5G K-SimNet: End-to-End Performance Evaluation of 5G Cellular Systems

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Abstract—We introduce 5G K-SimNet, a network simulator for evaluating end-to-end performance of the fifth generation (5G) cellular system. 5G K-SimNet provides the features of 5G new radio (NR), 5G core, multi-radio access technology (RAT) protocol, traffic management on multi-connectivity, and software-defined network/network function virtualization (SDN/NFV). In this paper, we present the features of 5G K-SimNet, scenarios that can be simulated by using the simulator, and the simulation results.

Index Terms—5G new radio, 5G core network, multi-connectivity, SDN, NFV, network simulator.

I. INTRODUCTION

Evolution to the fifth generation (5G) in cellular system is essential due to explosive mobile traffic and demand for high data rate service. Until 2018, 3GPP group have performed standardization of the 5G mobile communication system. As part of the first phase of 5G standardization, the deployment methodology of 5G new radio (NR), 5G core, and the necessity for network softwarization are discussed [1]. [2] provides an overview of the multi-connectivity operation by using long term evolution (LTE) and NR access technologies as non-standalone deployment of 5G NR, where 5G NR is deployed as secondary cell of LTE network. Software-defined network/network function virtualization (SDN/NFV) is discussed as a promising solution for network softwarization [3]. 5G NR standalone, which is discussed in the second phase, provides whole end-to-end 5G network architecture and protocols. It means that the fourth generation (4G) core, i.e., evolved packet core (EPC), should be completely replaced with 5G core, which includes access and mobility management function (AMF), session management function (SMF), and user plane function (UPF) with network softwarization [4].

An open-source millimeter-wave (mmWave) simulation tool is introduced by New York University (NYU) WIRELESS and the University of Padova for evaluating LTE-like 5G mmWave cellular networks [5], which is developed as a new module within the network simulator-3 (ns-3) [6]. ns-3 is an open-source platform that provides various protocols including Wi-Fi, LTE, etc., in C++. ns-3 mmWave simulation tool has the features of the 3GPP channel model, the dual connectivity functionality, the orthogonal frequency division multiplexing (OFDM)-based physical (PHY) layer, medium access control (MAC)-layer with their proposed flexible/variable transmission time interval (TTI) time division multiple access (TDMA) scheme, and the radio link control (RLC) layer. The end-to-end mmWave simulation runs with EPC, which is not 5G core.

An open-source SDN simulation module focused on OpenFlow protocol is included in ns-3 itself, but the version of module is outdated. It supports OpenFlow version 0.9.x. Most of recent commercial SDN switches now support OpenFlow version 1.3. Therefore, we attempt to import external module, named ofswitch13, which is developed by the University of Campinas. It includes SDN switches and a controller which have features of OpenFlow version 1.3. Representative features about flow tables, matching or table miss of OpenFlow version 1.3 are included except auxiliary connections or encryption functions.

In this paper, we introduce 5G K-SimNet, a network simulator for evaluating end-to-end performance of 5G system (5GS). It is developed as new modules of ns-3 with the features of 5G NR, 5G core, multi-radio access technology (RAT) protocol, traffic management on multi-connectivity, and SDN/NFV by using the existing simulators such as LENA and mmWave ns-3. Specifically, we update the channel model in ns-3 [7] to support the cross polarization antenna model [8]. We also add the analog beamforming model defined in the full dimension-multiple input multiple output (FD-MIMO) [9]. We implement multi-RAT protocol and split bearer for providing multi-path transmission on multi-connectivity architecture. We design a new handover procedure for secondary node (SN) change, which is not standardized in 3GPP specification but is necessary for low latency communication. We connect SDN switches with the next generation node B (gNB) and core network nodes, while enabling SDN application with an SDN controller. On the other hand, we also add virtualization modules which include workload generation based on user inputs and delay estimations of scaling in-and-out, and migration. We summarize key features of 5G K-SimNet and the existing simulators in Table I.

II. 5G K-SIMNET: MAIN FEATURES

Fig. 1 represents the simulator architecture of 5G K-SimNet, which is expanded from ns-3 and its SDN module [12].
| TABLE I: Key features of 5G K-SimNet and existing simulators |
|-------------------------------|------------------|-----------------------------|
| **Developer** | **LENA [10]** | **mmWave ns-3 [5]** | **5G K-SimNet** |
| **Description** | LTE/EPC simulation tool | mmWave cellular simulation tool | 5G end-to-end network simulation tool |
| **Core network model** | Simple EPC model with one gateway and MME | - Includes mmWave ns-3 RNC model | - Includes mmWave ns-3 RNC model
| | | - Split bearer for LTE-mmWave multi-connectivity | - Split bearer for LTE-mmWave multi-connectivity
| | | - Secondary node addition for LTE-mmWave multi-connectivity | - Secondary node addition for LTE-mmWave multi-connectivity
| | | - Secondary node handover | - Secondary node handover |
| **RRC model** | - System information (MIB, SIBs) | - Includes LENA RRC model | - Includes mmWave ns-3 PDCP model
| | - RRC connection Establishment | - Secondary node addition for LTE-mmWave multi-connectivity | - Reordering for in-sequence delivery
| | - RRC connection reconfiguration | - Includes mmWave ns-3 RLC model | - Duplicate elimination
| | | - System information (MIB, SIBs) | - Timer based discard
| | | - RRC connection Establishment | - Traffic management on split bearer
| | | - RRC connection reconfiguration | - Traffic steering
| | | - Includes LENA RRC model | - Traffic splitting
| | | - Secondary node addition for LTE-mmWave multi-connectivity | - Traffic duplication
| | | - Secondary node handover | - Traffic duplication |
| **PDCP model** | - PDCP headers defined by 3GPP | - Includes LENA PDCP model | - Includes mmWave ns-3 PDCP model
| | - Transfer data for both U and C-plane | - Steer traffic from LTE PDCP to mmWave RLC | - Reordering for in-sequence delivery
| | - Maintain PDCP sequence numbers | - Includes LENA PDCP model | - Duplicate elimination
| | - Transfer sequence number status to neighbor eNB for handover | - Steer traffic from LTE PDCP to mmWave RLC | - Timer based discard
| | | - Includes mmWave ns-3 PDCP model | - Traffic management on split bearer
| | | - Reordering for in-sequence delivery | - Traffic steering
| | | - Duplicate elimination | - Traffic splitting
| | | - Timer based discard | - Traffic duplication
| **RLC model** | - Three RLC models defined by 3GPP | - Includes LENA RLC model | - Includes mmWave ns-3 RLC model
| | - Transparent mode | - Expand RLC sequence space to handle huge amount of retransmission | - RLC buffer status measurement
| | - Unacknowledge mode | | - RLC buffer status reporting to traffic management function
| | - Acknowledge mode | | - Same as mmWave ns-3
| | - Simplified model: full-buffer model | | - Update channel model defined in 3GPP TR 38.901 [8]
| **PHY/MAC model** | - Frequency division duplex | - Time division duplex | - Uniform planar array (linear and cross polarized antenna)
| | | - Flexible frame structure | - (one-dimension full-connection model)
| | | | - Analog beamforming [9]
| **Antenna model** | - Isotropic model | - Uniform planar array (linear-polarized antenna) | - (one-dimension full-connection model)
| | - Cosine model | - Analog beamforming [7] | |
| | - Parabolic model | | |

It has the features of 5G NR, 5G core, multi-connectivity, SDN (OpenFlow version 1.3), and NFV modules for evaluating end-to-end performance. This section describes the key elements of 5G developed in 5G K-SimNet. A brief introduction goes as follows. (i) 5G NR differentiated from the existing 4G radio; (ii) Multi-connectivity for 5G NR; (iii) SDN/NFV technology for network virtualization and 5G core network differentiated from the existing 4G core.

A. **5G New Radio**

We implement two key elements of 5G NR based on mmWave ns-3 [5]: (i) a channel model from 0.5 to 100 GHz and (ii) beam-based MIMO operation.

3GPP provides the channel model from 0.5 to 100 GHz for performance evaluation of 5G NR [8]. The authors in [7] implemented the channel model based on the previous technical report, i.e., TR 38.900 [11]. The limitation of their study is that they have overlooked the channel model for cross polarized antenna array. Therefore, we update the parameters of the channel model based on the recent technical report [8], and also reflect cross polarized phase response given in [8, Eq. (7.5-28–29)].

Massive MIMO that uses multiple antennas has emerged as LTE MIMO evolves, and FD-MIMO that generates a beam including not only horizontal but also vertical direction is defined in the 3GPP standard [9]. We implement the parameters of two-dimension antenna array model such as the number and the radiation pattern of vertical (or horizontal) antenna elements. We also implement one of transceiver unit (TXRU) virtualization models, i.e., one-dimension full-
connection model, to make the direction of a beam vertical. Researchers can easily implement another TXRU virtualization models [9] to AntennaArrayModel class. The one-dimension full-connection model is defined as follows.

\[
w_{m,m'} = \frac{1}{\sqrt{M}} \exp\left(-\frac{2\pi}{\lambda} (m-1) d_V \cos \theta_{\text{tilt},m'}\right),\]

where \(w_{m,m'}\) is a weight between the \(m'\)-th TXRU and the \(m\)-th antenna element. \(M\) is the number of vertical antenna elements, \(\lambda\) is wavelength of the carrier frequency, \(d_V\) is the vertical antenna spacing, and \(\theta_{\text{tilt},m'}\) is the beam tilt angle generated by the \(m'\)-th TXRU. Fig. 2 shows the analog beam shape and the beamforming gain when \(M = 8, d_V = 0.8\lambda, \) and \(\theta_{\text{tilt},m'} = 120\) degrees. We can find the beams are formed not only in the 120 deg direction but also in the 40 deg direction, i.e., when tilt angle is 120 deg, beamforming gain is 14.47 dB, and when tilt angle is 43 deg, beamforming gain 10.56 dB.

FD-MIMO uses hybrid beamforming that combines digital precoding and analog beamforming. In this work, we implement only the downlink analog beamforming model\(^1\) and observe the received signal-to-noise ratio (SNR) when UE moves. For directional communication that uses analog beamforming, the best pair of the beams for transceiver is determined periodically. Therefore, we define the update period of an analog beamforming vector denoted by \(T\), which is determined by periodicity of channel state information-reference signal (CSI-RS) transmission [13].

**B. Multi-Connectivity**

The protocol model for multi-connectivity includes the LTE radio protocol for connecting control-plane (C-plane) and the dual 5G NR protocol for reliable user-plane (U-plane) connection. These entities reside entirely within a UE and an evolved node B (eNB)/gNB. The model, which is based on multi-connectivity [2], provides the cooperating network architecture between 4G LTE and 5G NR in the transition period from 4G to 5G. Fig. 3 shows the block diagram of multi-connectivity for U-plane in the downlink case. An eNB is deployed as a C-plane anchor node (master node, shortly MN) while gNB is deployed for boosting the user throughput or balancing load between eNB and gNB (as a SN). The downlink traffic is split at the packet data convergence protocol (PDCP) entity of eNB and routed to either the RLC entity at eNB or at gNB. In order to exploit the multi-connectivity, the traffic split function is deployed at MN and is defined for all traffic individually. The PDCP TX entity, the splitting layer, should perform the packet sequencing for the PDCP RX entity to re-order the split packets. On the other hand, the PDCP RX entity, the aggregating layer, should perform the packet re-ordering to guarantee in-sequence delivery of the received packet to the upper layer. We develop the multi-RAT protocol stack, the packet sequencing, packet re-ordering, and simple traffic split algorithm by exploiting the conventional LTE model developed by LENA project [10], and the mmWave radio model developed by NYU WIRELESS and the University of Padova [5]. Furthermore, the procedure for SN handover is developed, which is described in Fig. 4. Using this model, we can evaluate the performance of the protocol for multi-connectivity. For example, the following features can be evaluated: traffic split/routing algorithm, RLC queue management scheme, MAC scheduling algorithm, mobility supporting functions and so on. These algorithms and schemes can be modified or developed by users. The simulation results are as follows: (i) end-to-end performance such as transmission control protocol (TCP) and user datagram protocol (UDP) throughput, round trip time (RTT), and congestion window size, (ii) specific protocol performance such as PDCP packet drop rate, RLC queue size/delay, PHY signal-to-interference-

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\(^1\)We also have plan to extend this model to hybrid beamforming. It is possible to use a multi-user-MIMO (MU-MIMO) technique in which data is transmitted to a plurality of users using the same radio resources.
changes along the simulation time) of core NFs, i.e., mobility
the topology of user codes. Dynamic workloads (Workloads
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virtualization-related delays such as scaling delay or provi-
modules and SDN modules. Virtualization modules calculate
provided to the simulator, the simulator runs virtualization
should set their own simulation topology and parameters
simulation process of Fig. 5. For running a simulation, users
throughput per port.
SDN networks, and verify it by investigating SDN switch
and so on. User can control traffic which flows through
end-to-end performances including VM delay, network delay,
can be caused by introducing NFV technique to 5G core
functions which measure these side effects of introducing
Virtualization side effects mean additional delay compo-
ments, which do not exist on non-virtualized core networks.
Additional delays come from a VNF topology which is
decided by network operators. For example, scaling delay
can be caused by introducing NFV technique to 5G core
With NFV, each 5G core network function could be
run on a VM as VNF. If the VNF has 8 central processing
units (CPUs) but its workload exceeds it, NFV platform auto-
scales the VNF. In this case, the VNF is scaled-out, so two (or
more) VNFs might be operated. This auto-scaling takes some
delays such as provisioning or migration delays, so user might
experience longer latency due to NFV technique, temporally.
Other side effects can be evaluated with SDN. With SDN,
the network operator can control network traffic flowing
through core networks. Traffic re-routing or balancing op-
eration can be example cases. The simulation results are
end-to-end performances including VM delay, network delay,
and so on. User can control traffic which flows through
SDN networks, and verify it by investigating SDN switch
throughput per port.
The simulator calculates such side effects by following
simulation process of Fig. 5. For running a simulation, users
should set their own simulation topology and parameters
related to SDN/NFV operation. Once they (user codes) are
provided to the simulator, the simulator runs virtualization
modules and SDN modules. Virtualization modules calculate
virtualization-related delays such as scaling delay or provi-
sioning delay. First, simulation nodes are placed depending on
the topology of user codes. Dynamic workloads (Workloads
changes along the simulation time) of core NFs, i.e., mobility
management entity (MME) and packet data network/serving-
gateway (P/S-GW), are generated by using static workloads
of parameters of user codes. VNF delays are calculated after
configuring scaling thresholds, analyzing the topology and
VNF policies. SDN modules also place simulation nodes first.
They configure OpenFlow switches and a controller. After
then they run OpenFlow application such as QoS bandwidth
controller. The final simulation results come out by merging
results of virtualization modules and SDN modules.
We are also implementing essential parts of 5G core for
a downlink scenario: AMF, SMF, UPF [4]. With such NFs,
control signals such as user equipment (UE) registration, de-
registration or service requests are implemented based on
3GPP specification [15]. Control signal procedures of 5G
System differ from those of LTE System. In case of service
requests, authentication procedures are followed after radio
resource control (RRC) requests in LTE system. However, in
5GS, RRC requests are followed after authentication pro-
dcedures. It is a just representative case, however, procedures of
LTE and those 5GS show different points in details.

III. SIMULATION RESULTS

In this section, we illustrate various simulation scenarios
that can be simulated by using 5G K-SimNet and present the
Corresponding results and analysis.
A. 5G New Radio
Fig. 6(a) shows simulation scenarios where gNB, UE, and
building are located in x-y plane. The z-axis is omitted for
simplicity. A gNB is fixed on the y-axis, and its height is
21.5 m and a UE moves at a speed of 60 km/h in a direction
parallel to the y-axis. We also consider scenarios without
building. The gNB operates at 28 GHz band, and its total
number of antenna elements and the number of TXRUs are
64 and 32, respectively. Downlink packets for the UE are
continuously generated during the simulation time, which is
set to 6 s. The number of antenna elements and TXRUs for the
UE are 32 and 8, respectively. We set the T value to 160 ms
because the number of CSI-RSs should be set to the same
number of TXRUs in gNB and a minimum cycle of CSI-RS is
5 ms [13].
Fig. 6(b) shows the SNR values of received transport
blocks (TBs) when the building does not exist. In an ideal
case, where we know the channel matrix during the simulation,
the highest SNR values can be obtained by the best analog
beamforming vectors. We set the analog beamforming vector

Fig. 5. SDN/NFV simulation procedure.
update period $T=160$ ms to reflect the beam tracking procedure. We observe that the SNR values are lower than those of the ideal case. This is because the gNB and the UE transmit and receive data using analog beamforming vectors based on past channel information. Fig. 6(c) represents the SNR values of received TBs when the building exists. In both the ideal and non-ideal cases, we observe the SNR decreases sharply when the channel condition is changed to the non-line-of-sight (NLOS) due to the building. When the $T$ is applied, if the channel condition is changed, i.e., from LOS to NLOS, vice versa, the SNR value is zero. Therefore, we do not represent the minus infinity values on a log scale in Fig. 6(c).

### B. Multi-Connectivity

We set the simulation scenario for evaluating the performance of mobility supporting functions as shown in Fig. 7(a). A UE can simultaneously connect multiple base stations, eNB or gNB, on multi-connectivity architecture. Since, LTE communication has larger coverage but smaller capacity than mmWave communication, we deploy eNB and gNBs as the role of MN and SNs, respectively. Here, a UE has dual connection to two SNs to mitigate blockage effect of mmWave communication by exploiting diversity. Downlink user data is generated at server with the rate of 500 Mbps and arrives at MN through the core network. Here, we exploit multi-path transmission to transfer user data, that is, MN splits user data in two parts and forwards them to SNs for downlink. Split ratio can be determined by information including link status between each SN and a UE, queue status of each SN, and so on. The carrier frequencies of the two gNBs connected to a UE set to be different in order to avoid inter-cell interference. All the gNBs have the bandwidth of 1 GHz. We assume that all the gNBs and eNB are connected each other through X2 interface whose delay 1 ms. A UE moves at speed of 10 km/h in a direction parallel to the y-axis. Blockages are uniformly distributed in area with the density of 6000 blockages/km$^2$. The size of each blockage is randomly generated between 0 and 2 meters for both x and y dimensions.

The link capacity of mmWave communication is larger than that of LTE, but mmWave link quality can be rapidly changed due to its nature. In case that a UE can associate with one SN at a time, the amount of buffered traffic at associated SN grows quickly when the link quality gets worse even though its duration is very short. Hence, multi-connectivity is essential for enjoying the high capacity of mmWave links by mitigating QoS degradation by exploiting the diversity gain obtained from multi-path transmission. Fig. 7(b) shows the throughput performance of the mobile user, where two dotted lines and blue line present path throughput of 2 connected SNs and the total received throughput measured at UDP layer of UE, respectively. Since received packets are merged and reordered at PDCP RX entity as shown in Fig. 3, path throughput is measured at RLC RX entity. When there is an obstacle between a UE and its serving SN, the path throughput is severely degraded because received SNR from the serving SN is very low. We observe that the total throughput has the comparable value of the source rate and shows stable change over time with the help of traffic management on multi-
TABLE II: Virtualization parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>vP5-GW [capacity/workload]</th>
<th>vMME [capacity/workload]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU (ea)</td>
<td>[160/200]</td>
<td>[179/210]</td>
</tr>
<tr>
<td>Memory (GB)</td>
<td>[480/512]</td>
<td>[870/916]</td>
</tr>
<tr>
<td>Disk (GB)</td>
<td>[2400/3000]</td>
<td>[2430/4000]</td>
</tr>
<tr>
<td>Bandwidth (Mbps)</td>
<td>[9500/10000]</td>
<td>[9500/10000]</td>
</tr>
</tbody>
</table>

Fig. 8. SDN/NFV simulation scenario, scaling in and scaling out delays and traffic volume on links of SDN switch.

C. 5G Core: SDN/NFV

Fig. 8(a) illustrates a network topology for simulating SDN/NFV modules. There are two UEs attached to a gNB. The gNB is connected to an SDN network which is composed of a controller and three switches. Other side of the SDN network is connected to a virtualized core network, and a remote server is placed on the data network. With the topology, we measured additional delay due to virtualization and traffic volume on two links of the SDN switch.

Table II shows parameters related to virtualization environments. Virtualized core network functions are run on VMs, so the parameters include VM capacities and expected workloads on such VMs. These parameters affect simulation results of additional delays due to virtualization. Also, there is a parameter called 'link weight' related to SDN module, which controls traffic volume flowing links between two SDN switches. In Fig. 8(a), there are two links between the rightmost and central SDN switches. We set link weights of two links as 1:2 by adjusting link weight parameters so that network traffic is exactly controlled as the ratio.

IV. Conclusion

In this paper, we introduce 5G K-SimNet with the features of 5G NR, 5G core, multi-RAT protocol, traffic management on multi-connectivity, and SDN/NFV, which we have developed based on ns-3. Various performance metrics of 5Gs, which are end-to-end performance and the performance of specific protocol can be evaluated by using 5G K-SimNet. The former include RTT, transport layer throughput and congestion window size while the latter include PDCP packet drop rate, RLC queue status, and PHY SINR. We illustrate various scenarios that can be simulated by using 5G K-SimNet and present the corresponding results and analysis.

ACKNOWLEDGMENT

This work was supported by “The Cross-Ministry Giga KOREA Project” grant funded by the Korea government (MSIT) (No. GK18S04040, Research and Development of Open 5G Reference Model).

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