Performance Assessment of NB-IoT Protocol Over Satellite Channels

A Degree Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Pau Tanyà I Vinyeta

In partial fulfilment

of the requirements for the degree in

***TELECOMMUNICATION TECHNOLOGIES AND SERVICES* ENGINEERING**

Advisor: Ramon Ferrús

Barcelona, June 2021

Abstract

Cellular networks play a very important role in nowadays paradigm which goal is to establish connectivity all around the world. Low power wide area networks (LPWAN) seem to fit well within low-cost devices, which constitute a great part of the electronics market.

In this context, the narrowband internet of things (NB-IoT) protocol specified by the 3GPP is consolidating as one of the most adopted technologies in the field of LPWAN, together with LoRaWAN.

With the goal of reaching global coverage, the NB-IoT protocol, which was mainly designed for terrestrial cellular networks, is now being extended to be able to work also on satellite networks. The support of satellite access is seen as the enabler of truly massive machine-type communications (mMTC) into areas that cellular connectivity is limited or inexistent (remote areas, air and sea communications).

This thesis provides a performance assessment of the NB-IoT protocol under different satellite link conditions and transmission modes. The assessment is conducted using the MATLAB LTE Toolbox.

Resum

Les xarxes mòbils tenen un paper molt important en l'actualitat, ja que tenen com a objectiu establir connectivitat a tot el món. Les xarxes de baix consum i llarg abast (LPWAN) semblen encaixar bé en un entorn on els dispositius de baix cost constitueixen una gran part del mercat de l'electrònica.

En aquest context, el protocol NB-IoT especificat pel 3GPP es consolida com una de les tecnologies més adoptades en el context de LPWAN, juntament amb LoRaWAN.

Amb l'objectiu d'aconseguir una cobertura global, el protocol NB-IoT, que va ser dissenyat principalment per a xarxes de telefonia terrestre, ara s'està ampliant per poder treballar també en xarxes de satèl·lit. L'accés per satèl·lit és vist com la porta cap a comunicacions de tipus màquina massiva (mMTC) en àrees on la connectivitat cel·lular és limitada o inexistent (àrees remotes, comunicacions aèries i marítimes).

Aquesta tesi proporciona una avaluació del rendiment del protocol NB-IoT sota diferents condicions d'enllaç per satèl·lit i modes de transmissió. L'avaluació es realitza utilitzant la caixa d'eines MATLAB LTE.

Resumen

Las redes móviles tienen un papel muy importante en la actualidad, puesto que tienen como objetivo establecer conectividad en todo el mundo. Las redes de bajo consumo y largo alcance (LPWAN) parecen encajar bien en un entorno donde los dispositivos de bajo coste constituyen una gran parte del mercado de la electrónica.

En este contexto, el protocolo NB-IoT especificado por el 3GPP se consolida como una de las tecnologías más adoptadas en el contexto de LPWAN, junto con LoRaWAN.

Con el objetivo de conseguir una cobertura global, el protocolo NB-IoT, que fue diseñado principalmente para redes de telefonía terrestre, ahora se está ampliando para poder trabajar también en redes de satélite. El acceso por satélite es visto como la puerta hacia las comunicaciones de tipo máquina masiva (mMTC) en áreas donde la conectividad celular es limitada o inexistente (áreas remotas, comunicaciones aéreas y marítimas).

Esta tesis proporciona una evaluación del rendimiento del protocolo NB-IoT bajo diferentes condiciones de enlace por satélite y modos de transmisión. La evaluación se realiza utilizando la caja de herramientas MATLAB LTE.

Dedication

Aquesta tesis va dedicada a la meva família, especialment al meu pare i al meu germà per la força que m'han donat i la valentia que tenen.

Acknowledgements

I would like to thank my friends and career mates who have given me support all along my stay in Universitat Politècnica de Catalunya, as well as my thesis supervisor, Ramon, who has helped me a lot throughout the process of developing this thesis.

Thank you.

Revision history and approval record

Revision	**Date**	**Purpose**
0	06/06/2021	Document creation
1	18/06/2021	Document revision

DOCUMENT DISTRIBUTION LIST

Name	**e-mail**
Pau Tanyà I Vinyeta	pautanya@gmail.com
Ramon Ferrús Ferré	ramon.ferrus@upc.edu

Written by:		Reviewed and approved by:	
Date	06/06/2021	Date	18/06/2021
Name	Pau Tanyà I Vinyeta	Name	Ramon Ferrús Ferré
Position	Project Author	Position	Project Supervisor

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1. Introduction

Internet of things is spreading worldwide as a popular demand for a smart connected world. This leads to the standardization of new technologies capable to meet users demands. Among the list of these new standards, NB-IoT is consolidating as one of the most adopted LPWAN technologies.

However, global coverage requires of new systems where machine-type communication (MTC) can be also accessible in low-population areas, where current ground stations seem to be impractical. With this purpose, the 3GPP is willing to adapt NB-IoT via satellite, which was first presented in release 13 and is currently in study phase.

This thesis is the fruit of the recruitment of qualitative information about NB-IoT within a satellite environment, complimented with simulation results required to analyse how the communication at link-level behave and so how it can be improved in terms of efficiency.

A study of the different modulation and coding schemes (MCS) and high layer parameters is done to observe the dependence between signal-to-noise ratio (SNR), block error rate (BLER), coverage and efficiency. A trade-off among them may be required to close the link.

Channel characterization cannot be missed in this report. Additive white Gaussian Noise (AWGN) channel is the object under test for its' simplicity. However, tapped delay channel (TDL) will be presented as it represents a more accurate propagation model in the context of satellite communications.

Satellite speed and user mobility are also contemplated in terms of Doppler error. Doppler shift in the satellite can be fixed, but some residual Doppler may be left.

The assessment has been carried out using the MATLAB LTE Toolbox

1.1. Objectives

This project is aimed at providing a performance assessment of the NB-IoT protocol under different satellite link conditions. More specifically:

- Understand the structure -physical channels and signals- and operational settings of the NB-IoT protocol -e.g., single-tone/multi-tone transmissions, MCS, coverage enhancements levels and number of subframes and subframe repetitions.
- Characterize the operation of the Narrowband Physical Downlink Shared Channel (NPDSCH) and Narrowband Physical Uplink Shared Channel (NPUSCH) in terms of spectral efficiency and BLER, under different SNR levels and operational settings.
    - Characterize a set of different scenarios and transmission modes regarding the configuration options offered by the protocol -e.g., number of repetitions, number of subframes per transport block and MCS.
    - Analyse the effects related to AWGN channel and a channel with Rician tap delay.

    - Characterize Doppler shift, describe a way to compensate it and see how the communication reliability is affected by residual Doppler.
    - Analyse the impact of increasing/decreasing the number of repetitions.
- Estimate the satellite antenna effective isolated radiated power (EIRP) and the figure of merit (G/T) as a function of the achievable spectral efficiency for both, LEO and GEO satellite under different transmission modes.

1.2. Methodology

To develop the matter of this subject, an exhaust research over different technic papers and through 3GPPS documentation has been done. Not only to comprehend the technologies it englobes but also to see how simulations should be run and how the results should be interpreted.

Information about channel models and its impairments was studied, as well as satellite orbits and terminal knowledge.

After this process of research, a first touch with MATLAB NB-IoT libraries was necessary in order to know how to put all collected information into scene and how to properly set the simulation configuration in order to get handy results.

First, downlink NPDSCH channel was analysed; then NPUSCH channel. Both under the influence of an AWGN channel.

The obtention of the results first let to a range of suitable SNR values required for each MCS in the downlink and in the uplink. With these SNR values and using a link budget formula described in section 4.1, an estimation of the satellite antenna EIRP required for the downlink and the Gr/T required for the uplink has been done.

1.3. Workplan

In this section, the chronology of events and deliverables with a description is displayed.

1.3.1. Work packages

Project: General research in NB-IoT	WP ref: (WP 1)	
Major constituent: Information research	Sheet 1 of 10	
Short description: Take a first look on the standard and retrieve information about state-of-the-art protocol and its particularities.	Planned start date: 15/02/2021 Planned end date: 28/02/2021	
	Start event: 15/02/2021 End event: 28/02/2021	
Internal task T1: Read papers about NB-IoT. Internal task T2: List some of its specifications.	Deliverables:	Dates:

Project: Link budget Analysis	WP ref: (WP 2)	
Major constituent: Information research	Sheet 2 of 10	
Short description: Know about the link budget of a satellite-based NB-IoT system under different channel parameters. See how these parameters are related to delay, capacity, coverage, spectral efficiency and other specifications.	Planned start date: 17/02/2021 Planned end date: 28/02/2021	
	Start date: 17/02/2021 End date: 28/02/2021	
Internal task T1: Understand how each parameter affects the link. Internal task T2: Write down the required formulas.	Deliverables:	Dates:

Project: Search information about NB-IoT architecture	WP ref: (WP 3)	
Major constituent: Information Research	Sheet 3 of 10	
Short description: Retrieve information about physical channels and how they are scheduled and mapped in the different resource elements within the different transmission modes.	Planned start date: 19/02/2021 Planned end date: 28/02/2021	
	Start event:19/02/2021 End event: 28/02/2021	
Internal task T1: Read papers about NB-IoT Internal task T2: Write down and understand the structure of physical channels	Deliverables:	Dates:

Project: Search information about non-terrestrial networks.	WP ref: (WP 4)
Major constituent: Information Research	Sheet 4 of 10
Short description:	Planned start date: 22/02/2021

Retrieve information about non-terrestrial networks, state of the art, high-altitude platform systems and orbit acknowledgement.	Planned end date: 28/02/2021	
	Start event:22/02/2021 End event: 28/02/2021	
Internal task T1: Read papers about non-terrestrial networks. Internal task T2: Take notes on important parameters about NTN.	Deliverables:	Dates:
Project: LTE Toolbox	WP ref: (WP 5)	
Major constituent: MATLAB Simulation	Sheet 5 of 10	
Short description: Familiarize with MATLAB LTE Toolbox and understand its bases and how it works.	Planned start date: 01/03/2021 Planned end date: 07/03/2021	
	Start event: 01/03/2021 End event: 07/03/2021	
Internal task T1: Run LTE Toolbox examples and analyse the code.	Deliverables:	Dates:

Project: BLER-SNR Curve	WP ref: (WP 6)	
Major constituent: MATLAB Simulation	Sheet 6 of 10	
Short description: Simulation of the NPDSCH Block Error Example. Obtention of the first results in the downlink and the with an AWGN channel and no repetitions.	Planned start date: 08/03/2021 Planned end date: 18/04/2021	
	Start event: 08/03/2021 End event:06/06/2021	
Internal task T1: Simulate and obtain the BLER-SNR curve. Internal task T2: Make a table with the results and represent them in a graph. Internal task T3: Write the workplan document.	Deliverables: Workplan.pdf	Dates: 08/03/2021

Project: Higher layer parameters	WP ref: (WP 7)	
Major constituent: MATLAB Simulation	Sheet 7 of 10	
Short description: Obtention of the results varying higher layer parameters as number of subframes or number of repetitions.	Planned start date: 22/03/2021 Planned end date: 23/05/2021	
	Start event: 05/04/2021 End event: 06/06/2021	
Internal task T1: Change input parameters and run LTE Toolbox to obtain the relation BLER-SNR. Internal task T2: Make a table with the results and see the impact caused. Internal task T3: Write the critical review document.	Deliverables: CrtiticalReview.pdf	Dates: 14/04/2021

Project: BLER-SNR Curve	WP ref: (WP 8)	
Major constituent: MATLAB Simulation	Sheet 8 of 10	
Short description: Simulation of the NPUSCH Block Error Example. Obtention of the first results in the downlink with an AWGN channel. First with no repetitions, then with subframe repetition.	Planned start date: 19/04/2021 Planned end date: 23/05/2021	
	Start event: 19/04/2021 End event: 06/06/2021	
Internal task T1: Simulate and obtain the BLER-SNR curve. Internal task T2: Make a table with the results and represent them in graphs.	Deliverables:	Dates:

Project: Writing of the final report	WP ref: (WP 9)
Major constituent: Documentation	Sheet 9 of 10
Short description:	Planned start date: 8/06/2021 Planned end date: 20/06/2021

Write a solid document with the explanation of the final degree thesis, final conclusions and the steps taken to complete the analysis.	Start event: 8/06/2021 End event: 20/06/2021	
Internal task T1: Write the final report. Internal task T2: Revise, complete and upload the document.	Deliverables: DegreeThesis.pdf	Dates: 21/06/2021

Project: Oral Presentation	WP ref: (WP 10)	
Major constituent: Document	Sheet 10 of 10	
Short description: Prepare a visual presentation to be explained as a lecture in front of the court.	Planned start date: 22/06/2021 Planned end date: 04/07/2021	
	Start event: End event:	
Internal task T1: Prepare the required slides. Internal task T2: Revise slides and prepare the oral explanation.	Deliverables:	Dates:

1.3.2. Milestones

WP#	Task#	Short title	Milestone / deliverable	Date (week)
1	1	Search general information		1
	2	Compile information		1
2	1	Retrieve link budget information		1
	2	Note down formulas		1
3	1	Retrieve protocol architecture information		1
	2	Compile physical channels information		1
4	1	Read papers about non-terrestrial networks.		1

	2	Take notes on important parameters about NTN.		1
5	1	Run LTE NB-IoT uplink and downlink examples in MATLAB		3
6	1	Simulation of the BLER_SNR curve		4
	2	Representation of the results in a document		4
	3	Write the workplan document	WorkPlan.pdf	4
7	1	Simulation of different communication scenarios		8
	2	Representation of the results in a document		8
	3	Write the critical review document	CriticalReview.pdf	9
8	1	Simulation of NPUSCH.		10
	2	Increment subframe repetition		10
9	1	Creation of the final report		17
	2	Revision of the final report	DegreeThesis.pdf	17
10	1	Creation of the visual presentation	Presentation.ppt	19
	2	Preparation of the oral lecture		19

1.3.3. Work issues and delays

Researching through 3GPP documentation and dealing with the huge amount of information has been challenging. Not just to understand the technologies it holds but to see how simulation could be faced and how the results should be treated. Actually, research was not only part of the initial steps. The recruitment of information has been done all along the process of writing this thesis.

Simulation of the physical channels behaviour caused delays because of the difficulty to know in which way simulation should be set and how to properly treat the data obtained at the output.

Choosing the right channel model has specially delayed the obtention of results. The idea was to simulate both AWGN channel and a fading channel. I first assumed the fading one to be a Rayleigh model, which I lately found out it was not the appropriate one; it had to be a TDL channel with a Rician tap due to the line-of-sight path from a satellite. Eventually, only AWGN channel simulation has been done because of the difficulty to extend MATLAB TDL libraries to properly get BLER-SNR code.

1.4. Document structure

The purpose of this report is to gradually introduce the reader from general information to more specific technic features without getting lost in the way.

In the core of this report, the reader can find:

State of the art: Theorical introduction about existing IoT networks and NB-IoT general information. An introduction of non-terrestrial networks is also found.

NB-IoT physical layer: Explanation of protocol structure, system framing and physical channels and signals.

Operational conditions of NB-IoT for direct satellite access: Information regarding link budget, channel modelling, orbital and terminals parameters and introduction of Doppler shift.

Performance analysis and results: Explanation of the simulation environment, downlink and uplink transmission behaviour and factors to improve reliability and spectral efficiency. Numerical simulation results are presented here.

Conclusions: Finally, a closure part with a summary of conclusions about this project and future development.

2. Context and state of the art

IoT is gaining more and more importance as the number of smart devices is escalating in a vertiginous way. Technology -and so telecommunications – has to respond to this demand so power consumption, efficiency and battery life among other essentials do not constrain this growth. To guarantee the feasibility of a connected world, especially in remote areas, alternative protocols and designs have been proposed, each one adapting to certain features, limiting to others, and making it ideal to certain purposes.

2.1. IoT Networks

Currently, many LPWAN are built to support IoT communications. Some of them work in a licensed spectrum, whereas others are unlicensed.

SigFox and LoRa [1] are examples of non-cellular, unlicensed and non 3GPP standards, while LTE-M and EC-GSM-IoT [2] and NB-IoT are cellular, licensed and 3GPP-based standards.

	SigFox	**LoRaWAN**	**LTE-M**	**EC-GSM-IoT**	**NB-IoT**
Frequency	Unlicensed ISM bands: 868 MHz (Europe) 915 MHz (USA) 433 MHz (Asia)	Unlicensed ISM bands: 868 MHz (Europe) 915 MHz (USA) 433 MHz (Asia)	Licensed LTE band	Licensed GSM band	Licensed LTE band
Channel Bandwidth	100 Hz	125-500KHz	1.4MHz	200KHz	180KHz
Range	10 Km (urban) 40 Km (rural)	5 Km (urban) 25 Km (rural)	5 Km (urban) 25 Km (rural)	5 km - 15 km	1km (urban) 10km (rural)
Maximum Data Rate	100 bps	300 bps - 50 Kbps	1 Mbps	70 Kbps (GMSK) 240 Kbps (8PSK)	250Kbps
Battery Life	>10 years	>10 years	>10 years	>10 years	>10 years

Device Transmit Power	23dBm	20dBm	23dBm	23 dBm / 33 dBm	23dBm

Table 1: Comparison between different LPWAN standards.

2.2. NB-IoT Protocol

Narrowband Internet of Things is a Low Power Wide Area Network standardized by 3GPP Rel-13 as an answer to the ingrowth market in the field of IoT.

Communication between smart devices does not require high throughput ratios or long active time, only the necessary to function properly and fulfil the user expectations.

For this reason, NB-IoT must meet a certain grade of flexibility to fast-develop and not fall behind. To this purpose, NB-IoT physical layer and resource allocation is designed to fit well within Long Term Evolution (LTE) framework.

Unlike other standards, scalability of the NB-IoT network is significantly better, making the protocol a good choice of implementation.

2.2.1. Uses and applications

Connection between smart devices is now found in all daily activities, from smart wristbands to industrial machinery.

NB-IoT network has been widely employed in industry, agriculture, healthcare, logistics, smart cities and smart homes. Here is an overview of some of the major potential markets for NB-IoT services [3]:

- Agriculture and Livestock: Livestock tracking, IoT sensors to monitor feeders, soil or pollution rates. Also, intelligent rainfall prediction systems.
- Healthcare: Extensive real-time monitoring and alerting for age-related or chronical diseases.
- Industries: Autonomous and efficient machinery capable to manage and process stock. Smart diagnosis of production status and predictive maintenance. All of this by reducing production costs and making it easy for professionals.
- Smart homes: Anti-theft alarms, smart consumption, intelligent lightning, air conditioning and air quality monitoring.
- Smart cities: Intelligent Street lightning, traffic control, parking management, air quality monitoring, security and much more.

2.3. Non-terrestrial networks

RAN now are commonly deployed in ground base stations, which has been a fair solution to supply connectivity in great part of the globe, but still has weak points that require of innovative solutions. In urban areas such as cities, terrestrial ground stations work efficiently enough to be considered a good deployment choice. However, in rural zones, terrestrial networks are too impractical or cost-ineffective to reach such areas, so terrestrial networks are not feasible and other technologies must fill this gap.

Non-terrestrial networks (NTN) [4] seem to be an attractive solution and set a new paradigm over radio communications. High-altitude platform systems (HAPS) such as airplanes or airships like balloons are already in use. Satellite constellations have been also deployed.

Geostationary orbit (GEO) and Low-Earth orbit (LEO) have much greater cells -more than 100km of diameter in LEO and more 400km in GEO-, as its beamwidth is greater due to the long height -600 Km and 35786 Km respectively.

Although initial deployment requires a lot of investment and suppose a huge amount of money, satellite constellations are expected to be more efficient, sustainable and with low maintenance compared to terrestrial ground stations.

3. NB-IoT Physical layer

Although the object of this document is to present notes on crucial parameters and to model a satellite channel link, and not to extend in literature about protocol theory, some key parameters of NB-IoT must be presented to understand the standard behaviour and comprehend the simulation results.

3.1. Operation Modes

As it is expected to be suited in LTE framework, NB-IoT radio frames can be allocated in three different schemes: In-band, In-GuardBand and Standalone [5].

In-band mode: NB-IoT radio subframes are allocated inside LTE bandwidth, occupying LTE physical resource blocks (PRB) and taking capacity from LTE. The first three OFDM Symbols may be occupied by LTE control channel, so NB-IoT avoid these symbols. One of the constrains is the adjacent channel leakage ratio (ACLR), which may interfere with NB-IoT spectrum, so it has to be limited to a certain value - typically 45dB - with a frequency gap.

Guard band: NB-IoT radio subframes are allocated in the guard band between channels. As It is separated from LTE, it can occupy all symbols in the subframe.

Standalone: NB-IoT is allocated in channels which not correspond to LTE spectrum. It is completely separated from LTE and it can occupy all symbols in the subframe.

Figure 1: NB-IoT operation modes.

When it operates in in-band mode, depending on the LTE bandwidth, NB-IoT can be positioned in the following PRBs:

LTE Bandwidth (MHz)	PRB Positions for NB-IoT
3	2, 12
5	2, 7, 17, 22
10	4, 9, 14, 19, 30, 35, 40, 45
15	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72

20	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95

Table 2: In-band PRB positions destined to NB-IoT within LTE framework.

The number of PRB depend on the total bandwidth. The higher the bandwidth, the higher number of LTE PRBs, so more PRBs can be destined to NB-IoT.

Channel bandwidth $BW_{Channel}$ [MHz]	**1.4**	**3**	**5**	**10**	**15**	**20**
Transmission bandwidth configuration N_{RB}	6	15	25	50	75	100

Table 3: Channel bandwidth and transmission bandwidth configuration.

3.2. System Framing

NB-IoT takes the same physical structure from Legacy LTE, with frames and subframes. This way the deployment of the protocol is faster.

Each subframe lasts 1ms and has 2 slots, with 7 OFDM Symbols each and is allocated in one PRB. Each frame (10ms) is formed of 10 subframes[6].

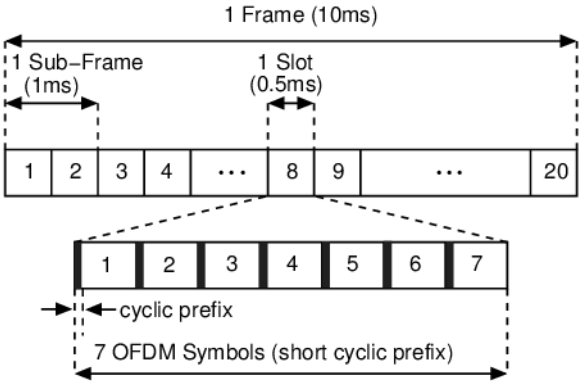

Figure 2: LTE physical frame, subframe, slot and symbol.

In the downlink, Orthogonal Frequency Division Multiple Access (OFDMA) takes place. This digital multi-carrier modulation scheme extends the concept of single subcarrier modulation by using 12 orthogonal subcarriers spaced 15KHz, corresponding to one physical resource block in LTE.

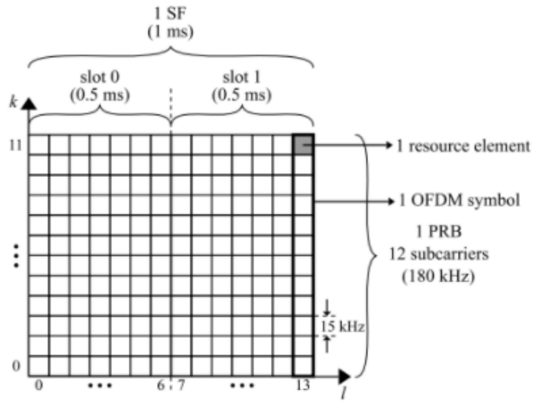

Figure 3: LTE physical layer structure.

In the figure, k is the subcarrier index and l the OFDMA symbol index in the subframe.

In the uplink, Single-Carrier Frequency Division Multiple Access (SC-FDMA) takes place. This way Peak-to-Average Power Ratio (PAPR) is lower and so battery power consumption.

Quadrature phase-shift keying (QPSK) is the only modulation format used in downlink transmissions. Moreover, only two bits can be used for each resource element (RE).

In the uplink, there are different transmission options depending on the number of tones used for the transmission:

Subcarrier Spacing	Number of tones	BW [KHz]	Number of Slots per RU	Number of RE per RU	Number of SC-FDMA Symbols	Slot Duration [ms]	RU Duration [ms]
3.75KHz	1	3.75	16	112	112	2	32
15KHz	1	15	16	112	112	0.5	8
	3	45	8	168	56	0.5	4
	6	90	4	168	28	0.5	2
	12	180	2	168	14	0.5	1

Table 4: Transmission configuration in the uplink.

Uplink may have single-tones of 3.75KHz or 15KHz subcarrier spacing (SCS).

Resource elements are the smallest physical unit. They are formed by one subcarrier inside one OFDMA Symbol.

Resource units (RU) are the smallest unit that can be transmitted in the uplink. Its size depends on if the number of transmission tones is single-tone or multi-tone.

With 3.75KHz SCS, slot duration is 2ms, four times the duration of a slot when SCS=15KHz, each RE has less bandwidth.

In multi-tone transmission, the higher the number of tones, the lower will be the duration of RU -as seen in the previous table-, as it can contain a greater number of REs in a shorter time.

Modulation format can be $\frac{\pi}{2}$-BPSK, $\frac{\pi}{4}$-QPSK and QPSK. The first two used in single-tone transmissions and QPSK for multi-tone transmissions. This allows a reduction of the PAPR and so a reduction of power consumption.

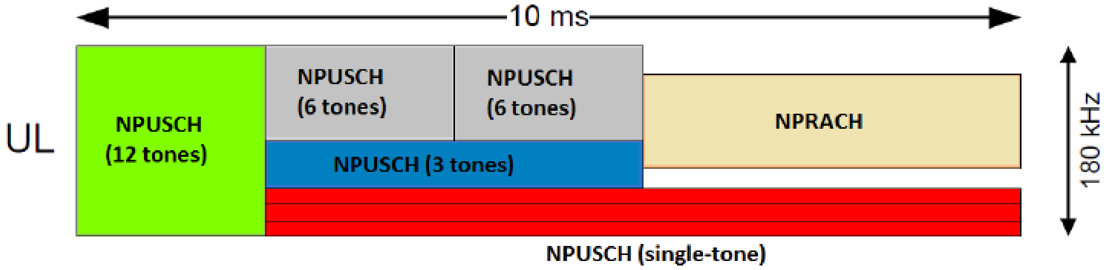

Figure 4: Example of uplink channels using different number of tones.

3.3. Channels and Signals

NB-IoT physical layer is suggested to fit in LTE physical layer, taking into account the constrains related with narrow bandwidth. Therefore, physical channels and signals have been taken from legacy LTE but some have been modified and adapted to work in NB-IoT framework [6].

In the downlink, the following channels are found:

3.3.1. Narrowband Physical Broadcast Channel

NPBCH sends cell and network configuration information. It carries the master information blocks (MIB). MIB is generated every 640ms -64 frames, not 4 frames as in LTE- and contains essential information to continue receiving information from eNodeB.

It is mapped in subframe number 0 of every frame, occupying all subcarriers and the last eleven OFDM symbols of the frame, except the REs already taken by NRS or CRS.

3.3.2. Narrowband Primary and Secondary Synchronization Signals

Time and frequency synchronization is achieved with **NPSS** and **NSSS**. NPSS is sent in the sixth subframe -which corresponds to subframe #5- of each frame. Is designed to allow devices to use a unified synchronization algorithm during initial acquisition without knowing the NB-IoT operation mode. NSSS contains cell ID and is sent in the tenth subframe -which corresponds to subframe #9- in every even numbered frame.

It is mapped in the RE grid occupying the first eleven subcarriers -NPSS- or all twelve subcarriers -NSSS- and the last eleven OFDM symbols of the frame, except the REs already taken by NRS or CRS.

3.3.3. Narrowband Physical Downlink Shared Channel

NPDSCH is dedicated to user data and system information blocks. It can be allocated in every subframe except #0, #5 and #9, which corresponds to NPBCH, NPSS and NSSS respectively. $l_{DataStart}$ parameter sets the initial OFDM symbol. In In-band operation mode its value is 3 (to avoid occupying OFDM symbols already in use by LTE) while in the other two modes its value is 0.

It is mapped in the RE grid from OFDM symbol = $l_{DataStart}$ to OFDM symbol = 13, occupying all REs except the ones already taken by NRS or CRS.

3.1.3.4. Narrowband Physical Downlink Control Channel

NPDCCH transmits control information like downlink and uplink scheduling, data acknowledgments -Hybrid Automatic Repeat Request (HARQ)- and also paging and random access response (RAR). It is allocated and mapped the same way as NPDSCH but $l_{NPDCCHStart}$ denotes the initial OFDM symbol.

3.1.3.5. Narrowband Reference Signal

NRS is the equivalent of Cell-Specific Reference Signal (CRS) for LTE and is transmitted through port 0 -if there is only one antenna port- or port 0 and 1 -if there are two antenna ports- with the purpose of cell search, downlink channel quality measurements and channel estimation. Channel estimation is important for increasing the capacity of OFDMA systems by improving the system performance in terms of bit error rate.

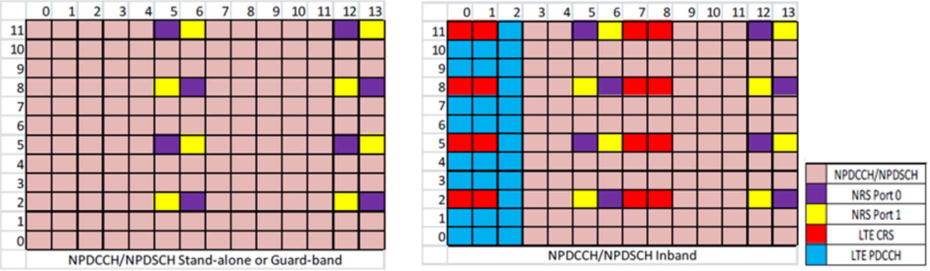

Figure 5: RE grid allocation for NRS.

The downlink framework depending on the operation mode is showed in the following figure.

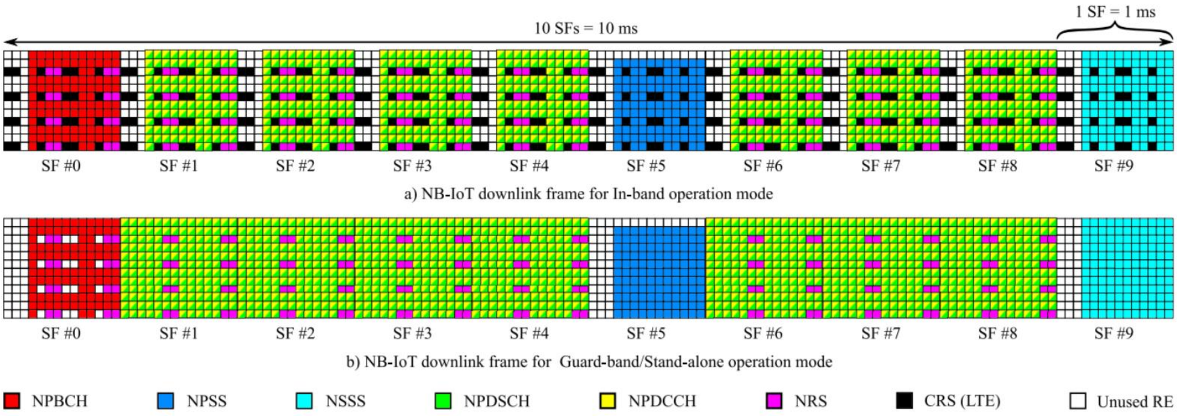

Figure 6: NB-IoT downlink frame for each operation mode.

In the uplink, the following channels are found:

3.1.3.6. Narrowband Physical Random Access Channel

NPRACH is in charge of initializing the communication between UE and eNodeB. This initial access establishes the radio link and scheduling request. It is sent by the UE.

3.1.3.7 Narrowband Physical Uplink Shared Channel

NPUSCH supports two formats: format 1, used to carry data to the user, and format 2, which is used to carry uplink control information regarding ACK/NACK. Format 1 modulation can be BPSK or QPSK, while format 2 BPSK is enough to carry the ACK/NACK bit -1 for ACK and 0 for NACK-. If the UE is located in a good channel environment, 12 tones and QPSK modulation can be used to achieve higher data rate. However, less tones, BPSK modulation and SCS of 3.75KHz can be used to close the link in poorer channel conditions.

Down below, a figure with uplink and downlink physical channels.

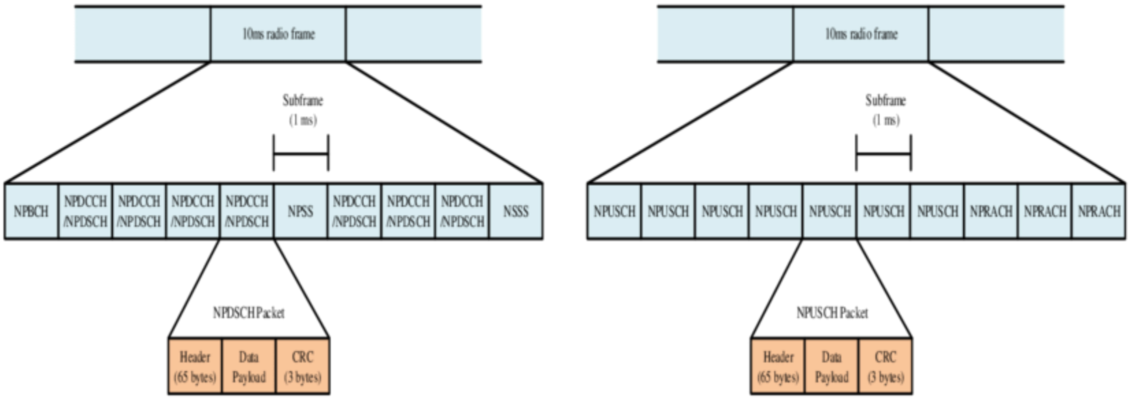

Figure 7: Downlink (left) and Uplink (right) frame structure.

4. NB-IoT operational conditions for satellite access

The will of this section is to inform about how the transmitted signal is affected by propagation matters as attenuation, multipath and Doppler shift. All this in a satellite access environment.

For this purpose, a link budget formula is first presented and a table with orbital and terminal parameters used in link budget and Doppler calculation is displayed.

4.1. Link budget

Link budget is the balance of the power gains and losses suffered in the system from the transmitter to the receiver. It is useful to know how much of the transmitted power will be received after antenna gains, propagation losses and additional attenuations due to cable wiring or temperature. It is used as a design aid to ensure that transmitted information will be received intelligibly. It is computed as follows:

$$SNR(dB) = \mathrm{EIRP(dBW)} + \frac{\mathrm{Gr}}{\mathrm{T}}\left(\frac{dBi}{K}\right) - FSPL(dB) - A_{loss}(dB) - Ad_{loss}(dB) - K\left(\frac{\frac{dBW}{K}}{Hz}\right) - 10\log_{10}(BW)$$

where:

$\mathrm{EIRP(dBW)} = 10\log_{10}(G_T P_T)$, is the isotropic radiated power, being G_T and P_T the gain and the power at the transmitter. K is the Boltzman constant and BW is the total bandwidth.

$\frac{\mathrm{Gr}}{\mathrm{T}}\left(\frac{dBi}{K}\right) = \mathrm{Gr(dBi)} - \mathrm{NF(dB)} - 10\log_{10}(\mathrm{To} + (\mathrm{Ta} - \mathrm{To}) \cdot 10^{-0.1 \cdot \mathrm{NF}})$, is the figure of merit, where G_r is the gain at the receiver, NF is the noise figure, To is the ambient temperature and Ta is the antenna temperature.

$FSPL(dB) = 10\log_{10}\left(\frac{4\pi D}{\frac{c}{fo}}\right)^2$, is the free space path loss, where: D is the slant range, c is the light speed constant and f_o is the carrier frequency.

$D = -R_E \cdot sin(\alpha) + \sqrt{R_E^2 \cdot \sin^2(\alpha) + h_s + 2 \cdot R_E \cdot h_s}$, where R_E is the Earth radius, h_s is the satellite height and α is the elevation angle.

However, SNR will not be calculated from this formula. SNR will be taken from MATLAB simulation results. EIRP -in the downlink- and $\frac{\mathrm{Gr}}{\mathrm{T}}$ -in the uplink- will be solved from the link budget formula.

EIRP and $\frac{\mathrm{Gr}}{\mathrm{T}}$ are design parameters which must be designed depending on the range of SNR required in the downlink and in the uplink, which are shown in section 5.

4.2. Orbit, terminal and satellite parameters

The study of the orbit parameters is centred in LEO and GEO orbiting scenarios [7].

Non-terrestrial network features the following elements:

- **Satellite gateway**: Ground base station which converts radio frequency (RF) signal coming from the satellite into internet protocol (IP) data.
- **A feeder link** between satellite and the gateway.
- **A service link** between satellite and UE.
- **The satellite** with the payload.

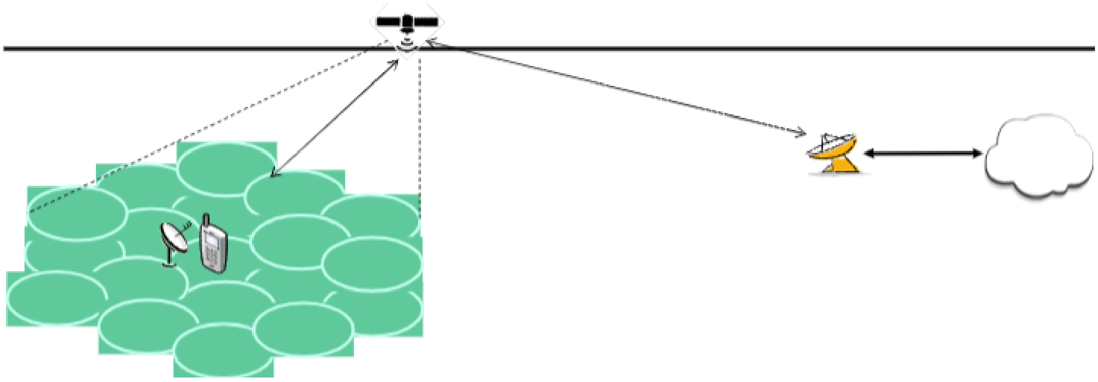

Figure 8: Non-terrestrial network scenario.

While LEO platforms are favourable because of their lower round trip time (RTT) and lower propagation loss in the communication link, they are responsible of an increased Doppler shift respect with GEO. Down below, a table with orbit, terminal and satellite parameters used is defined [8]. These parameters have been chosen from 3GPP specifications.

Parameter	**Downlink**	**Uplink**
Earth Radius [Km]	6371	6371
LEO Height [Km]	600	600
GEO Height [Km]	35786	35786
Elevation Angle [Degree]	80	80
Atmospheric Loss for LEO and GEO [dB]	0.5	0.5
Additional Loss LEO and GEO [dB]	1	1
Antenna Type	Omnidirectional	Omnidirectional
Carrier frequency [GHz]	2	2
Bandwidth [KHz]	180	3.75, 15, 45, 90, 180
Terminal Transmit Power [dBm]	-	23
Terminal Noise Figure [dB]	9	-
Transmit Antenna Gain [dBi]	-	0
Receiver Antenna Gain [dBi]	0	-
Terminal Ambient Temperature [k]	290	-

Terminal Antenna Temperature [k]	290	-

Table 5: Orbital and terminal parameters.

Parameters with no defined value will be object under study for satellite payload design.

4.3. TDL Fading Channel

AWGN channel model serves as a good approach to see the BLER curves and make an estimation of the QoS under white noise effects. Nevertheless, in real scenario there are ecos of the transmitted signal due to reflections at objects and structures found in the environment. The time lapse between the first and the last tap - signals with different path-received in the receiver is known as delay spread (Ds). This may lead to inter-symbol interference (ISI) between contiguous OFDMA symbols when received and integrated in the receiver.

An accurate model to characterise this effect is TDL channel [9].

The impulse response of the channel is modelled as:

$$\mathrm{h}(\mathrm{t}, \tau) = h_0(\tau)\delta(\tau) + \sum_{k=1}^{K-1} h_k \delta(\mathrm{t} - \tau_k)$$

where: $h_0(\tau)$ is the coefficient for the first tap – the line of sight path (LOS)- and h_k and τ_k are the coefficient and delay of the k^{th}path.

Due to the presence of a LOS tap with no shadowing, the first tap follows a Rician fading distribution, whereas other taps follow a Rayleigh distribution. Taps received with more delay will experience more attenuation as their path will be longer and with more.

4.4. Doppler Shift

The relative movement between the satellite and ground terminals cause a change in the perceived frequency at the receiver. This change is known as the Doppler shift. In GEO height, the slow relative motion between the orbit and the Earth does not cause much Doppler. This effect is much perceived in LEO, as orbital period is about 100 minutes and satellite speed is much higher.

The formula used to calculate Doppler shift in a satellite environment is defined in [10] section 6.9.2 as follows:

$$fd_{shift} = \frac{v_{sat}}{c} \cdot \left(\frac{R}{R+h} \cdot \cos(\alpha) \right) \cdot f_0$$

where: v_{sat} is the satellite speed -around 3000 m/s in GEO and 7500m/s in LEO-, R is the Earth radius, h is the orbit height, α is the elevation angle and f_0 is the carrier frequency.

With the parameters in table 5, the following Doppler shifts for GEO and LEO orbits are obtained:

$fd_{shift_{GEO}} = 537\ Hz$

$fd_{shift_{LEO}} = 8000\ Hz$

In principle, the Geostationary satellite points in a fixed Earth location and therefore almost no Doppler shift is induced except that due to possible UE motion.

Since OFDM is especially sensitive to the frequency offset, the Doppler shift may cause a loss of orthogonality between subcarriers, causing inter-carrier interference (ICI), so it is clear that there is an urge to compensate this shift, especially in LEO.

The Doppler Shift caused by UE mobility is calculated as:

$$f_D = v/\lambda_0 = v \cdot \frac{f_0}{c}$$

where: v is the UE speed, λ_0 if the wavelength of the signal and f_0 is the carrier frequency.

So, a device moving in a high-speed train at 300km/h would perceive a frequency shift of 555 Hz.

4.4.1. Doppler shift compensation at the Satellite

In order to compensate Doppler shift, the satellite must know the position of the UE and apply the maximum likelihood estimation (MLE) of the frequency offset. However, this would be impractical as a terminal may not be static, so a ground cell can be defined instead and apply MLE in the centre of the cell. MLE steps are described in [11].

$$\Delta(\theta,\epsilon) = \log\left(f(r|\theta,\varepsilon)\right)$$

Where: θ is the arrival time of a symbol, ϵ is the carrier frequency offset, and r is the vector of received samples.

Maximizing $\Delta(\theta,\epsilon) \quad \rightarrow \underset{(\theta,\epsilon)}{\max} \Delta(\theta,\epsilon) = \underset{(\theta)}{\max}\,\underset{(\epsilon)}{\max}(\Delta(\theta,\epsilon)) = \underset{(\theta)}{\max}\,\Delta(\theta,\hat{\varepsilon}_{ML}(\theta))$ The frequency offset estimator can be obtained.

In the paper mentioned before, a plot of the ML estimator performance is shown. From that, it is seen that at values of SNR near to 0dB, the SNR loss due to the residual Doppler is not much significant. This estimator can perform better with higher cyclic prefix.

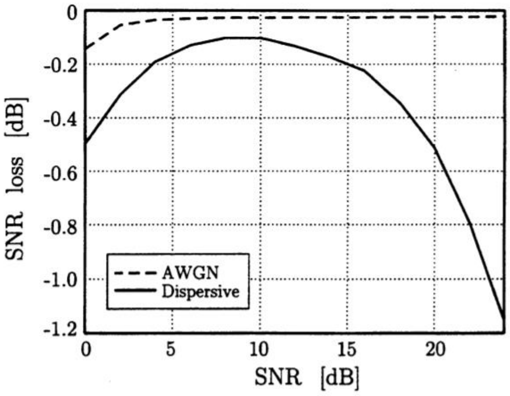

Figure 9: Performance of the ML estimator for AWGN and dispersive channel.

This way, Doppler in terminals located in the centre of the ground cell will be compensated, while the ones located at the extremes will experience residual error which should be considered.

5. Performance analysis and results

In his section, the simulation environment is presented and final results are shown. First, the downlink case, then the uplink. Both under the influence of an AWGN channel.

Earlier simulations were done with in-band operation mode, but they showed poor SNR values. This is because eNodeB divides the transmitted power between LTE and NB-IoT when NB-IoT is deployed in-band. For this reason, the mode of operation of NB-IoT selected for conducting the tests is Standalone.

Tables in the next sections will show which SNR level, data throughput, and spectral efficiency is achieved for each MCS under a quality of service (QoS) requirement, described below.

Once the SNR value is obtained for each MCS, the required EIRP and $\frac{\mathrm{Gr}}{\mathrm{T}}$ is calculated and displayed.

5.1. Simulation environment

Downlink and uplink simulations have been run through MATLAB LTE NPDSCH Block Error Rate and NPUSCH Block Error Rate library, respectively.

5.2. Downlink transmission performance

The performance analysis considers that the QoS of the system must ensure a BLER not worse than 10%, which tells that the communication link works properly and user service is not being altered by the impairments of the channel.

Different levels of SNR have been tested with all modulation and coding scheme indices (IMCS), from IMCS = 0 to IMCS= 13.

The bits are sent to the channel in transport blocks according to the downlink transport block size (TBS) defined in table 16.4.1.5-1 in [12].

In each running simulation, 100 transport blocks are transmitted in a range of different SNR values, erroneous blocks are counted at the receiver and a BLER-SNR curve is displayed at the end. SNR value sensibility is 0.1dB, so if SNR = [0, 0.1, 0.2, 0.3, …5] dB, 51 SNR values from 0dB to 5dB are being tested. Once the curve is obtained, the minimum SNR value that delivers a 10% BLER or less is kept.

In each simulation, one MCS is tested and one BLER-SNR curve is obtained.

The channel is an AWGN channel.

The spectral efficiency is calculated as:

$$SE = \frac{Throughput}{BW} = \frac{\frac{TBS}{TTI}}{BW}$$

where: $TTI = NSF \cdot Nreps \cdot T_{Subframe}$; $T_{Subframe} = 1ms.$

TTI is the transmission time interval, $Nreps$ and NSF are the number of subframes and the number of repetition for each subframe.

TBS is determined by NSF and IMCS if NPDSCH does not carry system information block 1 (SIB1-NB), or by SchedulingInfoSIB1 if it does carry SIB1-NB. In this later case, $Nreps$ and NSF are also controlled by SchedulingInfoSIB1.

SIB1-NB messages are transmitted via broadcast control channel (BCCH) and carry relevant information when evaluating if a UE is allowed to access a cell and defines the scheduling of other system information.

To ensure all bits transmitted are user data, no BCCH is transmitted and so no SIB1-NB is transmitted during simulation tests.

5.2.1. Baseline configuration for the NPDSCH

With no repetitions, one subframe and one antenna port, the following table is obtained:

MCS	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	16	-5.2	16	0.0889
1	24	-4.2	24	0.1333
2	32	-3.6	32	0.1778
3	40	-2.6	40	0.2222
4	56	-1.5	56	0.3111
5	72	-0.8	72	0.40
6	88	0.2	88	0.4889
7	104	0.7	104	0.5778
8	120	1.3	120	0.6667
9	136	2.1	136	0.7556
10	144	2.4	144	0.80
11	176	3.6	176	0.9778
12	208	4.9	208	1.155
13	224	5.5	224	1.244

Table 6: NPDSCH results. AWGN channel. ISF=0.

The graph below shows the order of magnitude of the EIRP that the satellite will be required to supply in the downlink under the levels of SNR in table 6. EIRP is solved from the link budget formula. Each point in the graph implicitly represents an MCS.

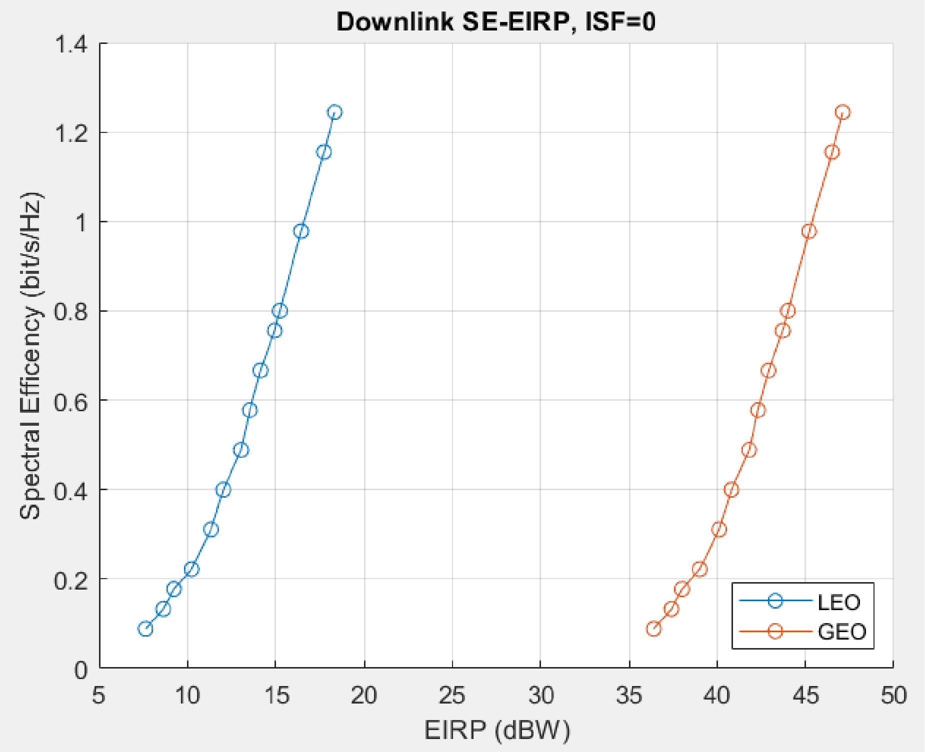

Figure 10: Spectral efficency in LEO and GEO as a function of EIRP in the downlink.

5.2.2. Impact of the number of subframes

In the downlink side, the parameter ISF controls the number of subframes (NSF) dedicated to NPDSCH, as seen in table 16.4.3.1-1 in [12].

Down below, two tables with best spectral efficiency case and best SNR case for each MCS are displayed. In appendix A, results with all ISF are shown.

Best spectral efficiency case for each MCS

MCS	**ISF / NSF**	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	6 / 8	208	-5.5	26.0	0.1444
1	5 / 6	208	-4.2	34.7	0.1926
2	2 / 3	144	-2.9	48.0	0.2667
3	2 / 3	176	-1.9	58.7	0.3259
4	2 / 3	208	-1.1	69.3	0.3852
5	7 / 10	872	-0.1	87.2	0.4844
6	7 / 10	1032	0.7	103.2	0.5733

7	7 / 10	1224	1.7	122.4	0.6800
8	6 / 8	1096	2.3	137.0	0.7611
9	6 / 8	1256	2.8	157.0	0.8722
10	4 / 5	872	3.4	174.4	0.9689
11	7 / 10	2024	4.6	202.4	1.1244
12	7 / 10	2280	5.6	228.0	1.2667
13	3 / 4	1032	6.7	258.0	1.433

Table 7: Best spectral efficiency case NPDSCH results. AWGN channel.

As done before, the graphs below show the order of magnitude of the EIRP that the satellite will be required to supply in the downlink to achieve the required SNR values for each MCS.

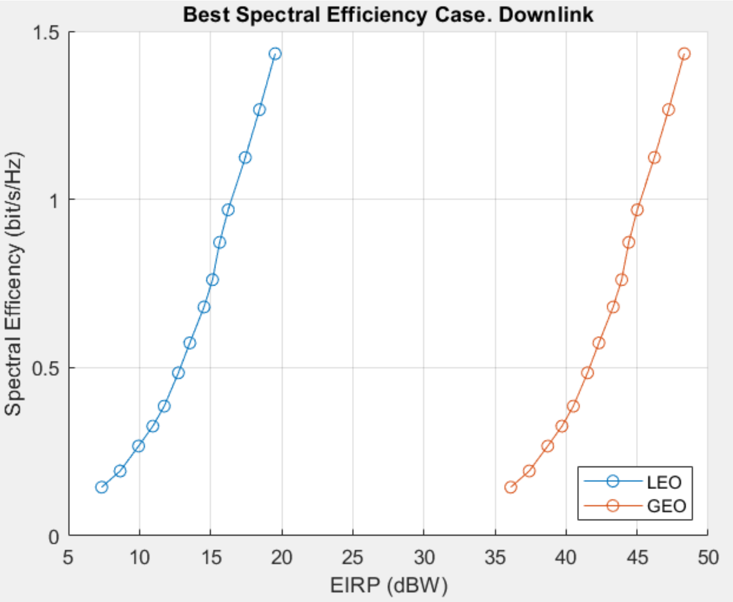

Figure 11: Best Spectral Efficiency case.

Best SNR case for each MCS

MCS	**ISF / NSF**	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	1 / 2	32	-6.5	16.0	0.0889
1	1 / 2 2 / 3	56 88	-4.7	28.0 29.3	0.1556 0.1630

2	1 / 2	72	-3.9	36.0	0.2000
3	4 / 5	256	-2.7	51.2	0.2844
4	1 / 2	120	-2	60.0	0.3333
5	1 / 2	144	-1.1	72.0	0.4000
6	1 / 2	176	-0.5	88.0	0.4889
7	0 / 1 2 / 3	104 328	0.7	104.0 109.3	0.5778 0.6074
8	0 / 1	120	1.3	120.0	0.6667
9	0 / 1 1 / 2	136 296	2.1	136.0 148.0	0.7556 0.8222
10	0 / 1	144	2.4	144.0	0.8000
11	0 / 1	176	3.6	176.0	0.9778
12	0 / 1 1 / 2	208 440	4.9	208.0 220.0	1.1556 1.2222
13	0 / 1	224	5.5	224	1.244

Table 8: Best SNR case NPDSCH results. AWGN channel.

As seen in the previous table, in some MCS, the same SNR value is achieved in two different ISF, so the one with best spectral efficiency is selected to compute the Efficiency-EIRP curve.

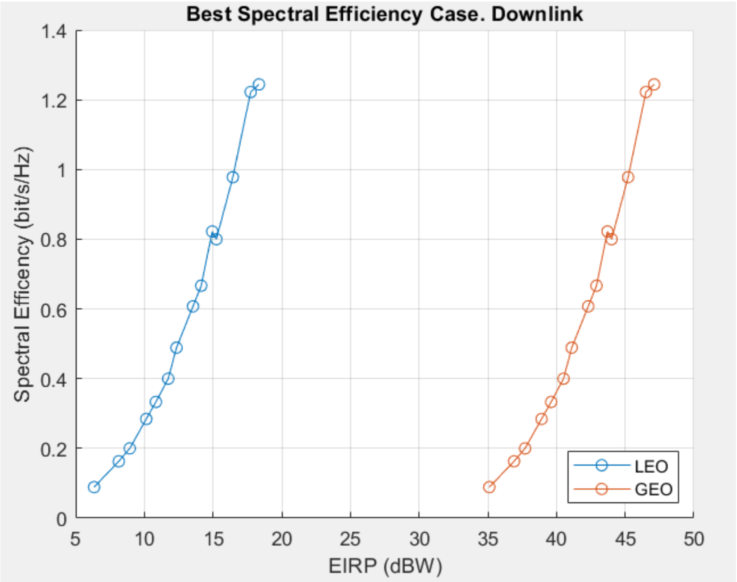

Figure 12: Best SNR case.

5.2.3. Impact of subframe repetition

Subframe repetition, which is set by the $Ireps$ parameter as defined in Table 16.5.1.1-3 in [12], marks how many times a subframe is transmitted. In the downlink, up to 2048 repetitions can be performed.

Doubling the number of repetitions leads to a gain of 3dB as increases reliability in a non-reliable channel. Repetitions extend coverage level but trades off data rate, as it can be seen in spectral efficiency formula.

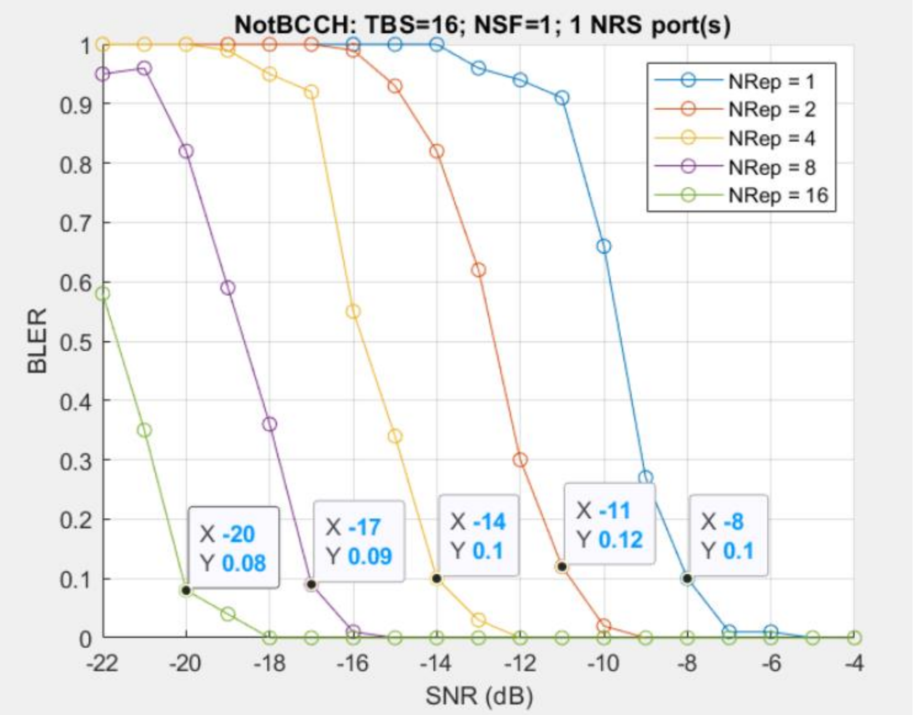

Figure 13: BLER as a function of SNR when Nreps= 1, 2, 4, 8 and 16. Downlink.

5.3. Uplink transmission performance

The same way it has been done in downlink, in the uplink, bits are transmitted in TBS acording to table 16.5.1.2-2 in [12], and again it is considered that the BLER is not worse than 10%.

As seen in section 3.2, NPUSCH can be sent in different bandwidths depending on the number of tones and the subcarrier spacing. So, both multi-tone and single-tone have been simulated in order to see how bandwidth afects the communication.

Only format 1 has been tested, as the information of interest is user data.

The channel here is also an AWGN channel.

The spectral efficiency is calculated as:

$$SE = \frac{Throughput}{BW} = \frac{\frac{TBS}{TTI}}{BW}$$

where: $TTI = Nru \cdot Tru$.

Nru is the number of RU transmitted.

Tru is the time it takes to transmit one RU.

5.3.1. Baseline configuration for NPUSCH

With no repetitions, one resource unit and one antenna port, the following tables for each bandwidth configuration -seen in table 4- are obtained.

QPSK **MT**:12subcarriers **SCS**:15KHz **Nru**:1 **Format**: 1

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	16	-3.7	16	0.0889
1	24	-3.0	24	0.1333
2	32	-2.2	32	0.1778
3	40	-1.9	40	0.2222
4	56	-1.1	56	0.3111
5	72	-0.3	72	0.4000
6	88	0.8	88	0.4889
7	104	1.3	104	0.5778
8	120	1.9	120	0.6667
9	136	2.6	136	0.7555
10	144	3.0	144	0.8889
11	176	4.4	176	0.9778
12	208	5.9	208	1.1556
13	224	6.8	224	1.2444

Table 9: NPUSCH format 1 results in multi-tone. 12 tones and SCS=15KHz.

QPSK **MT**:6subcarriers **SCS**:15KHz **Nru**:1 **Format**: 1

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency

0	16	-4.0	16	0.0889
1	24	-3.1	24	0.1333
2	32	-2.3	32	0.1778
3	40	-1.6	40	0.2222
4	56	-1.0	56	0.3111
5	72	-0.1	72	0.4000
6	88	0.6	88	0.4889
7	104	1.3	104	0.5778
8	120	2.0	120	0.6667
9	136	2.7	136	0.7555
10	144	3.2	144	0.8889
11	176	4.5	176	0.9778
12	208	5.8	208	1.1556
13	224	6.8	224	1.2444

Table 10: NPUSCH format 1 results in multi-tone. 6 tones and SCS=15KHz.

QPSK **MT**:3subcarriers **SCS**:15KHz **Nru**:1 **Format:** 1

MCS	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	16	-3.8	16	0.0889
1	24	-3.2	24	0.1333
2	32	-2.5	32	0.1778
3	40	-1.9	40	0.2222
4	56	-1.0	56	0.3111
5	72	-0.1	72	0.4000
6	88	0.7	88	0.4889
7	104	1.2	104	0.5778
8	120	2.0	120	0.6667

9	136	2.7	136	0.7555
10	144	3.1	144	0.8889
11	176	4.3	176	0.9778
12	208	5.8	208	1.1556
13	224	6.8	224	1.2444

Table 11: NPUSCH format 1 results in multi-tone. 3 tones and SCS=15KHz.

QPSK **ST**:1subcarriers **SCS**:15KHz **Nru**:1 **Format:** 1

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	16	-2.1	16	0.1333
1	24	-1.4	24	0.2000
2	32	-0.7	32	0.2667
3	40	0.0	40	0.3333
4	56	0.8	56	0.4667
5	72	2.3	72	0.6000
6	88	3.2	88	0.7333
7	104	4.3	104	0.8667
8	120	5.1	120	1.0000
9	136	6.0	136	1.1333
10	144	6.8	144	1.2000

Table 12: NPUSCH format 1 results in single-tone and SCS=15KHz.

QPSK **ST**:1subcarriers **SCS**: 3.75KHz **Nru**:1 **Format**: 1

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	16	-2.1	16	0.1333
1	24	-1.4	24	0.2000
2	32	-0.7	32	0.2667

3	40	-0.1	40	0.3333
4	56	1.0	56	0.4667
5	72	2.1	72	0.6000
6	88	3.1	88	0.7333
7	104	4.3	104	0.8667
8	120	5.1	120	1.0000
9	136	6.1	136	1.1333
10	144	6.7	144	1.2000

Table 13: NPUSCH format 1 results in single-tone and SCS=3.75KHz.

From SNR values in tables 9, 10, 11, 12 and 13, Gr/T is solved from the link budget formula and displayed in the following figures 14 and 15.

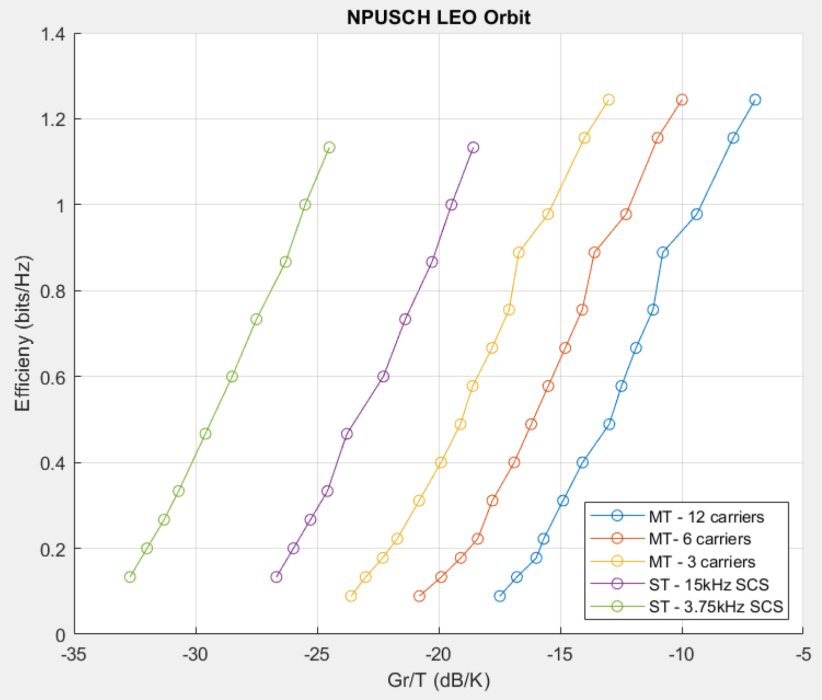

Figure 14: Spectral efficiency as a function of the figure of merit in LEO in the uplink.

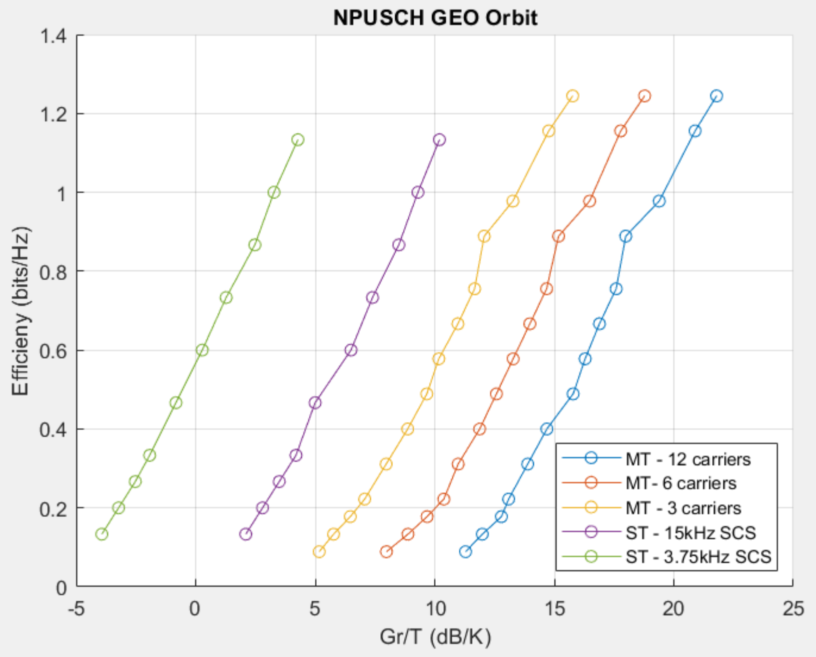

Figure 15: Spectral efficiency as a function of the figure of merit in GEO in the uplink.

5.3.2. Impact of subframe repetition

Subframe repetition, which is set by the $Ireps$ parameter as determined in Table 16.4.1.3-2 in [12] marks how many times a subframe is transmitted. In the uplink, up to 128 repetitions can be performed.

Doubling the number of repetitions leads to a gain of 3dB, so it has the same impact as the downlink case.

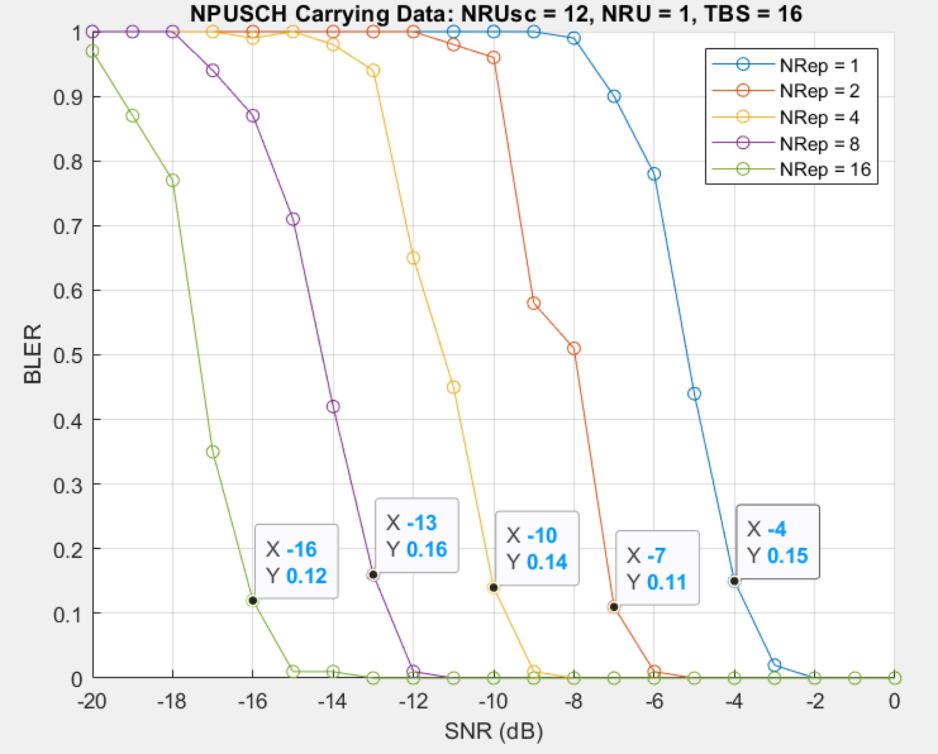

Figure 16: BLER as a function of SNR with Nrep=1, 2, 4, 8, 16. Uplink

6. Budget

This thesis does not contemplate any component costs as it just serves as a research and validation of different NB-IoT link-level configurations and presets.

As the assessment has been carried out using MATLAB, its license has been counted to calculate the budget -even though a student license has been used.

· MATLAB Standard Annual License: 800€

· Hours working in this project: 30Hours/week during 17 weeks

· Salary: 9€/hour

· Total Salary: 4590€

- **Total Budget**: 5390€

7. Environment Impact

Non-terrestrial networks are designed to avoid high-cost ground-based radio access networks which are inefficient in remote areas and requires good maintenance. To extend coverage to all the globe, it is mandatory the installation of thousands of radio masts and towers in thousands of cities, mounted above buildings or over the mountains and having a controversial impact in the environment. The proliferation of these infrastructures is often criticised by people living around them, which is a public concern.

The use of high platforms and satellites do not need ground sites and cells, which calls to a reduction of the previous mentioned buildings.

Terrestrial networks most likely will not meet people demands as smart devices are skyrocketing. NTN have a positive impact in rural areas where coverage and connectivity is not guaranteed now.

Initially, the deployment of such infrastructures will suppose a huge amount of money as a lot of investment must be done, but in the long term it will be cheaper and more efficient than current terrestrial networks.

However, to ensure that NTN give coverage to different zones, a mesh of hundreds of satellites shall be used. This leads to an increase of space traffic, and can be a real problem in the near future, so space debris risk mitigation is becoming a major concern.

Related to the previous issue, NTN also mean a threat to astronomy, as light pollution coming from satellite reflections have proved to reduce visibility in space observation.

Regarding NB-IoT technology, it is designed to work efficiently with low power. Power consumption is a major issue in this growing population world, so every step we make to reduce energy consumption has a good impact on our environment.

8. Conclusions and future development:

This project has provided an analysis of the NB-IoT protocol under different transmission configurations.

First, the structure and features offered by the protocol have been studied. The physical layer adopted from legacy LTE allows a fast deployment, as neither terminals nor base stations have to be modified to access this protocol.

Its capability to switch between MCS and bandwidth transmission options provides a great flexibility to adapt in different environment conditions.

To derive the required SNR value for each MCS level assuring a maximum BLER target of 10%, the NB-IoT PHY layer is implemented in MATLAB and the performance in terms of BLER vs SNR is evaluated through numerical simulations.

The link and device parameters were chosen in accordance with the latest 3GPP specifications, while the satellite parameters were left open for design. The achievable spectral efficiency as a function of satellite antenna EIRP and G/T were shown through numerical simulations for both, LEO and GEO satellite, and under different transmission modes.

The higher the MCS index, the larger is the payload of data sent -in TBS- and the spectral efficiency gets higher too. However, the receiver needs more SNR to decode the received message, and this is not always obtainable in bad propagation conditions. Still, lower MCS can be used, trading off data rate and efficiency for the sake of link reliability, needed to close the link.

In the uplink, using less frequency resources -i.e., using less tones or less subcarrier spacing- leads to a reduction in data throughput -and so in the efficiency-. Nonetheless, it may be required to close the link.

Overall, SNR ranges goes from around -5dB to 7dB -depending on the downlink and uplink transmission modes-, which are pretty much small.

Incrementing the subframe repetition pattern has shown to be linked to reliability improvement- 3dB gain every time the Nreps is doubled-, as the same information is sent various times, but this leads to low data throughput as more time is dedicated to the retransmission of the same information.

Instead, receiver diversity with two antennas leads to a gain of 3dB too.

As a further development, simulation under a tapped delay channel should be considered to get accurate results in a real environment, where multipath and Doppler error are considered.

Also, from the EIRP and Gr/T obtained values, a design of the payload and power consumption in the satellite could be performed.

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Glossary

ACLR	Adjacent Channel Leakage Ratio
AWGN	Additive White Gaussian Noise
BCCH	Broadcast Control Channel
BLER	Block Error Rate
CRS	Cell-Reference Signal
DS	Delay Spread
GEO	Geostationary Orbit
HAPS	High-Altitude Platform System
HARQ	Hybrid Automatic Repeat Request
ICI	Inter-Carrier Interference
IP	Internet Protocol
ISI	Inter-Symbol Interference
KPI	Key Performance Indicator
LEO	Low-Earth Orbit
LOS	Line of Sight
LPWAN	Low-Power Wide Area Network
LTE	Long Term Evolution
MCS	Modulation and coding scheme
MIB	Master Information Block
mMTC	massive Machine-Type Communication
NB-IoT	Narrowband Internet of Things
NTN	Non-Terrestrial Networks
OFDMA	Orthogonal Frequency-Division Multiple Access
PAPR	Peak-to-Average Power Ratio
PRB	Physical Resource Block
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RAR	Random-Access Response
RE	Resource Element
RF	Radio Frequency
RTT	Round Trip Time
RU	Resource Unit

SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SCS	Subcarrier Spacing
SIB1-NB	System Information Block 1 - Narrowband
SNR	Signal-to-Noise Ratio
TBS	Transport Block Size
TDL	Tapped Delay Line
3GPP	3^{rd} Generation Partnership Project

Appendices:

This section has been redacted to show further results.

Appendix A

The tables below show the impact of the subframe pattern in the downlink and how increasing the number of subframes tend to rise spectral efficiency whereas more SNR is required.

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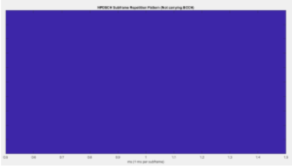

Downlink:

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	16	-5.2	16	0.0889
1	24	-4.2	24	0.1333
2	32	-3.6	32	0.1778
3	40	-2.6	40	0.2222
4	56	-1.5	56	0.3111
5	72	-0.8	72	0.40
6	88	0.2	88	0.4889
7	104	0.7	104	0.5778
8	120	1.3	120	0.6667
9	136	2.1	136	0.7556
10	144	2.4	144	0.80
11	176	3.6	176	0.9778
12	208	4.9	208	1.155
13	224	5.5	224	1.244

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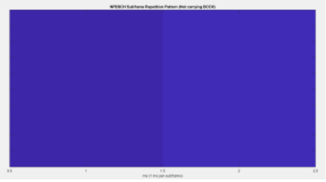

Downlink

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	32	-6.5	16	0.0889
1	56	-4.7	28	0.1556
2	72	-3.9	36	0.200
3	104	-2.2	52	0.2889
4	120	-2	60	0.3333
5	144	-1.1	72	0.400
6	176	-0.5	88	0.4889
7	224	1.1	112	0.6222
8	256	1.8	128	0.7111
9	296	2.1	148	0.822
10	328	3	164	0.9111
11	376	3.9	188	1.0444
12	440	4.9	220	1.2222
13	488	6.5	244	1.3556

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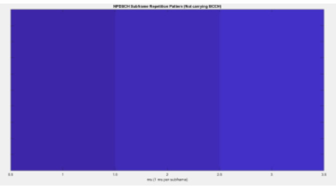

Downlink:

MCS	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	56	-6.4	18.667	0.1037
1	88	-4.7	29.333	0.1630
2	144	-2.9	48	0.2667
3	176	-1.9	58.667	0.3259
4	208	-1.1	69.333	0.3852
5	224	-0.8	74.667	0.4148
6	256	-0.3	85.333	0.4741
7	328	0.7	109.333	0.6074
8	392	1.9	130.667	0.7259
9	456	2.6	152	0.8444
10	504	3.2	168	0.9333
11	584	4.3	194	1.0815
12	680	5.3	226.67	1.2593
13	744	6.5	248	1.3778

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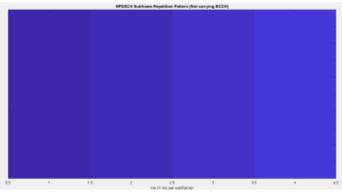

Downlink:

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	88	-6.1	22	0.122
1	144	-4.3	36	0.2
2	176	-3.2	44	0.244
3	208	-2.6	52	0.2889
4	256	-1.6	64	0.3556
5	328	-0.5	82	0.4556
6	392	0.2	98	0.5444
7	472	1.2	118	0.6556
8	536	1.8	134	0.7444
9	616	2.8	154	0.8556
10	680	3.1	170	0.9444
11	776	3.9	194	1.0778
12	904	5.3	226	1.2556
13	1032	6.7	258	1.433

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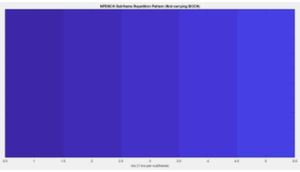

Downlink:

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	120	-5.9	24	0.1333
1	176	-4.2	35.2	0.1956
2	208	-3.3	41.6	0.2311
3	256	-2.7	51.2	0.2844
4	328	-1.3	65.6	0.3644
5	424	-0.2	84.8	0.4711
6	504	0.5	100.08	0.56
7	584	1.3	116.8	0.6489
8	680	2.1	136	0.7556
9	776	2.8	155.2	0.8662
10	872	3.4	174.4	0.9689
11	1000	4.2	200	1.1111
12	1128	5	225.6	1.2533
13	1256	6.2	251.2	1.3956

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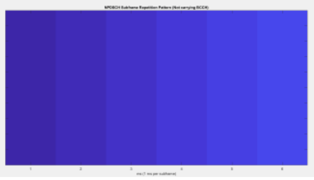

Downlink:

MCS	TBS	SNR [dB]	Data Rate [kbps]	Efficiency
0	152	-5.6	25.333	0.1407
1	208	-4.2	34.667	0.1926
2	256	-3.3	42.667	0.237
3	328	-2.3	54.667	0.3037
4	408	-1	68	0.3778
5	504	-0.2	84	0.4667
6	600	0.4	100	0.5556
7	680	1.2	113.33	0.6296
8	808	2	134.67	0.7481
9	936	2.8	156	0.8667
10	1032	3.5	172	0.9556
11	1192	4.2	198.67	1.1037
12	1352	5.4	225.33	1.2519
13	1544	7	257.33	1.4296

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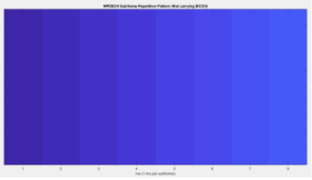

Downlink:

MCS	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	208	-5.5	26	0.1444
1	256	-4.6	32	0.1778
2	328	-3.4	41	0.2278
3	440	-2.2	55	0.3056
4	552	-1.2	69	0.3833
5	680	-0.3	85	0.4722
6	808	0.4	101	0.561
7	968	1.8	121	0.6722
8	1096	2.3	137	0.761
9	1256	2.8	157	0.8722
10	1384	3.6	173	0.9611
11	1608	4.5	201	1.1166
12	1800	5.4	225	1.250
13	2024	6.6	253	1.405

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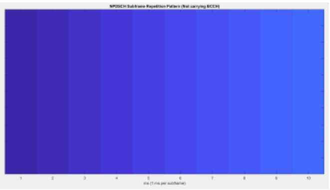

Downlink:

MCS	**TBS**	**SNR [dB]**	**Data Rate [kbps]**	**Efficiency**
0	256	-5.6	25.6	0.1422
1	344	-4.3	34.4	0.1911
2	424	-3.5	42.4	0.2356
3	568	-2	56.8	0.3156
4	680	-1.4	68	0.3778
5	872	-0.1	87.2	0.4844
6	1032	0.7	103.2	0.5733
7	1224	1.7	122.4	0.680
8	1352	2.1	135.2	0.7511
9	1544	2.8	154.4	0.8578
10	1736	3.6	173.6	0.9644
11	2024	4.6	202.4	1.1244
12	2280	5.6	228	1.2667
13	2536	6.5	253.6	1.4089