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Software Article

5G-air-simulator: An open-source tool modeling the 5G air interface ☆

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ABSTRACT

5G-air-simulator is an open-source and event-driven tool modeling the key elements of the 5G air interface from a system-level perspective. It implements several network architectures with multiple cells and users, different mobility and application models, a calibrated link-to-system model for physical and data-link layers, and a wide range of features standardized for both control and user planes, as well as a set of technical components recently designed for the 5G air interface (such as massive Multiple Input Multiple Output, extended multicast and broadcast transmission schemes, predictor antennas, enhanced random access procedure, and NB-IoT). The tool has been already used in different research activities to design and evaluate the performance of reference 5G-enabled use cases. Moreover, it allows a flexible configuration, arrangement, and extension of its capabilities to model both new scenarios and new technical components, hence supporting advanced studies willing to address the research questions emerging from the deployment of current and upcoming mobile systems.

Software metadata

Current software version	*20.02*
Permanent link to executables of this version	https://telematics.poliba.it/5G-air-simulator
Legal Software License	*GNU GPL v3.0*
Computing platform / Operating System	*Linux, macOS, Unix-like*
Installation requirements & dependencies	*libarmadillo-dev*
Support email for questions	telematics-dev@poliba.it

Code metadata

Current Code version	*20.02*
Permanent link to code / repository used of this code version	https://github.com/ELS-COMNET/COMNET-2019-1506
Legal Code License	*GNU GPL v3.0*
Code Versioning system used	*git*
Software Code Language used	*C++, CMake*
Compilation requirements, Operating environments & dependencies	*libarmadillo-dev, Linux, macOS, Unix-like*
Developer documentation / manual	https://telematics.poliba.it/5G-air-simulator
Support email for questions	telematics-dev@poliba.it

Motivation

Fifth generation (5G) network deployments are accelerating as vendors are trying to deliver a strong 5G ecosystem across the world earlier than expected [1]. Such an ecosystem aims to support an extreme variety of services, each one entailing different performance requirements. The 5G air interface, also known as New Radio, introduces flexible and heterogeneous capabilities for harmoniously handling these advanced services, ranging from a high-bandwidth Internet connection to the support of very high-speed vehicles and low-power devices deployed in large numbers. However, the effective integration and configuration of different components, protocols, and algorithms in complex network architectures with heterogeneous Quality of Service requirements is a challenging task to accomplish. As is well known, computer simulations

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are relentlessly engaged in the pursuit of existing research questions on how to design, evaluate, and optimize emerging communication technologies. At the time of this writing, only few tools model the 5G air interface. 5G-LENA combines both the LENA and mmWave modules to build a 5G simulator for the well-known ns-3. It is highly compliant with the latest standards, although it lacks many features (e.g., spatial user multiplexing, Massive MIMO, and Frequency Division Duplexing). On the other hand, Vienna 5G system-level simulator and 5G K-SimSys simulator offer a conspicuous feature set. Nevertheless, while they share some common functionalities with 5G-air-simulator, some features are only accessible through the Vienna and K-SimSys simulators (e.g. D2D, mmWave) and some are exclusive to the 5G-air-simulator (e.g. Massive MIMO, broadcasting). Moreover, they require the purchase of a license for commercial use, while being freely available for academic purposes.

The *5G-air-simulator* provides a significant step forward in this direction. The simulation platform is open-source and thus it is freely accessible to everyone. It may be leveraged as a valid tool for both the modeling of the New Radio key elements and the performance assessment of typical 5G scenarios with varying architecture configurations. For this reason, it allows Academia and Industry to address existing research questions by employing an effective instrument.

High-level description

5G-air-simulator inherits the core functionalities from the worldwide known LTE-Sim tool [2], starting from the object-oriented and event-driven paradigms. Besides, it gets the possibility to simulate from the system-level perspective several network environments as well as sophisticated and standard-compliant radio resource management methodologies for both the control and the user plane. Furthermore, the developed simulation framework significantly extends the aforementioned project by integrating additional features and new technical components, which are more suitable for 5G.

5G-air-simulator is written in the *C++* language, exploiting event-driven and object-oriented paradigms. At the time of this writing, it consists of more than 300 source and header files, 140 classes, and 60,000 lines of code. It covers several features, as summarized below:

- *Network Architecture.* The developed framework essentially models two different kinds of nodes: the User Equipment (UE) and the gNB. It then includes many scenarios reflecting typical conditions used in research and testing, ranging from a single cell to heterogeneous network configurations. There are either basic configurations for assessing the performance under ideal conditions or more realistic configurations with a full multi-sector environment considering multiple active base stations, each with multiple users, useful for evaluating research issues such as inter-cell and inter-sector interference, frequency reuse, and handover. In addition, *5G-air-simulator* includes various mobility models, ranging from UEs' movements with a constant speed towards a given or random direction, to a horizontal or vertical movement, with a certain probability to turn left or right (i.e., the Manhattan Model, for reproducing city environments).
- *Applications and Protocol Stack.* Data packets are generated by application models, then handled by the protocol stack, and finally transmitted and received by devices created during the simulations. There are several application models to address different scenarios, including video streaming, VoIP, and FTP, as well as constant bitrate and infinite buffer transmissions. In addition, the proposed simulator provides support for many other features of the protocol stack embracing both control and user planes. Specifically, the Radio Resource Control (RRC) handles data flows and handover procedures. The Packet Data Convergence Protocol (PDCP) controls the header compression of the packets. The Radio Link Control (RLC) manages the buffering, segmentation and reassembly, concatenation, and retransmission of data units, while also supporting different standardized data transfer modes (Transparent Mode, Unacknowledged Mode, and Acknowledged Mode). Media Access Control (MAC) implements the data transmission and reception, also with the Hybrid Automatic Repeat reQuest (HARQ) mechanism for achieving error recovery, the Adaptive Modulation and Coding (AMC) module, and the packet schedulers covering several radio allocation strategies.
- *Link-to-system model.* It provides an abstraction of both physical interfaces, link adaptation, and communication channels. Several calibrated channel models standardized by both 3GPP and ITU are employed to simulate many PHY layer phenomena, including path loss, shadowing, penetration loss, fast fading, noise power, and interference. The term calibrated means that the channel behavior of system-level simulations is in accordance with the guidelines provided by the 3GPP standardization entity. The transmitted signal is modeled through a power spectral density for each used radio resource and modified by the channel models during the propagation. Upon reception, a device calculates the Signal-to-Interference and Noise Ratio (SINR) for each used radio resource. Then, it maps these values to a single effective SINR by means of the Mutual Information Effective SINR Mapping (MIESM) method [3]. The effective SINR, which reflects the overall quality of the radio channel, is used on the one hand to estimate the BLock Error Rate (BLER) for the received data block, and, on the other hand, to compute the necessary information for a proper link adaptation procedure. The resulting Channel Quality Indicator (CQI) feedbacks are reported to the gNB. Here, the AMC module searches the optimal Modulation and Coding Scheme (MCS) to use for future transmissions. Moreover, during the resource allocation, the MCS is used to compute the Transport Block Size (TBS), by following a standardized procedure [4].
- *5G-related technical components*. The *5G-air-simulator* allows to investigate a series of simulation campaigns for typical 5G services recently considered in scientific literature and European projects, such as enhanced Mobile BroadBand (eMBB), Broadcast Multicast Services (BMS), Vehicle-to-everything (V2X), and massive Machine Type Communication (mMTC). Specifically, eMBB generally refers to those applications that require large amounts of data, such as streaming High Definition videos and downloading files. This requires a high aggregated throughput, hence demanding a considerable spectral efficiency. To this aim, the simulator implements Multiple-Input Multiple-Output (MIMO) and Massive MIMO transmission modes for increasing the throughput and spectral efficiency. On the other hand, BMS refers to multicast/broadcast schemes to realize one-to-many or one-to-all data distribution models. Well-known applications of BMS include video broadcasting during sports matches and concerts or emergency services for dangerous climate situations. For this reason, extended multicast and broadcast operations are considered in the proposed software to avoid the need for establishing multiple individual links for the transmission of the same data at the same time. In addition, the simulator models predictor antennas for fast-moving vehicles for the mitigation of a degraded Quality of Experience due to the rapidly changing radio environment, while ensuring a greater throughput. In the context of mMTC, *5G-air-simulator* implements an enhanced random-access procedure for the support of a massive number of connected devices. Moreover, it models NB-IoT operation to serve Internet of Things devices with high coverage and low power consumption.

Fig. 1 provides an overview of many customizable features offered by *5G-air-simulator,* grouped according to the main elements characterizing each scenario.

Impact overview

The proposed simulator improves the daily practice of its users while embracing different research fields that could take advantage of it. On the one hand, it already provides several built-in scenarios to conduct simulation campaigns for typical 5G use cases. A specific test is

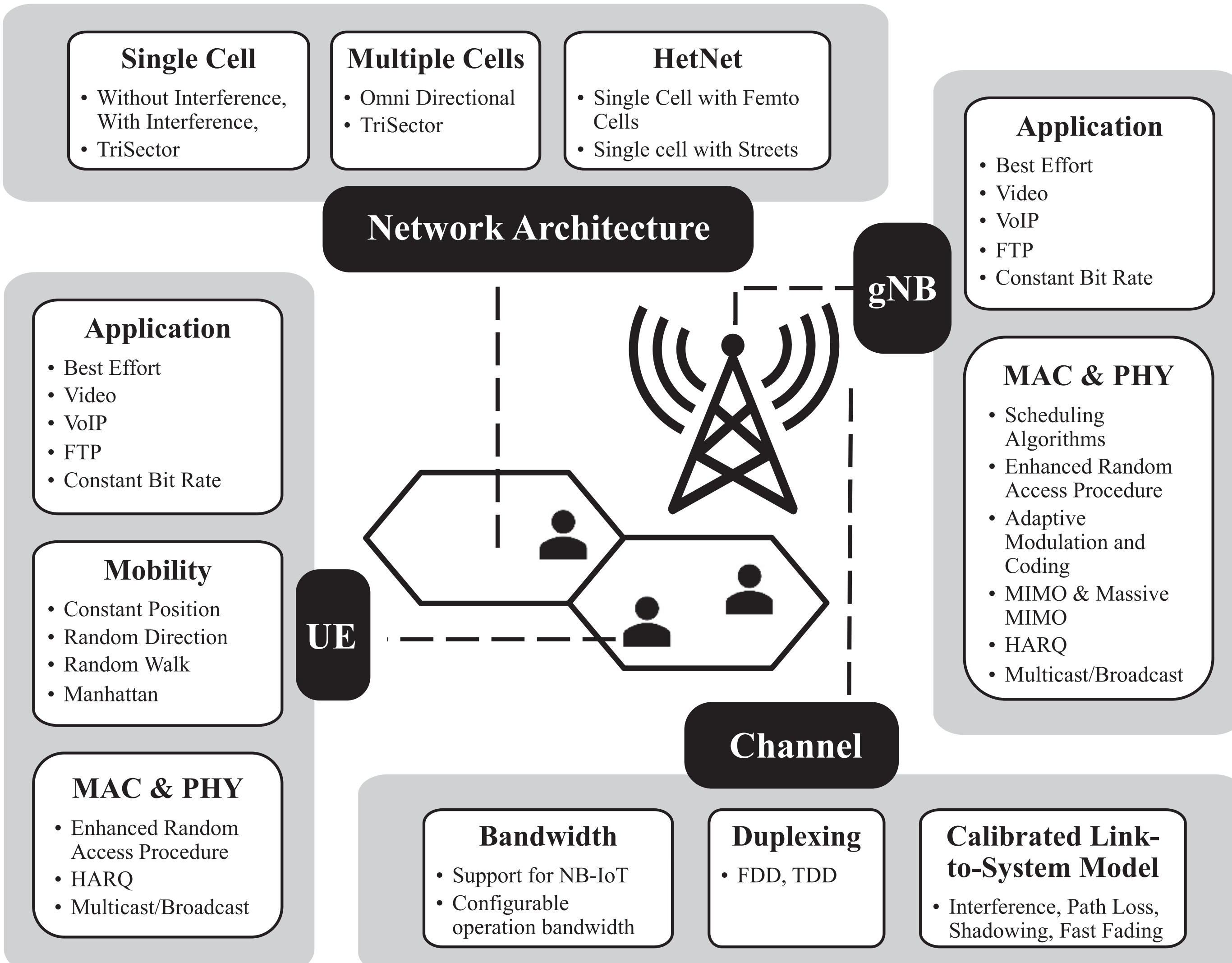

Fig. 1. Overview of many customizable features offered by 5G-air-simulator, grouped according to the main elements characterizing each scenario.

executed through a command line instruction that contains 1) the name of the software executable, 2) the name of the reference scenario to be investigated, and 3) a list of parameters to generally control the configuration of network deployments, technical components, algorithms, and protocols. This approach ensures an effective usage of the tool for users willing to evaluate the performance of customized use cases without requiring the editing of *C++* sources. On the other hand, during the execution of a simulation, *5G-air-simulator* provides a text trace whose lines report significant information about different events, e.g., transmission and reception of transport blocks and packets, as well as random-access actions and location data, as reported in Fig. 2. Since the text trace contains much information, it is possible to retrieve several key performance indicators, e.g., cell goodput, average user throughput, random-access collision rate, cell-edge throughput, packet delays, and Packet Loss Ratio, by processing the console output of each simulation run to extract the relevant data. Besides, according to the requirements for a specific research area, many more Key Performance Indicators may be retrieved by extending the current trace accordingly.

The proposed software has been designed with flexibility and extensibility at its core, therefore, it can be adopted to effectively pursue, with a limited additional effort, new research questions arising from new applications/services and features. For instance, adding new mobility and application models is as simple as writing new classes derived from the baseline code. Also, given the open-source nature of the tool, new technical components may be integrated in order to explore emerging research topics, such as cellular-connected drones, Network Slicing, Multi-access Edge Computing, etc. As a result, this tool is expected to reach a good visibility in both Academia and Industry, allowing researchers and practitioners to test, extend, and evaluate the advanced solutions for 5G.

5G-air-simulator has already been used in the EU H2020 Fantastic 5G project [5] and in the Italian Ministry of Economic Development project "Pre-commercial Trials of 5G technology using spectrum in the 3.6 - 3.8 GHz band - Milan Area", in collaboration with Vodafone Italia [6]. As for ongoing research projects, the tool could be used within the PRIN project no. 2017NS9FEY entitled "Realtime Control of 5G Wireless Networks: Taming the Complexity of Future Transmission and Computation Challenges".

Without any doubts, past, current, and future usage of the tool plainly confirms its ability to sustain a community of excellent researchers around 5G technologies, with the goals of 1) guaranteeing a long-lasting exploitation of scientific results, 2) offering a valid scientific and technological support for the development and the diffusion of modern service platforms built on top of 5G communication infrastructures, and (3) representing an opportunity for the cooperation among companies, Small Medium Enterprises, local authorities, research centers, Spin-off companies, and public administration. This clearly shows

```
RX CBR ID 119 B 0 SIZE 20 SRC 3 DST 0 D 0.003 0

RANDOM_ACCESS COLLISION UE 12 PREAMBLE 7 TIME 48

PHY_RX SRC 2 DST 7 X 240 Y -130 SINR 3.9366 RB 13 MCS 13 SIZE 1131 ERR 1 T 0.052

PHY_RX SRC 2 DST 3 X 199 Y 199 SINR 10.3639 RB 73 MCS 21 SIZE 113122 ERR 0 T 0.052

DROP VIDEO ID 681 B 29

TX INF_BUF ID 120 B 1 SIZE 1490 SRC 2 DST 3 T 0.052 0

PHY_RX SRC 2 DST 3 X 199 Y 199 SINR 10.1639 RB 12 MCS 15 SIZE 114672 ERR 0 T 0.053
```

Fig. 2. Excerpt of the output text trace provided by 5G-air-simulator.

not only its widespread use but also its impressive impact within and outside the intended user group.

Scholarly publications enabled by the software

The simulator already proved to be a valuable tool for different research activities and scientific contributions. At the time of this writing (December 2019), the paper presenting the original version of the proposed simulator, i.e., LTE-Sim, has gained more than 750 citations, according to Google Scholar, more than 450 according to Scopus and more than 300 according to Web of Science. Furthermore, there are many publications already exploiting the present version of the *5G-air-simulator* [7-11]. In addition, many results presented in some chapters of the book [12] have been realized thanks to the simulator presented in this article.

Conclusions

This article presented the *5G-air-simulator*, a calibrated open-source instrument for evaluating the design and the integration of new technical components for current and upcoming mobile radio interfaces. It provided an overview of the principal use cases planned or expected in 5G while describing the high-level functionality of the new *5G-air-simulator* tool. Besides, the present contribution explained how the pursuit of existing and novel research questions is improved thanks to the simulator, with a focus on its widespread use among several research groups, as confirmed by the projects in which the tool has been (or is going to be) employed and a large number of scholarly publications enabled by the software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.comnet.2020.107151.

B- Required Metadata

B1 Current executable software version

B2 Current code version

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