Impact of 5G Mobility on Teleoperation of CAVs

Rushikesh Zende*, Sree Ganesh Lalitaditya Divakarla*, Jason Carpenter, Rostand A. K. Fezeu, Ajay Kumar Gurumadiah, Eman Ramadan, Zhi-Li Zhang
University of Minnesota, Minneapolis, USA
zende039@umn.edu,divak014@umn.edu

ABSTRACT

Existing teleoperation approaches face significant challenges in achieving seamless and reliable communication between moving vehicles and remote stations over commercial 5G networks such as network stability, handover delays, and congestion, which can adversely affect teleoperation. In this study, we analyze the impacts of end-to-end latency in AV teleoperation over 5G networks within multi-CAV scenarios where vehicles compete for radio resources. Focusing on stringent latency requirements for real-time sensor data and control transmission, we evaluate WebRTC for video streaming and gRPC for a command delivery system, particularly in urban environments. We specifically explore essential 5G radio factors, including radio resource management, handover mechanisms, and network congestion, to quantify their impacts on end-to-end latency and control responsiveness. Identifying these limitations sheds light on how future 6G and Next-G networks need to be designed to support enhanced teleoperation capabilities, ensuring robust, scalable, and safe AV operations.

KEYWORDS

Multi-Connected and Autonomous Vehicles, Teleoperation, 5G Networks, WebRTC, gRPC, Network Handover

1 INTRODUCTION

Since DARPA's 2005 Grand Challenge [4], autonomous vehicles (AVs) have been intensely researched in academia and industry. Companies such as Tesla, Waymo, and Cruise have advanced towards SAE Level-4 autonomy [6], with limited robotaxi deployments in US cities [5]. However, achieving fully autonomous Level-5 AVs remains challenging due to unpredictable scenarios and recent failures, necessitating human oversight [3].

AV teleoperation (teleop) [2] bridges this gap, allowing remote human intervention when AVs encounter complex situations. Teleop is one of the emerging 5G applications which offer essential low latency and high bandwidth, but still face instability, congestion, and handover-related delays [8]. However, teleop effectiveness depends on low-latency video streaming and rapid command transmission. Hence, in this study we evaluate the performance of AV teleoperation using WebRTC which provides adaptive video streaming [7], and gRPC which ensures reliable command transmission in commercial 5G urban environments. We systematically analyze multi-AV teleoperation over commercial 5G networks, assessing the impact of 5G handovers and resource allocation on video streaming (WebRTC) and command latency (gRPC).

2 BACKGROUND

Autonomous driving levels range from conditional autonomy (Level-3) that requires human intervention to full autonomy (Level-5). Due to real-world limitations, teleoperation remains essential, combining real-time video streaming and remote vehicle control.

Although 5G supports teleop via low-latency and high-bandwidth communication, challenges persist including handovers, resource allocation, and signal quality. Metrics such as Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), and throughput critically affect connectivity. Vehicle movement triggers frequent handovers (events A1, A3, A5, and A6), causing latency, packet loss, and disruptions. Frequent "ping-pong" handovers, i.e., assuming the serving PCI is P_n, the next cell and the previous cell

* These authors contributed equally to this work.

were the same $P_{n+1} = P_{n-1}$, further degrade teleop performance, emphasizing the need for efficient handover management.

3 EXPERIMENT SETUP

Our experimental platform includes for hardware: FLIR Blackfly S GigE camera (video capture), Logitech G29 steering simulator, UMN's Connected Autonomous Vehicle (MNCAV), Samsung S22 Ultra smartphone (5G UE), and ASUS Strix Scar 16 laptop. The software stack employs ROS2 Humble, WebRTC, gRPC, Wireshark (network traffic analyzer), AWS cloud (teleop suite), and XCal (Phy layer 5G monitoring [1]).

We tested three UE setups with smartphones tethered via USB-Ethernet to laptops. An AWS instance (Ubuntu 22.04) served as the remote teleop station. Wireshark is used to capture packets on both the teleop station and onboard vehicle computer, operating on a 5G Standalone (SA) network.

Experiments included two scenarios: straight-line and urban loop drives in the U.S., involving multiple base station interactions. Network performance metrics at MAC/application layers were collected to analyze handovers, resource allocation, and QoE.

Teleop Quality of Experience (QoE) metrics evaluated:
• **Per-frame total delay**: time taken from frame generation at vehicle to playback-ready at teleop station.
• **Per-command delay**: time taken from command generation at teleop station till received at the vehicle, facilitated via gRPC over TCP.

Latency spikes during handover events (A1, A3, A5, A6) were specifically analyzed, highlighting performance impacts of rapid, successive handovers (ping-pong effect) on teleoperation responsiveness.

4 RESULTS

We evaluated teleoperation using WebRTC for IP camera video streaming and gRPC for control commands via a Logitech G29 simulator over commercial 5G networks. WebRTC streaming showed significant latency spikes during handover events (A1, A3, A5), impacting teleoperation responsiveness. RSRQ and RSRP fluctuations during handovers notably increased latency, emphasizing the need for stable network conditions.

QoE metrics—per-frame total delay, per-frame network delay, and per-command delay—were assessed in two scenarios:

1) Straight-Line Drive (3.5 miles): Latency spikes were prominent during handovers, highlighting the importance of optimized handover management.
2) Urban Loop Drive (3 miles): Frequent ping-pong handovers caused repeated latency spikes and degraded QoE.

Quantitative results:
• **Per-frame total delay**: 400ms (normal Handover event A3), 600ms (Ping-Pong Handover)
• **Per-command delay**: 60ms (normal Handover event A3), 260ms (Ping-Pong Handover)

5 CONCLUSION

This study sheds light on the feasibility of AV teleoperation over 5G networks, highlighting critical impacts of RSRQ, RSRP, and handover management on latency and streaming quality. Integrating WebRTC and gRPC supports effective teleoperation, but optimizing network conditions remains essential for achieving robust performance.

REFERENCES

[1] 2022. Accuver XCAL. https://www.accuver.com/sub/products/view.php?idx=6&ckattempt=2.
[2] 5Gaa. 2021. *Teleoperated Driving (ToD): System Requirements Analysis and Architecture.* Published: Retrieved from https://5gaa.org/content/uploads/2021/09/5GAA_ToD_System_Requirements_Architecture_TR.pdf.
[3] J. Brodkin. 2023. *After robotaxi dragged pedestrian 20 feet, Cruise founder and CEO resigns.* Published: Retrieved from https://arstechnica.com/tech-policy/2023/11/after-robotaxi-dragged-pedestrian-20-feet-cruise-founder-& and-ceo-resigns/.
[4] Martin Buehler, Karl Iagnemma, and Sanjiv Singh. 2007. *The 2005 DARPA Grand Challenge: The Great Robot Race.* Springer Science & Business Media. Google-Books-ID: euqA_iWt2TgC.
[5] A. J. Hawkins. 2022. *Waymo's driverless vehicles are picking up passengers in downtown Phoenix.* Published: Retrieved from https://www.theverge.com/2022/8/29/23323593/waymo-driverless-vehicles-passengers-downtown-phoenix.
[6] Wagner Koopman, P. 2016. *Challenges in Autonomous Vehicle Testing and Validation. SAE International Journal of Transportation Safety* 4, 1 (April 2016), 15–24. https://doi.org/10.4271/2016-01-0128 Publisher: Troy, MI: SAE International.
[7] Urgaonkar Spiteri, Kevin. 2020. *BOLA: Near-optimal bitrate adaptation for online videos. IEEE/ACM Transactions On Networking* 28, 4 (2020), 1698–1711. Publisher: IEEE.
[8] Carpenter Ye, Wei. 2023. *A Closer Look at Stand-Alone 5G Deployments from the UE Perspective.* In *2023 IEEE International Mediterranean Conference on Communications and Networking (MeditCom).* IEEE, 86–91.