2025 Design, Automation & Test in Europe Conference (DATE 2025)
Special Initiative "Autonomous Systems Design"

Teleoperation as a Step Towards Fully Autonomous Systems

Alex Bendrick*, Daniel Tappe*, Nora Sperling*, Rolf Ernst*, Andrea Nota †, Selma Saidi*, Frank Diermeyer‡
**Institute of Computer and Network Engineering*, *Technische Universität Braunschweig*, Germany
†*Professorship Embedded Systems*, *Technische Universität Dortmund*, Germany
‡*Institute of Automotive Technology*, *Technische Universität München*, Germany
*{bendrick, tappe, sperling, ernst, saidi}@ida.ing.tu-bs.de
†andrea.nota@tu-dortmund.de
‡diermeyer@tum.de

***Abstract*—In the foreseeable future, highly automated mobile systems, such as vehicles, robots, UAVs, or trains, will be confronted with difficult situations that require external support. The availability of such external support corresponds to level 4 driving automation and is an essential feature in current robotaxis and automated public transportation. While the first generation of level 4 prototypes relied on safety driver support, commercial systems are gradually moving towards support by teleoperation. Designing teleoperation support for level 4 systems is an end-to-end problem involving two main research and practical challenges, the teleoperation function defining the remote human interface with its scene representation and available control functions, and the real-time communication channel involving wired and wireless segments, which must provide reliable end-to-end data transport. Both challenges are tightly linked, and combined solutions are needed to reach the required safe teleoperation. Solutions can make use of the rich sensing and control system of a level 4 vehicle, which however can only be exploited if the communication channel provides adequate real-time access.**

I. Introduction

Highly automated mobile systems, such as vehicles, robots, UAVs, or trains, will be confronted with difficult situations that require external support. Such support can be provided locally, e.g. a driver, or remotely by human or automated teleoperation [1]. In robotaxis and public transportation, local drivers would be a major cost factor and deteriorate the cost benefits of automated driving. Therefore, at the current state of technology, teleoperation by a remote human driver appears as the only viable option.

The possible forms of teleoperation depend on the vehicle driving automation level, as defined in the related SAE standard J3016 [2]. In vehicles with SAE level 4 driving automation [2], the vehicle system must self-detect its inability to continue driving service and actively ask for driver support [2]. However, the driver is not obliged to support, but the vehicle must be self-sustained providing a fail-safe function, called Dynamic Driving Task (DDT) Fallback, such as pulling over to the shoulder, and discontinue regular service. This DDT fallback is a crucial distinction from level 3 automation, which is a main reason why vehicles below level 4 are less attractive for driverless public transport. Requiring a DDT fallback avoids excessive communication reliability requirements that traffic authorities could require for level 3 systems with teleoperation support. On the other hand, a teleoperator may temporarily leave the Operational Design Domain (ODD) ([2], 3.12 note 6), i.e. can execute operations that the automated driving was not qualified for.

To conclude, at level 4 driving automation, teleoperation is no required safety function, but opens a way to continue transportation service under failure to reliably and safely bring passengers to their destination, even under adverse conditions. Technically, teleoperation increases service availability [3], but must not increase safety risk due to an undetected error in the teleoperation channel. To confine complexity, teleoperation should maintain the DDT fallback of the supported level 4 system. In consequence, as long as active, teleoperation must guarantee correct communication and operation and self-detect an error to revert to the DDT fallback.

Now, we can formulate the teleoperation requirements. The remote driver must a) be able to see and perceive the current vehicle status and environment (remote perception) and b) be able to command the vehicle back into a state where the vehicle can resume level 4 operation (remote operation).

A. Remote Perception

A level-4 automated vehicle has a multitude of optical (camera, LIDAR) and radar sensors with increasing resolution and frame rate. The vehicle uses these sensors in combination to identify and classify objects and environment. One of the main reasons why the vehicle discontinues service is uncertainty in perception. To overcome vehicle perception uncertainty, the remote human must have human readable access to raw sensor data, possibly in a compressed form, because the vehicle results cannot be trusted in this situation. Coordination messages of SAE J3216 [4] might be helpful to evaluate intentions of other traffic participants, but cannot substitute raw sensor data evaluation. Even in compressed form, raw data transmission leads to much higher data rates than typical V2X messages [4], and is subject to short latency constraints to enable accurate and safe vehicle motion control. Some sources [1] assume a maximum latency of 300 ms for the

978-3-9826741-0-0/DATE25/© 2025 EDAA

V2X segment, a latency that has meanwhile been practically demonstrated for isolated but complete teleoperation loops with high sensor resolution [5]. A 300ms target might be slightly overambitious in larger networks with errors, but we can take the result as indicator that remote perception is fast enough for teleoperation. Channel reliability requirements are high, there must be no occasional freezing, delay variation or frame errors, as known from video conferencing systems.

B. Remote Operation

A second main reason for discontinued driving service is the disability to decide on where the vehicle should go and on which trajectory. While early teleoperation systems assumed detailed motion control (cf. [6], [7]), level 4 vehicles will maintain basic vehicle motion control including longitudinal and lateral motion ([2], 3.10 and fig.2). The teleoperator will only provide destination and direction of movement thereby relaxing the timing requirements. For cases, where the connection breaks during operation, the level-4 DDT fallback must provide a narrowly defined "object and event detection and response" (OEDR), to continue motion to a "minimal risk condition". [2]

This paper is composed of two parts. In the next Section II, the general challenges and aspects of teleoperation are first highlighted. In the second part, i.e. Section III, the aspect of reliable wireless communication is discussed. This Section III deals, first, with wireless connectivity and, second, with end-to-end connection management. Finally, Section IV draws the conclusion.

II. Teleoperation

A. General Challenges

Remote operation of vehicles necessitates addressing several critical challenges. One prominent issue is the latency inherent in transmitting sensor data from the vehicle to the operator's workstation and relaying the operator's control inputs back to the vehicle. This latency adversely affects the operator's ability to control the vehicle effectively. On the one hand, it can exacerbate the criticality of traffic scenarios by putting off corrective or preventive actions. On the other hand, it significantly increases the cognitive and physical workload of the human operator.

In the currently prevailing implementation of teleoperation systems, the operator directly manages the vehicle's control, including the stabilization layer of the driving task. This direct control paradigm is particularly sensitive to latency, as delays in communication amplify the operator's workload by requiring greater compensatory effort to maintain safe and efficient vehicle operation.

Moreover, the operator's perception of the vehicle's environment is inherently constrained. The sensory data provided to the operator is not only affected by latency but is also limited in quality and fidelity. Specifically, visual information is typically delivered in two-dimensional video streams, which are additionally restricted in terms of resolution, contrast, and field of view. In addition, motion perception of the ego vehicle, audible location, and spatial orientation of the remote environment are degraded. These limitations further impair the operator's ability to perceive and interpret the surrounding environment accurately. These constraints lead to reduced situational awareness and influence both decision-making behavior and attentional control. [8]

In addition to the fundamental challenges of the technology itself, further boundary conditions must be considered when operating vehicles with teleoperation support. Before the broad deployment and operation of teleoperated vehicle fleets on public roads, several unresolved questions must be addressed. A technical report [9] published by the Federal Highway Research Institute Germany categorized these open issues into five primary focus areas. The challenges mentioned above are assigned to the three technical focus areas: "vehicle, area of operation and functional safety", "workstation, ergonomics and occupational health and safety" and "communication technology". A holistic view is achieved by including the following topics in two further focus areas of the report: "Fitness to drive, competence and personnel requirements" and "Societal aspects, acceptance and road safety".

In the following, this paper will focus on the technical challenges.

B. System Overview

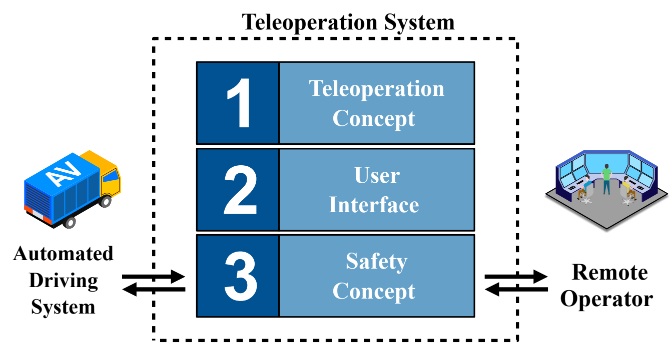

Fig. 1: Teleoperation System [10]

According to [10], a teleoperation system can be divided into three components (cf. Figure 1). The teleoperation concept, the user interface, and the safety concept. The teleoperation concept defines the interaction modalities through which the operator supports the vehicle's automation. These modalities may include direct control inputs, such as steering wheel angle and velocity specification, predefined trajectories, or high-level instructions targeting specific functions of the self-driving system. The user interface encompasses the human-machine interface on the operator's desk. The safety concept incorporates supplementary safety mechanisms, such as collision avoidance or monitoring real network bandwidth, designed to enhance the overall safety and reliability of the system.

The relevant components to this paper, safety concept and teleoperation concept, are described in more detail below. For the component user interface, please refer to [11] and [12].

1) Safety Concept: In teleoperation, communication – including the wireless segments – plays an important role, as it forms the basis for effective operation between the operator and the vehicle. However, it is crucial to state that a sudden loss of connection should not result in a safety-critical situation. The inherent susceptibility of wireless connections to interference necessitates that this risk is addressed within the system's safety concept, e.g., by integrating a dedicated DDT fallback.

Even if it is assumed in the context of automation level 4 that a connection interruption does not compromise safety, the frequency and duration of such interruptions significantly affect the performance of the mobility system. Consequently, these interruptions have a direct impact on the economic efficiency of the service. Therefore, while connection quality is not classified as a safety feature, there is an inherent trade-off between the resources required to maintain connection reliability and the overall economic efficiency of the teleoperation system.

As explained above, teleoperation is used when self-contained automated driving is no longer possible. The vehicle depends on the input of a human operator for continuous driving in a dynamic environment. Thus, in the current state of technology, any transient or persistent disconnection leads to emergency braking or minimum risk maneuvers to establish a minimum risk condition on short notice. Unforeseen disconnections and a short planning horizon of vehicle motion result in strong vehicle deceleration. This behavior is difficult to predict for other road users and reduces passengers' acceptance of the mobility system.

Solutions usually address both the vehicle side and the communication side. With the help of methods for predicting the quality of mobile network service [13], vehicle behavior can be adapted early depending on the prediction period. For example, if bandwidth restrictions are predicted, the vehicle speed can be reduced at an earlier stage so that highly dynamic maneuvers are not required. On the vehicle side, algorithms are used to extend the self-reliance of the teleoperated vehicle. [14] and [15] show approaches that allow an extended planning horizon for the human operator and thus avoid highly dynamic vehicle reactions.

2) Teleoperation Concept: In [16], the human driver was assigned as the critical reason for 94% of car crashes. This highlights that the objective of teleoperation should be to minimize human involvement in the decision-making process to the greatest extent possible. Instead, the focus should be on leveraging the safe and validated algorithms of the self-driving system as the primary decision-making mechanism, limiting human input to an absolute minimum.

Based on this approach, six teleoperation concepts were defined in [10] and compared with each other in terms of their application areas. Figure 2 shows the teleoperation concepts and arranges them according to the allocation of tasks between the human operator and the autonomous driving function.

The top of the figure shows the familiar sense-plan-act breakdown of the driving functions of an automated vehicle. In planning, a more detailed distinction is made between behavior planning, path planning, and trajectory planning. Below this, each teleoperation concept shows which sub-function is processed by the human operator and/or the AV function.

For a detailed presentation of the various teleoperation concepts, please refer to [10]. At this point, the distinction between remote driving and remote assistance should be noted. As long as the human operator is responsible for planning the trajectory, this is considered remote driving. If the vehicle takes over the trajectory planning, this is called remote assistance.

The teleoperation concept of perception modification can be emphasized as a consequence of reducing human decisions to a minimum. With this teleoperation concept, the human operator modifies or extends the machine-generated environment model. The entire downstream AV stack remains in function. The responsibility of the human operator is limited to the validity of its modifications to the environment model. Attributes such as "dynamic object" can be changed to "static object" to identify standstill vehicles that have not been recognized as parked. In addition, the drivable area can be extended if the perception algorithm is too conservative.

C. Trend

All teleoperation concepts share that the human operator needs high situational awareness to make correct and safe decisions. Consequently, the sensor data from the vehicle environment must be available to the operator in high quality and with low latency to ensure the data is up-to-date. Furthermore, communication reliability is a critical concern to ensure continuous service – and thus feasibility for real-world deployment. To further increase immersion and situational awareness, operator workstations are equipped with head-mounted displays in which the operator can experience the remote world in virtual 3D. In addition to 2D video streams and 3D object lists, 3D LiDAR point clouds are transmitted and displayed at the operator's desk. These increased requirements will pose new challenges for future mobile networks.

III. Reliable Wireless Communication

Teleoperation is an interdisciplinary application that must tackle a multitude of challenges across various engineering and research domains. Many publications and studies on teleoperated driving often focus on isolated problems, which fail to capture the complexity of the overall issue. A central aspect of this is communication, which is frequently abstracted to a high degree. The safety-critical nature of teleoperation imposes stringent timing and safety constraints on the wireless communication. Given the need to convey a detailed representation of a vehicle's environment to the remote operator (cf. Section II-C), it is indispensable to exchange high-quality and high resolution perception data gathered by the vehicle. However, specifically the end-to-end communication, i.e., sending (high-definition) perception data from the vehicle to the remote operator, which, based on the perception data, issues control

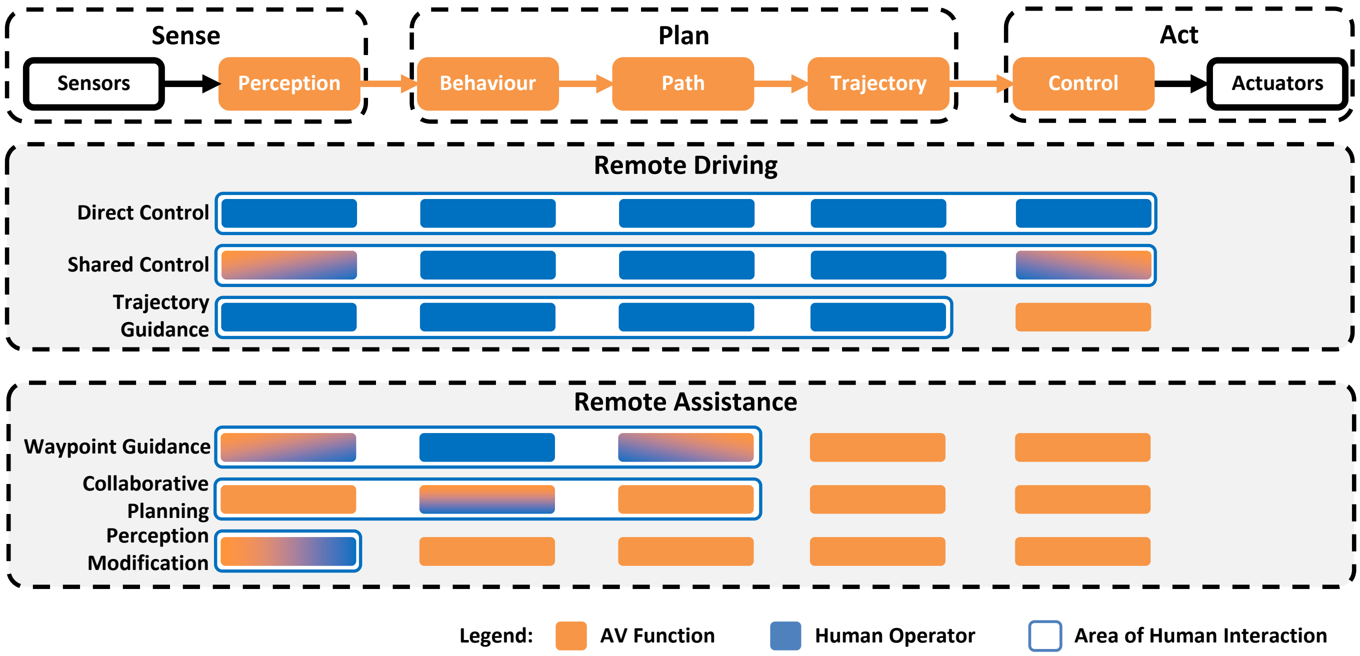

Fig. 2: Overview of teleoperation concepts. Colors show the task allocation between the human operator and the autonomous driving function. Bounding boxes illustrate the area of human interaction.

commands (cf. direct control, shared control or trajectories) that need to be sent back to the vehicle within the tight bounds of an application's deadline (e.g., $300\,\mathrm{ms}$), poses significantly challenges. Especially the reliable and timely transmission of large sensor data objects is a crucial aspect of teleoperation and has not been properly addressed yet. Despite the trend towards trajectory guidance systems or remote assistance which may allow to relax certain timing constraints, in general, timely and reliable data exchange is still crucial. While modern wireless technologies (802.11 and cellular) offer improvements with respect to data rates and reliability, so far these objectives remain mutually exclusive, allowing to either use higher data rates but without reliability guarantees or ultra-reliable low latency exchange of small (control) messages. To address these challenges, solutions are needed that complement one another and ultimately work together in a cohesive manner. Only through an integrative approach that takes all different aspects into account, effective and reliable communication for teleoperation applications can be ensured.

A. *Wireless Communication Technologies*

802.11 (WiFi) and cellular technology are the two main commodity-of-the-shelf wireless communication options that could enable exchange of large data, e.g., for teleoperation use cases. While both offer specific derivatives for Vehicle-to-Everything (V2X) communication (802.11p/bd and C-V2X), neither of those standards supports the data rates needed for teleoperation [17]. For teleoperation, cellular technology seems to be the main contender as the existing cellular infrastructure already offer extensive coverage and enables widely-available connectivity virtually anywhere, without the need for dedicated infrastructure development to support such use cases. Thereby, cellular networks are designed around a grid of cells, each served by a base station which serves as a central connection point for a wireless device – here a vehicle – and enables communication with a remote operator. Given the inherent mobility of (remotely operated) vehicles, handovers between cells need to be performed to maintain connectivity when traversing through multiple cells.

1) Challenges: Depending on the resolution, one can expect perception data streams for teleoperation ranging from few $\mathrm{Mbit/s}$ for H.265 encoded video streams or small high-definition maps up to $1\,\mathrm{Gbit/s}$ in case raw UHD images shall be exchanged. Both 802.11ax/be and cellular 5G (enhanced Mobile Broad Band (eMBB)) can support high data rates that would nominally be sufficient to transmit (raw or encoded) video streams, LIDAR point clouds or high-definition maps of a vehicle's environment. However, given the safety-critical nature of teleoperation, each perception data sample must be transmitted prior to a sample deadline (D_S) in order for the application to operate safely. Critically, this is complicated by the fact that wireless communication is subject to fluctuating channel conditions (signal strength, fading effects, interference, changes in available bandwidth) that make wireless communication inherently lossy and volatile.

In order to address reliability, i.e., loss-less data exchange under lossy circumstances, both 802.11 and cellular (5G) standards specify dedicated Backward Error Correction (BEC) mechanisms to correct inevitable packet-loss. (Hybrid) Automatic Repeat Request ((H)ARQ) mechanisms that perform retransmission based on missing or negative acknowledgments are used for this purpose. While the (H)ARQ mechanisms used by 802.11 and cellular standards work fine in improving the reliability of packet transmissions, they become inefficient when protecting the large sample exchange needed for teleoperation. Due to their size, large samples need to be transmitted in a fragmented manner. Then, all fragments need to be transmitted and received prior to D_S. The packet-level nature of state-of-the-art BEC means that each packet is subject to a packet-level deadline as the number of retransmissions is limited. Thus, the metric that is actually important from an application's point of view - which is the sample-level deadline – cannot be considered. Consequently, if a transient error prevents the successful transmission of a single packet, this loss cannot be recovered, even if the sample deadline would offer further time. As a result, state-of-the-art packet-level BEC is no feasible solution for safety-critical applications requiring reliable sample exchange that cannot tolerate residual errors. Importantly, while 5G Ultra-Reliable and Low Latency Communication (URLLC) and 802.11be wireless Time-Sensitive Networking (TSN) functionality claim to be capable of ultra-high reliability and low latency, those claims only hold true for small control data. While modern wireless technologies (802.11 and cellular) offer high data rates and high reliability, both cannot be combined, thus, leaving a gap that needs to be filled by novel solutions.

However, transmission errors are not the sole issue with wireless large data exchange. Even when using 5G technology, bandwidth limitations still exist. While the offered data rates would be sufficient for single applications, scaling effects in crowded areas can quickly lead to drastically increasing bandwidth demands on the network. This is combined with link adaptation, i.e., the dynamic adaptation of the Modulation Coding Scheme (MCS), in response to changing channel conditions (error rates, signal strength degradation, network congestion, ...), that causes varying transmission behavior with respect to resource requirements and, thus, timing. Furthermore, the channel is shared by multiple mixed-criticality applications, as non-safety-critical Over-the-Air (OTA) updates, infotainment streams or telemetry data may use the same channel alongside teleoperation. Moreover, even safety-critical applications can have widely varying requirements with respect to safety and Quality of Service (QoS). As a result of these dynamics and scalability concerns given the mixed-criticality environment, safe integration of these mixed-criticality applications becomes a none-trivial task. However, safety-critical applications such as teleoperation require reliability and timing guarantees to be practically feasible in a safe way.

The high degree of vehicle mobility further exposes the communication to volatile channel conditions. In addition to a lossy communication and fluctuating channel condition, teleoperation must also handle handovers (HOs) in cell-centric or access point based networks. A handover is triggered when degrading channel conditions, i.e. decreasing signal to noise ratio (SNR), are detected [18]. The most common reason for HO is the crossing coverage boundaries. During the HO data traffic must be rerouted to another Access Point (AP) or base station (BS). Rerouting includes AP/BS association and backbone rerouting. In consequence, the link between teleoperator and vehicle is interrupted. For current wireless networks the interruption duration T_{int} ranges from multiple $100\,\mathrm{ms}$ to several seconds [19], [20]. With a target latency range of $300\,\mathrm{ms}$ to $400\,\mathrm{ms}$, continuous real-time data exchange cannot be guaranteed.

In the following, we address some proposed solutions for providing reliability end-to-end communication in teleoperation applications. These comprise dedicated middleware protocols for reliable large data, mechanisms for dynamically reconfiguring applications and network properties and proactively predicting and managing latency violations.

B. Enabling Reliable End-to-End Connectivity

1) Reliable Transmission of Large Sensor Data: The W2RP and its extensions address the limitations of state-of-the-art wireless technologies with respect to error correction (see above) by exploiting application knowledge for improved error protection. This is enabled by the fact that W2RP is a middleware solution that directly integrates with the application. Compared to the usual packet-level BEC, W2RP extends the error correction to the scope of a whole sample. Thus, retransmission resources are not granted on a packet-level, but rather sample-level slack can be used for arbitrary fragment retransmissions (cf. Figure 3). This greatly improves flexibility for dynamic retransmission schedules within the whole sample deadline D_S, thereby significantly improving reliability as shown in [21]–[23]. Thus, W2RP can improve the reliability of sample exchange in various safety-critical large data use cases, including teleoperated driving. Importantly, while so far exclusively tested and evaluating using 802.11 technology,

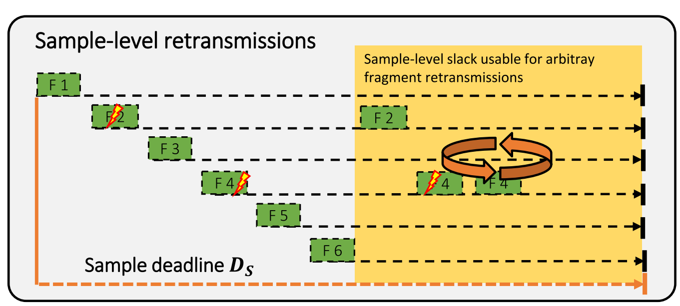

Fig. 3: Sample-level BEC as done in Wireless Reliable Real-Time Protocol (W2RP): Available slack can be used to perform retransmissions of arbitrary lost fragments within the scope of the complete sample-level deadline D_S.

W2RP has been designed in a technology-agnostic manner. Consequently, its principles can also be applied to cellular communication.

2) Continuous Connectivity in Mobility Scenarios: The necessity of seamless connectivity was already highlighted by the Third Generation Partnership Project (3GPP) for URLLC communication [24]. In the current state of the literature, multiple active data plane connections are the core mechanism to enable seamless connectivity [18], [25], [26]. Since the wireless network has no knowledge of a vehicle's trajectory, the next AP/BS is not known beforehand. Furthermore, interference induced link interruptions must be considered as well. Therefore, dual redundancy is unlikely to be sufficient to guarantee seamless connectivity. Consequently, a triple or N mode redundancy would be necessary. However, this approach is unfeasible for large data object exchange, due to the sharp increase in resource demands.

With the intention of avoiding active redundancy, [27] employs a Dynamic Point Selection (DPS) approach. Here a loss-less HO, can be achieved through proactive association with neighboring APs. Hence, each node forms a *cluster* or *serving set* of available APs around itself, leading to a user-centric Radio Access Network (RAN). Consequently, the critical path of the classic handover process can be reduced to loss detection and data plane path switching (cf. Figure 4).

While this approach does not lead to zero interruption time, it provides a deterministic upper bound for T_{int}. Utilizing a dedicated heartbeat protocol, loss detection can be achieved in less than $10\,\mathrm{ms}$ [27]. Furthermore, prior works on network reconfiguration suggest data plane switching times below $50\,\mathrm{ms}$ [28]. Hence, utilizing the above-mentioned DPS approach, a T_{int} below $60\,\mathrm{ms}$ are possible. With such low interruption times, HO events can be treated as burst errors and masked by sample level slack (cf. Section III-B1). As a result, continuous connectivity is achieved, while the degree of multi-connectivity is reduced to control messages needed to maintain APBS association.

3) Data Reduction of Large Sensor Data: Fast and efficient communication of sensor data is critical for teleoperation as the sensors mounted on the teleoperated vehicle serve as the only sensory input for the teleoperator. The quality of the driving performance and the confidence of the teleoperator is dependent on the *quality*, but also the *timeliness* of sensor data. The quality of the sensor data, for example the resolution of camera images or the compression rate of video streams, is crucial in determining the extent to which the teleoperator can perceive the vehicle's surroundings. However, the quality of the sensor data also determines its size, which in turn determines the data load generated by the sensor. The smaller the data, the easier and faster it can be transmitted. Accordingly, the timeliness of the data is also indirectly dependent on the data quality. For this reason, video encoders, that can drastically decrease sensor data size, are considered a key enabler for teleoperated driving. However, these improvements in data size come along with non-negligible deterioration of sensor quality.

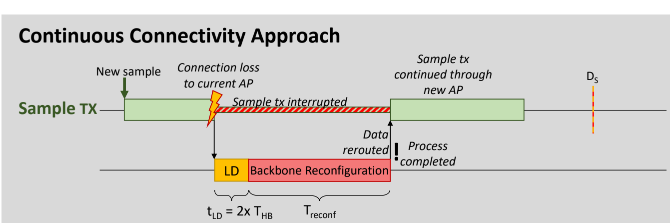

Fig. 4: Timing and sample transmission during the continuous connectivity approach.

If the quality is insufficient, it becomes challenging for the teleoperator to recognize small objects or objects in the background, as well as writing or graphics on signs. Naturally, sensor input like camera images contain so-called Regions of Interest (RoIs), which contain critical information for the driver on e.g. traffic lights or signs, but also pedestrians near a crossing. These RoIs are only a fraction of the whole sensor sample's size. Individual traffic light RoIs for example take up only about 1 % of the whole image sample of a front facing camera [29].

Sensor data is mostly communicated via push-based protocol, meaning, the sensor transmits every data sample to a receiver, as soon as a sample is available. However, teleoperation can benefit greatly from pull-oriented sensor data communication of e.g. RoIs selected by the teleoperator. This can become useful, when an autonomous vehicle has trouble detecting tricky objects like plastic bags, and requesting a confirmation on their classification. The teleoperator would be able to request certain sections of the camera image in higher quality. As can be seen in Figure 5, requesting ROIs at high resolution mitigates the drawbacks of high video/ image compression, without introducing large data load or latency [29]. However, this requires an intelligent middleware that allows this pull or request/reply communication, as sensors do not offer this functionality themselves.

4) Integration and Safety Guarantees: Previous works have shown that the protocols and mechanisms mentioned above can significantly improved reliability for applications exchanging large data when using 802.11 communication. This includes the capabilities to give certain guarantees and dynam-

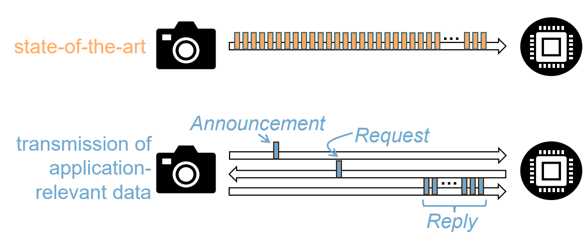

Fig. 5: The use of request/reply communication has the effect of significantly reducing the volume of data transmitted, as only the most relevant sections of data are transmitted, while the overall data load is kept to a minimum.

ically reconfigure applications at runtime in a coordinated manner, enabled by a combination with application-centric Resource Management (RM) [30]–[32]. However, in cellular networks, with their greater range and thus high number of communicating nodes per cell, probability of interference and fluctuating conditions is higher, complicating any reliable communication even more. Thus, additional means to bound these dynamics and potential for interference are required. Employing network slicing [33] and coordinating application (W2RP) behavior in unison with link (MCS) adaptation becomes a necessity in order to make W2RP and any of the mechanisms mentioned above feasible.

C. Adaptive Physical Network Control and Network Slicing

Safety-critical applications such as teleoperation rely heavily on precise end-to-end safety and QoS guarantees to ensure that deadlines are always met to achieve seamless operation and safety. Techniques that aim to provide timing guarantees can predict potential issues, prevent disruptions, and prioritize communication for high-priority tasks, ensuring minimal latency and maximum reliability. However, it requires a network infrastructure and methods capable of adapting to dynamic conditions and prioritizing time-sensitive data. This is especially challenging in wireless communication scenarios, where network congestion, interference, and signal degradation can lead to fluctuating QoS. Traditional methods rely on latency measurements or timestamps monitoring from received packets, known as *reactive* approach [34], where latency violations are detected after they occur. A more promising approach, shown in [35], [36], consists in *proactively* predicting latency before transmission rather than detecting violations only after they occur. By predicting latency violations early, systems can identify and mitigate risks early by triggering safety routines, (cf. DDT fallback), thereby increasing overall safety.

A complementary solution is designing an adaptive physical network control which refers to the ability of dynamically adjusting network parameters in response to changing conditions. This involves continuously monitoring the network environment such as traffic load, signal strength, and interference and making real-time adjustments to ensure the optimal flow of data. The previously mentioned methods for providing real-time QoS guarantees can further be extended with adaptive physical network control to make network adjustments. Possible adaptive mechanisms to operate within the critical time windows required for safe and effective control are beamforming [37] and dynamic resource allocation. While beamforming optimizes the power levels and direction of radio signals, the resource allocation prioritizes data streams based on their criticalities and requirements. The latter is addressed by network slicing, a key concept introduced with 5G.

Network Slicing enables the creation of multiple, independent logical networks, called slices, on the same physical infrastructure. In particular, network slicing looks at resources as a grid of multiple Resource Blocks (RBs). Each RB is two-dimensional and represents an allocation in the frequency and time domain as shown in Figure 6. Each slice is tailored to

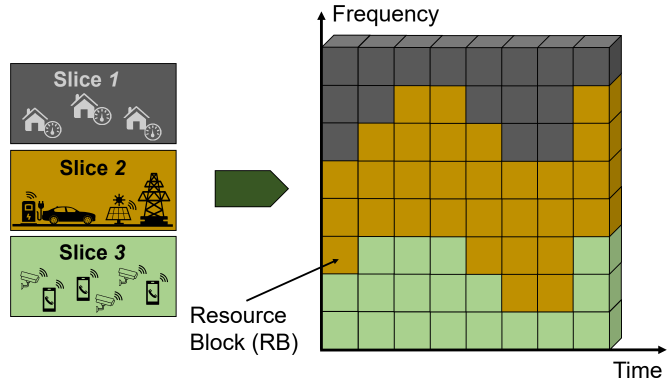

Fig. 6: Possible network slicing configuration. Multiple RBs are allocated to different slices.

the specific needs of different applications, offering customizable bandwidth, latency, reliability, and security guarantees. This capability is particularly beneficial in mixed-criticality environment, where different applications and types of data (e.g., control commands, sensor data, infotainment streams, telemetry data) have varying levels of urgency and bandwidth requirements. Thereby, network slicing allows operators to allocate dedicated resources to ensure low-latency streaming for mission-critical tasks, while simultaneously supporting other non-urgent services on separate slices.

D. Integrating Application-awareness and network-level control

Importantly, so far, network slicing still remains largely application-agnostic. Thereby, the focus primarily lies scheduling decision on a per-packet level. As mentioned previously, this is inefficient in case large data shall be exchanged. However, this limitation can be addressed by coordinating network slicing and W2RP via application-centric RM. By combining RM and network slicing, application requests to the RM can be translated into dedicated slices. Within these slices, W2RP can be used to protect large data streams against errors. Then, by constantly monitoring applications and network, dynamically adjusting slices according to changing channel conditions or application demands and reconfiguring applications (W2RP) in unison with link adaptation enables safe deployment of safety-critical applications. Thereby, these capabilities are indispensable for large scale deployment of teleoperation in the real-world.

IV. Conclusion

In applications with safety and high availability requirements, teleoperation is an essential requirement on the way to higher levels of system autonomy. The paper elaborates automated vehicles as an example. Practical experience in numerous and complex scenarios has demonstrated that vehicle teleoperation is effective, as long as the communication channel meets reliability and tight real-time requirements. We identified two main challenges, 1) communication channel reliability, availability and real-time guarantees and 2) the teleoperator interface with comprehensive representation of the vehicle scene and close interaction with the vehicle. Both challenges are tightly connected, as a realistic scene representation requires higher bandwidth than offered by current reliable communication standards, such as URLLC. The paper shows that solutions are possible, but require new end-to-end low latency protocols in combination with exploitation of advanced 5G network slicing and MCS adaptation that must be established and provided by the network operator.

References

[1] T. Zhang, "Toward automated vehicle teleoperation: Vision, opportunities, and challenges," *IEEE Internet of Things Journal*, vol. 7, no. 12, pp. 11 347–11 354, 2020.

[2] SAE International, "SAE J3016-202104: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles," April 2021.

[3] A. Avizienis, J.-C. Laprie, B. Randell, and C. Landwehr, "Basic concepts and taxonomy of dependable and secure computing," *IEEE Transactions on Dependable and Secure Computing*, vol. 1, no. 1, pp. 11–33, 2004.

[4] SAE International, "SAE J3216-202107: Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles," July 2021.

[5] J.-M. Georg, J. Feiler, S. Hoffmann, and F. Diermeyer, "Sensor and actuator latency during teleoperation of automated vehicles," in *2020 IEEE Intelligent Vehicles Symposium (IV)*, 2020, pp. 760–766.

[6] S. Gnatzig, F. Chucholowski, T. Tang, and M. Lienkamp, "A System Design for Teleoperated Road Vehicles," in *Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics - Volume 2: ICINCO,*, INSTICC. SciTePress, 2013, pp. 231–238.

[7] S. Neumeier, N. Gay, C. Dannheim, and C. Facchi, "On the way to autonomous vehicles teleoperated driving," in *AmE 2018 - Automotive meets Electronics; 9th GMM-Symposium*, 2018, pp. 1–6.

[8] F. Tener and J. Lanir, "Investigating intervention road scenarios for teleoperation of autonomous vehicles," *Multimedia Tools and Applications*, vol. 83, pp. 1–17, 12 2023.

[9] T. M. Gasser *et al.*, "Research needs in teleoperation," https://www.bast.de/DE/Publikationen/Fachveroeffentlichungen/Fahrzeugtechnik/Downloads-Links/TO-en.html, Federal Highway Research Institute Germany, Tech. Rep., 2024.

[10] D. Brecht, N. Gehrke, T. Kerbl, N. Krauss, D. Majstorović, F. Pfab, M.-M. Wolf, and F. Diermeyer, "Evaluation of teleoperation concepts to solve automated vehicle disengagements," *IEEE Open Journal of Intelligent Transportation Systems*, vol. 5, pp. 629–641, 2024.

[11] F. Tener and J. Lanir, "Design of a high-level guidance user interface for teleoperation of autonomous vehicles," in *Adjunct Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '23 Adjunct. New York, NY, USA: Association for Computing Machinery, 2023, p. 287–290. [Online]. Available: https://doi.org/10.1145/3581961.3609845

[12] M.-M. Wolf, R. Taupitz, and F. Diermeyer, "Should teleoperation be like driving in a car? comparison of teleoperation hmis," in *2024 IEEE Intelligent Vehicles Symposium (IV)*, 2024, pp. 3304–3311.

[13] M. Boban, M. Giordani, and M. Zorzi, "Predictive quality of service: The next frontier for fully autonomous systems," *IEEE Network*, vol. 35, no. 6, pp. 104–110, 2021.

[14] S. Gnatzig, "Trajektorienbasierte Teleoperation von Straßenfahrzeugen auf Basis eines Shared-Control-Ansatzes," Ph.D. dissertation, Technische Universität München, 2015. [Online]. Available: https://mediatum.ub.tum.de/1253158

[15] S. Hoffmann, D. Majstorović, and F. Diermeyer, "Safe corridor: A trajectory-based safety concept for teleoperated road vehicles," in *2022 International Conference on Connected Vehicle and Expo (ICCVE)*, 2022, pp. 1–6.

[16] S. Singh, "Critical reasons for crashes investigated in the national motor vehicle crash causation survey. (traffic safety facts crash•stats. report no. dot hs 812 506)," National Highway Traffic Safety Administration, Washington, DC, USA, Tech. Rep., 3 2018.

[17] W. Anwar, N. Franchi, and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," in *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, 2019, pp. 1–7.

[18] H.-S. Park *et al.*, "Handover Mechanism in NR for Ultra-Reliable Low-Latency Communications," *IEEE Network*, Mar. 2018.

[19] Y. Liu and C. Peng, "A Close Look at 5G in the Wild: Unrealized Potentials and Implications," in *IEEE INFOCOM 2023 - IEEE Conference on Computer Communications*. New York City, NY, USA: IEEE, May 2023, pp. 1–10.

[20] C. Pei, Z. Wang, Y. Zhao, Z. Wang, Y. Meng, D. Pei, Y. Peng, W. Tang, and X. Qu, "Why it takes so long to connect to a WiFi access point," in *IEEE INFOCOM 2017 - IEEE Conference on Computer Communications*, May 2017, pp. 1–9.

[21] J. Peeck, M. Möstl, T. Ishigooka, and R. Ernst, "A Middleware Protocol for Time-Critical Wireless Communication of Large Data Samples," in *2021 IEEE Real-Time Systems Symposium (RTSS)*, Dec. 2021, pp. 1–13.

[22] A. Bendrick, J. Peeck, and R. Ernst, "An Error Protection Protocol for the Multicast Transmission of Data Samples in V2X Applications," *ACM Transactions on Cyber-Physical Systems*, Aug. 2023.

[23] A. Bendrick and R. Ernst, "Hard Real-Time Streaming of Large Data Objects with Overlapping Backward Error Correction," in *IECON 2023-49th Annual Conference of the IEEE Industrial Electronics Society*, 2023, pp. 1–8.

[24] 3GPP, *3GPP TR 38.913; Technical Specification Group Radio Access Network; Study on Scenarios and Requirements for Technical Report Next Generation Access Technologies; (Release 17)*, Februrary 2022.

[25] J. Stanczak *et al.*, "Conditional Handover in 5G - Principles, Future Use Cases and FR2 Performance," in *IWCMC*, May 2022.

[26] M.-T. Suer *et al.*, "Multi-Connectivity as an Enabler for Reliable Low Latency Communications—An Overview," *IEEE COMST*, 2020.

[27] D. Tappe, A. Bendrick, and R. Ernst, "Continuous multi-access communication for high-resolution low-latency V2X sensor streaming," in *2024 IEEE Intelligent Vehicles Symposium (IV)*, Jun. 2024.

[28] A. Kostrzewa *et al.*, "Achieving safety and performance with reconfiguration protocol for ethernet TSN in automotive systems," *JSA*, Sep. 2021.

[29] N. Sperling and R. Ernst, "Reducing communication cost and latency in autonomous vehicles with subscriber-centric selective data distribution," in *2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring)*, 2024.

[30] R. Ernst, D. Stöhrmann, A. Bendrick, and A. Kostrzewa, "Application-centric network management - addressing safety and real-time in v2x applications," vol. 22, no. 2, Jan. 2023. [Online]. Available: https://doi.org/10.1145/3528411

[31] A. Bendrick, D. Tappe, D. Stöhrmann, and R. Ernst, "Synchronized lossfree reconfiguration of safety-critical v2x streaming applications," *IEEE Transactions on Vehicular Technology*, vol. 73, no. 10, pp. 15 636–15 652, 2024.

[32] A. Bendrick, D. Tappe, and R. Ernst, "Ultra reliable hard real-time v2x streaming with shared slack budgeting," in *2024 IEEE Intelligent Vehicles Symposium (IV)*, 2024, pp. 2289–2296.

[33] S. Zhang, "An Overview of Network Slicing for 5G," *IEEE Wireless Communications*, vol. 26, no. 3, pp. 111–117, 2019.

[34] X. Liu and A. Jaekel, "Congestion Control in V2V Safety Communication: Problem, Analysis, Approaches," *Electronics*, vol. 8, no. 5, 2019.

[35] L. Maile, J. Peeck, A. Nota, and S. Saidi, "Towards dynamic real-time latency bounds in 5g communication," in *2024 IEEE 14th International Symposium on Industrial Embedded Systems (SIES)*, 2024, pp. 112–119.

[36] A. Nota, S. Saidi, D. Overbeck, F. Kurtz, and C. Wietfeld, "Context-based latency guarantees considering channel degradation in 5g network slicing," in *2022 IEEE Real-Time Systems Symposium (RTSS)*, 2022, pp. 253–265.

[37] J. An and S. Saidi, "Hls-based approach for embedded real-time ray tracing in wireless communications," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 43, no. 11, pp. 3720–3731, 2024.