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Scheduling resources and managing HARQ retransmissions in Non-Terrestrial Networks

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To my parents
and friends

Abstract

The advent of 5G technology has revolutionized the world of mobile communication, offering higher throughput, lower latency and high reliability. As the demand for connectivity continues to grow, non-terrestrial networks (NTNs) have been identified by the Third generation Partnership Project as crucial for future 5-6G deployments, complementing terrestrial networks with the aim of increasing resiliency and providing connectivity in remote areas. The characteristics of NTNs, such as the long distances involved, the high propagation delay and the larger cell footprint, introduce complexities not typically encountered in their terrestrial counterpart, and the current protocol stack was not designed with such challenges in mind. Through a comprehensive literature review and the use of ns-3 network simulator, this work identifies key characteristics and constraints of non-terrestrial networks, evaluating existing protocols and highlighting their strengths and limitations in this challenging scenario, before finally delving into the adaptation and optimization of 5G New Radio Layer-2 protocols for NTNs, proposing innovative solutions and paving the way for new applications and services that leverage the full potential of 5G technology beyond traditional terrestrial boundaries.

Sommario

Through a comprehensive literature review and the use of ns-3 network simulator, this work identifies key characteristics and constraints of non-terrestrial networks, evaluating existing protocols and highlighting their strengths and limitations in this challenging scenario, before finally delving into the adaptation and optimization of 5G New Radio Layer-2 protocols for NTNs, proposing innovative solutions and paving the way for new applications and services that leverage the full potential of 5G technology beyond traditional terrestrial boundaries.

L'avvento della tecnologia 5G ha rivoluzionato il mondo delle comunicazioni cellulari, offrendo througput più elevati, minor latenza ed elevata affidabilità. Il crescere della domanda di connettività di rete ha portato il Third Generation Partnership Project (3GPP) a indicare le reti di comunicazione non terrestri (NTNs) come cruciali per le future reti di 5-6G. Il loro scopo è di complementare le reti di comunicazione terrestri, aumentandone la resilienza e fornenedo connettività nelle aree più remote. Le caratteristiche delle NTNs, come le lunghe distanze tra gli apparati a terra e la componente satellitare, i lunghi ritardi di propagazione e le grandi dimensioni delle celle, introducono delle complessità nuove rispetto alle reti terrestri, e lo stack protocollare attualmente in uso non è disegnato per affrontare queste sfide.

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TN terrestrial networks

NTN non-terrestrial network

NTNs non-terrestrial networks

HAPs high-altitude platforms

HAP high-altitude platform

UAVs unmanned aerial vehicles

UAV unmanned aerial vehicle

MEO medium earth orbit

HARQ hybrid automatic repeat request

ARQ automatic repeat request

NR new radio

LEO low earth orbit

GEO geosynchronous equatorial orbit

UE user equipment

RACH random access channel

gNB gNodeB

3GPP third generation partnership project

MAC media access control

RTT round-trip time

ACK acknowledgement

TB transport block

TBS total block size

SINR signal plus interference to noise ratio

SNR signal-to-noise ratio

NACK negative acknowledgement

1 Introduction

The term non-terrestrial networks (NTNs) denotes a category of networks where at least one link is routed via an aerial or space-borne vehicle such as high-altitude platforms (HAPs), unmanned aerial vehicles (UAVs) or telecommunication satellites.

1.1 The focus on non-terrestrial networks

The Third Generation Partnership Project [1] (3GPP), the standardization body developing protocols for mobile communication networks, recently put a great emphasis on the importance of the integration of different access technologies along with the existing terrestrial mobile telecommunication infrastructure [1].

The envisioned future for mobile communications, starting with the already established 5G new radio (NR) and expanding with the new sixth-generation cellular networks (6G), foresees the integration of a non-terrestrial component. The latest third generation partnership project (3GPP) releases (Rel. 17 and Rel. 18) require 5G and 6G networks to be able to provide non-terrestrial satellite access complementing the already existing terrestrial access technologies [14] [12].

[1] `3gpp.org`

1.2 Limitations of terrestrial networks

The following paragraphs present a few scenarios where terrestrial networks have some limitations, and NTNs can be used to provide connectivity.

1.2.1 Remote places

While terrestrial networks (TN) make the well-established foundation of today's mobile communication infrastructure, their own nature poses some intrinsic limitations to their deployment in certain scenarios, especially in rural and remote areas. Conditions such as harsh terrain and geographical impediments act as natural barriers to the deployment of terrestrial infrastructure. Moreover, ground infrastructure requires the presence of an already established reliable power grid, driving up the costs that telecommunication companies would have to sustain. The population density is often low in remote and rural places, so the already high infrastructure cost will hardly pay for itself, making this kind of market even more unattractive to private investors and further limiting the possibility for the people living there to access a resource which is becoming increasingly more important.

As studied and documented in [20], the issue of an inadequate broadband coverage in rural regions is an enormous challenge, but also a great opportunity to kick-start the economy of currently underdeveloped countries, promoting a more fair access to the internet and alleviating the problem of digital divide between different parts of the world.

1.2.2 Redundancy

Another limitation of the current terrestrial infrastructure is the lack of redundancy and robustness against natural disasters. Extreme events such as earthquakes, fires and floods, but also deliberate behaviors such as targeted attacks by terrorist organizations and sabotages can disrupt the connectivity even for a long period of time, causing significant economical damage and hindering the already difficult rescue efforts, potentially leading to loss of lives.

The simple installation of a greater number of base stations is not a viable solution because they all share the same weaknesses.

In this scenario, NTNs can act as redundant access methodology to decrease downtimes of terrestrial infrastructure, provide emergency communication services and also additional capacity when required.

1.2.3 Long distances and sensors

Remote equipment, offshore plants and distribution grids will also benefit from the research carried out in this field, since providing terrestrial connectivity in those scenarios is a challenging task. The installation of an underwater optical fiber link to serve a single endpoint, such as an offshore power plant in the ocean, would bear a disproportional cost compared to the functions required, and maintenance would be another challenging and expensive task. The deployment of a non-terrestrial network would provide connectivity on a global scale, therefore allowing internet access in isolated places without the need for a dedicated connection.

Consider now the problem of connecting of a number of sensors placed in a large area. When distances are large, solutions may either be the densification of radio stations or the use of a lower frequency in order to have a less severe propagation loss. However, those approaches have their downsides and are not always feasible. In this case, the large coverage area of NTNs will undoubtedly be useful to provide internet connection [18].

Other scenarios where NTNs can become useful in overcoming the limitation of their terrestrial counterpart are well described in [7] and [19].

1.3 Satellite types

Satellites are divided in three different categories depending on their orbiting altitude: geosynchronous equatorial orbit (GEO), medium earth orbit (MEO) low earth orbit (LEO) satellites. Each one has its own characteristics, as briefly described below.

1.3.1 GEO satellites

Orbiting at 35.786Km, GEO satellites appear stationary since their period is the same as the Earth rotation period. This vastly simplifies the tracking for

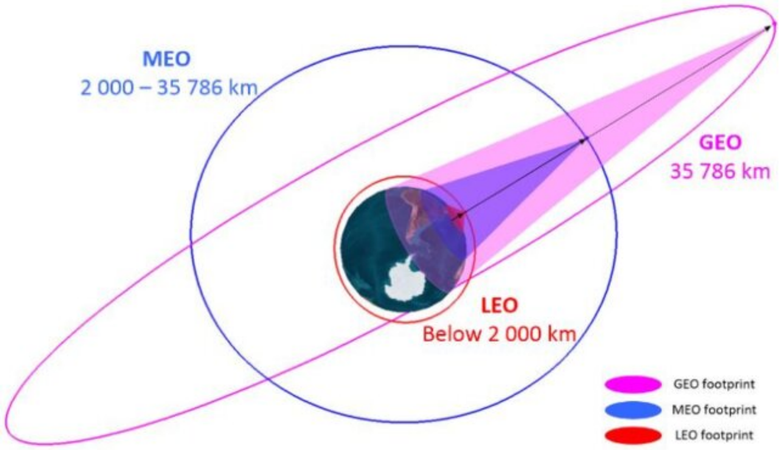

Figure 1.1: Approximate coverage areas for satellites at different orbits[10]

the ground equipment, since once the position of the user equipment (UE) is known, the relative position of the satellite is known, too.

Since GEO satellites are geostationary, continuous coverage to a designated area can be provided using as little as a single satellite, while the use of non-GEO satellites would require the deployment of a constellation, which is both more complex and more expensive.

Their higher altitude creates a large cell footprint, larger than both MEO and LEO, so the overall cost to provide coverage to the same area is lower.

The disadvantages of GEO satellites are mainly linked to the large distance with the UE: the transmission power and the antenna gain have to be higher to account for the greater propagation losses, and the propagation delay of the signal travelling at the speed of light is about 120ms, so if the UE sends a request to a server at time zero through a GEO link, the best-case delay will be of half a second without considering any protocol-related delay.

In addition to the positive aspects previously discussed, the larger cell footprint also means that a single satellite will be serving a massive number of users, so the total available capacity will have to be shared between a bigger number of actors, and the throughput experienced by each one of them will be reduced. Moreover, the high number of users leads to a large rate of initial access requests, with the possibility of channel saturation as described in [4].

1.3.2 LEO satellites

Orbiting below the altitude of 2.000Km, LEO satellites are the most promising solution in the realm of NTNs for a number of reasons hereby discussed.

The lower altitude entails a shorter propagation delay, and the smaller coverage area of each satellite means that the total number of users that need to be served is smaller.

The cost per satellite is significantly smaller than GEO and MEO satellites. However, given that they are not geostationary, a large constellation is needed to provide a continuous service, driving up the deployment costs significantly. As an example of those constellations, Fig. 1.2 depicts the LEO satellites employed by Starlink[2], with 4.808 units in service at the time of writing[3].

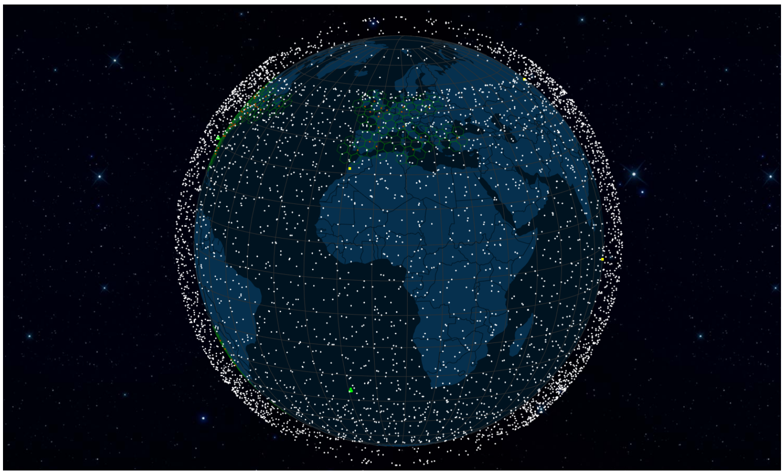

Figure 1.2: Starlink constellation as July 2024. Source: `satellitemap.space`

The smaller altitude at which LEO satellites orbit enables the use of higher frequency bands, since the experienced path loss is smaller compared to GEO satellites. This in turn allows for higher throughput, as detailed in [8]

The aforementioned solutions are not to be considered mutually exclusive. In fact, the multitude of possibilities that their combinations offer open to the study of various different scenarios, as detailed in [19]

[2]Starlink is a satellite internet constellation operated by Starlink Services, LLC, a wholly-owned subsidiary of American aerospace company SpaceX.

[3]Source: `satellitemap.space`

1.4 Current commercial solutions

Commercial solutions for satellite-based internet access have been available since a long time. However, the majority of internet service providers have been using GEO satellites, orbiting at a height of 35.786 km, therefore presenting all the limitations discussed in 1.3. The distance that the signal to travel offering limited throughput and large delays. While LEO constellations (400 km to 2.000 km) have proven to be a valid alternative, providing higher throughput and lower latency [21], they have the drawback of an increased Doppler shift due to their high speed relative to ground [8], and there is still no international standard with regard to the communication protocols to use.

This scenario led 3GPP to identify some work to be done to integrate non-terrestrial network (NTN) in cellular standards, calling for long-term research in this field [8]. This work will mainly focus on the

TODO: move this to state of the art Focusing on the media access control (MAC) sublayer, the large propagation delay of satellite links affects different aspects, making the actual implementation not suited for a NTN scenario. In the HARQ protocol, the retransmission timeout is likely to expire before a single round-trip time (RTT), leading to unnecessary retransmissions. Moreover, the limit on the maximum number of concurrent HARQ processes leads to a stop-and-wait behaviour, which may increase the energy consumption [4]. On the other hand, it has been noted that disabling HARQ would lead to an even worse performance penalty, therefore requiring a redesign for NTN [17]. Another 5G NR protocol which is negatively impacted in NTN is the initial access, since users at the center of the cell face a smaller propagation delay with respect to users at the cell edge [17] [11]. As a result, preambles of UEs placed near the cell edge may reach the satellite when the random access channel (RACH) opportunity has already expired, which may lead to collisions. During the initial access phase, UEs are not aware of their propagation delay, and the high mobility of gNodeB (gNB)s on LEO satellites causes a non-negligible Doppler shift. Those factors vary with the relative position and speed between the UE and the gNB, and the protocols for initial access must be modified in NTN to account for them [9].

It is clear that the future of mobile networks envisioned by 3GPP embraces NTNs, and considerable work has to be done. Research will bear a high impact towards a more connected, equal opportunity world.

1.5 Currrent state of the art

TODO: types of payloads: regenerative, and transparent or bent pipe

2 Simulation scenario

This chapter is focused on the discussion of the simulation software used to

2.1 Simulator

The results presented in this work have been obtained using the ns-3 network simulator tool. Ns-3 is a discrete-events network simulator specifically targeted to the research world.

There are a few reasons why this choice was made. First and foremost, the fact that this is a full-stack simulator played a crucial role,

2.2 Scenario

The simulated scenario consisted of a simple setup including a single UE ground terminal connected to a satellite acting as gNB. The satellite is then connected via an ideal link with no latency and high throughput to a node that acts as second endpoint of the communication.

The parameters of the satellite antenna follow the scenario 10 DL indicated in TR 38.321 **TODO: insert reference** and are reported in the code snippets 2.1 and 2.2.

```
// Satellite parameters
double satEIRPDensity = 40;     // dBW/MHz
double satAntennaGain = 58.5;   // dB
```

```
    double satAntennaDiameter = 5; // meters
```

Code 2.1: Satellite antenna parameters

```
    // UE Parameters
    double vsatAntennaGain = 39.7;        // dB
    double vsatAntennaDiameter = 0.6;     // meters
    double vsatAntennaNoiseFigure = 1.2; // dB
```

Code 2.2: UE antenna parameters

3 Scheduling problems

Before tackling the problems that the high propagation delay causes to the HARQ protocol, attention shall be put on the random access procedure and on the scheduler, both necessary to be able to receive packets. If those layers are not in working conditions, the communication will not take place.

3.1 Scheduling resources with propagation delay

TODO: Describe how the scheduler has to correct the allocated resources for the high propagation delay. Also, the first implementation did this only in the uplink but not reporting this information when allocating DL slots, so sometimes packets overlapped causing errors.

3.2 BSR timer

TODO: Describe how the BSR automatic timeout was discovered, the problem, show the plots in fixed_distance_si10_udp both the physical layer and the e2e throughput, highlighting the difference. Tell how this was fixed increasing the timer. It has to account at least for 2*tp. This is detailed in section 5.4.5 of https://www.etsi.org/deliver/etsi_ts/138300_138399/138321/18.01.00_60/ts_138321v180100p.pdf

3.3 Inflated BSR

TODO: Describe the mechanism whenever the send interval was smaller than an RTT, leading to bigger BSR so bigger grants, a lower latency but also some wasted capacity.

3.4 Reordering timer

TODO: The misalignment between the send interval and the propagation delay leads to the sending of fragmented packets since the grants are always a bit bigger than the packet UE has to send. However, the gNB reordering timer is configured for terrestrial networks, so it expires before we have a chance of receiving the full picture.

4 HARQ

4.1 Concurrent processes limit

One of the problems highlighted by the 3GPP technical report [4] on the matter of non-terrestrial networks regards the maximum number of concurrent HARQ processes.

4.1.1 Problem description

The details of HARQ protocol implementation in the 5G NR standard is extensively treated in many publications such as [5]. However, for the purpose of understanding what is a HARQ process and how it affects the throughput in a non-terrestrial scenario, a brief overview of a few key concepts is enough.

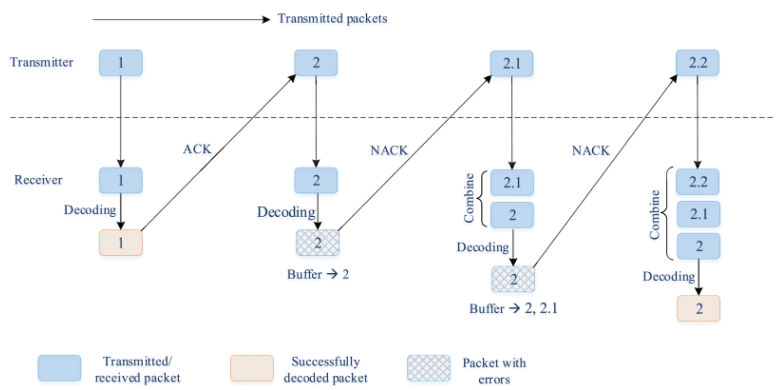

Figure 4.1: HARQ retransmission diagram [5]

HARQ working principle Fig. 4.1 gives an overview of how HARQ processes work. Upon successful reception, an acknowledgement (ACK) is sent back, triggering the transmission of the successive transport block (TB).

Should the receiver detect errors in the received TB, a negative acknowledgement (NACK) is relayed to the sender, which in turn proceeds to send some additional redundancy bits. The sender does not repeat the whole TB.

If the redundancy bits are still not enough to recover the previous packet, or another error occurs, a self-decodable retransmission is triggered.

Finally, if even the retransmission is affected by errors and the combination of the information received so far is not enough to complete the decoding of the TB, some additional redundancy bits are sent. After this fourth interaction, no further attempts are made to correct the packet [16].

This means that HARQ is a stop-and-wait protocol: designed to wait for the arrival of previous packet's ACK before sending the new one. While this enforces the delivery of ordered packets, it also brings the downside of severely underutilizing the channel capacity, wasting resources that could potentially be used for transmission instead [2].

This limitation is overcome by the introduction of multiple concurrent processes.

Processes A HARQ process starts when a TB is passed to the HARQ entity and finishes when the ACK relative to that same TB is received by the sender. After the ACK is correctly received, the next TB starts being processed. Considering a link with propagation delay τ_p, the minimum active time for a process is therefore $2\tau_p$.

The 5G NR standard allows the base station to configure the maximum number of concurrent HARQ processes each user can have, with the default value being 8 and the maximum 16 [3, 6].

Application in NTNs Since the propagation delay of NTNs is order of magnitude larger than their terrestrial counterpart, the limited number of processes lowers the maximum achievable throughput as detailed in the following toy example.

Example Consider an example scenario where each process tries to send a TB at the maximum possible rate, every $2\tau_p$, to a LEO satellite orbiting at 2.000Km, therefore having $\tau_p \approx 6$ms. Assuming the best possible conditions with no need for retransmissions and assuming that the base station grants the UE to the best possible clearance of 16 concurrent processes, the total send rate is of 16 transfer blocks every 12ms. In order to target a throughput of 50Mbps, the block size must therefore be of at least

$$\frac{\textit{target throughput} \times 2\tau_p}{\textit{number of processes}} = 37,5Kb$$

Doing the same calculation for a terrestrial scenario with the gNB placed at a distance of 600m from the UE, we obtain that the minimum total block size (TBS) must be of just $12b$. Both calculations do not factor in overheads, control information, channel access requests and processing delays, but are helpful to give an idea of the disproportion between the two conditions.

While the necessary block size for the NTN case is technically possible even with 4G, it necessitates a high signal-to-noise ratio (SNR) to work properly. This constraint becomes even more conservative in the non-terrestrial case, since retransmissions adds delays in multiples of propagation delay and are therefore more costly [15].

4.1.2 Possible solutions

Increasing the processes The easiest solution would be to increase the number of maximum concurrent HARQ processes. However, this comes with some caveats mainly regarding the higher computational capabilities required and higher power consumption, that can quickly become problematic in battery-operated equipments such as smartphones. Each process also requires the presence of a buffer on the receiver side, so additional resources are required at the gNB side, too.

Aggressive HARQ A more sophisticated approach could be the design of an aggressive version of the HARQ protocol, where each process is allowed to send multiple packets before receiving an ACK. Since each ACK packet already contains a field specifying the number of process it belongs to, the information identifying the specific packet within a process could be encoded using this field.

Disable HARQ Lastly, the option of disabling HARQ completely and rely solely on automatic repeat request (ARQ) retransmissions has been proposed by 3GPP [13]

4.1.3 Simulator configuration

While the number of concurrent HARQ processes can be configured in ns-3, it cannot exceed the value of 100. By performing some simple calculations, knowing that the SNR conditions allow for the transmissions of TBs with size of 1024B, to achieve a target throughput of 50Mbps on the best case of 6ms τ_p the necessary processes would be 74.

$$\frac{target\ throughput \times 2\tau_p}{total\ block\ size} \approx 74 processes$$

This does not account for the delays caused by retransmissions, so simulator crashes due to processes overflow are frequent while testing even the best case scenario.

5

Conclusions and Future Works

A	**B**
C	D
E	F
G	H

Table 5.1: Table example

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