Simu5G: A System-level Simulator for 5G Networks

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Abstract: This paper presents Simu5G, a new OMNeT++-based system-level simulator of 5G networks. Simu5G is built starting from the SimuLTE simulation library, which models 4G (i.e., LTE/LTE-A) networks, and is compatible with the latter, thus allowing the simulation of 4G-5G coexistence and transition scenarios. We discuss the modelling of the protocol layers, network entities and functions, and validate our abstraction of the physical layer using 3GPP-based scenarios. Moreover, we report profiling results related to Simu5G execution, and we describe how it can be employed to evaluate Radio Access Network configurations, as well as end-to-end scenarios involving communication and computation, e.g., with Multi-access Edge Computing applications.

1 INTRODUCTION

The fifth generation of cellular networks, known as 5G, is expected to bring significant changes to the wireless networking landscape. The advent of 5G systems, in fact, will be one of the main pillars of a technology revolution that will enable an unprecedented range of ICT services, such as smart cities, autonomous vehicles, augmented reality and Industry 4.0. Another, complementary pillar key technology that will benefit from the introduction of 5G will be Multi-access Edge Computing (MEC), which will bring cloud-computing capabilities to the edge of the network, allowing mobile users to capitalize the power of complex algorithms such as those based on artificial intelligence. The new generation of networks, coupled with MEC, will thus witness a tight integration of computation and communication in a unified infrastructure.

The Radio Access Network (RAN) of the 5G network is composed of base stations, known as gNodeBs (gNB) according to the 3GPP terminology, which allocate radio resources to a number of User Equipments (UEs). The latter can be any device endowed with cellular connectivity like, e.g., handheld devices, laptops, home gateways, connected vehicles or industrial machines. The 5G New Radio (NR) technology is based on the new radio access standard developed by the 3GPP. As far as the data plane is concerned, NR consists of a stack of layered protocols, which closely resembles that of 4G (LTE/LTE-Advanced) networks, to favour the incremental deployment of 5G and its coexistence with the existing 4G infrastructure.

The performance evaluation of 5G networks is of paramount importance, in at least two complementary facets. On one hand, there is a strong need to devise and validate *resource management* schemes for the 5G RAN: for instance, scheduling algorithms at the gNB, or the best partition of resources when *dual-connectivity* UEs are simultaneously connected to both a 4G and a 5G base station. The fact that the deployment of 5G is underway as we write, and that the above functions will mostly be realized in software, makes this all the more compelling. On the other hand, there is an even stronger need to assess the feasibility and performance of new-generation, 5G-based *services*. Several of these, such as autonomous driving or factory automation, will be latency-critical, and changes in the network configuration or deployment may have a drastic impact on their timing properties.

Both the above endeavours, which are clearly intertwined, call for a flexible system-level simulation tool, where the protocols, functions and entities of the 5G NR system are modelled in detail, following the current 3GPP standards, while still working at a packet

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level. There is a substantial paucity of such tools in the academic community. To the best of our knowledge, there are few existing system-level 5G simulators. 5G-LENA (Patriciello, 2019), based on ns3[1] is an evolution of the LENA simulator (Baldo, 2011) and the mmWave simulation module from ns3. It is focused on the simulation of MAC and PHY layer of NR and provides tools for the evaluation of Bandwidth Parts management. However, it does not model dual-connectivity scenarios or configurations with coexisting LTE-Advanced and 5G networks. There are also other 5G simulators, notably 5GK-Simulator[2], Vienna 5G SL simulator (Müller *et al*, 2018) and WiSE (Jao *et al,* 2018). These model the MAC layer and the physical link to a high level of fidelity, so that users can test (e.g.) new transmission and decoding schemes. The purpose of a system-level simulator is fundamentally different, i.e., to allow the testing of end-to-end services and scenarios, possibly at a large scale, including layer-3, layer-4, and application-layer protocols and logic. Some of the above tools do provide a system-level execution mode, which allows simulating link-level aspects on a large scale, by introducing simplification in modelling while significantly increasing execution efficiency. However, none of them simulate application packets flowing through the network.

In this paper, we present Simu5G[3], a new 5G simulator based on the well-known SimuLTE library (Virdis *et al*, 2014, 2015, 2019), used by industry and academia. Simu5G is based on the OMNeT++ simulation framework, and provides a collection of models with well-defined interfaces, which can be instantiated and connected to build arbitrarily complex simulation scenarios. Simu5G incorporates all the models from the INET library, which allows one to simulate generic TCP/IP networks including 5G NR layer-2 interfaces. In particular, Simu5G simulates the data plane of the 5G RAN (rel. 16) and core network. It allows simulation of 5G communications in both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes, with heterogeneous gNBs (macro, micro, pico etc.), possibly communicating via the X2 interface to support handover and inter-cell interference coordination. Dual connectivity between an eNB (LTE base station) and a gNB (5G NR base station) is also available. 3GPP-compliant protocol layers are provided, whereas the physical layer is modelled via realistic, customizable channel models. Resource scheduling in both uplink and downlink directions is supported, with support for Carrier Aggregation and multiple numerologies, as specified by the 3GPP standard (3GPP TR 38.300, TR 38.211). Simu5G supports a large variety of models for mobility of UEs, including vehicular mobility.

Simu5G allows one to code and test, for instance, resource allocation and management schemes in 5G networks, e.g. selecting which UEs to target, using which modulation scheme, etc., taking into account inter-cell interference coordination, carrier selection, energy efficiency and so on. Moreover, it allows one to instantiate scenarios where a user application, running at the UE, communicates with a MEC application residing at a MEC host (Nardini *et al*, 2018), to evaluate (e.g.) the round-trip latency of a new-generation service, inclusive of the computation time at the MEC host. More to the point, Simu5G can run in *real-time emulation* mode, enabling interaction with real devices. In fact, on one hand OMNeT++ allows real-time scheduling of events; on the other hand, the INET library allows can be configured so as to exchange IP packets between local applications or network interfaces and the simulator. These IP packets are processed by the simulator as if they were traversing the 5G cellular network. The above two features concur to allow a user to run live networked applications having an emulated 5G network in the middle, using the *same* codebase for both simulations and live prototyping, which abates the developing time and makes results more reliable and easier to demonstrate.

The rest of the paper is organized as follows. Section 2 briefly reviews the OMNeT++ framework and the SimuLTE library. Section 3 describes Simu5G. Its validation is described in Section 4, whereas Section 5 shows profiling results and the performance evaluation of two exemplary simulation scenarios. Section 6 concludes the paper and outlines future work.

2 BACKGROUND

This section introduces basic notions of cellular networks, then it describes the OMNeT++ simulation framework and the INET library, and finally the SimuLTE library, on which Simu5G is built.

2.1 An Overview of Cellular Networks

In this section we provide enough background for a reader to understand the modelling concepts described in the rest of this paper. The basic concepts underlying are common to both 4G (LTE) and 5G (NR) cellular networks, as standardized by the 3GPP. For this rea-

[1] https://www.nsnam.org/, last accessed April 2020.
[2] http://5gopenplatform.org, last accessed on April 2020.
[3] http://simu5g.org/, last accessed on April 2020.

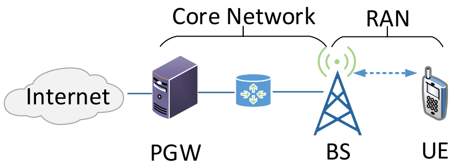


Figure 1: Architecture of a cellular network.

son, we will describe the concepts without specific reference to either standard.

A cellular network consists of a RAN and a Core Network, as shown in Figure 1. The RAN is composed of *cells*, under the control of a single base station (BS). UEs are attached to a BS and can change the serving BS through a handover procedure. BSs communicate with each other through the X2 interface, a logical connection which normally runs on a wired network. The Core Network consists of IP routers connecting an entry point, the Packet GateWay (PGW) to the BSs. Forwarding in the Core Network is carried out using the GPRS tunneling protocol (GTP).

In the RAN, communications between the BS and the UE occur at layer 2 of the OSI reference model. Layer 1 and 2 are implemented using a stack of four protocols, on both the BS and the UE. From the top down, we first find the Packet Data Convergence Protocol (PDCP), which receives IP datagrams, performs cyphering and numbering, and sends them to the Radio Link Control (RLC) layer. RLC Service Data Units (SDUs) are stored in the RLC buffer, and they are fetched by the underlying MAC (Media Access Control) layer when the latter needs to compose a transmission. The MAC assembles the RLC Protocol Data Units (PDUs) into Transport Blocks (TBs), adds a MAC header, and sends everything through the physical (PHY) layer for transmission.

Resources scheduling is done by the BS periodically, every Transmission Time Interval (TTI). On each TTI the BS allocates a vector of Resource Blocks (RBs) to backlogged UEs, according to its scheduling policy. A TB occupies a variable number of RBs, based on the Modulation and Coding Scheme (MCS) chosen for transmission. The MCS is selected by the BS, based on the Channel Quality Indicator (CQI) reported by the UE. The latter mirrors the Signal to Interference to Noise Ratio (SINR) perceived by the UE, quantized over a scale of 0 (i.e., very poor) to 15 (i.e., optimal). The CQI implicitly selects the MCS, hence the number of bits that one RB can carry.

In the downlink (DL), the BS transmits the TB to the scheduled UEs on the allocated RBs. In the uplink (UL), the BS sends *transmission grants* to UEs, specifying which RBs and MCS to use. UEs signal to the BS that they have UL backlog by sending Buffer Status Reports (BSRs) after a scheduled transmission, or by starting a Random ACcess (RAC) procedure in order to obtain a scheduling grant by the BS, if they are not scheduled. Scheduling and transmissions in the UL and DL directions are independent. The partitioning between UL and DL resources can be in frequency or time, leading to Frequency-division Duplexing (FDD) and Time-division Duplexing (TDD) deployments. In FDD, each direction uses a separate spectrum. In TDD, instead, the DL and UL legs share the same spectrum, and the two directions coexist alternating over time.

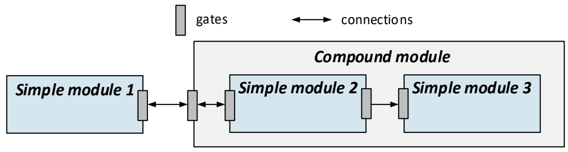


Figure 2: OMNeT++ module connection.

MAC transmissions in both directions are protected by a Hybrid-Automatic Repeat Requests. After a configurable number of TTIs, the receiver sends an ACK/NACK to the sender, which can then re-schedule a failed transmission. H-ARQ can be synchronous or asynchronous. In the first one, re-transmissions occur after a fixed number of TTIs, whereas no such constraints exist in the second case.

2.2 The OMNeT++ Framework and the INET Library

OMNeT++[4] is a well-known discrete-event simulation framework that can be used to model practically any kind of networks, including wired, wireless, on-chip networks, sensors networks, photonics networks, etc. Its main building blocks are *modules*, which can be either *simple* or *compound*. Modules exchange *messages* through *connections* linking their *gates*, which act as interfaces. A *network* is a special compound module, with no gates to the outside world, which sits at the top of the hierarchy. Connections must respect module hierarchy: with reference to Figure 2, simple module 3 cannot connect to 2 directly, but must instead pass through the compound module gate. Simple modules implement model behavior via *event handlers*, called by the simulation kernel on receipt of messages. For instance, a node can schedule a timer by sending a message to itself. Simple modules have an *initialization* and *finalization* function, that can be called in user-defined order at the start and the end of a simulation.

OMNeT++ separates a model's *behavior, description* and *parameter values*. The *behavior* is coded in

[4] http://omnetpp.org, last accessed March 2020

C++. The description (i.e., gates, connections and parameter definition) is expressed in files written in Network Description (NED) language. Parameter values are written in initialization (INI) files. NED is a declarative language, which exploits inheritance and interfaces, and it is fully convertible into XML. NED allows one to write *parametric* topologies, e.g. rings or trees of variable size. NED files can be edited both textually and through a GUI. INI files contain the parameter values that will be used to initialize the model. Multiple values or intervals can be specified for a parameter.

OMNeT++ Eclipse-based IDE facilitates debugging by allowing a user to inspect modules, turn on/off textual output during execution, visualizing the message flow in an animation, and displaying events on a time chart. OMNeT++ *studies* are generated from INI files, computing the Cartesian product of all the parameter values and generating independent replicas with different seeds for the random number generators. Multiple runs can be executed in parallel on a multicore machine. Rule-based data analysis allows a user to construct *recipes* to filter or aggregate data, which can then be applied to selected data files or folders.

INET[5] is a model library for OMNeT++. It implements models of many components of a communication network, such as communication protocols, network nodes, connections, etc. INET contains models for the Internet stack (TCP, UDP, IPv4, IPv6, OSPF, BGP, etc.), wired and wireless link layer protocols (Ethernet, PPP, IEEE 802.11, etc.), and provides support for developing custom mobility models, QoS architectures, etc.

Thanks to OMNeT++ modular structure, by incorporating the INET library a user can instantiate and connect protocol layers (e.g., an entire TCP/IP stack at a host, from the application to the MAC), and to quickly setup composite models, e.g., an IP router with an Ethernet card and a PPP WAN connection.

To allow emulation of real-life applications and protocols, INET provides modules that act as a bridge between the simulation environment and the real network interfaces in the host operating system. Packets received by the real interfaces appear in the simulation within such modules, whereas simulated packets sent to the latter are sent out on the real network interface. Emulation requires OMNeT++ to be configured with a *real-time event scheduler* synchronized with the system clock.

2.3 SimuLTE

SimuLTE is a popular simulation library built on OMNeT++. Since its publication in 2014, it has supported more than 90 published research works[6].

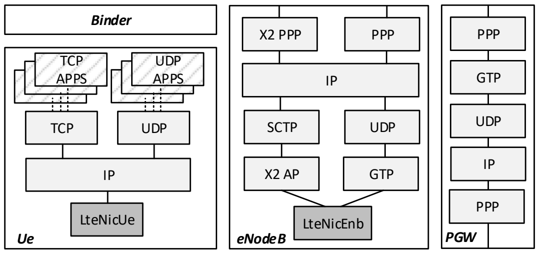


Figure 3: Main components of SimuLTE.

SimuLTE simulates the data plane of the LTE/LTE-A RAN and Core Network. Its main component nodes are shown in Figure 3. UEs and BSs (called *eNBs* in LTE) are implemented as compound modules, that can be connected with each other and with other nodes (e.g. routers, applications, etc.) to compose networks. Both have an *LTE* Network Interface Card (NIC) module, which implements the LTE protocol stack. The *Ue* module also includes IP and TCP/UDP protocols, as well as vectors of TCP/UDP applications. The *eNodeB* module includes two PPP interfaces: the X2PPP module allows the direct connection with neighbouring eNBs using the Stream Control Transmission Protocol (SCTP) protocol as specified by the standard, whereas the PPP module is connected to the PGW module.

SimuLTE simulates the *data plane*. Signalling and management protocols are not implemented in the current version (but they can easily be added). Control-plane interactions are instead modelled by adding a *Binder* module, which is visible from the other nodes and stores information about them (e.g., which node uses which resource frequency when). Control-plane interactions can then be easily modelled via queries to the Binder, without the need of complex logic.

The NIC module models all the sublayers of the LTE stack described in Section 2.2, each as a simple module. One aspect of interest is that SimuLTE models the tangible effects of propagation on the wireless channel at the receiver *without* modelling symbol transmission and constellations in the PHY. With reference to Figure 4, when a MAC PDU is sent from a sender to a receiver, an OMNeT++ message is exchanged between them. On receipt of the latter, the receiver applies a *channel model* to compute the received power. The channel model can be configured to incorporate fading, shadowing, pathloss, etc., and can be made arbitrarily complex. From the received power, the receiver computes the SINR, querying the Binder to know which other nodes were interfering on the

[5] http://inet.omnetpp.org, last accessed March 2020

[6] Google scholar search, February 2020.

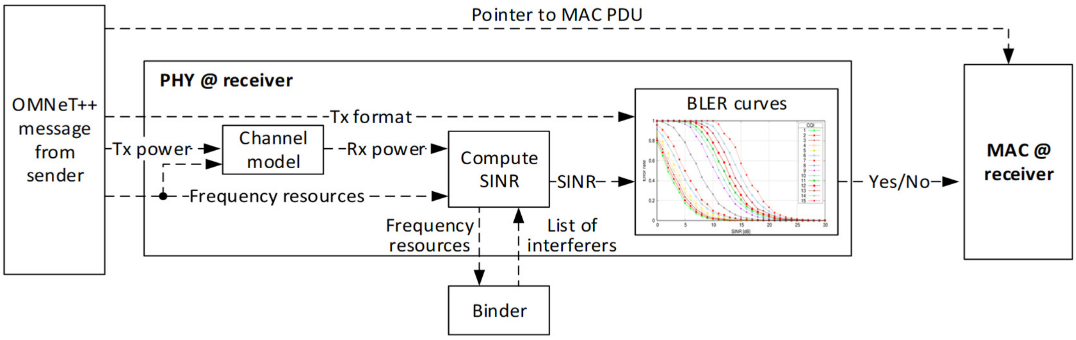


Figure 4: Block diagram of the modelling of the LTE physical layer within SimuLTE.

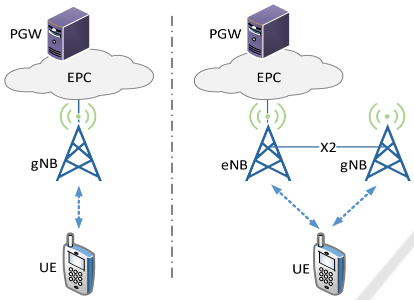


Figure 5: SA (left) and ENDC (right) deployment.

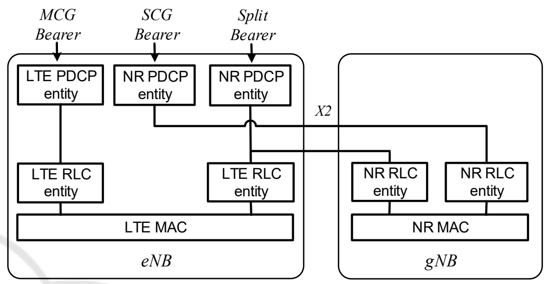


Figure 6: Interactions between eNB and gNB in an ENDC deployment.

same resources. Then, it leverages Block Error Rate (BLER) curves to compute the reception probability for each RB composing the ongoing transmission. BLER curves can be obtained from a link-level simulator. This makes it possible to translate a SINR and a transmission format to a probability of correct reception of the entire MAC PDU (some straightforward probability algebra is required if a MAC PDU occupies more than one RB). The above modelling abates the computational complexity of the decoding operation, hence the simulation running time, while preserving its correctness, and it still allows arbitrary channel models to be used. As we show in the next section, the same modelling philosophy is preserved in Simu5G.

3 MODELING 5G NEW-RADIO COMMUNICATIONS

The main components of Simu5G are the *NrUe* and *gNodeB* modules, obtained as extensions of the *Ue* and *eNodeB* modules described in Section 2.3. They maintain the same architecture shown in Figure 3, except for the *LteNic* modules that are replaced with their NR versions, called *NrNicUe* and *NrNicGnb*, respectively. We underline that this architectural choice allowed us to incorporate functionalities modelled in SimuLTE into Simu5G at no cost. These include, among others, UE handover and network-controlled device-to-device (D2D) communications, both one-to-one and one-to-many. Since these were described in recent standalone papers, they will not be mentioned further here.

In a typical network setting, the gNB is connected to the PGW to communicate with the Internet, as shown in Figure 5 (left). This is referred as StandAlone (SA) deployment. However, the 3GPP standard defines an E-UTRA/NR Dual Connectivity (ENDC) deployment, shown in Figure 5 (right), where LTE and 5G coexist (3GPP – TR 38.801). This option is of interest especially in the early development phases of 5G. In this configuration, the gNB works as a Secondary Node (SN) for an LTE eNB, which acts as Master Node (MN) and is connected to the Core Network. The eNB and the gNB are connected through the X2 interface and all NR traffic needs to go through the eNB. According to (3GPP - TR 37.340), the data flow between the eNB and the gNB is shown in Figure 6. With reference to the latter, data destined to a UE served by the eNB (Master Cell Group – MCG - bearer) follows the LTE protocol stack, whereas data destined to a UE served by the gNB (Secondary Cell Group – SCG - bearer) gets into the NR PDCP entity at the eNB and is transferred to its peering NR RLC entity in the gNB, via the X2 interface. The 3GPP standard also supports Split Bearers (SBs). With this feature, data belonging

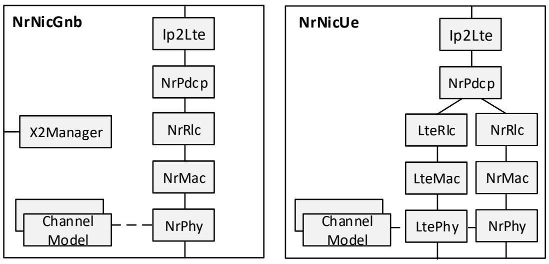


Figure 7: Structure of the NR NIC modules.

Table 1: NR numerologies.

μ	0	1	2	3	4
TTI (ms)	1	0.5	0.25	0.125	0.0625

to the same connection can traverse either the eNB or the gNB. The PDCP layer at the UE side will then reorder PDUs coming from LTE/NR RLC layers.

Simu5G allows one to deploy networks in both SA and ENDC configurations. In our modelling, the internal structure of the *NRNicGnb* module is shown in Figure 7 (left). It is composed of one submodule for each layer of the protocol stack, plus one *Ip2Lte* module that acts as a bridge with the IP layer. Data packets can be received from either the PGW through the *Ip2Lte* module or its master eNB through the *X2Manager* module in ENDC scenarios. Figure 7 (right) shows the *NrNicUe* module, which is equipped with two sets of PHY, MAC and RLC submodules to enable coexistence of NR and LTE. The NR versions of the layers are used for processing data coming from/going to the gNB, whereas the LTE ones are used for processing data coming from/going to the eNB, if any. As shown in the figure, the PDCP layer is unique. This way, packets belonging to a SB are handled by the same PDCP entity, which provides in-sequence delivery to upper layers.

3.1 NR Resource Management

NR communications can take place on several frequency *carrier components* (CCs), i.e., disjoint portions of frequency. Each CC has a number of RBs. Each e/gNB may implement multiple CCs, each characterized by its own carrier frequency, in the so-called *Carrier Aggregation* (CA) mechanism. To support CA, we modeled a *carrierAggregation* module to store all the information related to the CCs employed in the network. Like the Binder, it is modelled as global module visible by all e/gNBs and UEs in the simulation. It includes a vector of *N componentCarrier* submodules, whose carrier frequency can be configured via NED/INI. However, we need to take into account that e/gNBs and UEs might have limited capabilities in terms of supported frequency range, hence a gNB/UE

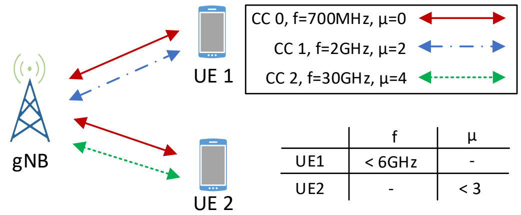


Figure 8: Example of UEs' capabilities.

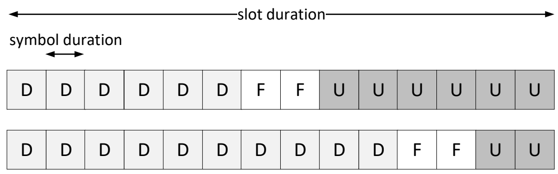


Figure 9: Examples of TDD slot formats.

may be able to use only a subset of the available CCs. As a result, a UE can be attached to an e/gNB only if the latter supports at least one of the CCs supported by the UE itself. The e/gNB, in turn, can schedule a UE in a given CC only if the UE supports that CC.

As with LTE, a NR radio frame is 10 ms long and consists of 10 subframes, each having 1ms duration. However, NR subframes are further divided into up to 14 *slots*, which are the NR TTIs, A *numerology index* μ defines the slot duration, as shown in Table 1. UEs are scheduled in slots. Supporting multiple numerologies allows a network to handle services with different QoS requirements. In our model, a different μ can be associated to each CC. Each *componentCarrier* module has its own parameter μ that can be configured via NED/INI. gNBs and UEs might support only a subset of numerologies, which constrains resource allocation. The example in Figure 8 shows a gNB supporting three CCs that employ different carrier frequencies and numerologies. The gNB serves UE1 and UE2, which have different capabilities in terms of supported frequencies and numerologies, as shown in the figure. For instance, UE1 only supports $\mu < 3$, whereas UE2 supports frequencies below 6GHz. According to that configuration, UE1 can be served by the gNB using CC0 and CC1, whereas UE 2 can be served by the gNB using CC 0 and CC 2.

Simu5G supports both FDD and TDD. In FDD, each CC has separate portions for UL and DL spectra. NR TDD allows one to choose among 62 possible slot formats (3GPP - TR 38.213), where individual symbols in a slot can be DL, UL or *flexible*. Examples of slot formats are shown in Figure 9. Flexible symbols can be assigned dynamically to either DL or UL transmissions, or kept idle as a guard interval to minimize the DL/UL interference. In TDD, the number of bytes that can be transmitted to/by a UE in a slot is therefore

```
Q = set of backlogged UEs
for each CC i active in this period
  U_i = set of UEs allowed to use
CC i
  Q_i = Q & U_i
  S_i = scheduling(Q_i)
  update Q
end for
S = U{S_i}
```

Figure 10: Pseudocode for the scheduling procedure.

smaller, since a smaller number of symbols is used. As we explain later in Section 3.3, this affects the computation of the TB Size (TBS) at the MAC level.

We model TDD slot formats as properties of the CC: this means that all gNBs using a CC will use the same slot format on it. Accordingly, we associate the slot format to the *componentCarrier* submodules. This greatly simplifies interference management, since it guarantees that DL and UL symbols can never interfere with each other. Therefore, their arrangement within a slot is immaterial, the only relevant information being their total *number*. We thus model a slot format as a triplet of integers $\langle n_{DL}, n_{UL}, n_F \rangle$, representing the number of DL, UL and flexible symbols, respectively. Their sum must be equal to the total number of symbols within a slot (i.e., 14). In the current version of Simu5G, flexible symbols can only be used as guard symbols. However, the above modeling allows one to easily design policies to assign flexible symbols to DL or UL dynamically.

3.2 PDCP and RLC Layers

We implemented a *NrPdcp* module as an extension of the *LtePdcp* module, to handle ENDC. The *NrPdcp* module is instantiated within the NIC of either a gNB or an eNB acting as MN in an ENDC setting. In the latter case, packets arriving from the upper layers need to be forwarded to either the eNB's RLC, or to the gNB acting as SN. To achieve this, each packet is marked *before* entering the PDCP layer, i.e. at the *Ip2Lte* module. The *NrPdcp* entity then redirects packets towards the RLC layer of either the eNB or the gNB via the X2 interface accordingly. The marking policy works at the packet level (rather than at the connection level), allowing finer granularity and dynamic management of SB functionalities. Moreover, it is user configurable, which allows a user to design and evaluate, e.g., load-balancing policies. The functionalities of the NR RLC layer are the same as LTE's, hence the *NrRlc* module is the same as the SimuLTE's *LteRlc* module.

3.3 MAC Layer

The MAC layer runs periodically, on each TTI. Multiple CCs may employ different numerologies, hence different TTI durations. However, TTI durations T_i are multiple of each other (see Table 1), hence we schedule MAC procedures at a period $T = \min_i T_i$. At any scheduling epoch *t*, the MAC performs operations only for CCs i s.t. $t \bmod T_i = 0$. Accordingly, a gNB runs an independent scheduler per CC.

gNB scheduling consists in allocating a vector or RBs to UEs. The pseudocode in Figure 10 shows an example of a scheduling procedure, which takes as input the set Q of backlogged UEs, then it allocates one CC at a time, e.g. starting from CC 0. For each CC i, the scheduler considers U_i, i.e. the set of UEs that can use CC i, to obtain $Q_i \subseteq Q$, which includes backlogged UEs schedulable on CC i. Then, the *scheduling* routine sorts Q_i according to a given policy (e.g. MaxC/I or PF) and scans it to allocate RBs to UEs. The *scheduling* routine produces a *schedule list* S_i, including the set of UEs allocated on CC i. UEs which clear their backlog are removed from Q, so that subsequent CCs will not consider them. With this approach, CCs are scanned in sequence, with no attempt to balance the load among CCs, minimize the number of active CCs, or schedule UEs where they perceive, e.g., the best SINR. However, a user can easily define a scheduler that achieves the above objectives by modifying the procedure in Figure 10. Optimal cross-CC scheduling policies can also be envisaged, possibly using external optimization solvers like IBM CPLEX.

After scheduling each CC, the scheduler obtains the global schedule list $S = \cup_i S_i$. For each element of S, the MAC layer builds a MAC Transport Block (TB) (in the DL) or issues a scheduling grant (in the UL). The TBS depends on both the number of allocated RBs and the CQI reported by the UE. The *NrAmc* C++ class determines the TBS according to the procedure defined in (3GPP - TR 38.214). According to the formulas in (3GPP - TR 38.214), the TBS is also a function of the number of DL(UL) symbols in the slot. When TDD is employed, the number of available symbols is defined by the slot format. The *NrAmc* class supports the ex

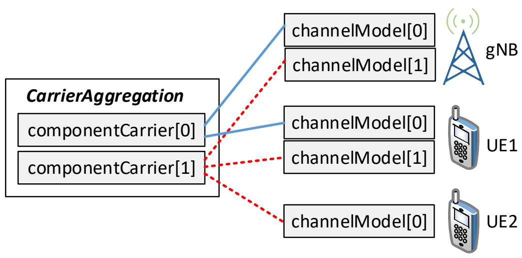


Figure 11: Example of CA configuration.

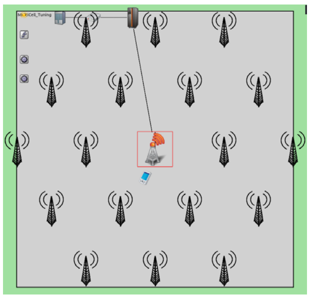


Figure 12: Simulation scenario.

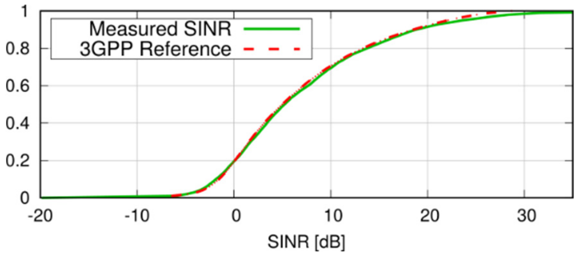


Figure 13: Measured SINR.

tended MCS table with higher modulation orders, i.e. up to the 256QAM modulation (3GPP - TR 38.214).

As far as H-ARQ is concerned, SimuLTE models one *HarqBuffer* for each UE, including a number (eight) of H-ARQ processes. Since every CC has its independent H-ARQ processes (3GPP - TR 38.300), we extended this model by adding a data structure (e.g. a map) that stores the set of *HarqBuffers* for every CC. Once a MAC TB has been created, it is inserted into the correct process included in its *HarqBuffer* corresponding to the CC in which the TB has been scheduled. Simu5G supports flexible timing for the NR H-ARQ feedback, which is asynchronous and can be configured from the NED/INI file.

3.4 PHY Layer

The architecture of the PHY module in Simu5G mirrors the one in SimuLTE, shown in Figure 4. Each MAC TB is encapsulated within an *AirFrame* message and sent to the destination module, which applies the model of the air channel to decide whether the AirFrame is received successfully or not. Since a MAC TB is associated with a given CC, the corresponding AirFrame is subjected to channel effects (e.g. path loss, shadowing etc.) that depend on that CC. This means that different channel models have to be applied to compute the SINR at the receiving side. For this reason, each gNB/UE is equipped with *a vector of channelModel* modules, as shown in Figure 7 and each of them is associated with one of the CCs available in the

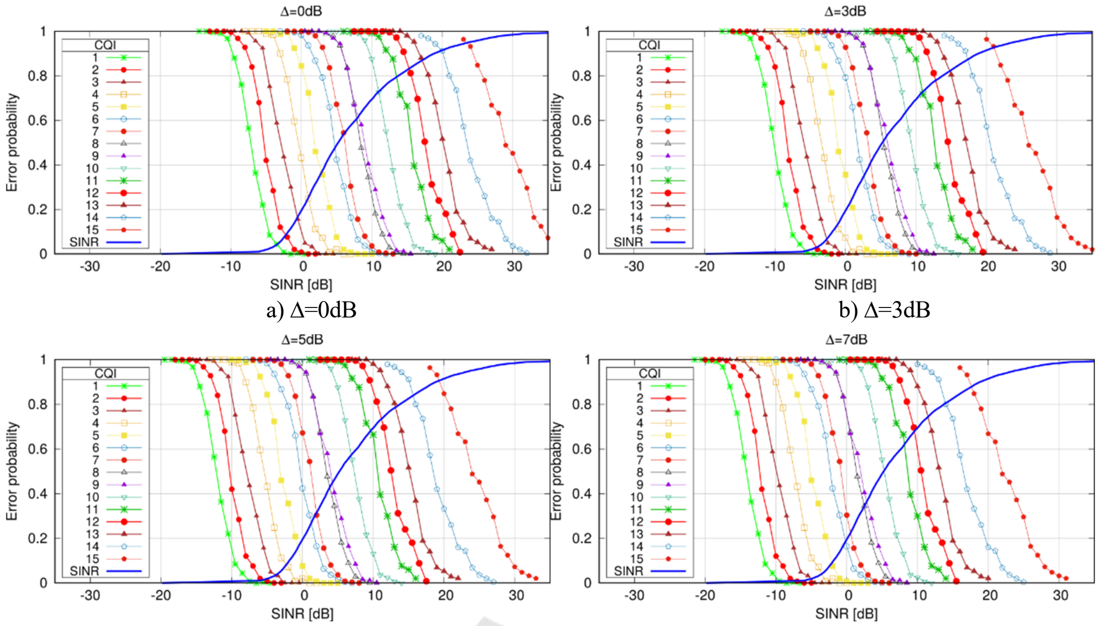
Table 2: Main simulation parameters.

Parameter Name	**Value**
#BSs	57
Inter-site Distance	500 m
#UEs	30 (uniform distribution)
Carrier frequency	700 MHz
Bandwidth	10 MHz (50 PRBs)
Fading + shadowing	Enabled
BS Tx Power	46 dBm
BS antenna gain	8 dBi
BS noise figure	5 dB
UE antenna gain	0 dBi
UE noise figure	7 dB
Path loss model	(3GPP - TR 36.873)
Load of interfering BSs	100% (Full buffer)
UE speed	3 km/h (80% indoor, 20% indoor)
Traffic type	CBR (240 kbps)
# of repetitions	50

carrierAggregation module. Figure 11 shows an example of such association, where the *carrierAggregation* module implements two CCs, whose indexes in the *componentCarrier* vector are 0 and 1, respectively. The gNB and UE1 are configured to use both CCs, hence they have two channel models, associated with the two CCs. UE2, instead, is configured with one channel model only associated with CC 1. Each transmitted AirFrame includes a control field specifying the CC it is transmitted onto, thus enabling the receiver to process it via the relevant *channelModel* module.

The PHY layer interacts with the *channelModel* modules via `getSinr()` end `error()` functions, which compute the SINR and check if the airframe is correctly decoded, respectively. The latter are the functions that need to be redefined when implementing a new channel model.

Simu5G comes with a default channel model called *Realistic Channel Model*, which is compliant with the 3D model described in (3GPP - TR 36.873). The SINR is computed on a per-RB basis as $SINR = P_{RX}/\left(\sum_j P_{RX}^j + R\right)$, where P_{RX} is the received signal power, P_{RX}^i is the power received from the i-th interferer and R is the Gaussian noise. When computing inter-cell interference, only transmissions occurring on the same CC are considered. For each RB i occupied by an AirFrame, the `error()` function obtains an error probability P_{err}^i from the received SINR by using the BLER curve related to the CQI used for transmission. Then, a uniform random variable $X \in [0;1]$ is sampled and the AirFrame is assumed to be corrupted if $X < 1 - \prod_i (1 - P_{err}^i)$, and correct otherwise.



a) Δ=0dB b) Δ=3dB

c) Δ=5dB d) Δ=7dB

Figure 14: BLER curves.

4 VALIDATION

In this section we show the results of the calibration of SimuLTE BLER curves. The calibration followed the guidelines reported by the 3GPP document (3GPP - RP-180524). In particular, we refer to the Urban Macro (UMa) scenario described in Table 4, config. A of the above document.

With reference to Figure 12, we simulated 57 cells deployed according to a regular hexagonal tessellation, whose inter-site distance is 500 m. Each site hosts three cells, radiating outwards according to the horizontal and vertical pattern described in (3GPP - RP-180524). We collect statistics only from the central site (three central cells), whereas the other cells only produce interference (occupying the whole spectrum). We randomly deploy 30 UEs in the three central hexagons, which attach to the cell from which they perceive the best SINR. 80% of UEs are assumed to be indoor, 20% outdoor. We assume DL traffic only and each UE receives a 240kbps Constant Bit Rate (CBR) traffic. The values in the following charts are obtained by averaging statistics from 50 independent repetitions, with 95% confidence intervals. The main simulation parameters are summarized in Table 1. Figure 13 shows that the Cumulative Distribution Function (CDF) of the SINR measured by UEs in the scenario described above overlaps the CDF of the SINR obtained by the calibration performed by 3GPP members and reported as attachment of (3GPP - RP-180524).

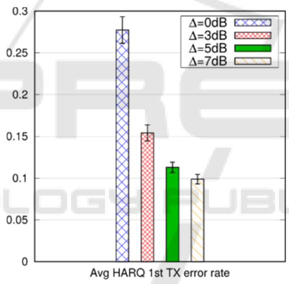


Figure 15: Average error rate after 1st TX attempt.

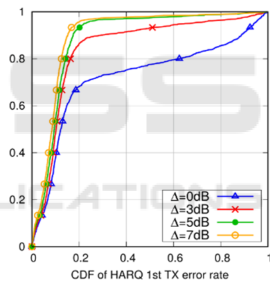


Figure 16: CDF of error rate after 1st TX attempt.

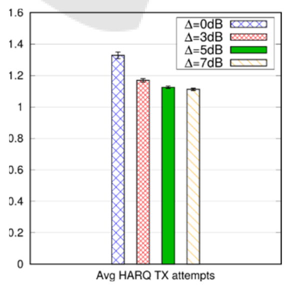


Figure 17: Average number of HARQ TX attempts.

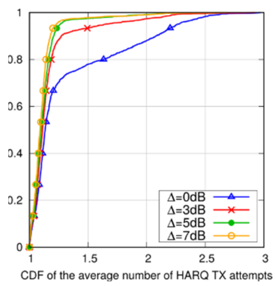


Figure 18: CDF of the number of HARQ TX attempts.

The successful reception of a MAC TB is evaluated using BLER curves, which link a SINR value to the error probability according to the given MCS/CQI. Figure 14(a) shows the BLER curves obtained from link-level simulations carried out with the Vienna LTE-A simulator (Mehlfuerer *et al.*, 2009). Such curves represent

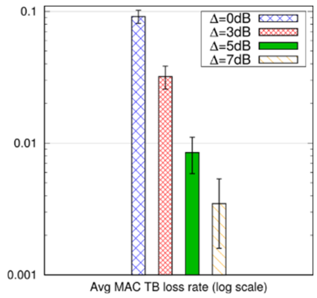


Figure 19: Average loss of MAC TBs.

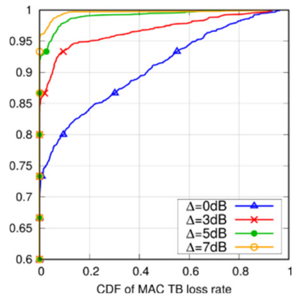


Figure 20: CDF of loss of MAC TBs.

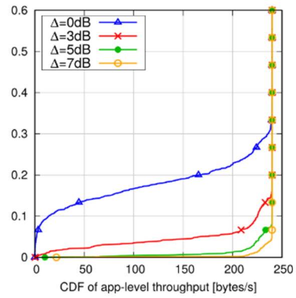


Figure 21: CDF of app-level throughput.

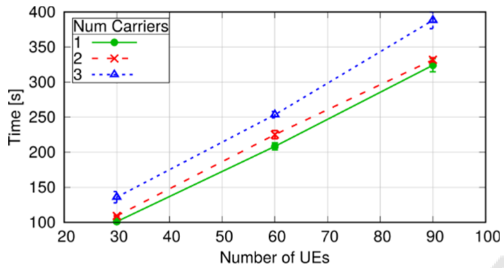


Figure 22: Execution time with increasing CCs.

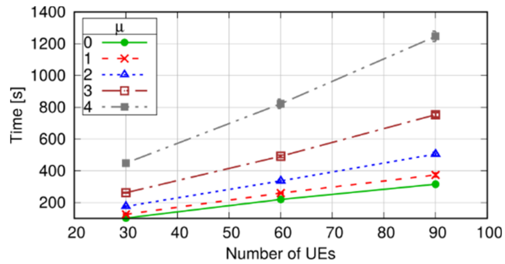


Figure 23: Execution time with increasing μ.

the error probability for a transmission occupying one RB. Since 3GPP recommends a target TB error rate of 10%, we carried out simulations with different versions of the BLER curves, i.e. shifted by a parameter Δ, which models the improvement in the sensitivity of a 5G receiver, in order to determine the curves that allow us to meet that target. The BLER curves obtained with Δ=3, 5, 7 dB are shown in Figure 14(b), (c) and (d), respectively, and they are useful to observe what CQI must be used by a UE to obtain a 10% TB error rate, given its SINR. The figures also include the CDF of the SINR measured by UEs in the above scenario for better comparison.

Figure 15 reports the average error rate for the first transmission attempt of TBs, i.e. the probability that the first transmission of a MAC TB is not decoded correctly. The employed shift increases from left to right. We observe that the rate is close to the target 10% error rate when a shift of either Δ=5dB or Δ=7dB are used.

Figure 16 shows the CDF of the error rate for the first H-ARQ transmission attempt, where we observe that the target 10% error rate is around the median value, whereas only a small fraction of UEs (i.e. ~5%) gets an error rate larger than 20% when Δ=5dB or Δ=7dB are employed. Figure 17 and Figure 18 report the average and the CDF of the number of H-ARQ transmission attempts to successfully decode a MAC TB. As expected, we obtain values close to 1. With Δ=5dB or Δ=7dB, the CDF shows that 95% of UEs need less than 1.26 transmissions.

In some cases, four H-ARQ transmissions (the maximum allowed) are not sufficient to correctly decode a TB. In those cases, the TB is considered lost. Figure 19 shows the average loss rate for a MAC TB. With Δ=5dB and Δ=7dB, the residual loss rate is 0.8% and 0.3%, respectively. Figure 20 reports the CDF of the same metric, where we observe that around 95% of UEs experiences no TB losses when Δ=5dB and Δ=7dB are used. The resulting application-level throughput is shown in Figure 21. Also in this case Δ=5dB and Δ=7dB provide the best results, where 95% of UEs is able to achieve the maximum throughput.

According to the above discussion, Δ=5, 7 dB are values providing more aligned results with the targets expressed by the 3GPP standard. In the following performance evaluation section, we fix Δ=5dB.

5 PERFORMANCE EVALUATION

This section reports profiling results related to Simu5G and shows how the latter can be employed to evaluate both RAN performance (e.g., the impact of numerologies) and end-to-end scenarios involving computation and communication.

5.1 Profiling of Execution Time

In this section we show how the duration of the simulations is affected when different configurations of CA and numerologies are used, with an increasing number of UEs. We consider the same deployment as in Figure 12, where an increasing number of UEs is deployed in

```
# configure the Carrier Aggregation modules
*.carrierAggregation.numComponentCarriers = 1
*.carrierAggregation.componentCarrier[0].carrierFrequency = 700MHz
*.carrierAggregation.componentCarrier[0].numBands = 6
*.carrierAggregation.componentCarrier[0].numerologyIndex = ${num=0,1,2,3,4}
# associate the CC to the channel models in the gNBs and the UEs
*.gNodeB*.lteNic.numCarriers = 1
*.ue[*].lteNic.numCarriers = 1
*.gNodeB*.lteNic.channelModel[0].componentCarrierIndex = 0
*.ue[*].lteNic.nrChannelModel[0].componentCarrierIndex = 0
```

Figure 24: Snippet of the INI configuration file.

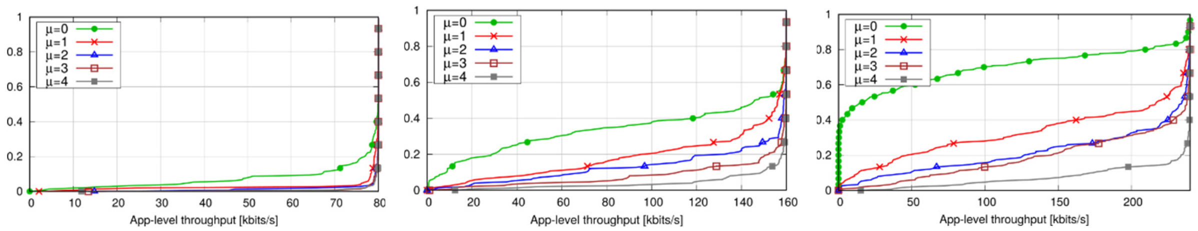


Figure 25: CDF of application-level throughput with different numerologies and increasing data rate.

the central site, i.e. served by the three central gNBs. We run ten seconds of simulation on an Intel Core(TM) i7 CPU at 3.60 GHz, with 16 GB of RAM, a Linux Kubuntu 16.04 operating system, and OMNeT++ version 5.3. Execution times are measured using the *date* Unix command to obtain the time at the beginning and at the end of the simulation, and computing the difference between the two values. The simulations are run in batch, after disabling the graphical user interface. Charts show the average values obtained from ten independent repetitions.

In order to assess the impact of CA, we consider three CCs, whose carrier frequency is 700MHz, 2GHz and 6GHz, respectively. Each CC has 10MHz bandwidth, resulting in 50 RBs. Figure 22 shows the execution time when one, two and three CCs are simultaneously active in the systems. UEs are assigned to one of the available CCs uniformly, hence traffic load is equally distributed among the CCs. The execution time depends linearly on the number of UEs. Fixing the number of UEs and increasing the number of CCs has little impact on the execution time, despite the fact that it entails running the scheduler more often on each TTI. On the other hand, increasing the number of UEs affects the number of operations required for CQI reporting and interference computation.

Figure 23 shows the execution times when different numerologies are employed. In this scenario only one CC is employed, i.e. the one at 700 MHz. As expected, the time increases with the index μ. This is because a larger μ implies a shorter TTI, hence both the gNBs and the UEs need to perform all their operations more frequently in the same simulated time.

5.2 Evaluating Different Numerologies

As described in Section 3, Simu5G allows one to assess the performance of different network configurations. In this section, we show how to configure some of the main simulation parameters and build a simple scenario for assessing the impact of different numerologies on the application-layer throughput at the UEs.

Using the scenario in Figure 12 as a basis, we assume an FDD deployment with DL traffic only, where 30 UEs receive a CBR traffic. We assume all the gNBs and UEs use one CC, whose bandwidth is 1.4MHz (six RBs). We selected such a small bandwidth so that the network saturates with a smaller number of UEs and the effects on their throughput are more evident. Figure 24 shows a snippet of the INI file, where we configure the parameters for CA and numerologies. First, the *carrierAggregation* module is configured with one CC by setting the *numComponentCarriers* parameter to 1. Then, the element of the *componentCarrier* vector with index 0 (i.e., the only element in this configuration) is configured with a carrier frequency of 700MHz and six RBs. The *numerologyIndex* parameter, instead, gets multiple values, represented by the iteration variable *${numerology}*, which ranges from 0 to 4. Using this syntax, the OMNeT++ environment allows us to automatically run one independent simulation run for each value of the iteration variable. Then, we configure the number of CCs used by gNBs and UEs, by setting their *numCarriers* parameter to 1. Finally, the *channelModel* module is associated to CC with index 0, by setting the *componentCarrierIndex* parameter.

We simulate the above scenario with increasing sending rate, ranging from 80 to 240 kbps. Figure 25 shows the resulting CDFs of the application-level throughput. As expected, we observe that when the traffic load increases and the network approaches saturation, the load of some UEs cannot be completely satisfied and the percentage of UEs that are not able to get their offered load is larger for lower numerology indexes μ (i.e., larger subcarrier spacings).

5.3 Evaluating a MEC Scenario

In this section we describe a proof-of-concept scenario involving migration of MEC applications running on a 5G network. We consider the scenario of Figure 26, where three servers representing Mobile Edge (ME) hosts are respectively co-located with three gNBs. One UE is linearly moving from the service area of gNB1 to that of gNB2 and gNB3, at a constant speed of 30 km/h. The UE offload tasks to the ME host periodically, with period $T = 200$ ms. For each offloaded task, the UE transfer the context to an ME application running within the ME host, which performs computations and sends the context back to the UE. We let $l_i \sim U(8,12)$ be the context size for task i (hence, the size of the i-th packet to be transmitted), measured in kbits. Moreover, we model the processing time at the ME host as $T_{proc} = (l_i \beta_i)/F$, where $\beta_i \sim U(100,300)$ are the cycles per bit necessary for processing task i and $F = 9$ Gcycles/s is the processing capacity at the ME hosts (Emara *et al.*, 2018).

We assume that at the beginning of the simulation the UE offloads its tasks to ME host 1. When the UE performs the handover to ME host 2 and 3, we consider the two following scenarios: *a)* the UE keeps offloading its tasks to ME host 1, and *b)* the UE offloads its tasks to the ME host co-located with the serving gNB, i.e. the ME service migrates according to the UE mobility. In the first scenario, data needs to be routed through the PGW, hence the additional latency is uniformly distributed between 15 and 35 ms (Emara *et al.*, 2018). In the second scenario, we assume that the migration needs a time in the range $(20s, 30s)$, which is compatible with the results in (Taleb *et al.*, 2019). More advanced migration algorithms and models can be easily implemented and tested within Simu5G.

Figure 27 shows the latency required for obtaining the result of the task offloading over time. The UE performs the handover at 64s and 124s, where the latency increases due to need of rerouting the traffic through the PGW. Without service migration, the latency always stays above 35ms. When the application migrates, the latency goes back to about 20ms after the transient. Figure 28 shows the same metric when μ = 3 is employed. As expected, the latency has the same evolution, except for scaled-down values due to shorter TTIs at the MAC layer.

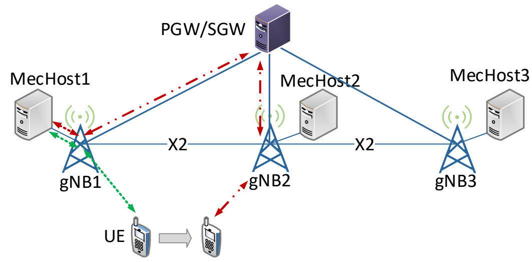


Figure 26: Simulation scenario with ME app migration.

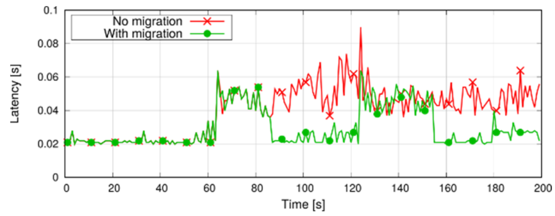


Figure 27: Latency of task offloading, μ=0.

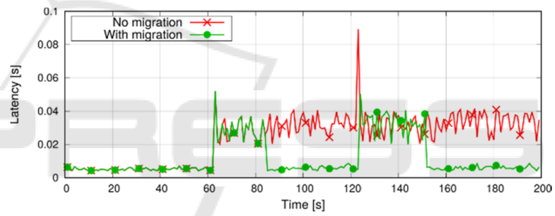


Figure 28: Latency of task offloading, μ=3.

6 CONCLUSIONS

This paper presented Simu5G, a new simulation library for 5G NR based on OMNeT++. To the best of our knowledge, this is one of only two libraries allowing end-to-end application-level communications in complex, heterogeneous scenario, thanks to its modular and INET-compatible modelling, and the only one modelling coexistence of 4G and 5G access in ENDC deployments. We have described Simu5G's resource management and protocol layers, and we have presented results which are representative of its capabilities and execution cost. Future work, well under way at the time of writing, involves evaluating the performance and capabilities of Simu5G running as a network emulator with real applications.

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