

Towards LTE-Advanced and LTE-A Pro Network Simulations

Implementing Carrier Aggregation in LTE Module of ns-3

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ABSTRACT

Carrier aggregation (CA) technology was introduced in 3GPP specification in Release 10, in 2011, as part of Long Term Evolution Advanced (LTE-A) standardization. Most of the operators recognized it as the most important technology in LTE-A since it allows to quickly turn investment in additional LTE carriers into higher data rates. This is because CA allows a quick adoption and an efficient usage of fragmented and non-contiguous spectrum. Additionally, CA is a key technology for enabling some of LTE-A Pro technologies which are proposed in Release 13 and 14, such as, aggregation with unlicensed frequencies in the downlink, known as licensed assisted access (LAA), and LAA with aggregation in the uplink, known as enhanced LAA (eLAA). In this paper we describe the CA extension of the LTE module of ns-3 network simulator that we have implemented and contributed to ns-3 community. Firstly, we describe the motivation and technology background. Then, we describe the extension from a technical perspective, highlighting the new application interface being introduced, and the modifications of prior ns-3 LTE model involving the control and data planes of both the user equipment (UE) and evolved node B (eNB) protocol stack. Finally, we provide description of example scenarios and the validation of the carrier aggregation feature providing a performance comparison of the LTE system with and without CA capability.

CCS CONCEPTS

•Networks → Network simulations; •Computing methodologies → Discrete-event simulation;

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KEYWORDS

Network Simulator 3 (ns-3), LTE-A, Carrier Aggregation

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1 INTRODUCTION

Several studies predict an exponential increment in data bit rate demand from cellular networks users. A much higher traffic demand is expected for mobile networks [8] in the near future, especially within urban areas. Indeed, the design requirements of the fifth generation (5G) specify 1,000 times more capacity per unit area with respect to 4G. On this matter, CA is a promising technology that allows to increment data rate by aggregating transmissions across multiple component carriers (CCs). CA is also an essential feature in LAA and eLAA technologies, defined respectively in Release 13 and 14 [6, 7], which enable licensed bands to be augmented by carriers located in unlicensed bands. Thanks to CA, Secondary Cells (SCells) can carry data transmissions in an unlicensed spectrum, while anchored to a primary cell (PCell) in the licensed spectrum, which maintains the essential control messages and also provides always available robust spectrum for real-time or high-value traffic. In a practical sense, CA brings to operators many competitive advantages: it allows to reach much higher capacity, scalability, more efficient load balancing, all of which results in considerably higher peak data rates, lower delays, better coverage and better QoS. However, research, implementation, comparison and testing of CA based technologies are usually very expensive in scalable environments, and so require the need for testing over high fidelity simulators. Thus, we consider that an LTE network simulator containing a CA feature holds an essential place in LTE-A, LTE-A Pro and 5G research.

Up to our knowledge, among the available LTE-A open source simulators, only LTE-Sim [12] provides CA functionality. LTE-Sim is a C++ object oriented open source simulator designed for supporting LTE and LTE-A technologies. The main drawback of this simulator is that it does not allow to simulate scenarios typical of CA, where component carriers are in unlicensed bands and LTE has to coexist with other technologies like WiFi. Moreover, it does not model TCP [10], which limits the range of scenarios and applications that can be evaluated. Regarding the CA feature and 3GPP oriented network in general, several studies have been carried out in 3GPP with proprietary simulators [7, 11]. However, the usage of proprietary simulators does not allow to reproduce the results and validate the models.

On the other hand, ns-3 is an open source simulator, which allows simulations also in heterogeneous technology context. Moreover, since it also models TCP, ns-3 simulator represents an integrated platform for enabling CA based simulations. In this paper we present an extension of the ns-3 LTE module to support the CA feature. The extension is publicly available at [9], and will be part of the next official ns-3 releases, starting from release ns-3.27.

2 CA TECHNOLOGY OVERVIEW

CA technology allows to aggregate radio resources belonging to different carriers, in order to achieve more bandwidth and a higher data rate. CA is introduced in 3GPP standard in Release 10 and the main references in the standard are [1–4]. CA can be used with both time division duplex (TDD) and frequency division duplex (FDD). However, since ns-3 supports only FDD LTE implementation, our focus in this work is on FDD CA. Each CC can have a particular bandwidth from those originally defined in LTE 3GPP R8: 1.4, 3, 5, 10, 15 or 20 MHz. CCs can be adjacent or non-adjacent, and can be located either in the same or in different frequency bands. Thus, the following configurations are possible: intra-band contiguous, intra-band non-contiguous, and inter-band non-contiguous. In order to maintain backward compatibility with the 100 KHz raster of LTE R8, and in order to preserve the orthogonality of the subcarriers, i.e. 15 kHz spacing, the CCs central frequency should be a multiple of 300 kHz. According to Releases 10-12 a maximum of five CCs can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. Moreover, for practical reasons, CA is only specified for a few combinations of E-UTRA operating bands and number of CCs. In CA configuration each band belongs to one of the following classes [5]:

- Class A: $N_{PRB,agg} \leq 100$, max number of CC=1,
- Class B: $N_{PRB,agg} \leq 100$, max number of CC=2,
- Class C: $100 < N_{PRB,agg} \leq 200$, max number of CC=2,
- Class D: $200 < N_{PRB,agg} \leq 300$, FFS¹,
- Class E: $300 < N_{PRB,agg} \leq 400$, FFS¹ and
- Class F: $400 < N_{PRB,agg} \leq 500$, FFS¹.

A bandwidth class is specified by the $N_{PRB,agg}$ which is the total number of aggregated physical resource blocks (PRB) and the maximum number of component carriers supported by a UE. Different configurations have been introduced in Releases 10, 11 and 12 supporting various numbers of bands in the DL/UL, inter and

¹For Further Study. A term used in 3GPP to indicate that a topic will be discussed further, and any agreements will be based on further analysis.

intra combinations, and FDD and TDD. However, as operators are planning aggregation of even more carriers, especially of those in 5GHz unlicensed spectrum, the constraint of a maximum of five CCs has become a limiting factor for defining further LTE CA configurations, especially for the downlink. For this reason, in Release 13 it is proposed to allow aggregation of up to 32 carriers, which corresponds to bandwidth of up to 640 MHz. Since this feature is still under standardization and trials, to this respect, the implementation of CA extension in ns-3 is based on the CA requirements that are defined in Releases 10-12.

In order to maintain backward compatibility and to achieve a smooth migration from LTE to LTE-A, each CC is treated as a separate cell, with its own unique cell identifier and its own system information (SI). Currently, devices that are not CA ready, can switch from one CC to the other through the handover procedure. On the other hand, a UE device that has CA capability tries to associate to the network by executing the random access procedure on a primary component carrier (PCC). After the association, additional resources can be configured; these carriers are generically called secondary component carriers (SCCs). The radio resource control (RRC) connection is handled only by one cell, the primary serving cell, which is served by the primary CC in the downlink and uplink (DL and UL PCC). It is also on the DL PCC that the UE receives non-access stratum (NAS) information, such as security parameters. The coverage of the serving cells may differ. This can be used in hetnet scenarios where different system deployment can be configured leveraging on CA. Depending on the scenario's circumstances, the serving cells can be:

- co-located and overlaid in the same frequency band: UEs within the cell coverage area can access to all CCs, so they can exploit all the CA functionalities to increase throughput.
- co-located and overlaid with different frequency band: can be used to boost the cell edge performance by taking advantage from the different propagation condition of the different carriers.
- not co-located: a macro-cell provides coverage while radio remote head and small cell provide improved throughput at the traffic hot-spots.

3 IMPACT ON LTE STACK ACCORDING TO 3GPP

The introduction of CA influences mainly the MAC and RRC. In order to keep R8/R9 compatibility each CC is treated as an R8 carrier. However, some changes are required, such as extension of RRC messages in order to handle the SCC information, and Medium Access Control layer (MAC) to allow simultaneous scheduling on a number of CCs. In order to maintain backward compatibility, in LTE-A, each UE establishes the cell connection following the R8 procedure. This includes a cell search and selection, followed by the SI acquisition phase and the random access procedure. As anticipated above, all the CCs broadcast their own SI and synchronization signals. The RRC is in charge of the connection procedure, and it selects the PCC. Once the UE is in connected state, the eNB RRC asks feedback from the UE on the class it belongs to and its capabilities. The RRC layer at the eNB is responsible to perform

reconfiguration, addition and removal of SCCs. 3GPP defines PCC as UE related and not as eNB related. In particular, the PCC is the CC that is perceived as the most robust connection for each UE. After the UE moves to the connected state, load balancing policies can be applied, e.g. the UE can be forced to perform handover towards a less congested CC. This modification in the connection procedure is the main impact that the CA function has on the RRC layer. CA is designed to be completely transparent to both Packet Data Convergence Protocol (PDCP) layer and Radio Link Control (RLC) layer. As a result, no modifications are needed in these two layers due to CA implementation. The only possible impact could be from the hardware/software point of view, i.e. due to potential throughput increase, larger buffers should be set at those layers to receive the data-streams coming from upper layers. The MAC layer is responsible to schedule the resources and handle the priority of the different flows, multiplexing the data-stream coming from the different transport channels and the Hybrid automatic repeat request (HARQ) mechanism. CA impact on the MAC layer depends on the CA scheduling scheme. Different options have been proposed for scheduling and it is up to the vendor the choice on the scheme to follow:

- Independent Carrier Scheduling, where each CC transmits its grant using its own physical downlink control channel (PDCCH) and the scheduler allocates traffic per CC-basis.
- Joint Carrier Scheduling, where all grants are transmitted in one CC. This solution is usually referred to as cross-scheduling.

In the case of independent carrier scheduling there is almost no impact on the MAC, while in the case of joint carrier scheduling the CA impact is significant.

4 NS-3 LTE MODEL CHANGES

The ns-3 LTE module has been extended with the design criteria of maintaining backward compatibility with LTE module and preserving its normal operation mode. Class `ComponentCarrier` is added to model a component carrier instance. It contains the configuration of the physical parameters of each component carrier, such as: uplink bandwidth, downlink bandwidth, uplink E-UTRA absolute radio frequency channel number (earfcn), and downlink earfcn. `LteEnbNetDevice` and `LteUeNetDevice` classes are extended so that each of them can contain a list of CCs, and some of the attributes that were formerly part of the `LteEnbNetDevice` and are carrier specific are migrated to the `ComponentCarrier` class. The attributes that are specific for the eNB CC are migrated to `ComponentCarrierEnb`, e.g. pointers to MAC, physical layer (PHY), scheduler, fractional frequency reuse algorithm instances, and attributes specific to the UE are migrated to `ComponentCarrierUe`. `LteUeNetDevice` has maintained the downlink earfcn attribute for initial cell selection purposes. In order to control the CCs operations, the component carrier manager (CCM) has been introduced at both the eNB and UE sides. The specific instances are called, respectively, `LteEnbComponentCarrierManager` and `LteUeComponentCarrierManager`. CCMs form a central part of CA extension and they will be explained in more details in the following sections. All the changes discussed up to now are shown in Figures 1 and 2.

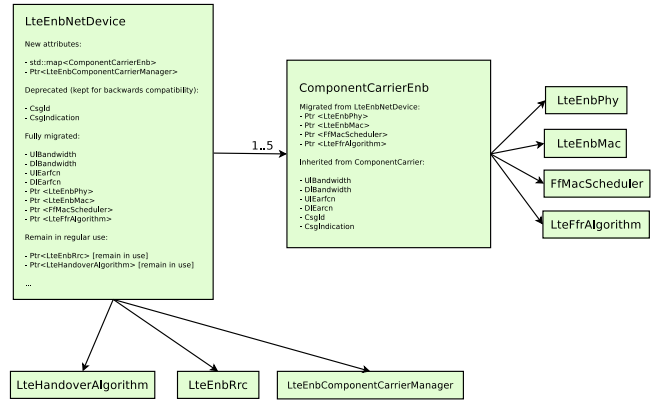


Figure 1: Changes in `LteEnbNetDevice` to support CA

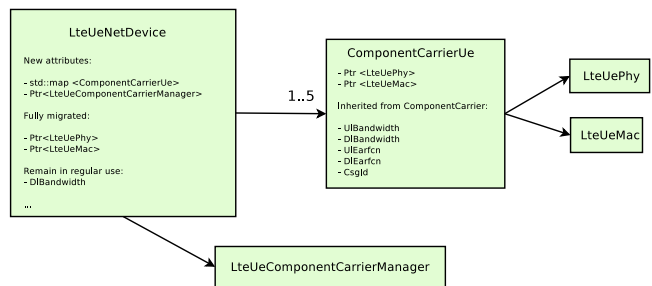


Figure 2: Changes in `LteUeNetDevice` to support CA

4.1 eNB Model for Control Plane

Figure 3 shows the class diagram of the control plane of eNB. During the design phase it was decided to maintain the same hooks as in the former architecture. To do so, for each CC, the PHY and MAC are directly associated to the RRC instance. The RRC instance is additionally connected to the `LteEnbComponentCarrierManager` to which it forwards a measurement report based on which the CCM can decide how to split the traffic among CCs. The RRC of both the eNB and UE is extended to allow measurement reporting for the secondary carriers. However, the measurement report triggering event A6 (neighbor becomes offset better than SCell) is not implemented yet. When the simulation starts, the number of CC is fixed, but only the PCC is enabled. The CA enabling procedure of SCCs is shown in Figure 4. The procedure starts once that UE is in the connected state. This part of the connection procedure is the same as in the previous implementation of LTE module. In order to simplify the implementation of CA extension, the UE Capability Inquiry and UE Capability Information are not implemented. This implies to assume that each UE can support the CA, and any specific configuration provided by the eNB to which is attached. The eNB RRC sends to the UE the secondary carrier configuration parameters through the RRC Connection Reconfiguration procedure. This procedure may be used for various purposes related to modifications of the RRC connection, e.g. to establish, modify or release RBs, to perform handover, to setup, modify or release measurements, to add, modify and release secondary cells (SCells). Once the carriers are configured, the `Reconfiguration Completed` message is sent back to

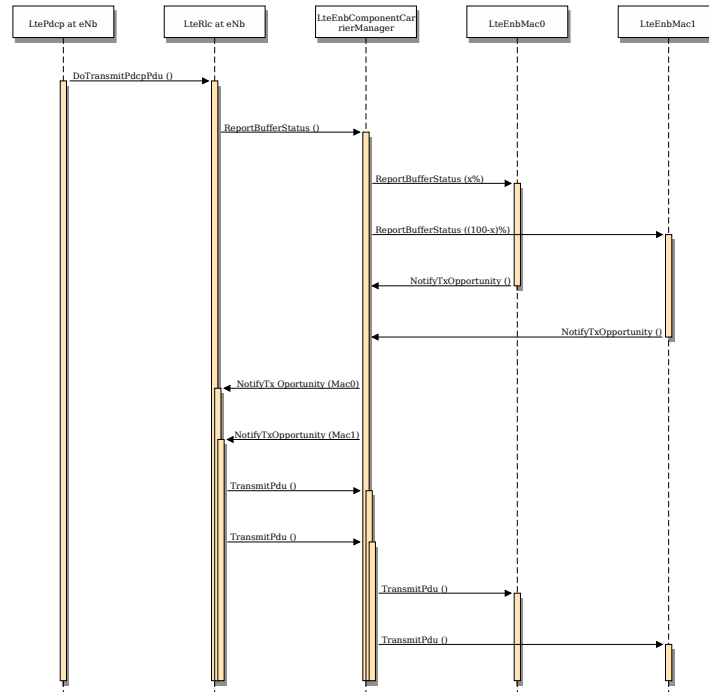


Figure 6: Sequence diagram of downlink buffer status reporting with CA

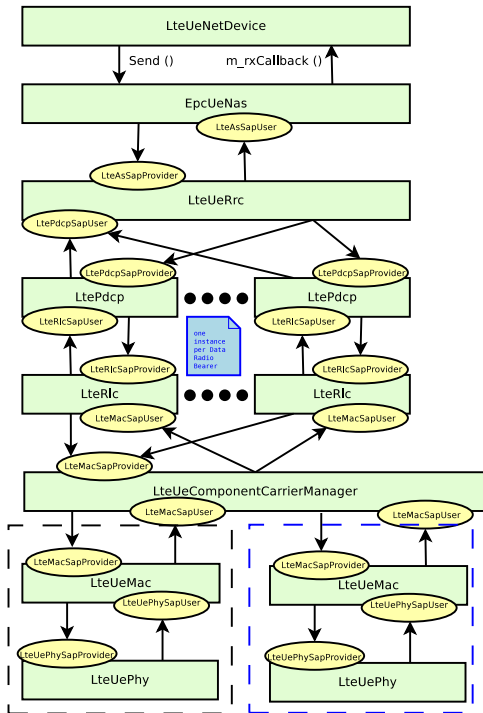


Figure 8: UE Data Plane Architecture

receives the BSR, it forwards it to LteEnbComponentCarrierManager. The latter, according to algorithm dependent policies, forwards a BSR to the CCs. An example of policy is to offload some portion of traffic to the secondary carrier only when is estimated that the primary carrier does not have enough capacity to serve all the traffic. The communication between the LteEnbRrc and the LteEnbComponentCarrierManager is done through a specific set of SAP functions which are implemented in the LteUeCcmRrcSapUser and the LteUeCcmRrcSapProvider.

4.5 Addition of new CCM SAP Interfaces

4.5.1 CCM SAP Interfaces for MAC. The CCM entity is implemented according to the SAP interface design. The following SAP interfaces are implemented for CCM and MAC in order to allow an additional message exchange specific to CA functionality:

- the LteCcmMacSapUser is provided by MAC and is used by the CCM
- the LteCcmMacSapProvider is provided by CCM and is used by the MAC layer

When the primary CC receives an uplink BSR, it uses the LteCcmMacSapUser to forward it to the CCM, which should decide how to split the traffic corresponding to this BSR among carriers. Once this decision is made, the CCM uses the LteCcmMacSapProvider interface to send back an uplink BSR to some of the MAC instances. In this way, the control over uplink BSR is moved from eNB MAC to CCM. Additionally, the LteCcmMacSapUser can be used by the MAC to notify its CCM about MAC specific information e.g. the PRB occupancy in the downlink. Such information then may be

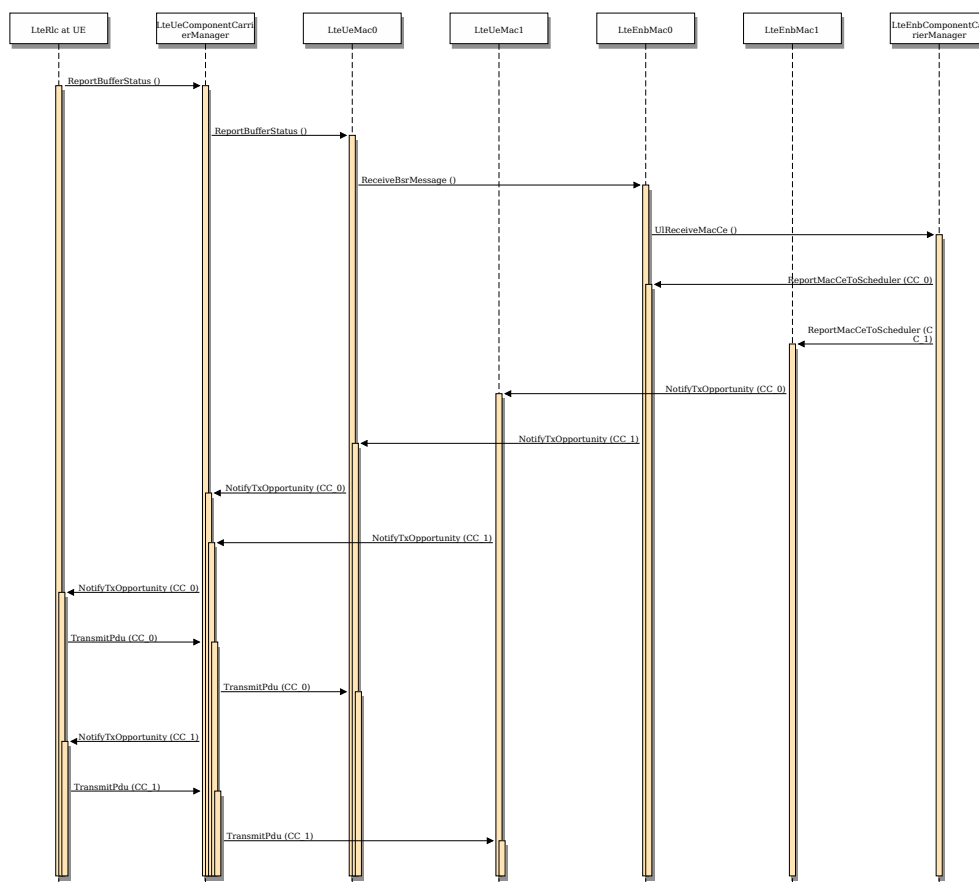


Figure 9: Uplink buffer status reporting with CA

utilized by the CCM to decide how to split the traffic and whether to activate or deactivate the secondary carriers.

4.5.2 CCM SAP Interfaces for RRC. The following SAP interfaces are implemented for CCM and RRC in order to allow an additional message exchange specific to CA functionality:

- the `LteCcmRrcSapProvider` is provided by the CCM and is used by the RRC layer
- the `LteCcmRrcSapUser` is provided by RRC and is used by the CCM

By using the `LteCcmRrcSapUser` the CCM may request a specific measurement reporting configuration to be fulfilled by the UEs attached to the eNB. When a UE measurement report is received, as a result of this configuration, the eNB RRC entity shall forward this report to the CCM through the `LteCcmRrcSapProvider::ReportUeMeas` SAP function. Additionally, the `LteCcmRrcSapProvider` offers different functions to the RRC that can be used to add and remove of UEs, setup or release of radio bearer, configuration of the signaling bearer, etc.

5 USAGE

The CA feature, disabled by default, can be activated by setting the boolean attribute `ns3::LteHelper::UseCa` to true. Component carriers configuration to be used in CA simulation can be specified in 3 different ways: a) by delegating the configuration to `LteHelper`, b) by using `CcHelper`, or c) manually by creating a `std::map` of `ComponentCarrier` objects. Option a) is the most simple, but the least custom. When this mode of configuration is used, the user may specify only the number of component carriers, but does not specify the carrier frequencies and bandwidths of SCCs. `LteHelper` uses this information to create a `ComponentCarrier` map, and it uses default parameters of `LteEnbNetDevice` to configure the primary carrier, while for the secondary carriers it calls a function of `CcHelper` which creates contiguous equally spaced carriers. An example of this kind of usage is shown in the `lena-simple` and `lena-simple-epc` programs which are extended with a configuration for CA.

Option b) allows the user to create a more specific configuration by configuring uplink and downlink frequencies and bandwidths of the PCC. Based on these parameters, `CcHelper` creates equally spaced carriers. An example of this type of CCs configuration is shown in `lena-cc-helper.cc`. Finally, the map created

in this way can be passed to the `LteHelper` by using its function `SetCcPhyParams`.

Finally, option c) allows to use a full level of control over CC configuration. First, the user creates a `std::map` where the key is index of component carrier starting from 0, where zero refers to the primary carrier. The value is an instance of `ComponentCarrier` which contains the following attribute members for configuration of the physical parameters: uplink bandwidth, downlink bandwidth, uplink earfcn, downlink earfcn. Hence, this mode allows the maximum control over CC configuration.

We decided to implement different modes of CC configuration to cover different use cases. E.g. users that wants to start quickly to use the CA feature, without having to know the details of the CA implementation, can do so by using modes a) and b), while, a user who wants a more custom configuration can achieve it by using mode c).

Another important parameter to be configured in CA simulations is the type of CCM. By default the `NoOpComponentCarrierManager` is selected, and as explained before, this means that CA is disabled. In order to activate carrier aggregation another CCM should be configured, e.g. `RrComponentCarrierManager`. The CCM can be configured through `EnbComponentCarrierManager` attribute of `LteHelper`. Finally, in order to allow CC functionality tracing, LTE PHY and MAC traces are extended to provide information per CC.

6 VALIDATION

The test suite `lte-carrier-aggregation` is an integrated ns-3 system test program that creates different test cases with a single eNB and several UEs, all having the same radio bearer specification. Different test cases are defined by using different SINR values, different numbers of UEs and different number of carriers. eNBs and UEs are configured to use the SCCs and the `RrComponentCarrierManager` is used to split the data traffic uniformly between CCs. We configure the RLC saturation mode, in order to always have data ready for transmission in the buffer. The test consists of checking that the throughput obtained over the different carriers are equal for both uplink and downlink. The test starts to count the throughput once that the RRC connection is established and the secondary carriers are enabled. This test suite can be run in a mode to write results to the output files by setting its `s_writeResults` boolean static variable to true. An example of running this test suite is shown in Figure 10. In this figure we show the performance of the legacy LTE with no SCCs, and the LTE with one and two supplemental downlink (SDL) carriers. As expected, the throughput is increasing linearly with the number of supplemental CCs.

7 CONCLUSIONS

In this paper we have presented an extension for the ns-3 LTE module to support the CA functionality. The CA extension is already merged with the ns-3 and will be available from the following ns-3.27 release. The work was initiated in the context of GSoC2015, but then has been evolved, also receiving interesting feedback from the industry. We have presented the modification of the models,

suggestions for usage and an example of the tests that we have performed. More information can be found in the official ns-3 documentation.

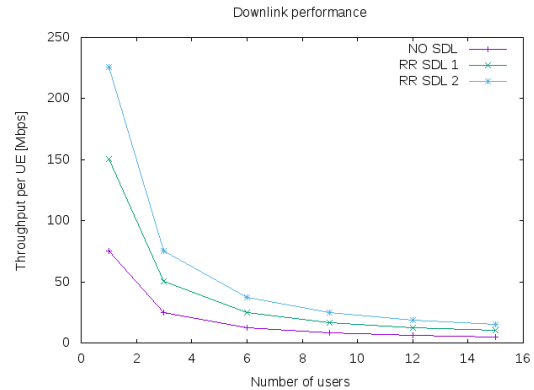


Figure 10: Throughput comparison of LTE, LTE with 1 SDL, and LTE with 2 SDLs

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