5G-EMANE: Scalable Open-Source Real-Time 5G New Radio Network Emulator with EMANE

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***Abstract*— In this paper, we present a detailed design, prototype, and performance of a new, high-fidelity, scalable, Fifth Generation (5G)-New Radio (NR) Network Emulator built on EMANE: 5G-EMANE (5G Extendable Mobile Ad-hoc Network Emulator). The associated software modules are based on the Open-Air-Interface (OAI) open-source models (openairinterface.org). Thanks to EMANE's PHY layer abstraction methodology, the resulting 5G-EMANE offers powerful customization capability that can capture a wide range of scenario diversity with respect to network size, channel models, terrain effects, MIMO antennas, and mobility patterns. The 5G-EMANE also offers a full-stack LTE emulator as part of 5G's non-standalone (NSA) operational scenarios and a full-stack 5G emulator as part of 5G's standalone (SA) mode. A PHY-less version of the 5G-EMANE without PHY abstraction modeling capability, called 5GEM or 5G Layer 2 (L2) Proxy, is offered as open-source software, allowing the 5G research community to evaluate and deploy a full 5G ecosystem using a cost-effective set of commodity PC hardware units for a wide range of scenarios with realistic user-level modeling assumptions but without the complexity of PHY abstraction. Both 5G-EMANE and 5GEM are built on the Small Cell Forum's nFAPI (network functional application platform interface) which enables real-time operation of the entire LTE and 5G stack without the actual over-the-air LTE/5G PHY implementation for multi-user scenarios. 5G-EMANE affords the military community to rapidly conduct research and experimentation while utilizing and integrating LTE/5G with other tactical communications and networking protocols available in EMANE. More importantly, it enables rapid development of new 5G features needed for military usage such as sidelink (SL) without costly and time-consuming over-the-air testbed prototypes.**

Keywords—5G NR, LTE, Open Air Interface (OAI), Standalone (SA), Non-standalone (NSA), EMANE, Sidelink (SL)

I. Introduction

As 5G NR becomes more and more widespread, there is a critical need to research and study the possible use cases and potential performance of emerging 5G standards, systems, solutions, and their adaptations under a wide range of scenarios. A lab based, scalable, high-fidelity, and open source 5G NR modeling and simulation tool, friendly to existing network system planning tools, will provide the ability for the community to evaluate and deploy a full 5G/NR ecosystem using a cost-effective set of commodity PC hardware units. EMANE is the emulation tool being utilized in this work to create various channel model scenarios to be used [1], in parallel with an open source package called Open Air Interface (OAI) [2]. OAI provides LTE/5G radios and base stations (eNB and gNB). In this work, additions were added to the OAI code to provide software-based testing of the real-time radio interfaces. These additions include bypassing the physical layer of the radio model and creating an abstracted version of this layer via the 5G Emulator (5GEM) with L2 Proxy. These developments have produced high-fidelity emulators that are faithful to LTE and 5G standards by constructing LTE/5G radio models and standardized nFAPI interfaces [3] with an emulated physical layer inside EMANE as well as a separate version that bypasses the PHY (5GEM). The resulting 5G-EMANE testbed allows for various customization and adaptations of 5G NR technologies to be enhanced in an open-source manner. In EMANE emulations, we want to model the multi-connectivity environment. In such a case, a user is connected to the network, through multiple parallel links, to simultaneously exploit frequency and space diversity. There are two levels of NR simulations: link-level and system-level simulations. The first kind of simulation describes the PHY level between two communication terminals. The second kind, system-level simulation, is an effective tool to evaluate the communication performance of a network system where there is multi-connectivity between nodes in the network. In this work, system-level simulations will effectively show accurate performance for deployment scenarios with various range of running applications in the network.

II. Motivation for Software-Based Testing

Software-based testing of a real-time radio interface implementation allows the network protocol stack to be stimulated by traffic at the MAC-layer (Layer 2) interface, as if there were a real physical layer on the southbound interface. This can be used for several purposes.

One utilization of this physical (PHY) layer abstraction is for improved validation tests. These include testing the implementation of the Layer 2 system and Evolved Core Network (EPC) or 5G Core Network (5GCN) with real stimulus for the purpose of a regression testing method. This is often to allow continuous software changes pushed by community developers to be automatically tested. This is primarily used in a so-called CI/CD (continuous integration/continuous delivery) community-based development framework and the most important feature for such testing is correctness in implementation of the interfaces and protocols. The actual codebase is put under test starting at a particular point in the protocol stack with the southbound components replaced by emulated traffic generators.

Another purpose is for performance evaluation of protocols using behavioral models for the physical layer processes. This is useful for evaluating the performance of algorithms such as schedulers or resource allocation mechanisms in scalable simulations. These scalable simulations include the number of network elements, both infrastructure and user-equipment. Coupled with a fully implemented user-equipment protocol stack it also allows testing of real-world applications in a purely synthetic but realistic end-to-end framework.

III. Open Air Interface Software and Additions

OpenAirInterface is a real-time implementation of the 4G/5G 3GPP protocol stack and comprises both core-network (Openair CN/OAI-5GCN) and radio-interface protocols (openairinterface5g). In addition to the 3GPP functional decomposition, OAI supports the additional functional split known as the nFAPI (network functional application platform interface) which is specified by the small-cell forum [1, 8, 9]. nFAPI allows the physical layer to be executed in a different networking element than the layer-2 protocol stack. It is based on the original interface known as FAPI which allowed software and chipset vendors to interoperate at the level of a system-on-chip but without an explicit networking specification between the two entities [1, 8, 9].

The first main functional entity is the so-called Virtualized Network Function (VNF) which comprises the layer 2/3 protocol entities from the 3GPP CU and DU function (in OAI terminology, MACRLC, PDCP, RRC) [2] as well as the networking interfaces with the 4G/5G core network (S1C and S1U).

The second main functional entity is the so-called Physical Network Function (PNF) which comprises the layer 1 protocol and signal processing entities as well as the necessary interfaces for radio-equipment. The small-cell forum specifies two primary interfaces to interconnect the PNF and VNF functions, P5 and P7 [1, 8]. P5 is responsible for passing semi-static capability and configuration messages between the PNF and VNF. It also responsible for controlling the activation/deactivation of the PNF and for radio-network discovery functions. The transport protocol used on the P5 interface is SCTP. P7 is responsible for exchanging real-time protocol information for every transmission-time interface (subframe in LTE, slot in 5G NR). The PDUs exchanged on P7 correspond to all of the 4G/5G transport channels and a configurable subset of the physical channels which are under dynamic control of the MAC layer. P7 uses the UDP transport protocol. nFAPI was conceived to be robust to imperfect network conditions and potentially long-latency links.

The 5G NR version of nFAPI is based on the recently specified NR FAPI interface which is made up of the same P5 and P7 interfaces as nFAPI but with PDUs reflecting the transport and physical channels of 5G NR. An additional interface P19 is used to control active antenna arrays in its underlying radio-unit. The latter allows the MAC scheduler to influence the beam-pattern of the active antenna array whether implemented in an analog or fully digital fashion.

In order to test the MAC/RLC-entity both for development and regression, OAI provides a pure software testing architecture shown in Figure 1. This method should supplement a full test using commercial UEs and different RF platforms or through testing equipment. This mechanism makes use of the OAI UE protocol stack replicated to emulate many concurrent UEs connected to the gNB (or eNB, for LTE) protocol stack via the nFAPI interface.

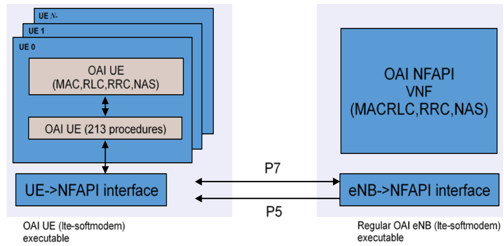

Fig. 1: UE Module for Testing nFAPI Interfaces and Development of MACRLC Scheduling Procedures. eNB (for LTE and NSA) and gNB (for NSA and SA modes) are exchangeable from the functional architecture standpoint.

In this work, several features were added the OAI source code for bypassed PHY layer support. The added functionality is discussed below.

- Creation of the nFAPI interfaces, including a run-time parameter for setting the emulation mode. nFAPI packets are processed and handled in the MAC layer and “stub” of the UE, rather than the PHY layers. The “stub” layer was developed in this work and lies between the MAC and unused PHY layer.
- Several queuing mechanisms were added to the UE for packet processing from the nFAPI interfaces. Many packets are UE specific and require filtering at the PDU level based on the RNTI.
- The Contention Based/Free Random-Access (CB/FRA) procedure was modified for bypassing the PHY layer for SA and NSA modes. The modifications include emulation of L1 messages and populating them into nFAPI messages for transport.
- Interfaces and hooks were implemented in both the UE and the base stations (gNB and eNB) software to allow data to be transmitted and received through the either proxy (EMANE proxy or open-source proxy).
- The UE PNF was ported into the proxy source code. This allows for a distributed UE environment; previously multiple UE scenarios with the L2-simulator is only possible within a single UE process [1, 3]. Now each OAI UE connects with its respective emulated UE PHY and transfers P7 messages over a custom SCTP socket.
- Uplink shared channel modeling features were added. The model emulation is used to drop packets based on the modulation and coding rates of the received packets from the EMANE (with PHY modeling) or L2 proxy (without PHY modeling).

- Timing improvements were made by adjusting the VNF based on periodic timing information packets from the PNF.
- Proper ACK/nACK transmissions for multiple DCIs requires modifications to the NR UE MAC layer. The gNB can require multiple ACKs to be received in a single slot which necessitates the UE to multiplex ACKs into a single UCI indication for transmission. Proper ACK/nACK handling resulted in bug fixes in the gNB ULSCH scheduler as well as new implementation of multiplexing in the NR UE MAC.
- Pairing of DCI, the configuration and payload was added to the NR UE stub function. The two nFAPI messages, DL_CONFIG_REQs and TX_DATA_REQs, are decoded, queued, and paired based on PDU RNTI information.
- Buffer sizes, socket options, and packet-segmentation metrics were updated to improve packet transport timing.

A. 5G nFAPI Additions: P5 and P7 Messages

P5 messages are now communicated solely between the PNF and VNF, with no reliance on the OAI UE. P5 messages are non-essential for the OAI UE; however, the process is still important to fully initialize the nFAPI process.

P7 nFAPI messages are packed and unpacked in the VNF and PNF. Several bug fixes were incorporated into the 5G nFAPI packing and unpacking functions, including fixing improper pointer math, correcting argument type casting, fixing invalid array packing based on bits vs. bytes mismatch,

B. Downlink and Uplink 5G P7 nFAPI Messages

Downlink packets are broadcasted to each UE via the PNF. This architecture was chosen because the channel modeling procedures in EMANE are heavy on the system. Filtering at the receiver rather than the transmitter helps support channel abstraction mechanism, given that the channel abstraction is highly computational and requires a large amount computing power. When the UE has attached to the gNB, it receives a UE-specific C-RNTI value. Once the C-RNTI value is validated and the UE is attached to the gNB, the UE then filters all received packets at the PDU level based on the C-RNTI. The attached UE does not process any PDUs that have an unmatching C-RNTI.

Uplink messages are gathered from each UE PHY and aggregated into a single message, based on the message type. Before the PNF sends the aggregated uplink packets, it waits for all corresponding UE messages to be collected, via a queuing function. Once all the messages within that frame have been received from all the UEs, the PNF unpacks, sorts the nFAPI messages based on their message type, and aggregates them together into multiple structs, each containing a particular message type. The new aggregated packets are sent from the PNF to the VNF.

C. PNF, VNF and Proxy Synchronization

In addition to the uplink and downlink P7 message transmission mechanism, a timer/sync message is required to synchronize the gNB, NR UE and the proxy. The original timing structure has been modified. Previously, the OAI team had a mechanism to send a periodic stimulation to the VNF; this was moved into the EMANE proxy. Now, a frame and slot indicator message controls the timing and reports a slot indication every 500 us. This tally of time ensures that the P7 message passing will conform to the timing requirements of the communication path, defined by the 3GPP specification. The downlink P7 messages must be packed and sent during one slot; while uplink messages must be packed, sent, queued, sorted, and aggregated within the time constraint (500 us).

IV. PHY LAYER ABSTRACTION IN 5G-EMANE

A basic pathloss shared channel model is implemented in this work and the functions were architecturally split between EMANE and the NRUE. The downlink shared channel modeling is conducted in the OAI NR UE to conserve EMANE processing power for the channel abstraction, which is highly computational and requires a large amount of computing power. The uplink channel modeling is conducted in EMANE because the PNF already unpacks the nFAPI messages for aggregation, as described in Section III.

The downlink channel abstraction begins with an effective SINR value, which is derived in the EMANE channel model and passed to the UE. The UE calculates the MCS based on the incoming SINR value. From there, the channel quality index (CQI) is extrapolated and utilized. Figure 2 shows an example of the various code block error rates (BER) at various SNR values for an SISO uplink TDL-C channel. MCS indices where the modulation order is increased from the previous index will have a decreased target code rate. The target code rate decrease is compensating for the increased modulation order to maintain proper spectral efficiency. This code rate adjustment can result in higher error rates at those specific MCS values (e.g., MCS index 9, 10 and 17 shown in Figure 2 below). See *Table 5.1.3.1-1*: *MCS index table 1 for PDSCH* in [7] for more details. A uniform random statistical model is used to determine whether the packet is dropped based on the look-up table packet drop rate; where the drop rate is dependent on the MCS and received SINR.

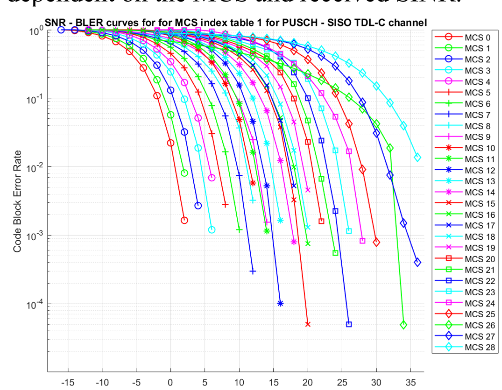

Fig. 2. BLER performances for SISO under TDL-C Channel

The uplink shared channel emulation conducted in EMANE took on a similar process. The main difference is that the packet drop/not-drop indicator is modified in EMANE based on current channel conditions, rather than in the receiver. Furthermore, the uplink packets rely on a timing advance field to determine the distance between the UE and base station. This timing advance will add or remove a delay in particular packet transmissions based on current location information.

D. 5G MIMO Channel Model Abstraction

The optimal solution to evaluate the system performance is the full PHY system simulation for every link in the network. However, simulation is time-extensive, and computations are highly complex. Due to this heavy computation cost, extensive system level simulation is generally avoided [4]. Instead, link level simulation is preferred and applied to the mapping mechanism to predict a system level simulation for the full network performance. The mapping methods, also known as PHY abstractions, allow for new link performance predictions in a fading channel, by using simulation results obtained under AWGN channel conditions, after mapping received SINRs to a single effective SINR [4]. The effective SINR is utilized because the received SINRs in each sub-carrier varies, and under a complex environment, there is no closed-form equation for Block Error Rate (BLER) performance. Figure 3 shows a high-level block diagram for general abstraction methods.

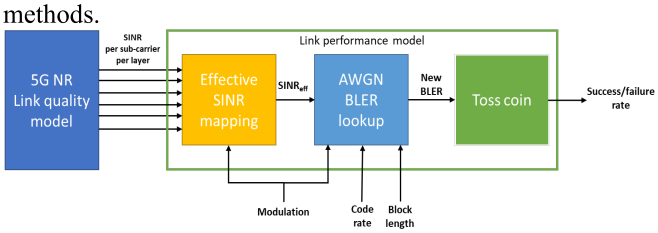

Fig. 3. General PHY Abstraction method

There are two Link-to-System Methods (L2SM) that are generally used, Exponential Effective SINR Mapping (EESM) and Mutual Information based Effective SINR Mapping (MI-ESM) [5].

- EESM is a simple mapping method in which all the sub-carriers for one mobile terminal use the same modulation and coding scheme (MCS).
- MI-ESM is more advanced, in which multiple MCS values are used for each of the UE sub-carriers.

In summary, the goal of the EESM channel abstraction is to predict system performance by generating BLER curves for specific channel models. The input to the abstraction is a chosen channel model and system specifications. Corresponding BLER curves are then reported from the link simulation. Finally, by mapping AWGN curve with the distribution of the effective SINR, new BLER is generated.

V. Full System Setup and Performance Results

Our 5G/NR emulation testbed consists of launching multiple UEs, each in their own CORE LXC [6]. These CORE containers allow us to easily launch each UE in EMANE while connecting to the 5G radio model selected. The base station is in its own container and will connect to the chosen radio model. In the case of the NSA UE, which is made up of an LTE UE and an NR UE, both LTE and NR UE processes are launched in a single container. Within the container, there is a socket between the two radio stacks to maintain the NSA interface during control plane setup. The eNB and gNB are separated into their own containers and are connected via the X2 interface. By launching this scenario in CORE, it provides a user-friendly GUI which can be used to help validate various channel models. The NR mode single UE scenario architecture is illustrated in Figure 4 below.

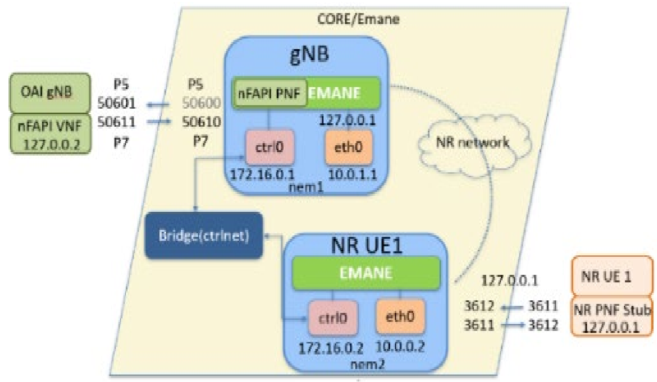

Fig. 4. Standalone (SA) Mode EMANE Proxy Design

Figure 5 and Figure 6 illustrate and compare the software architecture of 5GEM (without PHY abstraction) and 5G-EMANE (with PHY abstraction implementation in EMANE). It is noted that Layer 2 and above is identical to both 5GEM and 5G-EMANE.

Additionally, the model utilizes an abstracted PHY layer that is emulated in EMANE to conduct various channel condition models that influence the connectivity, stability, and throughput of the entire system. The details of the implementation are discussed in a companion paper submitted with the title "Physical Layer Abstraction for LTE and 5G New Radio with Imbalance Receiver in EMANE".

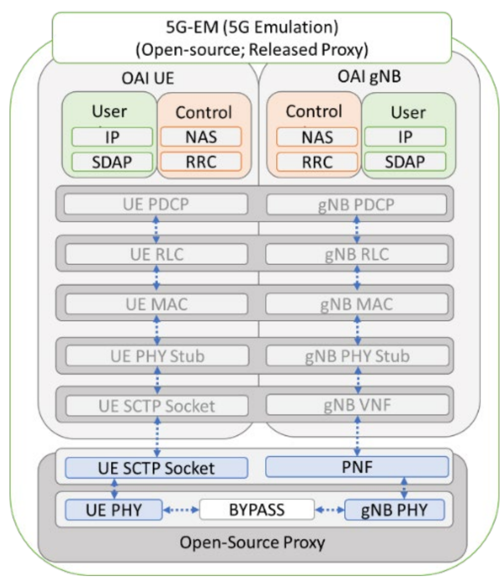

Fig. 5. 5GEM Software Architecture

Multiple UE testing has shown to be successful up to 15 NR UEs. Each UE is able to complete the entire CBRA procedure (this includes assignment of RNTI values, RACH generation, RAR response and all NRUE capabilities decoded). Once the CBRA procedure is complete, the gNB connects to the AMF and the OTA tunnel interface is established between each NRUE and the external data network, allowing for communication with external sources, such as google (8.8.8.8). An example of the scalable 5G MIMO scenario is shown below in Figure 7.

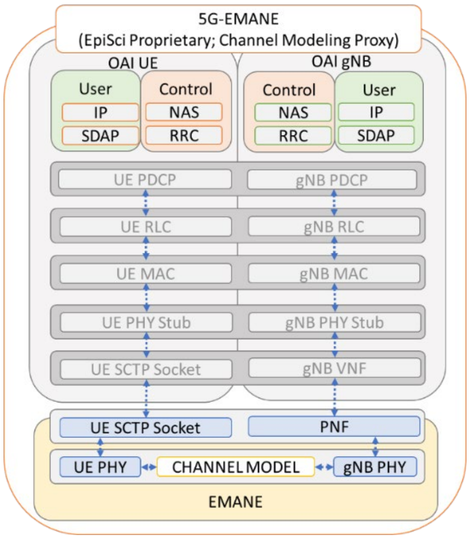

Fig. 6. 5G-EMANE Software Architecture

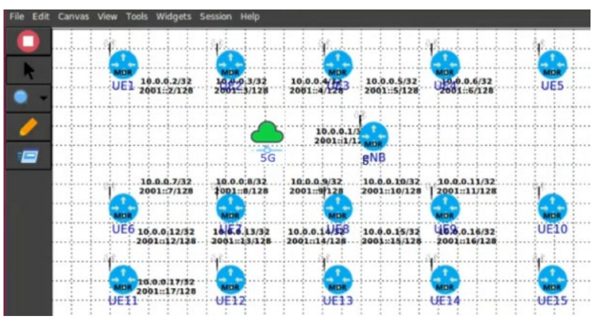

Fig. 7. Scalable 15 NR UE CORE Scenario

Table I below shows the final test results of various different modes. It shows the UE scalability, which indicates how many UEs are able to complete the random access (RA) procedure with the base station, connect to the MME/AMF in the EPC or 5GCN, respectively. It also shows that maximum throughput for each mode.

TABLE I. SUMMARY OF RESULTS

Mode	Scalability	Downlink Throughput	Uplink Throughput
LTE	30 UEs	20 Mbps	16 Mbps
SISO 5G (NR)	15 UEs	3-30 Mbps	100 Mbps
MIMO 5G (NR)	15 UEs	3-30 Mbps	100 Mbps
Non-Standalone (NSA)	12 UEs	3-30 Mbps	10 Mbps
LTE Handover	6 UEs	16 Mbps	10 Mbps

The full system results and achievements are described in Table II. These accomplishments and results include the full 5G radio protocol stack being executed in a scalable, reliable, high-fidelity manner while sending and receiving user plane traffic. These results were measured by utilizing a high-end 64-core CPU server.

TABLE II. CAPABILITY SUMMARY OF 5G-EMANE TESTBED

Functionality	Results
Completed an open source 5G proxy (5GEM) with 5G 3GPP-compliant nFAPI.	The open-source proxy available for the public to add their own L1 channel abstraction can be found here: https://github.com/EpiSci/oai-lte-5g-multi-ue-proxy.
Multiple 5G NSA UEs with 5G nFAPI	We have validated between 8-12 NSA UEs with IP traffic (ping tests). The “LTE UE” segment of the NSA UE is initially connected to the EPC and once the CFRA procedure between the “NR UE” and the gNB is complete, the bearer is modified in the EPC to support 5G IP traffic (EPC is now connected to the gNB).
Multiple 5G SA UEs with 5G nFAPI	We have validated between 10-16 SA UEs with IP traffic (ping, iperf and MGEN test). The currently supported throughput is now about 30 Mbps with about 40% packet loss; the expectation is ~100Mbps.
Multiple 5G NSA UEs with SISO PHY abstraction	We have validated between 8-10 NSA UEs with the SISO pathloss channel model. As a particular UE is moved farther from the base station, the ping traffic is delayed or stopped all together. Moving the UE back in range provides IP traffic once again.
Multiple 5G SA UEs with SISO PHY abstraction	We have validated between 10-16 SA UEs with the SISO pathloss channel model. As a particular UE is moved farther from the base station, the ping traffic is delayed or stopped all together. Moving the UE back in range provides IP traffic once again.
Multiple 5G SA UEs with MIMO PHY abstraction	We have validated 10-16 SA UE with the MIMO channel model.
Integration and test with over-the-air (OTA) 5G NR testbed	Validation testing of an emulated SA UE passing user plane IP traffic to a USRP has shown full system integration. This validation testing showed successful results as the IP traffic was able to start at either the USRP RX or emulated NR UE NEM in CORE and packets moved through the respective gNB, went to the 5GCN, and were transmitted to the receiving gNB stack and successfully moved through to the receiving UE (either USRP or the emulated NR UE, depending on uplink or downlink traffic).

Figure 8, below, demonstrates an example of one of the various scenarios; it depicts the CORE GUI, the NR EMANE radio model, the gNB and 2 SA UEs. As the user pulls a particular UE away from the gNB in real time, the IP traffic will be negatively impacted as the UE moves farther and farther from the gNB. Once the UE is moved closer to the gNB, the throughput is improved; all in real-time.

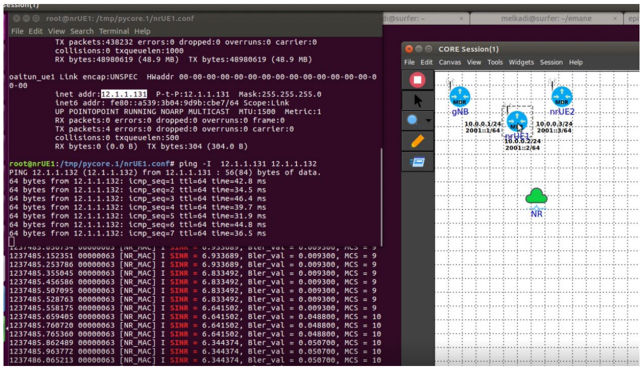

Figure 8: Channel Model Impact in Real-Time

VI. Future Work

Further development is required to see the expected throughputs for SA mode. Since the team was able to ensure all ACKs are received in the gNB and still saw low throughput, the team should investigate the PDCP/RLC packet segmentation and out-of-order packet procedure as the low throughput is attributed to out-of-order packets. The expectation is that the throughput work will be developed and debugged together with OAI to ensure a fully functional 5G emulated-L1 stack.

The team has also implemented LTE handover (HO), which will help to support 5G HO future work. For 5G Handover, there are two main types. These types have specific use cases and are strictly dependent on the network and base station architecture. The two main types of 5G handover are Xn-based and NG-RAN based. Xn protocol is HO between monolithic gNBs, which utilizes the current gNB architecture we have discussed herein. In this case, the gNB does not have a split architecture and is similar to the X2 HO procedure the team has previously implemented. The Xn handover requires an Xn interface to be brought up between the source and target gNB, and that both gNBs are connected to the same AMF (registration and coordination portion of the 5GCN). These requirements will require the EpiSci team to develop the Xn protocol and then conduct a similar HO procedure, as done for LTE.

The 5G NGAP architecture is fundamentally different from that of monolithic gNBs and Xn architecture. In 5G NGAP, what was previously recognized as a gNB, is now split into two pieces, the central unit (CU) and the distributed unit (DU). In this split architecture, the higher layer are maintained in the CU (like the SDAP, PDCP, and the RRC layer) and the DU hosts the real time function of the RLC, MAC and PHY layer. This split is beneficial for as it provides a larger coverage area and is more flexible with respect to hardware implementation.

Ultimately, the development efforts for 5G HO requires the user, customers, vendors, and engineers to determine which architecture will ultimately be supported. The supported architecture will be dependent on various different use cases. For example, on non-terrestrial application could include HO in space. This 5G HO would likely be best with the NGAP-based HO because the satellite or user equipment could quickly traverse across various different DUs while still maintaining central unit coverage. The current OAI implementation is moving in the direction of the split (NGAP-based) architecture. The reason for this is that they have vendors that have expressed their desire for a split architecture. However, even if OAI begins developing NGAP-based HO, it does not mean Xn should be excluded. Xn will allow usage of the current gNB deployment but will work to implement the Xn protocol.

Lastly, 5G sidelink (SL) is not currently available for military grade DoD applications and future development for SL features is paramount. The team intends to utilize the OAI code base to implement 5G SL. OAI has a complete LTE D2D implementation, which can be modified for NR support. Given EpiSci's OAI expertise and immense effort in both the PHY and MAC layers of the OAI NR UE, the scope of NR SL implementation is expected to be significantly reduced. The following list outlines the SL features we plan to implement in OAI, where much of the baseline code already exists.

1. Modify the RRC layer to support radio resource allocation via the sensing procedure and group cast functionality via security key management for a pre-authorized pool of UEs.
2. Modify the MAC and PHY layers to support the SL HARQ procedure and flexible slot structure support.
3. Develop SL PHY based on existing LTE D2D and NR PHY layers
4. Install OAI NR UE source code to SDR platform and conduct usability and prototype tests.

Acknowledgment

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