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System level performance analysis for 3GPP NB-IoT NTN solutions with small satellites and sparse LEO constellations

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Abstract

Complementing and extending the coverage reach of terrestrial networks with satellite access is one of the new connectivity frontiers being addressed on the path to beyond 5G/6G systems. In particular, the realization of almost ubiquitous connectivity in a seamless and cost-affordable manner for low-complexity, power-constrained devices is key to unleashing the potential of the massive IoT market, where the lack of global coverage and international roaming are currently standing as main limiting factors for market growth. To harness this potential, the 3rd Generation Partnership Project (3GPP), the standard development organization in charge of the mobile system specifications, is finalizing a first adaptation of the Narrowband Internet of Things (NB-IoT) protocol for non-terrestrial networks (NB-IoT NTN) as part of Release 17 specifications. This paves the way for integrated terrestrial-to-satellite connectivity solutions that could leverage and help further boost the large and growing 3GPP device and IoT application ecosystem. The NB-IoT NTN protocol is being designed to support different types of satellite deployments, including Geostationary Orbit (GEO), Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) constellations, single-beam and multi-beam satellite platforms, and Earth-moving and Earth-fixed satellite cells. In this context, this paper presents a system level performance analysis of a NB-IoT NTN deployment solution using nanosatellite in sparse LEO constellations, which is one of the most challenging scenarios in terms of achievable coverage footprint and satellite capacity due to the power and size constraints in the satellite platform. A framework for modelling such scenarios is described in the paper and estimations of system performance indicators such as number of connections that can be handled simultaneously, effective satellite footprint coverage area and supported device density (UEs/km^2) are provided for different representative operational configurations (e.g. multi-carrier configurations with anchor and non-anchor carriers) and traffic characteristics (e.g. application payload sizes). Our results demonstrate the technical feasibility of such a system and illustrate some of the relevant trade-offs between the system configurations and communication performance.

Keywords: 5G NB-IoT NTN, CubeSats, system level performance, connection rate

Acronyms/Abbreviations

5G New Radio (5G NR), Block Error Rate (BLER), Cell Area (CA), Connection Density (CD), Connection Rate (CR), Core and Terminals (CT, Downlink (DL), enhanced LTE eNB (ng-eNB), Geostationary Orbit (GEO), Key Performance Indicator (KPI), Long Term Evolution (LTE), Low Earth Orbit (LEO), Massive machine type communications (mMTC), Master Information Block (MIB), Medium Earth Orbit (MEO), Narrowband Internet of Things (NB-IoT), Non-Terrestrial Network (NTN), Orbit Parameter Message (OPM), QoS (Quality of Service), Radio Access Network (RAN), Random Access Channel (RACH), Service Architectures (SA), Solar Synchronous Orbits (SSO), System Information Block (SIB), Technical Specification Group (TSG), Terrestrial Network (TN), Time on Air (ToA), Uplink (UL), User Equipment (UE), Quality of Service (QoS)

1. Introduction

The IoT market has been accelerating in recent years, however the case of ubiquitous coverage has yet to be fully addressed. There has been an effort in 3GPP to standardize cellular NTN based on the well-known terrestrial cellular technologies: NR, eMTC and NB-IoT. Among them, NB-IoT is of special interest due to the ability to work in power-limited scenarios and provide extreme coverage.

Envisioned IoT use-cases in 5G-based satellite connectivity encompass connectivity in isolated regions (such as the arctic, deserts, oceans, jungle, forests, mountains or remote rural) where terrestrial infrastructure is insufficient for, e.g., data collection and tracking of aerial and maritime logistics. The multicast and broadcasting in NTN allow for scalability of some services on a new level with satellite cell sizes being up to hundreds of times larger. In addition, satellite connectivity may provide service continuity, which allows services to keep operating on the move and in the event TN services are disabled [1]. Fig. 1 depicts a Venn diagram of the service categories for new use-cases in 5G satellite access, which we will describe further later.

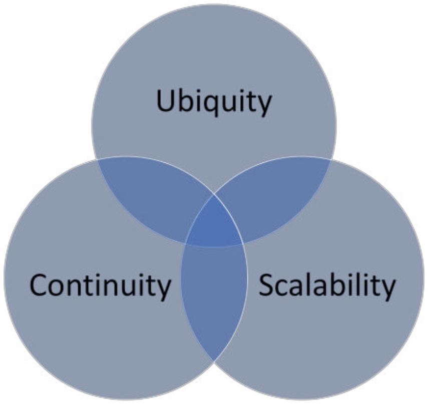

Fig. 1: Venn diagram of service categories for new use-cases in 5G satellite access.

The contribution of this work is threefold:

1. We give a broad overview of standardization work and challenges and solutions for both NTN in general and NB-IoT NTN specifically.
2. We introduce an analytical framework for evaluating NB-IoT NTN and cellular in general.
3. We evaluate the performance of a NB-IoT NTN based on a CubeSat in LEO in terms of peak throughput for UEs, supported connections per second, connections per km^2 and the cell area.

In this paper, the performance of a NTN NB-IoT communication system based on a LEO satellite is analysed at three interdependent levels: The link level, the system level, and the mission level. This work is focused on the performance of a cell with unicast message exchanges.

The link budget assumptions and fading models are based on the works in [2-5]. A MATLAB© simulation for NB-IoT including synchronisation signals, physical and logical channels has been developed based on the LTE toolbox [6] and used for evaluating the BLER performance for the fading profiles defined by 3GPP [2]. The complete analytical framework is proprietary and has been implemented in 3GPP utilizing the simulation results.

The remainder of this paper is organised as follows: Section 2 provides relevant background on the IoT NTN protocol specified by 3GPP, highlighting some of the main challenges and adopted solutions. Section 3 describes a reference scenario representative of NB-IoT NTN deployments using nanosats in LEO constellations, delineating the associated link budgets and operational parameters to be accounted for in the system performance analysis. Accordingly, Section 4 describes the assumptions and methods used to properly model the considered reference scenario and get numerical estimations of system performance indicators such as number of connections that can be handled simultaneously, effective satellite footprint coverage area and supported device density (in UEs/km^2). On this basis, Section 5 provides illustrative results for different configurations such as multi-carrier configurations with anchor and non-anchor carriers, and traffic characteristics such as application payload size. Finally, concluding remarks are given in Section 6.

2. IoT NTN protocol: background and challenges

In this section, the standardisation activities, and relevant technical specifications for NTN NB-IoT are summarised before an overview of the technical challenges and solutions of accommodating NTN with NB-IoT is given. A more in-depth treatment can be found in [7]. The overall architecture and description of (EUTRAN based) and (NG-RAN), respectively can be found in [8] and [9].

2.1 IoT NTN Standardisation

3GPP started a study on the technical challenges of supporting NR in the NTN scenario in Rel-15 [2], which was followed up by a study on potential solutions for supporting NR NTN in Rel-16 [3] and a study on supporting NTN for the mMTC technologies (i.e., eMTC and NB-IoT) in Rel-17 [4]. The NTN NB-IoT and NTN eMTC are commonly referred to under the same umbrella as IoT NTN. The Technical Specification Group (TSG) for Service Architectures (SA) studied satellite access in 5G in [1].

Channel models including NTN propagation and fading are presented in [2] based on the conventional framework of [5]. Technology specific link budgets are presented in [3,4]. By mid-2021 the study on IoT NTN ([4]) concluded and agreements on the specification of IoT NTN followed, see [10-13]. The agreements from RAN, CT and SA are summed up in [14], which serves as a convenient feature description for IoT NTN.

In RAN #96, Release-17, being the largest release from 3GPP ever, was frozen including the definitions for IoT NTN, albeit the standard is well-known not to be stable for commercial implementations in all respects. Rel-17 is targeted to be completely stable by the September (2022) Plenary.

Use-case	Service category	Example
Internet of things with a satellite network	Ubiquity	RF-capability limited IoT devices
Global (cellular)	Ubiquity	Global cellular service

satellite overlay		
Roaming between TN and NTN	Continuity	Shipping, tracking, logistics
Temporary use of a satellite component	Continuity	Crisis, Natural disasters, war (Disabling TN)
Optimal routing over TN and NTN	Continuity, Ubiquity	Remote automation, factories
Broadcast and multicast with satellite overlay	Scalability	TV, Radio, Streaming, IoT device updates

Table 1: Examples of use-cases for 5G NTN

2.2 NB-IoT Use-case and performance targets.

The use-cases of cellular NTN are categorised in [1] as "Service Continuity", "Service Ubiquity" and "Service Scalability" as depicted in Fig. 1. Some example use-cases are listed in Table 1 to illustrate the novelty of 5G satellite access and the potential productivity and business growth that it enables. The NTN technologies are to be evaluated against the same KPIs as defined in [15] for TN. However, in the context of Internet of Things and NB-IoT the more interesting use-cases are Service Ubiquity and Service Scalability, and in turn, KPIs such as the coverage or capacity of an NTN cell and the energy consumption of UEs are of interest.

2.3 NTN Challenges and Rel-17 Solutions

The challenges involved in moving from a terrestrial cellular network to a cellular NTN are outlined in [2]. In the following subsections we outline the challenges in relation to the change in the physical scenario, the introduction of moving base-stations and temporally intermittent coverage.

2.3.1 Changes in physical scenario

A broad group of challenges are based on the change in physical environment from terrestrial to the non-terrestrial case:

1. A larger propagation distance resulting in delays and increased path loss.
2. A fading environment with an arguable better LOS probability and fewer significant paths, but also dependency on the elevation angle from the UE towards the satellite.
3. Additional atmospheric losses in the link budget, as well as the change in antenna characteristics for satellite payloads.

The link-budget has been verified for the various NTN technologies in [3,4,16]. Here NB-IoT has the distinct advantage of being intended for power-limited use-case and extreme coverage scenarios. The narrow bandwidth transmissions that are allowed in the UL means that UEs can achieve an acceptable link budget in the UL direction even with omnidirectional antennas.

The fading environment has largely been found to be on par or even better than the fading environments known from terrestrial cellular networks [16].

The large and variable propagation delay between ng-eNBs and UEs causes asynchrony between the UL and DL. To align uplink and downlink frames for each UE a common timing advance parameter is broadcast as a reference for all UEs and a UE-specific offset from this reference, K_{offset}, has been introduced to account for variability in individual UE placement and satellite movement. These parameters are used to artificially shift the OFDM timeslots for the uplink forwards such that subframe n are aligned for UL and DL as seen at the UE. Furthermore, long UL transmissions are segmented with samples being inserted or discarded as needed to pre-compensate for the UL over each segment.

2.3.2 Introduction of base-station movement

Beyond these challenges are the challenges of having a moving ng-eNB in the NGSO case:

4. An RSRP that is a function of time even for stationary UEs.
5. Doppler effect due to the high relative speed between the ng-eNB and UE.
6. Tracking Areas are decoupled from the ng-eNB.

During a satellite fly-by the SNR of a UE will change over time, which should be accounted for by appropriate selection of modulation and coding scheme.

The UE is responsible for synchronizing to the DL, i.e., dealing with Doppler in the DL. The ng-eNB will indicate the last two MSBs of the ARFCN if the channel is on a 100 kHz raster, otherwise wherever a 200 kHz raster is used there is no such indication. This indication allows the UE to quickly adjust the carrier even in the most extreme Doppler conditions.

In the UL the UE must pre-compensate for the Doppler that the ng-eNB will see to avoid ISI. To facilitate this function the instantaneous ephemeris of the serving satellite is transmitted in SIB31 either as a pair of positional and velocity state vectors or as osculating Keplerian parameters. This is consistent with the OPM format recommended by the CCSDS [17].

Tracking areas (TA) have been defined as fixed by geolocation since in the NGSO case the cell will move, and so in contrast to terrestrial cellular networks, TAs and cell have been decoupled. The ng-eNB is allowed to send a Tracking Area List (TAL) and the UE shall only do TAU if it none of the TAs in the TAL kept by the UE is present in the TAL broadcast by the ng-eNB.

2.3.3 Temporal discontinuity in coverage

Lastly, the challenge of discontinuous coverage was identified. Discontinuous coverage in NTN is experienced in the temporal domain rather than the spatial domain, i.e., global, or near-global coverage can be obtained with a single satellite, but in an intermittent manner. During the rollout of satellite constellations service will necessarily be discontinuous coverage due to the limited number of satellites in orbit. Challenges related to discontinuous coverage regard differentiating UE behavior while in- and out of coverage:

7. Coverage prediction.
8. Energy management.

Coverage prediction is facilitated by SIB32. In the case of earth-fixed cells a scheduled ON-time for the cell is included in SIB32 to indicate the next coverage period to a device. In the earth-moving cell scenario prediction is based on SGP4 parameters transmitted in SIB32. SGP4 is a satellite industry standard for long term propagation. SGP4 is an analytical mean element set propagator, which allows for fast computation of the approximate satellite position up to weeks or months forward in time. This long-term prediction always has some error, so the SGP4 propagator is not a solution for UL synchronization, but the error grows slowly over time, which makes it advantageous for long-term prediction. SIB32 is updated by the network operator with a periodicity that keeps the SGP4 parameters valid.

Once a UE has detected a SIB32 it knows that the cell provides discontinuous coverage. A UE in discontinuous coverage may shut-off all AS procedures when out-of-coverage and resume its AS procedures when it gets back in coverage. This is tantamount to doing PSM when the UE is out-of-coverage with a wake-up time that is set in advance of the predicted start of a coverage period.

3. Reference scenario: link budgets and operational aspects

The reference scenario considered in this work for system level performance characterization is that of a sparse Walker constellation of CubeSats in LEO. Solar Synchronous Orbits (SSO) are considered with orbital heights in the range of 550 km and resulting in orbital speeds of ~7.6 km/s, speeds over earth's surface of ~7 km/s and are typically very close circular polar orbits. The sparse nature of the constellation means that UEs will experience discontinuous coverage, however the Walker constellation will cover the entire surface of Earth over time.

Considered link budgets are consistent with the so-called Set-4 scenario reported in [4]. Specifically, it is considered that scintillation in the atmosphere is 2.2 dB while atmospheric absorption is considered at 0.1 dB. A 3 dB polarization mismatch and another 3 dB shadowing allowance are considered. The noise-figure (NF) for the UE is 7 dB while it is fixed at 4.5 dB for the ng-eNB.

The link budget was evaluated for the edge of the set-4 NTN cell in [4, 18] to be -11.95 dB for DL and -3.1 dB for 15 kHz single-tone UL. This is a sufficient but far from optimistic margin for providing a cellular NTN service. However, these figures are for a cell width of 1700 km, which is very large, and UEs that are in front of the satellite's path on the ground may be on the cell edge but will soon find themselves in better conditions in the NGSO scenario. In the LEO case we have found in [16,19] that the obtainable SNR for a smaller cell using a CubeSat platform is up to -2 dB in the DL and up to 4.8 dB for 3.75kHz single-tone in the UL. This is a much better operation point for NB-IoT and closer to the use-case and parameters that we are investigating in this paper for acommercial NB-IoT NTN scenario.

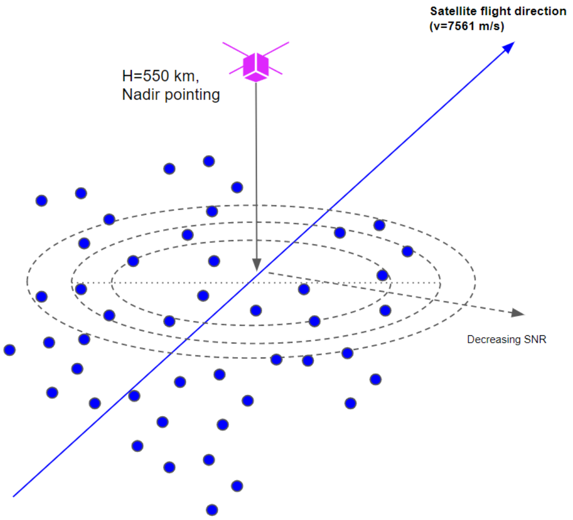

Fig. 2: Reference scenario. A satellite in its orbital track (purple) providing coverage to a set of UEs (in blue)

From an operational perspective, it is considered that an IoT device awakes when it knows a satellite might be in range (i.e., knowing the time for which a predicted elevation angle goes above a given threshold). Then, it initiates cell search, reads MIB/SIB, performs random access, and then exchanges procedural messaging. We consider that one IoT device sends one application message per pass. Terminals are uniformly distributed on Earth.

The Link budget parameters considered in this work are listed in Table 2.

Parameter	Value
UL Carrier frequency	1.9 GHz
DL Carrier frequency	2.1 GHz
Path Loss	'Friis'
Shadowing	3.0 dB
Polarization	3.0 dB

Atmospheric absorption	0.1 dB
Scintillation	2.2 dB

Table 2: Link budget parameters

The satellite under consideration is a CubeSat, 3U to 6U weighing at most #U 20.33, which makes the cost of launch relatively small especially when launching multiple CubeSats from the same launch vehicle or joining a CubeSat launch with another mission. The lifetime of CubeSats range from a few years to tens of years depending on initial orbit height and the mass of the CubeSat [20].

Solar panels delivering up to 40W of power is feasible for a 3U CubeSat. In this scenario it is assumed that 32 watts are available for the RF front-end. At an assumed 25% efficiency for the RF power amplifier for OFDM, which yields 8 watts transmission power. We shall investigate three power levels, 2 watt, 4 watt and 8 watt as noted in Table 3.

A 9.3dB gain antenna with a 50x30 degree half power bandwidth (HPBW) and a 4 dB noise-figure is assumed yielding a G/T of -19.47 dB. The transmitted power can be varied between three modes: 33 dBm, 36 dBm and 39 dBm. The parameters are listed in **Table 3**.

Parameter	Value
Orbital Height	550 km
Total transmission power	{33, 36, 39} dBm
Power for RF front-end	24 Watts
Peak antenna gain	9.3 dB
Half power bandwidth	50 degrees ; 30 degrees (cross track ; along track)
Noise Figure	4 dB
G/T	-19.5 dB

Table 3: Satellite parameters

The UE is an IoT device with an omnidirectional antenna, i.e. an antenna gain at 0 dB for every angle. The noise-figure of the UE is 7dB, which is typical for a UE chipset for LTE-m/NB-IoT. This results in a G/T of -31.7 dB. These parameters are listed in Table 4.

Parameter	Value
Transmission power	23 dBm
Peak antenna gain	9.3 dB
Noise Figure	7 dB
G/T	-31.7 dB
Transmission mode	3.75 kHz

Table 4: UE Parameters

The UE is considered to be stationary, and the rotation of the earth is neglected, so the cross-axis coordinate of each UE remains constant. Two traffic modes are defined for the UE:

1. The UE transmits once per satellite fly-by:
    a. Default: The UE wakes-up, synchronizes and transmits at a random time doing the fly-over.
    b. Optimal: The UE wakes-up ahead of the optimal time for beginning a procedural exchange, synchronizes and only initiates a procedural exchange at the optimal time.

Parameter	Value
Number UL channels	2
Number DL channels	2
Application payload size	50 Bytes
RACH format	0
CE0: RAO periodicity	80 ms
CE0: #repetitions	2
CE0: #subcarriers	12
CE0: #reattemps	3
CE0: threshold	-3 dB
CE1: RAO periodicity	80 ms
CE1: #repetitions	8
CE1: #subcarriers	24
CE1: #reattemps	4
CE1: threshold	-
defaultPagingCycle-r13 (T)	128
nB-r13 (nB)	T/2

Table 5: RAN configuration

The parameters for the RAN configuration of resources are found in Table 5. The RACH and Paging channel have been initially sized such that the paging capacity is greater than the RACH capacity, which is greater than the capacity in PUSCH/PDSCH in terms of connection rate.

4. System model and methodology for performance analysis

The analytical framework of the NTN communications system is layered in a hierarchical manner. First, the link-level performance is analysed in terms of fading performance or block error rate (BLER) during transmissions, link-budget analysis and basic peak PHY bit-rate analysis. Secondly, performance of the network configuration conditioned on the link-level performance is analysed in terms of Paging-, RACH- and messaging capacity along with cell shape and size.

4.1 Link-level performance

Performance at the link-level is dictated by the achievable link-budget the fading performance in the specific environment. In NB-IoT, the UL allows for either single-tone (ST) or multi-tone (MT) transmission which, depending on the available power headroom in the link-budget, may provide increased transmission bandwidth. In NB-IoT the reduced 3.75 kHz SCS ST transmission provides an even further reduction in the required power for UL transmissions. The link budget and fading performance are evaluated in this work for a cell pass in the same way as for [16], for the atmospheric loss parameters of [4] and the NTN_TDL_C model [2] for ST transmissions with 3.75 kHz ST. The obtained SNR thresholds for the UL for the different combinations of modulation and coding schemes (MCS) and number of repetitions are shown in Table 6.

Reps MCS	1	2	4	8
0	*0.35*	*-2.20*	*-3.90*	*-4.14*
1	*1.90*	*-1.10*	*-3.10*	*-3.25*
2	*0.96*	*-1.47*	*-3.39*	*-3.66*
3	*1.95*	*-0.80*	*-2.45*	*-2.79*
4	*2.94*	*0.40*	*-2.05*	*-2.12*
5	*4.20*	*0.70*	*-1.25*	*-1.59*
6	*4.80*	*1.30*	*-1.00*	*-1.16*
7	*5.80*	*1.60*	*-0.35*	*-0.90*
8	*6.75*	*2.08*	*-0.07*	*-0.58*
9	*7.65*	*2.70*	*0.55*	*-0.12*
10	*8.35*	*2.80*	*0.70*	*-0.06*

Table 6: 3.75 kHz SCS UL SNR thresholds in dB for NTN_CDL_C model in rural conditions at 60-degree elevation angle and a UE movement speed of 11 km/h.

Given a fixed link budget and fading model, the achievable physical bitrate, T_{PHY}, can be determined. The number of subframes, SF, required to transmit a transport block can be looked up in [21] for the range of supported transport block sizes (TBS) given a payload block length of B bits. Furthermore, based on **Table 6**, the applicable number of repetitions and MCS to transmit such transport block can be found for a given SNR. The MCS, TBS and number of repetitions are found together under the condition of minimizing the time on air, ToA [ms], in (1). Practically, (1) can be solved fast by matrix operations.

$$ToA_B = \text{minimize}(SF(B, MCS) \cdot nReps(y, MCS))$$
(1)

Considering only the overhead of NPSS, NSSS and NPBCH - the PHY-rate is simply the number of Bytes that can be transmitted per second as per (2).

$$T_{PHY} = B \cdot \left(\frac{3}{4} \cdot \frac{10^3}{ToA_B}\right) \qquad (2)$$

T_{PHY} is determined separately for DL and UL as T_{PHY}^{PDSCH} for PDSCH, and T_{PHY}^{PUSCH} for PUSCH by utilizing the respective tables in [21] for PUSCH and PDSCH.

4.2 System-level performance

Performance at the system-level is determined by the cell configuration, which trades-off RACH-, paging-, and data-capacity for static and dynamic overheads. An example of a static overhead is that of RACH and paging, which limits the resources available for PUSCH and PDSCH, respectively. Whereas a dynamic overhead is encountered in PUSCH and PDSCH as signalling overhead depending on the procedure. Examples of NAS procedures are Attach/Detach, Tracking Area Update and Data over NAS (DoNAS). Further information regarding these procedures can be found in [22,23]. These NAS procedures involve messages in the RAN that do not carry payload data but are essential for setting up the cellular system. In this work, these messages will be regarded as signalling/overhead when calculating the throughput as the throughput shall be defined as the number of app-payload bytes transmitted per second.

4.2.1 Peak throughput

After attaching to the network, an idle UE may go through the random access (RA) stage before initiating a Scheduling Request to open a data radio bearer. While this is not a mandatory feature in NB-IoT UEs, it is the conventional approach of LTE. In this manner when transmitting large amounts of data over the user plane (U-plane) only a single control packet must be sent for each transport block to be transmitted in PUSCH/PDSCH. Once enough transport blocks have been sent the messaging for establishing and tearing down the radio bearer becomes negligible, and we have an effective data rate of (3).

$$T_{UP} = T_{PHY} \cdot \frac{1}{1 + \dfrac{SF(DCI)}{SF(B, MCS) \cdot nReps(\gamma, MCS)}} \qquad (3)$$

Another transmission mode is to utilize the control plane (CP)-optimized flow, which is a mandatory feature for NB-IoT UEs. This feature, also known as Data-over-NAS (DoNAS), allows for transmission of smaller payloads without setting up a radio bearer. That is, by this method a payload is attached onto an otherwise small control message so there is no need for further signalling. As an initial estimate one may consider that there are 4 messages being exchanged on PUSCH/PDSCH apart from the payload that is being piggybacked, which yields (4).

$$T_{CP} = T_{PHY} \cdot \frac{1}{4} \tag{4}$$

Eq. (1)-(4) provide a basis for an initial assessment of the peak throughput throughout a cell. However, to assess the actual behaviour throughout a cell with a better granularity, we: (i) compute the relevant geometry throughout the footprint of a satellite, (ii) compute the time to exchange messages sequences as implicit in Eq. (1)-(4) and traverse the geometric grid and link-budget of the footprint over time, (iii) estimate configured overheads from e.g. RACH and Paging, and finally (iv) compute the remaining PDSCH/PUSCH capacity for the exchange of the specified message sequences.

4.2.2 Capacity – supported connection rate

The capacity – in terms of supported connection rate - can be calculated throughout the entire satellite footprint as the inverse of the “sum time on air” during the messaging sequences on PUSCH and PDSCH, respectively. Finally, additional non-anchor carriers should be accounted for and the minimal PUSCH or PDSCH capacity would bottleneck the system capacity. A mixture of traffic with different traffic characteristics (payload size and transmission rate) and various transmission procedures (Attach, Tracking Area Update, DoNAS) can be accounted for by computing the CDF of capacity throughout the footprint of the satellite and then sampling the distributions according to the traffic profile.

The capacity can be denoted in terms of connection rate (CR), which is the number for UEs per second that can complete a given procedure (or message exchange) such as DoNAS. CR is defined in (5).

$$CR = \min(CR^{PDSCH}, CR^{PUSCH}) \tag{5}$$

For

$$CR^{PDSCH} = \frac{O^{PDSCH}_{anchor} + O^{PDSCH}_{nonanchor} \cdot (n_{ch} - 1)}{TOA^{PDSCH}_{Exchange}}$$

$$CR^{PUSCH} = \frac{O^{PUSCH} \cdot n_{ch}}{TOA^{PUSCH}_{Exchange}} \cdot \frac{180}{BW}$$

Where n_{ch} is the number of NB-IoT carriers and O^{PDSCH}_{anchor}, $O^{PDSCH}_{nonanchor}$, and O^{PUSCH} are static overhead fractions on PDSCH and PUSCH, respectively for anchor and non-anchor carriers and $ToA_{exchange}$ is the time on air through the entire procedural exchange given for PUSCH or PDSCH, respectively.

4.2.3 Capacity – supported connection density

Another denomination for capacity is the Connection density (CD) which is the supported density of procedural exchanges throughout the cell. CD is defined in (6).

$$CD = \frac{CR \cdot t}{W \cdot V_g \cdot t} = \frac{CR}{W \cdot V_g} \tag{6}$$

Where W is the width of the cell and V_g is the velocity of the satellite over the surface of earth.

4.2.4 Cell area and width

We define a cell as a logical entity. A cell encompasses the region where a UE can synchronize and successfully exchange all messaging before the LEO satellite has moved too far away. NAS procedures can be completed successfully anywhere between two borders defined by the earliest possible synchronisation time and latest possible time to successfully end a procedural message exchange. The cell area (CA) is then computed as the area that is encompassed by these two boundaries. The cell width is the maximal distance cross-track within the cell.

4.2.5 Paging capacity and overhead

In Eq. (5) CR is defined as a function of the static overhead on PDSCH and PUSCH. The static overhead on PDSCH depends on the transmitted System Information Blocks (SIB)s and the time allocated for paging. The overhead in the uplink depends on the amount of resources allocated for RACH. Dynamic overhead, i.e., all messages not carrying a payload including control in PDCCH and PUCCH are included in the described model for message exchanges.

The paging overhead is described as in [4], as the product of the number of UEs that can be paged per paging opportunity, $N_{UEperPO}$, the number of paging opportunities per second, R_{PO}, and finally the number of carriers n_{ch}.

$$C_{paging} = n_{ch} \cdot R_{PO} \cdot N_{UEperPO} \tag{7}$$

In NB-IoT we calculate the number of paging occasions per second as (8), which we insert into (7).

$$R_{PO} = 100 \cdot nB/T \tag{8}$$

Where nB and T are system parameters, which configure the rate of paging frames and -occasions. This is the case for both eMTC and NB-IoT because not every frame may carry paging due to repetitions incurred from the coverage extension capabilities.

The paging overhead can be found as the ratio between the average number of paging opportunities in a second and the total number of subframes within a second as per (9).

$$O_{paging} = \frac{R_{PO}}{10^3} \tag{9}$$

4.2.6 Random access capacity and overhead

The capacity, or the number of successful access grants per RAO, of the random-access stage is tightly coupled to the blocking rate of the same, which is determined by the offered load, the amount of resources dedicated to RACH and the number of reattempts that are allowed for each CE-level in the RACH. The blocking rate, P_{Block}, can be found as in [24]. To evaluate the capacity of RACH we shall define the capacity of RACH as the successful offered load on RACH as per Eq. (10).

$$C_{RACH} = (1 - P_{Block}) \cdot \lambda_{RACH} \tag{10}$$

Here, λ_{RACH} is the sum of the load offered to all CE levels without considering reattempts. However, the blocking probability is evaluated over all CE-levels such that reattempts and load increases between CE-levels are accounted for. This can be accomplished by successive numerical evaluations of the Markov model for the process in **Fig. 3** in a gradient descent manner.

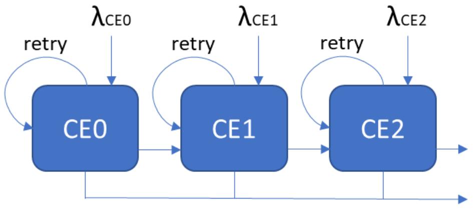

Fig. 3: NB-IoT RACH as a Markov chain

The overhead of the RACH is evaluated as the sum of the ratio between RACH time-frequency resources per random access opportunity (RAO) and total amount of PUSCH resources between the beginning of consecutive RAOs for each CE-level.

5. Results and Discussion

The link budget is plotted in Fig. 4 and Fig. 5 given the parameters listed in Table 2 through Table 4 yielding a maximum SNR in the DL of -1.4 dB and a maximum SNR in the UL of 4 dB for a transmission power of 36 dB. The corresponding maximal throughputs are listed in Table 7. Notice that the considered maximal power per channel is half of the available transmission power since the system configuration dictates two channels both in the UL and DL.

Here, the throughput is limited by the maximal number of repetitions that are being considered, which in this case is 8 repetitions. The UP rate in the DL is lower than the CP rate whereas the reverse is true for the UL. This is due to a) the relatively higher bitrate in the DL where the bandwidth is 180kHz and the single DCI therefore has a relatively larger impact on the throughput b) the assumption of all messages for a CP exchange of data are assumed equal.

TX @ 30 dBm	UL	DL
Maximal SNR	4 dB	-7.4 dB
PHY rate	0.23 kB/s	0.9375
UP rate	0.2 kB/s	.007 kB/s
CP rate	0.059 kB/s	.23 kB/s
TX @ 33 dBm	UL	DL
Maximal SNR	4 dB	-4.4 dB
PHY rate	0.23 kB/s	2.34 kB/s
UP rate	0.2 kB/s	0.26 kB/s
CP rate	0.059 kB/s	0.59 kB/s
TX @ 36 dBm	UL	DL
Maximal SNR	4 dB	-1.4 dB
PHY rate	0.23 kB/s	6.25 kB/s
UP rate	0.2 kB/s	0.53 kB/s
CP rate	0.059 kB/s	1.56 kB/s

Table 7: Maximum throughputs at the three considered transmission power levels in the DL and 3.75 kHz ST-transmissions in the UL.

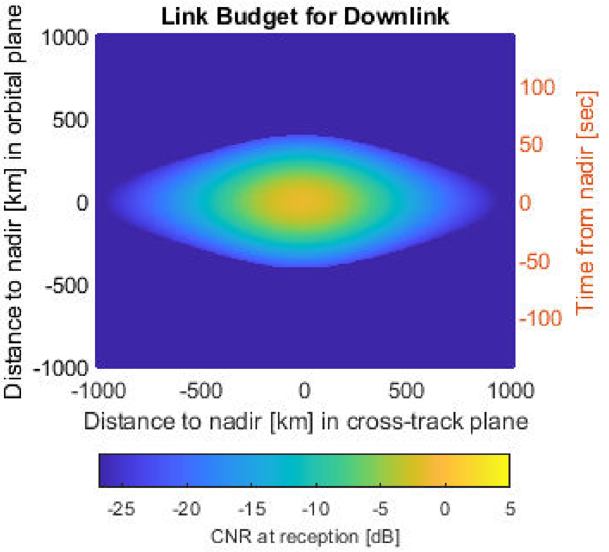

Fig. 4: Link-budget for downlink for DL TX power of 36 dBm per carrier.

5.1 System level performance

The paging capacity was found to be 1600 opportunities/s, well above the expected cpapacity – so in theory the number of paging ocassions could be scaled down by a factor of 2 to 4. However, the paging mechanism in Rel-17 NB-IoT is expected to introduce some overhead on the paging load due to the exact TAs of individual UEs not being known in many cases where a list of TAs is the best knowledge the network maintains on a UE position. The overhead from paging on PDSCH carriers, is only 5% on PDSCH where an additional 38% overhead from synchronisation signals, broadcasting and system information blocks was found for the anchor carrier.

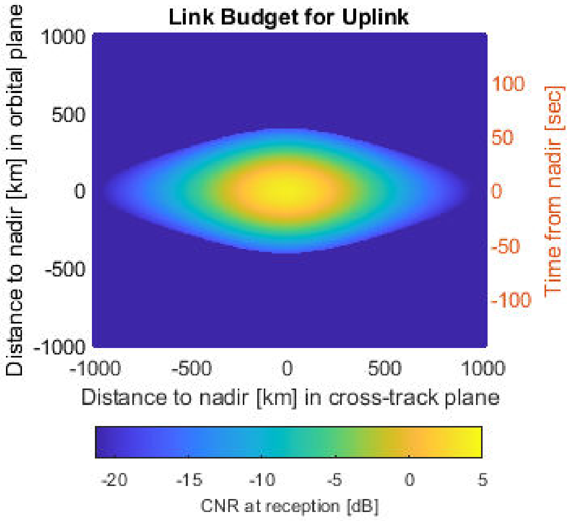

Fig. 5: Link-budget for uplink

The RACH capacity was evaluated and can be found in Fig. 6 where a capacity of 200 attempts per second leads to a success rate of 99.5%. This results in 31.5% overhead on the UL carriers.

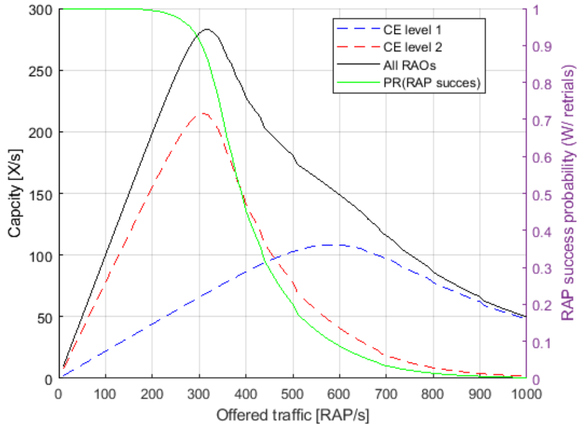

Fig. 6: Random access channel capacity

5.1.1 50 Bytes MO DoNAS

First, we shall consider the exchange of the 50 Bytes payload specified in Table 5 in the mobile originating (MO) direction, that is as an application payload generated by the UE and transmitted towards the ng-eNB.

The achievable connection rate throughout the cell at 36 dBm TX power in the DL is plotted in **Error! Reference source not found.** Intuitively the capacity usage of UEs on the edges of the cell take up more resources than UEs near nadir. The cell shape in this LEO scenario is squeezed in the forward direction while UEs are synchronizing to the cell and - under the assumption that synchronisation can be maintained – the shape drags a 'tail' behind it where UEs can do data exchanges, but at a capacity cost for the cell.

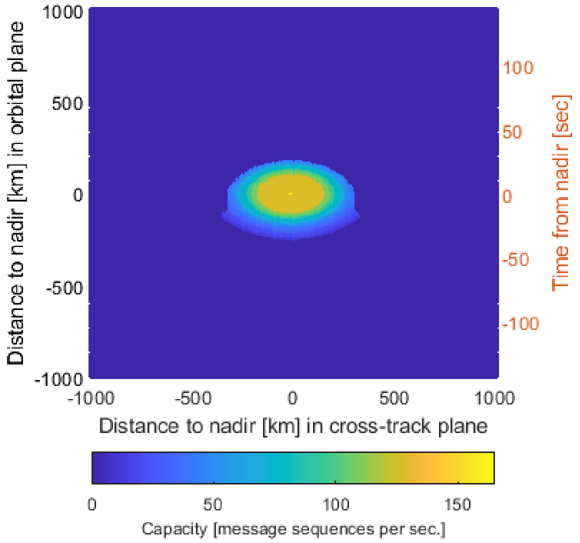

Fig. 7: Heatmap of achievable connection rates for 50 Bytes application payload MO DoNAS at a DL TX power of 36 dBm per carrier.

Each UE performs one procedural exchange per fly-over. The two transmission modes investigated were 'default mode' where the UE wakes up and starts exchanging messages at a random time and 'optimal mode' where UEs wake up and wait for the optimal time to start exchanging messages. The CDF for these behaviours are plotted in Fig. 8 for a DL TX power of 36 dBm. The mean values for connection rate and connection density are listed in Table 8 for the three DL transmission power levels.

TX @ 30 dBm	
Coverage Area	28,183 km^2
Mean 'Default' CR	7.4 conn/s
Mean 'Default' CD	0.0029 conn/km^2
Mean 'Optimal' CR	13.4 conn/s
Mean 'Optimal' CD	0.0053 conn/km^2
TX @ 33 dBm	
Coverage Area	136,860 km^2
Mean 'Default' CR	30.4 conn/s
Mean 'Default' CD	0.0076 conn/km^2
Mean 'Optimal' CR	49.2 conn/s
Mean 'Optimal' CD	0.0123 conn/km^2

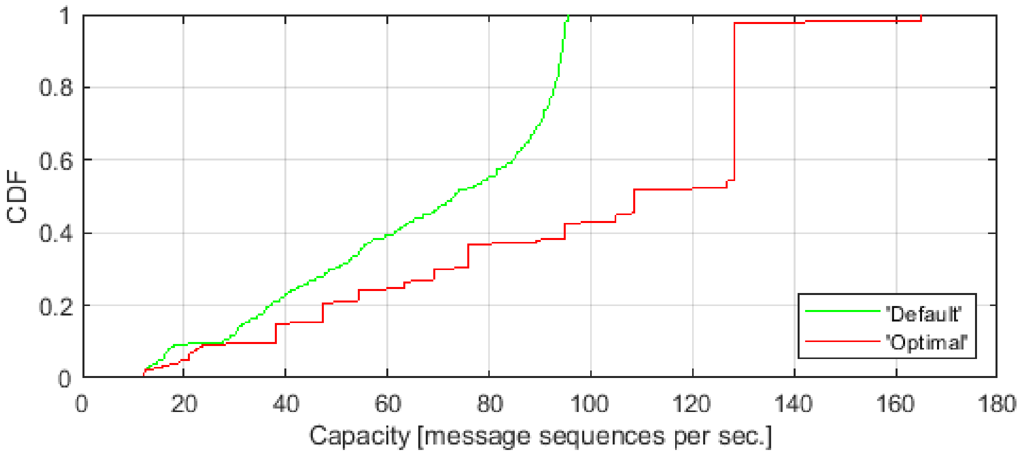

Fig. 8: CDF of achievable connection rates in the 'Default' and 'Optimal' operation modes for 50B application payload MO DoNAS at a DL TX power of 36 dBm per carrier.

TX @ 36 dBm	
Coverage Area	216,010 km^2
Mean 'Default' CR	66.2 conn/s
Mean 'Default' CD	0.0137 conn/km^2
Mean 'Optimal' CR	95.6 conn/s
Mean 'Optimal' CD	0.0197 conn/km^2

Table 8: The mean connection rates for 50B application payload MO DoNAS.

Given the same power budget, one could have 4 times as many DL carriers with 30 dBm per carrier relative to the two carriers for DL at 36 dBm per carrier. The system with more carriers would then have a larger ratio of non-anchor carriers to anchor carriers, which would boost the achievable capacity. However, the cost of such a configuration would be the cell coverage area as per Table 8 and furthermore the QoS of individual UEs would also degrade.

5.1.2 50 Bytes MT DoNAS

In the case of mobile-terminating (MT) traffic the 50B application payload is generated outside the core network and transmitted from the ng-eNB to the UE. We assume that the UE was paged correctly and otherwise evaluate the procedural exchange in the same way, except that the application payload is now encapsulated in a DL NAS message.

The resulting connection rates are given in Table 9. Here PDSCH is a strong bottleneck compared to PUSCH and the capacity is markedly lower than for MT transmissions. This is an effect of the limited power budget onboard a satellite. However, for a multicast service which is more dependent on coverage area than unicast capacity, there is ample opportunity to scale well beyond conventional TN as the cell coverage area remains above 200k km.

TX @ 30 dBm	
Coverage Area	22,708 km^2
Mean 'Default' CR	5.1 conn/s
Mean 'Default' CD	0.0021 conn/km^2
Mean 'Optimal' CR	8.2 conn/s
Mean 'Optimal' CD	0.0034 conn/km^2
TX @ 33 dBm	
Coverage Area	140,320 km^2
Mean 'Default' CR	17.6 conn/s
Mean 'Default' CD	0.0043 conn/km^2
Mean 'Optimal' CR	28.1 conn/s
Mean 'Optimal' CD	0.0069 conn/km^2
TX @ 36 dBm	
Coverage Area	232,970 km^2
Mean 'Default' CR	36.7 conn/s
Mean 'Default' CD	0.0072 conn/km^2
Mean 'Optimal' CR	59.3 conn/s
Mean 'Optimal' CD	0.0116 conn/km^2

Table 9: The mean connection rates for 50B application payload MT DoNAS.

5.3 System level performance: trade-offs

The communication system – given a fixed power budget then becomes a trade-off between three service KPIs: Coverage, QoS and system capacity. One can consider the amount of power and spectrum available to be constitute available resources for configuring the service. In Fig. 9, the available resources are the sum length of the service vectors. The following results are on performance trade-offs within the defined scenario.

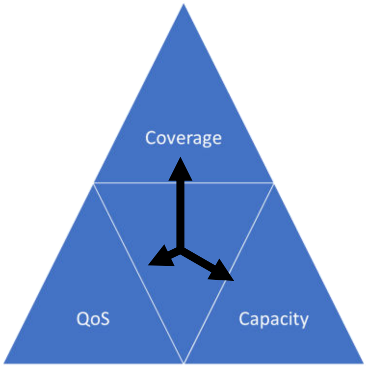

Fig. 9: Service performance trade-off

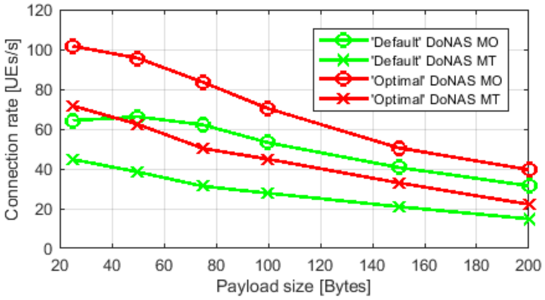

Fig. 10: Mean connection rate as a function of the payload size in bytes for both MO and MT DoNAS.

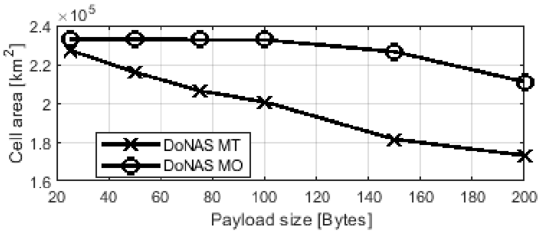

Fig. 11: Cell coverage area as a function of payload size for both MO and MT DoNAS.

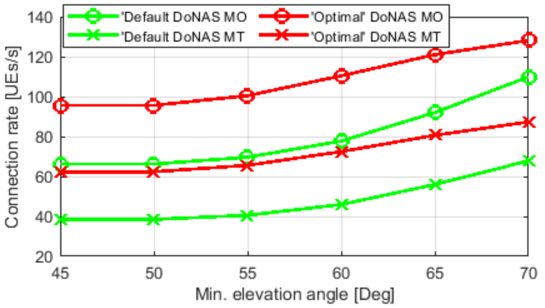

Fig. 12: Mean connection rate as a function of a minimal elevation angle for both MO and MT DoNAS.

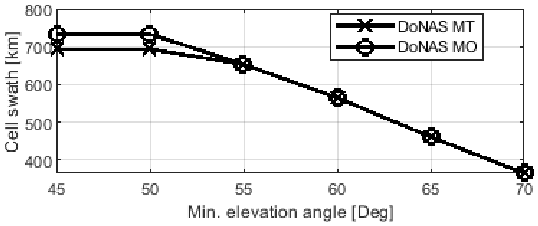

Fig. 13: Cell coverage area as a function of a minimal elevation angle for both MO and MT DoNAS.

Intuitively an increase in payload sizes yields a decrease in the capacity as per Fig. 10. This effect is greater for MO traffic due to the limited bandwidth of PUSCH transmissions in this work (3.75kHz).

The cell coverage area is decreased as a function of the payload size too as can be observed in Fig. 11 since we defined the cell coverage area limit as the latest time a UE may begin a transmission to finish it successfully. Here PDSCH is a greater bottleneck due to its greater bandwidth (180 kHz) and in turn relatively higher amount of noise and thus worse received SNR.

Coverage could be sacrificed in order to achieve a higher capacity by restricting cell access to a given area by for example requiring a minimal elevation angle to allow the UE access – in practise realisable by accessing barring the RACH with a corresponding SNR threshold.

The mean connection rate as a function of a minimum elevation angle requirement is plotted in Fig. 12 where we see a positive correlation. The more restrictive the cell is, only allowing UEs better link-budget conditions to transmit, the higher the capacity of the cell becomes. The flip side of this trade-off is depicted in Fig. 13 where the cell coverage area can be seen to be equivalently negatively correlated.

5.3 System level performance: Scalability

The scalability of NB-IoT NTN is explored in Fig. 14 where the capacity is evaluated against the number of carrier pairs. Notice that here each PDSCH carrier is transmitted at 36 dBm and only the first carrier is considered an anchor. With a sufficient power budget, a very large number of connections per second can be supported in NB-IoT NTN.

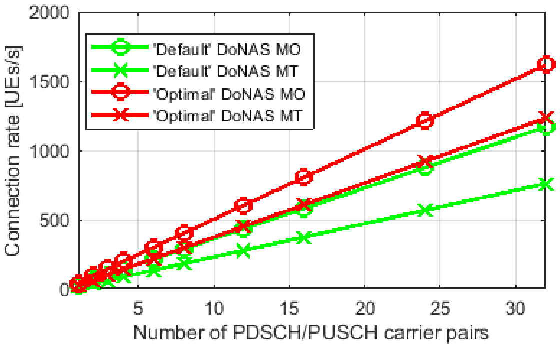

Fig. 14: Mean connection rate as a function of the number of PUSCH/PDSCH carrier pairs.

The power budget required to support 32 carriers at 36 dBm transmission power is 640 watts assuming an efficiency of 20% for the RF-front ends power amplifier. This is out of range for a CubeSat, but 4 carries could be within reason allowing for several hundreds of connections per second. As we have seen the capacity can be further enhanced by restricting access to UEs in better conditions.

6. Conclusions

In this work, a framework for performance analysis of NB-IoT NTN at the system-level has been presented along with numerical results for the performance from a UE perspective and from a system perspective.

The analytical framework covers peak-throughput and latency (time on air + propagation), connection rate and connection density along with defining cell shape and size. The main finding for the presented LEO scenario is that a service for devices reporting sporadically - and especially small packets – can be supported for numerous devices. While the connection density was found to be 0.0197 conn/km^2 for the 50B MO DoNAS traffic, this is based on every UE going through one exchange per fly-by and no restriction on access for UEs in poor conditions.

The achievable connection density should be scaled by the ratio of the mean transmission interval for UEs to the orbital period of ~1.6 hours. Furthermore, the number of satellites in the constellation providing service for the UEs would provide another scaling factor. So, a mean transmission rate of once per day with a constellation of 16 satellites would yield an achievable density of 4.73 connections per km^2 over a coverage area of 232k km, which could be scaled up even further by utilizing additional carriers.

6. Further work

The performance of an NTN communication system is also impacted at the satellite mission level in terms of orbit and constellation patterns. Specifically, the validity time of the ephemeris information included in SIB31 and SIB32 are impacted by the orbit and the accuracy and delay of the ephemeris-determination solutions. It is nontrivial from a communication systems perspective that the validity time of various parameters is not deterministic but depends on the specific orbit of the satellite with some expected variation due to randomness.

In this work it was been assumed that the UE would perform UL compensation correctly, but it is paramount that the longevity of validity of SIB31 broadcasts is investigated to fix rate of SIB31 updates to allow for UEs synchronize the UL for the duration of transmission or optimally for an entire procedural exchange.

SIB32 is used for long-term prediction of coverage opportunities, from a few days to a week ahead in time, and so the SGP4 ephemeris that is broadcasted in SIB32 should be updated at a pace such that it is reasonably accurate within a week for any UE that happens to receive the broadcast. The UE energy consumption in the discontinuous coverage case is heavily impacted by the time spent without coverage and the time spent searching for networks should the coverage prediction fail. So, investigations of SIB32 are warranted not only for configuring the SIB32 update rate in practise, but also for evaluations of the UE power consumption.

References

[1] 3GPP, Study on using satellite access in 5G (Release 16), Technical Report (TR) 22.822, V16.0.0 (2018-07)
[2] 3GPP, Study on New Radio (NR) to support non-terrestrial networks (Release 15), Technical Report (TR) 38.811, V15.4.0 (2020-09).
[3] 3GPP, Solutions for NR to support non-terrestrial networks (NTN) (Release 16), Technical Report (TR) 38.821, V16.1.0 (2021-05)
[4] 3GPP, Study on Narrow-Band Internet of Things (NB-IoT) / enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN) (Release 17), Technical Report (TR) 36.763, V17.0.0 (2021-06)
[5] 3GPP, Study on channel model for frequencies from 0.5 to 100 GHz (Release 14), Technical Report (TR) 38.901, V17.0.0 (2022-03)
[6] MATLAB 2021b and LTE Toolbox Release 2021b, The MathWorks, Inc., Natick, Massachusetts, United States.
[7] X. Lin, et al., 5G from Space: An Overview of 3GPP Non-Terrestrial Networks, in IEEE Communications Standards Magazine, vol. 5, no. 4, pp. 147-153, Dec 2021, DOI: 10.1109/MCOMSTD.011.2100038.
[8] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2, Technical Report (TR) 36.300, V17.0.0 (2022-04)

[9] 3GPP, NR; NR and NG-RAN Overall description; Stage-2, Technical Report (TR) 38.300, V17.0.0 (2022-04)

[10] Gilles Charbit, NB-IoT/eMTC support for Non-Terrestrial Networks (NTN), 3GPP TSG RAN meeting #93-e RP-212312 (2021-09)

[11] Gilles Charbit, NB-IoT/eMTC support for Non-Terrestrial Networks (NTN), 3GPP TSG RAN meeting #94-e RP-213349 (2021-12)

[12] Gilles Charbit, et al, NB-IoT/eMTC support for Non-Terrestrial Networks (NTN), 3GPP TSG RAN meeting #95-e RP-220749 (2022-03)

[13] Gilles Charbit, et al, NB-IoT/eMTC support for Non-Terrestrial Networks (NTN), 3GPP TSG RAN meeting #96 RP-221546 (2022-06)

[14] Gilles Charbit, et al, Summary for NB-IoT/eMTC support for Non-Terrestrial Networks (NTN), 3GPP TSG-SA meeting #96 SP-220455 (2022-06)

[15] 3GPP, Study on scenarios and requirements for next generation access technologies (Release 14), Technical Report (TR) 38.913, V17.0.0 (2022-04)

[16] Sørensen, R.B., et al.,
5G NB-IoT via low density LEO Constellations.
SSC21 - Small satellite Conference 2021, Aug. 7-12, https://digitalcommons.usu.edu/smallsat/2021/all2021/198/ [Accessed: June 8, 2022]

[17] The Consultative Committee for Space Data Systems (CCSDS), ORBIT DATA MESSAGES, Recommendation for Space Data System Standards, CCSDS 502.0-B-2 (2009-11)

[18] Mediatek, Link Budget Results for IoT NTN, R1-2104573 (2021-05)

[19] Guadalupi, M., Ferrer, J., Ferrús R., et al, Designing a 3GPP NB-IoT NTN service for CubeSats in low density constellations, International Astronautical Congress 2021, Oct. 25-29, http://hdl.handle.net/2117/362349 [Accessed June 16, 2022].

[20] Qiao, L., et al., Analysis and comparison of CubeSat lifetime, In Proceedings of the 12th Australian Space Conference (pp. 249-260), July 2013

[21] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, Technical Specification (TS) 36.213 (Release 8), V17.2.0 (2022-06)

[22] Magnus Olsson, et al., “EPC and 4G Packet Networks: Driving the Mobile Broadband Revolution”, Second Edition (2013), Academic Press

[23] Stefan Rommer, et al. ”5G Core Networks: Powering Digitalization”, First Edition (2019), Academic Press

[24] Martiradonna S, Piro G, Boggia G. On the Evaluation of the NB-IoT Random Access Procedure in Monitoring Infrastructures. Sensors (Basel). 2019;19(14):3237. Published 2019 Jul 23. DOI:10.3390/s19143237