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Research Article

Comparative Analysis of Open-Source Platforms Used in 5G New Radio Simulations

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Keywords

5G New radio,
Free5GC,
Open5GS,
OpenAirInterface(OAI),
IEEE testbed,
MATLAB.

Abstract

This study aims to comprehensively examine the open-source platforms used for simulation and testing processes in the field of 5G new radio technology and offer solutions to address diverse needs. In this study, we compare open-source platforms such as Free5GC, OpenAirInterface, Open5GS, IEEE 5G/6G Innovation Testbed, and MATLAB 5G Toolbox based on different factors such as how the network is set up, what versions they support, what hardware they need, how they use databases, if they can emulate in real-time, their simulation capabilities, and other features, as well as the support from the community and documentation. In addition to all these, the platforms have been evaluated for their accuracy, real-world compatibility, accessibility and developability, installation difficulties, and computational load. In addition, the main possible improvements are listed. The analysis determined that the Free5GC and Open5GS platforms are suitable for simulating 5G New Radio (NR) core network functions. The OpenAirInterface platform, in contrast, offers a more powerful and flexible structure at both the core and radio access network (RAN) levels. The IEEE 5G/6G Innovation Testbed provides a physical test environment and more realistic results thanks to its hardware-based structure. MATLAB 5G Toolbox stands out for academic studies with its channel modeling, simulation capability of various layers, and academic prototyping. These evaluations provide findings that contribute to the advancement of next-generation wireless communication systems by assisting researchers and developers in selecting the best simulation environment for their specific needs.

1. Introduction

1.1. Purpose and Importance of Research

Technology continues to advance rapidly across all sectors. Technological advancements have led to innovations in telecommunications and numerous other fields. Beginning in the early 1980s with voice transmission, this evolution of innovation has progressed over the years, with new features developed to meet diverse needs, culminating in the systems used today. 5G, a currently used and evolving telecommunication system, offers advantages such as high data rates, low latency, and high connection capacity [1]. Although the number of open-source 5G simulation and test platforms has increased with this development, there is still a lack of comprehensive benchmarking studies based on criteria such as installation difficulty, resource consumption, real-time emulation capabilities, and suitability for practical application. In this context, this research aims to fill this gap by presenting a structured comparison of the effectiveness and functionality of open-source platforms that facilitate the implementation of 5G new radio (NR) simulations based on both document review and pre-installation experiences to keep pace with academic and industrial development and guide future work.

Open-source platforms are important tools for creation, configuration, testing, and development of 5G networks. Open-source platforms are crucial for fully realizing the potential of 5G technology and accelerating research. Community input continuously improves and updates open-source platforms due to their flexibility and customization opportunities. Users can adapt open-source platforms to their specific needs and develop innovative solutions. This study compares the platforms across various aspects.

It provides recommendations to help users meet their needs, enhancing the knowledge of academic researchers, industry professionals, and developers, and facilitating the faster adoption of 5G applications.

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This study aims to provide a valuable roadmap for the future of 5G. Analyzing open-source platforms will support the efficient development and integration of 5G systems into sustainable communication solutions.

1.2. 5G Technology and Core Network Architecture

Compared to previous generations, 5G technology enables higher data rates, lower latency, and greater connectivity, fostering the development of new and innovative applications. 5G is a key technology that continues to evolve and deliver various services in academia and industry. The 5G network supports three primary use cases: massive machine-type communications (mMTC), ultra-reliable low-latency communications (URLLC), and advanced mobile broadband (eMBB) [2]:

- Enhanced Mobile Broadband (eMBB): High-speed broadband data transmission. This use case is designed for applications such as 4K/8K video downloading, high-speed video streaming, virtual reality (VR), and augmented reality (AR). eMBB supports broadband data transfers, providing users with high-speed, low-latency connections [3].
- Ultra-Reliable Low Latency Communication (URLLC): Meets critical communication needs where speed is more important than bandwidth, with end-to-end latency of 1 ms or less [3].
- Massive Machine-Type Communications (mMTC): Communication of large-scale devices and sensors. This case includes Internet of Things (IoT) applications, enabling communication among thousands or millions of sensors or devices with low energy consumption, low cost, and low data rates [3].

The 5G Core network was created to efficiently provide these cutting-edge services. The 5G network's main management and control system is called the 5G Core. It is software-based and has several features that maximize data transmission, session management, and user access:

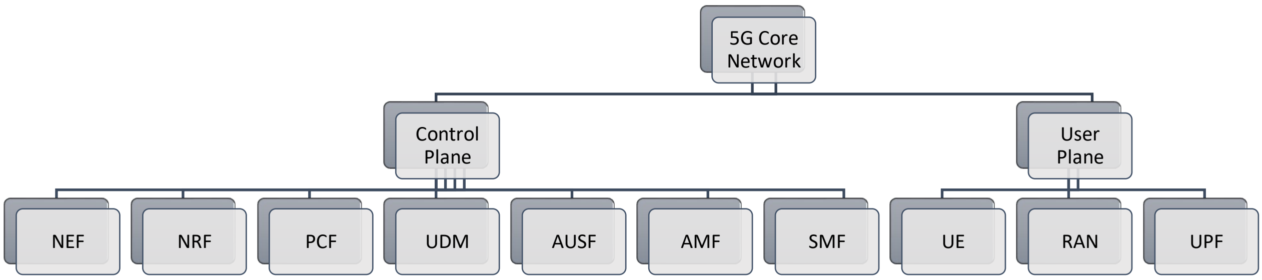

Figure 1. 5G Core Network Functions

- UPF (User Plane Function): Responsible for routing and processing user data.
- SMF (Session Management Function): Provides creation and management of user sessions.
- AMF (Access and Mobility Management Function): Manages user access and mobility.
- AUSF (Authentication Server Function): Performs authentication processes.
- UDM (Unified Data Management): This system is responsible for managing and storing user information.
- PCF (Policy Control Function): Manages the implementation of service and quality policies.
- NRF (Network Repository Function): Manages subscriber registration and local information.
- NEF (Network Exposure Function): Enables the 5G network to communicate with external systems in a secure and controlled manner.

1.3. The Importance of Platforms in 5G Development

Simulations are critical in analyzing 5G NR performance during research and development. Emerging simulation techniques allow researchers and engineers to easily evaluate the performance of mobile communication systems by mimicking their behavior under real-world conditions. Simulation tools play a significant role in improving user experience and network efficiency. Detailed simulation models that recreate real-world environments enable more accurate and reliable results.

Simulation facilitates the analysis of complex systems. 5G technology features a multi-layered structure and diverse scenarios. This complexity makes real-time tests challenging and limits them to physical experiments. Simulations offer researchers and engineers greater flexibility in system design, allowing them to account for mobility scenarios, user number fluctuations, and service quality variations.

Simulations also accelerate implementation by enabling rapid evaluation of results. Real laboratory tests can hinder research and development because they are time-consuming and costly, but simulation tests mitigate these drawbacks. Thus, simulation is a budget-friendly and sustainable alternative, enabling rapid development of innovative studies and facilitating error detection.

2. Methodology

This study conducts a qualitative assessment to compare open-source 5G simulation platforms. The comparison is based on installation experiences gained by analyzing documentation, installation guides, community discussions, and virtual environments. Key evaluation criteria include installation difficulty, features supported, hardware resources required, simulation capabilities, community support, and licensing models. Where appropriate, test environments were set up and inspected for short periods to check the ease of installation and basic functionality of the platforms. Analysis of current documentation and academic sources supported the comparison.

3. Open-Source Platforms

Open-Source Platforms The emergence of 5G has led to the development of numerous open-source simulation platforms. Open-source platforms serve as testbeds for validating development-phase work by adhering to standards and providing public access to code [2]. Notable platforms include Free5GC [4], OpenAirInterface [5], Open5GS [6], IEEE Testbed [7], and MATLAB 5G Toolbox [8].

3.1. Free5GC

3.1.1. General definition and characteristics

Free5GC is a Linux Foundation project developed by the National Yang Chiao Tung University (NCTU) [4]. This Go language-based open-source platform for 5GC provides a 5G core development environment based on 3GPP R15 [9]. Initially, the National Yang Ming Chiao Tung University (NCTU) made significant contributions to the project, with many researchers and engineers contributing to its development due to its open-source nature. Free5GC is available under the Apache 2.0 license, allowing free use for commercial purposes, and is continuously improved with new features [10].

Free5GC is based on NextEPC, an open-source implementation of the 4G/5G 3GPP core network, and includes PCRF, MME, SGW, PGW, and HSS. The development of the 5G core network in Free5GC occurs in three phases. The first phase is the 5G non-standalone (NSA) architecture, which supports the core elements of the 5G core using the existing 4G LTE core network and defines only SMF, AMF and UPF, operating based on 4G elements; the second phase is the SA architecture, which uses a fully standalone 5G core network and 5G NR access network, and operates based on a service-based interface (SBI); and the third phase is the addition of the uplink classifier ULCL and the non-3GPP interworking function N3IWF, which are the core elements supporting non-3GPP access to SA [2].

Free5GC is an open-source platform specifically for testing the 5G Core Network (5GC), the central component of the 5G network architecture. This platform includes core network functions essential for basic 5G services, such as user identity and quality of service. These functions consist of components such as AMF, SMF, UPF, NRF, NSSF, UDM, UDR, AUSF, and PCF. It also supports features such as registration, authentication, NAS security, Service request and Qos, PDU session setup and modification, Multiple UPFs and ULCL, multi-slice and DNN, Dynamic/static IPv4 address allocation, and UP security.

Its advantages include: its open-source nature, which allows user customization and flexibility; its free availability to students and researchers; and its continuous development through community contributions. However, it also presents disadvantages, such as installation and configuration difficulties, and insufficient support and maintenance.

3.1.2. Installation and usage steps

Installing Free5GC requires a Linux environment. For quick installation without complex configurations, the Free5GC Compose method is suitable. For installation in a Kubernetes environment, the Helm method can be used. Alternatively, a virtual machine with Ubuntu can be created using VirtualBox for installation from scratch, compiling and installing using the source code provided on the project page. However, virtual machine installation is more complex and requires significant Linux expertise. The Free5GC Compose method is recommended for quick platform initialization and use.

Docker and Kubernetes are used for the container deployment of Free5GC. Containers are primarily used to run applications in virtual environments. This method accelerates development and deployment by improving resource efficiency and isolation. Compared to virtual machines, containers use fewer resources, isolate application components, and offer independent management, providing users with increased speed. A detailed installation and configuration guide is available on the project's website.

Example use case: In [9], Free5GC captures and analyzes network traffic during the setup and operation of the 5G core network function. Researchers can implement Free5GC in a testbed to validate session establishment and PDU session connection procedures.

3.2. OpenAirInterface

3.2.1. General definition and characteristics

OpenAirInterface is a 5G radio access network (RAN) project developed by Eurocom to foster innovation in wireless networking and communications. This C-based open-source platform for 5G core networking provides a 5G full-stack development environment based on 3GPP Release 16 [2]. Based on the OAI radio front-end architecture, it includes basic radio access network functions that manage connections between user equipment (UE) and radio base stations (eNB), enabling communication. It provides an open-source software implementation of LTE and LTE-Advanced features, fully compliant with 3GPP standards. OAI covers two main components of the LTE system architecture: (1) the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and (2) the Evolved Packet Core (EPC) [2]. It also covers the entire protocol stack from the physical layer to the network layer and offers highly realistic emulation modes. OAI has two unique features. These include its open-source, standards-compliant, SDR-based software implementation of LTE, and its highly realistic emulation capability for repeatable and scalable system evaluations [11].

The OpenAirInterface open-source platform has several sub-projects, including OAI RAN, Core Network, and the OAM Project Group.

- OAI RAN, the 5G stack, offers an open-source solution supporting both NSA and SA configurations. It includes L1 and L2 simulation frameworks for testing multiple user equipment (UE). Additionally, OAI's MIMO multi-antenna operations and CU/DU separation enable 5G to achieve high data transfer rates, with ongoing efforts to improve performance [5].
- The OAI-5G Core Network project is designed to provide 3GPP-compliant 5G SA and offers flexibility for various scenarios. Its service-oriented architecture allows it to meet diverse performance requirements. The OAI 5G CN supports multiple user equipment and PDU sessions simultaneously and provides various deployment options. CN component features are continuously tested with professional testers, commercial gNodeBs, and open-source RAN simulators [5].
- The OAI Operations and Maintenance (OAM) project group facilitates the management, monitoring, and maintenance of OAI RAN and Core Network functions. OAM implements and maintains management interfaces recommended by the O-RAN Alliance, such as O1, E2, and the Open Fronthaul Interface. FlexRIC, an O-RAN-compliant RAN Intelligent Controller, provides a flexible solution for low-latency and resource-constrained applications, while the Multi-access Edge Computing (MEC) platform integrates various MEC applications [5].

OAI also supports features such as connection, registration, session management, N2 relay, HTTP/2 FQDN support, paging, and partial network slicing. Universities and educational institutions can use this open-source platform to enhance the understanding and teaching of wireless communication technologies, develop and test new wireless protocols, conduct 4G/5G network simulations, explore IoT and M2M applications, establish private networks and public safety solutions, research wireless networks, and contribute to future wireless technology development. The platform can be reconfigured to suit user needs and offers significant potential for research and development of communication scenarios. It is also open to continuous improvement through community contributions. However, it also has disadvantages, including complex installation and limited support due to its ongoing development.

3.2.2. Installation and usage steps

The OAI code is readily accessible on its website without requiring account creation or a license agreement. The software enables the deployment of a fully compatible 4G eNodeB and EPC on a standard x86-based PC [12]. Running the OAI software requires a Linux operating system and the installation of necessary libraries. Users can access resources such as EURECOM's GitLab account for OAI software installation, distribution, configuration, and support [13]. Similar to Free5GC, the latest software version can be downloaded, installed with appropriate hardware, and deployed via Docker. The community also has access to training materials for real-time emulation and simulation. Developer documentation includes test setup and development guidelines. OAI can also be integrated with Free5GC.

Example use case: As in [11], OAI can be deployed with SDR hardware support to build a 5G RAN and perform realistic physical layer experiments. The platform allows researchers to thoroughly test multi-user MIMO and resource scheduling in crowded network situations, and its ability to simulate real conditions makes studies more accurate.

3.3. Open5GS

3.3.1. General definition and characteristics

Open5GS, another open-source platform, is developed by NextEPC. Open5GS is a 3GPP Release 17-compliant, C-based, 5G core open-source project, with its commercial license held by its developer, NextEPC [2]. This platform offers a comprehensive solution for users seeking to build private NR/LTE mobile networks for testing, research, or applications. The Open5GS platform has two core architectures: Open5GS 4G/5G NSA core and Open5GS SA core. The 4G/5G NSA core includes MME, PCRF, HSS, SGWC, SGWU, PGWU/UPF, and PGWC/SMF. This architecture is divided into core control and user planes [14]. The SA core includes AMF, SMF, NRF, SCP, UPF, AUSF, UDM (which includes UDR), PCF, NSSF, and BSF components. This core architecture uses only a single user plane function, making the SA architecture simpler than the NSA architecture.

With its comprehensive suite of packages and libraries, Open5GS provides a highly efficient 5G core network and ensures full compatibility with active sessions and connections [15]. The deployed 5G core network enables access to various web-based applications and supports a wide range of services, including multimedia streaming [15].

Open5GS offers a flexible and scalable implementation due to its modular architecture. Developers and researchers can customize functionalities, such as enabling network slices and managing quality of service parameters, to meet specific requirements. Open5GS is compatible with various radio access technologies, enhancing LTE usability with 5G. In addition, it offers easily accessible documentation and community support, which is a great advantage for academia and industry. The platform emphasizes standards compliance and guarantees interoperability with other components and systems in the telecom world. As with other open-source platforms, users should take some precautions regarding installation and management, and the capabilities of the project should be considered before using it. In open-source projects, sometimes incomplete or outdated documentation may be encountered, which is another disadvantage that causes difficulties for users in terms of documentation.

3.3.2. Installation and usage steps

A Linux operating system is also required to run the Open5GS software. Users can access the source code of the project and other necessary documentation on GitHub [16]. With the help of the codes required for the installation of the software, the open5GS 5G core is first installed on Ubuntu, and the necessary dependencies are installed. Any service or network function can be started, terminated, and restarted using a specific set of commands provided in the documentation. After installation, 5GC components are configured. The main ones are registration management (to register and unregister a user equipment in 5G), connectivity management (to establish and release control plane signaling links between the UE and AMF via the N1 interface), availability management (to ensure that a UE is always accessible), mobility management (to know about the UE's location in the network), and configuration of the AMF [15]. MongoDB-based subscription can be used to add UE devices [15]. Again, we can use UERANSIM to test Open5GS with UE and gNB. In addition, Open5GS can be integrated with other 5G test tools such as OAI and UERANSIM.

Example use case: In [17], a comparative study is conducted by deploying a 5G standalone (SA) testbed that combines open-source RAN and core network solutions. Open5GS can be evaluated in terms of controlled single-cell and single-UE scenarios. The study indicates that Open5GS demonstrates high robustness and user-friendliness during its integration, showing stable connectivity and consistent performance, especially in uplink and downlink speeds in different configurations.

3.4. IEEE 5G/6G Innovation Testbed

3.4.1. General definition and characteristics

The IEEE 5G/6G Innovation Testbed is a cloud-based, end-to-end 5G network emulator that enables the testing and realization of 5G products and services. The testbed was built on the recommendations of a technical advisory board consisting of technology companies such as AT&T, EXFO, Samsung, VMware, and China Mobile [18]. Developed by the IEEE Communication Society (ComSoc) and various academic and industrial partners, it is based on 3GPP releases 15, 16, 17, and 18 standards; IEEE standards; SDR technology; edge computing and artificial intelligence; and mmWave and terahertz technologies. Designed to enable companies to bring products and services to market faster through collaboration, this platform provides a continuously accessible test and development environment. The cloud-based 5G network simulator enables the development of 5G technologies by providing a flexible, easily accessible, and secure environment according to the needs of the industry. The existence of this cloud-based digital hub provides a great advantage by eliminating the need for physical travel and hardware. It also facilitates the development of innovative solutions to enhance existing 5G technology and shape future 6G functionalities using open-source components. Another important advantage is that it enables the testing of artificial intelligence-supported systems that are becoming more prevalent due to technological advancements. It offers high accuracy as it simulates a real-world environment. Although the subscription-based model provides an advantage over the excessive costs and restrictive conditions of commercial licensed platforms, the subscription fee is one of the disadvantages of this platform compared to completely free platforms. Another downside is that the installation documentation is hard to understand and requires expertise. In addition to all this, you may also experience hardware and software compatibility issues.

The platform provides an environment for a user to quickly test protocol compatibility and the load characteristics of the particular system under test. The testbed is organized into two functional components [19]:

- A network tool component assists in the execution of test cases defined as 3GPP call flows. The network broker generates test data that is consumed by an analytics component.
- The analytics component helps to present descriptive information about the test data generated by the network broker. It visualizes and presents the results to the user to help them make inferences about the testing performed.

Apart from these two functional components, Testbed also has a GUI that helps the user to operate the functions of the Analytics component as well as the Network Agent. With the help of GUI, the user can execute test cases and analyze the results of the same with the help of graphs and tables that help the user make inferences about the tests that took place during a period.

Testbed can do things like make audio and video calls, stream videos with the MEC platform, integrate DPDK-based UPF, connect with physical O-RAN from another company, control traffic, create network slices, set up a private 5G network (with RU from NI), monitor metrics (using Grafana), manage tests, organize cloud resources, support CAMARA API, automate processes, manage lifecycles, and coordinate multiple clusters [20]. In addition to these capabilities, Testbed can simulate various nodes:

- 5G Nodes: gNodeB, AMF, AUSF, UDM, UDR, SMF, PCF, UPF, NSSF, NRF, NEF, SMSF, CBCF

- 4G/5G Interwork Nodes: HSS_UDM, PCRF_PCF, PGWC_SMF, SPGWC_SMF, PGWU_UPF, SPGWU_UPF

- Ratio Nodes: NEAR_RT_RIC, GNB_CU_CP_FSM, GNB_CU_UP_FSM, GNB_DU_FSM

3.4.2. Installation and usage steps

Although this platform, which operates on a Linux operating system or through a virtual machine, is regarded as one of the open-source platforms, an account must be created by purchasing a subscription for a specified fee for installation and use. To experience the platform, you can reach out to the appropriate authorities to initiate the trial version. After you create an account, representatives from the project team will share the necessary documents with you and provide guidance. The project team provides support throughout all these stages. The platform comprises various components for both hardware and software. The hardware includes SDR, mmWave, and sub-6GHz antennas; FPGA- and GPU-based processing platforms; as well as Edge and Cloud server infrastructure components. Meanwhile, the software features open-source 5G/6G solutions such as OpenAirInterface and srsRAN, along with various simulation environments and AI/ML integration tools like TensorFlow and PyTorch. Once all these components are provided, test scenarios are established by ensuring compatibility between the hardware and software, allowing you to evaluate performance metrics through the necessary integrations.

Example use case: In [18], the IEEE 5G/6G Innovation Testbed validated the integration of AI-enabled control mechanisms in 5G network slicing. Researchers can simulate dynamic resource allocation strategies across virtual network slices and test new service orchestration techniques.

3.5. MATLAB 5G Toolbox

3.5.1. General definition and characteristics

The MATLAB application began to be developed by Cleve Moler at the University of New Mexico in the late 1970s and was released as a commercial product by MathWorks in 1984. It is considered one of the most widely used simulation platforms for academic and research. It has a large library of functions, making it an ideal program for solving problems in engineering fields. It includes a powerful 5G toolbox to perform both link-level and system-level simulations [21].

MATLAB 5G Toolbox offers tools and features to help create simulations of 5G radio networks based on 3GPP standards, which are used for modeling, testing, and checking 5G and advanced communication systems [21]. It supports the features of 3GPP NR Release 15 and later. With this toolbox, you can run simulations and analyze the physical and MAC layers of 5G, create and test 5G signals, model and evaluate how transmission channels work, and improve studies using artificial intelligence and machine learning techniques [21]. Using this toolbox, users can configure, simulate, and analyze 5G communication links. In addition to all these, it offers users the opportunity to simulate 5G NR end-to-end wireless communication links. You can also use this toolbox to evaluate the performance of RF transmitters and receivers. By utilizing the channel state information for MIMO and beamforming, users can set their transmission parameters and perform the desired tests easily, thanks to its easy interface. Frequency-time resource sharing between multiple UEs in a 5G NR network can be simulated.

The 5G Toolbox simulates the functions of the 5G NR physical (PHY) layer in GNBs and UEs. The PHY layer is central to the toolbox's signal processing capabilities. It also provides several key functionalities in the media access control (MAC) layer and the radio link control (RLC) layer that the PHY interfaces with. A usual system-level simulation done in the MATLAB 5G Toolbox uses UE and gNB objects, which are made up of classes and properties related to the 5G protocol layers [21].

This simulation-based toolbox offers researchers the advantage that its moderate computing power is not as compute-intensive as real-time systems. Its code can be easily edited and configured. It provides 5 G-specific coding and modulation support such as LDPC, polar coding, QAM, and OFDM. It creates a wide usage area with the opportunity to analyze realistic channel models. In addition to all these, it has proven its usability in various studies due to its widespread and long-standing use. The biggest advantage is that it is simulation-oriented, so it offers fast testing and does not require real 5G hardware. In addition to this advantage, the disadvantages are that it is not suitable for real-time 5G network performance tests, and there is a license fee.

Overall, MATLAB stands out as an important tool in the simulation of 5G NR systems by providing a versatile platform for research, development, and testing purposes. Its capacity for systematic experimentation and deep performance analysis directly contributes to ongoing advances in the deployment and optimization of next-generation wireless technologies.

3.5.2. Installation and usage steps

You can access this commercially licensed program by paying a certain fee. Installing MATLAB is sufficient and does not require additional hardware. Upon purchasing and installing the current licensed version of MATLAB, it will automatically install all necessary libraries and toolboxes. You can easily access the MATLAB download file from the platform's own web page and get the necessary help for installation and use from the help and support team. After completing the installation, you can easily run 5G simulations with the necessary commands or codes. For example, you can create a simple 5G NR waveform, simulate 5G NR PDSCH, perform BER performance analysis on different channels, and perform throughput evaluation.

Example use case: In [21], researchers use MATLAB 5G Toolbox for system-level calibration and evaluate physical and MAC layer performance in different channel models to validate link adaptation algorithms under various vehicular communication scenarios.

4. Comparison of Platforms

Free5GC, OpenAirInterface, Open5GS, IEEE 5G/6G Innovation Testbed, and MATLAB 5G Toolbox stand out among the open-source platforms used in 5G NR simulations [22]. Comparing these platforms and knowing what differences they have is important in terms of deciding which one to work with. We aim to facilitate platform selection for researchers, engineers, and the communication industry through these comparisons. Table 1 shows the capability evaluation of these platforms.

Table 1.Software, hardware and capability assessments of open-source 5G core networks

Feature	Free5GC	OAI	Open5GS	IEEE 5G/6G Innovation Testbed	MATLAB 5G Toolbox
3GPP Release Support	15	16	17	15 and later	15 and later
CPU Architecture	ARM & x86	ARM & x86	ARM & x86	Thanks to the cloud-based architecture, it is possible to access the test environment on different devices and operating systems	x86-64
Minimum Hardware Requirements	RAM: 8GB HDD: 160GB 1 CPU	RAM: 8GB HDD: 40GB 2 CPUs	RAM: 8GB HDD: 10GB 1 CPU	RAM: 8GB HDD: 10GB 2 CPUs	RAM: 8GB HDD: 40GB 4 CPUs
Operating System Compatibility	Linux & Windows	Linux (Red Hat & Ubuntu)	Linux (Debian & Ubuntu)	Windows & macOS & Linux	Windows & macOS & Linux
Programing Language	Go	C++ & C	C	Vaious	MATLAB
License Model	Apache 2.0	OAI Public License	GNU AGP3.0	Membership required	Commercial license
NB-IoT Support	No	Partly	No	Partly	Partly (Thanks to LTE toolbox)
Database Used	MongoDB	MySQL	MongoDB	IEEE DataPort	MySQL & MongoDB
Docker Support	Yes	Yes	Yes	Yes	Yes
Real-time Emulation Support	No direct support	Yes (Real-time emulation is possible with advanced SDR integration)	No direct support	Yes (Can be tested with real hardware)	No (Does not perform real-time emulation, performs analytical modeling)
Simulation Support	Yes (Can simulate 5G core)	Yes (There is 5G NR simulation)	Yes (Can simulate 5G core)	Yes (There are various 5G and IoT simulations)	Yes (Can simulate at 5G system level and connection level)
Supported Components	5G core	5G Core & RAN	5G Core	5G & IOT application	5G waveforms and system level simulations
Community and Support	Active community	Active community	Active community	IEEE members	MathWorks Support

Free5GC offers flexibility to developers thanks to its high modularity while complying with third-generation 5G specifications. In addition, it is based on a microservices architecture, which facilitates the integration of distributed systems. It has an easy-to-use interface, which makes it attractive for research. However, this platform can only simulate the 5G core network, so there is no support for direct real-time emulation. Due to this lack of support, it cannot offer high accuracy.

Conversely, Open5GS features a more simplified structure and aims to fulfill the primary functions of communication networks. It can mimic a 5G core network, just like Free5G, but it doesn't allow direct real-time emulation. This platform is especially optimized for low-resource scenarios and allows users to quickly evaluate 5G infrastructures. Thanks to its flexible structure and active platform support, users can customize their system by selecting only the required components and modules. As a result, it offers a suitable alternative for low-resource or prototype development projects.

OpenAirInterface facilitates the transformation of 5G networks into research and applications by offering a wide range of use cases and active community support. Unlike other platforms, it can simulate not only the 5G core network but also the RAN and perform real-time emulation thanks to SDR integration. A specific community of users and developers supports this platform, which has the potential to offer customized solutions to users.

The IEEE 5G/6G Innovation Testbed is notable for its ability to evaluate real-world applications designed to comply with standard development processes. It provides users with ease of access thanks to its cloud architecture. It supports various 5G simulations as well as IoT simulations. This platform is particularly suitable for industrial testing and validation processes.

Researchers widely use MATLAB to validate theoretical contributions, models, and designs through simulations [23]. It offers powerful tools for mathematical modeling and algorithm development, enabling testing and analysis in various channels with signal processing and enhancement techniques. It can create custom waveforms and protocols and simulate 5G, LTE, and WLAN standards, among other features. It cannot emulate in real time but has extensive simulation capabilities. This capability makes it a preferred choice for researchers and developers.

Table 2.Activities that platforms can carry out

Free5GC	OpenAirInterface	Open5GS	IEEE 5G/6G Innovation Testbed	MATLAB 5G Toolbox
• Examination of 5G core network architecture and functions • Network slicing and service-oriented architecture applications • Deployment and testing of private 5G networks • Integration with other open-source projects	• Create test cases with multiple UE and PDU sessions. • N2 Analysis of handover and paging mechanisms • Evaluation of partial network slicing applications • Integration with open-source RAN solutions	• Implementing and testing advanced security protocol • Integration and performance analysis of VoLTE and VoNR services • Simulation of 5G roaming scenarios • Development and management of private 5G networks	• Evaluating the performance of products and services on 5G networks • Verification of core network functions and compatibility testing • Analyzing the impact of authentication and encryption on different 5G platforms • Integration and optimization of services into 5G networks	• Simulation and analysis of 5G physical and MAC layers • Creating and testing 5G waveforms • Modeling and performance evaluations of transmission channels • Optimization studies with artificial intelligence and machine learning techniques

Each of these platforms contributes uniquely to 5G simulation studies, and this comparative analysis shows their strengths and weaknesses and guides users in deciding which platform they should use for 5G network research and application development. Table 2 highlights the key work performed by these platforms, which will help researchers and developers to identify the most suitable option for similar work.

Table 3.5G simulation tools: performance and availability analysis

Platform	Installation Difficulty	Processing Load	Truth	Improvability
Free5GC	Medium	Medium	High	Expandable (Open source)
OAI	Medium-High	High	High	Expandable (Open source)
Open5GS	Easy	Medium	High	Expandable (Open source)
IEEE Testbed	Difficult	High	High (Real world data)	Customizable
MATLAB 5G Toolbox	Easy	Medium	Medium	Medium

In Table 3, an analysis is performed in terms of performance and usability. It can be said that OAI and IEEE Testbed provide more accurate results than other platforms, thanks to their real-time emulation capabilities. Despite being open-source platforms, MATLAB's commercial license and IEEE Testbed's subscription requirement set them apart from other platforms in terms of accessibility. While some platforms stand out with their ease of installation and simplicity of architecture, others offer added value to experimental research by providing realistic simulation environments. All these comparisons will guide users in the platform selection process.

As shown in Figure 2, the estimated setup times in the first graph vary significantly between platforms. These durations were calculated during the installation phase of the platforms and may vary depending on the researcher's level of knowledge. The IEEE 5G/6G Innovation Testbed requires subscription setup and coordination, and this requirement causes it to have the longest setup time. OAI comes right after it and has a longer setup time than other platforms due to both the RAN and core network structure. In the second graph, the approximate CPU usage rates of different platforms under typical scenarios are compared. OAI shows the highest CPU usage due to both RAN and core network emulation activities, while MATLAB 5G Toolbox, being entirely simulation-based, exhibits the lowest load.

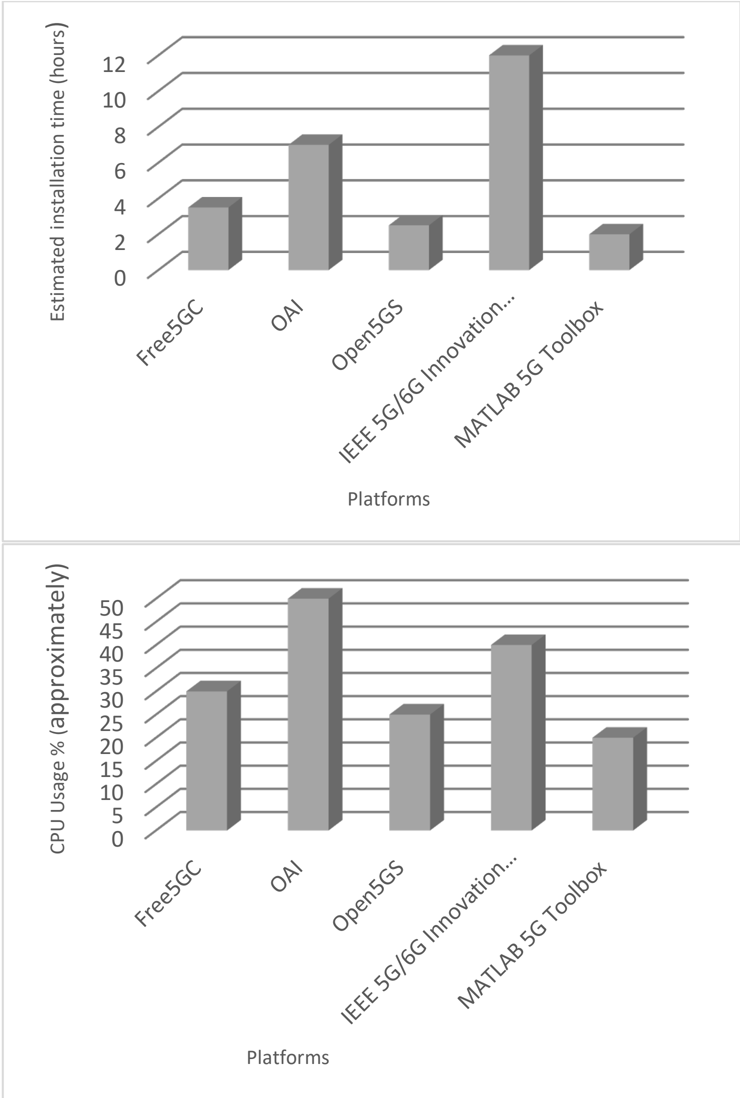

Figure 1.Installation time estimation for 5G platforms and CPU usage

5. Limitations

While the study aims to provide a comprehensive summary, it is important to emphasize that the comparisons are mostly based on documentation. Due to resource constraints and the continued evolution of platforms, full experimental benchmarks on real hardware could not be performed for all platforms. Therefore, performance metrics, CPU utilization, and setup times are based on industry-reported figures, documentation, and simulated conditions. Open-source systems are constantly changing with continued development; therefore, platform specifications may differ depending on the latest changes.

6. Results and Conclusions

Analyzing the foundations of 5G technologies effectively is important not only in academia but also in industrial applications. Open-source platforms are important projects for researchers and developers by offering innovative solutions with high potential in the field of telecommunications. In this study, the features, application areas, advantages, and disadvantages of each open-source platform are examined, their usability for 5G NR simulations is evaluated, and their importance for studies in this field is emphasized.

As a result of the comparisons, Free5GC and Open5GS offer ease of use in core network simulations, but they cannot perform real-time emulation. OpenAirInterface offers simulation at both the core and RAN levels and provides more realistic test environments thanks to its emulation capability. IEEE 5G/6G Innovation Testbed reduces the need for physical testing and accelerates test processes thanks to its cloud-based structure. MATLAB 5G Toolbox stands out in academic research with its powerful simulation tools but is limited for real-time testing.

The flexibility and accessibility of open-source platforms are important factors enabling 5G technologies to spread to a wider audience. This comparative analysis will lead researchers and developers to choose the 5G simulation platform that best fits their project needs. To further develop these open-source platforms in the future, frequent updates to existing documentation and support resources to improve the user experience will have a major impact. Joint projects should encourage knowledge sharing and increase the usability of these platforms. This will make 5G technologies more advanced and widespread. Ultimately, 5G simulations will accelerate the effort to develop innovative solutions in both academic and practical applications by using these platforms more actively.

Nomenclature

3GPP: The 3rd Generation Partnership Project
5G NR: 5th Generation New Radio
5G: 5th Generation Mobile Network
5GC: 5th Generation Core
6G: 6th Generation Mobile Network
AMF: Access and Mobility Function
AR: Augmented Reality
AUSF: Authentication Server Function
BSF: Binding Support Function
CBCF: Cell Broadcast Center Function
CN: Core Network
CP: Control Plane
CU/DU: Central Unit/Distributed Unit
DNN: Data Network Name
eMBB: Enhanced Mobile Broadband
eNB: Evolved Node B
EPC: Evolved Packet Core
E-UTRAN: Evolved Universal Terrestrial Radio Access Network
FPGA: Field Programmable Gate Array
gNB: Next Generation Node B
GNB_CU_CP_FSM: GNB's CU (Central Unit) control plane finite state machine
GNB_CU_UP_FSM: CU user plane FSM of gNB
GNB_DU_FSM: State machine of the DU of the gNB
GUI: Graphical User Interface
HSS: Home Subscriber Server
HSS_UDM: Home Subscriber Server/Unified Data Management
IoT: Internet of Things
LDPC: Low-Density Parity Check
LTE: Long Term Evolution
M2M: machine-to-machine
MAC: Medium Access Control
MEP: Multi-Access Edge Computing
MIMO: Multiple Input Multiple Output
MME: Mobility Management Entity
mMTC: Massive Machine Type Communications
N3IWF: Non-3GPP Interworking Function
NCTU: National Yang Chiao Tung University
NEAR_RT_RIC: Near-Real Time RAN Intelligent Controller
NEF: Network Exposure Function
NR: New Radio
NRF: Network Repository Function
NRF: Network Repository Function
NSA: Non-Standalone Architecture
NSSF: Network Slice Selection Function
OAI: OpenAirInterface
OAM: OAI Operation and Maintenance
OFDM: Orthogonal Frequency Division Multiplexing
O-RAN: Open Radio Accessible Network
PCF: Policy Control Function
PCRF: Policy and Charging Rules Function
PCRF_PCF: Policy Control and Charging Rules Function/Policy Control Function
PDU: Packet Data Unit
PGW: Packet Data Network Gateway
PGWC_SMF: Packet Gateway Control/Session Management Function
PGWU_UPF: Packet Gateway User Plane / User Plane Function
PHY: Physical Layer
QAM: Quadrature Amplitude Modulation
QoS: Quality of Service
R15: Release 15
R16: Release 16
R17: Release 17
R18: Release 18
RAN: Radio Accessible Network
RLC: Radio Link Control
SA: Standalone Architecture
SBI: Service-Based Interface
SCP: Service Communication Proxy
SDR: Software Defined Radio
SGW: Service Gateway

SGWC: Serving Gateway User Plane
SGWU: Serving Gateway User Plane
SMF: Session Management Function
SMSF: Short Message Service Function
UDM: Unified Data Management
UDR: Unified Data Repository
UE: User Equipment
ULCL: Uplink Classifier
UP: User Plane
UPF: User Plane Function
URLLC: Ultra-Reliable Low Latency Communication
VoLTE: Voice over Long-Term Evolution
VoNR: Voice over New Radio
VR: Virtual Reality
WLAN: Wireless Local Area Network

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. 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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