WIP: An Open-Source Tool for Evaluating System-Level Performance of NB-IoT Non-Terrestrial Networks

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***Abstract*—Satellite Communication is expected to play a leading role in 5G & Beyond networks. Current studies, however, focus the attention on physical and link-level aspects, while ignoring to evaluate system-level performance. This paper presents a novel simulation tool, conceived as a new module for the open-source 5G-air-simulator, modeling NB-IoT satellite-based communication systems. Specifically, it implements several link-to-system abstraction models, the cell selection procedure, and a configurable satellite constellation. Furthermore, these essential features are successfully integrated within the rest of the 5G-air-simulator, thus offering the opportunity to test flexible network deployments (e.g., by varying the number and the distribution of users) under different application statistics. To demonstrate the actual effectiveness of the developed tool, this work also presents a preliminary performance assessment of an NB-IoT satellite-based communication system enabling reference monitoring scenarios.**

I. Introduction

Satellite Communication (SatCom) is expected to have a primary role in 5G & Beyond networks [1]. Thanks to its ubiquity capabilities and the robustness against natural disasters, SatCom fosters network spread in a cost-effective way, by delivering connectivity where telecommunication infrastructures are lacking (i.e., oceans, forests, and deserts). Moreover, it offers additional connections to offload terrestrial networks, hence strongly promoting the scalability of mobile networks. For these reasons, SatCom results particularly effective for Machine Type Communication (MTC) scenarios, envisaged for IMT-2020 and beyond [2], especially when a huge number of low cost devices need connectivity in large areas not covered by terrestrial networks. A number of recent studies also considered NarrowBand IoT (NB-IoT) as a promising technology for 5G satellite MTC [3]–[9]. However, the scientific literature is mainly focusing the attention on physical and link-level analysis only. At the same time, recent works suggest that there is a growing demand for flexible tools for designing and testing new algorithms and protocols for NB-IoT-based satellite scenarios. Nonetheless, at the time of this writing, and to the best of authors knowledge, there are no system-level simulators available to the research community that specifically address the considered scenario.

To bridge this gap, the work presented herein proposes an open-source implementation of an NB-IoT satellite-based communication system, built upon the 5G-air-simulator tool [10]. Indeed, 5G-air-simulator already provides support for a variety of NB-IoT features and appears as a solid instrument to carry out system-level analyses of a number of technical components already standardized by the 3GPP.

Section II provides information about the implemented link-to-system abstraction models (embracing transmission, propagation, and reception mechanisms), as well as a new mobility model and the cell selection procedure, which have been successfully integrated within the rest of the 5G-air-simulator. Section III investigates a preliminary performance evaluation of the simulated NB-IoT satellite-based communication system for a reference monitoring scenario. Finally, Section IV concludes the paper.

II. The Proposed Simulation Module

In line with 3GPP guidelines [11], this work assumes to use Low Earth Orbit (LEO) satellites for guaranteeing feasible communication links with a satisfactory levels of Signal to Noise Ratios (SNRs). However, a single LEO satellite may not be able to run across its entire orbit at the aforementioned rate. Therefore, it is necessary to consider several satellites per orbit, forming a constellation, to drastically reduce the time periods during which ground-based devices remain without satellite coverage [12]. In this context, the Cubesats are a solution that provides low costs and several simplifications in the system deployments for the satellite constellation.

Every satellite of the LEO constellation implements a Base Station. As a consequence, Non Terrestrial Network (NTN) terminals are expected to perform again the network attach procedure each time they are covered by a different satellite.

Each NTN terminal is a 3GPP NB-IoT User Equipment (UE) able to use a direct satellite access, thanks to an adapted Uu interface. The NB-IoT technology is used to implement the service link, established between the NTN terminal and the remote satellite.

It is important to stress that, during the creation of the NTN terminals in the configured scenario, only uplink channels are

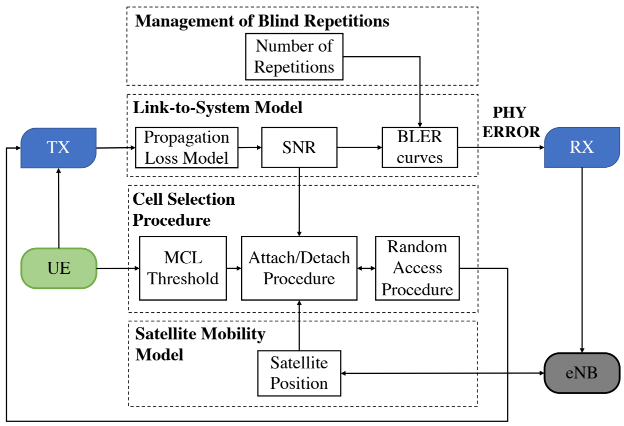

Fig. 1. Overall vision of the interaction among the implemented simulator features.

considered, i.e., the downlink transmission is not modeled. Moreover, only Single-Tone transmissions are taken into account, in order to both achieve better performance due to the increased robustness over the service link and further exploit NB-IoT capabilities to manage a multitude of users thanks to its wise bandwidth management.

Figure 1 shows a general overview of the implemented module and remarks the interaction between different building blocks, presented below.

The first extension introduced in the 5G-air-simulator is the handling of the blind repetitions. It provides the transmission in a bundle of the same Transport Block, replicated for a specified number of times. This key-feature enables the communication even at low SNR values. Indeed, it is crucial to maximize both the visibility time and the total throughput.

The number of total blind repetitions can be set for the Narrowband Physical Uplink Shared Channel (NPUSCH) transmissions via the `FrameManager::SetNRep` method. Then, this value is retrieved when performing the scheduling procedure. Specifically, now the methods `RUsAllocation` of both the implemented scheduler classes (i.e., FIFO and Round Robin) take into account this parameter while assigning Resource Units (RUs) to users and finalizing the scheduling procedure. In this way, the reception event happens after the correct amount of time, which depends on the number of repetitions and the actual slot duration, as well as on the number of RUs allocated to the UE.

The Link-To-System (L2S) model is of fundamental relevance since it offers a simplified (but still accurate) abstraction of transmission, propagation, and reception functionalities. It associates a link-level analysis to the system-level simulation tool. A simplified channel model contains the SNR expressions for both downlink and uplink channels, and the BLock Error Rate (BLER) curves for each transmission mode.

The 5G-air-simulator did not originally model the radio channel for NB-IoT. Thus, a new propagation loss model is developed to evaluate the signal received by the satellite, considering the non-idealities of the channel in the satellite scenario.

Specifically, the SNR is analytically modeled by taking into account the power gains and losses due to the propagation over the radio channel. Given the elevation angle of the service link, i.e., θ_{el}, and the carrier frequency, f_c, the SNR quantifying the link performance, evaluated in dB, can be modeled as follows [13]:

$$\begin{aligned} SNR(\theta_{el}, f_c) = P + G_{ANT}(\theta_{el}, f_c) - PL(\theta_{el}, f_c) - \\ -L_{imp}(\theta_{el}, f_c) + DCF(\theta_{el}, f_c) - N, \end{aligned} \quad (1)$$

where P represents the signal transmission power and G_{ANT} represents the sum of the antenna gains of satellite and NTN terminal (in dBi). PL is the free space path loss that accounts for the radio wave attenuation due to the propagation, and L_{imp} represents additional losses due to all the impairments considered, such as the attenuation due to air, fog, atmospheric gas absorption, droplets and rainfall, polarization, and scintillation. In addition, DCF is the sum, in dB, of the diagram correction factors of transmitting and receiving antennas. Finally, the noise power N can be evaluated by taking into account the system noise power at the receiving antenna (for a detailed computation of the system noise power please refer to [14]).

For this purpose, a new header file is defined containing the results of the link-level analysis, such as the received power from the satellite at NTN terminal side and the received power from the NTN terminal at satellite side at different elevation angles, as well as the BLER curves for each transmission mode.

The new method `BLERvsSINR_NBIoT_SAT::GetRxPowerfromElAngle_SAT` evaluates the received power at the satellite side for each value of the elevation angle experienced by the NTN terminal. As a consequence, during the reception, the satellite retrieves an SNR value related to the uplink configuration used for the transmission, which reflects the quality of the channel. In essence, this SNR value is exploited to estimate the BLER for the received block using new SNR-BLER curves, which determines the probability that it has been correctly received.

To this end, the BLER is estimated by considering the chosen Modulation and Coding Scheme (MCS), the number of used RUs, the number of NPUSCH blind repetitions, and the SNR experienced at the satellite during the reception. The BLER value is drawn by `BLERvsSINR_NBIoT_SAT::GetBLER_SAT`, using SNR-BLER curves stored into the header file and generated using the MATLAB LTE Toolbox.

A further extension is related to the new mobility model, which manages the movement of the satellites by tracking their position and defining their coordinates in the selected scenario.

For the purposes of the simulation, and without loss of generality, satellites movement was considered exclusively in one direction on a reference axis of the Cartesian plane, i.e., the x-axis. The point value of the considered position refers to the centre of the beam that covers the area on the ground. Based on the number of satellites in the orbit and the time instant, this method provides the updated value of the position according to the following equation:

$$x_{Sat}(t) = x_{0,Sat} + v_{sat}(t \mod \Delta T_{sat}), \quad (2)$$

where $x_{0,Sat}$ corresponds to the initial position of the satellite, v_{sat} represents the relative speed of the satellite spot beam on the Earth, t represents the time instant considered and the modulo operation is needed to exploit the periodicity of the position function. Finally, ΔT_{sat} represents the elapsed time between two different satellites. It is given by T_{orbit}, that is the time taken by the satellite to make one complete revolution around the Earth, e.g., about 94 minutes, over $N_{sat\_per\_orbit}$, that is the number of the satellites in a single orbit. ΔT_{sat} may be expressed as:

$$\Delta T_{sat} = \frac{T_{orbit}}{N_{sat\_per\_orbit}}. \quad (3)$$

The position of the satellites is useful for determining whether the entities involved in the communication, i.e., NTN terminals and the satellite, are actually in reciprocal visibility and therefore able to communicate or not. For this purpose, a new extension is introduced. This computation is performed within the `UserEquipment::UpdateUserPosition` method. First, NTN terminals not having an empty transmission buffer measure the power of the downlink signal received from the satellite. To this end, an essential parameter to determine the maximum coverage the cellular system can support is defined by the Maximum Coupling Loss (MCL).

Once the MCL goes under a defined threshold, i.e. 164 dB, the NTN terminal starts the attach procedure to the satellite.

The NTN terminal continuously monitors the downlink power signal in order to maintain the connection with the satellite. Thanks to this approach, the simulator can model an error during the Random Access Procedure. If so, the procedure has to be rescheduled again. On the other hand, the NTN terminal may fail the attach procedure even if it accomplishes the Random Access Procedure, breaking the possibility to communicate.

III. Performance Evaluation

In order to demonstrate the actual effectiveness of the developed tool, the conducted system-level study highlights how network and satellite configuration significantly impact system performance.

For simulation purposes, the fixed area on the Earth that contains the NTN terminal was chosen with a circular shape as the same size of the satellite spot beam. At the application layer, the selected traffic model is the periodic uplink reporting [15]. In fact, monitoring is one of the most common use cases for MTC in NTNs [11]. Regarding the Random Access, the number of possible Narrowband Physical Random Access Channel (NPRACH) preambles is the maximum allowed by the standard, i.e., 48. We chose 240 ms as the NPRACH periodicity while the Backoff Parameter is set to 2048 ms. In this way, the probability of collisions due to the preamble retransmissions may be mitigated. Moreover, it is important to

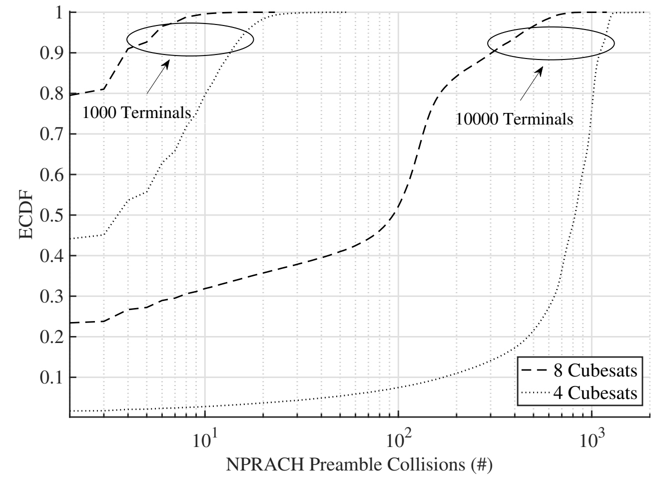

Fig. 2. ECDF of the NPRACH Preamble collisions

emphasize that these values are also compatible with higher RTTs typical of NTNs [8].

Only one coverage class has been considered, selecting an MCL threshold value of 164 dB. The duration of the simulation has been chosen in order to allow a vision of at least 8 cycles of visibility by the satellites on the area involved in the communication. It is considered a 20 MHz bandwidth from 1980 MHz to 2000 MHz frequency and a single NB-IoT carrier.

Different KPIs have been measured by processing the output trace files. Figure 2 illustrates the ECDF of the number of NPRACH preamble collisions. First of all, the number of Cubesats in the Satellite Platform greatly impacts NPRACH performance. In fact, with fewer Cubesats, ground terminals remain without satellite coverage for longer periods. As soon as they return in visibility, a great burst of NPRACH preamble transmissions occurs, hence leading to several collisions. Besides, also a greater number of NTN terminals leads to an overall higher number of preamble collisions, as expected. For instance, with 4 Cubesats and 10000 NTN terminals, the probability of having less than 100 collisions is below 10%. This demonstrates that NPRACH represents a bottleneck for dense network deployments.

End-to-End packet delays are reported in Figure 3. They are computed by taking into account the influence of cell selection, Random Access Procedure, scheduling decisions, and the actual physical transmission. Following the previous NPRACH considerations, the most noticeable feature is that the constellation numerousness significantly affects the end-to-end packet delays. In particular, more Cubesats allow covering NTN terminals for more protracted periods, hence reducing end-to-end delays. Besides, the amount of time needed to complete the Random Access Procedure increases with a higher number of NTN terminals. Indeed, when more users perform the Random Access Procedure, the number of collisions rises. As a consequence, packet delays also grow with the number of NTN terminals.

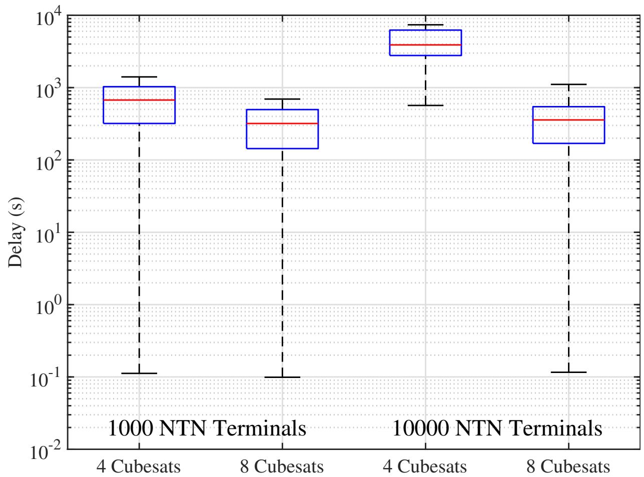

Fig. 3. Box plots of the end-to-end packet delays. Each box plots identifies the median delay (i.e., the red line), the 25^{th} and the 75^{th} percentile (i.e., the bottom line and the top line of the blue rectangle), as well as the minimum and the maximum measured delay value (i.e., the edges of the vertical black line).

TABLE I
PACKET DELIVERY RATIO

	1000 NTN Terminals	10000 NTN Terminals
4 Cubesats	92.66%	1.04%
8 Cubesats	99.41%	79.20%

To conclude, the packet delivery ratio (i.e., the ratio between correctly received packets and transmitted packets) is analyzed for all the sets of simulations. Specifically, Table I shows the achieved average delivery ratio. Evidently, 8 Cubesats constellations hold the greatest packet delivery ratios. Conversely, when a massive number of NTN terminals is deployed, performance is extremely reduced. As a case in point, the packet delivery ratio is only about 1% with 4 Cubesats and 10000 ground terminals. This is due to the extreme number of NPRACH preamble collisions.

IV. CONCLUSIONS

This work presents an extension of the open-source 5G-air-simulator modeling an NB-IoT satellite-based architecture. The proposed tool promises to support the research on NB-IoT satellite based communication system. Furthermore, to prove its capability, a set of preliminary performance indices has been carried out based on the monitored scenario. These results show the impact of the constellation configuration in terms of latency and service reliability. In fact, the simulation tool highlights that proper constellation dimensioning is crucial. NPRACH preamble collisions are moderate with more satellites per orbit, providing a lower packet delay. Consequently, the NTN terminals experience a higher average delivery ratio. At the time of this writing, the validation of the developed module is ongoing. Afterwards, the module will be part of the official 5G-air-simulator repository. Moreover, future work may also extend the system-level investigation to evaluate the impact of the constellation configuration on more complex network topologies, the performance of a multi-tone uplink and downlink channel configuration, as well as the analysis of the energy consumption.

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