Empirical Evaluation of Bit Rate and Latency in a Private 5G Cell for Slow-Speed Vehicles in an Urban Environment

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***Abstract*—5G was developed a few years ago to support various verticals, including connected vehicles. Now that commercial deployments of 5G networks are available, it is crucial to empirically evaluate their performance in real-world scenarios. This study measures the performance of a private 5G campus network for a connected car in terms of downlink (DL) and uplink (UL) bit rates, as well as latency metrics including round-trip time (RTT) and jitter. The car is driven at controlled speeds of 10 km/h, 20 km/h, and 30 km/h on an urban street. Subsequently, we analyze the impact of speed on the probability distributions of these performance metrics. Notably, our observations suggest that 5G performance slightly improves at higher speeds. We attribute this to increased spatial diversity, as higher speeds enhance the likelihood of experiencing stronger received signal power levels across diverse locations.**

***Index Terms*—Connected cars, speed of vehicle, private 5G campus network, empirical performance evaluation, bit rate, latency, jitter.**

I. Introduction

It has been more than a few decades since humans started wishing for fully autonomous cars—vehicles that can drive themselves without human intervention while being safer, more efficient, and more comfortable than human-driven cars. Although many challenges have already been addressed, there is still a path ahead—whether short or long—before self-driving cars become a technological and commercial reality.

Wireless connectivity offers significant potential for cars. Imagine how safe and efficient it would be if an intelligent car could proactively respond to changes in its surroundings by receiving real-time information. Connected cars can also cooperate with other connected road users to enhance the safety of all maneuvers and optimize the use of road capacity. As we can see from these examples, the concepts of connected cars and self-driving cars are deeply intertwined. As a result, transportation has always been one of the key vertical industries that modern wireless communication technologies should support. This was also one of the primary goals during the design of 5th generation cellular network (5G) a few years ago. Now, as 5G networks have become commercially available, it is the right time to empirically evaluate their performance in real-world scenarios to understand how different parameters affect it. Obviously, empirical performance evaluations can either validate the successful achievement of design goals or provide valuable lessons for future designs.

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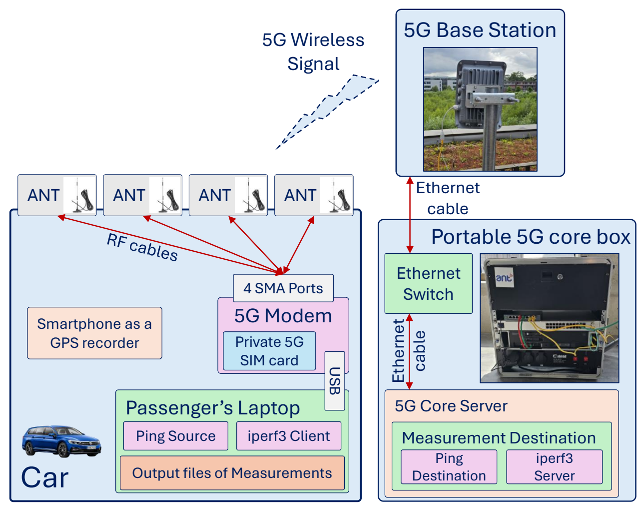
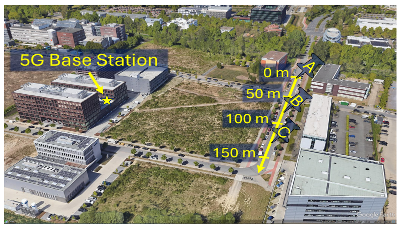


Fig. 1: Measurement Setup Architecture

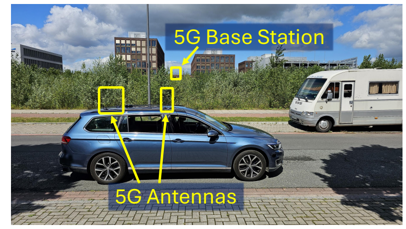
In cellular networks, one of the key differences between vehicular use cases and non-vehicular ones is that in vehicular use cases, the network users—connected cars—are almost always in motion at varying speeds in different environments, ranging from low speeds on city streets to high speeds on highways. Hence, investigating the effects of mobility on network performance is of great importance.

In the existing literature, several empirical studies evaluate the performance of 5G networks, such as those presented in [1]–[10]. Although their measurement results provide valu-

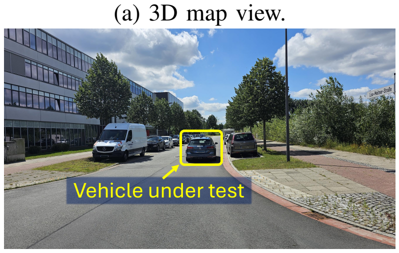


(a) 3D map view.

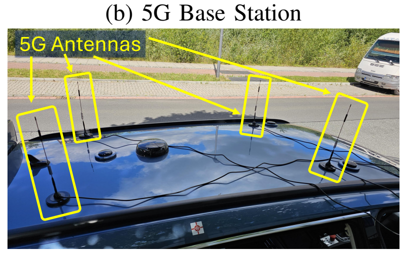
(b) 5G Base Station



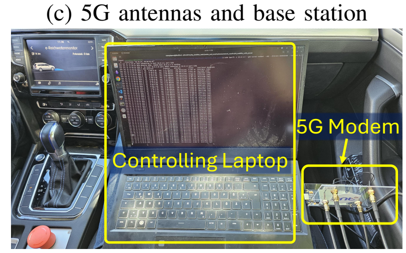
(c) 5G antennas and base station



(d) Vehicle under test



(e) Antennas on toproof



(f) Controlling laptop and modem

Fig. 2: Vehicular user equipment, environment, and street where the measurement campaign was conducted.

able insights into the capabilities of 5G networks, they do not specifically focus on vehicular applications. Using an in-motion vehicle as an information-gathering tool for assessing network coverage is common practice among all mobile network operators (MNOs). However, this method, which is known as a *drive test*, is typically employed for non-vehicular use cases. Only a limited number of studies have examined 5G performance in mobile scenarios [11]–[15] or vehicular scenarios [16]–[23]. Moreover, in these studies, vehicle speed is not reported. Due to the practical challenges of conducting performance measurements in controlled environments, some researchers have developed platforms to gather quality of service (QoS) data on busy and challenging roads and streets [24]–[28]. It might be necessary to embed such test and measurement infrastructures and mechanisms, which can systematically collect and analyze QoS data on a large scale, into the architecture of wireless networks as integral components. This approach could ensure well-functioning and always-optimized networks in the future, particularly for challenging applications like vehicular ones. Among the available studies, only a few have reported 5G measurements in vehicular scenarios that include vehicle speed [26], [29]–[33]. Moreover, none of these studies specifically examine the impact of speed on the performance metrics of 5G networks.

In this study, we aim to measure bit rate in both downlink (DL) and uplink (UL) directions, as well as latency in terms of round-trip time (RTT) and jitter, for a single, slow-moving vehicle in an urban environment while connected to a single base station (BS) of our private 5G campus network. Due to practical constraints, we limited the scope of these measurements to low speeds and urban environments, as these settings reflect typical conditions within cities where most of our time is spent. Additionally, we focused on a single-cell scenario due to similar practical constraints. Multi-cell scenarios, involving handovers between different BSs, as well as investigations in other environments and at higher speeds, require detailed experiments in future research. In the following sections, we will first describe the measurement methodology, then present the obtained results, and finally conclude with a summary.

II. Measurement Methodology

The measurement setup is shown in Fig. 1. It consists of a private 5G campus network from a local vendor, MECSware, including a server that runs 5G core network functions connecting through an Ethernet switch to an outdoor BS. The Ethernet switch also provides power for the BS in the form of power over Ethernet (PoE). The BS is located on the terrace of our lab in the NEOS building, at the University of Bremen, Germany, and faces toward Lise-Meitner-Straße Street. The building, street, and surrounding environment are shown in Fig. 2a. Other cars were rarely observed crossing the street during the measurement campaign. In the street, we drove a car equipped with four 5G antennas on its roof. The antennas are connected via 2-meter coaxial cables to a 5G modem, Quectel RM510Q-GL, which was connected to a laptop via a USB port. The car, BS, vehicle, modem, and controlling laptop are shown in Fig. 2. Please note that there were other antennas on the roof of the car which are irrelevant to this measurement campaign. The relatively long length of the 5G whip antenna, attached to the car's rooftop with its magnetic mount, is due to its wide range of supported frequency bands. In addition to the 3.75 GHz band used for our private campus network, the antenna also supports several sub-GHz bands. Further details of the measurement setup and 5G network configuration are provided in Table I.

First, we measured the reference signal received power (RSRP) at three fixed locations—points A, B, and C in Fig. 2a—conducting two measurements at each location for all four antennas, resulting in eight values. To achieve this, we used a specific AT command on the modem (`AT+QRSRP`). The statistics of the measured RSRP values, which were reasonably consistent with each other, are reported in Table II.

Network Configuration	
Number of user equipments (UEs)	1
BS transmission power	23 dBm
Carrier Frequency	3.750 GHz
Bandwidth	100 MHz
Duplexing	Time-division duplexing (TDD)
DL to UL Capacity Ratio	5:5
3GPP TDD Slot Configuration	FR1.30-5
3GPP Quality Class Indicator	5QI-9
RLC Mode	Acknowledged Mode (AM)
DL-UL Transmission Periodicity	2 ms
Subcarrier Subspacing	30 kHz
MIMO	2-layer (2T2R)
Equipment	
5G Campus Private Network	MECSware campusXG®
Base Station	Outdoor Small Cell SCO5164P
UE Modem	Quectel RM510Q-GL
UE Laptop's processor	AMD® Ryzen 5 5500u
UE Laptop's memory	32 GB
UE Laptop's OS	Ubuntu 22.04.4 LTS
UE Antenna	CompoTEK CTA 3807/5/DT/SM/T1
UE Antenna Gain	5 dBi
Smart Phone (as a GPS Recorder)	Samsung Ultra S23

TABLE I: Measurement setup parameters.

Location	**RSRP**	
	Ave. [dBm]	**Std.** [dBm]
Point A	-103.50	2.29
Point B	-103.00	5.05
Point C	-105.12	4.88
All (A, B, and C)	-103.88	4.36

TABLE II: Average and standard deviation of RSRP at various locations.

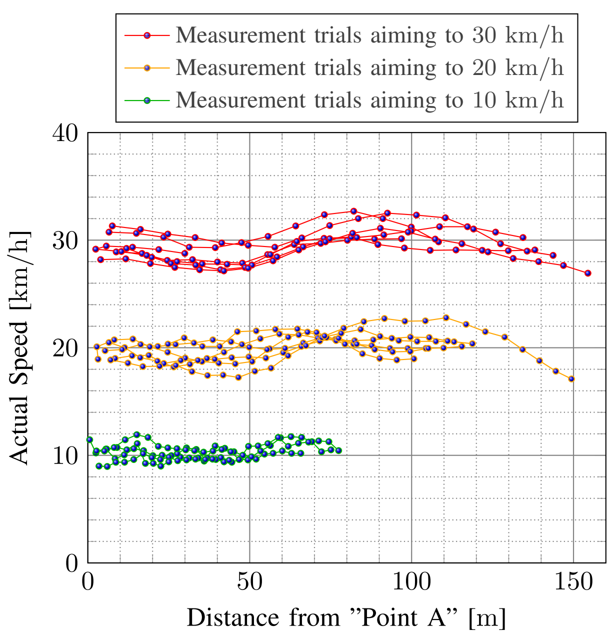
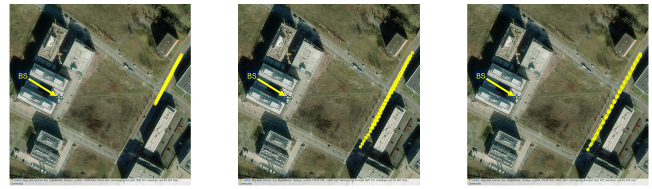


Fig. 3: Actual speed at various points along the drive track for all measurement trials, obtained from GPS recorder data, demonstrating the accuracy and consistency of manually maintained constant speeds.



(a) 10 km/h (b) 20 km/h (c) 30 km/h

Fig. 4: Tracks map.

Next, we measured the RTT using the following command.

```
sudo ping -c 1000 -i 0.001 {destination IP address}
    ↪ > outputfile_trialID.txt
```

It is worth mentioning that TDD influences latency as DL and UL packets must wait for their respective time slots before transmission. Lower RSRP, which increases the need for retransmissions, further increases the RTT. Additionally, large data packets that exceed the size of a single radio frame and require fragmentation also experience longer RTTs. In our measurements, we used the default packet size of `ping`, which is 64 bytes encapsulated within an IP packet.

Next, we measured the bit rates for DL and UL using the following two commands, respectively, in the bash terminal of the controlling laptop running Ubuntu.

```
sudo iperf3 -c {Server IP address} --udp --bitrate
    ↪ 600000000 --interval 0.1 -R --json --logfile
    ↪ outputfile_trialID.txt
```

```
sudo iperf3 -c {Server IP address} --udp --bitrate 0
    ↪  --interval 0.1 --json --logfile
    ↪ outputfile_trialID.txt
```

For measurements at different speeds, we drive the car from Point A to Point C while manually maintaining a constant speed of 10 km/h, 20 km/h, and 30 km/h. These speeds were chosen because, within cities, vehicle speeds typically fall within this range, and speeds greater than 50 km/h are generally prohibited on urban streets. We did not choose speeds of 40 km/h and 50 km/h due to practical constraints, such as the limited distance available on the selected street with 5G coverage and the time required for each test.

Before conducting the actual measurements on the street with the vehicle under test, we conducted some trial measurements in the lab to determine the time required for each measurement. Based on these trials, we limited the `ping` packet number to 1000 packets per trial to ensure that each measurement would be completed within approximately 10 seconds, which is the maximum time available on the chosen street at the speed of 30 km/h. We maintained the 10-second duration for all measurement trials to simulate consistency across all scenarios. However, fixing the time inevitably limits the distance we can drive at lower speeds. The trajectory for each measurement trial is shown in Fig. 4.

For each performance metric—DL bit rate, UL bit rate, and RTT—we conducted two measurements at each speed value, resulting in a total of six trials per speed value. However, since

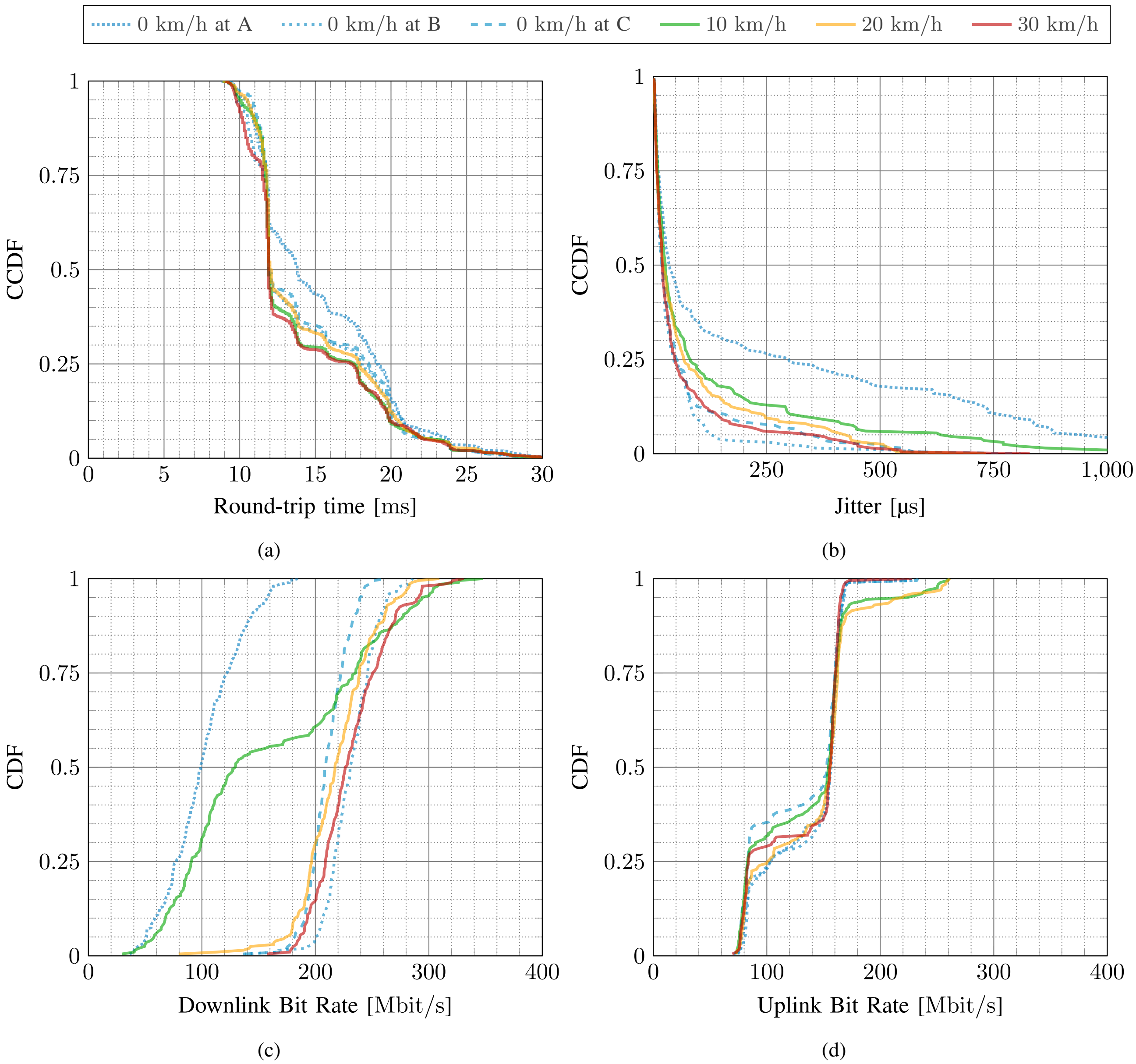


Fig. 5: Cumulative distribution of measured performance metrics.

Measurement scenarios	**Speed**	
	Ave. [km/h]	**Std.** [km/h]
Trials aiming to 10 km/h	10.28	0.71
Trials aiming to 20 km/h	19.99	1.15
Trials aiming to 30 km/h	29.45	1.54

TABLE III: Average and standard deviation of speed across different measurement trials, obtained from GPS recorder data.

we observed negligible differences between the two trials, we combined their measured samples to create a larger dataset. The exact speeds for all trials are shown in Fig. 3. As we can see, as reported in Table III, the manually-maintained constant speed exhibited reasonably low variation.

The inter-arrival jitter is defined as the average deviation in the latency of packets, calculated from the difference between the inter-arrival times of successive packets at the receiver and their corresponding inter-transmit times at the transmitter. Specifically, it is the mean of $D(i+1,i)$, as given by the following equation:

$$\begin{aligned} D(i+1,i) &= (R_{i+1} - R_i) - (S_{i+1} - S_i) \\ &= (R_{i+1} - S_{i+1}) - (R_i - S_i) \end{aligned} \quad (1)$$

where R_i and S_i are the reception time and transmission time of the i^{th} packet, respectively. To measure the inter-arrival jitter, we used `iperf3`, which is capable of reporting inter-arrival jitter in addition to measuring bit rate.

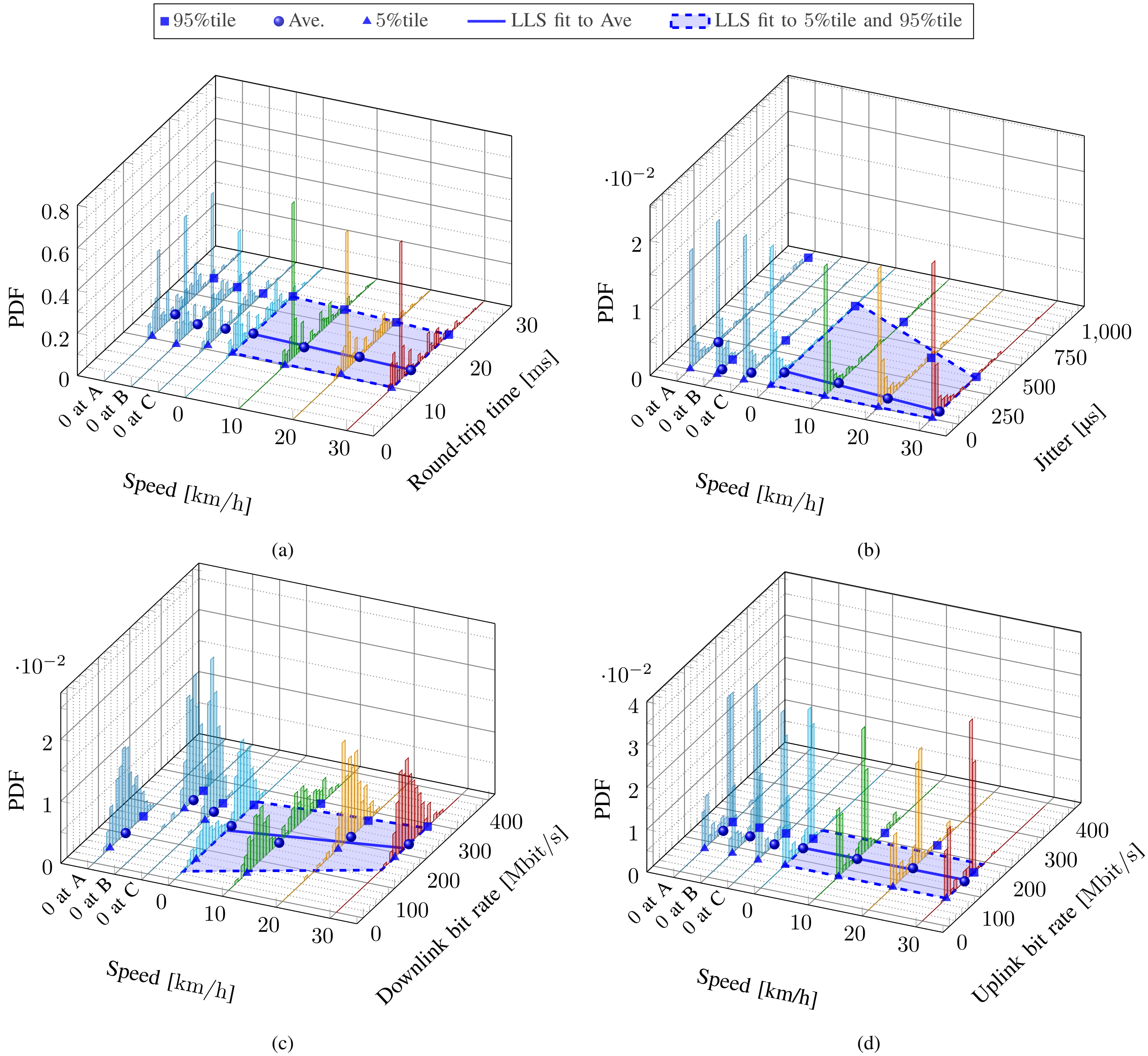


Fig. 6: Performance parameters at different speeds. The x-axis ticks '0 at A,' '0 at B,' and '0 at C' indicate stationary measurements, with speed of 0 km/h, taken at points A, B, and C, respectively. The data presented at x-axis tick '0' is a merge of all measurements taken at these stationary points.

Performance metric	**Average**		**Standard Deviation**		**5%tile**		**Median**		**95%tile**	
	slope (a)	**abscissa (b)**	**slope (a)**	**abscissa (b)**	**slope (a)**	**abscissa (b)**	**slope (a)**	**abscissa (b)**	**slope (a)**	**abscissa (b)**
Round-trip time [ms]	−0.0223	14.71	−0.0018	4.28	−0.0106	10.30	−0.0105	12.19	−0.0401	23.35
Jitter [µs]	−1.9394	121.65	−5.1053	261.44	−0.0050	4.21	−0.1599	26.14	−11.7226	698.10
Downlink bit rate [Mbit/s]	1.7230	166.20	−1.4222	72.88	3.8667	27.45	1.5153	172.23	0.7610	263.30
Uplink bit rate [Mbit/s]	0.0950	136.00	0.0074	39.87	−0.0017	77.03	0.0463	154.41	−0.1199	195.73

TABLE IV: The least squares linear fit coefficients, slope (a) and abscissa (b). The performance metrics P can be estimated versus speed S in km/h using $P = a \cdot S + b$.

III. Results and Discussion

The complementary cumulative distribution function (CCDF) of RTT and jitter, as well as the cumulative distribution function (CDF) of DL and UL bit rates at different speeds of $10\ \mathrm{km/h}$, $20\ \mathrm{km/h}$, and $30\ \mathrm{km/h}$, along with those related to stationary measurements ,i.e., $0\ \mathrm{km/h}$, at points A, B, and C, are shown in Fig. 5.

As shown in Fig. 5a, the CCDF of RTT exhibits a step-like behavior. Each downward step represents transmitted data packets that required one more repetition in the hybrid automatic repeat request (HARQ) process compared to the packets in the previous step category. When the UE is located in areas with good signal conditions, characterized by higher RSRP values, most transmitted data packets require only one transmission to successfully reach their destination. This results in the CCDF appearing as a nearly straight line on the left side, close to the plot's vertical axis. Conversely, in poor signal conditions, with lower RSRP values, more packets require additional repetitions to successfully reach their destination, causing the CCDF curve to exhibit smaller steps and shift to the right, farther from the vertical axis. However, in both cases, the starting points, indicating the minimum required RTT, and the endpoints, corresponding to packets with the highest number of repetitions, are identical.

Being in motion can make the UE encounter a various RSRP levels at different locations. Therefore, the distribution of RTT for a UE in motion can be considered a mixture of distributions from different stationary locations. Furthermore, as shown in Fig. 5b, jitter is lower at higher speeds, likely due to fewer required repetitions in better signal conditions.

The same behavior is also observed in the CDF of DL and UL bit rates. In poor signal conditions, a lower modulation and coding scheme (MCS) order is chosen for communication, resulting in a lower bit rate compared to better signal conditions, where a higher MCS order is selected. When a UE is in motion, the bit rate becomes a mixture of the bit rates from the various locations along its trajectory. This mixed behavior is evident in both Fig. 5c and Fig. 5d.

To better understand the dependence of the measured performance metrics on speed, we depict their probability density function (PDF) using 3D plots in Fig. 6. The figure also illustrates their average, 5th, and 95th percentiles, along with the linear least square (LLS) fit to these values. This figure demonstrates how the mixture distribution for a UE in motion changes with speed, resulting in slightly improved performance. The numerical values corresponding to these fitted lines are reported in Table IV.

IV. Conclusions

We assessed the impact of vehicle speed on the communication performance of a connected car, operating within a single-cell 5G campus network, while driving at slow speeds of $0\ \mathrm{km/h}$, $10\ \mathrm{km/h}$, $20\ \mathrm{km/h}$, and $30\ \mathrm{km/h}$ on an urban street.

Our empirical measurements of 5G performance for the connected car at stationary locations where the RSRP was on average $-103.88\ \mathrm{dBm}$ with a standard deviation of $4.36\ \mathrm{dBm}$, revealed that a 5G BS with a $100\ \mathrm{MHz}$ bandwidth, operating in TDD mode with equal time allocation to DL and UL, can provide average DL bit rate, UL bit rate, RTT, and jitter of $166.20\ \mathrm{Mbit/s}$, $136.00\ \mathrm{Mbit/s}$, $14.71\ \mathrm{ms}$, and $121.65\ \mu\mathrm{s}$, respectively. The standard deviations for these measurements are $72.88\ \mathrm{Mbit/s}$, $39.87\ \mathrm{Mbit/s}$, $4.28\ \mathrm{ms}$, and $261.44\ \mu\mathrm{s}$, respectively. These measurements were taken with only one UE—the car—connected to the network.

Notably, in the specific environment where our measurements were conducted, these performance metrics slightly improved with increasing speed. Specifically, RTT and jitter decreased at rates of $-0.0223\ (\mathrm{ms})/(\mathrm{km/h})$ and $-1.9394\ (\mathrm{ms})/(\mathrm{km/h})$, respectively, while DL and UL bit rates increased at rates of $1.7230\ (\mathrm{Mbit/s})/(\mathrm{km/h})$ and $0.0950\ (\mathrm{Mbit/s})/(\mathrm{km/h})$, respectively.

This improvement is plausibly attributed to increased spatial diversity at higher speeds. At higher speeds, the probability distribution of performance metrics reflects a mixture of distributions from a greater number of locations, leading to higher overall performance due to the diversity of signal conditions encountered.

Our findings underscore the importance of considering speed and mobility in the design and optimization of 5G networks for vehicular applications.

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