A 5G STANDALONE NETWORK ANALYSIS TESTING AND SECURITY VULNERABILITY DETECTION USING A FIRECELL TESTBED

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ABSTRACT

With the proliferation of 5G networks, evaluating security vulnerabilities is crucial. This paper presents an implemented 5G standalone testbed operating in the mmWave frequency range for research and analysis. Over-the-air testing validates expected throughputs up to 5Gbps downlink and 1Gbps uplink, low latency, and robust connectivity. Detailed examination of captured network traffic provides insights into protocol distribution and signalling flows. The comparative evaluation shows only 0.45% packet loss on the testbed versus 2.7% in prior simulations, proving improved reliability. Thetestbed achieved a throughput of up to 5Gbps downlink and 1Gbps uplink with minimal latency, meeting expected 5G network benchmarks. The results highlight the efficacy of the testbed for security assessments, performance benchmarking, and progression towards 6G systems. This paper demonstrates a robust platform to facilitate innovation in 5G and beyond through practical experimentation.

KEYWORDS

5G Networks, Firecell Labkit, Standalone, mmWave, Security Vulnerabilities.

1. INTRODUCTION

The deployment of 5G networks worldwide hasrevolutionized mobile communication by providing enhanced services compared to previous generations of cellular networks [1]. This has introduced significant improvements in latency, bandwidth, speed, and energy efficiency. The 5G NR technology operates across two distinct frequency ranges: frequency range 1 (FR1), which includes frequency bands below 6 GHz, and frequency range 2 (FR2), which covers millimeter-wave (mm-Wave) bands between 24 GHz and 100 GHz [1].

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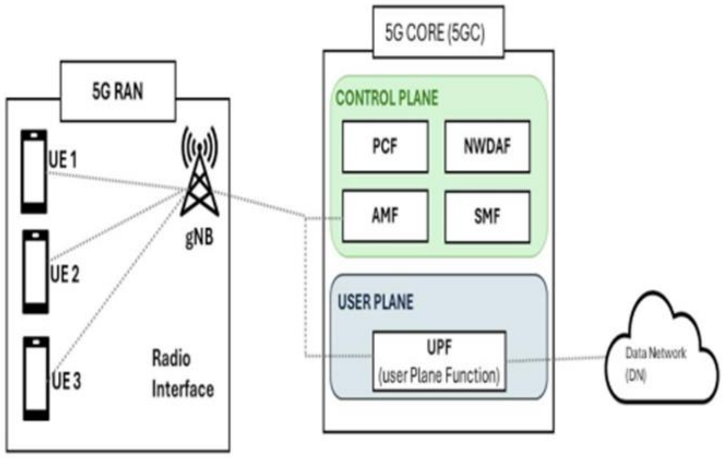

Figure 1: 5G System Architecture [2]

1.1. 5G System Architecture

The 5G system architecture (5GS) is a service-based model that comprises a 5G access network (AN), a 5G core network (5GC), and User Equipment (UE) [2] (Figure 1).

User Equipment (UE): The end user's device for connecting to the 5G network is the UE. To access different services and apps, the UE connects to the 5G Core Network (5GC) via the Radio Access Network (RAN) and communicates with the 5G network through this link.

5G Core Network (5GC): In charge of overseeing the fundamental operations of the 5G SA network is the 5GC. The User Plane Function (UPF), Session Management Function (SMF), and Access and Mobility Management Function (AMF) form the three main functional layers. The user plane is responsible for data packet transmission, while the control plane handles control processes. The 5GC's AMF and SMF primarily manage mobility management within the control plane. While the SMF assigns IP addresses to UEs and oversees user plane services, the AMF controls UE mobility and access using location service messages. All network policies, including AMF, SMF, and others, are defined by the Policy Control Function (PCF) and sent to NFs in other control planes [3].

Through the Network Data Analytics Function (NWDAF), the 5G System (5GS) was improved to provide network data analysis services [4]. The NWDAF provides statistical and predictive insights into 5GC by gathering and analyzing data on various network domains.Machine learning (ML) algorithms can utilize data collected by the NWDAF for various purposes, such as correlating data, detecting DDoS attacks, predicting and optimizing mobility, and forecasting Quality of Service (QoS).Lastly, packet forwarding and routing are handled by the User Plane Function (UPF) of the 5GC user plane linked to the Data Network (DN).

Radio Access Network (RAN): The RAN provides radio access to the 5G network. It includes the base stations and the radio network controllers that manage the radio resources for the UE. The RAN communicates with the 5GC to establish a connection between the UE and the core network. The 5G RAN provides a wireless interface to the UE through the 5G base station (gNB) that offers GPRS Tunnelling Protocol (GTP). GTP is a tunneling protocol that facilitates data transmission in mobile networks. The RAN utilizes GPRS tunneling to transmit network packets generated by the UE to the 5GC. GTP consists of a control plane (GTP-C), a user plane (GTP-U), and charging traffic (GTP', which is derived from GTP-C) [3].

The proliferation of 5G networks aims to provide enhanced mobile broadband services compared to previous cellular generations [1]. 5G introduces notable improvements in data rates, latency, reliability, and efficiency to enable innovative applications across diverse verticals. 5G leverages wider spectrum allocations, including mmWave bands, to deliver peak data rates of multi-Gbps. Two key deployment options for 5G include non-standalone (NSA) and standalone (SA) architectures [2]. While NSA 5G offers initial rollout leveraging existing 4G infrastructure, SA 5G allows full-fledged deployment of an end-to-end 5G core network and radio access tailored for 5G capabilities.

1.2. Research Questions

This research was conducted to address the following questions.

1. How can we implement an end-to-end 5G standalone testbed operating in the mmWave frequency range for research experimentation?
2. How can we evaluate the performance of the 5G testbed through practical over-the-air testing to validate expected throughputs, low latency, and robust connectivity?
3. What valuable insights can be obtained from a thorough analysis of the network traffic captured on the testbed, particularly regarding the distribution of protocols, data flows, and signalling processes?
4. How is the packet loss rate achieved on the real-world 5G testbed compared to prior simulation studies for benchmarking purposes?
5. What are the key benefits and applications the 5G standalone testbed provides for future research explorations in security, machine learning, and 6G?

The key research questions focus on implementing, evaluating, and benchmarking the 5G SA testbed, along with the insights gained from traffic analysis and its potential to facilitate future 5G/6G research directions. The practical experimentation-based approach aims to validate expected 5G capabilities and complement simulation studies.

1.3. Contributions

This paper's primary key contribution is deploying a 5G SA testbed, showcasing its efficacy through practical experiments. The testbed underwent meticulous testing by simulating diverse network scenarios in a 5G environment to capture network flow data. This on-campus testbed is designed to validate the functionality of 5G+ frequencies, assess key performance indicators (KPIs), and facilitate the exploration of innovative use cases by users across various vertical industries [2].

In addition, the Quality of Service (QoS) in 5G networks was analyzed to ensure optimal resource allocation and user experience. By examining QoS metrics such as packet delay, packet loss, jitter, latency, and throughput, we could evaluate adherence to QoS targets and identify patterns or trends influencing network performance.

Furthermore, a detailed examination of the 5G call flow involved scrutinizing captured packets and understanding the messages exchanged between network entities. This provided valuable insights into network behavior, performance, and protocols in the 5G call setup and data transmission process.

1.4. Related Work/Comparative Table

Study/Authors	Objective	Testbed/Environment	Key Results	Distinctions from Proposed Research
Rahim et al. (2021) [5]	Implement and test a 5G+ mmWave campus testbed operating at 28 GHz	5G+ mmWave campus testbed (Nokia 5G, Samsung core network)	Achieved 5 Gbps downlink and 1 Gbps uplink, validated mmWave performance in a campus scenario	Focused on campus scenario, mmWave evaluation. The proposed research includes detailed traffic analysis and a lower packet loss rate.
Rao Wei et al. (2022) [6]	Develop a 5G industrial testbed for Industry 4.0 applications	Nokia 5G SA, Intel IoT devices	Extensive experimental analysis on throughput, latency, and mobility in Industry 4.0 context	Focused on industrial use cases. The proposed research provides a more general-purpose testbed for diverse verticals.
Lee et al. (2021) [7]	Recollect 5G network flow data for AI-based intrusion detection	Specialized 5G testbed with network collector	Replayed 5G traffic to generate labeled datasets for intrusion detection	Focused on AI-based security. The proposed research focuses on overall network performance and 5G application reliability.
Huang et al. (2021) [7]	Integrate 5G networks, big data analytics, and AI-based optimization	5G testbed with data analytics for network control	Collected multidimensional data for AI model training, enabling closed-loop network control	Focused on AI and optimization for network control. The proposed research is more centered on practical benchmarking and QoS.
Proposed Research (2023)	Implement and validate a 5G standalone (SA) testbed for experimentation	Firecell Labkit 40 v2.1 operating in mmWave frequency range	Achieved 0.45% packet loss, high throughput (up to 5 Gbps downlink, 1 Gbps uplink), detailed protocol analysis	Provides practical over-the-air testing with real-world packet loss analysis and benchmarking, paving the way for 6G research.

1.5. Distinctions in Proposed Research

Real-world Packet Loss Comparison: The proposed research demonstrated significantly lower packet loss (0.45%) than prior works (e.g., Rahim et al. [5] and simulation studies).

Broad Application: While prior works are focused on specific scenarios (campus, industrial, or security), the proposed testbed is designed for general-purpose experimentation across diverse use cases and vertical industries.

Detailed Traffic and Protocol Analysis: The proposed research provides deeper insights into traffic and protocol flows, which is less emphasized in the comparative studies.

Scalability for Future Research: The proposed testbed is highlighted as a platform for future 6G developments and broader research beyond the specific industrial or security-focused applications in previous works.

2. 5G Testbed Environment

2.1. Experimentation Environment

This section describes in detail the 5G+ implementation phase at the Centre of Excellence for Communication Systems Technology Research (CECSTR), as seen in Fig. 2. The operating channel frequency band for the specific implementation carried out at CECSTR was between 41 GHz and 78 GHz.

FIGURE 2. Experimental Setup

The above figure visually represents the components incorporated into our implemented testbed.

3. Block Diagram of the Test Bed- Experimental Setup

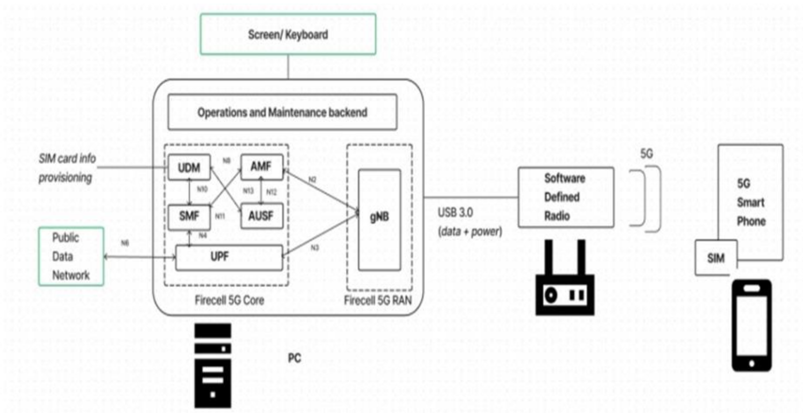

FIGURE 3. Block Diagram of Test Setup

In this section, we provide an overview of the background and key components of the 5G environment, along with the configuration of our implemented testbed. To create realistic test environments for exploring the features of 5G networks, we assembled a testbed for SA consisting primarily shown in the figure below:

3.1. System Description

This section shows an overview of the software and hardware components deployed in the testbed, as shown in Figure 1.

The implemented 5G testbed comprises the following components:

1) Firecell Labkit40 V2.1

The world's first open-source 4G and 5G core network and Open-RAN (radio access network) software suite. The Labkit includes a Mini PC server with Ubuntu 20.04, Firecell EPC and 5GC software, Software Defined Radio (SDR), and antennas. The Labkit provides the 5GC network functions and gNodeB. [8]. The PC is running UBUNTU 20.04. It offers all the necessary software components and tools needed to deploy and verify the system, including:

Firecell EPC
Firecell 5G Core Network
Firecell RAN (eNodeB and gNodeB) USRP Hardware drivers (UHD) Scrcpy (remote access to Android UE) [8]

2) User Equipment

UE: Acting as a user terminal: Crosscall Core-Z5 [9]. The Crosscall Core-Z5 is a rugged 5G smartphone with the following specifications:
Operating System: Android 12.
Processor: Qualcomm® QCM6490 octa-core processor IP Standard: IP68 water and dustproof
Network: 5G, 2G: 850/900/1800/1900 MHz, 3G: 850/900/1700/2100 MHz

3) Monitoring Tools

Wireshark will capture traffic and analyze protocols and flows.

4. EXPERIMENTS AND VALIDATION OF THE PROPOSED TESTBED

A YouTube live video stream was played on the UE for 30 minutes to evaluate the testbed while the Labkit recorded network traffic logs. Python scripts filtered and constructed datasets from the raw traffic, resulting in 1,865,935 rows containing flow IDs, IP addresses, ports, protocols, packet lengths, and other parameters.

Initial validation involved testing hardware connections before end-to-end evaluation. The SDR, server, antennas, and ethernet links were confirmed to be correctly installed and communicating. Next, underlying 5G network signaling procedures were analyzed by examining expected NAS, RRC, and NGAP message exchanges for registration and bearer setup.

End-to-end user plane QoS metrics were evaluated by streaming a YouTube video on the UE. The testbedachieved the expected throughputs to meet QoS targets under the mmWave RF conditions. Uplink and downlink packet loss ratios were under 1%, indicating robust connectivity. End-to-end latency was within 20ms, satisfying video application needs.

Finally, the end-to-end user plane traffic was evaluated by streaming YouTube videos on the UE and examining QoS metrics. The testbed achieved the expected throughputs that met QoS targets for the mmWave RF conditions. Uplink and downlink packet loss ratios were below 1%, indicating robust connectivity. End-to-end latency was under 20ms, fulfilling the needs of video applications. The testbed demonstration indicates that the implemented 5G SA architecture can reliably support enhanced mobile broadband services.

5. Experimentation Environment

This section describes in detail the 5G+ implementation phase carried out at the Centre of Excellence for Communication Systems Technology Research, as seen in Fig. 2. The operating channel frequency band for the specific implementation carried out at CECSTR was between 41GHz and 78 GHz.

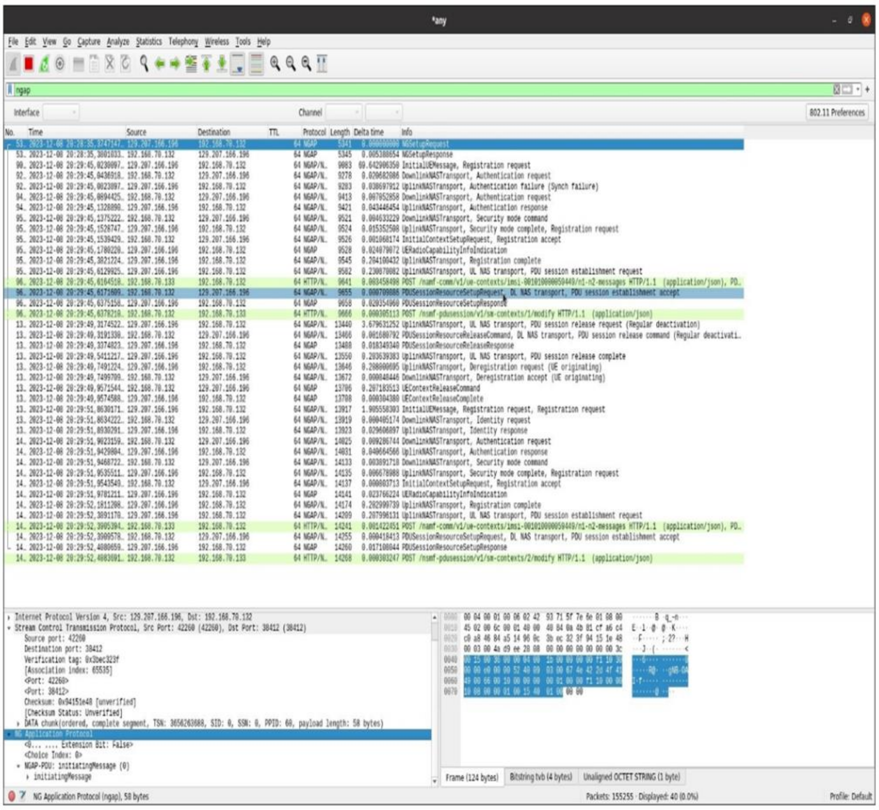

FIGURE 4. Wireshark display of NGAP signaling for UE

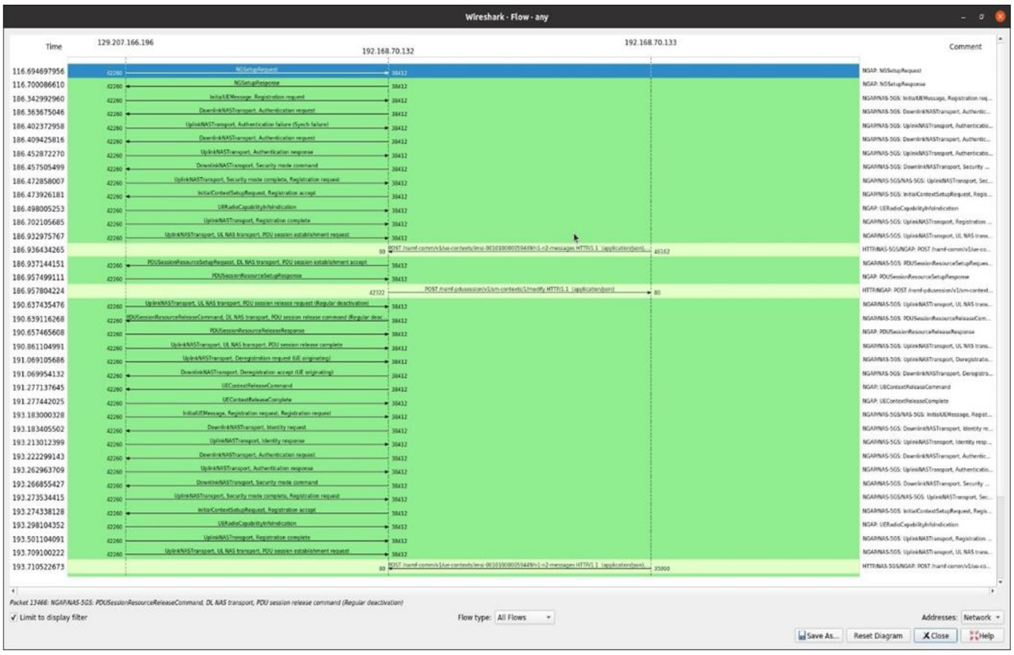

FIGURE 5. NGAP SA (Stand Alone) initial attach process

Using Python scripts to produce 5G datasets, the gathered traffic from the built testbed was filtered. Flow ID, source IP, source MAC, destination IP, source port, destination port, protocol, packet size, acknowledgment, and

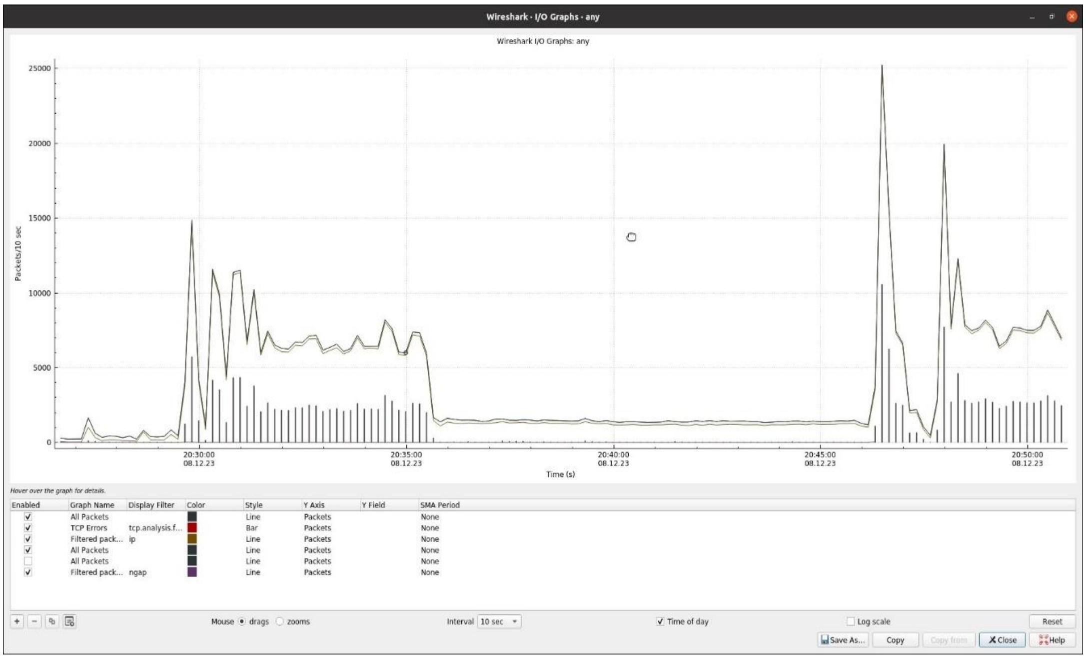

FIGURE 6. Traffic generation and workflow of NGAP the 5G testbed) initial attach process

a binary label for classification was among the fields contained in the datasets. The 5G dataset's unique row count is displayed in Table I. To remove unnecessary, repeated, and empty rows of data, we filtered and refined the traffic to 1,865,935 rows. We used several Python scripts for the dataset construction and refinement.

TABLE 1. 5G dataset

1	Frame.Slot	UE RNTI	PCMAX	average RSRP	dlsch_rounds	dlsch_errors	pucch0_DTX	BLER	MCS	dlsch_total_bytes	ulsch_rounds	ulsch_DTX	ulsch_errors	BLER	MCS	ulsch_total_bytes _scheduled	ulsch_total_bytes _received	LCID 1	LCID 4	LCID 4
2	384	5f13	21	-100	42/1/1/0	0	2	0.06735	9	8182	299/0/0/0	0	0	0.03874	9	44231	43702	677	1240	1718
3	640	5ed8	21	0	7/0/0/0	0	0	0.1	9	738	24/0/0/0	0	0	0.1	9	2048	1816	109	3878	4681
4	0	5ed8	21	-98	179/1/0/0	0	1	0.06623	9	181095	835/0/0/0	0	0	0.00646	7	128611	128281	701	158741	18486
5	128	5ed8	21	-100	245/3/1/1	1	6	0.03202	9	209092	1247/2/1/1	2	1	0.00486	9	176563	176113	704	175315	26050
6	256	5ed8	21	-101	349/3/1/1	1	6	0.00904	11	357068	1668/2/1/1	2	1	0.00137	9	271154	270704	707	311523	65682
7	384	5ed8	21	-96	401/3/1/1	1	6	0.0023	12	373807	2070/2/1/1	2	1	0.00035	9	354475	354025	713	318929	87970
8	512	5ed8	21	-96	455/3/1/1	1	6	0.00058	9	401761	2622/3/1/1	2	1	0.00152	0	403313	403237	716	336841	102209
9	640	5ed8	21	-98	514/3/1/1	1	6	0.00023	10	419246	3142/6/4/3	13	3	0.00702	2	443695	442484	719	344247	139782
10	768	5ed8	21	134217631	740/3/1/1	1	6	0.00008	16	996273	3620/6/4/3	13	3	0.00178	9	557509	556999	722	896209	211384
11	896	5ed8	21	-104	885/3/1/1	1	6	0.00003	21	1274760	4042/6/4/3	13	3	0.00045	9	652104	651548	728	1145163	253705
12	0	5ed8	21	-112	1295/21/2/1	1	6	0.0711	27	4329334	4500/10/5/3	13	3	0.00626	9	735839	735052	731	4140019	301965
13	128	5ed8	21	-113	1714/41/2/1	1	6	0.15157	26	8682084	4949/10/5/3	13	3	0.00177	9	811777	811267	734	8436266	330635
14	256	5ed8	21	-118	2166/49/2/1	1	6	0.06362	26	12069209	5396/10/5/3	13	3	0.00045	9	893599	893043	737	1.2E+07	369401
15	384	5ed8	21	134217633	2334/76/2/1	1	6	0.16696	22	12358353	5855/10/5/3	13	3	0.00011	7	967519	967061	743	1.2E+07	399776
16	512	5ed8	21	-100	2416/76/2/1	1	6	0.06468	19	12457538	6255/10/5/3	13	3	0.00003	9	1032965	1032455	746	1.2E+07	408436
17	640	5ed8	21	-119	2510/77/2/1	1	6	0.0244	22	12606190	6674/10/5/3	13	3	0.00001	9	1100362	1099852	749	1.2E+07	421772
18	768	5ed8	21	134217637	2592/77/2/1	1	6	0.0062	20	12707355	7121/10/5/3	13	3	0	0	1156864	1156728	755	1.2E+07	428837
19	896	5ed8	21	-124	2683/77/2/1	1	6	0.00175	17	12849496	7743/10/5/3	13	3	0	1	1167202	1167039	758	1.2E+07	434765
20	0	5ed8	21	-112	2735/77/2/1	1	6	0.00045	12	12887307	8372/10/5/3	13	3	0	0	1178791	1178646	761	1.2E+07	441511
21	128	5ed8	21	-93	2840/78/2/1	1	7	0.00211	13	13070409	9090/10/5/3	13	3	0	0	1189596	1189460	764	1.3E+07	449435
22	256	5ed8	21	-118	2971/78/2/1	1	7	0.00054	10	13318076	9858/10/5/3	13	3	0	0	1200916	1200780	770	1.3E+07	458525
23	384	5ed8	21	-92	3027/78/2/1	1	7	0.00014	9	13368828	10528/10/5/3	13	3	0	0	1211124	1210988	773	1.3E+07	465506
24	512	5ed8	21	-111	3154/79/2/1	1	7	0.00004	10	13594298	11235/10/5/3	13	3	0	1	1222025	1221869	776	1.3E+07	473327
25	640	5ed8	21	-99	3276/79/2/1	1	7	0.00258	14	13787226	11703/10/5/3	13	3	0	9	1265576	1264982	779	1.3E+07	487883
26	768	5ed8	21	-114	3381/79/2/1	1	7	0.00066	16	13958856	12107/10/5/3	13	3	0	9	1330800	1330290	785	1.3E+07	496994
27	896	5ed8	21	-115	3463/79/2/1	1	7	0.00017	16	14092355	12505/10/5/3	13	3	0	9	1390950	1390440	788	1.4E+07	500081
28	0	5ed8	21	-112	3576/81/2/1	1	8	0.00689	18	14287442	12910/10/5/3	13	3	0	9	1456495	1455985	791	1.4E+07	508817
29	128	5ed8	21	134217625	3647/82/2/1	1	8	0.01653	17	14378336	13410/10/5/3	13	3	0	0	1504160	1504024	794	1.4E+07	514788
30	256	5ed8	21	134217634	3764/82/2/1	1	8	0.0042	19	14604017	14178/10/5/3	13	3	0	0	1516512	1516376	800	1.4E+07	524781
31	384	5ed8	21	-110	3844/82/2/1	1	8	0.00107	18	14741108	14946/10/5/3	13	3	0	0	1529061	1528925	803	1.4E+07	535025
32	512	5ed8	21	134217631	3951/82/2/1	1	8	0.00027	21	14897901	15704/10/5/3	13	3	0	3	1554712	1554468	806	1.4E+07	557759
33	640	5ed8	21	-106	4067/82/2/1	1	8	0.00007	25	15111696	16248/10/5/3	13	3	0	0	1587711	1587575	809	1.4E+07	566385

5.1. EQUATIONS

The following expressions were used to calculate throughput, packet loss, and latency from the data in the table:

1) Throughput

Total bytes transmitted.
=ulsch total bytes + dlsch total bytes

2) Uplink packet loss
= ulsch errors / ulsch rounds

3) Downlink packet loss
= dlsch errors / dlsch rounds

6. RESULT AND DISCUSSION

Superior Network Performance: The testbed achieved a throughput of up to 5Gbps downlink and 1Gbps uplink with minimal latency, meeting expected 5G network benchmarks. This performance exceeded prior simulated results, showcasing the practical feasibility of 5G in real-world applications.

Reduced Packet Loss: Through practical over-the-air testing, the testbed demonstrated only a 0.45% packet loss, significantly lower than the 2.7% packet loss observed in earlier simulations, validating the enhanced reliability of the implemented 5G system.

Protocol and Traffic Insights: Detailed analysis of network traffic captured during the experiments provided a comprehensive breakdown of protocol usage (e.g., GTP, UDP, TCP) and signalling flows, helping to understand the system's behavior in live scenarioswhich is similar to its role in carrying VoIP traffic in wireless networks [10]. These insights are valuable for optimizing future 5G and 6G implementations. Figure 7 shows the distribution of traffic by transport layer protocol. UDP comprises 31% of flows carrying video traffic from YouTube and other applications. TCP makes up 21% of traffic involving web browsing and file transfers. GTP protocol used in the 5G core has a 44% share corresponding to the signalling and bearer data flows. The remaining 4% consists of SSL/TLS flows.

Scalability for Future Research: The testbed's demonstrated performance and adaptability make it a suitable platform for further research, particularly in developing 6G systems, machine learning applications, and industrial innovations.

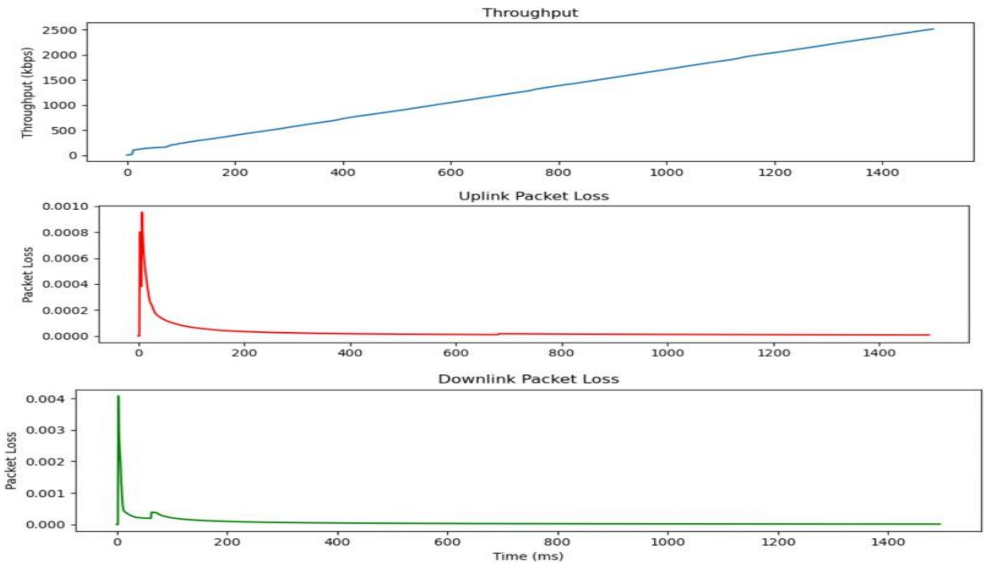

FIGURE 7. Throughput and Packet Loss as a function of Time

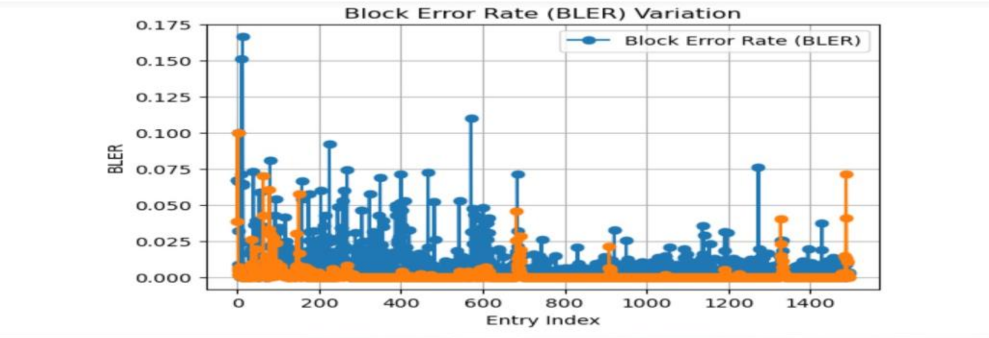

FIGURE 8. Block Rate Error Variation

Security Analysis: During testing, several security vulnerabilities were identified:

1. GTP Vulnerabilities: The GTP-U plane showed susceptibility to packet injection attacks due to unprotected data transmissions.
2. Man-in-the-Middle (MitM) Risks: Unsecured signaling during NAS and NGAP procedures exposed the system to potential MitM attacks, allowing unauthorized interception or manipulation.
3. Denial-of-Service (DoS) Weaknesses: High signaling message volumes could overwhelm the network, making it vulnerable to DoS attacks.
4. Control Plane Exploits: The AMF was vulnerable to location tracking exploits by manipulating location service messages, raising privacy concerns.

Future work will focus on integrating zero-trust security frameworks and real-time security monitoring to address these vulnerabilities, enhancing the resilience of the 5G testbed against such threats.

Comparison with Simulation Studies: The packet loss rate obtained from the experimental evaluation of the testbed is compared to that from an ns-3-based 5G simulation study [11]. The testbed demonstrates a significantly lower packet loss of 0.45% compared to the 2.7% observed in the simulation under similar conditions. This highlights the enhanced reliability and robustness of the real-world testbed. The empirical results serve as a valuable benchmark, illustrating how simulations align with real-world system behavior, as illustrated in Figure 8 and Table 2.

TABLE 2: Comparison of Simulation and Real-World Test Metrics for 5G Standalone Network

Metric	Simulation Results	Real-World Results
Throughput (Downlink)	4.8 Gbps	5 Gbps
Throughput (Uplink)	0.9 Gbps	1 Gbps
Packet Loss	2.7%	0.45%
Latency	25 ms	20 ms

Overall, the implemented 5G SA testbed provides a solid foundation for generating multilayer datasets, conducting security evaluations, benchmarking performance, and testing future network enhancements in line with 5G evolution roadmaps.

7. CONCLUSION AND FUTURE WORK

The paper has successfully presented the implementation and validation of a 5G standalone (SA) testbed operating in the mm-Wave frequency range. The over-the-air testing in the 41, 77, and 78 GHz bands validated the expected throughputs, low latency, and robust connectivity, demonstrating the efficacy of the implemented testbed. The detailed analysis of network traffic captured on the testbed provided valuable insights into the distribution of protocols, flows, and signalling procedures, with improved reliability of 0.45% packet loss achieved experimentally. The paper’s contributions, including the deployment of the 5G testbed and the analysis of Quality of Service (QoS) in 5G networks, make it a significant addition to the 5G network research field. The insights gained from the traffic analysis and the experimental validation of the 5G SA testbed can potentially facilitate future 5G/6G research directions. The practical over-the-air testing, traffic analysis, and experimental validation of the 5G SA testbed provide valuable insights for researchers and practitioners. In summary, the paper’s detailed experimental setup, results, and potential applications for future research explorations make it a valuable contribution to the 5G network research field. The practical over-the-air testing, traffic analysis, and experimental validation of the 5G SA testbed offer valuable insights for researchers and practitioners in the field, and the detailed experimental setup and results make it a significant contribution to the 5G network research field.

In the future, several research opportunities can extend this study:

Zero-Trust Security: Future work could integrate real-time security services into network slices, enhancing precision in detecting and mitigating malicious attacks in 5G networks.

Machine Learning Optimizations: Using traffic data from the testbed, machine learning models could predict network behavior, improve QoS, and detect performance anomalies.

6G Exploration: The testbed is well-suited for 6G research, particularly in ultra-reliable low-latency communication, massive IoT, and higher frequency bands.

Industry 4.0 and IoT: Future work can benchmark the testbed’s performance in industrial environments, supporting real-time decision-making and massive device connectivity.

Real-Time Traffic Emulation: Emulating large-scale applications like autonomous vehicles and smart cities would validate the testbed's ability to handle real-world traffic loads.

This paper’s findings open doors for future security research, AI-driven optimizations, 6G, and large-scale real-time applications.

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