Millimeter Wave Cellular Networks for Teleoperated Vehicles: A Simulation Study

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***Abstract*—Recent advances in Vehicle-to-Everything (V2X) communication have significantly improved road safety. However, the requirements of future vehicular applications are rapidly surpassing the capabilities of current generation cellular networks. Future wireless networks are expected to use millimeter wave (mmWave) frequencies due to spectrum availability and promises of very high throughput and ultra-low latency. These frequencies suffer from high path loss and are sensitive to mobility, which poses new challenges for V2X. In this paper, we investigate vehicular communication at mmWave frequencies through extensive simulation. We design, implement, and simulate various vehicular scenarios to investigate the impact of mmWave frequencies and mobility on system performance, with a specific focus on teleoperated driving applications due to their high uplink throughput requirements. Our simulation results demonstrate the potential of mmWave networks for vehicular communication, while highlighting the need to address challenges such as limited uplink capacity and poor reliability.**

***Index Terms*—vehicular communication, V2X, mmWave, teleoperation, simulation, ns-3, 5G, cellular**

I. INTRODUCTION

Vehicle-to-Everything (V2X) communication has received a lot of attention over the past decade due to its large number of possible applications, ranging from increased road safety and traffic efficiency services to in-car entertainment solutions [1], [2]. V2X is an umbrella term for several distinct types of communication involving vehicles, such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and Vehicle-to-Road Side Unit (V2R). Currently, there are two standardization entities working on V2X access protocols: the Institute of Electrical and Electronics Engineers (IEEE) and the 3rd Generation Partnership Program (3GPP). Each entity has two generations of V2X standards. IEEE has their 802.11p [3] and 802.11bd [4] standards, providing V2V and V2I capabilities. Similarly, 3GPP has specified the Long Term Evolution (LTE)-V2X [5] and New Radio (NR)-V2X [6] specifications, which also provide Vehicle-to-Network (V2N) capabilities through existing cellular network standards (4G LTE and 5G NR) [7].

Today, LTE-V2X and 802.11p are being integrated into a wide range of vehicles, and more and more roads are being equipped with the associated road infrastructure. Although these standards already increase road safety, we face significant challenges in achieving the stringent requirements of advanced vehicular use cases using today's network infrastructure [8]. One key example is teleoperated driving, which enables a remote driver to operate a vehicle over the network. This use case requires high uplink (UL) throughput and ultra-low End-to-End (E2E) latency to transmit multiple video feeds from the vehicle to the remote driver with minimal delay [9]. In addition, the shift towards millimeter wave (mmWave) and sub-THz frequencies for next-generation wireless networks promises extremely high data rates and ultra-low latency, but they suffer from high losses and require beamforming, which is extremely challenging in highly mobile environments.

Although V2X communication and mmWave frequencies are certainly not new concepts, we have limited knowledge and quantitative data on the combination of both. More specifically, the use of mmWave frequencies in cellular networks for V2N communication has not yet been thoroughly explored. Therefore, our objective is to investigate the use of these mmWave frequencies in a vehicular environment. We conduct an extensive simulation study to 1) measure the E2E performance of V2N communication using mmWave frequencies; and 2) investigate whether a mmWave Radio Access Network (RAN) can provide the capacity to support the UL throughput and latency requirements for teleoperated driving.

II. RELATED WORK

Previous studies have explored mmWave communication in vehicular contexts, although with different scopes and goals. Zugno et al. [10] conducted E2E performance evaluations of mmWave V2X communication using ns-3 and the MilliCar[1] module. However, they primarily focused on V2V communication over Sidelink (SL), and not on V2N or V2I. Khan et al. [11] investigated mmWave V2I communication for various next-generation use cases in urban traffic scenarios, but the scope of their study did not include mobility at highway speeds or teleoperated driving applications.

We aim to bridge these gaps in our study by conducting E2E mmWave simulations for a teleoperation use case. To do so, the simulator must meet several requirements: 1) support for 5G NR; 2) support for operation at Frequency Range 2 (FR2) through mmWave channel models; 3) implementation of higher layer protocols for E2E simulations; and 4) mobility models for simulating highly mobile vehicular environments. Among the various available simulators, ns-3[2] emerges as a widely used option in academia for system-level network simulations. By default, ns-3 does not offer models to simulate mmWave RANs, but there are two community-maintained modules that allow users to perform 5G simulations at mmWave frequencies: the `mmWave` module [12] and the 5G-LENA `NR` module [13]. Both modules can simulate a mmWave 5G Non-Standalone (NSA) network, which means that 5G gNodeB (gNB) are connected to a 4G core consisting of a Mobility Management Entity (MME), a Serving Gateway (SGW), and a Packet Data Network Gateway (PGW). Although the `mmWave` module provides more advanced features, such as various types of handovers [14], [15], we opt for

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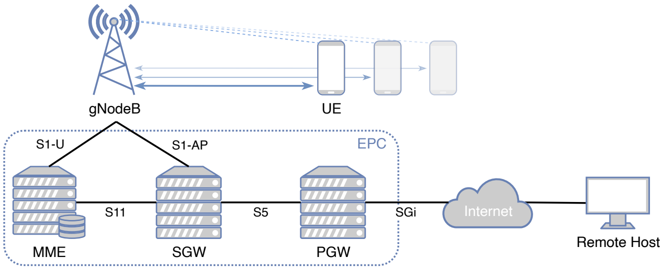
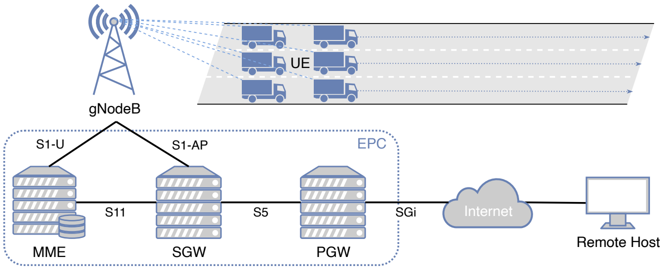
[1] MilliCar: https://github.com/signetlabdei/millicar

[2] ns-3: https://www.nsnam.org



(a) Stationary scenario. A single UE device is placed at various distances from the gNB and transmits UL data to the remote host.



(b) Teleoperation scenario. One or more teleoperated vehicles drive down a highway, sending UL video data to a remote operator.

Fig. 1: Generic structure of the scenarios under investigation.

the `NR` module due to its strong focus on 3GPP standard compliance and thorough model validation [13].

In summary, we perform E2E mmWave simulations using a 5G NSA network and a RAN capable of operating in FR2 (24.25-52.6 GHz). We use a carrier frequency of 26 GHz in our simulations, representing the 3GPP n258 band approved for use in Europe [16]. The simulation scenarios we consider are limited to a single gNB due to the lack of handover support in the `NR` module. While our study does not require multi-gNB functionality, its inclusion could be valuable for future work.

III. METHODOLOGY

In this section, we present the set of scenarios that we designed and implemented into the simulator to investigate teleoperation at mmWave frequencies.

A. *Scenarios*

We design and investigate two scenarios: a stationary scenario and a teleoperation scenario. The stationary scenario, shown in Fig. 1a, contains a single stationary User Equipment (UE) device that transmits UL data to a remote host. With this scenario, we intend to explore the limits of mmWave with respect to the distance between the transmitter and the receiver, creating a baseline for the teleoperation scenario. As a result, the simulation environment encompasses mmWave communication in perfect radio transmission environments. Therefore, the results obtained from this scenario serve purely as a best-case baseline and are not an accurate representation of real-life network performance.

The teleoperation scenario is a scenario with On-Board Units (OBUs) and is intended to represent an environment in which teleoperated vehicles move at highway speeds. Through this scenario, depicted in Fig. 1b, our objectives are twofold: 1) to explore the influence of UE mobility on the stability of the mmWave network; and 2) to assess whether a mmWave RAN can meet the capacity, latency, and distance requirements necessary for the operation of one or more teleoperated vehicles. As a result, the teleoperation scenario has more realistic network conditions than the stationary scenario. Furthermore, we investigate two variants of this teleoperation scenario: an ideal teleoperation scenario, which is configured with a dynamic Time Division Duplex (TDD) pattern, and a realistic teleoperation scenario, configured with a fixed downlink (DL)-heavy TDD pattern commonly used in cellular networks. The ideal variant again serves as a baseline to test the limits of the RAN in a highly mobile environment, while the variant with the fixed TDD pattern is intended to investigate the performance of a RAN with a commonly employed resource allocation scheme.

TABLE I: Uplink target requirements for teleoperation [17]

Target Requirement	**Target Value**
Network throughput	75 Mbps
Network latency	<50 ms

B. *Target Requirements*

To establish the operational requirements for our teleoperation scenarios, we leverage insights gained from the 5G-Blueprint European research project [18], [19], which aimed to design seamless cross-border teleoperated transport using 5G. Specifically, we align our requirements with the Automated Driver-in-Loop Docking use case defined by the project, focusing on remote docking of articulated vehicles in logistical settings. The practical requirements for this use case suggest the need for three High Definition (HD) video streams per vehicle to provide a live view of the environment to the remote operator [17]. For simplicity, we focus on achieving adequate UL throughput and latency for these video feeds, which is by far the most challenging requirement, and we disregard additional telemetry data and vehicle control interfaces in our simulations. In summary, Table I lists our target requirements used to evaluate the suitability of the network to support remote driving applications.

C. *Simulation methodology*

To evaluate the performance of the mmWave network in the various scenarios, we collect the following three Key Performance Indicators (KPIs) across our simulation runs: 1) mean UL Signal to Interference plus Noise Ratio (SINR); 2) mean UL Packet Data Convergence Protocol (PDCP)-level throughput; and 3) mean UL PDCP-level latency. In total, we perform $N = 50$ independent simulation runs per scenario.

Table II presents the simulation parameters used for both stationary and teleoperation scenarios. Throughout our simulations, we utilized the *V2V-Highway* version of the 3GPP Statistical Channel Model (SCM), as described in Technical Report (TR) 38.901 [21], and the majority of RAN parameters conform to the guidelines and recommended default values provided in 3GPP TR 37.885 [22] for simulating V2X environments above 6 GHz. However, for simplicity, we modified and excluded some parameters. We replaced the default stochastic 3GPP condition model by a model that always assumes Line of Sight (LOS) connectivity to mitigate simulation issues. The default condition model, which switches between LOS

TABLE II: Common simulation parameters and KPIs

Parameter	Value
RAN	
Carrier frequency	26 GHz
Bandwidth	200 MHz
Numerology	2 (SCS = 60 kHz)
gNB Tx power	43 dBm
UE Tx power	23 dBm
UE antenna array	2 × 4 UPA
gNB antenna array	4 × 8 UPA
Beamforming	Direct path
Channel model	3GPP SCM (*V2V-Highway*[1])
Condition model	Always LOS
Antenna element	Isotropic
Power allocation	Uniform over full BW[2]
MCS table	3GPP TS 38.214 table 1
Network	
Transport protocol	UDP
Packet size	1000 B
Environment	
gNB height	5 m
UE height	3 m
Minimum UE-gNB distance	50 m
KPIs	
Mean UL SINR	
Mean UL PDCP-level throughput	
Mean UL PDCP-level latency	

A list of simulation parameters used for all scenarios, as well as the KPIs captured across all of our simulation runs.

[1] This can also be used for V2R (among others) [20].

[2] Always uses all Resource Blocks (RBs) for the average SINR calculation.

and Non-LOS due to vehicles (NLOSv) states, occasionally causes link failures when switching to NLOSv, resulting in an interrupted simulation run. Consequently, our performance metrics are relevant only for LOS connections. Furthermore, we used an isotropic antenna element model to facilitate comparison with theoretical limits. Although a more realistic antenna element would marginally increase the gain of the resulting antenna array, the impact on the results would be relatively small. Finally, we did not configure any additional Core Network (CN) latencies, which means that our results only reflect the latency introduced by the RAN.

In addition to the common simulation parameters, Table III defines parameters specific to each of the considered scenarios. For each simulation run in the stationary scenario, a single UE is positioned at a fixed distance from the gNB and transmits as much traffic as possible to a remote host via the gNB and the CN. Each run has a simulation time of 1 s, and the UE is displaced across independent simulation runs in intervals of 10 m. Conversely, the teleoperation scenario contains one, three, or six UEs driving down a highway at 90 or 120 km/h, each sending a data stream of 75 Mbps to the gNB configured with either a dynamic or fixed TDD pattern.

IV. RESULTS

A. Stationary Scenario

The simulation results for the stationary scenario are presented in Fig. 2, showing the mean SINR and throughput as functions of distance. The latency results for this scenario are omitted, as the data transmission rate used exceeds the theoretical capacity of the mmWave link, causing the UE transmission buffer to immediately reach full capacity. Consequently, the resulting latency measurements are unrealistic and do not provide meaningful insights.

TABLE III: Scenario-specific simulation parameters

Parameter	Value	
	Stationary	**Teleoperation**
RAN		
gNB noise figure	5 dB	7 dB
UE noise figure	5 dB	10 dB
Shadowing	Disabled	Enabled
Interference	None	Co-channel
TDD pattern	Dynamic[3]	{Dynamic[3], `DDDSU`[4]}
Network		
Traffic rate	Full buffer	75 Mbps
Environment		
UE-gNB distance interval	10 m[5]	N/A
Simulation time	1 s	N/A
Number of UEs	1	$\{1, 3, 6\}$
UE velocity	N/A	$\{90, 120\}$ km/h

A list of scenario-specific simulation parameters.

[3] For each slot, the first and last symbol are reserved for DL and UL control. The remaining 12 symbols are dynamically allocated to DL or UL data, depending on the traffic.

[4] In `D` (resp. `U`) slots, the first symbol is for DL (resp. UL) control, while the rest is for DL (resp. UL) data. In `S` slots, the first symbol is reserved for DL control, the last symbol for UL control, and the rest for DL data.

[5] The interval with which we shift the UE across independent simulation runs.

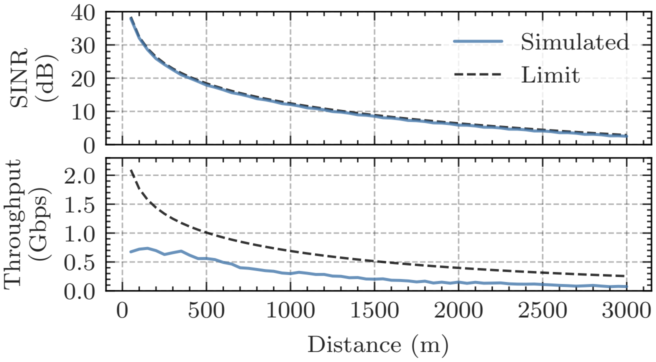


Fig. 2: Average UL SINR and throughput for a single stationary UE transmitting at 26 GHz. The SINR and throughput limit, as defined in Section IV-A, represent the theoretical maximum values based on the Friis transmission formula and Shannon's theorem, respectively.

The SINR and throughput results are accompanied by their theoretical limits. The SINR plot shows the theoretical Signal to Noise Ratio (SNR), and is calculated using the formula:

$$\mathrm{SNR}^{[\mathrm{dB}]} = P_{\mathrm{rx}}^{[\mathrm{dBm}]} - N_T^{[\mathrm{dBm}]} - \mathrm{NF}_{\mathrm{rx}}^{[\mathrm{dB}]},$$

where $P_{\mathrm{rx}}^{[\mathrm{dBm}]}$ is the received power, $N_T^{[\mathrm{dBm}]}$ is the thermal noise at $T = 290\,\mathrm{K}$, and $\mathrm{NF}_{\mathrm{rx}}^{[\mathrm{dB}]}$ is the receiver noise figure. The received power is computed using the Friis equation:

$$P_{\mathrm{rx}}^{[\mathrm{dBm}]} = P_{\mathrm{tx}}^{[\mathrm{dBm}]} + G_{\mathrm{tx}}^{[\mathrm{dBi}]} + G_{\mathrm{rx}}^{[\mathrm{dBi}]} + \mathrm{FSPL}^{[\mathrm{dB}]},$$

where $P_{\mathrm{tx}}^{[\mathrm{dBm}]}$ is the transmit power, $G_{\mathrm{tx}}^{[\mathrm{dBi}]}$ (resp. $G_{\mathrm{rx}}^{[\mathrm{dBi}]}$) is the antenna gain of the transmitter (resp. receiver), and $\mathrm{FSPL}^{[\mathrm{dB}]}$ is the Free-Space Path Loss between transmitter and receiver. Subsequently, the resulting SNR value is used to compute the maximum achievable throughput based on Shannon's formula:

$$C = B \cdot \log_2\left(1 + 10^{\frac{\mathrm{SNR}^{[\mathrm{dB}]}}{10}}\right) \cdot r_{\mathrm{symb}},$$

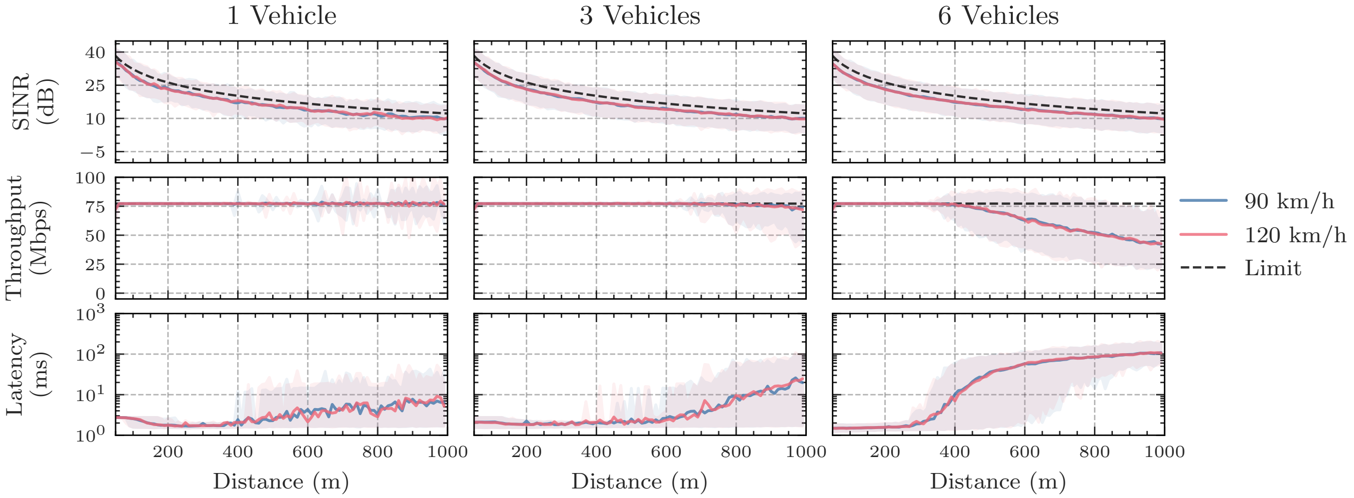


Fig. 3: Average UL SINR, throughput, and latency for the ideal teleoperation scenario with one, three, and six UEs. The SINR limit shows the theoretical SINR, as defined in Section IV-A, while the throughput limit represents the total amount of data sent (around 77 Mbps: 75 Mbps + headers).

where C is the maximum capacity, B is the total bandwidth used, and r_{symb} represents the maximum ratio of Orthogonal Frequency-Division Multiplexing (OFDM) symbols in a slot that can be allocated for data transmission. In dynamic TDD mode, we set $r_{\text{symb}} = 12/14$, since 12 of 14 symbols in a slot can be dynamically allocated for data (see Table III).

Our obtained simulation results reveal that the mean SINR has little deviation from its theoretical counterpart. This is expected considering that the RAN configuration of the stationary scenario represents an ideal radio propagation environment. In contrast, the simulated throughput curve shows a significant discrepancy with the theoretical maximum, primarily caused by the spectral efficiency limitations imposed by the Modulation and Coding Scheme (MCS). Our findings underscore the potential of mmWave in stationary LOS scenarios, as illustrated by the hundreds of Mbps achieved over several kilometers.

B. *Teleoperation Scenarios*

Fig. 3 presents the average SINR, throughput, and latency of the ideal teleoperation scenario for one, three, and six simultaneously teleoperated vehicles. Unlike the stationary scenario, the latency results are included here, as they provide valuable insights regarding network stability. In these scenarios, each vehicle transmits at a fixed data rate well within the theoretical limits of the mmWave link. Consequently, the UE buffers begin to fill only when the link cannot support user demand, which is reflected by increased latency.

The SINR exhibits minimal variation with increasing vehicle count and velocity. For a single vehicle, we observe that our target throughput can be maintained over a considerable distance using the dynamic TDD structure, with sporadic deviations peeking at 7.1 Mbps around the 1 km mark. A closer inspection of the dynamic resource allocation reveals enormous variations in the ratio of UL OFDM symbols per frame (min: 8.0 %, max: 85.7 %, mean: 32.5 %, std: 14.9 %). The UL symbol allocation ratio is highly dependent on distance and MCS, highlighting the importance of such a flexible TDD scheme for achieving our target KPIs. While latency remains relatively low with a maximum of 8.1 ms, the standard deviation reaching up to 12.2 ms indicates occasional network instability. With three vehicles, we notice a decrease in throughput after 700 m, where latency starts to show deviations between 13.4 and 31.1 ms, rendering the network unstable for remote driving. The presence of six vehicles amplifies these problems, with throughput deteriorating after 400 m and latency exceeding the target 50 ms.

In the realistic teleoperation scenario, our findings remain consistent between scenarios featuring one, three, and six vehicles: teleoperation is not viable using the fixed DL-heavy TDD pattern. Even with a single vehicle, throughput degradation begins at 450 m, accompanied by increased latency and jitter.

C. *Summary*

Our simulation results reveal significant limitations in achieving the required UL throughput and latency targets, especially when the network is configured with a fixed TDD pattern. Although our simulations provide valuable insights, there are important factors that we have not considered that will have a significant impact on E2E performance. First, core network latency, which was not included in our simulations, will add to the latency results we presented and will therefore further limit the feasibility of teleoperation applications. Furthermore, we used perfect beam tracking in our simulations, while in reality, the development of robust beam tracking algorithms for highly mobile environments remains an open challenge. Finally, our results apply only to LOS links, since we did not consider NLOS scenarios. Dealing with NLOS will be crucial to make high capacity mmWave and sub-THz links reliable.

V. CONCLUSION & FUTURE WORK

In this paper, we investigate the feasibility of using mmWave cellular networks for teleoperated driving applications through an extensive simulation study. Our findings highlight the potential of high-frequency communication, but

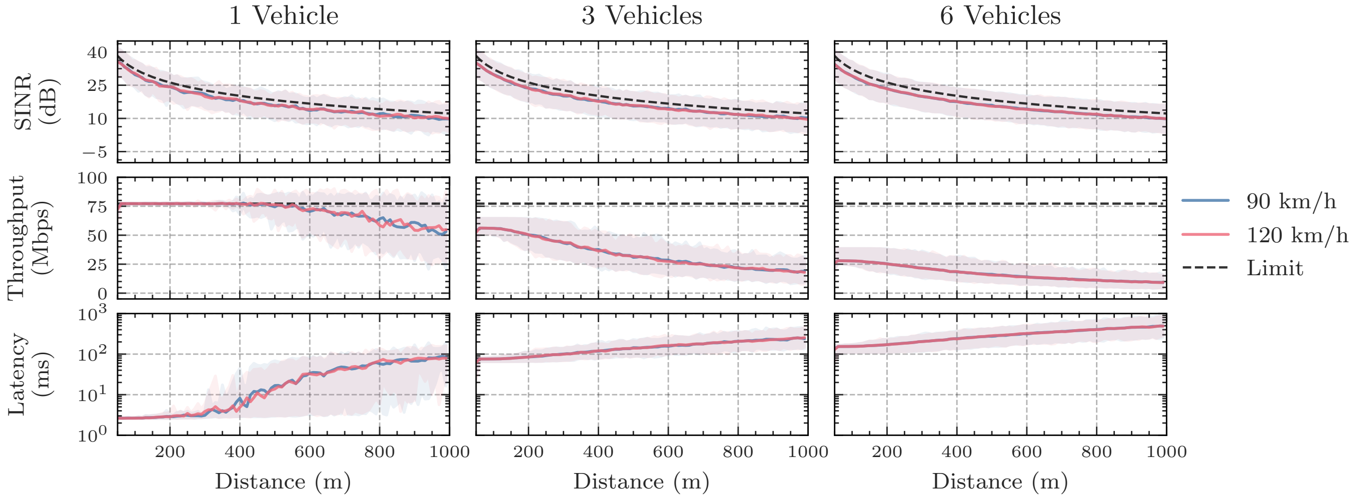


Fig. 4: Average UL SINR, throughput, and latency for the realistic teleoperation scenario with one, three, and six UEs. The SINR limit shows the theoretical SINR, as defined in Section IV-A, while the throughput limit represents the total amount of data sent (around 77 Mbps: 75 Mbps + headers).

also identify challenges. First, the downlink-heavy resource allocation found in current cellular networks restricts the uplink capacity, emphasizing the need for a more dynamic resource allocation scheme. Second, the reliability of mmWave links leaves much to be desired, indicating the need to be complemented with Multi-Connectivity (MC) or mesh networking techniques for link redundancy and range extension.

In future work, we plan to investigate the use of mesh networking as a possible solution to address the challenges related to reliability and NLOS links. This entails assessing the trade-offs between additional reliability through redundant links and extended range through multi-hop communication, considering their impact on complexity and latency.

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