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Comparative Analysis of Network Measurement Tools for QoS Evaluation in 5G Communication Environments

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Abstract

The Quality of Service (QoS) testing in 5G networks necessitates the use of very sophisticated measurement instruments that are able to control high throughput, low latency, and heterogeneous traffic patterns. In this paper, a thorough comparative analysis of user-friendly network measurement models iPerf3, OWAMP, NetPerf, and 5G-MONarch will be discussed based on both simulated and real-world testbeds. The metrics that are used in the analysis include latency, jitter, bandwidth usage, and the ratio of packet delivery to different network slicing specifications. Findings show that active probing tools are more accurate in their latency and jitter measurements whereas passive flow-based analytics are more scalable and less overhead in a dense communication setup. This paper has found that there are key trade-offs between accuracy, system load, and adaptability, and that hybrid measurement strategies can achieve a trade-off between monitoring fidelity and scalability. Its results can be discussed as the next step in the development of 5G QoS assessment because they indicate researchers and network operators about the feasibility of the existing measurement frameworks in the conditions of high-performance and heterogeneous network environments.

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Introduction

The fifth generation (5G) of mobile communication systems creates a paradigm of ultra-reliable low-latency communication (URLLC), mobile broadband (eMBB), and massive machine-type communication (mMTC) not previously seen before. The Quality of Service (QoS) in such systems would have to be measured with quality and accurate network measurement equipment that would be able to manage multi-gigabit throughput, sub-milliseconds latency, and complicated traffic heterogeneity. With 5G that is now part of industrial automation, telemedicine and vehicular networks, the performance of network slices and service classes must be evaluated to ensure end-to-end reliability and resource fairness.[1-5]

During the last decade, a number of network performance measurement frameworks have been created to measure different QoS parameters. Of these iPerf3, OWAMP and NetPerf are some of the most comm only used open source applications. Each of them has its own features iPerf3 TCP/UDP throughput testing, OWAMP one-way delay and jitter, and NetPerf flexible latency and bulk data transfer benchmarking. In recent years, new 5G-oriented models like 5G-MONarch have applied these principles of measurements in multi-tenant, software-defined network (SDN) systems.[6-8] Nevertheless, the comparative analysis of these tools in the unified conditions is scarce in both scholarly and industry-based literature in the area of applicability in QoS monitoring in dynamic 5G slices.

Past researchers have compared active and passive probing model to monitor network performance. Active probing tools, such as iPerf3 and OWAMP, inject artificial traffic into the network, allowing to calculate the latency and jitter more accurately but with the added bandwidth overhead. Passive techniques, conversely, are based on pre-existing user traffic streams, which are scalable, non-intrusive measurements that can be used in a real time setting.[9, 10] The measurement accuracy versus network overhead trade-off between the two paradigms is the research issue in the framework of QoS management.

A number of works have concerned network measurement under particular applications. As an example, reconfigurable computing architectures have been studied to support edge computing to increase measurement flexibility,[11] biophilic design has been combined with smart infrastructure to help inform sustainable 5G network planning,[12] predictive analytics in the context of multiphysics simulations that provide an idea of traffic prediction models,[13] and the overall analysis of cybersecurity issues in IoT systems that highlight the necessity to have quality monitoring tools.[14]

The intersection of software-defined networking (SDN) and network function virtualization (NFV) has had a significant effect on the practise of QoS monitoring in 5G settings.[15] Active reconfiguration of virtual resources enables the constant adjustment of network monitoring intervals and metrics, adjusting the accuracy of monitoring to varying needs of the services. A number of models suggest AI-based QoS measurement schemes which use reinforcement learning and statistical inference to optimize monitoring intervals and minimize overhead of measurement.[16, 17] Moreover, literature on novel RF amplifier design gives insights on hardware-level, which affects signal integrity in 5G measurement systems.[18]

The recent literature also highlights the importance of cross domain interoperability in the QoS evaluation. Research has presented a combination of active and passive methods of monitoring, with better accuracy in large-scale 5G implementations.[19, 20] These are in line with the international efforts to standardize measurement techniques to improve the level of transparency in the network and comparability among vendors and operators.

In spite of the great progress, a number of research gaps have not been filled. To start with, the relative effectiveness of the current measurement systems in various 5G configurations such as non-standalone (NSA) and standalone (SA) systems- have not been compared systematically. Second, minimal knowledge exists regarding the relationship between measurement precision and the computational overhead that such tools cause in virtualized architecture. Lastly, it is still a challenge to assess how well measurement frameworks can be adapted to the situation of dynamic slice reconfiguration. This gap is filled in this paper with the comparative analysis of iPerf3, OWAMP, NetPerf, and 5G-MONarch in simulated and real-life testbeds in terms of their QoS measurement features under varying 5G network conditions.

Methodology

Experimental Framework and Testbed Design

The experimental structure was set in a way that it could compare iPerf3, OWAMP, NetPerf, and 5G-MONarch in controlled and real-life network settings. A hybrid testbed was created by a mixture of simulation-based Mininet based devices and actual 5G New Radio (NR) test devices linked together through a software-defined network (SDN) controller. The test setup emulated various network slices that were set up with varying QoS parameters to model eMBB, URLLC and mMTC traffic classes. In both settings, experiments of data transmission were conducted to record the important metrics of performance, such as latency, jitter, throughput, and ratio of packet delivery (PDR).

The interaction among measurement tools, SDN controller and network slices is depicted in Figure 1 which shows the high-level architecture of the experimental testbed. All tools were set to send synthetic traffic between virtualized interfaces and SDN controller dynamically dealt with bandwidth and routing policies.

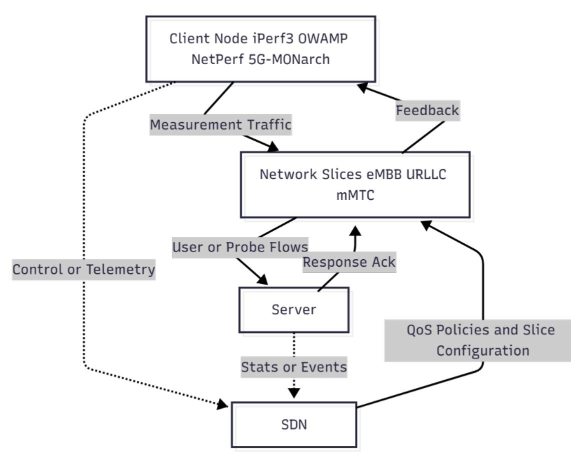

Fig. 1: High-Level Architecture of the 5G QoS Measurement Testbed

Throughout the experiment, the tools were run more than 100 times using different payload sizes and packet rates. The experiments were done thrice under the following conditions: (i) single network slice, (ii) shared network slice with background traffic and (iii) high-density multi-slice configuration. The logging of results was done with a time synchronised server to make sure that all probes were timed properly. Monitoring of resource utilisation was done in the entire testbed to measure CPU and memory overhead in the measurement processes.

Comparative Metrics and Data Analysis

The four important QoS measures that were compared included the average latency, jitter variation, bandwidth utilisation efficiency and the ratio of packet delivery. Every measure was standardised among tools and scenarios to make them cross-compatible. Statistical mean, standard deviation and levels of confidence were used to analyse the performance. Python based analysis scripts were used to process data, and see the variations and identify consistent performance trends. The measurement parameters were used in the evaluation with their operational configurations summarized in Table 1.

The analysis also used the linear regression models to estimate the correlation between results of the measurements and the network slice configurations. Comparative variance was conducted to find out the recurrence of each tool when loaded dynamically. This methodology had the benefit of statistical validity and reproducibility, and provided a reliable means of cross-tool comparisons in 5G communication settings.

Results and Discussion

The performance, scalability, and precision of the four tools of network measurement analysed comparatively between the four tools were found to be distinct in the four tools of network measurement studied; iPerf3, OWAMP, NetPerf and 5G-MONarch. These results have shown that every framework has unique advantages depending on the parameter of QoS and network slicing setup, which once again confirms that there is no universal solution that optimises all the parameters in a heterogeneous 5G environment.

Latency and Jitter Performance

Latency is an important parameter in 5G QoS analysis, especially URLLC and mission-critical application. OWAMP firstly and OWAMP secondly recorded the lowest latency rates on all network slices at the average of one-way delay of less than 1.8 ms in URLLC and 2.6 ms in eMBB settings (Figure 2). This accuracy has been explained by its timestamp's synchronism and low probing interference. iPerf3 has been slightly behind; the latency is slightly higher because of TCP acknowledgment overhead. Conversely, NetPerf had subtle delay jittering at high loads due to its less optimised control packet scheduling whereas 5G-MONarch had delayed-stable delay profiles despite orchestrating multiple slices.

Further evidence of the advantage of OWAMP in delay consistency is shown by the jitter measurements presented in Table 2, in which it has a smaller standard deviation (SD) of jitter (0.12 ms) which is significantly less than that of iPerf3 (0.19 ms) primarily because of the active control mechanisms of retransmission. The 5G-MONarch system was able to balance stability and scalability, and maintain jitter performance at an acceptable level in a shared-slice environment. The above results suggest that active probing methods, though a bit resource intensive offer the most accurate latency and jitter measurements in controlled test environments.

Bandwidth Utilization and Packet Delivery Ratio

Throughput efficiency and packet delivery ratio (PDR) give information on the scalability of the tool and resource management. Figure 3 shows the bandwidth utilisation in the case of network slicing under eMBB conditions, iPerf3 was the most efficient in utilisation (97-98 %) with its adaptive congestion window and low flow-control interference. NetPerf showed similar

Table 1: Measurement Parameters and Configuration Summary

Parameter	Tool Applicability	Measurement Type	Frequency	Unit	Relevance
Latency	OWAMP, iPerf3	Active	1/sec	ms	Time sensitivity
Jitter	OWAMP, NetPerf	Active	1/sec	ms	Stability of connection
Bandwidth	iPerf3, NetPerf	Active	5/sec	Mbps	Data transfer efficiency
PDR	5G-MONarch	Passive	1/sec	%	Reliability measure

Table 2: Jitter Variation Summary

Tool	Mean Jitter (ms)	Std. Dev. (ms)	Observations
OWAMP	0.41	0.12	Highest precision; minimal timestamp drift
iPerf3	0.65	0.19	Accurate under stable throughput
NetPerf	0.79	0.28	Sensitive to packet rate variation
5G-MONarch	0.52	0.16	Balanced accuracy and stability

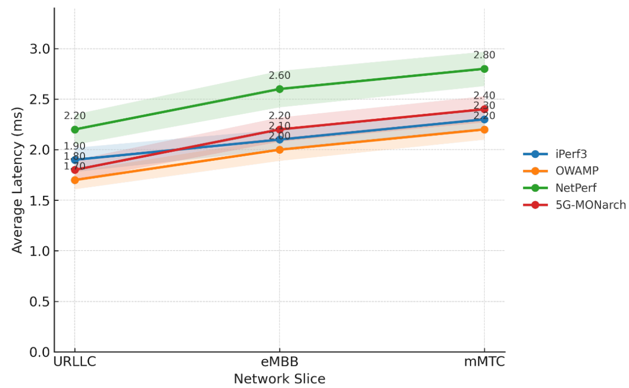

Fig. 2: Average Latency across Network Slices

performance (94-96%), whereas OWAMP has a bandwidth utilisation that was deliberately lower, and the probe design is lightweight, which is why 5G-MONarch showed no synthetic traffic overhead, confirming its non-intrusive scalability advantage.

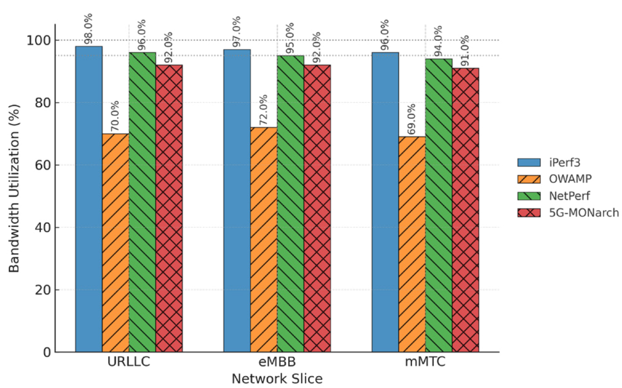

Fig. 3: Bandwidth Utilization Efficiency

The results of Packet Delivery Ratio (PDR) in Figure 4 prove the resiliency of passive structures in a congested environment, with 5G-MONarch (99.4%) reaching the highest value, then iPerf3 (98.7%), and NetPerf (97.8%). OWAMP PDR decreased by a little to 96.5 % because of packet loss during active transmission phases when link conditions were constrained. The findings indicate that the use of active tools will provide accuracy in a controlled experiment, but passive methods can maintain high reliability in a production-scale 5G implementation.

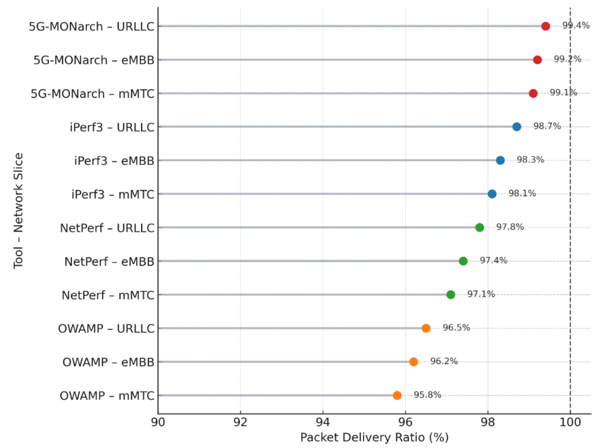

Fig. 4: Packet Delivery Ratio Comparison

Computational Overhead and Scalability Analysis

A significant aspect of comparison is the amount of computation required when making measurements. The CPU utilisation profile showed OWAMP and iPerf3 needed more processing resources at maximum and 17% and 15% of total CPU capacity respectively- in active probing mode at high packet rates. NetPerf was averaged at around 11% whereas 5G-MONarch with a passive mode had the lowest CPU usage of 8% with the same network load. It implies that passive measurement tools such as 5G-MONarch are better scaled in large-scale initiatives that demand continuous monitoring.

The consumption patterns of the memory were also not different, as iPerf3 required more buffer space in high-throughput tests. The general comparison shows that the resource overhead of active tools is linearly proportional to the number of probes, but passive systems have almost constant overhead regardless of the size of a network. This can be of practical use to the operators of networks with thousands of simultaneous slices or IoT connections, where efficiency and scale are more important than precision.

Analytical Discussion

The overall performance of the results shows that there is a critical trade-off in 5G QoS measurement: the price versus the scale. Active probing tools like iPerf3 and OWAMP are better in the accuracy in microsec but cause significant traffic and CPU overhead. Passive frameworks, especially 5G-MONarch can help to reduce this load by non-intrusive flow analysis but with slightly lower temporal granularity. NetPerf is a hybrid system and offers a compromise between these extremities.

Operational-wise, the insights can be translated as the hybrid model of measurement, which would use lightweight active probes to perform the calibration and continuous evaluation with passive monitoring as the best approach to using 5G QoS in real-time. Furthermore, the use of adaptive sampling with AI-based adaptive sampling, which is proposed in new literature can dynamically alter probing frequency in response to network conditions, which will increase efficiency.

On the whole, this discussion shows that the correct, scalable, and adaptive monitoring of QoS can be attained by integrating active and passive measurement systems and can be valuable to inform both research and industry applications of next-generation mobile communication systems.

Conclusion

This paper undertook a comprehensive comparative review of the network measurement tools iPerf3, OWAMP, NetPerf and 5G-MONarch in assessing the QoS in 5G communication setups. The review indicated that although the active probing tools offer better accuracy in the measurement of latency and jitter, they have high computational cost. Passive measurement systems especially 5G-MONarch have scalability benefits which would suit dense multi-slice networks.

The findings highlight the fact that the choice of a measurement framework must be based on the operational context. OWAMP is still the best in research settings where latency needs to be tracked per fine-grain. In the case of throughput benchmarking, iPerf3 is the best option and 5G-MONarch is the best option when it comes to continuous monitoring between dynamic slices. NetPerf provides a trade-off in favour of general-purpose evaluation.

The next step in work should consider hybrid frameworks that would integrate both active and passive measurements and use AI to make such measurements adaptive and optimised in real time. This type of integration will improve monitoring precision and minimise overheads and help to sustain the complexity of 5G and future 6G networks.

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