

Downlink Coverage and Bit Rate Performance of LEO-Based Non-Terrestrial Networks for NB-IoT

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Abstract—The integration of Narrowband Internet of Things (NB-IoT) with Non-Terrestrial Networks (NTNs) has emerged as a prominent enabler for global IoT connectivity in regions where terrestrial infrastructures are unavailable or impractical to deploy. Although IoT traffic is inherently uplink-oriented, performance of the downlink transmissions is equally vital for maintaining reliable system operations, yet it has so far received considerably less attention. This paper presents a comprehensive study of downlink coverage and bit rate performance in LEO-based NB-IoT NTN systems. Using simulations with realistic satellite constellation models at 600 km and 1,200 km altitudes, we evaluate minimum link availability, downlink Signal-to-Noise Ratio (SNR) distributions, and achievable physical-layer bit rates under various antenna configurations and constellation sizes. Our results demonstrate that 1,200 km constellations consistently provide stronger downlink performance than their 600 km counterparts. Notably, for LEO 1200, with 60 satellites equipped with 0.4 m aperture antennas, end devices can maintain valid connections with the satellites for approximately 30% of the time—almost four times higher than for LEO 600, and more than 65% of devices achieve bit rates above 3.5 kbps, satisfying the 3GPP TS 22.261 requirement of 2 kbps experienced data rate. Furthermore, smaller aperture antennas, despite offering lower peak gain, are shown to improve robustness by producing wider beams, which yield more stable SNR distributions and superior minimum link availability compared to larger apertures.

Index Terms—Bit rate, Coverage, Downlink, NB-IoT, Non-terrestrial Network, SNR

I. INTRODUCTION

Narrowband-Internet of Things (NB-IoT) was standardized by 3GPP in Release 13 to enable IoT device connectivity over mobile network infrastructures [1]. Recently, NB-IoT has been accepted by ITU-R as a decisive solution for 5G systems providing massive machine type communications (mMTC) service [2]. While NB-IoT inherently offers broad coverage capabilities, the rapid expansion of Internet of Things (IoT) applications continues to introduce diverse use cases and, consequently, new and demanding communication scenarios. In particular, IoT devices are being deployed in remote or isolated locations where terrestrial networks are unavailable or impractical to deploy, such as oceans, forests and deserts. In these cases, ensuring service continuity and enabling timely deployment requires approaches that go beyond the limits of terrestrial networks [3]. To address this challenge, non-terrestrial IoT communication has been introduced as a natural progression in the evolution of mobile IoT communication

technologies [4]. In fact, Non-Terrestrial Networks (NTNs) have long been recognized as a practical complement to existing cellular systems for both mobile broadband and IoT services, providing an alternative means of connectivity and improving the readiness and reliability of communications in remote or critical environments. In Release 17, 3GPP standardized support for NB-IoT over NTN, covering Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO), Low Earth Orbit (LEO) satellites, as well as High Altitude Platform Stations (HAPS) [5]. Among the standardized platforms, LEO satellites have emerged as the preferred option for current NB-IoT NTN deployments, mainly due to their ability to cover relatively large areas of Earth's surface while still offering lower propagation delay, reduced path loss, and lower cost and size in comparison to GEO and MEO satellites [6]. However, due to the fast motion of LEO satellites, several issues need to be faced, such as high Doppler shift and limited visibility time per satellite [7].

Owing to its significant potential, NB-IoT NTN has attracted increasing attention in recent years from both the academic community and the industry. Given the predominantly uplink-driven characteristics of IoT traffic, much of the existing research has been focusing on analyzing uplink performance in NB-IoT NTN systems. Nevertheless, the downlink plays an equally vital role, serving essential functions such as synchronization, control signaling, and the transmission of commands or updates to end devices (EDs).

This study aims to model and evaluate the coverage capabilities and downlink bit rate performance of LEO-based NB-IoT NTN. By covering different constellation configurations and antenna sizes, the study provides a comprehensive evaluation of the downlink performance of NTN systems based on NB-IoT technology, which is capable of achieving 3GPP TS 22.261 requirements on experienced data rate. It is observed that the LEO 1200 satellites provide four times better performance in terms of connectivity compared to the LEO 600 constellations. Finally, the study revealed that low-aperture antennas with wider beams provide a more robust connection by achieving better SNR values.

The main contributions of the study include:

- A realistic analysis of the minimum link availability that can be guaranteed for NB-IoT EDs for satellite constellations deployed in near-polar orbits at LEO altitudes of

600 km and 1,200 km.

- An evaluation of downlink Signal-to-Noise Ratio (SNR) performance under varying satellite constellation sizes and antenna configurations.
- A derivation of the achievable downlink bit rates at the physical layer, with a benchmark comparison against the 2 kbps experienced data rate requirement defined in 3GPP TS 22.261 [8].

The remainder of this paper is organized as follows. In Section II, we give a brief overview of related studies focused on LEO-based NTN. Section III provides a detailed description of the simulation parameters and scenarios. The obtained results are presented and discussed in Section IV. Finally, Section V concludes the paper.

II. RELATED STUDIES

Several studies have been conducted on NB-IoT NTN link budget and data rate. Kim and Jo [9] analyzed the uplink link budget for three-dimensional orbits with up to 162 LEO satellites and proposed a technique for residual Doppler shift compensation by adding Demodulation Reference Signal (DMRS) symbols and reducing satellite beam coverage. The study reported that adding just one DMRS symbol remarkably saves 72 satellites to achieve 23.55 h of service time per day.

Kodheli *et al.* [10] provided a link budget analysis for NB-IoT NTN on LEO and GEO satellites. The study's simulation results showed that, in the downlink case, to enable an NB-IoT system capable of achieving the highest possible spectral efficiency, a minimum Equivalent Isotropically Radiated Power (EIRP) of 25 dBW is needed for a LEO satellite at 600 km altitude, and 57 dBW for a GEO satellite at 35786 km altitude. In the uplink, for a 12-carrier transmission mode, a minimum antenna gain-to-noise-temperature (G/T) of -2 dB/K is required for a LEO satellite and 28 dB/K for a GEO satellite.

Sciddurlo *et al.* [11] conducted link-level and system-level investigations to optimize physical transmissions, satellite constellation, and protocol architecture for an NB-IoT NTN system operating with 24 LEO satellites. Their proposed protocol stack enables the transmission of small payloads generated by the EDs at the application layer while mitigating impairments associated with satellite links. The authors reported that when the entire protocol stack is implemented onboard the satellites, communication latencies range between 16 and 75 minutes. Furthermore, their findings showed that employing the early data transmission scheme can reduce latency by up to 40%.

Testi *et al.* [12] analyzed the NB-IoT NTN system throughput based on varying random access window periodicity. The number of users was modeled as a Poisson point process distribution. The results show that the proposed analytical model closely matches the simulation results, with a maximum throughput achieved with a 320 ms random access window.

Wang *et al.* [13] conducted a similar study based on adapting non-orthogonal frequency hopping in a random-access channel to improve system access time and overall throughput. The proposed scheme achieves 99% detection probability

while providing better performance in environments with more than 0.0011 users/km²/channel.

Although all studies focused on NTN systems, the predominant communication direction was considered to be from the EDs to the satellites (uplink). However, downlink communication is of equal importance. In particular, synchronization, control signaling, and even user data in the form of message acknowledgments or firmware update data to the EDs are transmitted in the downlink. Therefore, this study aims to analyze the performance of the downlink direction as a crucial part of NB-IoT NTN systems.

III. SIMULATION SETUP

To evaluate the downlink performance of LEO-based NB-IoT NTN, a series of comprehensive simulations were carried out in the MATLAB environment. The implementation utilized the Satellite Communications Toolbox [14] and the Antenna Toolbox [15]. This section outlines the simulation setup and provides a summary of the parameters used in the simulations.

TABLE I: Simulation setup

Parameter	Value
Simulation time	2 h
Number of satellites	24–36–48–60
Satellite altitudes	600 / 1,200 km
Inclination angle	87.4° / 97.7°
Number of orbital planes	12
Number of EDs	500
Min. elevation angle	30°
ED distribution area	22.7 million km ²

A. Satellite Constellations and ED Distribution

The simulation parameters are summarized in Table I. In this study, we analyzed two LEO satellite constellations with varying altitudes and orbital inclinations. The first constellation was modeled after the third shell of the Starlink LEO system, with satellites positioned at an altitude of 600 km and an inclination of 97.7°, corresponding to a near-polar orbit [16]. This inclination allows satellites to travel from pole to pole, ensuring global coverage. Due to Earth's rotation, successive orbits pass over different longitudes, preventing any region from being excluded. In the simulations, satellites were deployed progressively, beginning with twenty-four satellites and eventually reaching sixty, distributed across twelve equally spaced orbital planes. Each satellite has an orbital period of roughly 95 minutes, completing about 15 orbits per day. At 600 km altitude, the coverage footprint of each satellite at a 30° elevation angle is approximately 2.1 million km².

The second constellation was based on the Eutelsat OneWeb system, operating at an altitude of 1,200 km with an inclination of 87.4°, also following a near-polar orbit [17]. Similar to the first constellation, the deployment was carried out incrementally, starting with twenty-four satellites and increasing to sixty, evenly distributed across twelve orbital planes. At an

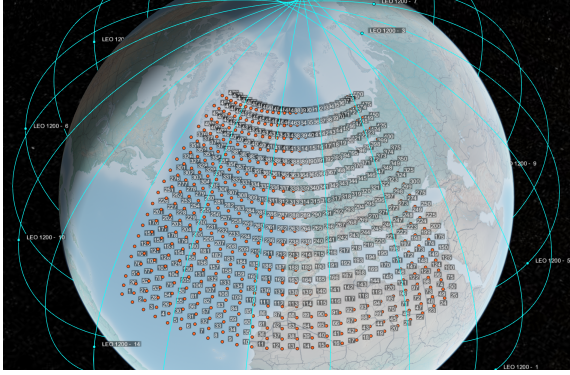


Fig. 1: Satellites deployment and EDs distribution.

altitude of 1,200 km, each satellite has an orbital period of about 109 minutes, completing approximately 13 orbits per day. The coverage footprint of each satellite is approximately 6.75 million km² at a 30° elevation angle.

The ED distribution region includes Europe, parts of the North Atlantic Ocean, and North Africa, covering a total area of approximately 22.7 million km². In this region, 500 EDs were uniformly deployed, as illustrated in Fig. 1. Each ED therefore represents an area of about 45,400 km². The primary objective is to utilize the EDs as probes to measure system performance in terms of coverage capability and downlink signal strength. Since the coverage footprint of a satellite is significantly larger than the area occupied by a single ED, devices located in close proximity are expected to experience nearly identical coverage conditions and comparable received signal strengths. Therefore, the number of deployed EDs is sufficient, as further increasing their density would not provide meaningful additional insights into coverage and signal strength statistics, while considerably increasing the computational demand of the simulations.

TABLE II: Transmitter and receiver parameters [10], [18].

Transmitter		Receiver	
Carrier frequency	2 GHz	Maximum G/T	-15 dB/K
Bit rate	26 kbps	Receiver system loss	1 dB
System loss	2 dB	Pre-receiver loss	1 dB
Link bandwidth	180 kHz	Required E_b/N_0	0 dB

B. Transmitter, Receiver and Antenna Model

The transmitter and receiver parameters were selected according to 3GPP specifications in [10] and [18]. The rudimentary parameters are summarized in Table II.

Based on the antenna specifications for LEO satellites operating at 1,200 km and 600 km altitude in [18] and [19], the parabolic reflector antenna was chosen as the antenna model for simulation. The satellite antenna models were simulated using MATLAB Antenna Toolbox. The antenna apertures and maximum transmit gains vary across satellite calibration sets. The satellite parameters are summarized in Table III and

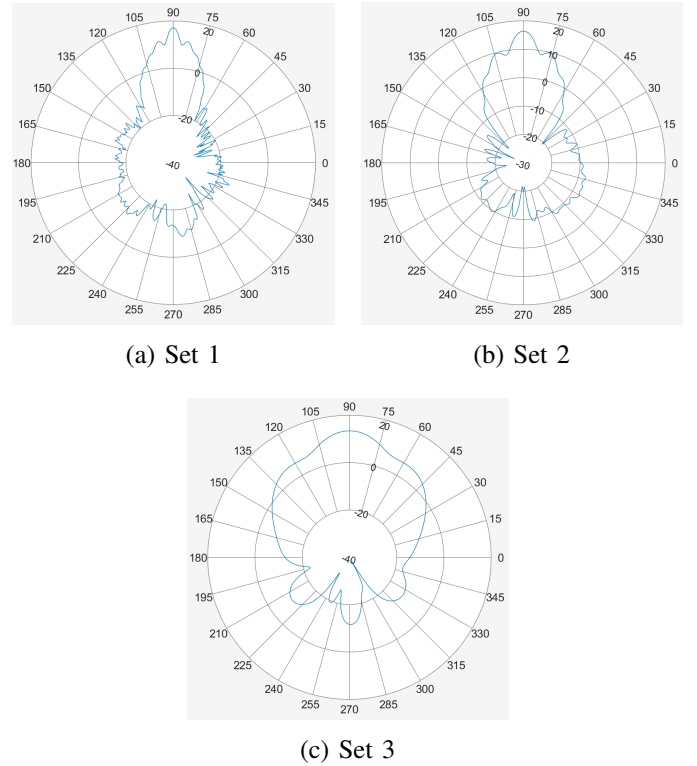


Fig. 2: Radiation patterns ($f = 2$ GHz, $\varphi = 0^\circ$) of satellite's parabolic reflector antennas across calibration sets.

TABLE III: Satellite parameters [18], [19].

Set	Altitude	Antenna aperture	EIRP density	Tx max gain	Beam diameter
1	LEO 600	2 m	34 dBW/MHz	30 dBi	50 km
	LEO 1200	2 m	40 dBW/MHz	30 dBi	90 km
2	LEO 600	1 m	28 dBW/MHz	24 dBi	90 km
	LEO 1200	1 m	34 dBW/MHz	24 dBi	190 km
3	LEO 600	0.4 m	28.3 dBW/MHz	16.2 dBi	234 km
	LEO 1200	0.4 m	33.7 dBW/MHz	16.2 dBi	470 km

the corresponding antenna radiation patterns in the S-band (2 GHz) are shown in Fig. 2.

As it can be seen from Table III, larger antenna apertures, as in Set 1 and Set 2, yield higher transmit gains, allowing for stronger signals at the cost of reduced beamwidth. Although such configurations are suitable for high-capacity, localized IoT applications, they require precise beam pointing from the satellites as NB-IoT EDs are typically equipped with simple omnidirectional antennas and do not actively track the satellite beam. In contrast, Set 3, with a smaller aperture of 0.4 m, offers a lower transmit gain of 16.2 dBi. While signal strength is more diluted in this configuration, it can offer very wide beams of 234–470 km that significantly extend coverage. In addition, it can be seen from the table that altitude also directly influences beam diameter, with 1,200 km orbits producing roughly double the beamwidth compared to 600 km for the same antenna size.

IV. RESULTS AND DISCUSSION

This section presents the obtained results. First, the minimum link availability that various satellite constellations and antenna configurations can guarantee for the EDs is analyzed. Then, we investigate the downlink SNR distributions. Finally, we derive the achievable downlink bit rates at the physical layer and compare them with the 2 kbps experienced data rate requirement specified in 3GPP TS 22.261.

A. Minimum Link Availability

We begin by examining the minimum service link availability that can be guaranteed for NB-IoT EDs under different LEO satellite constellations and antenna aperture configurations. Here, the minimum guaranteed link availability is defined as the lowest availability level observed among all EDs within the distribution region. Accordingly, this metric ensures that every ED in the region is able to maintain a valid communication link with the satellites for at least the specified duration of time.

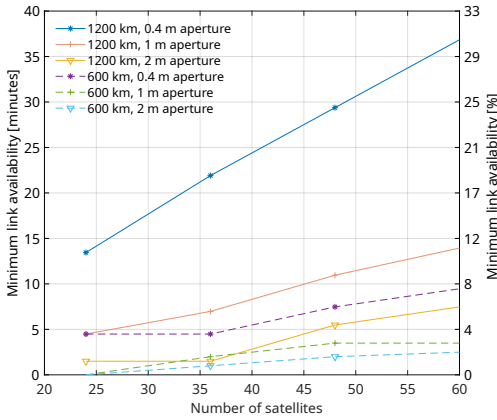


Fig. 3: Minimum link availability across satellite constellations and antenna configurations over 2 hours.

Fig. 3 illustrates the minimum link availability provided to EDs as a function of the number of satellites deployed. It can be seen that the LEO 1200 constellation with 0.4 m antenna aperture achieved the best performance, with availability ranging from 14 minutes at 24 satellites to over 35 minutes at 60 satellites, corresponding to approximately 11% and 30% of the simulation time, respectively. Furthermore, larger apertures at the same altitude yield lower availability due to their reduced beamwidths and more varied SNR distributions, as will be discussed in Section IV-B. It should be emphasized that the results were obtained for the entire ED distribution region, without employing satellite beam-pointing toward any specific area. Another notable observation is that the performance of the LEO 1200 constellation with 2 m antenna aperture is worse than that of the LEO 600 constellation with 0.4 m aperture, despite the fact that at a higher altitude, the LEO 1200 satellites have a much wider coverage footprint and

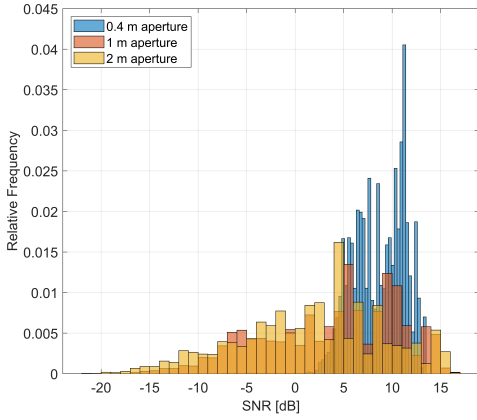
lower orbital velocity. This emphasizes the impact of antenna configurations on the performance of NB-IoT NTN systems.

The LEO 600 constellations generally demonstrated inferior performance compared to their LEO 1200 counterparts with the same satellite counts and antenna configurations. The best performance was achieved by the constellations with 0.4 m aperture, with availability ranging from 4.5 minutes at 24 satellites to 9.5 minutes at 60 satellites, corresponding to 3.7% and 7.9% of the simulation time, respectively. The performance of the LEO 600 constellations with 1 m and 2 m apertures is much worse, with minimum link availability of only 2.9% and 2.1% for 60 satellites, respectively. Notably, at 24 satellites, the minimum link availability for the 1 m and 2 m apertures was 0%, indicating that certain EDs within the distribution region did not receive any coverage from the satellites during the entire simulation period.

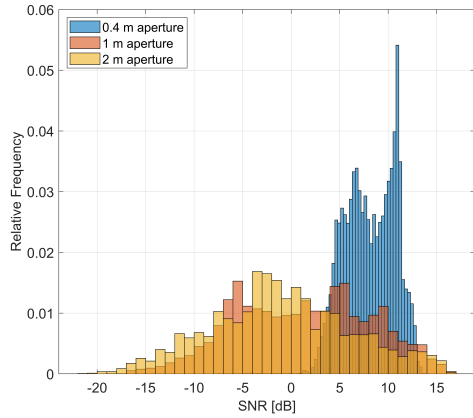
B. SNR Distribution

The histograms of the downlink SNR for LEO 600 constellations are presented in Fig. 4. It can be seen that the smallest antenna aperture of 0.4 m produces a distinctly narrower and more sharply peaked distribution, with most of the probability mass concentrated around 5 dB to 12 dB. In contrast, the larger apertures of 1 m and 2 m result in much wider distributions, ranging from -20 dB to 15 dB. The concentration of the 0.4 m aperture's SNR distribution at higher values demonstrates its robustness. This effect arises from the broader beam associated with the smaller aperture, which reduces the sensitivity of the received signal to satellite motion dynamics. Furthermore, the wider beam ensures that EDs at various positions within the satellite footprint experience more stable link quality. This property is particularly beneficial for NB-IoT EDs, which typically operate under stringent power and robustness requirements. In contrast, the larger apertures of 1 m and 2 m generate narrower beams that, although capable of providing higher gain in ideal alignment, are much more vulnerable to misalignment and Doppler dynamics inherent in LEO-based NB-IoT NTN systems. As a result, the effective SNR distribution for the larger apertures becomes more variable and shifts toward lower values, despite also including a small fraction of instances with very high SNR exceeding 15 dB.

The results for the LEO 1200 scenarios are shown in Fig. 5. It can be seen from the figure that the SNR distributions here exhibit a similar overall pattern to those observed in the LEO 600 cases, with the 0.4 m aperture producing a more concentrated distribution centered around higher SNR values, whereas the 1 m and 2 m apertures demonstrate broader distributions spanning a wider range. However, a key difference between the two altitudes is that the overall SNR range for LEO 1200 is shifted by approximately 5 dB toward lower values. This shift reflects the increased path loss associated with the higher orbital altitude, which leads to reduced received SNR at the EDs. Nevertheless, most of the distribution remains within acceptable ranges, from 0 dB to 6 dB for the 0.4 m aperture, and from -15 dB to 10 dB for the 1 m and 2 m apertures. While antennas with smaller



(a) 24 satellites



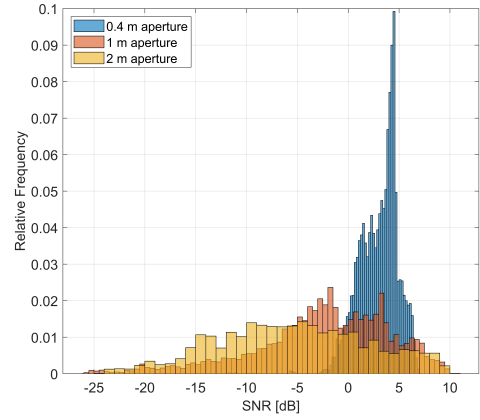
(b) 60 satellites

Fig. 4: SNR distribution for LEO 600 constellations.

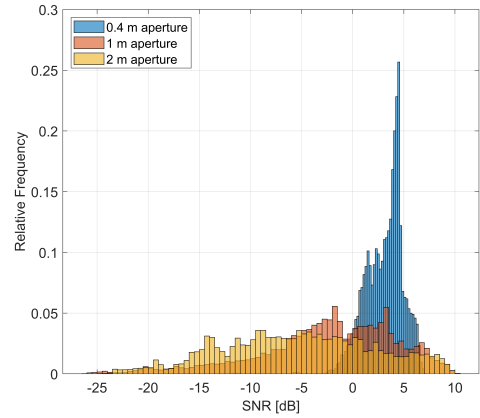
apertures generally demonstrate better performance, it is worth emphasizing that larger apertures remain essential for more demanding applications requiring focused spot beams, where precise beam pointing would be employed.

C. Physical-Layer Bit Rate

The capacity of the system has to do with the number of EDs that can maintain a valid service link with the network and be satisfied with the service. Having examined link availability and SNR distributions, at the final stage of our analysis, we derive the downlink physical-layer bit rate from the obtained SNR values and compare it with the 2 kbps data rate requirement specified in 3GPP TS 22.261 [8]. It is important to note that the specification defines this target as the experienced data rate at the application layer. However, when accounting for additional signaling and protocol overheads (e.g., Media Access Control, Radio Link Control, Packet Data Convergence Protocol, User Datagram Protocol/Internet Protocol or Non-IP Data Delivery), achieving 2 kbps at the application layer necessitates a higher physical-layer bit rate. We conservatively estimate this requirement to be at least



(a) 24 satellites



(b) 60 satellites

Fig. 5: SNR distribution for LEO 1200 constellations.

3.5 kbps and, accordingly, adopt this value as the threshold for evaluating the downlink capacity of the NB-IoT NTN system.

The required SNR values corresponding to a Block Error Rate (BLER) of 10% for different Modulation and Coding Schemes (MCS) were obtained through simulation in [10] and subsequently mapped to the Transport Block Size index (I_{TBS}) and number of repetitions in [20]. The resulting mapping is presented in Table IV. Based on this mapping, the physical-layer bit rates achieved at the EDs were calculated.

Fig. 6 shows the percentage of EDs achieving capacity above the 3.5 kbps threshold over the entire simulation period, whenever a link is available for the EDs. It can be seen that the constellations at 1,200 km altitude significantly outperform those at 600 km, owing to their ability to provide longer coverage time. In specific, with 24 satellites equipped with 0.4 m antenna, 26.8% of EDs can achieve or exceed the target bit rate for LEO 1200, compared to only 14.8% for LEO 600. When the constellation size increases to 60 satellites, 65.2% of EDs can reach or exceed the threshold for LEO 1200, while this number is only 24.4% for LEO 600.

With regard to antenna aperture, for LEO 1200 constellations, smaller apertures provide great improvements over

TABLE IV: SNR to I_{TBS} and repetitions mapping [10], [20].

I_{TBS}	Repetitions				
	1	2	4	8	16
0	-5.8	-8.3	-10.6	-12.8	-14.7
1	-4.9	-7.2	-9.7	-11.9	-13.8
2	-3.9	-6.2	-8.8	-11.0	-12.9
3	-3.0	-5.4	-8.0	-10.4	-12.2
4	-2.0	-4.6	-7.2	-9.6	-11.4
5	-1.1	-3.7	-6.3	-8.9	-10.8
6	-0.2	-2.8	-5.6	-8.0	-10.0
7	0.7	-1.9	-4.7	-7.3	-9.3
8	1.4	-1.3	-4.1	-6.8	-8.9
9	2.2	-0.4	-3.3	-6.0	-8.1
10	3.1	0.4	-2.4	-5.2	-7.3
11	4.2	1.4	-1.5	-4.3	-6.6
12	5.5	2.7	-0.4	-3.3	-5.6
13	6.9	3.9	0.9	-2	-4.4

larger ones. For instance, at 60 satellites, the difference between the capacities of the 0.4 m aperture and the 2 m aperture is almost 22%. This effect is attributed to the fact that at a higher altitude, the wider beam produced by the smaller aperture is greatly magnified. In contrast, for LEO 600, the smaller apertures only produce marginal improvements over larger ones. This occurs because the SNR values for LEO 600 are generally favorable, so once a link is established between satellites and EDs, the threshold is almost always met. Therefore, in this regime, coverage capability is the determining factor, and as can be observed in Fig. 6, the difference in coverage between the apertures is not as pronounced for the LEO 600 constellations as it is for the LEO 1200 constellations.

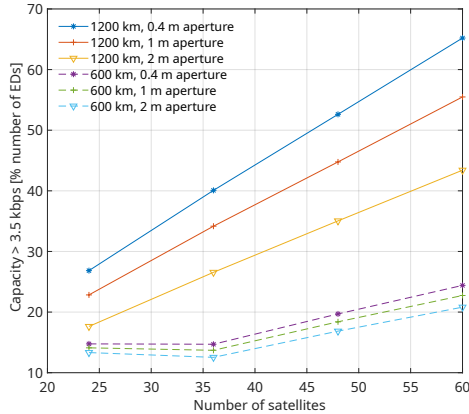


Fig. 6: Percentage of EDs achieving physical-layer downlink bit rates above 3.5 kbps.

V. CONCLUSION

NB-IoT NTN has emerged as a key enabler for extending IoT services to areas beyond terrestrial coverage, with LEO

constellations offering an optimal trade-off between latency, coverage, and link budget. This study presented a comprehensive assessment of downlink performance for LEO-based NB-IoT NTN, considering satellite altitudes of 600 km and 1,200 km, various antenna configurations specified by 3GPP standards, and constellation sizes ranging from 24 to 60 satellites.

Results show that the LEO 1200 constellations can provide superior service compared to the LEO 600 constellations, primarily due to their larger coverage footprints and lower orbital velocity. With 60 satellites at 1,200 km equipped with 0.4 m aperture antennas, the EDs can be guaranteed a minimum link availability of 30% of the time, while this figure is only 7.9% for LEO 600. Furthermore, for the 1,200 km altitude, antenna aperture size has a pronounced impact on minimum link availability, with smaller apertures significantly outperforming larger ones under the same constellation size. This effect is less significant for LEO 600. Regarding downlink SNR, it was demonstrated that all 3GPP-defined satellite calibration sets achieve relatively good SNR distributions, with most of the probability mass falling in acceptable range. Nevertheless, the 0.4 m aperture consistently outperforms the 1 m and 2 m apertures, with most SNR values concentrated in the range of 5–12 dB for LEO 600 and 0–6 dB for LEO 1200. This finding indicates that the 0.4 m aperture, while reducing peak gain, proved advantageous by offering wider beams that improved coverage continuity and stabilized SNR distributions. In terms of physical-layer bit rate, under the 0.4 m antenna configuration, more than 65% of EDs in the LEO 1200 scenario with 60 satellites achieve downlink bit rates above the 3.5 kbps threshold, thereby meeting the 2 kbps experienced data rate requirement specified in TS 22.261 [8]. In contrast, for the LEO 600 scenarios, this requirement can only be satisfied for 24.4% of EDs, even with 60 satellites deployed.

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