System Level Evaluation and Validation of the ns-3 LTE Module in 3GPP Reference Scenarios

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ABSTRACT

LTE networks represent the latest generation implementation of communications technologies for mobile users. As such, simulation tools are essential in the development of new radio resource management (RRM) techniques for LTE. In this paper, we evaluate the LTE module of the ns-3 simulator in a set of 3GPP reference scenarios for system level simulation. Downlink spectral efficiency, user throughput distribution and SINR distribution in a basic LTE configuration are compared against 3GPP results, which are based on an aggregate of 17 industrial simulators. Results show that the ns-3 LTE module achieves similar performance to the one obtained by the 3GPP industrial simulators in the evaluated cases, both in terms of SINR distributions and users' throughput.

KEYWORDS

ns-3, LTE, System Level Simulator, validation

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1 INTRODUCTION

Implementation and deployment of new technology is always tied to preliminary simulation and testing. New technology goes through a cycle of software simulation, hardware-in-the-loop evaluation, and field trials of the system before actual deployment. The initial step, software simulation, is generally the least expensive one, but at the same time requires accurate modeling of real-world phenomena. Significant importance is attached to the validation of these software simulators, in order to ensure the fidelity of the results achieved through simulations.

In the area of LTE networks there have been several software simulators developed. Most of these are built by industry and therefore not available to the general public for research. However, there are a few broadly used simulators which are open-source, such as the Vienna simulators [1], LTE-sim [2], and the ns-3 LTE module [3]. These simulators are outcomes of academic research and the open-source community. Open-source simulators enable other researchers to develop their own systems on top of the existing platforms, or even modify the simulators to better fit their own needs.

ns-3, a well documented simulator for networks, already has several components within the LTE module that were validated individually (e.g., MAC schedulers or the adaptive modulation and coding module). However, to the authors' knowledge, there is no system level validation of the LTE module itself. As such, system level simulation results obtained with the ns-3 simulator might differ from those obtained by the industrial simulators and/or real-world results.

The contribution of this paper is two-fold. First, we validate the ns-3 LTE module against a set of 3GPP reference results for system level simulations of an urban LTE deployment [4] considering full buffer traffic. The 3GPP results are obtained by aggregating data from 17 industrial simulators, and provide reference CDF curves for users' SINR and throughput, together with spectral efficiency results. Second, we also provide new evaluation results under bursty traffic conditions, and additionally for a rural scenario. While specifications for these scenarios are proposed in 3GPP [4], there are no results reported. Our work also compares these new results achieved under bursty traffic against the available 3GPP full buffer results.

Our own results, obtained with ns-3, are also available on GitHub [5], together with code that can be used to plot or reproduce them.

The rest of this paper is organized as follows: Section 2 introduces the reference 3GPP scenarios considered for evaluation, Section 3 presents the steps required for the implementation of these scenarios in ns-3, Section 4 shows the results obtained by ns-3 in a side-by-side comparison with the 3GPP reference results and also presents the new results obtained in case 3 and under bursty traffic, and finally Section 5 presents our conclusions with regard to the system level evaluation of the performance of 3GPP LTE reference scenarios and the validation of ns-3's LTE simulator.

2 3GPP REFERENCE SCENARIOS

3GPP provides a set of reference scenarios, along with performance results, which can be used for validation. The reference scenarios we chose for validation are 3GPP Case 1, an urban macro cell setup, and Case 3, a rural one. These account for different distances between eNBs, and for different UE densities and distributions. For each of these cases, we considered both full buffer and bursty traffic. These

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Table 1: 3GPP Reference Scenarios Parameters

Parameter	Value
Antenna Height	32 m
Antenna Beamwidth	70°
Maximum Attenuation	25 dB
Cell Tx Power	46 dBm
UE Power Class	25 dBm
Pathloss Model	$128.1 + 37.6 \log_{10} R$, where R dist in km
UE height	1.5m
Carrier Frequency	2 GHz
UE speed	3 km/h
Minimum Distance Between UE and cell	35 m
Downlink Scheduler	Round Robin
Transmission Type	1x2 SIMO FDD
Bandwidth	20 MHz (10 MHz downlink/10 MHz uplink)
Distance between cells	**Case 1**: 500 m **Case 3**: 1732 m
UE distribution	**Case 1**: 25 uniformly distributed UEs per cell **Case 3**: [10-100] non-uniformly distributed UEs, w/ uniform distribution within macro-cell
Antenna downtilt (3D case)	**Case 1**: 15° **Case 3**: 9°

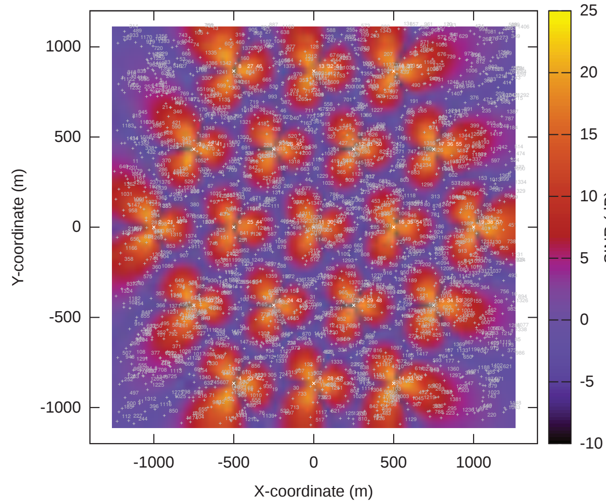

Figure 1: 3GPP Case 1 Deployment

scenarios are taken from the 3GPP technical report TR 36.814 [4], which in turn is based on TR 25.814 [6]. A full description of the reference scenarios requires inspection of both of these documents. TR 25.814 provides macro-cell parameters for a baseline macro-cell system evaluation, and TR 36.814 augments this information with details on 3D antenna patterns, while the previous standard focused only on horizontal (2D) patterns. Detailed descriptions of the initial macro-cell system can be found in table A.2.1.1-3 of TR 25.814 [6], with the later modifications available in table A.2.1.1-2 of TR 36.814 [4].

Both Case 1 and Case 3 assume a hexagonal grid setup, with 19 cell sites and 3 sectors per site, as can be seen in Fig. 1. This implies one central site, surrounded by 2 rings of additional sites (the inner ring comprises 6 sites, while the outer rings comprises 12 sites).

Further specifications for the 3GPP reference scenarios can be found in Table 1. The first set of parameters are common for both Case 1 and Case 3, while the individual parameters are presented at the bottom of the table.

Both 3GPP cases require implementation of full buffer and bursty traffic. There are several options available for bursty traffic in TR 36.814 [4] regarding the arrival rate and file size. In this paper we consider 2MB files, based on table A.2.1.3.1-1 in TR 36.814, with a Poisson arrival rate λ of 0.2 files/sec (i.e., on average 1 file every 5s per UE).

The 3GPP case 1 scenario is the only case that contains detailed information regarding SINR and throughput CDFs for full buffer traffic. This is used for the calibration of the simulator, whose configuration is presented in the next section.

3 REPLICATING 3GPP REFERENCE SCENARIOS IN NS-3

The LTE module of ns-3 can be configured either through command line arguments where simulation parameters can be passed directly, or through ns-3's attribute system configuration. The module also contains some helper classes, which can be used for easier configuration of specific components (e.g., the `LteHelper` class). However, some parameters must be passed directly through the ns-3 attribute system (e.g., UEs height), as there are no helper classes available for them.

A set of example files are already provided within ns-3's LTE module. From these, we selected the lena-dual-stripe example for adaptation to the 3GPP scenarios, as we considered it to be the most complete/detailed example. We also enabled the EPC (Evolved Packet Core) model, which was necessary for simulating full buffer and bursty traffic, as this specific module includes core network interfaces and implements end-to-end IP connectivity. We removed the code related to femto-cells and buildings from lena-dual-stripe, and re-configured the topology to represent the one recommended in the 3GPP scenarios.

Some requirements for the 3GPP scenarios were easier to implement than others. The following sections present the parametrization and configuration necessary to replicate the 3GPP reference scenarios, in ascending order of complexity.

3.1 Direct Parametrization in ns-3

Many of the parameters that must be configured for 3GPP case 1 and case 3 are directly available through the lena-dual-stripe variables. UEs can be placed uniformly within an area, with a chosen density (in number of UEs per m^2), through a command line argument. This allows for an average number of users to be set per cell, rather than a fixed number.

One sample drop for 3GPP Case 1, where 1425 UEs (25 UEs x 19 sites x 3 sectors/site) were uniformly placed in a rectangular area encompassing the 19 sites, is shown in Fig. 1. With ns3's random algorithm placement, we obtain on average 25 UEs in an eNB. Some discrepancies in terms of numbers of UEs per eNB can be noticed in particular between edge cells (from the outer ring) and center cells, the former with a tendency of having more UEs than the latter. This is also because UEs in edge cells do not have other cells to connect to, and also experience better SINR conditions since there is not much interference from other cells (this is true in particular for the cells placed in the corners of the rectangle).

Other parameters that can be configured directly from the command line of the lena-dual-stripe program are full buffer traffic, downlink-only functionality, UE speed, bandwidth allocations for downlink/uplink, eNB transmission power and number of eNB sites. The `LteHelper` class can be used to configure antenna-related parameters (i.e., model type, height, beamwidth, maximum attenuation, downtilt), the round-robin scheduler, the handover algorithm and pathloss model parameters (after distance conversion from km to m). The transmission mode (i.e., SIMO) and UE's mobility model and height can only be adjusted through ns-3's attribute system.

3.2 Additional Configuration in ns-3

Some parts of the configuration required to replicate the 3GPP reference cases need additional setup. Even though cell deployment in ns-3 can be done through the `LteHexGridEnbTopologyHelper` class, this only allows allocation of odd/even numbers of sites per row, with a difference of at most 1 site between two rows of sites (e.g., 4-5-4-5-4). For the configuration required for the 3GPP reference scenarios, there is a 3-4-5-4-3 row setup, as can be seen in Fig. 1. Therefore, the cells' locations must be configured manually in the lena-dual-stripe code, based on the Cartesian coordinate system. We selected these coordinates so that the sites were at the required distance from their immediate neighbours (i.e., 500m or 1732m, depending on the 3GPP case in use).

While full buffer traffic was already implemented in the lena-dual-stripe example using UDP applications, through a set of helper classes in ns-3 (e.g., internet stack, UDP client, and routing helpers), bursty traffic required additional work. We implemented bursty traffic as a UDP application, with the use of the `OnOffApplication` class. The helper class enabled applications which send 2Mbytes as fast as possible. For each UE, an application is set to start after n seconds, where n is generated using an exponential random variable with a mean of 5s. The `PacketSink` class was also modified to measure the time of arrival of the first packet and last packet of the burst, as required by 3GPP.

For 3GPP Case 3, there was a requirement of [10-100] UEs/cell, with non-uniform density. However, there are no further specifications in the 3GPP standard [4] as to what kind of non-uniform distribution should actually be used. In this paper, we simulated a scenario with one cluster location. We used a uniform density of approximately 11-12 UEs/cell for the initial drop of users in a rectangular area encompassing the 19 sites, resulting in a total of 660 UEs. Afterwards, we chose a circular area with a radius of 1000 for the uniform drop of an additional 90 UEs, to simulate a clustered/non-uniform distribution of UEs in some of the inner sites. A sample drop for this case is shown in Fig. 2. It can be seen that there are more users in the lower left quadrant, distributed around the (-1200,-1400) point, which represents the center of the 1000m circle/cluster.

3.3 Configuration Limitations of ns-3

There is no option in ns-3 to place UEs at a minimum distance from eNBs when using the uniform random position allocator classes. As a result, instead of having 35m minimum distance between UEs and

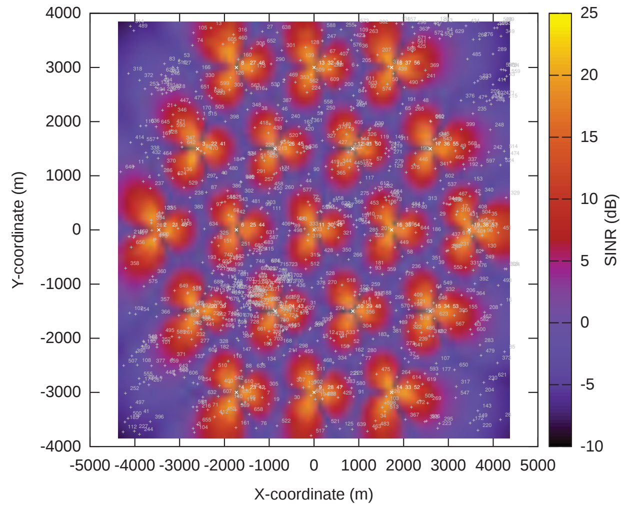

Figure 2: 3GPP Case 3 Deployment

eNBs[1], we have a minimum of 30.5m (when considering an antenna height of 32m and UE height of 1.5m). For this requirement to be implemented, UE placement would have needed to be configured externally to ns-3, while taking into account eNB locations.

4 RESULTS AND ANALYSIS

For each 3GPP case and traffic combination (i.e., full buffer or bursty), we performed a total of 30 different trials/runs in ns-3. Each run has a different independent UE placement/drop, and the evaluation is performed only on the UEs attached to the inner 7 sites (21 eNBs). The outer ring is used only for interference purposes, since ns-3 does not have a wraparound feature.

We compared the results against the ones provided in 3GPP's TR 36.814 [4]. Some of the 3GPP results were only available in graphical format, including the UEs' SINR and throughput CDFs. These CDFs are presented only for 3GPP Case 1 with full buffer traffic, as results for bursty traffic or for 3GPP Case 3 are not available in TR 36.814. The other system performance metrics required by 3GPP are mentioned in section A.2.1.4 of TR 36.814. For full buffer traffic these are: mean user throughput, throughput CDF, and median and 5% worst user throughput. For bursty traffic, considering user perceived throughput during active time, the required metrics are: user perceived throughput CDF, percentage of users with 1% or more dropped packets, median and 5% worst user perceived user throughput, and average user throughput.

UE SINR values were extracted from ns-3's PHY KPI file (`ns3::PhyStatsCalculator::DlRsrpSinrFileName`). UE full buffer downlink throughput values were taken from ns-3's RLC KPI file (`ns3::RadioBearerStatsCalculator::DlRlcOutputFilename`), while for bursty traffic we computed throughput with a modified version of the `PacketSink` class, as the available ns-3 KPI file did not provide sufficient information.

[1]This minimum distance is specified in the 3GPP standards as "distance between UE and cell", so we assumed that this is the actual distance between the UE and the antenna location in a 3D space, rather than between the UE and site position's in a 2D plane.

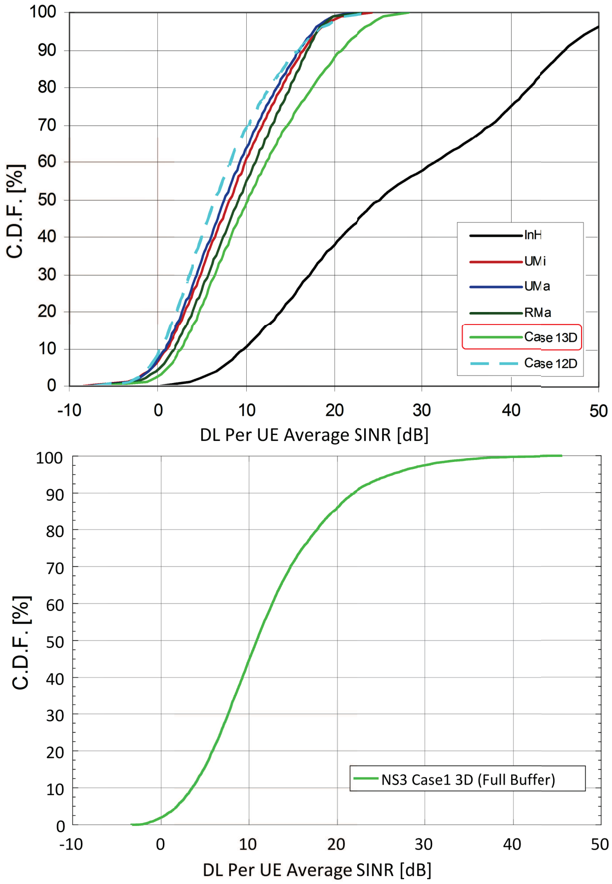

Figure 3: Case 1 UE SINR CDF: 3GPP [4] (top) vs. ns-3 (bottom)

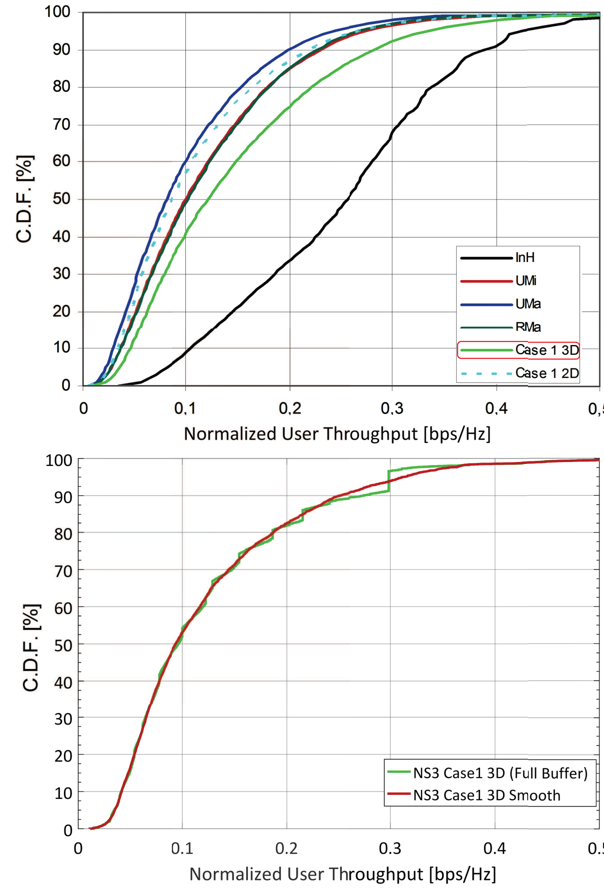

Figure 4: Case 1 Full Buffer UE Throughput CDF: 3GPP [4] (top) vs. ns-3 (bottom)

4.1 Full Buffer Traffic

Full buffer traffic results were computed over a 100 TTI interval for each run. The ns-3 simulator first goes through an initial setup stage, where UEs are (re-)allocated to cells depending on their SINR, and server-client applications are started. Performance stabilizes after approximately 300-400ms, therefore the 100 TTI for which we report results are taken from the [0.4-0.5s] interval after start-time.

4.1.1 3GPP Case 1. Fig. 3 presents a side-by-side comparison between the 3GPP results (top, Case13D light-green curve) and results obtained by the ns-3 simulator (bottom) for UEs' SINR CDF[2]. It can be noticed that ns-3 closely matches the 3GPP Case1 3D curve, with the exception of the top 5% UEs in terms of SINR. The top 5% UEs in ns-3 achieve a better SINR than the ones in the 3GPP simulations. This might happen because the minimum possible distance between ns-3's UEs and eNBs is 30.5m, instead of the required 35m.

[2]Note that the ns-3 results could not be superimposed in the upper plots from Figures 3 and 4 since, as previously mentioned, the 3GPP results are only available in graphical format in the standards.

A similar comparison can be found in Fig. 4, where 3GPP's throughput CDF (top) is presented side-by-side with ns-3's (bottom), in the same color scheme (light-green for both curves). It can be noticed again that the curves are quite similar, although ns-3's curve presents a stepped pattern. We believe this may be due to how ns-3 quantizes the modulation coding scheme (MCS) and code block (CB) sizes, since there are 27 values used for MCS, and only 9 values for CBs, instead of 188 possible. As a result, there are only 243 effective code rates (ECR, or MCS-CB combinations), as opposed to 5076 ECRs possible [7, 8]. This quantization choice was done in order to reduce the computational complexity of ns-3. In practice, we noticed from the ns-3 KPI files that fewer than 100 ECRs were used across all the UEs involved during our simulations.

We also present a smoothed CDF version of ns-3's throughput (red) in Fig. 4, which was processed in Matlab from the initially stepped CDF (green), by averaging points with the closest neighbour values. This smoothed curve more closely matches the curve in the upper part of the figure, Case1 3D, which represents an average over 17 curves obtained by industrial simulators. Again, a

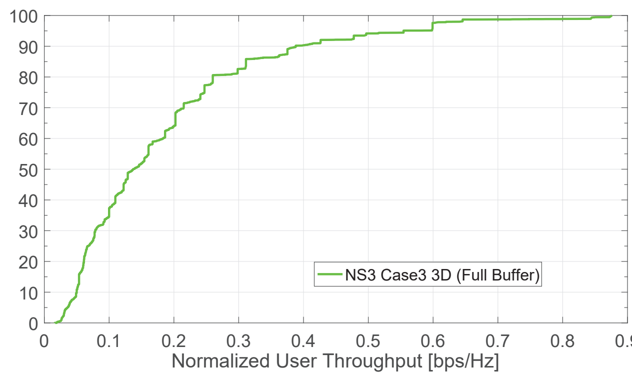

Figure 5: Case 3 Full Buffer UE Throughput CDF in ns-3

better throughput can be noticed for the top 5% UEs, since they benefit from better SINR.

A comparison between results obtained by ns-3 and the averaged results of 3GPP's industrial simulators is presented in Table 2. The 3GPP results also include a coefficient of variation between the industrial simulators, which represents the standard deviation divided by the average value. Additionally, besides spectral efficiency values, the last row of the table presents the actual throughput values (in Mbps) obtained at cell and UE level by ns-3.

Even though the throughput CDF values are computed considering only the downlink bandwidth (10 MHz), ns-3 results for cell spectral efficiency values are equivalent to 3GPP reference results only when the whole bandwidth of 20 MHz is considered in the computations for ns-3's cell spectral efficiency. Given that the ns-3 UE throughput CDF values match the 3GPP values, we expect the overall cell spectral efficiency to also be similar. Results for the other metrics are computed only over the downlink bandwidth, as in the CDF case.

While section A.2.1.4 in TR 36.814 (on system performance metrics) additionally specifies that for evaluation of a reference scenario also mean and median throughput values for UEs should be reported, there are no such reference values provided in TR 36.814 itself, therefore in Table 2 we only provide the results obtained with ns-3.

Table 2: Full Buffer Results Comparison Case 1

Case1 3D	Cell Spectral Efficiency	Cell-edge User Spectral Efficiency	Mean Throughput	Median Throughput
3GPP	1.5 bps/Hz (5% variation)	0.035 bps/Hz (15% variation)	N/A	N/A
ns-3	1.16 bps/Hz (2.32 downlink)	0.035 bps/Hz	0.12 bps/Hz	0.09 bps/Hz
ns-3 (actual T-put)	*23.25 Mbps*	*0.35 Mbps*	*1.16 Mbps*	*0.87 Mbps*

4.1.2 3GPP Case 3. As required in the performance metrics considerations section of TR 36.814, for 3GPP Case 3 only throughput results were acquired. Fig. 5 illustrates UEs throughput CDF, and Table 3 presents the statistics required by 3GPP. In Case 3 there are no reference results provided by 3GPP that can be used for comparison.

Mean and median throughput values are higher than in Case 1, because there are fewer UEs per cell on average: about 12-13 users in Case 3 compared to approximately 25 in Case 1. However, cell edge users have slightly worse throughputs, 0.32Mbps in Case 3 vs 0.35Mbps in Case 1, since they are much further away from eNB antennas (up to 866m vs 250m). This happens even though the edge UEs have almost double the bandwidth (in number of RBs) available than in Case 1 (approximately 4 RBs/UE in Case 3 compared to 2 RBs/UE in Case 1).

4.2 Bursty Traffic

For bursty traffic, an interval of 5 seconds (the mean arrival rate of one 2MB file per UE) in real-time was employed for gathering ns-3 results, specifically the [0.4-5.4s] interval after the simulator's start time. Only the UEs that actually produced traffic were selected for computations, since approximately 35% UEs do not produce any traffic in the first 5.4 seconds of the simulation. Results for bursty traffic are based only on perceived throughput values (in Mbps), according to the requirements in section A.2.1.4 of TR 36.814 [4]. Since there are no reference results provided by 3GPP for bursty traffic, the only results presented are the ones obtained in ns-3.

4.2.1 3GPP Case 1. The perceived throughput CDF for Case 1 with bursty traffic is presented in Fig. 6, while the other statistics are shown in Table 4. A sudden jump can be noticed at the top 1-2%. This represents the maximum throughput achievable on the 10MHz bandwidth with ns-3, which is approximately 75Mbps, and occurs for UEs that are close to the eNBs, when there is no traffic for other UEs within the same eNB.

Table 3: Full Buffer Results Case 3

Case3 3D	Mean Throughput	Median Throughput	5% Worst User Throughput
ns-3 normalized	0.17 bps/Hz	0.12 bps/Hz	0.032 bps/Hz
ns-3 actual	1.75 Mbps	1.24 Mbps	0.32 Mbps

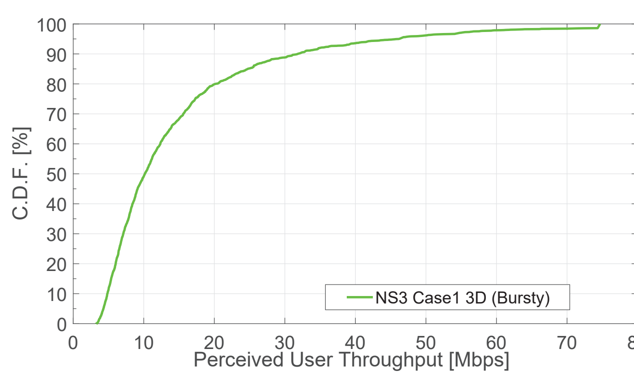

Figure 6: Case 1 Bursty Traffic UE Throughput CDF in ns-3

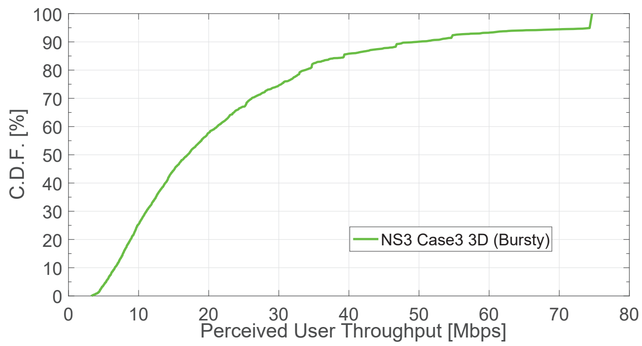

Figure 7: Case 3 Bursty Traffic UE Throughput CDF in ns-3

4.2.2 3GPP Case 3. For Case 3 with bursty traffic, the perceived throughput CDF is shown in Fig. 7. Additional throughput-related statistics are presented in Table 4. Mean throughput values in this case are better than in Case 1, 23.03 Mbps vs. 14.98 Mbps, as UEs in Case 3 have more bandwidth available (almost double the RBs on average), despite having lower SINR due to larger distance between eNBs and UEs. In this particular case, there are more UEs able to achieve the maximum rate of 75Mbps (about 5%), as there are fewer overlapping UEs bursts in the same eNB. This occurs even though, on average, the UEs are further away from the eNB. However, in this particular case, edge users from the ns-3 simulations show lower throughput when compared to edge users in the 3GPP reference sceanarios.

Table 4: Bursty Traffic Results ns-3

Bursty Traffic	Mean Throughput	Median Throughput	5% Worst User Throughput	Users with 1% or more dropped packages
ns-3 Case1	14.98 Mbps	10.16 Mbps	4.27 Mbps	3.15%
ns-3 Case3	23.03 Mbps	16.99 Mbps	5.36 Mbps	2.89%

We have made all these results available on GitHub for replication [5], containing the ns-3 modified code used to generate them, and matlab scripts used for plotting the results and computing the statistics.

5 CONCLUSIONS

We aimed to validate the ns-3 LTE module at system level against the data provided from TR 36.814 [4] in a set of 3GPP recommended scenarios.

The scenarios taken into account were Case 1, an urban setup with 500m between macro cells and high UE density, and Case 3, a rural setup with 1732m between macro cells, and low UE density. For the reference results provided in TR 36.814, we have shown that ns-3 achieves similar performance to the 3GPP calibration data available in terms of SINR CDFs, throughput CDF and spectral efficiency statistics. However, we also noticed some small differences in the ns-3 throughput CDF, as this presents a stepped pattern due to the way ns-3 quantizes code block sizes.

An additional contribution of this paper is represented by our performance analysis while considering bursty traffic, as we show how ns-3's LTE module performs under different conditions than full buffer traffic. Additionally, we have performed the same type of performance analysis for 3GPP Case 3, considering both full buffer and bursty traffic. Case 3 is a reference scenario for which there were no previous results available, unlike Case 1 with full buffer traffic where reference results are provided by 3GPP. Finally, as a contribution to the research community, our configuration scripts and the 3GPP calibrated ns-3 LTE simulator files are made available online on github, and can be used as a baseline for further evaluations.

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