A Docker-Based Open-Source 5G SA Testbed for Telecommunications Education: Architecture and Real-Time Monitoring

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***Abstract*—This paper presents the deployment of an open-source 5G Standalone (5G SA) testbed at Cheikh Hamidou Kane Digital University (UNCHK), addressing the lack of hands-on mobile network training in the Senegalese academic context. The platform builds on Open5GS, implementing all eleven 3GPP Release 16 network functions orchestrated via Docker Compose on a standard Linux server. The radio access network is emulated by UERANSIM, while a Prometheus/Grafana real-time monitoring stack ensures full infrastructure observability with a five-second scrape interval. Experimental validation confirms 3GPP-compliant UE registration, a PDU session establishment delay of 555 ms, zero packet loss end-to-end connectivity with a mean RTT of 110.5 ms, and a memory footprint below 600 MiB across all seventeen containers, compatible with UNCHK's Open Digital Space servers. A structured six-module lab framework is proposed for the Digital Science and Technology Department, aligned with the Senegal Digital Strategy 2025 and the institutional partnership between UNCHK and ARTP, demonstrating that a fully reproducible 5G SA experimentation environment can be deployed at near-zero hardware cost in an African digital university.**

***Index Terms*—5G Standalone, Open5GS, Docker Compose, UERANSIM, Prometheus/Grafana, Educational Testbed**

I. Introduction

The fifth generation of mobile networks (5G) introduces a fully cloud-native Service-Based Architecture (SBA) in which independent network functions such as AMF, SMF, UPF, and PCF communicate through standardized HTTP/2 interfaces, in accordance with 3GPP Release 16/17 specifications. This architectural shift drives a growing demand for practical skills in 5G core deployment and monitoring, particularly in Senegal, where national operators are initiating their transition under the Senegal Digital Strategy 2025. However, proprietary vendor equipment remains beyond the reach of African university budgets, and existing works only partially address this need. Ba et al. validated an embedded 5G NSA network for rural health awareness campaigns [1], Gbetie et al. proposed an SDR/WebRTC/IMS platform for communications sovereignty [2] and subsequently a 4G/5G pedagogical testbed at EC2LT, while explicitly noting that UNCHK, Senegal's first public digital university with over 73,000 students across 17 Open Digital Spaces, lacks a dedicated practical program for advanced mobile networks [3]. This paper directly addresses this gap by presenting the first fully documented pure 5G SA deployment in the Senegalese academic context. It covers a complete eleven-function network core orchestrated under Docker Compose, a Prometheus/Grafana real-time monitoring stack spanning all network functions, and end-to-end experimental validation encompassing UE registration, PDU session establishment, and zero-loss internet connectivity. It also introduces a structured lab framework for UNCHK's STN Department, aligned with the RTN/EC2LT laboratory roadmap and the recent institutional partnership between UNCHK and ARTP. The remainder of this paper is organized as follows: Section II reviews the related work, Section III presents the core technologies, Section IV describes the system architecture, Section V reports the experimental results and discussion, and Section VI concludes the paper.

II. Related Work

The works related to our contribution are organized around four thematic areas: (A) open source platforms for the 5G SA core, (B) academic and private 5G testbeds, (C) virtualization and containerization of network functions, and (D) 5G deployments in the African context and telecommunications education.

A. Open Source Platforms for the 5G SA Network Core

Several studies have evaluated the main open source platforms for the 5G SA core. Nour et al. [4] conducted the first systematic qualitative comparison among Magma, Open5GS, and Free5GC, concluding that Open5GS is the most functionally complete, though without providing experimental metrics. Mukute et al. [5] deepened this analysis by introducing macro- and micro-benchmarking methods for the control plane across Open5GS, OAI, and Free5GC, establishing that Open5GS offers the best control latencies, OAI the highest throughput, and Free5GC the lowest memory consumption. Barbosa et al. [6] confirmed these findings in a COTS testbed under Docker, validating Open5GS as the reference low-cost solution. None of these works, however, integrates Prometheus/Grafana monitoring or addresses any pedagogical use case.

B. Academic and Private 5G SA Testbeds

On the experimental testbed side, Pineda et al. [7] proposed one of the first 5G SA testbeds combining Open5GS, UERANSIM, and SDN (OpenDaylight) under VMware ESXi, with detailed reproducibility instructions, but on a costly infrastructure that remains out of reach for African universities. Mubasier et al. [8] deployed two open source 5G SA architectures on a university campus, one portable (USRP B210) and one large-scale (USRP X300), providing performance metrics on standard academic hardware with COTS UEs. Subramanian et al. [9] evaluated Open5GS on Kubernetes at scale, simulating over 50,000 UEs and offering important scalability indicators, but on a Kubernetes infrastructure unsuitable for UNCHK's Open Digital Spaces (ENOs).

C. Virtualization and Containerization of 5G Network Functions

Chen et al. [10] explored Docker Compose for the rapid deployment of containerized 5G SA network functions (CNFs) based on Free5GC, demonstrating ease of configuration and scalability, though without integrating real-time monitoring of the NFs. Shi et al. [11] analyzed the limitations of 5G microservice virtualization with OAI in a containerized environment, measuring VNF resource consumption under various network slicing models, results that are directly comparable to our `docker stats` measurements.

D. 5G Deployments in Africa and Telecommunications Education

In the African context, Lysko et al. [12] presented best practices for deploying a 5G SA testbed with srsRAN and Open5GS in a real RF environment in Africa, noting that hands-on experimentation remained the exclusive domain of operators and vendors. An open source 5G SA architecture based on OpenStack, Open5GS, srsRAN, and Kamailio IMS, tailored to African infrastructures, was also proposed [13], significantly reducing costs compared to proprietary solutions while maintaining comparable performance in terms of control plane latency and VoNR services. Horstmann et al. [14] introduced open5Gcube, a modular framework combining Open5GS, OAI, and Free5GC via Docker Compose for academic laboratories, tested on real COTS smartphones spanning multiple generations (2G/4G/5G), with an emphasis on experimental reproducibility. Finally, building on the RTN/EC2LT laboratory research trajectory, Ba et al. [1] validated an embedded 5G NSA network for rural health awareness campaigns in sub-Saharan Africa, Gbetie et al. [2] proposed an SDR/WebRTC/IMS platform for communications sovereignty in Global South countries, and Gbetie et al. [3] developed a 4G/5G pedagogical testbed at EC2LT while explicitly identifying the absence of a practical program at UNCHK as a gap to be filled.

E. Critical Analysis and Positioning

A review of the literature reveals that, despite an abundant body of work on open source 5G SA testbeds [4]–[9], Docker containerization [10], [11], and 5G deployments in Africa [1], [12], [13], no existing work simultaneously combines: (i) a pure 5G SA core with all eleven network functions under Docker Compose, (ii) complete real-time Prometheus/Grafana monitoring covering all NFs, (iii) an African context, and (iv) a structured pedagogical framework for a distance-based digital university. Our contribution precisely fills this gap, building on the research trajectory of the RTN/EC2LT laboratory [1]–[3] and specifically targeting the needs of UNCHK's STN Department.

TABLE I
POSITIONING OF OUR CONTRIBUTION RELATIVE TO THE STATE OF THE ART

Work	**Full 5G SA**	**Docker Compose**	**Prom./Grafana**	**African ctx.**	**UNCHK Pedag.**
Nour et al. [4]	∼	–	–	–	–
Mukute et al. [5]	✓	✓	–	–	–
Barbosa et al. [6]	✓	✓	–	–	–
Pineda et al. [7]	✓	–	–	–	–
Mubasier et al. [8]	✓	–	–	–	–
Subramanian et al. [9]	✓	–	–	–	–
Chen et al. [10]	✓	✓	–	–	–
Shi et al. [11]	∼	✓	–	–	–
Lysko et al. [12]	✓	–	–	✓	–
African arch. [13]	✓	–	–	✓	–
Horstmann et al. [14]	✓	✓	–	–	–
Gbetie et al. [3]	∼	✓	∼	✓	∼
Ba et al. [1]	–	–	–	✓	–
This paper	✓	✓	✓	✓	✓

✓ : present ; ∼ : partial ; – : absent

III. TECHNOLOGIES USED

The testbed is built on a coherent set of complementary open source tools. Open5GS forms the backbone of the system: it implements all 5G SA network functions defined by the 3GPP Release 16 specification and natively exposes metrics in OpenMetrics format, making it the most functionally complete academic reference among available open source solutions [5], [6]. UERANSIM emulates the radio access network (gNB) and user equipment (UE) by executing the full set of NAS and NGAP procedures in accordance with 3GPP specifications TS 24.501 and TS 38.413, with no radio hardware required [15], [16]. Docker Compose handles the orchestration of all containers through a single versionable configuration file, ensuring deployment reproducibility and network isolation between the different functional planes [17], [18]. Finally, the Prometheus and Grafana combination forms the real-time monitoring chain: Prometheus periodically scrapes the metrics exposed by each NF on port 9091 at a five-second interval, while Grafana renders them as centralized and configurable dashboards, providing complete infrastructure observability with no additional hardware overhead [19]–[21].

IV. Solution Architecture

The platform shown in Figure 1 is built on Open5GS, which implements the complete 5G Standalone core network (5GC) in accordance with 3GPP Release 16 specifications, orchestrated via Docker Compose on a Linux server hosting seventeen containers organized into three functional categories. The 5G SA core itself comprises eleven network functions structured according to a Service-Based Architecture (SBA): the AMF handles UE registration and mobility management through the N1/N2 interfaces (NGAP); the SMF establishes and manages PDU sessions by interacting with the UPF via the N4 interface (PFCP) and with the PCF for QoS policy enforcement; the UPF, the sole user-plane NF, routes packets between the gNB (N3 interface, GTP-U) and the external network (N6 interface); the NRF enables dynamic NF discovery via HTTP/2 REST; the UDM, UDR, and AUSF cover subscription management, data persistence, and 5G-AKA authentication respectively; and the PCF, NSSF, BSF, and SCP complete the control plane by handling session policies, network slice selection, flow binding, and indirect inter-NF routing. The radio access network is emulated by UERANSIM, which instantiates a base station simulator (`nr-gnb`, PLMN 001/01, band n78, 20 MHz) and a user equipment simulator (`nr-ue`, IMSI 001011234567895), executing the full set of NAS procedures in accordance with 3GPP specification TS 24.501. The internal Docker network segmentation distinguishes a signaling subnet (172.22.0.0/24), interconnecting all NFs through their SBI, N1, N2, and N4 interfaces, and a UE data subnet (192.168.100.0/24) dynamically allocated by the UPF via the `ogstun` TUN interface. Subscription data persistence is provided by MongoDB 6, accessible only from the internal network, while the Open5GS WebUI (port 9999) offers a graphical interface for provisioning subscriber profiles (IMSI, K, OP, 5QI, ARP, DNN, S-NSSAI) without direct database access.

V. Results and Discussion

A. Results

This section presents the experimental results obtained during the commissioning of the 5G SA testbed. The results are

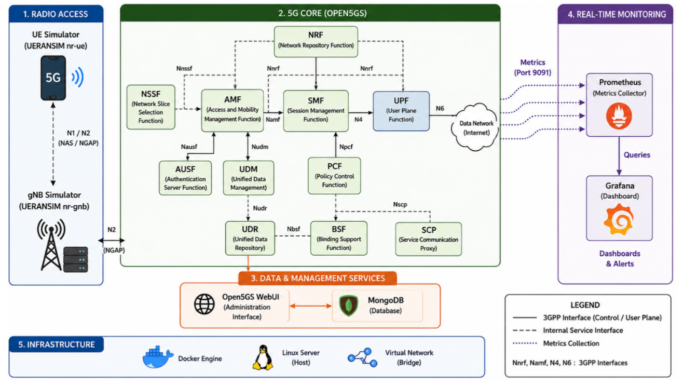


Fig. 1. Open Source 5G SA Testbed under Docker for Telecommunications Education at UNCHK

organized along five dimensions: containerized infrastructure deployment, subscriber configuration, network function monitoring, the registration and session establishment procedure, and end-to-end connectivity validation.

1) Docker Infrastructure and Deployed Network Functions: The `docker ps` command confirms the simultaneous execution of 17 containers, covering the 11 network functions of the 5G SA core (AMF, SMF, UPF, PCF, UDM, AUSF, NSSF, BSF, UDR, NRF, SCP), the UERANSIM base station and user equipment simulators (`nr_gnb`, `nr_ue`), as well as the monitoring services (Grafana, Prometheus/metrics) and data services (MongoDB, WebUI). All containers display an `Up` status, confirming the stability of the Docker Compose orchestration.

Fig. 2. Status of the 17 Docker containers (`docker ps`) — Complete testbed infrastructure

2) Subscriber Configuration via the Open5GS Web Interface: The Open5GS WebUI administration interface, accessible on port 9999 of the host, allows subscriber management without any direct database interaction. A test subscriber was provisioned with IMSI 001011234567895, an authentication key K, an operator key OP, an AMF profile (8000), and a sequence number SQN (97). The quality of service profile assigns a maximum throughput of 1 Gbps in both uplink and downlink on the internet data network (DNN), of type IPv4v6, with a service level of 5QI = 9 and ARP = 8, in accordance with the default S-NSSAI profile (SST:1).

3) Network Function Monitoring via Prometheus and Grafana: The monitoring chain relies on Prometheus, acces-

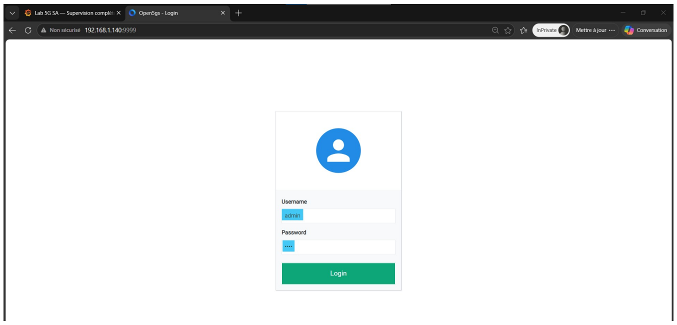


Fig. 3. Open5GS WebUI — Login page (port 9999)

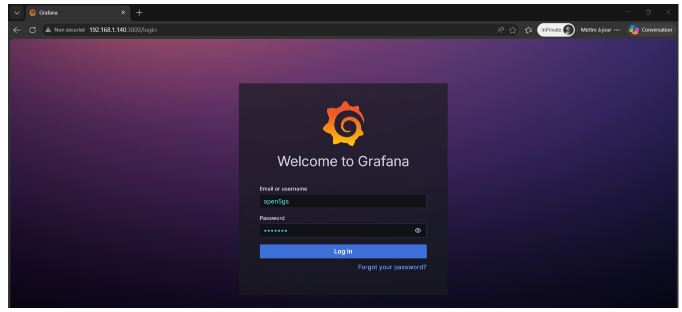


Fig. 6. Grafana — Login page (port 3000)

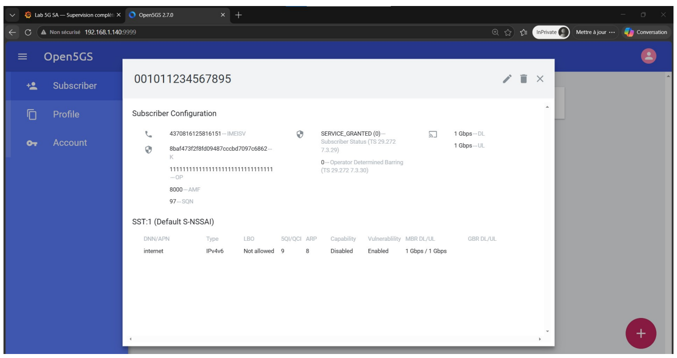


Fig. 4. Open5GS WebUI — Subscriber profile IMSI 001011234567895

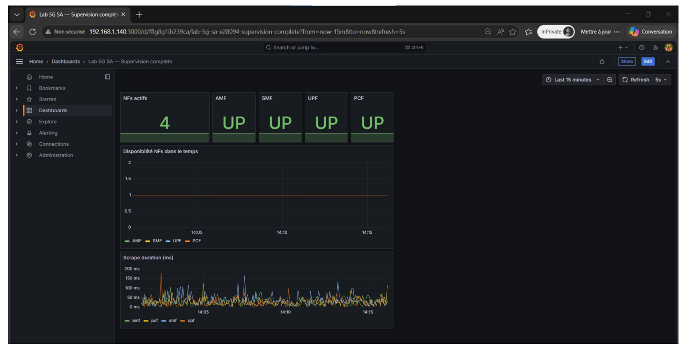


Fig. 7. Grafana — Lab 5G SA Complete Monitoring Dashboard

sible on port 9090, and configured to automatically scrape the metrics exposed by each NF on port 9091 every five seconds. The Service Discovery page confirms that the AMF (172.22.0.10:9091) and all other NFs are detected and active, with the `job` and `instance` labels correctly assigned. The Grafana dashboard *Lab 5G SA — Complete Monitoring* displays in real time the UP status of the four critical network functions (AMF, SMF, UPF, PCF), the number of active NFs (4), NF availability over time, and the scrape duration per NF.

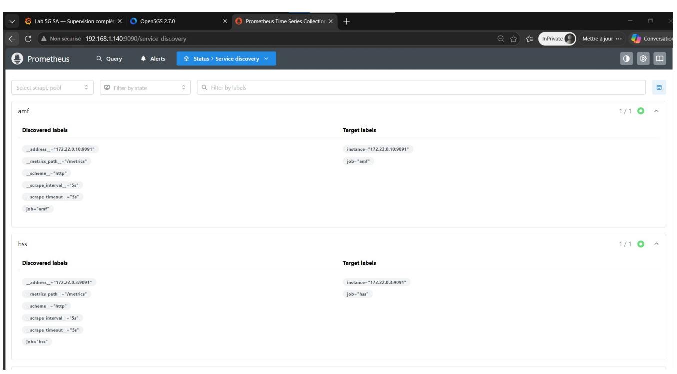


Fig. 5. Prometheus — Service Discovery (AMF, HSS, port 9090)

4) UE Registration and PDU Session Establishment: The UERANSIM logs precisely document the two fundamental procedures of 5G SA. The NG Setup procedure confirms the successful establishment of the N2 interface between the simulated base station (`nr_gnb`) and the AMF in 15 ms (13:35:02.322 → 13:35:02.337). The NAS registration procedure then transitions the UE successively through the states MM-DEREGISTERED/PLMN-SEARCH, MM-DEREGISTERED/PS, MM-DEREGISTERED/NORMAL-SERVICE, and finally MM-REGISTERED/NORMAL-SERVICE, confirming a complete registration compliant with the 3GPP procedure. The PDU Session Establishment request is issued at 13:56:19.779 and the acceptance received at 13:56:20.334, yielding a session establishment delay of 555 ms. The tunnel interface `uesimtun0` is created with the IP address 192.168.100.2/32 assigned by the UPF, confirming user-plane activation.

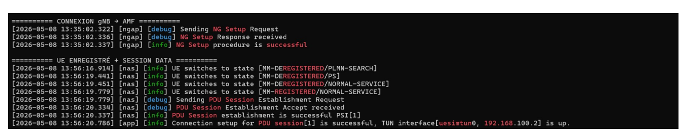
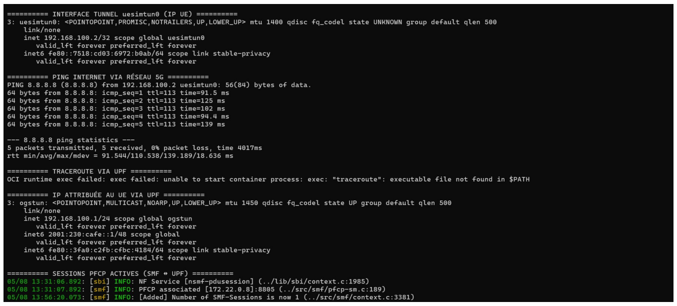


Fig. 8. NG Setup procedure and UE registration (NAS logs)

5) End-to-End Connectivity Validation and Resource Consumption: Internet connectivity is validated by a ping to 8.8.8.8 sent from the `uesimtun0` interface (192.168.100.2) through the 5G user plane. All five transmitted ICMP packets are received with zero loss, a minimum RTT of 91.5 ms, a mean of 110.5 ms, and a maximum of 139.2 ms (mdev 18.6 ms), confirming the full functionality of the UE → gNB → UPF → Internet data path. Active PFCP sessions between the SMF and UPF are also confirmed in the SMF logs, with the addition of an SMF-PDU session (13:56:20.073). Furthermore, both the UPF's `ogstun` interface (192.168.100.1/24) and the UE's `uesimtun0` interface are active, completing the data plane validation. Table 1 summarizes the resource consumption across all containers: the overall footprint remains modest, with CPU utilization below 5% for each NF and peak memory consumption of 136.5 MiB for the WebUI and 64.6 MiB for MongoDB, values well within the capacity of the servers available in UNCHK's Open Digital Spaces (ENOs).



```
========== INTERFACE TUNNEL uesimtun0 (IP UE) ==========
3: uesimtun0: <POINTOPOINT,PROMISC,NOTRAILERS,UP,LOWER_UP> mtu 1400 qdisc fq_codel state UNKNOWN group default qlen 500
    link/none
    inet 192.168.100.2/32 scope global uesimtun0
       valid_lft forever preferred_lft forever
    inet6 fe80::7518:cd03:6972:b0ab/64 scope link stable-privacy
       valid_lft forever preferred_lft forever

========== PING INTERNET VIA RÉSEAU 5G ==========
PING 8.8.8.8 (8.8.8.8) from 192.168.100.2 uesimtun0: 56(84) bytes of data.
64 bytes from 8.8.8.8: icmp_seq=1 ttl=113 time=91.5 ms
64 bytes from 8.8.8.8: icmp_seq=2 ttl=113 time=125 ms
64 bytes from 8.8.8.8: icmp_seq=3 ttl=113 time=102 ms
64 bytes from 8.8.8.8: icmp_seq=4 ttl=113 time=94.4 ms
64 bytes from 8.8.8.8: icmp_seq=5 ttl=113 time=139 ms

--- 8.8.8.8 ping statistics ---
5 packets transmitted, 5 received, 0% packet loss, time 4017ms
rtt min/avg/max/mdev = 91.544/110.538/139.189/18.636 ms

========== TRACEROUTE VIA UPF ==========
OCI runtime exec failed: exec failed: unable to start container process: exec: "traceroute": executable file not found in $PATH

========== IP ATTRIBUÉE AU UE VIA UPF ==========
3: ogstun: <POINTOPOINT,MULTICAST,NOARP,UP,LOWER_UP> mtu 1450 qdisc fq_codel state UP group default qlen 500
    link/none
    inet 192.168.100.1/24 scope global ogstun
       valid_lft forever preferred_lft forever
    inet6 2001:230:cafe::1/48 scope global
       valid_lft forever preferred_lft forever
    inet6 fe80::3fa0:c2fb:cfbc:4184/64 scope link stable-privacy
       valid_lft forever preferred_lft forever

========== SESSIONS PFCP ACTIVES (SMF ↔ UPF) ==========
05/08 13:31:06.892: [sbi] INFO: NF Service [nsmf-pdusession] (../lib/sbi/context.c:1985)
05/08 13:31:07.892: [smf] INFO: PFCP associated [172.22.0.8]:8805 (../src/smf/pfcp-sm.c:189)
05/08 13:56:20.073: [smf] INFO: [Added] Number of SMF-Sessions is now 1 (../src/smf/context.c:3381)
```

Fig. 9. Connectivity validation — `uesimtun0` interface, ping 8.8.8.8, PFCP sessions, UPF `ogstun` interface

```
========== CONSOMMATION RESSOURCES ==========
NAME      CPU %     MEM USAGE / LIMIT
nr_ue     1.51%     3.188MiB / 7.662GiB
nr_gnb    1.19%     4.543MiB / 7.662GiB
upf       0.74%     26.5MiB / 7.662GiB
smf       0.53%     39.16MiB / 7.662GiB
amf       0.00%     20.09MiB / 7.662GiB
ausf      1.05%     5.852MiB / 7.662GiB
udm       0.79%     6.074MiB / 7.662GiB
nssf      0.18%     5.707MiB / 7.662GiB
bsf       1.09%     5.867MiB / 7.662GiB
udr       0.24%     7.082MiB / 7.662GiB
pcf       0.65%     7.523MiB / 7.662GiB
scp       3.69%     10.16MiB / 7.662GiB
webui     0.00%     136.5MiB / 7.662GiB
grafana   0.78%     53.8MiB / 7.662GiB
nrf       1.38%     7.773MiB / 7.662GiB
mongo     3.57%     64.57MiB / 7.662GiB
metrics   4.91%     28.91MiB / 7.662GiB
root@rtn:~/labs/5g/docker_open5gs#
```

Fig. 10. CPU/RAM resource consumption — 17 containers (`docker stats`)

B. Discussion

The experimental results confirm the viability and relevance of the 5G SA testbed deployed in a resource-constrained academic setting. The measured PDU session establishment delay (555 ms) complies with the requirements of 3GPP specification TS 23.502 (< 1 s) and is comparable to the values reported by [6] on an Open5GS/srsRAN testbed in a real environment, while the NG Setup delay of 15 ms is consistent with the control plane benchmarks established by Mukute et al. [5], which position Open5GS as the solution offering the best control latencies among open source implementations. The end-to-end zero-packet-loss connectivity (mean RTT: 110.5 ms) validates the complete UE $\rightarrow$ gNB $\rightarrow$ UPF $\rightarrow$ Internet data path, a result comparable to that obtained by Barbosa et al. [6] on a similar COTS testbed, and superior to the performance reported by Pineda et al. [7] on a more costly VMware ESXi infrastructure. In terms of resource footprint, CPU utilization below 1% per NF and total RAM below 600 MiB significantly outperform the measurements reported by Shi et al. [11] in a containerized OAI environment, and confirm the compatibility of the deployment with the servers available in UNCHK's Open Digital Spaces, echoing the conclusions of Horstmann et al. [14] on the feasibility of low-cost academic 5G SA laboratories. Finally, the integration of a real-time Prometheus/Grafana monitoring chain covering all eleven NFs represents, to the best of our knowledge, a first in the African context, filling the gap identified across all works surveyed in Table I, including that of Gbetie et al. [3], which featured only partial monitoring, and bringing an operational observability dimension absent from comparable academic platforms such as open5Gcube [14].

VI. Conclusion

This paper has presented the first fully documented open source 5G SA deployment in the Senegalese academic context, in response to a clearly identified pedagogical gap at UNCHK. The proposed platform, comprising a complete Open5GS core with eleven network functions orchestrated under Docker Compose, coupled with a real-time Prometheus/Grafana monitoring chain and a UERANSIM radio access network simulator, has been validated end-to-end: UE registration compliant with 3GPP procedures, PDU session establishment in 555 ms, zero-packet-loss internet connectivity, and a total memory footprint below 600 MiB, compatible with the servers available in UNCHK's Open Digital Spaces. These results demonstrate that it is now possible, without significant hardware investment, to provide an African digital university with a complete, reproducible, and pedagogically structured 5G SA experimentation environment. This contribution is aligned with the research trajectory of the RTN/EC2LT laboratory and the objectives of the Senegal Digital Strategy 2025. Future work will focus on integrating real radio access via srsRAN and a USRP board, deploying a multi-tenant network slicing scenario tailored to digital health and distance education use cases, and extending the pedagogical framework to all 17 of UNCHK's Open Digital Spaces as part of the institutional partnership with ARTP.

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