Management and Content Delivery for Smart Networks: Algorithms and Modeling

Academic Year 2024-2025

L2: High Altitude Platform Stations (HAPSs) for a greener Radio Access Network (RAN) operation

Background

The rapid surge in mobile traffic demand, particularly driven by the rollout of 5G networks, presents a significant challenge for existing terrestrial Radio Access Networks (RANs). As illustrated in Figure 1, mobile data traffic is projected to nearly triple in the coming years, placing immense pressure on the current RAN infrastructure. Terrestrial RANs, composed of on-ground base stations, may struggle to meet this escalating demand efficiently and sustainably.

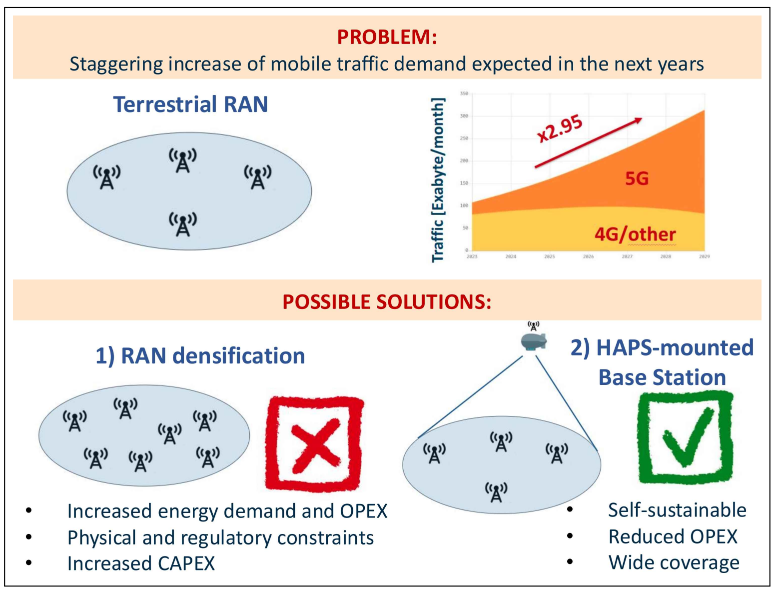


Figure 1: Possible solutions to cope with the staggering increase of mobile traffic demand.

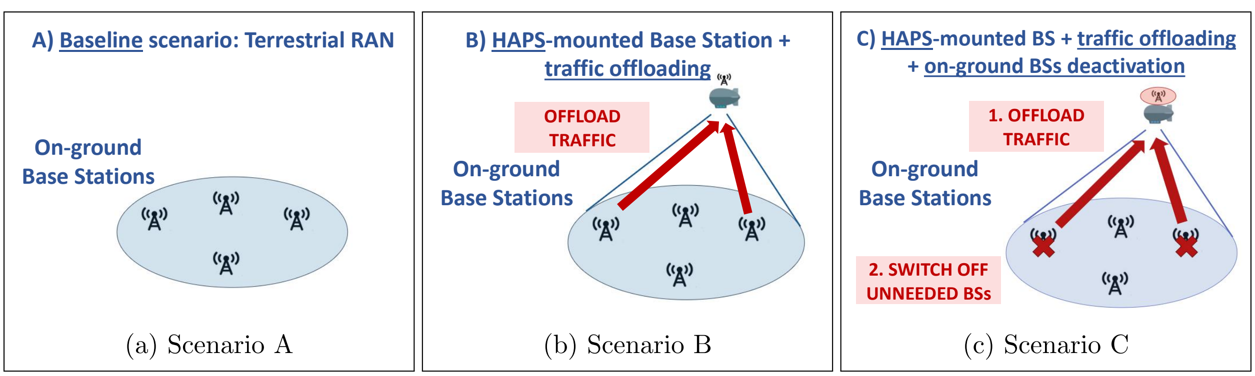
To address this issue, a widely adopted solution is represented by the RAN densification, consisting in deploying additional terrestrial base stations (BSs) to increase capacity and better handle peak demand. However, this approach leads to higher energy consumption and operational expenditures (OPEX), alongside increased capital expenditures (CAPEX) due to the installation of additional BSs. Furthermore, this BS deployment is typically dimensioned to handle peak traffic loads but remain underutilized for the majority of the time, resulting in inefficient resource usage. Finally, regulatory and physical constraints may hinder the unrestricted expansion of the terrestrial RAN infrastructure, especially in urban environments, where space and permissions are limited. In contrast, **High Altitude Platform Stations (HAPSs)** offer a promising and sustainable alternative to cope with this issue. These aerial platforms, which can be airships or aircraft operating in the stratosphere at an altitude of around 20 km, can be equipped with a base station to provide additional capacity to the terrestrial RAN. Due to their high altitude, they can cover wider areas than individual on-ground BS. Furthermore, HAPSs are fully-self-sustainable, since they are powered by renewable energy produced by photovoltaic panels installed on its surface, combined with some battery storage. This HAPS characteristic allows the HAPS-mounted BS to handle mobile traffic at no operational cost, as its operation fully relies on green energy. These benefits make HAPS very promising to provide a more scalable, sustainable and efficient solution to support the future mobile traffic landscape.

Scenarios

Consider the following incremental scenarios depicted in Figure 2:

- **Scenario A** consists of an urban area where baseline mobile coverage is provided by N terrestrial BSs, that can be modeled as a queuing system with N servers, each with a separate buffer. This **baseline scenario** representing a portion of the terrestrial RAN is shown in Figure 2a.
- On top of this, in **Scenario B**, a HAPS-mounted BS provides additional capacity over the same area covered by the N on-ground BSs, as illustrated in Figure 2b. **A fraction of the traffic demand of the terrestrial BSs can be offloaded to the HAPS** according to a defined offloading strategy, as long as the capacity of the HAPS-mounted BS is sufficient to carry all the mobile traffic transferred from the terrestrial RAN.
- Finally, in **Scenario C** (Figure 2c) we introduce the possibility to **switch off terrestrial BSs during those periods in which they do not carry any data to transmit**, since their traffic is fully offloaded to the HAPS-mounted BS, in order to save energy.

N.B. When modeling the traffic profiles and defining the capacity of the terrestrial BSs, consider that the capacity of a terrestrial BS (modeled by the average service rate) is typically overdimensioned with respect to the BS traffic demand, hence the average BS service rate results quite higher than the average traffic arrival rate. The capacity of the HAPS-mounted BS can be comparable or higher than the capacity of a terrestrial BS.



(a) Scenario A (b) Scenario B (c) Scenario C

Figure 2: Scenarios.

A : N base stations
- Each Bs is modeled as queuing system (MM1 or MMc)
- packets arrive following a poisson process - exp dist inter arrival

B : Add HAPS
- this can offload traffic from the ground BSs
- rest is the same

C : Haps + offloading + BS Deactivation
- Bs has no traffic --> can be turned off to save energy
- more detailed traffic types also intriduced

Tasks

N.B. Lab 1 and Tasks 1-3 of Lab 2 contribute to a maximum of 2 points overall. Task 4 of Lab 2 is optional and can provide up to 1 additional point, for a total maximum score of 3 points for the entire lab activity.

what is the warm-up time :
when the system starts to work at the begining is empty or underloaded
- over time, queue length, delays and server utilization grow
- performance metrics are not reliable

Task 1:

Consider the baseline scenario, which a **terrestrial RAN consisting of N BSs** (*Scenario A*). Assume that the traffic inter-arrival times are modeled with an exponential distribution having constant average arrival rate.

1.a - Observe the system behavior during the warm-up transient period and identify the transition to the steady state.

1.b - Try to apply a method to remove the warm-up transient in your simulations.

Task 2:

Now, consider the case in which a **HAPS-mounted BS is integrated to provide additional coverage to the same terrestrial RAN composed by a cluster of N** BSs (*Scenario B*). A fraction of the traffic of the terrestrial BSs can dynamically be offloaded to the HAPS. To model a realistic scenario, assume that the mobile traffic varies over time during the day, hence defining a traffic profile characterized by a different value of average packet arrival rate at every hour of the day (or every half an hour), depending on the type of considered area.
Select either of the following area types to define the traffic profile to use in your simulations:

- **Business area**: in this area the traffic typically features two peak periods, one in the morning and one in the afternoon after lunchtime, whereas as the evening approaches the traffic rate tends to decrease.
- **Residential area**: in this area the traffic is relatively low in the morning hours, whereas it tends to gradually increase in the afternoon, to achieve the highest value in late afternoon-evening, when people get back home from work.

You can **perform your analysis considering a time window of few hours in a day**, for instance **8 a.m.-8 p.m**.

2.a - Design an adaptive offloading strategy that allows to dynamically transfer some traffic from the terrestrial BSs to the HAPS, provided that the HAPS capacity is sufficient to handle all the transferred traffic (i.e., if the HAPS is busy in transmitting packets and its buffer is already full, no additional packets should be forwarded to the HAPS from the terrestrial RAN, but they would rather be handled by terrestrial BSs). For example, the strategy should take decisions about which terrestrial BSs should be offloaded (*All the N BSs? Giving priority to a subset of BSs, maybe the least loaded? Different BSs depending on the daytime? ...*).
Evaluate the system performance under the defined HAPS offloading strategy based on relevant metrics, such as the average busy time of each terrestrial BS, queuing and waiting delays, the fraction of terrestrial RAN traffic handled by the HAPS...

2.b - Compare the system performance under HAPS offloading (*Scenario B*) against the baseline scenario (*Scenario A*), in which all the traffic is handled by the terrestrial BSs throughout the day.

Task 3

Considering *Scenario B*, investigate how the number of terrestrial BSs affect the system performance:

3.a - Try to double the number of terrestrial BSs, while keeping the mobile traffic demand unvaried. Highlight how the system performance under HAPS offloading changes.

3.b - Now, shift the focus to the planning of a terrestrial RAN supported by a HAPS-mounted BS, with the goal of minimizing the CAPEX associated to the installation of on-ground BSs. Starting from the a number of BSs equal to $2N$, as tested in sub-task 2.d), try to progressively remove an increasing number (that we denote K) of BSs from the terrestrial RAN. This should be done while maintaining the same traffic demand and enabling HAPS offloading. For each value of K, evaluate key performance metrics —such as CAPEX reduction, traffic loss, queuing delay, average busy time and buffer occupancy of terrestrial BSs and HAPS-mounted BS— to assess the system behavior.
Determine the maximum number of BSs that can be removed without significantly degrading system performance –particularly in terms of traffic loss and delay metrics– thus achieving a trade-off between CAPEX reduction and Quality of Service?

Task 4 - Optional [1]

Focus on *Scenario C* in which terrestrial BSs whose traffic is fully offloaded to the HAPS can be switched off to save energy, under the following assumptions:

- Two types of traffic coexist:
  - **Delay-sensitive (D) traffic:**
    (i) **Bursty** (40% of D packets): real-time video streaming, online gaming, voice communications;
    (ii) **Not-bursty** (60% of D packets): video streaming, VoIP applications;
  - **Delay-tolerant (T) traffic:**
    (i) **Bursty** (20% of T packets): file downloads, bulk data transfers (backup traffic, software updates);
    (ii) **Not-bursty** (80% of T packets): web-browsing, background services
- The fractions of delay-sensitive traffic and delay-tolerant traffic are denoted as f_D and f_T, respectively, such that $f_D + f_T = 1$.
- The packets served by the HAPS-mounted BS incur an **additional delay resulting from the propagation time** between the terrestrial user equipment and the HAPS, in both uplink and downlink paths.
- The terrestrial RAN is modeled as a queuing system with N servers, each with a distinct buffer.

[1] Lab 1 and Tasks 1-3 of Lab 2 contribute to a maximum of 2 points overall. Task 4 of Lab 2 is optional and can provide up to 1 additional point, for a total maximum score of 3 points for the entire lab activity.

4.a - Design an HAPS offloading strategy that enables the periodical deactivation of some terrestrial BSs, by fully shifting their traffic to the HAPS.
Given a constant energy consumption for each terrestrial BS which is in an active state and assuming that deactivated BSs consume no energy, quantify the total energy saving achieved in *Scenario C* relative to *Scenario A*.
Are there specific times of the day during which greater energy savings can be achieved, and what factors contribute to this variation?

4.b - Design an HAPS offloading strategy that accounts for the delay sensitivity of type D traffic, with the goal of minimizing the delay of D packets. The strategy should guide the assignment of incoming packets to either terrestrial base stations or HAPS, and prioritize type D packets in the scheduling process. How are performance and energy savings affected in this case?

4.c - Try to vary the proportion between the values of f_1 and f_2. How does the variation of these configuration parameters affect the system performance under the operation of HAPS offloading?

Final remarks

Discuss in your report the main findings emerged from the various investigated scenarios. Support your claims and observations by plotting graphs that report the most significant performance metrics from different cases and help to highlight the relevant findings under variable configuration settings. Remember to always specify the unit of measure for the parameters and metrics represented in the graphs. For each graph, check that the main configuration settings that have been adopted to obtain the corresponding simulation results are reported.

Group and Final Reporting

You are expected to work in groups of up to three students. Each group is required to prepare a **single** report describing results of **all labs in the course**. This report must not exceed 15 pages. You need to delivery both the written report and your source code.