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QoE Evaluation of Real-Time Remote Operation with Network Constraints in a System-of-Systems

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***Abstract*—With the advent of robotics, remote operation gained momentum as it allows for the control and feedback of distant systems, thus reducing human logistics and risk. Despite the growing popularity of fully autonomous systems, remote operation still retains a significant relevance due to operative requirements like manual overrides in critical situations. Such a requirement calls for a robust and reliable remote operation experience. We propose an evaluation system following a system-of-systems architecture to assist in the development of remotely operated applications with tested resilience against network effects. The system has an extensible architecture allowing the swap of real and virtual components and enables the evaluation of remote operation applications in unreliable network environments. In a proof-of-concept study, the system is implemented and used to evaluate the impact of network constraints on a teleoperated high-speed driving scenario. Our results show that the baseline setup leads to approximately equal (± 0.9 %) end-to-end driver performances. Thus, other evaluations are primarily affected by additional constraints, enabling our system for extensive analyses. Comprehensive drive trials show that network latency steadily mitigates driving performance, whereas packet loss can be compensated well up to a specific value. In addition, our Quality of Experience (QoE) surveys show the subjective ratings of participants exposed to network impacts.**

I. INTRODUCTION

Remote Operation (RO) is a promising application field for diverse sectors. Telemedicine [1] can be a key enabler for solving poor medical infrastructure in rural regions. Industry 4.0 will not only benefit from high grades of edge automation but also remote operation allows safe machine control, which became a global aspect during the *COVID-19* pandemic, enabling workers to work from home. Modern rescue robotic systems will also rely on remotely operated unmanned vehicles to explore disaster areas and collapsed buildings without endangering rescue personnel. Fleets of remotely operated drones can cover large maritime areas and thus drastically reduce the time for locating shipwrecked persons. Teleoperated Driving (ToD) is a demanded Vehicle-to-Everything (V2X) application and is closely related to the superordinate term of Remote Operation. It is capable of paving the way towards fully autonomous driving and proposes a solution for unknown situations. The issue of how autonomous vehicles will behave in unfamiliar situations and still act safely is not finally answered. ToD offers the ability to install expert drivers into the system to take over in critical situations, as depicted in Fig. 1. Although this is a popular use case, a rolled-out ToD service over the 5th Generation of Mobile Communication Networks (5G) might also change whole occupational fields, such as cab and truck drivers. To evaluate the QoE in a reproducible laboratory setup for different use cases, we present our RO system-of-systems architecture in this work. It runs on standard computers without the need for special hardware or software components. The mission center, with its peripherals, but also the operating environment, is fully extensible. Also, the network side of our approach is presented in a cabled ground setup in this work but allows for fast integration into Hardware-in-the-Loop (HiL) systems.

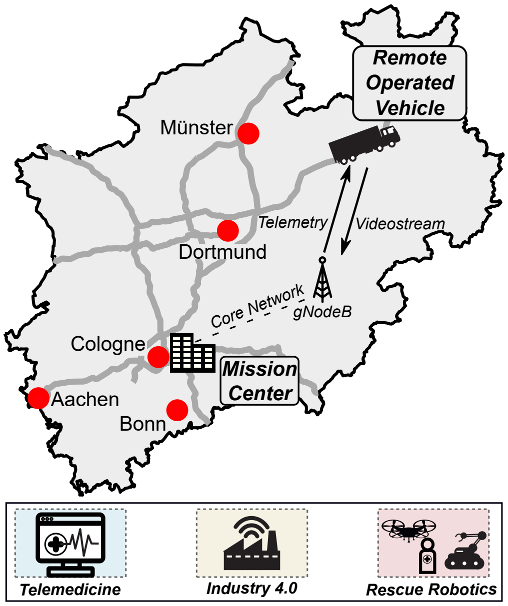

Fig. 1. 5G is expected to bring the necessary power to enable high precision and safe remote operation across large distances. Drawn here is vehicular teleoperation on highways in the German state of North Rhine-Westphalia as one kind of remote operation. Nevertheless, application fields are diverse, and other sectors will also benefit from reliable remote operations. (Map: © OpenStreetMap Contributors, CC BY-SA).

The contributions are summarized as follows:

- Presentation of the **system-of-systems architecture** for our evaluation setup on remote operation.
- Open system design to **substitute the underlying operating environment** with any other simulation or real-world application and extend the **network and channel analysis** with hardware-in-the-loop approaches.
- **Comprehensive evaluation on the impact of network constraints** on the QoE in a high-speed and high preci-

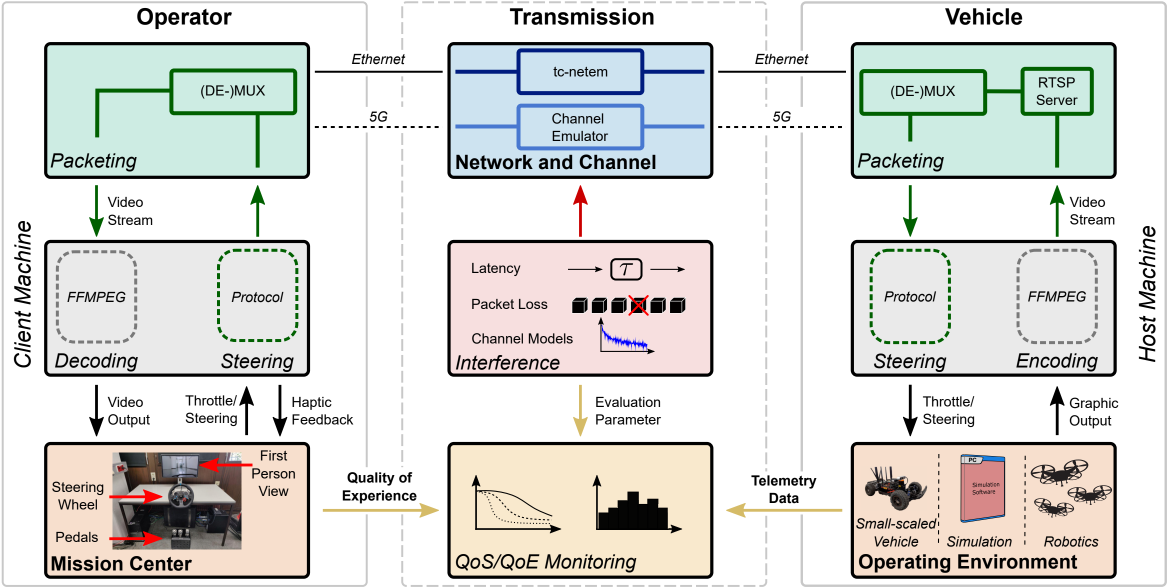

Fig. 2. System-of-systems model of our proposal for the QoE evaluation of remotely operated applications. The controlled integration of network and channel constraints enables reproducible QoE evaluations for diverse operating environments. Application-specific needs can thus be identified, and solution approaches tested to enhance safety and precision.

sion driving case study.

The remainder of the paper is structured as follows. After discussing the related work in Sec. II, we present the prerequisites and aspects of our system architecture in Sec. III. An extensive case study on teleoperated driving is carried out in Sec. IV. Finally, we provide an outlook on potential extensions and use cases of our system in Sec. V.

II. RELATED WORK

The technical requirements and approaches of Remote Operation (RO) have been researched intensely in the past years. Besides the pure evaluation of Quality of Service (QoS) aspects, the Quality of Experience became more and more important. QoE expresses the end-to-end relations between different QoS grades and application-specific requirements. A QoE analysis for telemedical operations is presented in [2]. Tärneberg et al. [3] present a QoE campaign for remote operation in an industry 4.0 context. The authors of [4] and [5] evaluated the QoE for teleoperation. Their results indicate poorer driving performances for higher latency. A HiL system for robotic operation in constrained environments is presented in [6]. In [7], the authors present a framework for comprehensive network stress testing. General use cases of ToD are described in [8]. From there, we focus on the direct control in our case study in Sec. IV, but to which our proposal is not limited. Service requirements on reliability, latency, and data rate are presented in [9] and [10]. The author of [11] gives a general overview and outlook on machine-controlled ToD. Neumeier et al. [12] present real-world measurements of existing telecommunication networks in Germany and assess their feasibility for teleoperation. There exist other simulators for Teleoperated Driving [13] [14]. The authors of [15] use a *Formula 1* game to train an algorithm for autonomous driving. Detailed analysis on the latency contributors in a ToD system is provided in [16], and the delay composition for ultra low latency video streaming is discussed in [17]. To cope with situations under poor data rate and latency conditions, the 5G Automotive Association (5GAA) introduced the term *predictive QoS* [18], which covers predicting network changes and, in turn, changing the driving behavior accordingly. Research on related prediction techniques in this context has been presented in [19], where the authors make latency predictions based on deep learning. The authors of [20] present an approach for end-to-end data rate prediction based on machine learning.

III. APPROACH

In Fig. 2, we show our system-of-systems evaluation model, which can be divided into operator's and vehicle's side and the transmission component in between. The boxes' colors indicate symmetries on the respective sides. Through the utilization of generic interfaces, our approach offers flexibility for the transfer and integration into other systems.

Both the operator and vehicular side consist of Input and Output (I/O) entities. On the right side, this can be a simulation engine, such as a realistic driving simulator, as well as various robotic platforms. On the left side, peripheral hardware, such as a display, a steering wheel, and gas, and brake pedals, take the role of Human Machine Interfaces (HMIs) for our setup. The subsequent building blocks are the I/O processing components, for which en- & decoders from the open-source *FFMPEG* library and built-in *USB IP* drivers are utilized. The components are orchestrated in respective high-performance computers, on which the network interfaces are installed. We present the simulator setup in Sec. III-A and discuss the atomic components.

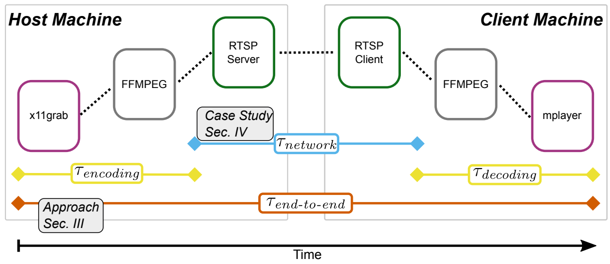

Fig. 3. High-level latency model of a video streaming system according to [16]. This work presents an approach for end-to-end analyses, providing a case study on network constraints. Nevertheless, the impact of interdisciplinary fields like computing, source coding, and limitations of resource-constrained devices may also be modeled and investigated.

The connection between both end-sides is routed over a network component and channel module in which we emulate and apply various constraints to the data transmission. More details are provided in Sec. III-B. The QoS/QoE monitor processes numerical measurement inputs, as well as surveyed driver assessments.

A. Prerequisites for the Proposed Remote Operation Evaluation Setup

As mentioned before and shown in Fig. 3, we use the *FFMPEG* library for video encoding, which also provides a lightweight screen grabbing utility called *x11grab*. We captured the screen with a resolution of 1920 by 1080 pixels and a framerate of 60 Hz. Following, we present important settings applied to optimize the video encoding for low latency. First, we use the well-established *H.264* video codec together with a chroma subsampling of 4:2:0. Besides different settings regarding keyframe intervals and the explicit ban of bidirectional frame prediction, we use *FFMPEG*'s *veryfast* and *zerolatency* flags. For the decoder on the operator's side, we use *mplayer* together with its *benchmark* settings to strongly reduce the decoding latency for visualization. The video transmission is realized using the Real-Time Streaming Protocol (RTSP), which can handle higher latency and packet loss than a direct UDP transmission. An overview of the video parametrization is given in Tab. I. As we assume latency to have a crucial impact on the QoE, we evaluated the end-to-end latency of this setup by streaming the display of a timer with a resolution of 1 ms and comparing the values of the transmitter and receiver by capturing both with an external camera.

As seen in Fig. 4, the baseline *H.264* configuration and the *veryfast* coding option have end-to-end latency between 500 ms and 700 ms, which is unsuitable for high-speed scenarios as in our case study in Sec. IV. With the *H.264* configuration mentioned above, up to 88 % lower end-to-end latency is achieved. This pre-evaluation shows that roughly 60 ms streaming delay needs to be accepted, as the video feed is essential. For comparison, the authors of [16] report similar values, whereas in [17] a value of 20 ms by using specialized encoding and decoding hardware is achieved.

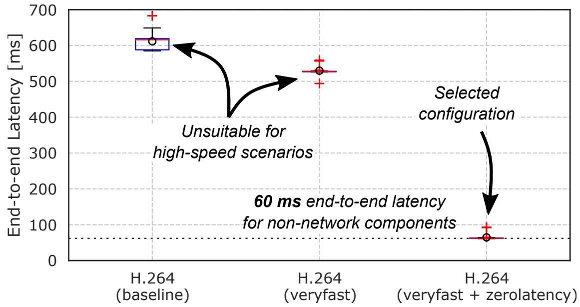

Fig. 4. Evaluation of the end-to-end latency for non-network components under consideration of different video codec configurations. The usage of bidirectional frames requires buffering and, thus, introduces too much video delay for high-speed scenarios.

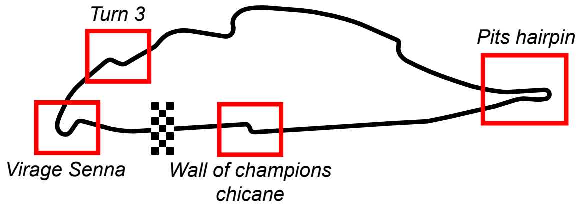

Fig. 5. Evaluation circuit of the Canadian Grand Prix in Montreal with highlighted characteristic turns (Map: © OpenStreetMap Contributors, CC BY-SA).

B. Network and Channel Emulation for Stress Testing

Our proposal implements the network connection as a direct link, which is further influenced to emulate the end-to-end behavior of different communication technologies. The used tool *tc-netem* allows shaping the outbound traffic of a given network interface regarding latency, packet loss, and more.

We share the assumption discussed by 5GAA in [10], concluding that the remote operator is interacting with given visual input, thus, reducing the operation to a feedback-action control loop. The operator needs to wait for the visual information to assess the effect of a previous action before making the following action. Therefore the exact composition of uplink and downlink latency is not critical, as long as the round-trip latency is below a specific value. We, therefore, focus on the application of uplink constraints in our case study in Sec. IV. However, our system is still capable of including uplink- and downlink-separated constraints to evaluate asymmetrical conditions.

We assume latency and packet loss to have a noticeable impact on the performance of the remote operation. Thus, we define incremental steps to analyze both. In [10], a latency of 200 ms is described as a worst-case scenario and is, therefore, the highest considered latency in our case study. Additionally, network latency of 40 ms, 80 ms, and 120 ms is reported and evaluated as intermediate steps.

Service level reliabilities are noted to be 99 % or higher. Besides a packet loss of 0.1 % and 1 %, we, therefore, extend our evaluation horizon to 2.5 % and 5 % to carry out a worst-case analysis.

TABLE I
CONFIGURATION PARAMETERS OF THE VIDEO STREAM

Parameter	**Value**
Encoding	
Framework	*FFMPEG*
Screen capture	*x11grab*
Resolution	1920 x 1080
Framerate	60 Hz
Videocodec	H.264
Preset/Tune	veryfast/zerolatency
Pixel format	*YUV420p*
Decoding	
Framework	*mplayer*
Setting	*benchmark*
Threads	2
Network	
Protocol	RTSP

IV. CASE STUDY: TELEOPERATED DRIVING AS A REMOTE APPLICATION

Although the centralization of teleoperators' workplaces might enable business and sustainability considerations, a successful deployment is strictly dependent on a proficient network infrastructure that meets the QoS requirements from regulatory organizations. Typical requirements are latency, reliability, and data rate. However, values differ from reference to reference, which are primarily addressing different speed profiles. Reports from [9], for instance, state a 5 ms latency, while references from [10] allow latency from 10 ms to 200 ms. This raises the question, what the end-to-end impact of QoS constraints on the driving quality, expressed as QoE, is.

A. Proposal for a Quality of Experience Evaluation Methodology

In this section, we present the methodological aspects of our QoE evaluation. We separate the considered Key Performance Indicators (KPIs) into objective and subjective categories. Ten drivers, all non-professional, are asked to go on a time trial of three laps per evaluation without prior knowledge about applied constraints and in a randomized order. The first lap is a flying lap to reduce the impact of a slow start.

TABLE II
PARAMETERS OF THE QUALITY OF EXPERIENCE EVALUATION SETUP

Parameter	**Value**
Laps per driver	3
Total drivers	10
Visual driving assistance	Racing line, colored speed indicator
Race settings	Flying lap, time trial
Evaluation order	Random

Because the used racing simulation is unknown to most drivers, an appropriate warm-up phase is given on a different track. This measure ensures that the drivers get used to the overall drive feeling of the simulator, which is, although it has a high grade of realism, different from a regular car. Therefore we expect the learning curve for better vehicle handling to be flattened. After drivers consider themselves to perform laps safely, they get a second warm-up phase in the native environment on the Montreal track to mitigate possible performance gains through track experience.

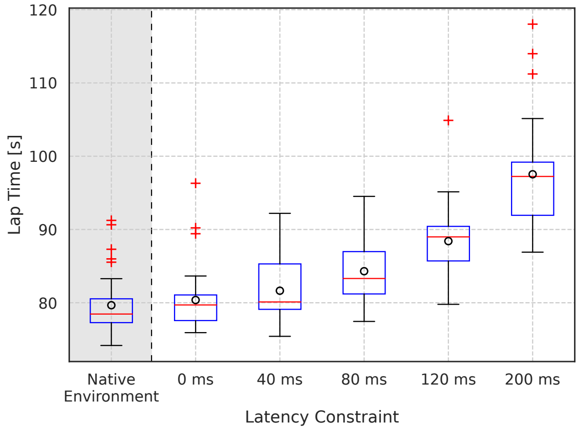

Fig. 6. QoE vs. latency evaluation: Averaged lap times of ten drivers on Montreal track for different latency constraints. The native environment serves as comparison to the networked counterparts with given delays.

We evaluate the lap time as the primary KPI to assess the driving performance. The driver is asked to rate the QoE regarding the following topics after each 3-lap evaluation. A scale from 1 to 5, where 5 is the best score, is used, and the overall results are evaluated as Mean Opinion Score (MOS). The QoE topics are as follows:

- **Video Quality:** How good was the overall video quality?
- **Artifacts:** How were the geometric details displayed?
- **Stuttering:** How frequently did stuttering occur?
- **Usability:** How good was the overall usability?

Video quality is rated from *Perfect* (5) to *Bad* (1). Artifacts and stuttering are conducted based on their occurrence from *None* (5) to *Often* (1). The overall usability of the video feed for the teleoperation task is described from *Perfect* (5) to *Unusable* (1). The parametrization of our drive trials is summarized in Tab. II.

B. Teleoperated Driving Performance with Applied Network Latency

To analyze the driving performance, we let all test drivers perform driving in the conducted setups. Fig. 6 shows the distribution of the averaged lap time according to the presented methodology in Sec. IV-A. We consider the evaluation where video and steering are transmitted over the host-to-client connection, but without adding constraints, as our baseline approach. Compared to the direct steering on the native simulation computer, the mean lap time only shows a slight (0.9 %) but negligible increase. Thus the occurred latency by video en- and decoding is low enough to be fairly unnoticed by the drivers. Further added latency then leads to increased

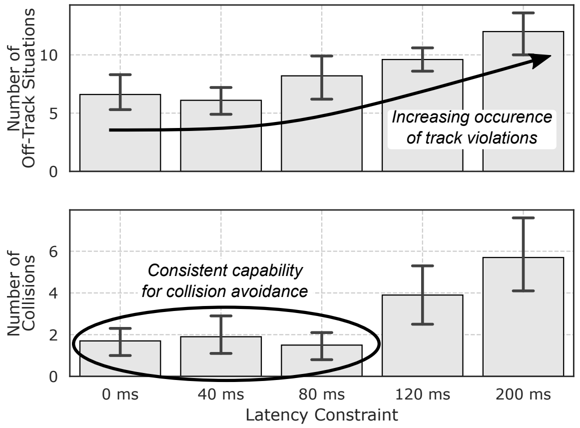

Fig. 7. Evaluation of the driving accuracy as an objective QoE performance indicator with latency constraints.

lap times compared to the native results, as the drivers are required to lower their speed to drive safely. This can be seen in the constantly growing lap times, where a low latency (40 ms) causes an increase of 2.5 %, and 80 ms lead to a growth of 5.8 %. Even higher latency values show more significant performance issues. A latency of 120 ms leads to 11 % higher lap times. Even worse, 22.4 % are observed with 200 ms, which is the worst-case latency from [10]. Fig. 5 shows the circuit of the race track and highlights some characteristic turns and chicanes. With introduced network latency, the driver's steering suffers from the delayed visual feedback, thus, disturbing the control loop and decreasing the driving accuracy. In the ”pits hairpin” (c.f. right side in Fig. 5), a 180° right turn is followed by a left-bound outtake. Hard braking, large steering actions, and quick directional changes are required to avoid a collision with the wall and stay on track. Under latency conditions, the driver needs to anticipate information delay strongly, which has shown to be most successful in a passive driving style. Similar requirements are set in the ”Virage Senna”. The main problem with latency is the oversteering during these sharp turns, which worsens when the driver tries to compensate for position errors realized in the delayed video. Therefore the finding back on line takes a longer time, which also contributes to the increased lap times.

Shown in Fig. 7 is the analysis of driving accuracy. An increasing trend is noticed for off-track situations because drivers tend to leave the ideal line and cut corners stronger. Network latency constraints of 0 ms and 40 ms do not show much difference here. This also holds for the number of collisions. Collisions are a little bit less frequent with 80 ms latency. One possible interpretation is that this latency constraint is noticeable for the driver but still quite manageable. The drivers thus are aware of the conditions, try to compensate, and drive a little slower and safer. The slower driving is also indicated by the lap times with a 3 % increase compared to 40 ms. Higher latency leads to more off-track situations and collisions. Especially drivers with an aggressive steering behavior (i.e., those who prefer a short but hard steering over a smooth and steady one) were confronted with problems, as they tried to counteract according to delayed visual information.

Summarized, we agree with the findings of [4] and [5] and observe growing mitigation of the driving performance correlated with increasing network latency. Compared to the video transmission base latency of roughly 60 ms, an added network latency of 40 ms leads to a total end-to-end latency of 100 ms.

According to the empirical analysis of [21], 100 ms is a well-known human latency perception threshold in literature, but depending on the task, it might lay significantly lower. We, therefore, point out that the considered latency constraints need to be evaluated in a scenario-specific context, which means that other critical network latency might be valid for e.g., slower scenarios. However, the results show that our system architecture can be used in comprehensive QoE evaluations and can assist in determining critical scenario-specific thresholds.

C. *Impacts of Service Level Packet Loss*

In addition to the performance reduction through latency-related behavior, packet loss can also be a critical component of ToD. We configured the video codec to use the so-called *I*, and *P* frames only. *I* frames contain the full image, whereas *P* frames are predicted forwards and must be reconstructed jointly with the last *I* frame. Packet loss is thus expected to cause corrupted or missing frames on the receiver side. Although the decoder can compensate a certain amount of missing frames, the missing of an *I* frame also means a lot of missing information. This leads to artifacts and image errors as the following *P* frames can not reconstruct the image entirely. Missing *P* frames are more likely to cause a stuttered image. Especially in complex chicanes (c.f. Fig. 5, ”wall of champions chicane” and ”turn 3”), the image content changes rapidly. Because of this, image reconstruction is more challenging, so artifacts are more noticeable here than on straights.

Fig. 8 shows the lap times with applied packet loss. Values of 0.1 % and 1 % correspond to service reliability levels of 99 % and higher, as discussed in [10]. These two evaluations, as well as a packet loss of 2.5 %, do not show substantial effects on the end-to-end performance compared to each other, although we observe an increase of the average lap time between 1.9 % and 2.4 % with respect to the native environment. A packet loss of 5 % causes a massive break in the performance and increases the average lap time by 25.5 %. The reason for this are frequent video disturbances because the capability of the video decoder for compensating missed frames is exceeded. An analysis of the effect on subjective ratings is provided in Sec. IV-D.

In Fig. 9, the driving accuracy is evaluated. The number of off-track situations and collisions match with the corresponding lap times. For packet loss below 5 %, these are consistent and do not show much impact. Again, with the introduced interferences for 5 %, the performance significantly worsens, and the driver cannot avoid inaccurate driving anymore.

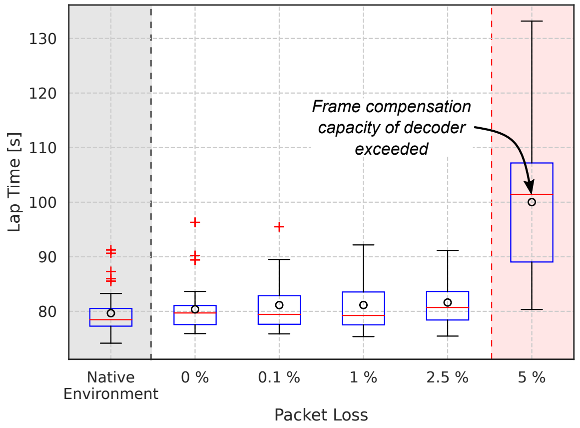

Fig. 8. Averaged lap times on Montreal track as an objective QoE measurement. For different packet loss, a stable driving performance is observed, which rapidly drops, when the error compensation capacity of the decoder is exceeded.

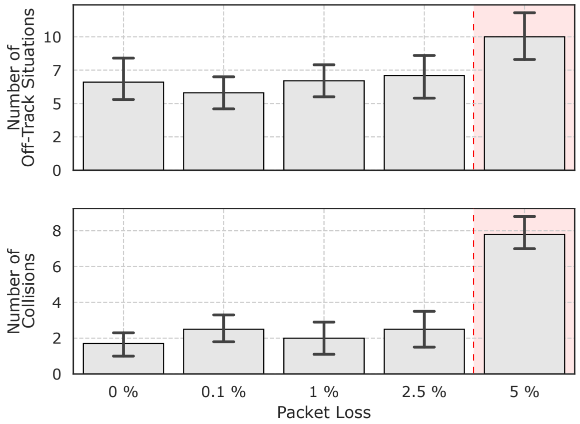

Fig. 9. Impact of packet loss on the QoE, expressed as number of off-track situations and number of collisions, respectively.

Depending on the decoder configuration, the compensation capacity for missing frames is variable. A less aggressive video codec can potentially work sufficiently with higher packet loss, which in turn requires a trade-off with low latency demands. However, especially the loss of *I* frames is crucial and leads to uncontrollable situations, which are inexcusable in high-speed scenarios. Thus, QoS prediction [18] is necessary to warn and enable the driver to slow down in advance to fulfill the task safely.

D. Subjective Ratings: Mean Opinion Score as QoE Indicator

In addition to the previously presented evaluation of QoE indicators based on driving performance and accuracy, the drivers may find different constraints more challenging than others, although they achieve similar performances. Increased stress can have a particular impact on the drivers' effort to fulfill their task, or in turn, how long they can operate the vehicle before getting too exhausted. We thus present the subjective driver rating in Fig. 10. With applied latency constraints, the participants rated the video quality relatively high on average. This was expected because the network latency is applied to the whole video stream and thus, should not harm the decoding. This holds as well for observed artifacts and stuttering, in which categories the ratings are also fairly high. Regarding the overall usability, the drivers rated with a decreasing trend for higher constraints. These results were expected and indicated the higher stress to the driver. The results show that latency compensation is needed for higher network latency to sustain, at least, a usable remote operation QoE.

The video quality is rated progressively worse for higher packet loss but is still considered reasonable on average. This is because artifacts and stuttering were conducted in separate categories, which are the primary end-to-end effects. Regarding occurred artifacts, the participants awarded high ratings, except for a packet loss of 5 %, which has frequent artifacts as a consequence. In our particular case study, this means that the driver had a standing image for a fraction of a second and thus had to steer the vehicle blindly, causing collisions and off-track situations.

Stuttering got more and more significant with every increase of packet loss. Even if the resulting driving performance (c.f. Sec. IV-C) remained at a certain level, the MOS scores reveal that the drivers were indeed affected. The linear effect of stuttering also condenses on the ratings of the overall usability. Which also decreases for a packet loss of up to 2.5 %. With a packet loss of 5 %, the usability rating rapidly drops. From an average of 3.0 to an average of 1.1, the combined effect of the stuttering and artifacts is observed.

V. Outlook on Potential Extensions and Enhancements of the Evaluation System

A. Hardware-in-the-Loop: Remote Operation Experience over 5G

A substantial advantage of our approach is the possibility of swapping particular components. Although we utilized the system to analyze the effect of different network constraints, RO requires the realization over cellular networks like 5G and beyond, which means latency and packet loss come in a combined, dynamic figure, which we did not cover in this work. Therefore, to perform HiL testing, we propose substituting our network component (c.f. Fig. 2) with a channel emulator for realistic fading conditions. Furthermore, the private 5G cell usage offers the possibility to plan the network based on its requirements. The industrial sector, for instance, is one of the first to be expected to integrate 5G-based RO into its logistical and production processes. In [22], the concept of demand-based configuration was shown, which can also be applied for the RO setup and extract an use case-specific QoS, but also QoE evaluation.

B. Integration of Robotic Platforms into the System-of-Systems

Another component to be substituted is the operating environment. Even if the used racing environment is highly realistic and sets a highly challenging task to the teleoperator, this is not to be expected the primary use case for RO. Based on our architecture, this can be replaced by any other

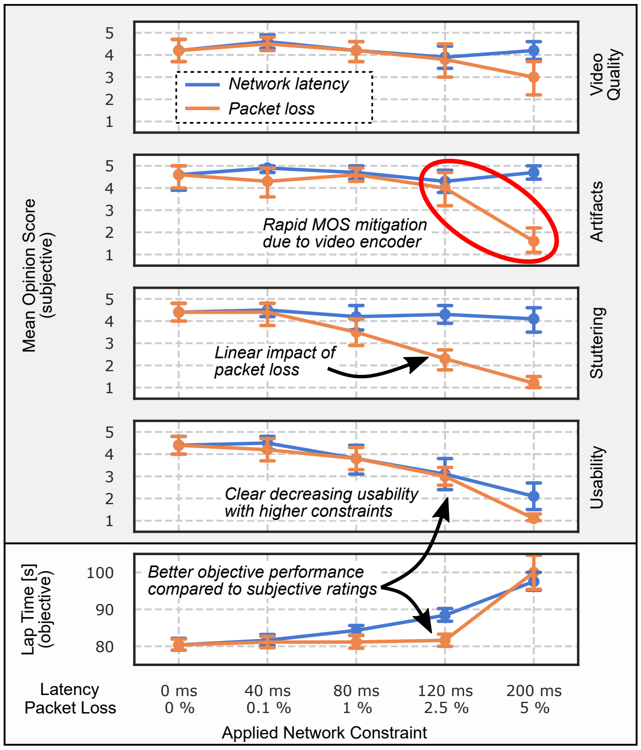

Fig. 10. Comparison of MOS ratings for applied network constraints by the drivers. Blue lines show the scores for additional latency, where a deterioration is primary expressed in the usability. In orange, different packet loss leads to distinct effects on the MOS.

simulation that offers a good grade of realism. For example, today's driving schools already include simulators in their training course before going onto the road. The integration of those simulators into our system-of-systems is possible nearly effortless, meaning that state-of-the-art simulators from driver's education can be used for remote operator training as well. But apart from RO simulations, real vehicles can also be introduced, such as real cars or, for a less complex environment, small-scaled vehicular platforms like radio-controlled cars. Especially in search and rescue missions, Unmanned Aerial Vehicles (UAVs) are a great application for remote operation. As natural disasters occur more frequently, the use of affordable and flexible deployable UAVs instead of expensive human-crewed aircraft to get an overview of the situation becomes more and more important. While the teleoperation of UAVs has different requirements regarding latency as, e.g., ground vehicles, a high QoE has to be met to allow, e.g., locating a missing person in the video stream.

VI. CONCLUSION

In this paper, we presented a system-of-systems architecture for combined QoS and QoE evaluations of remote operation applications. Its modular design seamlessly allows swapping network and channel components and the potential operation environment between simulations and real-world scenarios. First drive tests have shown noticeable end-to-end impacts induced by network constraints, motivating further research like the transition to HiL and the integration into embedded systems. Scenario-specific network planning also offers great potential for QoE-aware optimization techniques. In future work, we will transfer our system to various operation environments and use inter-domain knowledge. With this, we will integrate so-called radio environmental maps, which contain spatial network and channel information, into the system architecture to evaluate the QoE in consideration of mobile network KPIs.

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