Accepted for presentation in: IEEE 101st Vehicular Technology Conference (VTC-Spring), Oslo, Norway, June 2025.

RISE: Multi-Link Proactive Low-Latency Video Streaming for Teleoperation in Fading Channels

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***Abstract*—Throughput-critical applications, such as teleoperation, require robust and low-latency communication systems to ensure seamless performance. In this work, we propose the open-source predictive multi-link teleoperation video stream system for fading channels called Reliable Intelligent Stream Encoding system (*RISE*). It features a proactive bitrate control based on predicted channel conditions together with a modified version of the *SEAMLESS* multi-link protocol. Additionally, video stream queue feedback is evaluated to dynamically adjust the bitrate if predictions are too optimistic. Thereby, video transmission delays are minimized, preventing video frame drops due to an unacceptable age-of-information. We validate the performance of *RISE* in a laboratory setup using realistic radio channel emulation. The results demonstrate significant latency and video frame delivery improvements compared to conventional single-link and constant bitrate approaches. By leveraging *SEAMLESS* in addition to using the predicted bitrate with queue feedback approach, the median data rate of the video stream was doubled. Furthermore, *RISE* prevents frame drops in all investigated channel configurations while minimizing the queue delay. Thus, the proposed approach demonstrates the potential for improvement in the overall reliability of real-world teleoperation systems.**

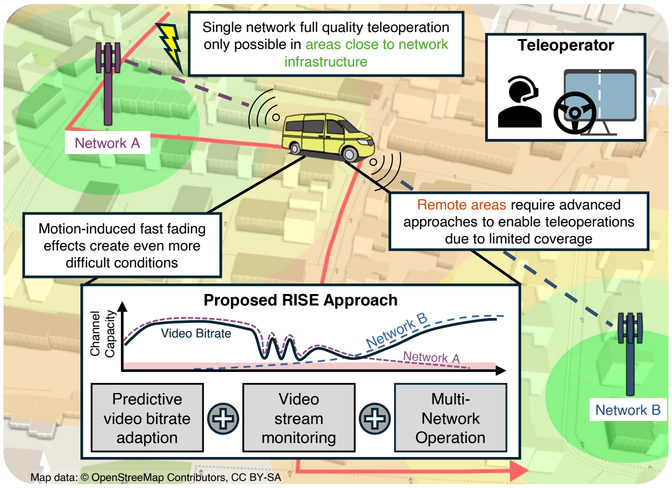


Fig. 1. Proposing the *RISE* approach for reliable teleoperation video streams utilizing predictive video bitrate adaption and proactive multi-link communication, counteracting the effects of challenging fading channels.

I. INTRODUCTION

Teleoperation systems are increasingly critical in multiple applications. On the one hand, they can increase comfort in logistics and efficiency in vehicle management. On the other hand, they are crucial for improving safety when operating in hazardous environments or enabling autonomous driving and logistics by providing a fallback solution in difficult situations. Thus, teleoperation maximizes autonomy uptime and is a viable backup solution during trials.

However, challenges in different fields need to be overcome to enable teleoperation. One key challenge is the robust and low-latency communication via wireless communication links to enable reliable remote control. In addition to the required control commands, a high-quality and low-latency video stream needs to be served at all times, inducing a high load on the network infrastructure. Due to the nature of mobile radio channels, the link capacity especially in vehicular scenarios can change rapidly due to factors like mobility and interference. A sudden degradation of the video stream quality might be the result. Furthermore, delays in communication can lead to a loss of situational awareness of the remote operator.

While multi-user capacity restrictions can be solved using network slicing, physical channel effects and possible interference are omnipresent. As illustrated in Fig. 1, this might lead to the necessity of multi-Mobile Network Operator (MNO) networking, as the high communication demands of teleoperation might not be sufficiently covered at all places and MNOs, as shown in [1].

We introduce the open-source multi-link **R**eliable **I**ntelligent **S**tream **E**ncoding system *RISE*, to address the challenges proposed in this paper. The contributions are summarized as follows:

- Adapting a **multi-link communication protocol** for a reliable teleoperation system
- **Predictive bitrate adaption**: Based on real-time channel quality estimation and feedback from the current video stream, we integrate a video bitrate adaption mechanism.
- Evaluation of the proposed framework in challenging **realistic fading channel** conditions

The remainder of the paper is structured as follows. After discussing the related work in Sec. II, the multi-link predictive bitrate approach is introduced in Sec. III. Afterwards, an overview of the methodological aspects is given in Sec. IV. Finally, detailed results of the proposed proactive video encoding system in different configurations are provided in Sec. V.

II. REQUIREMENTS AND APPROACHES TO TELE-OPERATED DRIVING

Several sources have worked out requirements of tele-operated driving on the communication network [2–6]. These

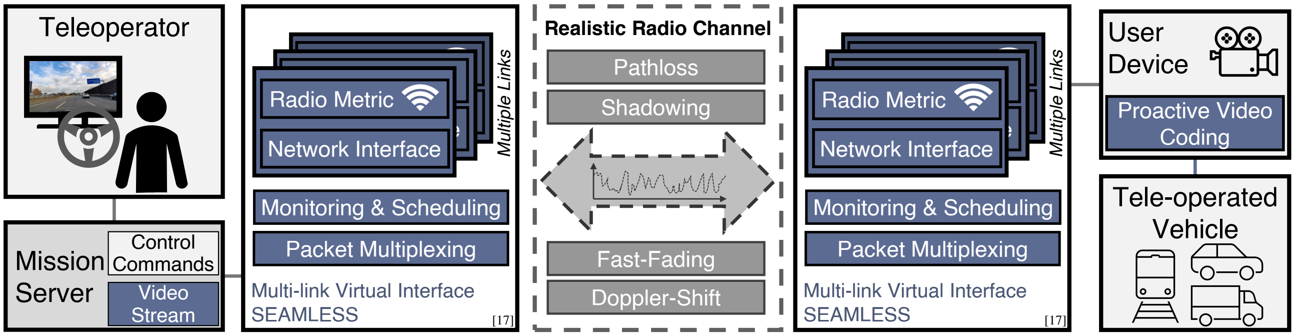


Fig. 2. Proposed architecture for multi-link tele-operated driving scenarios with proactive video coding.

target mainly data rate, latency and reliability aspects. While downlink requirements for control commands are commonly low, the uplink data rate requirements are more demanding on the network and vary from work to work. The *5G Automotive Association (5GAA)* demands an uplink data rate of 32 Mbit/s for direct teleoperation with a velocity of up to 50 km/h [4]. In [5], an uplink requirement of only 25 Mbit/s is demanded for velocities of up to 250 km/h. However, [5] requires a strict latency requirement of under 5 ms compared to 100 ms stated in [4]. While some works use an end-to-end latency, others use the network latency or the Round-Trip Time (RTT) [6]. However, all works agree that a low latency is crucial for teleoperation. At higher latencies [7, 8] but also at a variable latency [9], driving performance tends to deteriorate strongly.

While exact communication requirements depend on the scenario, their fulfillment cannot be guaranteed at all places and at all times. That is why several works investigated ways how to increase the reliability of teleoperation applications. One method is to use communication-based route planning to avoid low connectivity regions and a too-high density of tele-operated vehicles [10]. Also, the fulfillment of the data rate requirements can be increased by using multi-MNO networking, as shown in [1]. Additionally, real-time predictions of the expected data rate can help to proactively react to bad channels in advance and, thus, prevent sudden service interruptions. If a low connectivity situation can be predicted, adaptions like reducing the video stream bitrate can be issued in the teleoperation process [11]. In this case, the available data rate can be intelligently balanced between video streams of different cameras [12]. That can also be seen as a prefiltering step of different streams and a single encoding of a combined video stream [13]. Some commercial teleoperation companies adapt the video bitrate based on feedback from the receiver [14]. However, this approach has the disadvantage that the adaption process is delayed by the network RTT.

For safety reasons, robustness and reliability aspects are commonly analyzed in simulation environments [15]. These have the advantage of reproducible analysis without external influences. However, due to simulating the whole system, modeling accuracy of single aspects like fast-fading effects of the mobile network channel may be restricted or neglected. These effects are stochastic [16] and affect all wireless communications.

III. RISE: MULTI-LINK PROACTIVE VIDEO ENCODING

In this paper, we will emulate a teleoperation system consisting of a tele-operated vehicle controlled via two mobile networks over a fading channel by a teleoperator. The schematic of the proposed architecture is illustrated in Fig. 2. Key components to overcome the challenges of a realistic channel, consisting of slow- and fast-fading and doppler-shifts are the multi-link approach *SEAMLESS* and proactive and adaptive video encoding. These parts of the proposed *RISE* approach shall be explained in the following subsections.

A. *Multi-X Connectivity using* SEAMLESS

Since a single network can only meet the requirements for teleoperation in limited cases and a redundancy concept is also indispensable for robust and real-time capable transmission, a multi-link approach is pursued in this work. In [17], the multi-link protocol *SEAMLESS*[1] was introduced. We leverage *SEAMLESS* in this work as a key enabler for multi-link connectivity. Based on an encapsulation approach, it allows transparent tunneling of application layer data streams similar to a virtual private network. By keeping all networks on hot standby, *SEAMLESS* allows scheduling decisions on a data packet level. *SEAMLESS* implements packet reordering on the receiver side to minimize out-of-order packets in the event of a link change between networks with different latencies. At the same time, *SEAMLESS* carries out a link assessment at the network level, monitoring key performance indicators such as round trip time and packet errors. Furthermore, the transmission of keep-alive packets enables statements to be made about link quality without the need for a flow of user data. In addition to integrated naive scheduling decisions such as scheduling according to the lowest round trip time or round robin, *SEAMLESS* enables incorporating external data for use in scheduling by providing an open radio metric API. As shown in [17], link selection can, e.g., also be carried out based on the signal strength of wireless systems. We use this API in this paper to incorporate the prediction of the data rate of the links into the link selection. Thus, *SEAMLESS* always prefers the link with the highest predicted data rate. In our proposed setup, *SEAMLESS* connects the teleoperation application and the remote operator.

[1] https://github.com/tudo-cni/seamless

B. Predictive Channel-adaptive Video Encoding

The main goal of adaptive video coding is to follow the channel characteristics and network utilization as closely as possible. However, no matter how good the prediction is, there will be errors due to the stochastic behavior of mobile radio channels. Therefore, we also added a reactive buffer-based correction factor to our proactive approach.

This approach has the following advantages: With correct predictions, no latency is introduced due to transmitter buffering. Only in the case of deviations of the predictions from the experienced channel, potential video quality is lost or additional latency is built up. In this case, immediate action is taken to correct the encoder bitrate. Thus, a low-latency video transmission without losses due to buffer overflows is guaranteed.

Predictions may be performed by Machine Learning (ML) in public networks with multiple users [1]. In a private mobile network or when using a slice for teleoperation, the data rate can be inferred from channel characteristics due to the reduced overall complexity. Based on the current channel conditions, a solution space of possible combinations of Modulation and Coding Scheme (MCS), Resource Blocks (RBs) and transmit power can be examined. If less data needs to be transferred, less RBs can be scheduled with a higher MCS, as enough transmit power is available to provide a sufficient Signal-To-Noise-Ratio (SNR). That is why, the best possible tuple of MCS, RBs and transmit power for the maximum data rate needs to be estimated in case of an inactive or not fully occupied link. For this, the spectral efficiency C is looked up by the current MCS using the appropriate MCS table [18]. While the spectral efficiency will be well below the Shannon limit [19], a proportional relation between the spectral efficiency, the Bandwidth B, and the uplink SNR as in Eqn. 1 is assumed in this work.

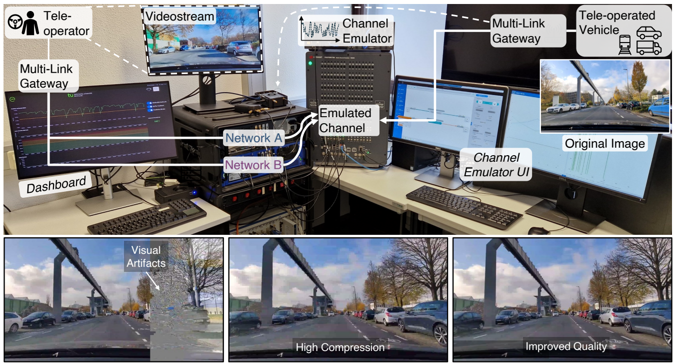
$$SNR_{\text{UL}} \propto 2^{C} - 1 \tag{1}$$

Thus, SNR SNR_{UL} can be improved by increasing the transmit power by the remaining power headroom P_{HR} of the modem. At the same time, SNR_{UL} will decrease, if the transmit power needs to be distributed over more RBs. As the result, a new uplink SNR SNR'_{UL} can by calculated by

$$SNR'_{UL} = SNR_{\text{UL}} + P_{\text{HR}} - 20 \cdot log_{10}\left(\frac{RB_{\text{max}}}{RB}\right) \tag{2}$$

By using Eqn. 1 to convert SNR'_{UL} to a spectral efficiency C', a predicted MCS MCS' can be looked up [18]. Finally, the tuple of MCS', RB_{max} and $P_{\text{TX, max}}$ can be used to calculate the possible data rate using the formula specified in [20].

As high differences in resource utilization and transmit power may lead to higher prediction inaccuracies, a increasing headroom (increasing with the difference in used RBs) is subtracted from the resulting data rate. Additionally, a feedback of the backlog of already encoded frames is used to adapt the bitrate. This is implemented using a correction factor $C_{\text{F,N}}$, which is further detailed in the following section.



Constant Bitrate (Single-Link) **Predicted Bitrate & Feedback (Single-Link)** **RISE: Reliable Intelligent Stream Encoding (Multi-Link)**

Fig. 3. Overview of the laboratory setup for proactive encoding and multi-link communication for teleoperation performance evaluation and demonstrations of single link constant bitrate, single link predictive bitrate streaming and the proposed RISE approach.

IV. METHODOLOGY

We simulate two 5th Generation of Mobile Communication Networks (5G) networks with two *Amarisoft* software defined radio-based base station emulators, as shown in Fig. 4. These are connected to two *Quectel RM520* modems via a *Keysight Propsim* channel emulator simulation both connections in real-time. The modems are connected to a System on a Chip (SoC) device simulating the tele-operated vehicle. On the Next Generation Node B (gNB)-side, another SoC aggregates the two 5G links and acts as the teleoperation mission server.

Either *iperf3* data rate measurements are performed, or a pre-recorded video of a driving vehicle [2] is transmitted over the channel. That enables us to reproducible evaluate the scenario, change video encoding behavior, and link selection behavior.

The base stations emulators are set up to simulate two 5G networks with a bandwidth slice of 20 MHz for teleoperation with a uplink-centered configuration. With the help of the channel emulator, we induce Tapped Delay Line (TDL) channel models including fast-fading [21]. Compared to Clustered Delay Line (CDL) channel models, these are more challenging due to their lacking spatial consistency with low correlation in between tabs. Detailed parameters are given in Tab. I. The path-loss to the gNBs is set to a one-minute-long scenario for reproducibility.

For video streaming, we use *GStreamer* [22]. We set it up to encode a video stream based on a variable bitrate, which is calculated as described in Sec. III-B. A Conversion step for live playback is carried out before encoding. For low-latency encoding, the *ultrafast* preset of H.264 is used in conjunction with tuning for *zerolatency*. The intra-frame refresh method is used, avoiding delay due to long Group of Picturess (GOPs) during encoding. By using intra-refresh, video stream bitrate spikes usually occurring at I-frames are prevented.

After encoding, a copy of the video stream is written to a file for later reference. A queue is connected between the encoder and the Real-Time Transport Protocol (RTP) transmission part buffering video frames until transmission. By monitoring the

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[2] https://tinyurl.com/rise-video

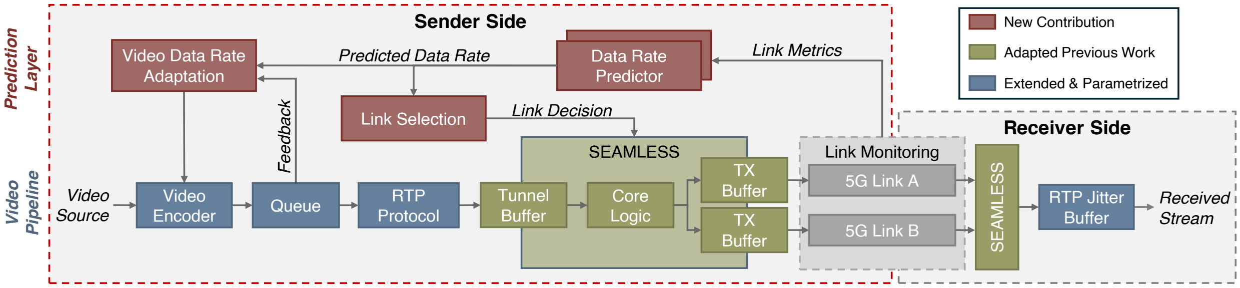

Fig. 4. Block diagram overview of the multi-link video streaming pipeline utilizing *SEAMLESS* and a proactive data rate prediction with queue feedback.

current queue state, feedback can be given to the data rate predictor. A correction factor $C_{\mathrm{F,N}}$ for the encoder bitrate is adapted based on the current frame delay d of the queue, as formulated in Eqn. 3.

$$C_{\mathrm{F,N+1}} = \begin{cases} \min(1.05 \cdot C_{\mathrm{F,N}}, 1.0) & d \leq 2 \\ \max(0.9 \cdot C_{\mathrm{F,N}}, 0.4) & 2 < d \leq 3 \\ \max(0.7 \cdot C_{\mathrm{F,N}}, 0.05) & d > 3 \end{cases} \tag{3}$$

If the queue is empty or below two video frames, the correction factor is increased until no reduction of the data rate is performed. Starting from three frames in the queue, the correction factor is decreased by a set factor if the delay changes. At high delays, the correction factor is changed more drastically every iteration and the minimum value of the correction factor is lower to quickly decrease the queue backlog.

The RTP transmission sink is set up to transmit the encoded frames in the queue using User Datagram Protocol (UDP) via *SEAMLESS*. UDP has a lower overhead than Transmission Control Protocol (TCP) and prevents unnecessary retransmission of old video data. By slightly reducing the Maximum Transmission Unit (MTU), space is given for *SEAMLESS* packet headers. The headers used in the system are considered for the bitrate by the data rate predictor.

The link-selection of *SEAMLESS* is configured to use the link with the currently highest data rate estimated by the data rate predictor. While the *SEAMLESS*-internal reorder buffer is disabled, a RTP jitter buffer is used to reorder possibly out-of-order received video stream packets. Packet-losses and frame drops are registered and logged for evaluation. The queue length of the tunnel interface of *SEAMLESS* and of the modems interfaces are set to ten packets from the default of 500 to minimize buffer-induced latency. The maximum video frame queue size is set to 250 ms (15 frames). Depending on the current bitrate, the queue length and buffer sizes can be converted into worst-case delays. That underlines the necessity of optimizing the individual buffers and choosing an appropriate prediction to provide these delays. Due to the continuous transmission and the resulting buffer state report, gNBs will schedule RBs accordingly avoiding scheduling delay induced by the 5G network.

The approach for link data rate prediction described in Sec. III-B is used for both 5G links. A margin of 20 % is subtracted from the calculated data rate to consider possible non-ideal effects and reduce the probability of filled buffers. The necessary input values are queried from the modems every 300 ms and are extrapolated using regression of past values to filter extreme values and track value developments. Invalid values are discarded and replaced with minimum values.

TABLE I
PARAMETERS OF THE EVALUATION SETUP

Parameter	**Value**
Base station configuration	
Center frequency	Netw. A: 3.489 GHz, netw. B: 3.775 GHz
Bandwidth	20 MHz
TDD-pattern	5 ms period, 2 DL, 7 UL slots
Wireless channel configuration	
Fading models	• Simple channel (see path loss in Fig. 5) • Medium channel (simple plus fast fading TDL-A [21] $\tau_{\mathrm{rms}} = 30\,\mathrm{ns}$, $\Delta f = 10\,\mathrm{Hz}$) • Demanding channel (simple plus fast fading TDL-C [21] $\tau_{\mathrm{rms}} = 300\,\mathrm{ns}$, $\Delta f = 100\,\mathrm{Hz}$)
Antenna configuration	Single Input Single Output (SISO)
Doppler speed	30 km/h
Video stream configuration	
Max. bitrate	32 Mbit/s
Min. bitrate	1 Mbit/s
Resolution	1920x1080 pixel @ 60 fps
Encoder buffer size	1600 kB
Codec	H.264, intra-refresh frames
Preset	Ultrafast, zero latency
Transport protocol	RTP via UDP
MTU	1350 B
UDP buffer size	12.5 kB
RTP jitter buffer latency	$\leq$ 20 ms
SEAMLESS [17] configuration	
Link-selection	Best link
UDP-buffer size	12.5 kB
Reorder buffer	Disabled
Monitoring interval	20 ms
Interface buffer size	10 Packets

V. ENABLING ROBUST TELEOPERATION USING PROACTIVE MULTI-LINK COMMUNICATION

For evaluation *RISE*[3], we chose a scenario of two gNBs with a given path-loss course, as shown in Fig. 5. This scenario ensures reproducibility while pointing out key advantages of the different approaches. In Fig. 5, the data rate measured with *iperf3* in the given attenuation scenario is displayed. While only the slow-fading is applied in the center subplot, in the lower subplot slow- and fast-fading is applied. Despite the attenuation being the same in both cases, the achievable data

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[3] https://tinyurl.com/rise-source

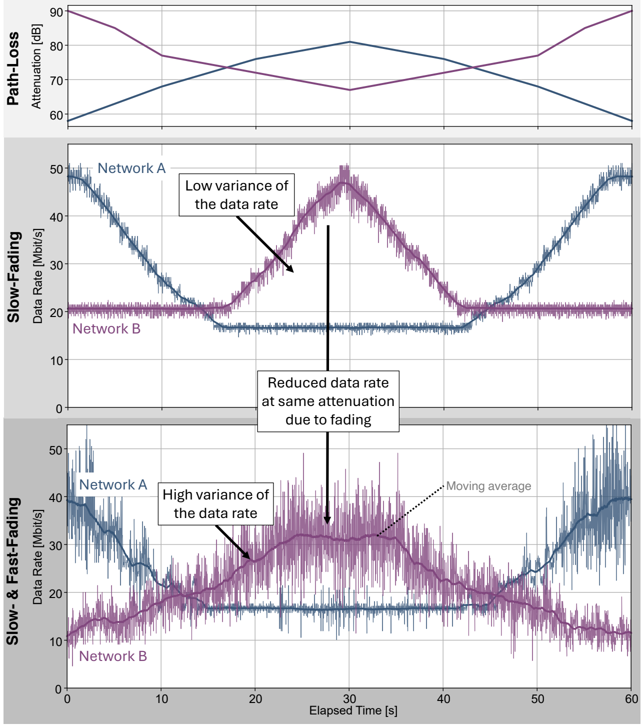


Fig. 5. Maximum achievable data rate via slow-fading and medium fast-fading channel in the evaluation scenario.

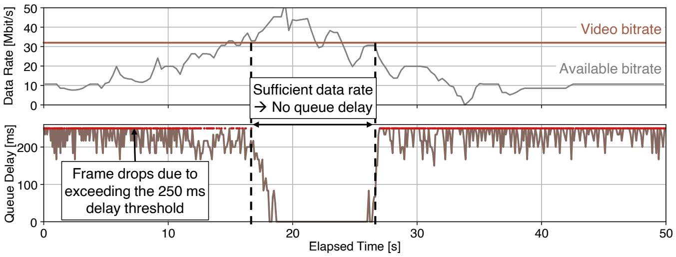
rate differs significantly between the slow-fading and the fast-fading measurements. Due to the fast-fading, the data rate is reduced and the variation increases significantly. While the data rate is partly over 30 Mbit/s on average, it deteriorates to below 15 Mbit/s for short intervals. In addition to different cell parametrizations, this is why a signal-strength-driven data rate prediction and link selection is not sufficient for bitrate adaption. Rather, the achievable MCS in conjunction with the number of RBs determines the data rate.

As a result, traditional constant bitrate video stream transmissions via a fading channel (c.f. Fig. 6a) will result in a high delay or a high frame loss depending on the maximum tolerable delay. This is illustrated in Fig. 6b. In contrast to the case shown in Fig. 6a, the video bitrate is varied based on the predicted available channel data rate. Nevertheless, queue delay spikes appear over the shown timespan. Due to the stochastic nature of fading channels, deep drops in the data rate may not be predictable. When the data rate was assumed too high, image data has to be buffered at the transmitter. That is why we propose to utilize feedback from the video transmitting queue additionally, as described in Sec. IV. Ensuring that the video encoder bitrate stays below the predicted bitrate in case of a significant queue delay can effectively reduce the overall delay (c.f. Fig. 6c). As a result, no frames need to be dropped due to their age of information being over the maximum frame delay.

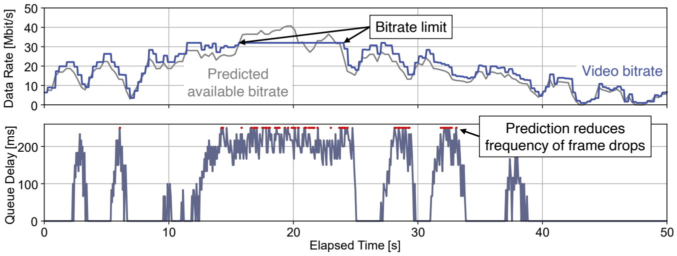
Additionally, multi-link networking via *SEAMLESS* is evaluated. As a result, the link capacity is increased significantly, as shown in Fig. 7. Still, a high delay in conjunction with a high loss of frames due to buffer overflows are the result with the constant bitrate approach. By using a data rate prediction as proposed in Sec. III, the queue delay and the percentage of dropped frames can be reduced significantly.

Still, frame drops and high delays cannot be excluded due to sudden link capacity fluctuations. That is why the video queue feedback is still required for *RISE*. By using multi-link in conjunction with the proactive bitrate prediction with feedback, no lost frames are recorded and the queue delay is minimized. At the same time, a twice as high data rate compared to the single link approach is reached, improving the video quality shown by the increased Peak SNR (PSNR).

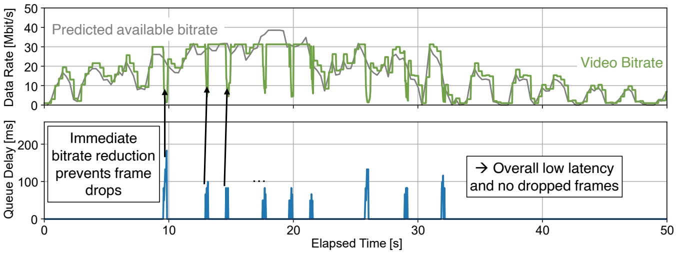
Different kinds of fading channels pose different challenges to the communication link. In the case of multi-link communication via a slow-fading channel, the predictive bitrate control approach is mostly sufficient to keep delays low, as shown in Fig. 8. While a *slow-fading* channel shows a relatively predictable data rate, fast-fading channels increase the deviation of the data rate over time. In order to further validate our approach, we tested it on a more demanding channel. The results for the multi-link case are shown in Fig. 8: While the achieved data rate decreases at the demanding channel, the delay is kept minimal due to the proactive feedback approach of *RISE*. Thus, our proposed method enables low latency teleoperation even in demanding communication channels while leveraging the advantages of multi-link communication.



(a) Video encoder set to constant bitrate



(b) Video encoding adjusted according to predicted bitrate



(c) Video encoding adjusted by predicted bitrate and queue feedback

Fig. 6. Illustrating the working principle of different proposed video streaming approaches.

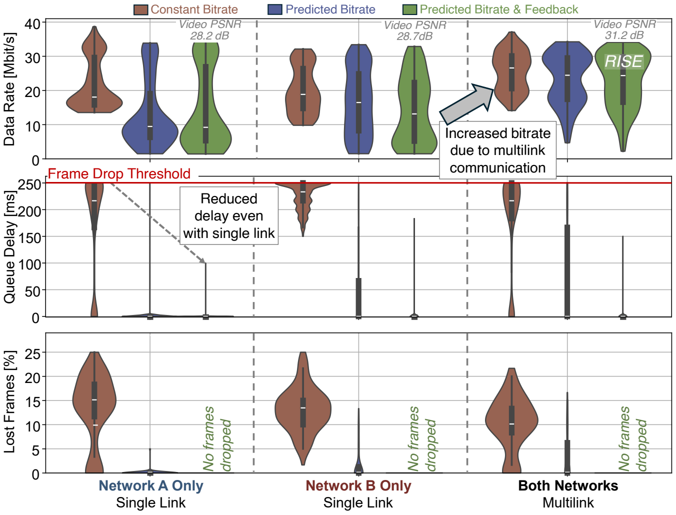


Fig. 7. Data rate, queue delay and frame loss of **single- and multi-link** video streaming approaches via a **medium fast-fading channel** showing the advantages of the *RISE* multi-link approach.

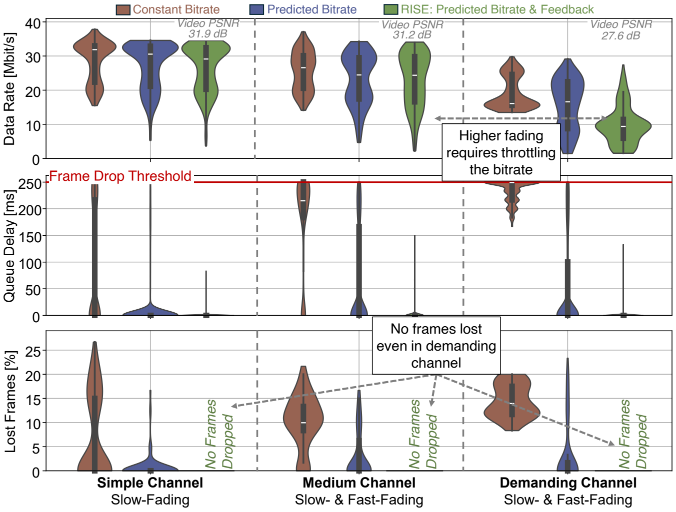


Fig. 8. Data rate, queue delay and frame loss of **multi-link** video streaming approaches via **different fast-fading channels** showing the superiority of predictive bitrate selection with queue feedback.

VI. CONCLUSION

In this paper, we analyzed the challenges of limited coverage and probabilistic channel effects, mobile networks pose on tele-operated driving. We improved the overall Quality of Experience (QoE) of teleoperation applications by utilizing the proactive multi-link approach *RISE*. With the help of predictive video encoding, *RISE* reduces latency and prevents frame drops. Using multiple networks improved the possible video bitrate and, thus, the overall quality of perception and service availability. In addition, video bitrate adaption based on the video stream status at the transmitter increased reliability while preventing slow reaction times due to large control loops.

In the future, we aim to evaluate our teleoperation system in more scenarios under different channel models and in real-world public mobile networks, leveraging ML for data rate predictions.

ACKNOWLEDGMENT

This work has been partly funded by the Federal Ministry of Education and Research (BMBF) via the project *6GEM* under funding reference 16KISK038, by the Deutsche Forschungsgemeinschaft (German Research Foundation) under project number 508759126, and was further supported by the project DRZ (Establishment of the German Rescue Robotics Center, 13N16476).

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