Realistic Field Trial Evaluation of a Tele-operated Support Service for Remote Driving over 5G

Grigorios Kakkavas*, Maria Diamanti*, Kwame Nseboah Nyarko†, Matthias Gabriel†,
Vasileios Karyotis*, Klaus Mößner† and Symeon Papavassiliou*
*School of Electrical & Computer Engineering, National Technical University of Athens
Iroon Polytechniou 9, Zografou, Athens, 15780, Greece
e-mails: {gkakkavas, mdiamanti, vassilis}@netmode.ntua.gr, papavass@mail.ntua.gr
†Professorship for Communications Engineering, Technical University Chemnitz
Str. der Nationen 62, 09111 Chemnitz, Germany
e-mails: {kwame-nseboah.nyarko, matthias.gabriel, klaus.moessner}@etit.tu-chemnitz.de

***Abstract*—In this paper, we focus on the development and realistic field trial evaluation of a Tele-operated Support (TeSo) service for remote driving over 5G mobile communications. The presented prototype was created within the context of the transport vertical of the "5G HEalth, AquacultuRe and Transport (5G-HEART)" 5G PPP Phase 3 project and was meticulously tested and evaluated in several realistic test cases over a commercial 5G Non-Standalone (NSA) deployment. A vehicle equipped with appropriate sensors and actuators was actively controlled from a distance of 36 km, exchanging sensor data and video streams in the uplink and vehicle-control commands in the downlink with the remote operations center. This work is among the first experimentally-driven quantitative analyses of such an application with a real pilot using an actual vehicle. Our objective was to validate the feasibility of the proposed TeSo service by evaluating relevant performance metrics, such as latency, jitter, throughput, and loss rate. Moreover, our extensive testing aimed to identify salient features and emerging challenges from the prototype, which can aid in a two-fold manner: first, paving the way for the eventual commercialization of the service, and second, guiding standardization effort for a relevant emerging market in the near future.**

***Index Terms*—5G mobile communications, remote driving, teleoperation, prototype, real pilot, transport vertical**

I. Introduction

Remote driving is one of the primary Vehicle-to-Everything (V2X) services of the transport vertical defined by the standardization bodies (e.g., the Third Generation Partnership Project (3GPP) [1]), with ongoing research focusing on the detailed functional and network connectivity requirements. Its application is particularly investigated in hazardous situations where passengers are not able to maneuver the vehicle due to personal limitations or externally imposed restrictions. Generally speaking, remote driving plays the role of an intermediate step—or even a complement—to the fully autonomous vehicle technology by providing the required safety and fail-over functionality when necessary. Although the corresponding user and network requirements have undergone several specification phases by the standards, with extensive theoretical analyses in the literature [2], [3], validating their feasibility under realistic conditions remains an open problem that is entangled with the mobile network's performance and the advancements therein.

Prior to the commercial deployment of 5G sites, the feasibility validation of individual V2X functionalities (e.g., high-bandwidth Augmented Reality (AR) - Virtual Reality (VR) video streaming, video and audio distribution in high mobility environments, etc.) was performed using network simulation environments. Gradually, the deployment of research-oriented 5G trial sites was initiated by the converged efforts of academia and industry, resulting in the first attempts to perform field trials of different V2X services (e.g., platooning, cooperative autonomous driving, remote driving). The latter field trial efforts were small-scale and concerned with testing primitive V2X service components. Their main objective was to experiment with the proper configuration of the respective trial sites to achieve the desired Quality of Service (QoS). To accelerate the progress of standardization activities and product development processes, feedback from realistic field trials that capitalize on the ongoing commercial deployment of 5G sites needs to be provided.

This work is aimed at addressing the aforementioned need. To that end, we set out to validate the feasibility and evaluate the performance of a fully-functional Tele-operated Support (TeSo) service prototype developed for remote driving in the context of the transport vertical of the "5G HEalth, AquacultuRe and Transport (5G-HEART) Validation Trials" 5G PPP Phase 3 project [4], under realistic conditions. Specifically, we executed field trials involving a remote driving-enabled vehicle over the existing Vodafone's 5G Non-Standalone (NSA) deployment in Schlettau, Germany. In doing so, we assumed the perspective of the developers or end users of such a TeSo service that use the mobile infrastructure as provided without any control over its components and their configuration. During the trials, video recordings of the vehicle's routing and raw captures of the traffic exchanged between the vehicle and the remote operation center were collected while performing different maneuvering scenarios (i.e., test cases). The recorded data was then post-processed to compute the achieved throughput, latency, jitter, and packet loss rate of both downlink and uplink communications.

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The article's main contributions can be summarized as follows:

(i) We present the software design and implementation details of the TeSo service prototype developed for the 5G-HEART EU project, emphasizing the end-to-end application architecture and the type of data transferred between the vehicle and the remote operation center.

(ii) We discuss in detail the field trials setup, the different test cases scrutinized, and the measurement methodology used to capture the traffic exchanged between the vehicle and the remote operation center.

(iii) We validate the feasibility of the TeSo service by numerically evaluating the achieved one-way latency, jitter, throughput, and loss rate, after post-processing and analyzing the raw captured traffic.

The remainder of the article is organized as follows. Section II outlines the related work dealing with field trials of V2X services in the transport vertical. Section III introduces the high level TeSo service prototype's design and software implementation details, while Section IV describes the employed field trial setup, test cases and measurement tools. The numerical evaluation and the conclusions drawn regarding the TeSo service's feasibility over 5G are presented in Sections V and VI, respectively.

II. Related Work

A limited amount of field trial works can be found in the literature, e.g., [5]–[7], quantifying the 5G network's performance bounds in high-mobility environments via considering different experimental setups and evaluation objectives. In [5], the achieved Signal-to-Noise Ratio (SNR) and throughput of a mmWave Vehicle-to-Infrastructure (V2I) communication on a highway is investigated. Several Remote Radio Units (RRUs) were installed along the test track with 450-750 m intermediate distances between them, resulting in 1.5 Gbps downlink throughput for 90% of testing time under proper beamforming, handover, and mobile relaying configurations. Complementarily, in [6], the achieved latency and reliability of Vehicle-to-Vehicle (V2V) communications between trucks forming a platoon in a real express highway environment is studied. The trucks exchanged control message packets over an inter-truck distance of about 35 m, achieving latency below 1 ms and reliability above 99.999%. Concerning extreme-mobility cases, a field trial aboard a test train running at 360 km/h is conducted in [7], with two RRUs installed 1 km from the railway. The trial showed that more than 100 Mbps throughput could be observed in approximately 80% of coverage, confirming the stability of 5G transmissions.

Regarding the feasibility of providing holistic V2X services, such as tele-operated support for remote driving, only a handful of field trial studies exist. The first attempts focused on laboratory experiments of a TeSo service prototype and determined the service's performance bounds over 4G and 5G technologies, as the work in [8]. Subsequently, small-scale field trials of actual remote-driving enabled vehicles were performed in [9], [10], aiming to provide initial insights

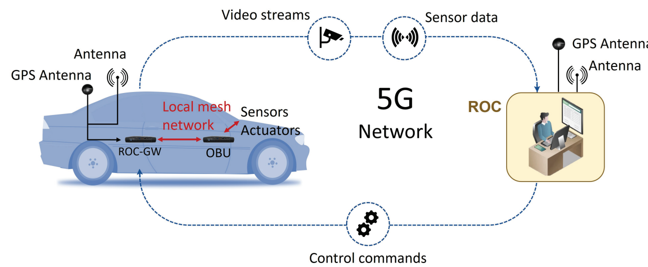


Fig. 1. End-to-end system architecture.

regarding the improvements in the achieved latency between 5G and 4G, and 5G and WiFi-enabled V2X communications, respectively. Pursuing a different objective, the work in [11] describes the experiments conducted in a multiple Public Land Mobile Network (PLMN)-enabled 5G SA testbed of the Aalto university in Finland. The scope of the field trials is to measure the achieved SNR and Reference Signal Received Power (RSRP) during the remote control of a Level 4 (L4) automated vehicle while switching between two PLMNs. A recent work in [12] proceeds to the field trial experimenting with a remote driving application over mmWave frequencies. The authors follow a from-theory-to-practice approach and properly configure the employed testbed based on their theoretical findings about the network's optimal physical layer design. Given a gNodeB installed 470 m away from the vehicle, a maximum 50 Mbps uplink throughput and approximately 6.5 ms Round Trip Time (RTT) are achieved.

As evidenced by the above brief outline of related work, most studies up to this point focus on testing remote driving services in fully-controlled environments with the goal of identifying the optimal network setup and configuration. The literature lacks realistic field trials that use the existing commercially deployed 5G sites as a black box to provide tangible insights about the feasibility of the remote driving use case in practice, which is precisely the gap that we aim to fill with the present work.

III. Tele-operated Support Service: Design and Implementation

Fig. 1 depicts the end-to-end system architecture of the developed TeSo service prototype. As can be seen, the Remote Operations Center (ROC) is located at a remote site and is composed of a GUI application that displays the received video streams and telemetry data to the human operator while accepting as input the remote control commands that must be transmitted to the vehicle. It is a multi-threaded desktop application developed from scratch using the `Qt5` framework. At the vehicle, there are the following components interconnected in a local mesh network created by leveraging the capabilities and the features of the `DRAIVE Link` [13] framework (i.e., node autodiscovery and publish/subscribe messaging pattern):

- four cameras mounted on each side of the vehicle, several sensors recording ambient and operational data, and the

actuators needed for transforming the remote control commands into physical movements;
- an On-board Unit (OBU) that aggregates the sensor data and transforms the proprietary data structures into predetermined standard formats and vice-versa (for the remote control commands); and
- the Remote Operations Center - Gateway (ROC-GW), which orchestrates the bidirectional communication with the Remote Operations Center (ROC) over the network.

ROC-GW is a command-line application implemented in `C++` on top of the `DRAIVE Link` middleware. It operates as a publisher with three output pins corresponding to the remote control commands received over the network from ROC and as a subscriber with seven input pins corresponding to the video streams and the sensor data received over the local mesh from OBU. Generally speaking, the output pins craft the data received over the network into suitable messages and push them into the mesh. In contrast, the input pins decompose the messages they receive from the mesh to further process and transmit them over the network. Data is structured and formatted in suitable `FlatBuffers` tables for easier serialization. In total, there are seven different table data types:

1. the JPEG-encoded frames of the four video streams (camera),
2. the vehicle's velocity in meters per second (vehicle state),
3. the current steering wheel angle in radians and the percentage of throttle and brake (automation state),
4. the geographic coordinates (GNSS position),
5. the preferred throttle percentage (throttle control),
6. the preferred brake percentage (brake control), and
7. the preferred wheel angle in radians (steering wheel control).

The data transmissions over the network are realized using the publish-subscribe messaging pattern provided by the `ZeroMQ` asynchronous messaging library, using appropriate sockets (PUB or SUB) at the respective endpoints and encapsulating the Flatbuffers data objects into ZeroMQ messages.

IV. Field Trial Setup, Test Cases and Measurement Scheme

In this section, we present the experimental setup and the test cases we employed for the comprehensive performance evaluation of the developed TeSo service in a real pilot.

A. Test Cases

The primary objective of the conducted validation trials is to assess the performance of the developed TeSo service prototype under realistic conditions when used over 5G mobile communications. To that end, several test cases regarding simple maneuvers performed by the remotely controlled vehicle have been trialed in an open rural space at Schlettau, Germany, over Vodafone's commercial 5G NSA network operating at band n77 (TDD on 3450 MHz). The trials were conducted during office hours on weekdays, and the vehicle's velocity was up to 25 km/h. The distance between the BS and the vehicle varied from 60 to 120 meters, resulting to an RSRP range of -62 to -87 dBm. The remote operation center was located in Chemnitz, Germany, around 36 km away from the vehicle.

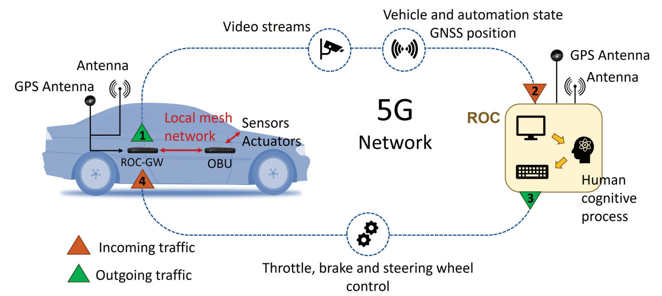


Fig. 2. Complete operational cycle and measurement scheme.

In particular, the following test cases have been considered:
- *TC01*: Straight Maneuver
- *TC02*: Turn Right Maneuver
- *TC03*: Lane Change Maneuver
- *TC04*: Parking Maneuver

For each test case, several iterations were conducted across three days to account for the varying environmental and network conditions. The vehicle was remotely controlled from about 36 km away, and raw measurements were collected, capturing the exchanged traffic between ROC and ROC-GW. Said measurements were later post-processed to calculate relevant KPIs for the downlink (DL) and uplink (UL) communications.

Specifically, the quantitative analysis regards the achieved one-way latency, jitter, throughput, and packet loss for each data type stream, defined as follows:
- *one-way latency*: the mean of the time differences of the reassembled ZeroMQ Message Transport Protocol (ZMTP) messages recorded at the respective source and destination endpoints,
- *jitter*: the mean of the absolute time differences between consecutive reassembled ZMTP messages,
- *throughput*: the mean throughput of the underlying TCP streams calculated over the whole duration of each test case iteration, and
- *packet loss*: the proportion of lost segments for the respective TCP streams.

B. Setup

As can be seen in Fig. 2, the operation cycle of the proposed TeSo service can be divided into three components:

(i) the local mesh network at the vehicle side interconnecting the vehicle's sensors and actuators, the OBU, and ROC-GW,
(ii) the GUI application at the remote location that brings the human operator into the control loop of the vehicle, and
(iii) the network infrastructure (including 5G functionality) realizing the communications between ROC-GW and ROC.

The typical end-to-end sequence of steps is as follows. First, the four cameras mounted on each side of the vehicle and the rest of the sensors capture ambient and operational data, which are processed and transformed into a predetermined standard format by the OBU and ultimately reach the ROC-GW (i.e., vehicle integration). Then, the data is transmitted over the network to the ROC application using the publish-subscribe messaging pattern of the ZeroMQ library. There, the video streams and the other telemetry data are presented to the human operator, who processes this information, decides the proper course of action, and issues the corresponding remote control commands (i.e., human cognitive process). These are transmitted back to the ROC-GW over the network, and they go through the OBU to finally reach the appropriate actuators of the vehicle.

Within the scope of our experimental analysis, we focus on evaluating the performance of the aforementioned network component. The remaining two components are considered constants and not relevant for our purposes that primarily regard 5G mobile communications. Vehicle integration is fixed at a hardware level and hardwired, whereas the human operator's cognitive process and reaction time cannot be directly measured. Moreover, it is not possible to match the exact data (e.g., video frames) that instigated a specific reaction from the operator. Taking all of the above into consideration, we perform measurements (i.e., capture the outgoing and the incoming traffic) separately for each data type on the indicated monitoring points (points 1-2 and 3-4 in Fig. 2) in the UL and the DL between the ROC-GW and the ROC.

C. Measurement and Analysis Tools

As previously described, the performance of the TeSo service prototype is evaluated by capturing the outgoing and incoming traffic at the two devices hosting ROC-GW and ROC. To achieve this, we employ the `tcpdump` command-line packet analyzer on the appropriate network interfaces with a Boolean expression that indicates the underlying port range used by the service, and we record the matching traffic in two PCAP files. Moreover, the required clock synchronization of the two hosts is accomplished via their Pulse-Per-Second (PPS) synchronization to the GNSS reference time, attaining a mean PPS signal jitter of 1-20 µs. These raw measurements are post-processed by leveraging the `Wireshark` network protocol analyzer. In particular, the ZeroMQ Message Transport Protocol (ZMTP) messages exchanged between ROC-GW and ROC are decoded using the `ZMTP Wireshark Dissector` [14] plugin. The corresponding messages are identified, and the respective one-way latencies and jitter are computed with a Python script based on the `Pyshark` packet parsing module. Throughput and packet loss are calculated over the underlying TCP streams using the statistics tools provided by Wireshark.

V. Results and Discussion

In order to evaluate the developed prototype's performance under realistic conditions, several iterations of each test case described in Section IV have been conducted over a commercial 5G NSA deployment, over which we have no administration or management control, without any special accommodations or configurations made for our particular use case. In that way, we assume the perspective of the TeSo service's developers or end users and assess its feasibility and usability over a typical mobile network infrastructure in a rural area. Generally speaking, each of the employed data types analyzed in Section III corresponds to a different data stream between ROC-GW and ROC that is realized over distinct ZeroMQ sockets. Separate values for the one-way latency, jitter, throughput and loss rate can be calculated for every data stream. Table I presents in fine-grained detail the computed KPIs per individual data stream for a specific iteration of TC01.

TABLE I
KPIs per Data Stream for an Iteration of TC01

Data Stream	Mean Lat. (µs)	Mean Throughput (bps)	Jitter (µs)	Loss Rate (%)
GNSS Pos.	30159.16	4651.69	9149.09	0
Front Cam.	42378.31	2165787.34	7730.31	0.053820
Back Cam.	40180.17	1490055.50	6375.40	0
Right Cam.	38176.08	1436088.75	8467.67	0.043837
Left Cam.	44091.86	1643104.52	8520.49	0.041779
Throttle Ctrl.	24432.25	220.72	3915.70	0
Brake Ctrl.	24633.00	22.30	5245.50	0
Wheel Ctrl.	25190.55	7088.25	5144.67	0
Vehicle State	30791.02	4257.11	8893.27	0
Autom. State	30882.94	4180.73	9533.60	0.103627

Our preliminary requirement analysis [3] has concluded that the use case of remote driving support demands increased achieved throughput for the uplink and low latency in both directions to enable environment awareness, sense of presence, spatial cognition, and real-time response. Indeed, downlink communications from ROC to ROC-GW correspond to the remote control commands and therefore are low-data-rate but latency-critical. On the other hand, uplink communications from ROC-GW to ROC are dominated by the four camera streams, and as such, they are latency-critical and best-effort. Based on the above observations, we summarize the achieved performance of the TeSo service prototype in Table II, which contains three iterations of each test case and the following representative KPIs:

- *UL Throughput*: the sum of the mean throughput of the four camera streams,
- *UL Jitter*: the average of the jitter of all uplink data streams (i.e., GPS position, front/back/right/left camera, vehicle state, and automation state),
- *DL One-Way Latency*: the mean one-way latency of the wheel control data stream as an archetypal remote control signal, and
- *DL Loss Rate*: the loss rate of the wheel control data stream as an archetypal remote control signal.

TABLE II

PERFORMANCE OVERVIEW OF CONDUCTED TEST CASES

Performance Metric	**TEST CASE 01** Iteration 1	**TEST CASE 01** Iteration 2	**TEST CASE 01** Iteration 3	**TEST CASE 02** Iteration 1	**TEST CASE 02** Iteration 2	**TEST CASE 02** Iteration 3
UL Throughput (bps)	6735036.11	6982371.35	5045466.27	5916670.03	5566629.89	5620498.30
UL Jitter (µs)	8381.40	7572.23	6837.95	4618.62	8024.03	7354.10
DL One-Way Latency (µs)	25190.55	25846.59	30392.13	21906.50	25381.07	23771.94
DL Loss Rate (%)	0	0	0	0	0.05302	0

Performance Metric	**TEST CASE 03** Iteration 1	**TEST CASE 03** Iteration 2	**TEST CASE 03** Iteration 3	**TEST CASE 04** Iteration 1	**TEST CASE 04** Iteration 2	**TEST CASE 04** Iteration 3
UL Throughput (bps)	5313905.29	7313642.54	6893067.80	5969259.77	5806356.36	6009750.87
UL Jitter (µs)	7764.61	7817.11	11168.06	8728.49	7899.35	8167.15
DL One-Way Latency (µs)	37430.55	25744.58	25829.40	34021.36	38603.73	32460.00
DL Loss Rate (%)	0	0	0	0	0	0

Fig. 3 illustrates the evolution of UL Throughput (i.e., the sum of the throughput of the four cameras) for the first iteration of each test case throughout the trialing time. It should be noted that the total execution time of each test case is different; therefore, the four curves terminate at distinct time points. The particular trend of the four curves is related to the achieved RSRP at the specific geographic location of the vehicle at each trial phase, indicating, for example, the existence or not of obstacles that attenuate the signal or coverage holes. At the same time, it is also affected by the traffic of the geographical area around the trials' location at the corresponding time points. Most importantly, though, UL Throughput depends on the JPEG compression level of the camera frames, a parameter that can be configured at the ROC-GW. Consequently, there is a certain degree of freedom for the operator who can adjust the compression level until reaching the desired balance between UL Throughput and image quality at the ROC GUI application.

On the other hand, DL One-Way Latency is the most crucial and non-flexible parameter affecting the functionality of the TeSo service. Fig. 4 depicts the DL One-Way Latency (i.e., the one-way latency of the wheel control data stream) for the third iteration of each test case. Specifically, in Fig. 4a, the achieved DL One-Way Latency of each test case is presented across the received ZMTP data messages in the form of a scatter plot to better illustrate its temporal behavior. Next, Fig. 4b provides a comprehensive statistical analysis of the minimum, maximum, and mean latency values, the first and third quartiles, and the existing outliers, while Fig. 4c illustrates the Cumulative Distribution Function (CDF) of the achieved DL One-Way Latency. Overall, the results reveal that most of the time, the DL One-Way Latency lies within the range of 20–40 ms. Empirically, the achieved latency values were sufficient for controlling the vehicle during the conducted trials without an issue. However, even lower values could be achieved if deemed necessary by moving ROC at the edge or employing a targeted URLLC slice.

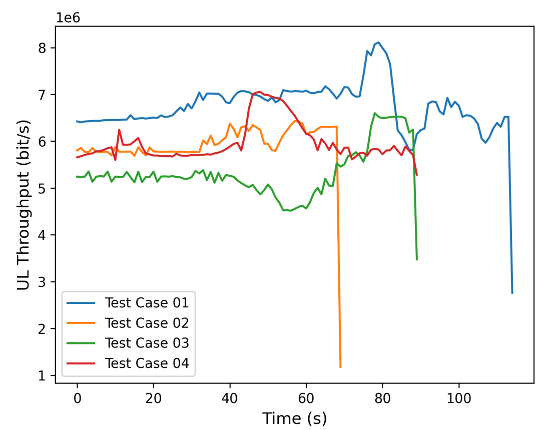
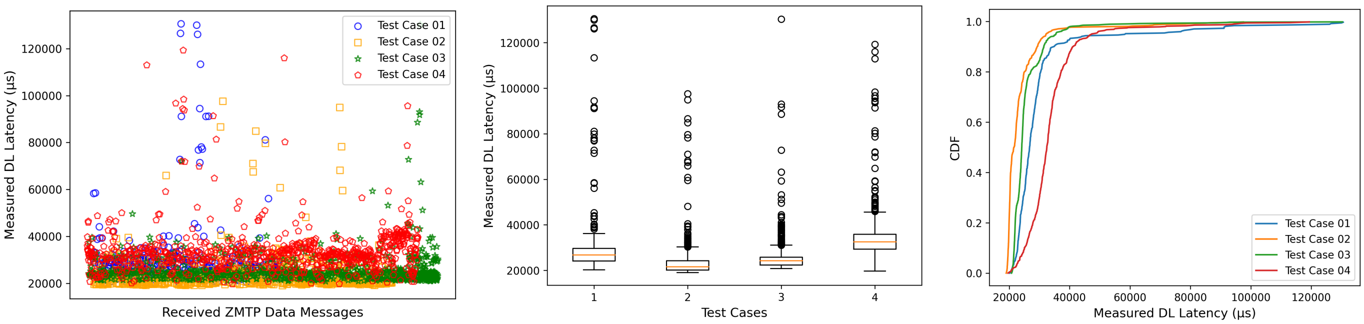


Fig. 3. UL Throughput for the first iteration of each test case.

VI. CONCLUSION

This work presented a realistic field trial of a tele-operated support (TeSo) service for remote driving over 5G mobile communications. First, the design and the technical implementation of a fully functional TeSo service prototype developed in the context of the transport vertical of the 5G-HEART EU project were presented in detail. Then, the prototype's performance was evaluated in terms of well-known KPIs based on four test cases in a real pilot with an actual vehicle over a commercial 5G NSA deployment. The conducted experimental analysis assumed no administrative control over the 5G network configuration and no particular setup to accommodate the examined remote driving use case. Instead, it assessed the feasibility of such a TeSo service over a generic-purpose commercial infrastructure that was used as provided to the network operator's clients.



(a) Scatter Plot

(b) Box Plot

(c) Cumulative Distribution Functions

Fig. 4. One-Way DL Latency for the third iteration of each test case.

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