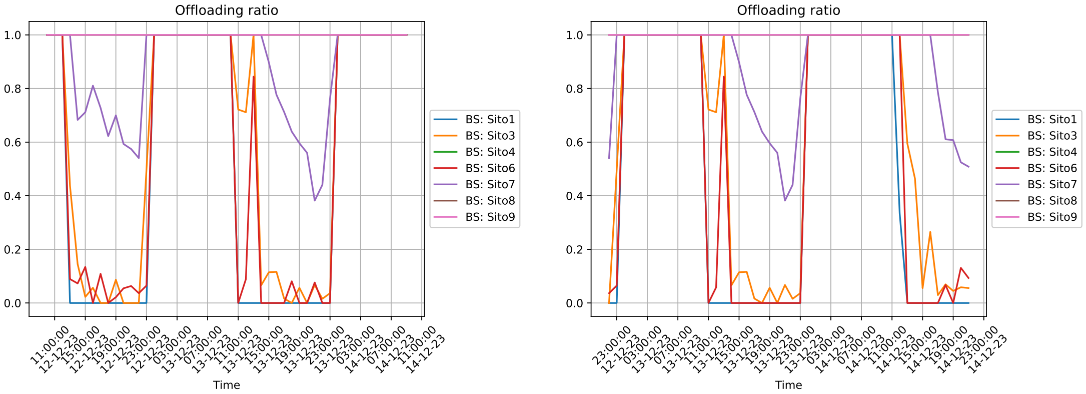
The applied method comes with the aim of giving offloading priority to those BSs which are characterized by higher transmission powers and thus by higher power consumption. Indeed, by advantaging such BSs with respect to the ones with lower power transmission, the expected result is to partly **fill the gap** in the different BSs' autonomy, which was one of the major problems described in section 4.3.1.
Results achieved by strategy n.3, with an optimized BSs priority order, are depicted in figures 4.11, 4.12 and 4.13. Autonomy of ground BSs measured in hours is coherently shown in table 4.12.



(a) 10:00. **(b)** 22:00

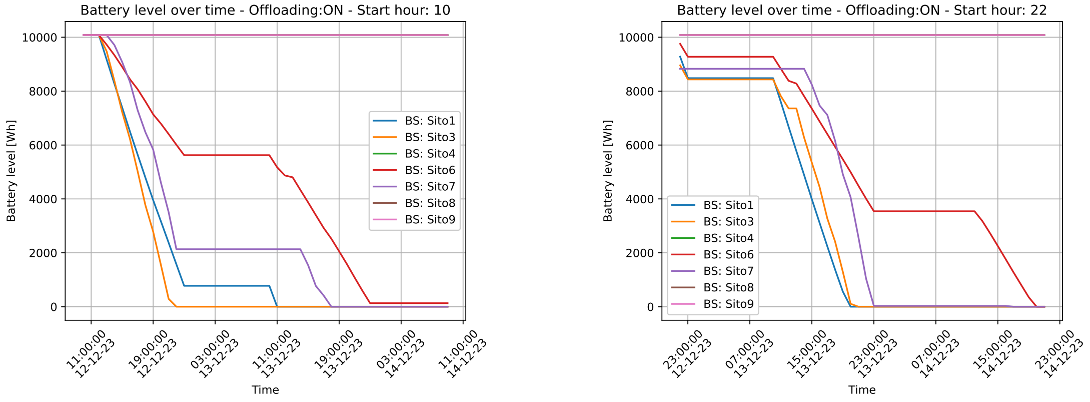
Figure 4.11: Optimized strategy n.3: traffic volume managed by HAPS and ground BSs over time.

Looking at figure 4.11, it is not possible to spot a clear difference in trend with respect to the one depicted in figure 4.8. At the same time, figures 4.9 and 4.12 show similar trends as well. This is due to the fact that a change in the priority order of BSs does not directly affect the volumes of offloaded traffic.
Instead, what is clearly affected by such order change are the possibilities of offloading given to the different BSs. Therefore, the new optimized strategy positively impacts on the autonomy of the terrestrial BSs, increased by up to 1100% with respect to the baseline (in the case of *Site 8*), as confirmed by figure 4.13 and tables 4.12 and 4.13.



(a) 10:00. **(b)** 22:00

Figure 4.12: Optimized strategy n.3: offloading ratios over time.



(a) 10:00.

(b) 22:00

Figure 4.13: Optimized strategy n.3: ground BSs battery level over time.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	25	12	48	48	32	48	48
22:00	22	23	48	46	43	48	48

Table 4.12: Optimized strategy n.3: back-up batteries autonomy (hours).

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	14	4	43	30	28	44	43
22:00	9	13	41	28	38	44	42

Table 4.13: Optimized strategy n.3: autonomy enhancement w.r.t. baseline (hours).

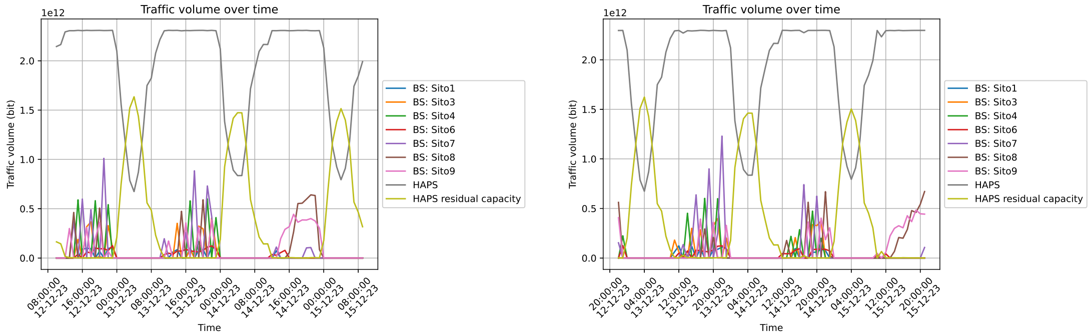
Overall, the performance of optimized strategy n.3 can be considered satisfying, with great part of the BSs efficiently managing to preserve their batteries during the whole duration of the simulation. The autonomy of ground BSs is sensitively enhanced with respect to basic strategy n.3.
Nevertheless, the last BSs in the priority order still tend to be disadvantaged with respect to the first ones. This results in some BSs, namely *Site 1* and *Site 3*, running out of power relatively early with respect to the others.
This issue, together with the results of all the strategies described so far, leads to the conclusion that using a **fixed** BSs offloading priority order is indeed successful in ensuring a BS autonomy improvement with respect to the baseline. However, it may not be the most suitable choice when it comes to ensure a fair and equal treatment to all the BSs.

4.4 Dynamical BSs priority order

This section is going to expose the offloading strategies involving the usage of a **dynamic BSs priority order**.
In particular, the strategies yet to be described are designed to determine an *ad-hoc* priority order every hour, in order to dynamically adapt to the circumstances while taking into account different parameters, including the different BSs' battery level.

4.4.1 Strategy n.4

Strategy n.4 is designed to **dynamically** adapt the offloading priority order **every hour**, focusing on the batteries charge levels of the BSs.
In this case, offloading priority is given to those BSs which report **lower charge levels**. In fact, since the traffic offloading procedure allows a sensitive reduction in power consumption, it can undoubtedly be exploited by those BSs whose battery levels are the most critical.
To test the performance of such strategy, two **72-hour long** simulations were run, one programmed to start at 10:00 and the other at 22:00.
Results are reported as follows.



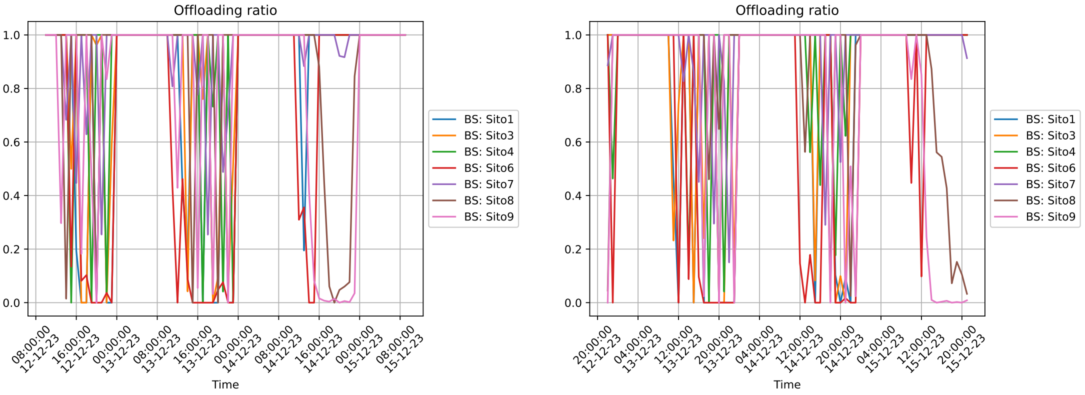
(a) 10:00.

(b) 22:00

Figure 4.14: Strategy n.4: traffic volume managed by HAPS and ground BSs over time.

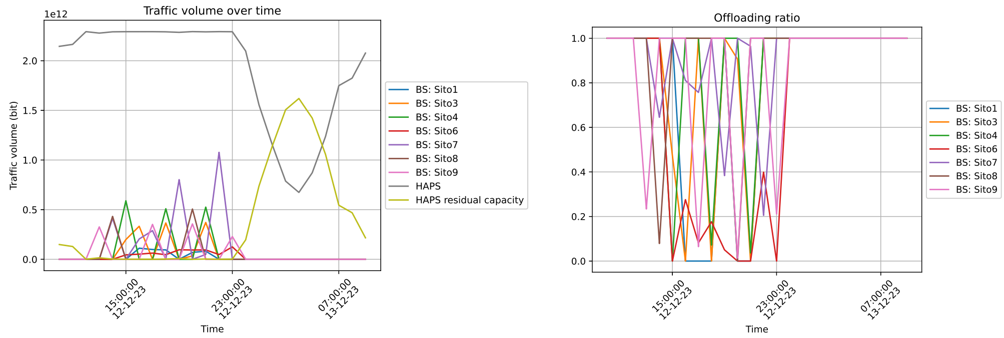
Figures 4.14 and 4.15 clearly show a more efficient and dynamic exploitation of the HAPS channel's capacity. Since the priority order gets updated one time per hour, the BSs get the opportunity to offload bigger volumes of traffic according to their residual battery level. In fact, the BS reporting the lowest charge level has the entire HAPS channel's capacity (i.e. 2.26 Tbit) at its disposal, while the residual capacity available for the highest-battery-level BS reaches a minimum value of 42.94 Mbit. The application of such system results in the overall HAPS

capacity getting utilized in a smarter manner.
For sake of clarity, a closer look to the trend of traffic volumes and offloading ratio data is provided in figure 4.16, focusing on a time span of 24 hours only. Looking at the graphs, it is evident that the whole BSs priority mechanism is more dynamic with respect to the strategies previously exposed.



(a) 10:00. **(b)** 22:00

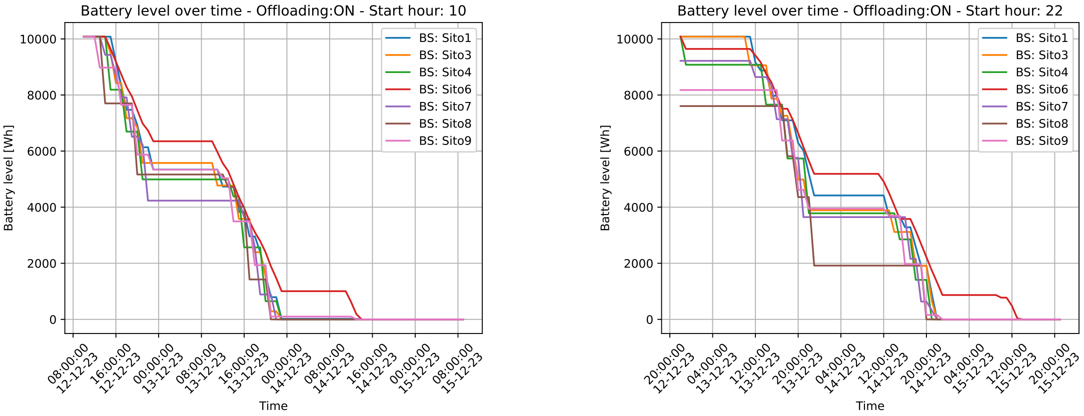
Figure 4.15: Strategy n.4: offloading ratios over time.



(a) Traffic. **(b)** Offloading ratio.

Figure 4.16: Strategy n.4 performance: a closer look.

Figure 4.17 depicts the BSs' back-up battery levels over the simulation time. The trend appears linear and there are no relevant fluctuations, indicating a fair treatment among all the BSs.
Table 4.14 confirms these observations and highlights a sensitive enhancement for what concerns the BSs' autonomy. Indeed the values of battery duration achieved by strategy n.4 are increased by up to 920% (in the case of *Site 9*) with respect to the ones measured for the baseline.



(a) 10:00. **(b)** 22:00

Figure 4.17: Strategy n.4: ground BSs battery level over time.

Starting hour	**Site 1**	**Site 3**	**Site 4**	**Site 6**	**Site 7**	**Site 8**	**Site 9**
10:00	52	37	37	52	36	35	51
22:00	48	48	47	64	48	46	49

Table 4.14: Strategy n.4: back-up batteries autonomy (hours).

Starting hour	**Site 1**	**Site 3**	**Site 4**	**Site 6**	**Site 7**	**Site 8**	**Site 9**
10:00	41	29	32	34	32	31	46
22:00	35	38	40	46	43	42	43

Table 4.15: Strategy n.4: autonomy enhancement w.r.t. baseline (hours).

In conclusion, strategy n.4, exploiting a dynamic priority order based on residual battery charge levels, have achieved performance results which are to be retained more than satisfying. In fact, it is capable of ensuring an autonomy increase up to the 920% (*Site 9*) with respect to the baseline determined in section 4.1. This results acquire even more importance if considered that they are achieved assuring a fair and similar treatment to all the involved BSs, thus avoiding excessive gaps among the different autonomy levels.

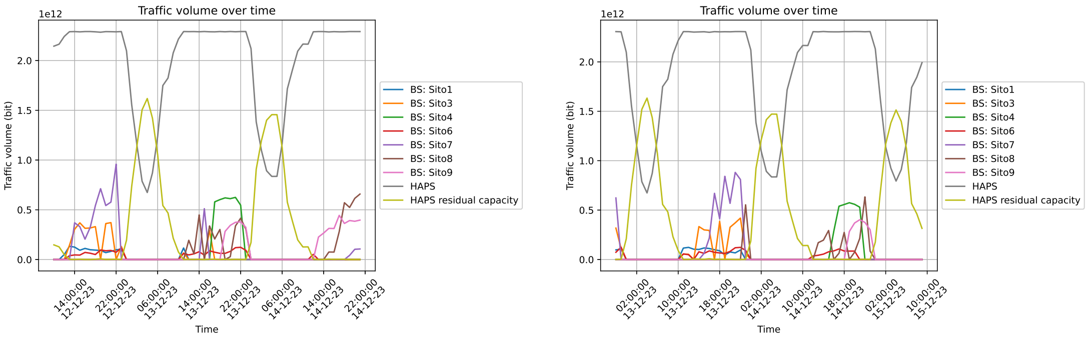
4.4.2 Strategy n.5

Strategy n.5 implements a dynamic BSs priority order similarly to the case of previous strategy, but it additionally performs a **forecasting operation**, with the

aim of estimating the residual autonomy of the various BSs.
In particular, at each timestep (i.e. 1 hour), the residual autonomy of each BS is computed exploiting both its current battery charge level and its maximum transmission power.
Equation 4.2 describes how the residual autonomy of a BS at time t ($A(t)$) is estimated:

$$A(t) = \frac{BL(t)}{P_{tot}^{TX}} \tag{4.2}$$

where $BL(t)$ is the current battery charge level, updated as in equation 3.14, and P_{tot}^{TX} is the total maximum transmission power calculated through equation 4.1. The operation's result is an estimation of the residual battery autonomy, expressed in number of hours.
According to strategy n.5, offloading priority may be given to those BSs which report shorter estimated residual battery autonomy, in order to reduce their energetic demand.
Two **60-hour long** simulations, one starting at 10:00 and the other at 22:00, were performed to assess the strategy's performance.
Results obtained through the application of such strategy are coherently shown in figures 4.18, 4.19 and 4.20, and in table 4.16 for what concerns the BSs autonomy.

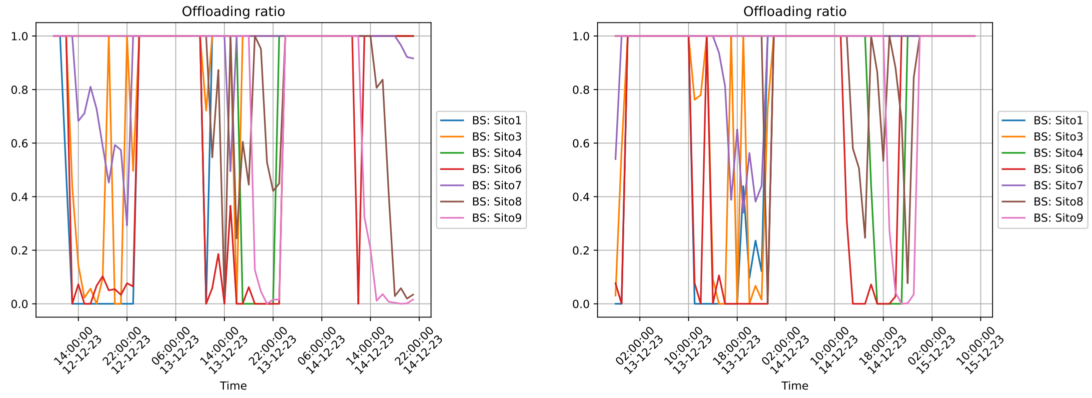


(a) 10:00.

(b) 22:00

Figure 4.18: Strategy n.5: traffic volume managed by HAPS and ground BSs over time.

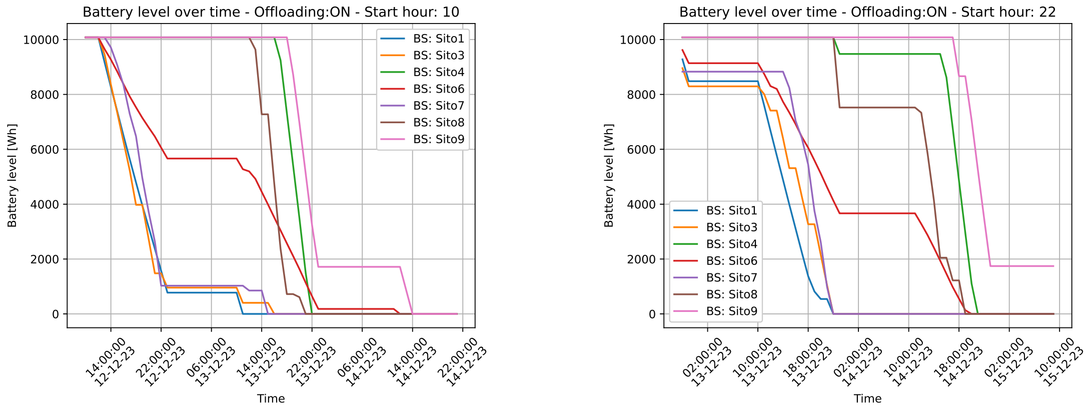
Both the plots depicted in figures 4.18 and 4.19 show trends similar to the ones observed in the case of strategy n.4, with a dynamic and fast changing allocation of offloading capacity to the different BSs. This surely indicates a more efficient exploitation of the HAPS' capacity with respect to the fixed-order strategies.



(a) 10:00. **(b)** 22:00

Figure 4.19: Strategy n.5: offloading ratios over time.

For what concerns the autonomy of BSs, the plots shown in figure 4.20, along with tables 4.16 and 4.17 report battery duration data sensitively enhanced with respect to the baseline.
Nevertheless, the decreasing trend of the different battery charge levels appears to be less linear than the one achieved by strategy n.4. In fact, it is possible to observe a clear difference in the charge trend of different BSs. This is partly due to the fact that the BSs priority order is hourly updated on the base of forecasted residual autonomy, instead of current battery level.



(a) 10:00. **(b)** 22:00

Figure 4.20: Strategy n.5: ground BSs battery level over time.

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	25	30	36	50	29	35	52
22:00	24	24	47	46	24	45	60

Table 4.16: Strategy n.5: back-up batteries autonomy (hours).

Starting hour	Site 1	Site 3	Site 4	Site 6	Site 7	Site 8	Site 9
10:00	14	22	31	32	25	31	47
22:00	11	14	40	28	16	41	54

Table 4.17: Strategy n.5: autonomy enhancement w.r.t. baseline (hours).

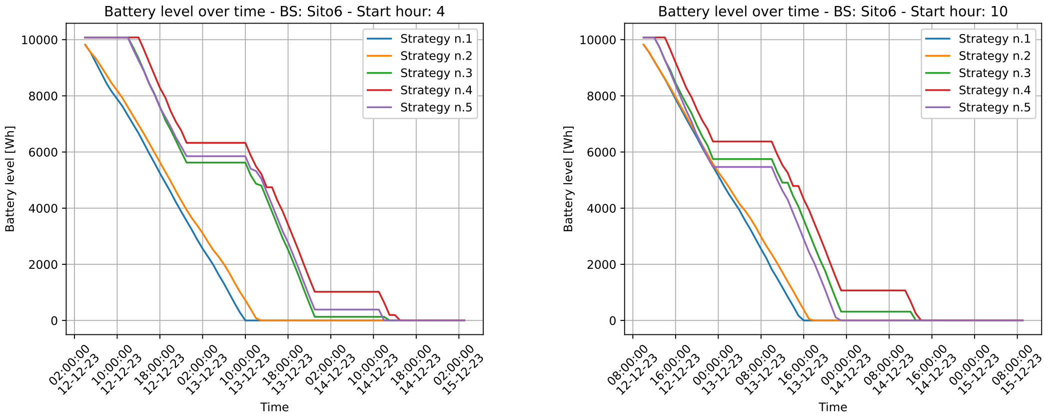
In conclusion, strategy n.5 provides satisfying results in terms of increased autonomy and exploitation of the HAPS channel's capacity. However, it does not manage to flatten the differences between the treatments delivered to different BSs.

4.5 Strategies cross-comparison

Within this last section, we are going to expose a cross-comparison among the different strategies already described, in order to determine which one is the most suitable to be implemented in a real world scenario.
To do so, the BS covering **Site 6** was chosen and its autonomy was assessed by the usage of different strategies, whose behaviours were then compared among each other.
In particular, the tested strategies are reported as follows.

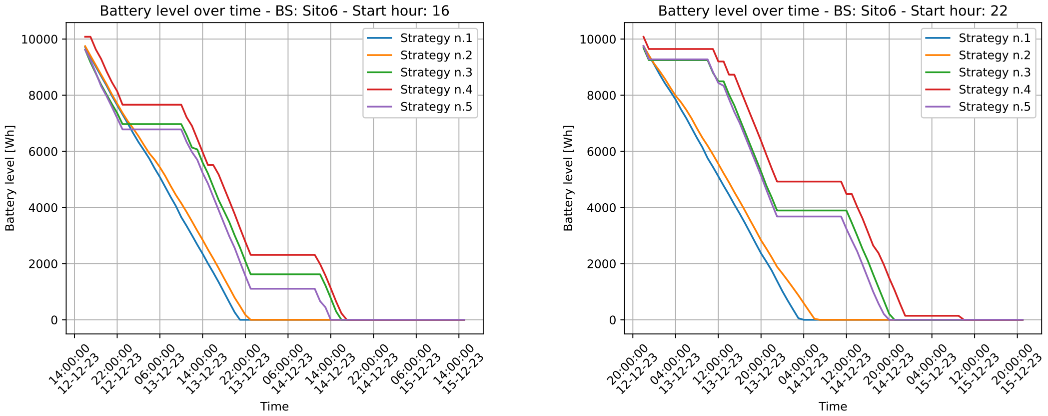
- **Strategy n.1**, where the technologies to offload for each BSs were set according to table 4.2.
- **Strategy n.2**, making every BS offload the traffic relative to the technology with the highest traffic volume at the given time instant.
- **Strategy n.3**, performing offloading of all the BSs in a round-robin scheme, letting them offload the traffic sector by sector until the HAPS channels gets saturated.
- **Strategy n.4**, introducing a dynamic BS offloading order, giving offloading priority to BSs reporting the lowest level of battery charge.
- **Strategy n.5**, utilizing a dynamic BS priority order based on the forecast residual battery autonomy of each BS.

The optimized BSs priority order reported in table 4.11, based on maximum transmission power values, was exploited for strategies n.1, n.2 and n.3.
Several simulations were performed, applying the five strategies yet listed and varying the starting hour of the day, in order to have an overlook on the strategies performance as complete as possible.
Figure 4.21 depicts the trend of *Site 6* BS's battery charge level over time. Such trends are reported for each one of the considered five strategies, and for four different starting hours of the day, in such a manner that the various differences can be easily spotted and analyzed.



(a) 04:00

(b) 10:00



(c) 16:00

(d) 22:00

Figure 4.21: *Site6* BS's autonomy - Strategy comparison.

Table 4.18 reports the **autonomy performance** of the *Site 6* BS for every strategy and different starting hours of the day. Finally, table 4.19 shows the **additional hours of autonomy** gained by the *Site 6* BS utilizing various strategies.

Starting hour	**Baseline**	**S1**	**S2**	**S3**	**S4**	**S5**
04:00	18	30	33	43	59	43
10:00	18	30	32	37	53	37
16:00	18	29	31	48	50	46
22:00	18	30	33	47	62	46

Table 4.18: *Site 6* BS's autonomy (hours) for different strategies.

Starting hour	**S1**	**S2**	**S3**	**S4**	**S5**
04:00	12	15	25	41	25
10:00	12	14	19	35	19
16:00	11	13	30	32	28
22:00	12	15	29	44	28

Table 4.19: *Site 6* BS's autonomy enhancement w.r.t baseline (hours).

Overall, **strategies n.1** and **n.2**, implementing a technology-wise offloading system, show linear discharging trends, similar to the ones observed in the case of the baseline shown in figure 4.1. However, such strategies still manage to provide a slight improvement in terms of autonomy, guaranteeing a decent number of additional hours of autonomy to the BS with respect to the case when no offloading is performed at all.
On the other hand, **strategy n.3**, exploiting a sector-wise offloading scheme with the implementation of a fixed BSs priority order, successfully enhances the results achieved by the previous two strategies. In fact, the BS's autonomy is reported to be sensitively increased after the application of such strategy, as confirmed both by the data reported in table 4.18 and the graphs depicted in figure 4.21.
Strategy n.4, with the implementation of a dynamic BSs offloading priority order, managed to further enhance the autonomy of the BS, reaching unmatched results in terms of battery charge duration. Furthermore, as coherently exposed in section 4.4.1, such strategy allows a better and more dynamic exploitation of the HAPS channel's capacity, giving a fair share of offloading capacity to each BS according to its current battery level.
Finally, **strategy n.5**, relies on a dynamic BSs priority order similar to the one exploited by the previous strategy, however it takes into account the BSs' forecasted residual autonomy, estimated using the values of maximum transmission power. Even though it eventually manages to achieve satisfying results in terms of autonomy enhancement, it still does not match the performance expressed by strategy n.4, showing smaller autonomy levels and, as described in detail in section 4.4.2, creating a gap among the BSs for what concerns the allocated offloading

capacity, thus not always assuring a fair treatment to some of them.
In conclusion, having adequately analyzed the results obtained, **strategy n.4** appears to be the most suitable one to be implemented in a real world scenario. Such strategy, in fact, can make a BS achieve a maximum of 44 additional hours of battery autonomy (table 4.19) with respect to the baseline (i.e. 62 total hours of autonomy), thus enhancing the reliability and resilience of a urban RAN during critical circumstances such as the occurrence of a blackout.

Chapter 5

Conclusions and future work

This last chapter comes with the aim of exposing the conclusions of the performed study, along with some general considerations about the effective impact the analyzed solutions can have on the management and enhancement of modern RANs. Finally, some hypotheses for future further studies and possible experimentation are going to be discussed.

5.1 Conclusions

Due to the outstanding growth that urban RANs have been experiencing during the last decade, some related issues such as energy management and traffic demand handling have become of crucial importance for the successful operation of the wireless networks themselves. Along with such factors, the reliability and resilience of RANs have assumed primary importance, due to the critical role telecommunications play in the management and operation of every technological asset, either civil or military.

Considering these premises, it appears clear that network providers, operating dense urban RANs, have developed a urgent necessity for smart and quickly deployable solutions, capable of enhancing the reliability of networks during normal operation and assure the continuous service delivery during temporary energy shortages (as in the case of large-scale blackouts), thus increasing the resilience of the networks. In this context, the solution proposed by the present document is to integrate urban RANs with HAPSs, equipped with solar panels to ensure energetic autonomy and networking hardware to operate as aerial BSs. Such solution comes with the aim of partly offloading to the HAPS the traffic normally handled by terrestrial BSs in critical conditions or emergency events, in order to elongate the autonomy of the ground BSs' back-up batteries. Such operation may be performed to maintain unaltered the service delivery to the end users, while keeping to assure a sufficient

QoS level.
The study has clearly proved that the integration of an aerial platform into a dense urban RAN can achieve satisfactory results in terms of ground BSs autonomy. In fact, several offloading strategies were explored, and their results were consequently analyzed. For every one of the considered strategies, the overall results in terms of ground BSs autonomy were all more than satisfactory with respect to the case in which no offloading is performed at all. This goes to prove that HO is, in all cases, a general enhancement of reliability and resilience of the RAN it is applied to.
In particular, promising results were obtained by the algorithm indicated as strategy n.4, which implemented a sector-wise traffic offloading mechanism, along with a dynamical BSs offloading order, designed to give priority to the BSs with the lowest residual battery charge level. Indeed, through such strategy, it was possible to achieve optimal results in terms of autonomy increase, while assuring a fair treatment among the various BSs involved in the RAN. The algorithm allowed a maximum increase of 46 hours of autonomy with respect to the considered baseline, and it successfully avoided sensitive gaps in the benefits the different BSs received by HO.
Furthermore, it was also possible to observe rather satisfactory results for strategies n.3 and n.5. Both the algorithms were based on a sector-wise traffic offloading which aimed at fully exploiting the HAPS channel's capacity. Nonetheless, while in the case of strategy n.3 the BSs would perform traffic offloading in a fixed order, strategy n.5 would dynamically give offloading priority to the BSs with the shortest residual battery autonomy (estimated for every ground BS using their battery charge level and their maximum transmission power). The two strategies respectively reported maximum values of autonomy enhancement of 44 and 54 hours with respect to the baseline. Although such data are significant in terms of autonomy increase, strategies n.3 and 5 still showed some minor issues related to the different treatments for different BSs.
The method applied by strategy n.4 to assign the offloading priority to the various BSs is based on the present level of battery charge declared by the BSs themselves. This factor clearly indicates the importance of such information (namely the current back-up batteries level) in the fair distribution of offloading capacity to the many BSs. It is no surprise, in fact, that during emergency events such as power shortages or even blackouts, the current battery level of terrestrial BSs is an information that might be always taken into account in the development of strategies targeted at keeping the whole network fully operational.
In conclusion, the study has proved that HAPSs can have a huge impact on the reliability of modern urban RANs, effectively assuring enhanced battery autonomy for all the ground BSs and therefore delivering services with satisfactory QoS even under critical conditions. HAPSs are a disruptive technology in constant evolution and it comes without saying that they are going to play a progressively more

relevant role in the future of wireless networks and telecommunications in general.

5.2 Future developments

The study yet described has set a solid starting point for further studies and analyses that may eventually be carried out in the future, in order to additionally assess the actual capabilities of HAPSs in the domain of dense urban RANs.
One critical aspect that may undoubtedly be investigated is the HAPS behavior from the point of view of energy. Indeed, since in our analysis the HAPS was always considered as energetically autonomous, it would be rather indicative to simulate and gather more precise data concerning the electricity production and consumption of HAPSs. It would be useful, in fact, to compare the estimated production of typical solar panels and the consumption of an HAPS while it is handling traffic offloaded by ground BSs. This information could surely give a better overview of the actual affordability of such solution in a real operational scenario, and help to have a better understanding of the whole system itself.
On second hand, it would be rather useful to experiment the usage of HAPSs in larger scale RANs. In fact, in the study we carried out, the simulated scenario (exposed in section 3.1) only considered a limited network with a relatively small number of ground BSs and just one HAPS to support them. Therefore, further analyses could be performed to simulate larger networks exploiting more than one HAPS. More complex offloading strategies may thus be explored, with the aim of coordinating the action of different HAPSs over a large geographical area and optimizing their joint operation to enhance the reliability of the various RANs.
Finally, it may be advisable to go beyond the simulation domain and perform some specific tests on the field, utilizing a basic HAPS-mounted cellular BS. Even though such experimentation would be undoubtedly complex to design, plan and carry out, it could provide reliable and indicative results regarding the impact of HAPS usage on RANs. Indeed, to gather real data from a real case of application could confirm and even enhance the results already achieved through software simulation.

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