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The Radio Degradation Challenge: Fostering a Joint System Design of Robotics and Communication for Better Application Robustness

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***Abstract*— Robot competitions are a valuable platform in robotics research for evaluating various designs in situations and environments of interest, such as challenging terrain or complex manipulation tasks. Since challenging network conditions are expected in the targeted scenarios, integrating them into competitions is necessary to evaluate the performance of robotic designs in network-constrained environments and to foster communications considerations during the design of robotic systems. This paper proposes and demonstrates an integration approach for custom network degradation in robotic competitions. The competitions attended yielded performance evaluations of the robots under network degradation and highlighted optimization potential, which in one case even led to network setup enhancements and raised the robot's overall performance by 40%. One aspect of the carried out enhancements is demonstrated in an experiment to explain the observed performance increase. The results showcase the impact of network degradation on the evaluated robots' performance and illustrates potential gains achievable through optimization of the data transmission pipeline.**

***Video Abstract*—Demonstration video available online at: *https://tiny.cc/RadioDegradationChallenge*.**

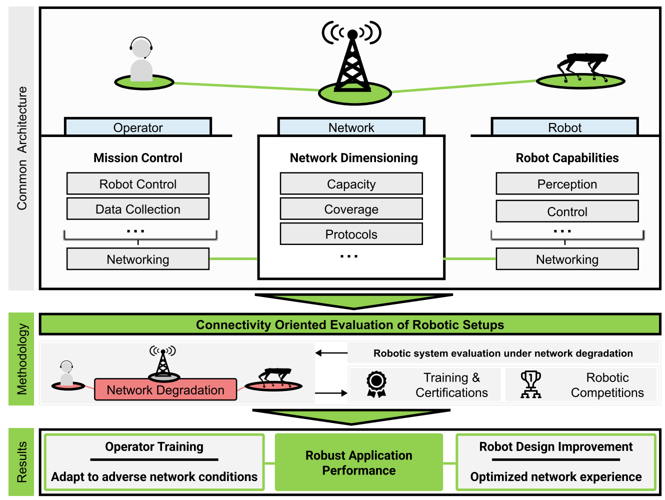

Fig. 1. Fostering the integration of connectivity-oriented considerations in robotic system design can enhance the network experience and strengthen the overall system performance.

I. INTRODUCTION

In the rapidly evolving field of robotics, ensuring the reliability and efficiency of robotic systems is critical. While testing individual components or isolated functionalities helps grade the quality of a system's constituents, an integrated evaluation approach in real-world conditions is necessary to uncover critical issues that may arise from the complex interactions of a robotic setup. Since most robotic setups are remotely controlled or monitored, the evaluation of such systems, therefore, also requires a connectivity-oriented approach. Connectivity-oriented testing involves evaluating the robustness and performance of communication protocols, data integrity, and synchronization across different modules and their impact on the overall system performance. This approach is particularly crucial for systems featuring distributed architectures, such as those based on the Robotic Operating System (ROS), where seamless interaction between nodes is essential for overall system functionality[1]. Leveraging the controlled network degradation presented in [2], a connectivity-oriented evaluation process was developed in this work to evaluate robotic systems through simulation of challenging network environments. The gains from this process, summarized in Fig. 1, are twofold: training the operators against adverse network conditions while providing the robotic system designers with enhancement insights. The contributions of this work can be summarized as follows:

- A **connectivity-oriented evaluation architecture** leveraging controlled radio degradation.
- An **integration** of the **presented architecture** within a robot competition.
- The **impact** of the **radio degradation challenge** on robot performance
- The resulting **network enhancements** initiated by the teams.

The remainder of the paper is organized as follows: After discussing related work in Sec. II, the integration of connectivity-oriented assessment in robot competitions based on network degradation is presented in Sec. III followed by evaluation results from the competitions given in Sec. IV. Finally, potential gains optimization are discussed in Sec. V.

II. RELATED WORK

Given that modern robotic solutions are fundamentally software-driven, the importance of software testing in robotics cannot be overstated. Robotics systems integrate complex software components that manage perception, planning, control, and interaction with the environment. Ensuring the reliability and robustness of these software components is crucial for the overall performance and safety of robotic systems. Previous research has extensively explored various methodologies for software testing in robotics. In [1]

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an integration testing approach composed of test scenarios and a family of communication testing criteria for publish/subscribe systems is proposed. Robotic systems must interact with the environment and therefore also integrate complex hardware equipment to physically interact with the environment such as arms for dexterity and manipulation, and wheels or legs for mobility. Integration test approaches must therefore cover the hardware aspect of the robotic systems by testing them in the field or in similar fields conditions. The experiece report compiled in [3] discusses field-testing techniques and practices on industrial robots in-depth and models the field testing processes, test design and testing activities with details about artifacts, and reported challenges and solutions.

Benchmarking, being one of these techniques is commonly used in the field of robotics to measure and compare the performance of robotic systems in specific areas as shown in [4], where the research challenges and progress in robotic manipulation in competitions is discussed. Robotic competitions offer a valuable platform for benchmarking robotic capbilities on a flexible. While local competitions may help foster robotic in specific countries and regions, global competitions facilitate the scientific exchange on an international and more global scale. For instance, the Rescue Robot League (RRL) of the RoboCup [5] aims to foster the development of rescue robots in post-disaster scenarios such as earthquakes.

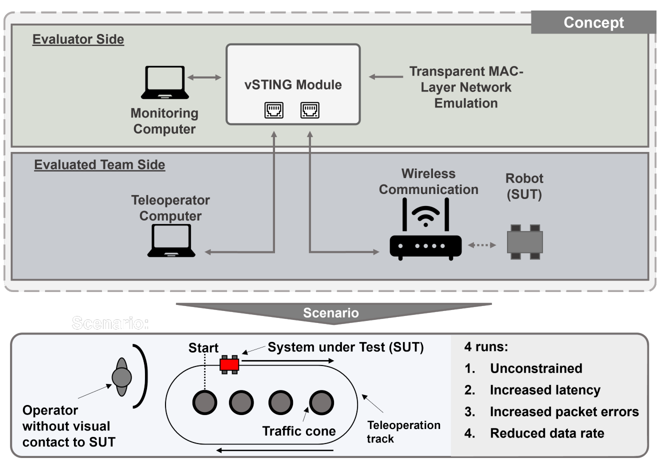

Fig. 2. Evaluation setup for teleoperation performance under network constraints as shown in [2]

The Subterranean Challenge organised by the Defense Advanced Research Projects Agency (DARPA) is another competition example [6]. It addresses underground search-and-rescue missions for multi-robot teams tasked with localizing and reporting the locations of objects of interests within Global Positioning System (GPS)-denied subteranean tunnels that pose a real challenge to wireless connectivity. Network connectivity being a critical aspect of most robotic setups, virtual STING (vSTING) a solution for a flexible connectivity-oriented evaluation of robotic setups through

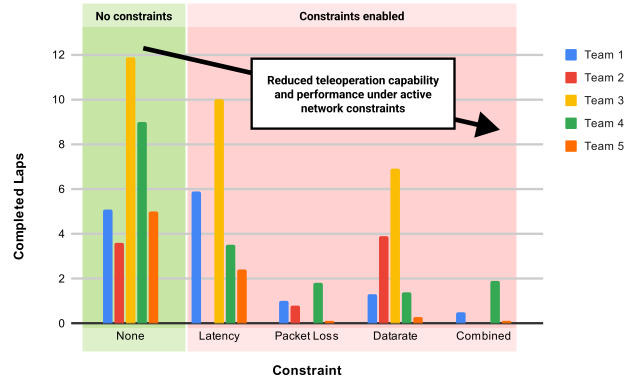

Fig. 3. Results of the optional vSTING-enabled teleoperation challenge at the RoboCup Rescue German Open 2022.

controlled network degradation was presented in [2]. The solution was demonstrated in a optional challenge during the 2021 and 2022 editions of the RoboCup Rescue German Open. The optional challenge in described in Fig. 2 highlighted the strong impact of the various network degradation settings on the robots' performance as shown in Fig. 3.

III. Radio Degradation In Robotic Competitions

Since the network behavior of a robotic system can noticeably affect its performance in real-world deployments, network considerations must be included in the benchmarking and evaluation framework of robotic competitions. The architecture presented in Fig. 4 proposes a means to this end through the integration of controlled radio degradation using the vSTING module[2] in the competition's system-level architecture. The vSTING module is referred to in the following as the radio degradation module.

A. *Connectivity-Oriented Evaluation Architecture*

Following the presented architecture, a radio degradation module must be installed within the operator box of each challenge's lane, such that any network traffic between the robot and operator goes through the radio degradation module. In wired setups, the radio degradation module is installed as a switch between the operator and the robot. In wireless setups, the radio degradation module is installed as a switch between the operator and wireless hardware interface instead, i.e. the access point in case of Wi-Fi.
Although the radio degradation solution can be deployed without any additional hardware in each lane in a distributed fashion while providing centralized control [7], the hardware solution is better suited for situations requiring a certain level of decentralized decision-making, which is often the case in competitions with parallel tracks.

B. *Degradation Settings and Scoring Rules*

The radio degradation settings and scoring rules must be defined with care. The implementation details of the proposed architecture during the 2024 editions of both the German Open and World Open of the RRL [5] are presented

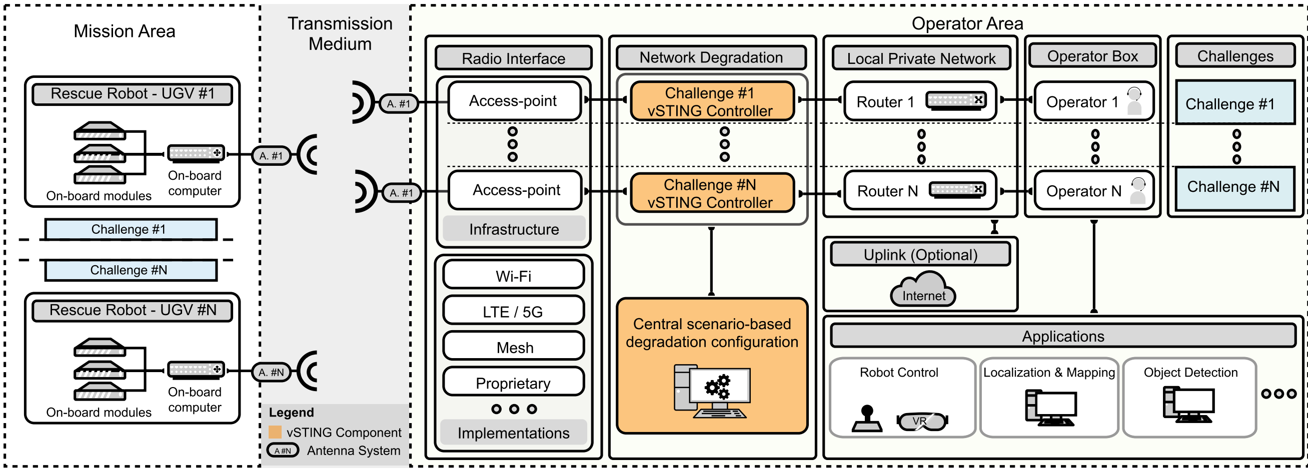

Fig. 4. General architecture concept for integrating network degradation within a robot competition.

here. The network degradation settings were chosen to replicate an old Wi-Fi Standard (IEEE 802.11b) under congestion and challenge the teleoperation capabilities of the robots with a delayed system response time. The degradation settings were therefore initially an additional latency of 100 ms and +/-20 ms jitter and a throughput limit of 10 Mbits per seconds. The throughput limit was lifted to facilitate the first integration of the radio degradation in the competitions.

The additional difficulty that arises through network degradation calls for an incentive to motivate teams to take on the challenges with network degradation. The incentive was defined as a point multiplier, and the overall scoring rules were as follows: teleoperated robots without network degradation received no point multiplier, teleoperated robots with network degradation gained a multiplier of two and autonomous robots had a multiplier of four. Network degradation was not proposed for autonomous robots to let them to display their autonomous capabilities unhindered.

Within the integration of radio degradation in both covered competitions, radio degradation was only available in challenges focussing primarily on robot mobility: *Crossing Ramps* (Challenge 2) and *Continous Ramps* (Challenge 10). In such lanes, each traversal from start to end or inversely is counted as a drive repetition and is rewarded with a point. A corresponding multiplier is then applied depending on the used difficulty level. Using this initial partial integration approach allows a progressive integration within the competitions and observation of the results and impact of network degradation for planing and preparation of an eventual deeper integration in future years. While the overall scoring at the RoboCup RRL is not limited only to mobility, this initial integration of network degradation focussed solely on the mobility. The scoring is summarized in Tab. I.

TABLE I

SCORING RULES SUMMARY

	Parameter	**Value**
General	Challenges	2 and 10
	Point scoring	Lane traversal in any direction
	Max Mobility repetitions	10 Repetitions
	Max Mobility duration	10 Minutes
Multiplier	Teleoperation	No Multiplier
	Teleoperation & Network Degradation	x2
	Autonomous	x4

IV. EVALUATING ROBOTS UNDER RADIO DEGRADATION

The implementation of the radio degradation challenge, as seen in Fig. 5 during the German Open and World Open of the RoboCup RRL 2024 editions enabled evaluating the network resiliency of the participating robotic systems. The results of this evaluation are presented here.

A. Evaluation Methodology

Robot performance was recorded in both the network and mobility domains. In the network domain, the data throughput consisting of the amount of packets successfully delivered from the robot to the operator was observed. Since the challenges with radio degradation were focused on mobility, the network traffic from the robot to the operator mostly consisted of the video stream which enabled robot teleoperation. In the mobility domain, the radio degradation impact on mobility was recorded through the mobility score of the robot, expressed as the number of completed drive repetitions in the respective challenge arena. A drive repetition is completed by traversing the arena from one edge to the other and at most ten repetitions can be completed.

B. RoboCup Rescue German Open 2024

The German Open of the RRL was held in April in Kassel, Germany and welcomed eight teams in total. The radio degradation was used by four teams during the tournament and the impact on their network throughput is shown in Fig. 6.

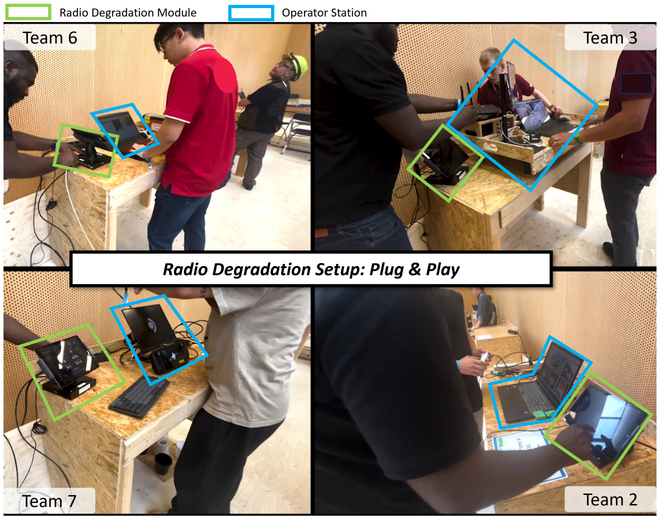

Fig. 5. Plug and play setup of the radio degradation within challenges at the RoboCup Rescue 2024: No complex configuration required.

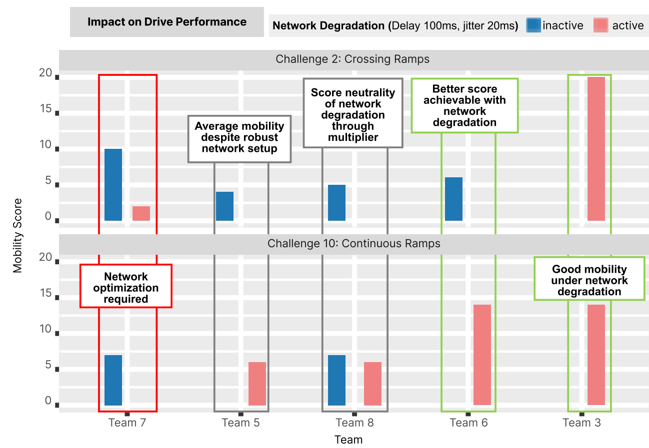

Fig. 7. Network degradation impact on mobility during the RoboCup Rescue World Open 2024.

Comparing the throughput with regard to individual network setup characteristics of the robots shows a certain pattern. Network setups based on Transmission Control Protocol (TCP) featured higher throughput under radio degradation and for team 3 especially, a strong deterioration of the teleoperation capability. User Datagram Protocol (UDP)-based network setups however saw a negligible impact on their throughput and were therefore unhindered in their teleoperation.

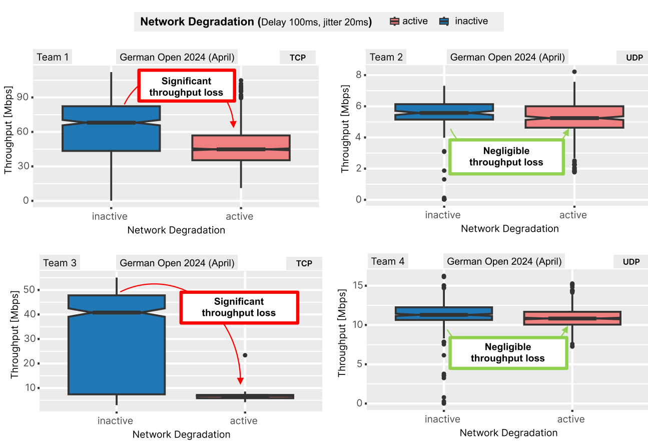

Fig. 6. Network degradation impact on throughput of participants at the RoboCup Rescue German Open 2024.

C. RoboCup Rescue World Open 2024

The World Open of the RRL was hosted in July in Eindhoven, Netherlands and welcomed 25 teams in total. Seven teams took on the radio degradation challenges. The performance of these teams was recorded using the mobility score and is shown in Fig. 7. Since the usage of radio degradation could be decided individually for each challenge, it was not used consistently by each of the teams. The collected results however bring some insights on the teleoperation performance and the opportunity of the radio degradation multiplier for some teams.

From the results, it follows that the mobility of the team 7 is strongly impaired by network degradation. So much that the multiplier brings no benefit to its mobility score under degradation. Taking on network degradation for this team requires prior optimization of its network setup. The network degradation had a score neutral impact on team 8. The decrease in mobility caused by network degradation could be compensated by the multiplier. Team 5 presented an average mobility which seemed to paired with a robust network setup. Upgrading its mobility could lead to a greater score in combination with the network degradation multiplier. Team 6 showed good mobility and network resiliency but did not consistently used network degradation, thereby losing potential points in the *Crossing Ramps* challenge. Team 3 capitalized on its good mobility and robust network setup the most through consistent usage of network degradation.

D. Enhancing Network Robustness

During the German Open 2024, team 3 competed with and without network degradation as shown in Fig. 6 and was made aware of the optimization potential of their setup in this area. Within their preparations for the World Open 2024, network optimization mostly consisting of two steps was carried out under our guidance. First, they switched from ROS 2 to Real Time Streaming Protocol (RTSP), a dedicated streaming protocol, for the video stream transport between robot and operator. Secondly, H264 video encoding was used to reduce the required bandwidth of the video stream.

This new setup was then consistently used with network degradation during the World Open 2024 which made comparison between active and inactive degradation for this team in the sole context of the World Open 2024 impossible.

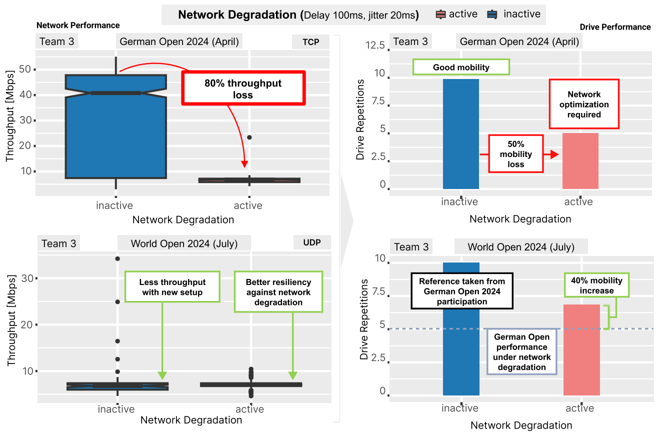

Fig. 8. Comparing network degradation impact on team 3 between the German Open and the World Open editions of the RoboCup Rescue 2024. Optimizing the video streaming solution in between the competitions enhanced resiliency against network degradation.

However, the use of standard lanes during the German Open and the World Open, as proposed in [8], and the fact that the robot's mobility was mainly unchanged enables comparing against its performance without radio degradation at the German Open 2024 a few months earlier. The comparison is illustrated in Fig. 8 and shows the achieved improvement in network resiliency, which resulted in an increase of nearly 40% in mobility under network degradation.

With these enhancements between the two competitions for team 3, the radio degradation could successfully raise awareness on network resiliency while resulting in a resilient network setup that led to a better mobility performance.

V. Exploring Network Robustness Enhancements

Team 3 optimized its network setup and leveraged its strong mobility under network degradation as shown in Sec. IV. The approach they followed, using specialized protocols for video transmission can be applied to other types of data. In this section, we demonstrate the gains of the first step of their network optimization, which consisted of switching from ROS2 to RTSP for video data transport. This is done to illustrate the impact of the transport protocol without the obvious benefits of throughput reduction resulting from H264 encoding in the second optimization step. The conducted experiment is illustrated in Fig. 9 and compares the achieved throughput and frame rate when transmitting a video stream with active and inactive network degradation while using respectively the robotic middlewares ROS1 and ROS2, and the dedicated video streaming protocol RTSP over TCP and UDP. The network degradation settings were consistent with those used during the RoboCup RRL 2024 competitions. Details on the experimental setup can be found in Tab. II.

The experiment result shows a throughput loss of 50% for the ROS1 streaming setup under network degradation. The received video frame rate is impacted and oscillates between 8 and 30 fps, which indicates an unstable video stream. The

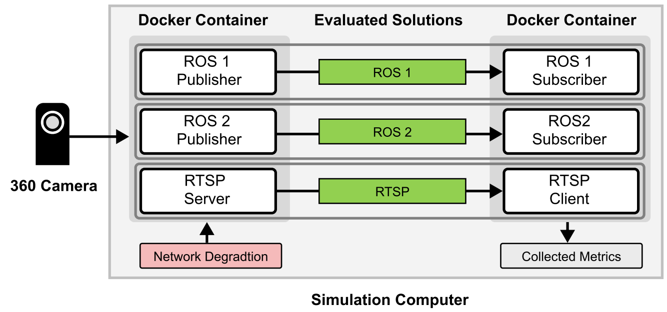

Fig. 9. Setup of the video streaming solution comparison experiment.

TABLE II
PARAMETERS OF THE STREAMING EVALUATION SETUP

	Parameter	Value
Stream	Camera	Ricoh Theta
	Frame rate	30 fps
	Throughput	50 Mbps
	Resolution	3840x1920
ROS1	Version	noetic
	Solution	ROS Image Transport
	Image Transport	Compressed
	Transport Protocol	TCP
ROS2	Version	Humble
	QoS Reliability	Best Effort
	QoS History	Keep Last
	Solution	ROS Image Transport
	Image Transport	Compressed
	Transport Protocol	UDP
RTSP	Server	MediaMTX
	Version	1.8.5
	Transport Protocol	TCP, UDP

ROS2 streaming setup achieves reference throughput and frame rate in average, however with a noticeable variation and frequent outliers below average indicating slight video freezes. The RTSP with TCP transport streaming setup shows an average throughput and frame rate similar to the reference values. However, regular strong outliers below average indicate temporary video freezes. A stable stream is observed when using RTSP with UDP.

As a general observation, RTSP offers a more stable video transport than the evaluated ROS solutions. Furthermore, the jitter component of the network degradation has a noticeable impact on the TCP based setups. On the other hand, the connectionlessness and absence of handshaking of UDP, while exposing the data to any unreliability of the underlying network fares better against the jitter component of the network degradation and are beneficial in time-sensitive applications such as video streaming for teleoperation.

This brief comparison stresses the importance of using dedicated and suitable protocols and solutions for data transmission. A wider comparison and evaluation with recent streaming protocols and further variants of the ROS1 and ROS2 transport solutions is envisioned as future work. Furthermore, using specialized or dedicated transmission

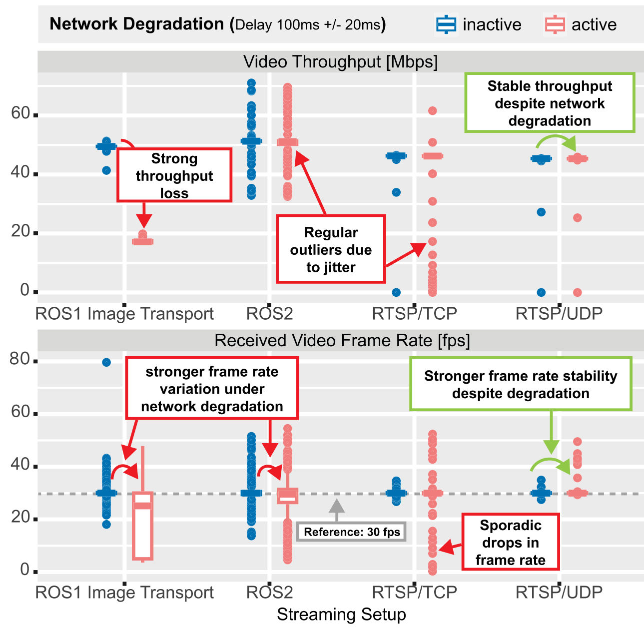

Fig. 10. Basic comparison of network degradation impact on video streaming solutions: RTSP, the dedicated video streaming solution, offers a more robust data transport.

procotols is just but one among possible approaches for an optimized network setup. Radio access redundancy, which may consist in using well adjusted heterogeneous combinations of multiple radio networks and technologies to compensate each other's weaknesses can be considered [9] as well.

For a network co-design of communication protocols and robotic control, it is essential to systematically challenge the robotic control with certain network characteristics to determine current limitations and optimize the control algorithms. Therefore, the presented approach has been designed to be used for realizing 6G robotic control use cases, such as the immersive, Mixed Reality (XR)-assisted control of robots, in which complex operations are performed by humans via teleoperation in challenging radio environments [10]. The vSTING approach which enabled the radio degradation challenge in this work allows to emulate future characteristics of the 6G air interface prior to its actual physical availability.

VI. Conclusion

This work presents a connectivity-oriented evaluation approach to foster the integration of network considerations in the design of robotic systems and achieve better application robustness.

A general architecture for implementing connectivity-oriented evaluations in robotic competitions through controlled radio degradation was proposed and implemented within two RoboCup RRL competitions in 2024. The differentiated impact of radio degradation on the robots was recorded. Design enhancements by a team for better network robustness between the two competitions was carried out with our cooperation and resulted in a mobility increase of 40% under network degradation. The enhancement's impact was demonstrated in a comparative experiment on video streaming protocols, the results of which highlighted the benefits of using dedicated protocols for data transmission if and where possible.

A wider comparison on video streaming protocols featuring recent and state-of-the-art solutions is considered for future work.

Acknowledgment

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