

# A 5G Campus Network Architecture Enabling Cooperative V2X Communication for Autonomous Driving

*This paper investigates the integrative development and real-world evaluation of Vehicle-to-Everything (V2X) communication architectures for autonomous driving in 5G standalone campus networks. The focus is on Cellular V2X Day-2 use cases as well as the application of network slicing, mobile edge computing, and ultra-reliable low-latency communication to support safety-critical scenarios. For this purpose, a 5G campus network is being deployed at the Ostfalia University of Applied Sciences, equipped with sensor-based roadside units that transmit real-time environmental data to vehicles through collective perception. An autonomous shuttle serves as a test platform for analyzing complex traffic situations. The results indicate that 5G-based V2X communication significantly improves reliability, responsiveness, and situational awareness, thereby providing a key foundation for future cooperative and connected mobility systems.*

**Keywords:** 5G campus network, V2X, autonomous driving, collective perception, cooperative intelligent transport systems

## Introduction

Highly automated driving is expected to fundamentally transform future mobility systems. Current Advanced Driver Assistance Systems (ADAS), and their more advanced extensions toward predictive ADAS (pADAS), primarily rely on onboard sensor data, which inherently limit perception to the vehicle's immediate surroundings. Even with predictive capabilities, environmental conditions such as occlusions, adverse weather, or complex urban layouts significantly constrain sensing reliability and foresight.

V2X communication addresses these limitations by enabling vehicles to exchange information with other vehicles, infrastructure, and network components, thereby extending perception beyond line-of-sight. While Day-1 use cases already support basic safety messaging, more advanced Day-2 use cases – particularly those relevant for pADAS and cooperative automated driving – require high data rates, ultra-low latency, and high reliability to enable predictive and coordinated maneuvers (Car 2 Car Consortium, 2021) (3GPP, 2023).

Fifth-generation (5G) mobile networks, especially in standalone (SA) mode, introduce key technological enablers such as Ultra-Reliable Low-Latency Communication (URLLC), network slicing, and Mobile Edge Computing (MEC). These capabilities provide the necessary technological and infrastructural foundation for cooperative perception and real-time decision-making, which are essential for both autonomous driving and next-generation pADAS functionalities (Habak, et al., 2023).

Building on previous conceptual work, this paper presents the implementation and evaluation of a V2X architecture within a dedicated 5G campus network (Pramme, et al., 2024). The main contributions of this work include the design and deployment of a 5G-SA based V2X architecture for autonomous driving, the integration of heterogeneous roadside unit sensor systems for collective perception, the implementation of MEC-supported real-time data processing, the experimental evaluation using a real-world autonomous shuttle, and the derivation of architectural design guidelines for future Cooperative Intelligent Transport Systems (C-ITS).

## State of the Art

The integration of 5G and V2X communication has become a pivotal enabler for the development of highly automated and cooperative intelligent transportation systems (ITS) (Marten Wille, et al., 2010). While early V2X architectures relied on DSRC or LTE-V2X, the deployment of 5G SA networks characterized by enhanced (Chen, et al., 2016) support for Ultra-Reliable Low-Latency Communication (URLLC), network slicing, and Mobile Edge Computing (MEC) has significantly expanded the functional and performance capabilities of connected mobility ecosystems (Sicong, et al., 2022) (An & Chang, 2023).

The introduction of 3GPP Release 16 has enabled the transition from Day 1 to Day 2 use cases, which go beyond basic warning functions and allow for cooperative overtaking maneuvers, remote vehicle operation, and collective perception through shared sensor information (Chen, et al., 2016). The improved PC5 interface allows prioritization and resource pooling, and thus plays a crucial role in enabling direct, timely communication between vehicles and infrastructure, increasing reliability and efficiency.

A key advancement is the introduction of network slicing, which allows virtual, isolated networks to operate on a shared physical infrastructure – each optimized for specific requirements: a URLLC slice for critical security applications with sub 1ms latency and over fault tolerance, a high-throughput slice for transmitting high-resolution LiDAR or video data, and a management slice for control and monitoring. Studies show that this architecture improves resource utilization by up to 40 % and significantly reduces interference between services (Chen, et al., 2023).

**Table 1.** *Overview of communication technologies and their features*

Feature	LTE-V2X	5G C-V2X (Release 16)	Important for
Latency	20 – 50 ms	< 10 ms (URLLC)	Real-time-control
Reliability	~ 99 %	> 99.999 %	Safety-critical applications
Throughput	~10 Mbps	< 1 Gbps	High-resolution sensor data
Network Slicing	No	Yes	Service differentiation

MEC Support	Limited	Native	Local decision-making
Collective Perception	Basic	CPM-based	Extended awareness

The goal is to create a shared, enhanced environmental model. This enables vehicles to detect obstacles obscured by visibility issues such as curves or buildings, significantly improving detection accuracy in critical situations. However, challenges remain achieving the theoretically expected latency of less than 1 ms is often not guaranteed in dynamic, urban environments, as factors such as interference, movement, and environmental conditions affect performance (Habak, et al., 2023). Furthermore, uncertainties persist regarding scalability in densely populated areas, data security and privacy, and interoperability between different platforms and manufacturers. Although several European testbeds, such as 5G-ACIA<sup>1</sup> and the C-Roads<sup>2</sup>, are already delivering initial results, integrated, real-world test environments that combine all components 5G-SA, slicing, MEC, multi-sensor infrastructure, and autonomous vehicles in a cohesive, practical context are still lacking. This gap shall be addressed with the 5G-Campus-Network<sup>3</sup> at the Ostfalia University in Wolfenbuettel Germany, which acts as a living laboratory to validate the end-to-end performance of 5G-V2X in complex, safety-critical scenarios and to develop architectural guidelines for future cooperative transportation systems.

## Concept

A key element of this research project is the establishment of a reference test track on the Wolfenbuettel campus of the Ostfalia University of Applied Sciences. This track is equipped with a comprehensive infrastructure for vehicle-to-infrastructure (V2I) communication. The test track integrates Road Side Units (RSUs) that support bidirectional data exchange via standardized WiFi-protocols. This enables connected vehicles to be provided with real-time traffic information, dynamic route guidance, and context-related data, such as the detection of pedestrians, cyclists, and public transport users.

The RSUs are connected to a heterogeneous sensor network consisting of high-resolution cameras, LiDAR systems, radar devices, and laser scanners, enabling multimodal environmental perception. Depending on latency, data privacy, and application requirements, the acquired sensor data is either processed locally on-site or forwarded to a central traffic control center. This data fusion capability supports advanced use cases in ITS, including cooperative hazard detection and hazard analysis.

Autonomous vehicles utilize sensor fusion from four primary sensors: cameras, ultrasonic sensors, radar, and LiDAR. While each of these modalities

<sup>1</sup>5G-ACIA is the central global forum for shaping 5G in the industrial domain. <https://5g-acia.org>

<sup>2</sup>C-Roads Germany is a pilot project for the introduction of cooperative intelligent transport systems (C-ITS) <https://www.c-roads-germany.de/english/>

<sup>3</sup><https://niedersachsen.digital/foerderung-fuer-5g-campus-kishuttle-projekt/>

1 offers specific advantages, it also has inherent limitations: cameras exhibit  
2 reduced performance in adverse weather and lighting conditions; radar enables  
3 reliable detection in all environmental conditions, but its long wavelength  
4 prevents detailed object classification; and LiDAR, despite its high spatial  
5 resolution, reaches its limits in dense fog or heavy rain.

6 While 4G LTE is sufficient for less critical V2X services such as advanced  
7 routing, future applications for cooperative driving – such as platooning,  
8 intersection collaboration, and emergency braking – require extremely reliable,  
9 low-latency communication. The introduction of 5G New Radio (5G NR) meets  
10 these requirements through improved spectral efficiency, end-to-end latency of  
11 less than 10 ms, support for massive Machine-Type Communications (mMTC)  
12 and URLLC (Jouini, et al., 2023).

13 Furthermore, 5G NR enables centimeter-level positioning through real-time  
14 kinematics (RTK) combined with GNSS, crucial for high-precision localization  
15 in automated driving. The integration of Mobile Edge Computing (MEC) into  
16 the 5G architecture enables distributed data processing at the network edge,  
17 thereby reducing latency, bandwidth requirements, and onboard computing  
18 resources. This is essential for real-time decision-making in dynamic traffic  
19 environments.

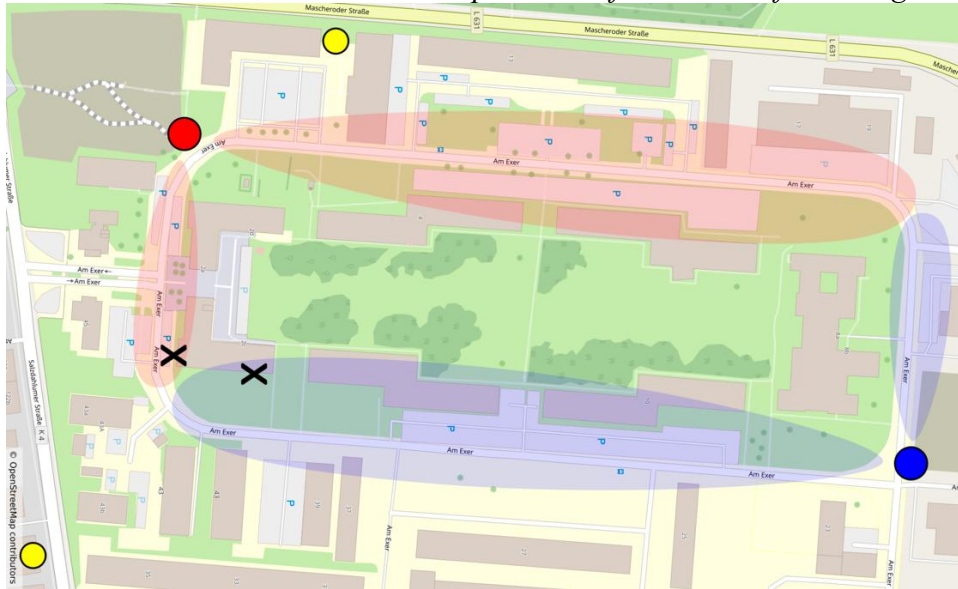
20 Given the high data throughput and stringent timing requirements of  
21 autonomous driving research, a dedicated, private 5G radio access network  
22 (RAN) has been implemented on campus (Carmen Lucas-Estan, et al., 2021).  
23 This private 5G network ensures deterministic performance with sub-5 ms  
24 latency and provides a secure, scalable, and reproducible test environment. The  
25 infrastructure supports the development, validation, and benchmarking of next-  
26 generation V2X applications and enables controlled experimentation with  
27 cooperative driving functions, edge-based AI-applications, and multi-agent  
28 coordination.

29 This test environment serves as a living laboratory to advance research in  
30 connected and autonomous mobility and offers a unique platform for  
31 interdisciplinary collaboration and innovation in intelligent transportation  
32 systems to establish a fully autonomous shuttle service in a controlled urban  
33 environment near the campus. The system utilizes conventional sensors,  
34 consisting of cameras, LiDAR, and ultrasonic sensors, supplemented by V2X  
35 communication and a campus-wide, 3GPP-compliant 5G standalone network.

36 The autonomous shuttle operates on a 1.2 km circular route with several  
37 intersections, where visibility is obstructed by buildings (see Figure 1). Equipped  
38 with a multi-sensor fusion system, the vehicle communicates via C-V2X (PC5  
39 interface) with a road infrastructure unit (RSU) at a three-way intersection. The  
40 RSU features a high-resolution radar sensor and processes local object data. This  
41 data is used to generate traffic perception models (CPMs) to share real-time  
42 perception information with nearby vehicles. The entire system is connected via  
43 a 5G campus network, which enables network slicing for dedicated remote  
44 control and safety-critical data transmission. Edge computing nodes are  
45 deployed at the periphery of the campus network to enable sensor data

1 processing and decision support, while also providing the foundation for remote  
2 operation.

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4 **Figure 1.** University campus with antennas of the 5G campus network and  
5 network coverage: red and blue circle shows own antennas, yellow circles  
6 illustrate carrier antennas, X marks positions of 5G routers for testing



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9 This testbed enables empirical investigation of the following research questions:

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11
- 12 • RQ1: How do network slicing and 5G SA improve communication quality (latency, jitter, packet loss) between the vehicle and a remote teleoperator?
  - 13 • RQ2: To what extent do V2X Day-2 use cases particularly collective perception enhance situational awareness and safety in complex intersection scenarios?
  - 14 • RQ3: Can the theoretical 1ms latency target of 5G SA and URLLC be achieved in practice under real-world conditions, and how does this impact remote operation responsiveness?
  - 15 • RQ4: How does MEC-based offloading of perception and planning tasks improve decision-making speed and overall traffic safety?
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## 23 Experimental Setup

24  
25 The heart of this scenario is the pADAS which is an evolutionary step  
26 beyond classic ADAS functions. Inside a densely populated urban environment  
27 with complex street layouts, architectural obstacles, and significantly reduced  
28 visibility caused by tight angles and dense construction, a modified Volkswagen  
29 ID.Buzz serves as the central test platform within a highly connected ecosystem  
30 based on 5G infrastructure and C-V2X communication. Specifically modified  
31 for research in autonomous and cooperative mobility, the vehicle features a

1 comprehensive sensor platform that integrates additional high-resolution  
2 cameras, multi-frequency radar sensors, and lidar systems alongside the original  
3 equipment. These sensors generate a continuous, high-throughput data stream  
4 particularly the video streams from the cameras and the raw data from the radar  
5 sensors which must be processed in real time and communicated via the 5G  
6 campus network.

7 The test vehicle is also prepared for autonomous driving and teleoperation  
8 a key requirement for validating pADAS and cooperative scenarios. It has direct  
9 access to the vehicle actuators, particularly the steering and lateral control  
10 systems, as well as the braking and acceleration systems, via a standardized CAN  
11 bus interface. This architecture enables precise, safety-critical control via  
12 software both in autonomous mode and during teleoperation. Control is achieved  
13 through a redundant and fail-safe architecture, ensuring that a failure in channel  
14 or control systems causes the vehicle to transition into a safe state (e.g.  
15 emergency braking, emergency parking).

16 Sensor fusion takes place on a dedicated, high-performance edge computing  
17 unit (NVIDIA Orin), enabling local processing, object recognition, and predictive  
18 trajectory analysis in real time. Via the 5G network, the vehicle continuously  
19 receives high-resolution, multimodal data streams from a variety of  
20 infrastructure elements – including intelligent traffic lights, camera and radar  
21 stations, and edge computing nodes at strategically important intersections. This  
22 data includes not only precise positioning and speed information for all road  
23 users, but also dynamic traffic flow analyses, pedestrian movement predictions,  
24 and real-time status updates from traffic light control systems.

25 Unlike reactive systems that react to current sensor data, pADAS uses  
26 predictive algorithms based on a combination of historical traffic data, machine  
27 learning, real-time traffic models, and cooperative data from the C-V2X  
28 network. pADAS not only detects existing hazards but also anticipates potential  
29 conflict situations before they occur. The system detects at an early stage that an  
30 approaching vehicle is entering the intersection at high speed from an obscured  
31 direction based on movement patterns, traffic flow forecasts, and signals from  
32 other vehicles and activates a predictive driving strategy: targeted deceleration,  
33 precise stop positioning, or a safe distance adjustment – all within milliseconds  
34 to avoid a collision. Additionally, the vehicle is confronted with an unexpected,  
35 sudden disruption: an obstacle, such as a fallen scaffold or a broken-down  
36 vehicle, blocks the current lane, while traffic rules especially a solid line prevent  
37 safe overtaking.

38 In this scenario, pADAS activates its cooperative decision architecture,  
39 which is based on the integration of local sensor fusion, cloud-based traffic  
40 modeling, and real-time cooperation with other vehicles and the central traffic  
41 management center (TMC). Within milliseconds, a request is sent via the 5G  
42 network to the TMC, which has a comprehensive traffic model and real-time  
43 traffic data. At the same time, an evaluation of alternative routes and safe  
44 diversion strategies is carried out, with the decision based not only on traffic  
45 rules, but also on the current traffic load, vehicle density and the safety of all  
46 involved.

To ensure the technical feasibility and safety of pADAS-based and teleoperated vehicles in complex urban environments, quantifiable, empirically validated performance targets are crucial, in addition to theoretical latency predictions. The following table summarizes the expected latency values for critical communication and control paths within the project, based on modeling, simulations, and the technical specifications of the test vehicle. These values are defined not as guarantees, but as predicted performance targets that will be verified and optimized through a structured validation process.

**Table 2.** *Predicted and quantifiable latency targets in the 5G-C-V2X system with pADAS and teleoperation including a validation approach within the project*

Component	Expected Latency	Measurement Method	Influencing Factor	Validation approach
C-V2X data transmission	< 10 ms (realtime)	End-to-end measurement via 5G testbed	Network load, site density, QoS classification, edge processing	Field test in urban scenario, laboratory validation with 5G emulators
Teleoperation (video stream + control)	< 20 ms (real-time interaction)	Latency measurement via RTT (round trip time), frame delay analysis	Bandwidth reservation, QoS prioritization, edge rendering, network stability	Continuous measurement, comparison with human reaction time (approx. 150–200 ms)
pADAS decision processing (local fusion)	< 50 ms (incl. sensor fusion & prediction)	On-board logging with timestamp, GPU/CPU profiling	Sensor latency, algorithm complexity, data compression	Benchmarking with real traffic data, simulations in CARLA/Sumo
Cloud traffic modeling (TMC integration)	< 100 ms (real-time update)	API response time measurement, latency analysis in the Cloud Edge stack	Data aggregation, cloud server location, data formatting	Comparing model forecasts with real traffic data (e.g. OpenStreetMap + IoT sensors)
Cross-system latency (pADAS → Teleoperation)	< 150 ms (critical path)	End-to-end measurement across the entire communication path	Combined network and system latency, QoS management, prioritization	Stress tests with high traffic density, simulation of disruptions (e.g. network interruption)

The vehicle's entire software architecture is based on ROS 2<sup>4</sup> (Robot Operating System 2), a standardized, distributed, and safety-oriented platform for autonomous systems. ROS 2 serves as the central middleware for sensor fusion, data processing, 5G-C-V2X communication, pADAS decision logic, and teleoperation. The use of the Data Distribution Service (DDS) protocol enables low-latency, time- and data-driven communication between components, ensuring compliance with predefined latency constraints. ROS 2 also allows for

<sup>4</sup><https://www.ros.org>

1 modular development, algorithm reusability, and a unified interface architecture,  
2 simplifying the integration of sensors, edge computing, cloud services, and  
3 teleoperation units.

4 Each communication component is assigned a specific measurement  
5 method based on real-world data from laboratory and field tests. Influencing  
6 factors (e.g., network load, QoS prioritization, edge processing) are explicitly  
7 considered to represent realistic scenarios. The validation approach comprises a  
8 combination of 5G testbeds, field measurements in urban intersection scenarios,  
9 laboratory validation with emulators, and benchmarking with human reaction  
10 times as a reference. The ROS 2-based system architecture itself is integrated  
11 into the measurement campaigns: Latency, throughput, and reliability are  
12 measured and analyzed not only at the network level but also within the ROS 2  
13 node interactions (e.g., between sensor nodes, pADAS nodes, and teleoperation  
14 nodes). The goal is to ensure that all critical paths from sensor data transmission  
15 through pADAS decision-making to teleoperation operate within the predefined  
16 latency limits to guarantee the safety, reliability, and acceptance of autonomous  
17 mobility. The integration of ROS 2 is not merely a technical decision but a  
18 central research approach that ensures the system's transparency, reproducibility,  
19 and scalability.

## 20 21 22 **Measurement Setup**

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24 The measurement setup is designed to capture end-to-end system  
25 performance under realistic operating conditions of the autonomous driving  
26 platform. The primary focus is on glass-to-glass (G2G) latency, which includes  
27 all processing stages from sensor acquisition to final visualization.

28 To validate the performance effects of 5G SA, URLLC, and related  
29 technologies, an independent measurement system is employed.

1        Figure 2 illustrates the concept of the G2G measurement setup. The Device  
2 Under Test (DUT), representing the actual V2X communication and processing  
3 pipeline, is separated from the measurement system to avoid interference. While  
4 the DUT is responsible for capturing, transmitting, and rendering video data, the  
5 measurement system operates independently to ensure unbiased latency  
6 measurements.

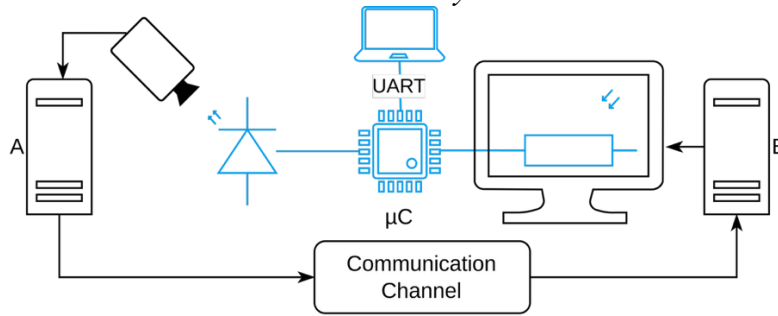
7        The measurement system consists of a Light Emitting Diode (LED) and a  
8 Light Dependent Resistor (LDR), both connected to a central microcontroller.  
9 The implementation is realized in a bare-metal configuration to minimize  
10 software-induced delays. During operation, the LED is triggered to emit a light  
11 signal that is captured by the camera system of the DUT. After passing through  
12 the complete processing and communication pipeline, the displayed image is  
13 detected by the LDR. This experimental setup is depicted in

ONLY FOR REVIEW

1 Figure 2.  
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1 **Figure 2.** *Glass-to-glass latency measurement setup with independent*  
 2 *microcontroller-based LED/LDR system*



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4  
5 The resistance of the LDR is continuously monitored using an internal  
6 Analog-to-Digital Converter (ADC) of the microcontroller. A polling-based  
7 approach is used to ensure deterministic timing behavior. This method achieves  
8 an internal response time of below 1 ms, which is negligible compared to the  
9 overall system latency. As a result, the measurement setup captures the full end-  
10 to-end delay, including sensor acquisition, encoding, transmission, decoding,  
11 and rendering.

12 The measurement pipeline within the DUT starts with image acquisition  
13 from onboard camera systems integrated into the autonomous shuttle. The raw  
14 sensor data is processed within a ROS2-based software stack, where  
15 preprocessing, synchronization, and data handling are performed. The image  
16 data is then encoded and transmitted via the 5G Standalone campus network.

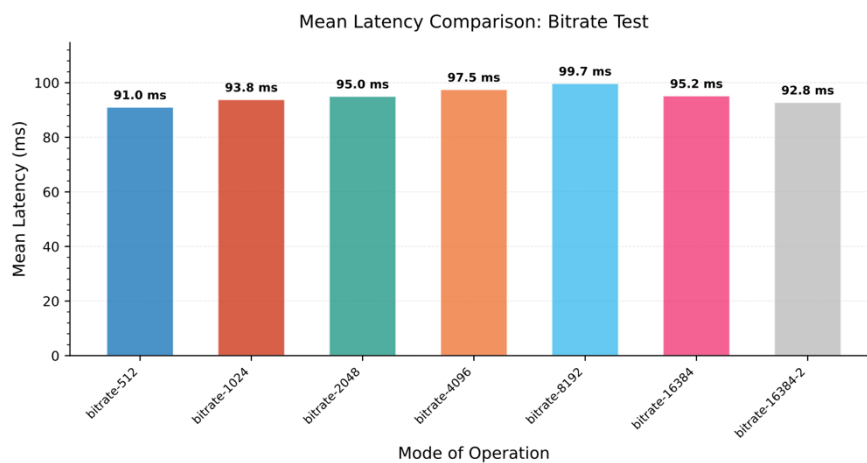
17 Different configurations are evaluated to analyze system performance under  
18 varying conditions. These include variations in frame rate (30 FPS and 60 FPS),  
19 the number of camera streams, and different radio cell and antenna  
20 configurations within the 5G network. Upon reception, the data is decoded and  
21 rendered, completing the glass-to-glass path.

22 To isolate the impact of the communication layer, additional reference  
23 measurements are conducted using a local setup without wireless transmission.  
24 Latency measurements are repeated multiple times to capture both mean values  
25 and variance, enabling a comprehensive analysis of system performance and  
26 identification of bottlenecks across processing and communication stages.

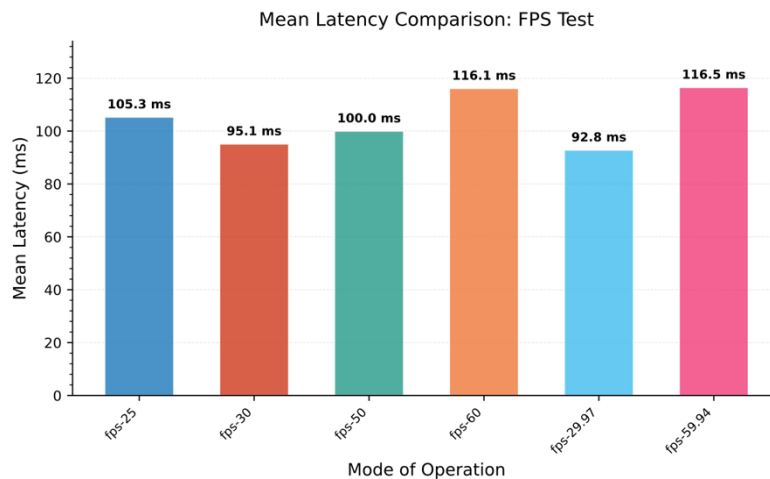
27 To systematically determine the performance of the test system, a structured  
28 data strategy was developed to ensure that the measurement results are both  
29 reproducible and meaningful. Due to the large number of adjustable parameters  
30 particularly in the area of camera and encoding settings. A complete parameter  
31 combination would drive the number of measurement series to unmanageable  
32 proportions and render analysis impossible. To avoid this, a preparatory step was  
33 carried out before conducting the actual 5G-based measurement series. These  
34 secondary measurement series served to analyze the impact of the individual  
35 parameters on image quality, data traffic, and processing time, and to identify an  
36 optimal parameter catalog that guarantees both high visual quality and efficient  
37 data transmission. Based on this, a conservative but representative parameter  
38 catalog was defined, which is now used for all main measurement series with 5G  
39 transmission.

1 The choice of bitrate has a decisive influence on the visual quality of the  
 2 transmitted camera image. In scenarios with low motion dynamics within the  
 3 field of view, no significant differences in image quality are discernible between  
 4 different bitrates, indicating that compression is efficient and virtually lossless  
 5 in such cases. In contrast, at bitrates below 1024 kbit/s, noticeable compression  
 6 artifacts appear, especially with fast movements or high detail densities. These  
 7 artifacts manifest as blocking, color gradients, or distortions, which can impair  
 8 object recognition and overall perception. This underscores the need to adapt the  
 9 bitrate to the dynamic requirements of the scenario to ensure sufficient image  
 10 quality even under demanding conditions—a crucial aspect for applications in  
 11 safety-critical environments such as autonomous vehicles.

12 **Figure 3.** Secondary measurement series to determine the optimal CBR bit rate



14 The secondary measurement series in Figure 3 shows that the bit rate has  
 15 only a minor influence on the overall transmission latency. The maximum  
 16 difference between the measurements at a bit rate of 512 kbit/s (91.0 ms) and  
 17 8192 kbit/s (99.7 ms) is only 8.7 ms, which is less than ten percent of the average  
 18 latency and therefore negligible. These results indicate that the latency in this  
 19 setup is primarily determined by the processing and transmission times of the  
 20 network components, and not by the amount of data per unit of time. However,  
 21 since bit rates below 1024 kbit/s lead to significant image distortion—especially  
 22 in dynamic scenes—a bit rate of 1024 kbit/s in constant bitrate mode (CBR) is  
 23 chosen as the optimal compromise, ensuring sufficient image quality with  
 24 acceptable latency. Besides the bit rate, the frame rate also plays a crucial role  
 25 in motion perception and potential latency. Since a change in the scenario is only  
 26 detected with the next image captured by the camera, higher frame rates result  
 27 in shorter waiting times for transmission and processing. For example, the  
 28 potential latency at 60 frames per second is approximately 16 ms, compared to  
 29 approximately 33 ms at 30 frames per second, which significantly improves  
 30 responsiveness. This underscores the importance of carefully matching both the  
 31 bit rate and the frame rate to ensure both visual quality and temporal  
 32 responsiveness in safety-critical applications.  
 34

1 **Figure 4.** *Secondary measurement series to determine the optimal frame rate*

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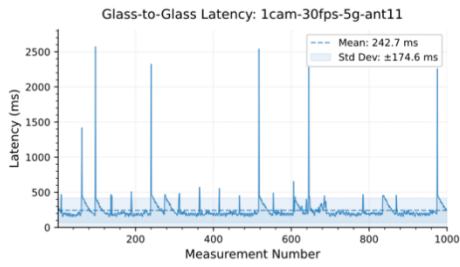
4 The secondary measurement series in Figure 4 reveals significant  
 5 differences in latency between the various frame rates, contradicting the initial  
 6 assumption that higher frame rates necessarily lead to lower latency. In fact, the  
 7 measurements at 60 fps show a significantly higher latency than those at 30 fps,  
 8 thus refuting the expectation of an inverse relationship between frame rate and  
 9 latency. This discrepancy suggests a profound influence on the data processing  
 10 chain that is not solely determined by the frame rate. Possible causes could lie in  
 11 the camera's processing load, the synchronization between sensor and encoder,  
 12 buffer management within the system, or the utilization of network and  
 13 computing resources. Since frame rates of 30 and 60 fps are widely used in both  
 14 common hardware infrastructure and on standard displays, and offer good  
 15 divisibility, these two values are chosen as suitable reference points for further  
 16 analysis. The observed deviation from theoretical expectations illustrates that  
 17 latency in V2X systems is not solely determined by the frame rate, but rather by  
 18 complex interactions between hardware, software, and the network. This  
 19 phenomenon presents an interesting research avenue, highlighting the need for  
 20 in-depth, system-wide analysis of data paths – especially when combined with  
 21 5G transmission and edge processing.

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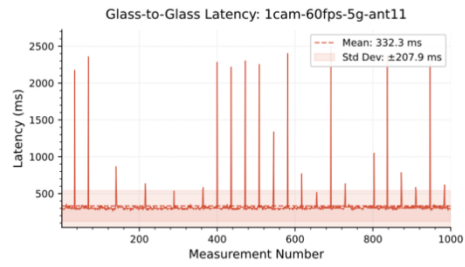
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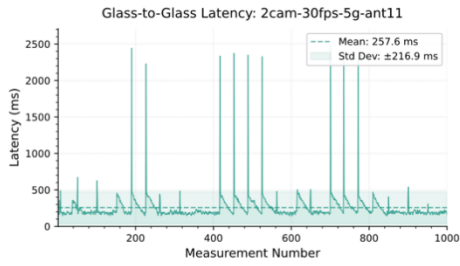
1 **Figure 5.** Main measurement series: Latency over time in 8 configurations



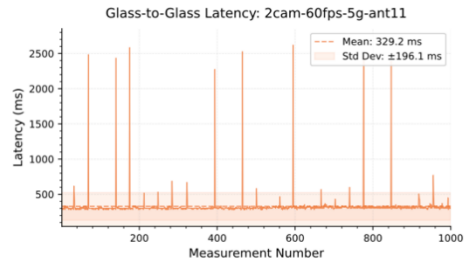
(a) 1x Camera, 30 FPS via antenna 11



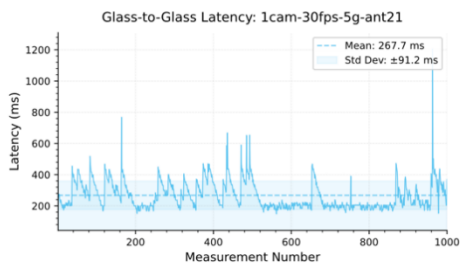
(b) 1x Camera, 60 FPS via antenna 11



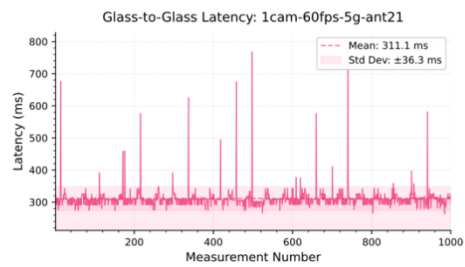
(c) 2x Camera, 30 FPS via antenna 11



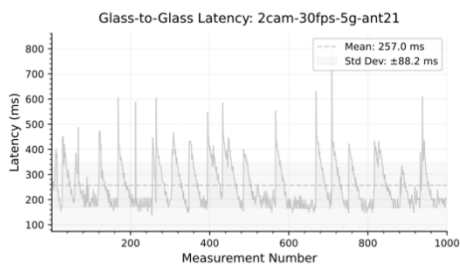
(d) 2x Camera, 60 FPS via antenna 11



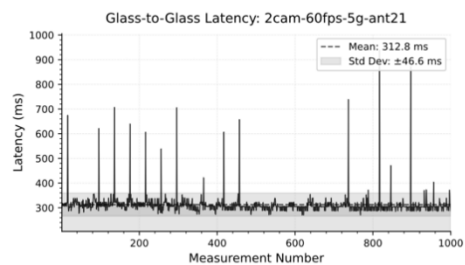
(e) 1x Camera, 30 FPS via antenna 21



(f) 1x Camera, 60 FPS via antenna 21



(g) 2x Camera, 30 FPS via antenna 21



(h) 2x Camera, 60 FPS via antenna 21

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All measured series in

1 Figure 5 exhibit average latencies exceeding the defined performance  
2 target, indicating a systemic challenge in the data transmission chain. Analysis  
3 of the measurement data reveals that several points in the system design  
4 particularly those outside the 5G infrastructure, such as connections between the  
5 camera, encoder, edge server, and the 5G modem contribute significantly to the  
6 overall latency. These connections have not yet been investigated or optimized  
7 for network congestion or the impact of protocol mechanisms like the Nagle  
8 algorithm. Since such factors are known to increase latency for example, through  
9 packet buffering or delayed transmission for packet aggregation—there is  
10 considerable potential for optimization. The minimum values, at 139.1 ms are  
11 particularly noteworthy, demonstrating that the lower limits of the latency are  
12 significantly lower than the average and thus proving the technical feasibility of  
13 meeting the specifications. This observation suggests that targeted optimizations  
14 such as adjusting network parameters, disabling latency-inducing algorithms, or  
15 improving data flow control could allow latency targets to be met or even  
16 surpassed. The results thus underscore not only the need for a holistic analysis  
17 of all data paths but also the relevance of software and protocol optimizations  
18 that have been neglected until now.

19 The significant difference in standard deviations between the measurement  
20 series of the two radio cells is striking: Radio cell 11 exhibits a considerably  
21 higher mean standard deviation of 198.88 ms compared to radio cell 21 at 65.58  
22 ms. Assuming that the technical configuration of both cells is identical, the  
23 crucial difference lies in their spatial arrangement and the way they are  
24 connected to the rest of the test environment's network. The infrastructure for  
25 connecting the antennas is provided by the Ostfalia University data center and is  
26 largely transparent for this project, meaning that no precise statements can be  
27 made about the number of network hops, the routing between the networks, the  
28 transmission speeds, or the utilization of the connections. It is only known that  
29 the antenna of radio cell 21 is connected to the network via a wireless directional  
30 link – information that initially led to the expectation that radio cell 21 would  
31 exhibit poorer latency performance. However, the observed performance is  
32 exactly the opposite: Cell 21 shows lower variance, suggesting more stable and  
33 predictable data transmission. Another significant difference concerns the  
34 position of the measurement setup: While the setup for Cell 11 is reachable from  
35 both cells, for Cell 21 it is reachable only via that specific cell. This could  
36 indicate that the measurement setup's radio module roams between the two cells  
37 during the measurements, which would lead to increased latency variance for  
38 Cell 11. Based on these observations, two working hypotheses are derived: First,  
39 that the routing between the cells and the 5G core is significantly different  
40 between Cells 11 and 21 – a hypothesis that could be verified by comparing the  
41 network map of the Ostfalia data center. Second, that the measurement setup's  
42 radio module does indeed roam between the cells, which could be verified by  
43 analyzing the cell protocol data. To minimize side effects and validate the  
44 results, it is also recommended to conduct a further series of measurements with  
45 a symmetrically positioned measurement setup equidistant from both cell  
46 towers. Such an arrangement would make it possible to isolate the effects of

1 roaming and different routing and to better understand the causes of the observed  
2 variance.

## 3 4 5 **Results and Discussion**

6  
7 This section presents the experimental results of the conducted  
8 measurements and discusses their implications with respect to the applicability  
9 of 5G-based V2X systems for autonomous driving. The analysis focuses on  
10 glass-to-glass latency, system stability, and the identification of performance  
11 bottlenecks.

12 The primary performance metric considered in this work is the glass-to-  
13 glass (G2G) latency, capturing the complete processing chain from sensor  
14 acquisition to final visualization. The measurements reveal that, in the 5G-based  
15 setup, the latency ranges between 242 ms and 267 ms for 30 FPS configurations,  
16 and 311 ms to 332 ms for 60 FPS configurations. In comparison, the local  
17 reference setup without wireless transmission exhibits lower latencies of  
18 approximately 176 ms at 30 FPS and 286–290 ms at 60 FPS. The difference  
19 between both configurations indicates that the additional latency introduced by  
20 the 5G communication link lies in the range of 60–90 ms. These results  
21 demonstrate that, while the 5G network contributes to overall delay, it does not  
22 dominate the latency budget. Instead, a substantial portion of the delay originates  
23 from processing and system-level components.

24 A notable observation is the increase in latency when transitioning from  
25 30 FPS to 60 FPS configurations. Contrary to the expectation that higher frame  
26 rates may reduce perceived latency due to shorter frame intervals, the results  
27 show a consistent latency increase. This behavior can be attributed to the  
28 increased computational load imposed on the system. Higher frame rates lead to  
29 more frequent encoding, transmission, and decoding operations, which in turn  
30 intensify resource contention within the processing pipeline. Additionally,  
31 buffering and synchronization effects become more pronounced, further  
32 contributing to the observed latency increase. These findings highlight the  
33 importance of considering system-level constraints when optimizing V2X  
34 communication performance, as improvements at the communication layer  
35 alone do not necessarily translate into lower latency.

36 The experimental results reveal significant differences in latency behavior  
37 depending on the selected radio cell. While one antenna configuration provides  
38 relatively stable latency characteristics, another exhibits high variance with  
39 extreme latency peaks exceeding 2000 ms. Such variations indicate that radio  
40 conditions, including signal quality, interference, and resource allocation, have  
41 a substantial impact on communication performance. For safety-critical V2X  
42 applications, this variability represents a major challenge, as deterministic  
43 behavior is essential.

44 These findings underline the necessity of careful network planning and  
45 optimization in 5G campus deployments. Mechanisms such as dynamic resource

1 scheduling, interference management, and optimized antenna placement are  
2 crucial to ensure consistent performance.

3 The analysis clearly shows that the 5G communication link is not the  
4 primary bottleneck. Instead, the majority of the delay is introduced by the  
5 application and processing pipeline. The most significant contributors include:  
6

- 7 • ROS2 middleware overhead, particularly in message serialization and  
8 transport
- 9 • Video encoding and decoding processes
- 10 • Single-threaded execution of critical components
- 11 • Buffering and synchronization mechanisms

12  
13 The independence and high temporal resolution of the measurement system  
14 ensure that these effects are accurately captured, reinforcing the validity of the  
15 results. This insight is particularly relevant for future system design, as it shifts  
16 the optimization focus from purely communication-centric approaches toward  
17 holistic system-level improvements.

18 For teleoperation scenarios, the observed end-to-end latency exceeding  
19 240 ms is above commonly accepted thresholds for real-time control, which are  
20 typically below 200 ms. This suggests that the current system configuration is  
21 not yet suitable for safety-critical remote driving applications without further  
22 optimization. In contrast, for cooperative perception use cases, the latency is still  
23 within an acceptable range. In these scenarios, the transmitted information is  
24 used to enhance situational awareness rather than to directly control the vehicle.  
25 The ability to detect occluded objects and share this information across the  
26 network provides a significant safety benefit, even with moderate latency.  
27

## 28 29 **Future Work**

30  
31 The results of this study reveal several promising directions for future  
32 research and system improvement. A primary focus will be the reduction of  
33 latency through system-level optimization. This includes improving the ROS-2-  
34 based processing pipeline by minimizing serialization overhead, reducing  
35 buffering effects, and enabling parallel processing of computationally intensive  
36 tasks. In particular, the use of hardware acceleration for video encoding and  
37 decoding will be investigated to significantly reduce processing delays.

38 Another key direction is the deeper integration of MEC. Future work will  
39 explore the offloading of processing tasks such as sensor fusion and object  
40 detection to edge nodes in order to reduce onboard computational load and  
41 improve scalability. This also includes the development of adaptive task  
42 distribution strategies between vehicle and infrastructure. From a networking  
43 perspective, further research will focus on enhancing the reliability and  
44 determinism of 5G communication. This includes advanced network slicing  
45 configurations, optimized resource allocation, and improved radio planning to  
46 reduce latency variance. The observed differences between radio cells highlight

1 the need for systematic network optimization in campus deployments. In  
 2 addition, future work will extend the evaluation to more demanding V2X use  
 3 cases, including cooperative maneuvering, platooning, and teleoperation. These  
 4 scenarios require stricter latency guarantees and will serve as benchmarks for  
 5 further system improvements.

6 Finally, the scalability of the proposed architecture will be investigated by  
 7 extending the system to larger deployments with multiple vehicles and RSUs.  
 8 This includes analyzing network load, interference effects, and system  
 9 robustness under realistic traffic conditions, as well as exploring the integration  
 10 of future communication technologies beyond 5G.

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