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SEAMLESS: Radio Metric Aware Multi-Link Transmission for Resilient Rescue Robotics

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Abstract— **Wireless communication technologies are designed to cover specific scopes of use cases and, therefore, possess strengths and weaknesses inherent to their designated application area. As a critical enabler for robotic remote operations, wireless communications are expected to perform optimally, sometimes even in situations outside the respective technology's intended deployment scope. Since a single technology can hardly ever meet the high requirements, various approaches to aggregate multiple communication links, so-called multi-links, have emerged in recent years. In this paper, we propose the novel open-source multi-link solution SEAMLESS to provide reliable connectivity in the context of rescue robotics in search and rescue missions. It improves flexibility by supporting general internet protocol service tunneling and multiple schedulers. As wireless technologies can not be assessed solely on the basis of network key performance indicators, an open radio monitoring interface is implemented, allowing radio metric aware scheduling. A comprehensive evaluation is carried out in two experiments, in both indoor and outdoor testing sites. The results showcase the benefits of the proposed radio metric multi-link scheduling by demonstrating a reliable high-resolution video transmission in challenging radio environments over Wi-Fi 6 and public cellular 5G.**

I. INTRODUCTION

Ensuring robust and reliable communication is becoming increasingly crucial in Search and Rescue (SAR) missions. In addition to connecting human operators, more and more rescue missions are also supported by robotic systems. Since a significant benefit of these systems is the advantage of remote control, a reliable connection via wireless radio technologies is essential for both Unmanned Aerial Vehicles (UAVs) and Unmanned Ground Vehicles (UGVs). Because of the potential susceptibility to interference of a single radio technology, so-called multi-link approaches are the current focus of research. These aggregate multiple communication technologies to compensate for the failure of one by the others. Fig. 1 shows such a rescue robotics scenario in which a UAV and UGV are used for the search for a missing person. Both systems are connected using a multi-link approach, combining multiple communication technologies such as locally deployed technologies and public Wide Area Networks (WANs). The latters, including public cellular networks and satellite systems, are used to improve coverage and reliability. Due to rough terrain, the UGV has to rely on its multi-link connectivity as debris interrupts the Line-of-Sight (LOS) communication link with the Operators.

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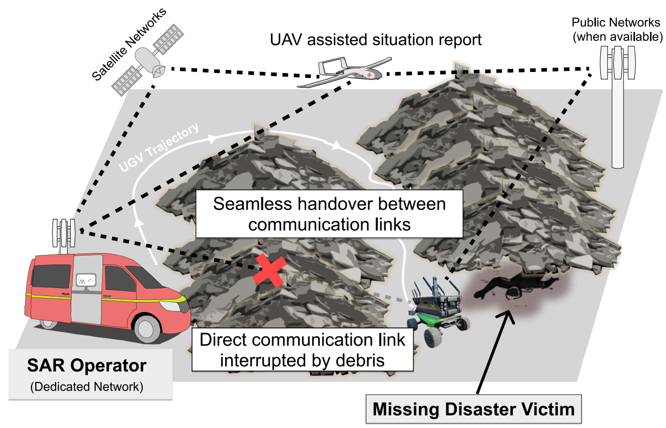

Fig. 1. Presenting a multi-connectivity robotic SAR mission for a missing person, assisted by a UAV-based situation reporting. In challenging radio conditions, where the primary communication link is obstructed, the UGV seamlessly switches to a secondary link.

Current state-of-the-art multi-link solutions either lack full Internet Protocol (IP) layer application support or are very complex to extend and maintain. Furthermore, current implementations only focus on network layer metrics like Round Trip Time (RTT) and Packet Error Rate (PER) for their scheduling decisions, which do not allow an in-depth assessment of wireless technologies and their characteristics. Therefore, the usage of wireless technologies like Wi-Fi can result in sudden connectivity failures not detectable by the scheduler because the latency stays low in networks with low traffic, even though the station faces challenging radio channel conditions. Our novel multi-link approach SEAMLESS addresses these limitations by implementing full IP layer tunneling and a radio metric aware scheduling. The implementation also focuses on maintainability and extensibility and is available at [1].

The contributions of this paper are as follows:

- Proposing a novel robust multi-link solution called SEAMLESS
- Comparing existing multi-link solutions from an end-user point of view
- Implementation of a radio metric based scheduling using an open radio metric interface

The remainder of the paper is structured as follows. After discussing the related work in section II, we present our approach SEAMLESS in section III and compare it to existing solutions in Tab. I. Afterward, we conduct two rescue robotics evaluation scenarios in section IV. We evaluate SEAMLESS in terms of throughput, RTT and PER, and demonstrate a high-resolution 360° video transmission.

TABLE I

Comparison of the proposed Multi-Link Approach with state-of-the-art solutions from an end user's perspective

	MPTCP [2]	**MPQUIC [3]**	**MLVPN [4]**	**SEAMLESS** *Proposed Approach*
Transport Protocol	TCP	UDP	UDP	UDP
Supported Application	Only TCP Services[1]	Only QUIC Service[1]	Any IP Services *Tunneling and Encapsulation*	Any IP Services *Tunneling and Encapsulation*
Scheduling Metrics	IP-Layer *RTT, Packet loss*	IP-Layer *RTT, Packet loss*	IP-Layer *RTT, Packet loss*	IP and Radio-Layer *Open Radio Metric Interface*
Available Scheduler	Default[2] RoundRobin Redundant	RoundRobin LowestRtt	Weighted RoundRobin	RoundRobin Lowest Round Trip Time Radio Metric Aware
Application Area	Stationary	Stationary	Stationary	Dynamic
Extension Effort	Complex *Kernel Module &* *C Language*	Moderate *Go Language &* *Extension of QUIC*	Moderate *C Language*	Straightforward *Rust Language &* *Modular Design*
Portability	Difficult *Requires Kernel Support*	Easy *Userspace Application*	Easy *Userspace Application*[3]	Easy *Userspace Application*[3]

[1] Tunneling requires additional tools.
[2] First send data on subflows with the lowest RTT until congestion-window is full. Then, start transmitting on the subflows with the next higher RTT.
[3] Encapsulation requires basic support for TUN/TAP devices; present in all major operating systems.

II. Related Work

An overview of the possible wide-ranging use cases of robotic systems in search and rescue is provided by [5]. In this context, the hardening of communication links can be done in several ways. [6] suggests that the Robotic Operation System (ROS) should be optimized in multi-robot networks to reduce latency and jitter. [7] presents a rudimentary approach to combining different communication technologies. They use a low-data rate but reliable link for important control data and a high-datarate unreliable link for video data. [8] adapts the application video protocol for heterogeneous wireless networks focusing on energy efficiency. Different approaches for multi-link communication have also been explored. For example, the authors of [9] employ multiple Long Term Evolution (LTE) networks to evaluate single- and multi-link performance in maritime rescue missions. [10] analyzes the behavior of Multi-Path TCP (MPTCP) [2] in wireless networks and [11] explicitly in the context of rescue robotics. In [12], the authors assess communication technologies interconnected to a transparent multi-link using MPTCP. Furthermore, [13] implements and evaluates the possibility of a modular scheduler interface for MPTCP. Another multi-link extension of the also well-known protocol Quick UDP Internet Connections (QUIC), called Multi-Path QUIC (MPQUIC), is described in [3]. Additionally, [14] implements a mobility-aware scheduler for MPQUIC and evaluates it using a markov mobility model. Like MPTCP is limited to Transmission Control Protocol (TCP) traffic, MPQUIC is also limited to application traffic using QUIC as its application protocol. A further comparison between the mentioned multi-link approaches MPTCP, MPQUIC, MLVPN and the presented approach SEAMLESS, regarding different aspects ranging from implementational differences to portability, is presented in Tab. I.

III. System Concept and Implementation

The new multi-link approach presented here represents consequent further thinking of existing multi-link approaches. Moreover, it aims at solving their shortcomings. In the following, we will highlight the most significant design decisions and compare them to existing approaches.

A. Hardware Independence

Binding to specific hardware is ruled out to enable the best possible portability and a wide field of applications. Accordingly, SEAMLESS, similar to MPQUIC and Multi-Link Virtual Private Network (MLVPN) is implemented as far as possible in the userspace. Only a basic support for `TUN/TAP` devices must be given, but these are usually present in all major operation systems. That way, SEAMLESS can easily be ported to any so-called unix-like system and with slight adjustments to close to all available systems. This directly contrasts solutions such as MPTCP, which requires appropriate kernel support and, thereby, relies on system manufacture support, especially when looking at Commercial off-the-shelf (COTS) solutions.

B. Supported Applications

Furthermore, SEAMLESS should be able to support all kinds of IP traffic and not be limited to a specific transport protocol, which would require modifications to the application layer protocol or particular applications. Solutions like MPTCP and MPQUIC function on the transport or application layers, respectively. They only support traffic specifically configured to use TCP or QUIC for their transmission or require additional tooling to allow other traffic. Inspired by the concept of Virtual Private Networks (VPNs) and specifically MLVPN, we implement an IP packet encapsulation and tunneling, allowing SEAMLESS to function as a virtual

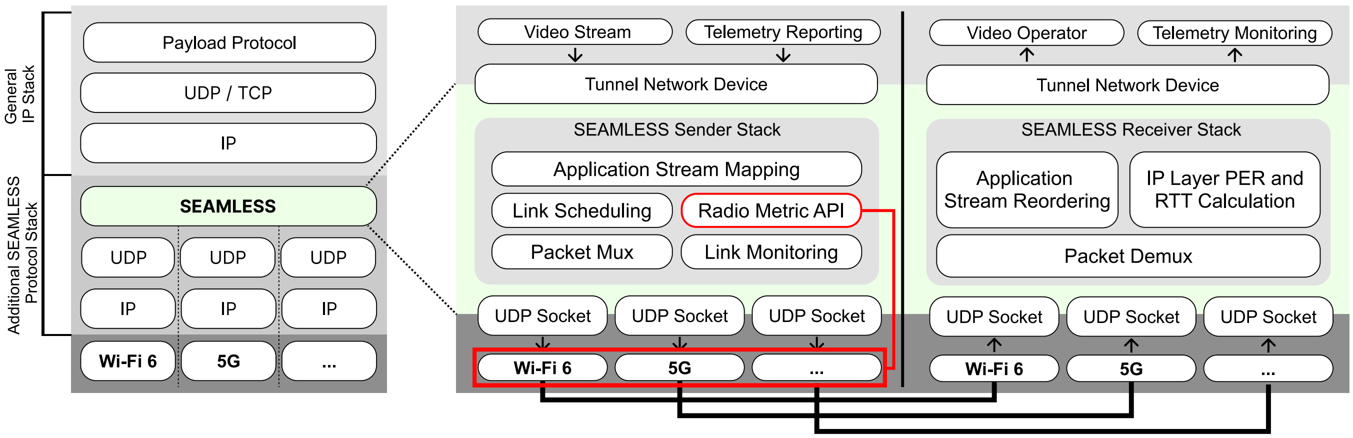

Fig. 2. The Architecture of the proposed SEAMLESS protocol stack, including sender and receiver routines and exemplary payload applications. The approach aggregates multiple radio technologies and utilizes the measured radio metrics for the link scheduling decisions.

network interface for the host system. All IP traffic can be transmitted transparently. The corresponding protocol stack is shown in Fig. 2. Further, it is also possible to route traffic from external hosts via SEAMLESS with appropriate routing rules, from which robotic systems can benefit as they mostly use companion systems to make the robot's internal services remotely accessible.

C. Transport Protocol

Next, the selection of a proper transport protocol is required. Based on the previously chosen encapsulation/tunneling approach, TCP was ruled out due to complications when transmitting TCP using TCP, which can drastically reduce application layer throughput, as shown in [15]. Similar to MPQUIC and MLVPN, User Datagram Protocol (UDP) is chosen as the transport protocol for SEAMLESS due to the low transport layer overhead. Since SEAMLESS is intended to be a transparent tunnel and the corresponding applications have not been specifically configured, corresponding redundancy and security concepts at the application level are assumed.

D. Application Area, Schedulers and Scheduling decisions

Even though the basic usability of MPTCP and MPQUIC in dynamic scenarios has been shown in [12] and [14], both of them, together with MLVPN, generally aim for more static scenarios. This can be seen from the implemented schedulers for selecting the corresponding communication paths. Besides RoundRobin and a statically weighted RoundRobin scheduler in MLVPN, the implemented schedulers only use network layer metrics such as RTT and PER to select the active link. While this approach works for static low-dynamic connections, it is not well suited for changing communication topologies such as wireless networks. A typical example would be the RTT in Wi-Fi, which remains constantly low, even at a considerable distance from the Access Point (AP) until a rapid increase or failure occurs. Here, the corresponding schedulers can only react. Furthermore, scheduling based on packet loss automatically leads to accepting the corresponding packet loss. We implement an open radio metric interface for the scheduler in SEAMLESS, which makes current metrics, such as the signal strength, available to the scheduler. Based on this information, trends can be derived, allowing a change of the serving link in time. A threshold for each aggregated technology can be defined, below which it will be considered unusable. After that, the next prioritized technology is used. Between the changes, a hysteresis is kept to prevent ping-pong hand-over effects.

E. The SEAMLESS Protocol

A corresponding protocol was defined to realize the multi-link functionality. First, a variable number of aggregated links can be defined. These are bound via corresponding UDP sockets and constantly monitored via integrated link monitoring. On the one hand, this uses the data packets to calculate statistics such as RTT and PER. On the other hand, it must also be ensured that sufficient up-to-date information is available about the currently unused links. For this purpose, keepalive packets are periodically transmitted over all links that the other side acknowledges. Based on the collected data, links are pre-selected. This way, corresponding threshold values can be defined for RTT, PER and the duration of the absence of keepalives, based on which links are generally sorted out. During transmission a separate packet header is added to calculate and exchange meta information, which contains information such as the links sequence number and timestamps.

SEAMLESS also allows different schedulers to be used for separate applications. For this purpose, the incoming application packets are analyzed and specially scheduled if a corresponding configuration is available. For example, links with a low capacity can be generally excluded for high data rate applications. When switching from one technology to another, jumps in latency can occur, resulting in an out-of-order situation. Respectively, an application-based reordering is implemented in the receiver stack to counteract. The SEAMLESS stack for the sending and receiving side is illustrated in Fig. 2.

IV. Experiments and Validation

In this section, the functionality of SEAMLESS is evaluated in two rescue robotics scenarios. The first scenario focuses on the basic functionality of the radio metric scheduling compared to a single link technology. In the second scenario, we evaluate SEAMLESS in an outdoor test field with the requirements of a high-resolution 360° video stream. Both experiments are conducted with the same mobile robotic system. It is equipped with the camera hardware mentioned above, an Intel AX201 Wi-Fi 6 modem, a Quectel RM500Q 5G modem and an x86-based Lattepanda 3 Delta embedded system running SEAMLESS. The robotic system is displayed in Fig. 3.

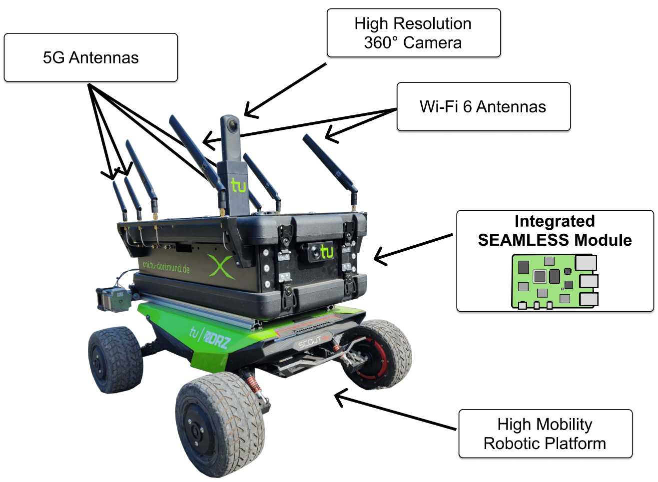

Fig. 3. Photo of the high mobility rescue robotics platform used for the experiments. It is equipped with a high-resolution 360° camera module together with 5G and Wi-Fi 6 connectivity. The SEAMLESS gateway is located in the modular payload housing.

A. Scenario 1: Inspection of load-bearing pillars in an damaged office building

The first scenario focuses on the routine inspection of load-bearing pillars in a damaged office building. The robotic system travels the trajectory displayed in Fig. 4 and stops at nine different waypoints for about 10 s to perform the corresponding check of the pillars.

First, a single link Wi-Fi 6 measurement is conducted as a baseline. An existing infrastructure with two Wi-Fi 6 APs in both building wings are assumed, as displayed in Fig. 4. For reproducibility, we use a generated UDP traffic of 25 Mbps representing a high-resolution low latency videostream. Fig. 5 shows the course of the Wi-Fi RSSI and the achieved data rate over the run. The different inspection stops are reflected in the Received Signal Strength Indicator (RSSI) course by plateau behavior, with points 3 and 7 showing the transition areas. They can also be identified as challenging environment, where the data rate drops nearly to zero, followed by a typical Wi-Fi buffer burst transmission after the connection is reestablished. In these areas, the transmission quality for secure and resilient communication is no longer given and thus represents the areas to be bridged with SEAMLESS.

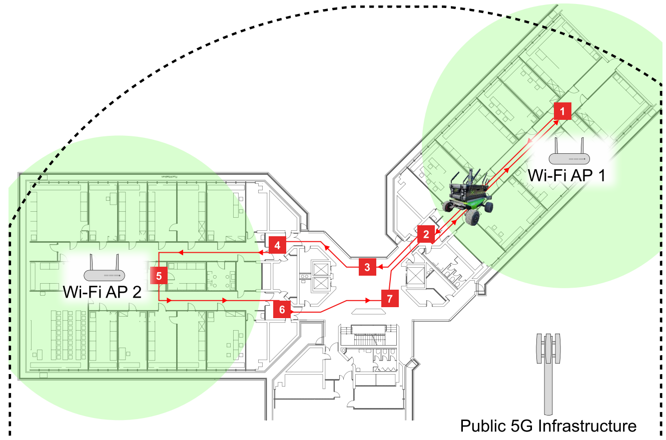

Fig. 4. Indoor evaluation scenario consisting of two Wi-Fi AP and public 5G infrastructure. Additionally, the red line highlights the trajectory of the mobile robotic system.

The second measurement focuses on the presented SEAMLESS radio metric scheduling approach, which extends Wi-Fi 6 by utilizing a public cellular 5G network. An additional VPN connection is used to transmit data through the public cellular 5G connection securely. The RSSI was chosen as the scheduling metric for Wi-Fi and Reference Signal Received Power (RSRP) for cellular. Wi-Fi defines a roaming threshold at which a station increases its scanning interval for new APs and thus increases the probability of an AP roaming. As Wi-Fi roaming is not interruption-free, according to the

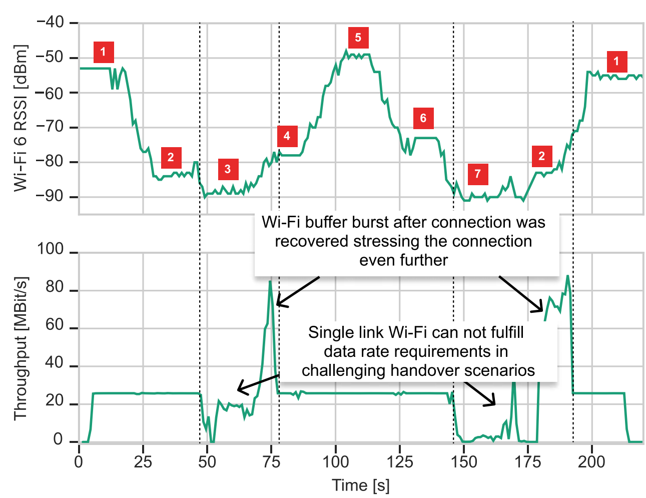

Fig. 5. Data transmissions in the indoor scenario using only the Wi-Fi 6 connect present typical handover situations with occasional decrease in achievable throughput.

Wi-Fi roaming thresholds from Linux [16] and Apple [17] of −70 dBm, a higher threshold of −65 dBm was selected as the trigger for SEAMLESS. In the upper part of Fig. 6 both the RSSI and the RSRP are displayed. The lower graph shows the throughput of both the individual technologies and the goodput of SEAMLESS. The expected scheduling behavior can be observed. When the RSSI drops below −65 dBm, the multi-link seamlessly switches the data stream to the public cellular 5G connection. Additionally, the overall acceptable overhead of 12 % of SEAMLESS can be seen, which is further increased for public cellular 5G due to the VPN connection.

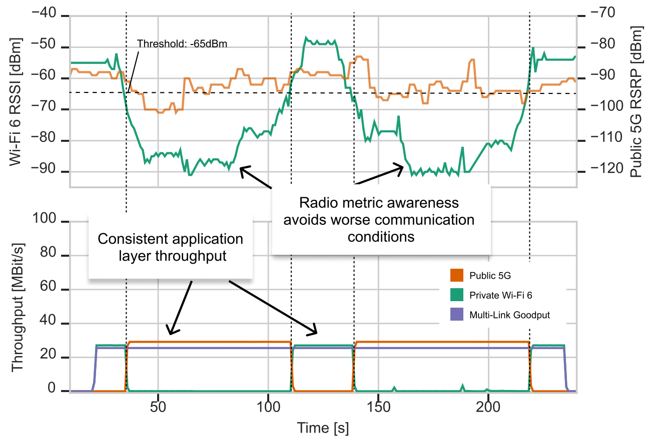

Fig. 6. Multi-link enabled payload data transmission over Wi-Fi 6 and 5G in the indoor inspection scenario. The sender's data rate is fixed to 25 Mbps UDP traffic.

In addition to the data rate, latency/RTT and PER are essential indicators for a stable remote operation. Accordingly, in Fig. 7, RTT and PER are plotted for the individual paths of Wi-Fi 6 and public cellular 5G, as well as for the aggregated SEAMLESS connection. In order to draw a qualitative conclusion about the suitability for teleoperation, the service requirement for mobile robots defined in [18] is also plotted. According to the document, this is 50 ms for a one-way delay, so we assume a symmetrical RTT of 100 ms as the upper limit.

Concerning the latency, the behavior discussed in Fig. 5 can be seen for Wi-Fi 6. The latencies are very low, ranging to 0.745 ms, but some outliers exceed the requirement threshold stated in [18] with maximums of up to 2055 ms. Combined with the recorded PER of 5.28 %, this again shows that Wi-Fi alone is not a valid option. It can be seen that SEAMLESS benefits from both technologies. The

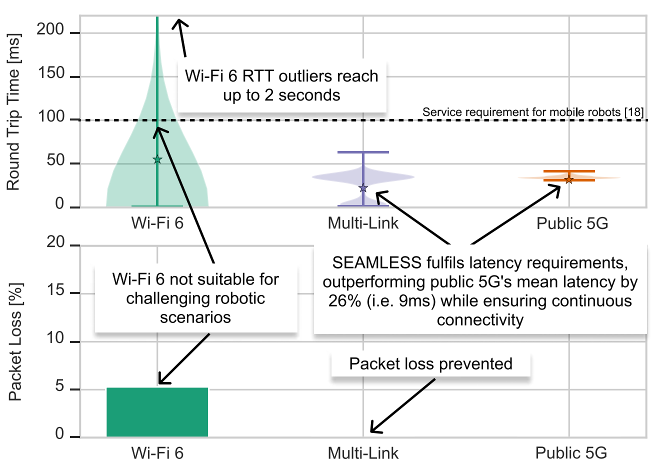

Fig. 7. RTT and PER comparison of SEAMLESS with both Wi-Fi 6 and public cellular 5G in the indoor inspection scenario. Indicating the benefits of the multi-link approach compared to the individual technologies. Note that "*" represents the RTT mean.

Wi-Fi 6 connection allows a lower RTT mean of 9 ms or 26 % compared to public cellular 5G. Furthermore, both Wi-Fi 6 PER and high RTTs can be avoided by switching to 5G. Since SEAMLESS schedules based on radio metrics, latencies still exceed the maximum of 5G but stay below the shown threshold. In general, SEAMLESS meets the service requirements for mobile applications in this scenario.

B. Scenario 2: Rescue robotics 360° video feed in the outdoor area

The second scenario includes the outdoor area of the German Rescue Robotics Center (German: DRZ), recreating the robotic-assisted scouting of a collapsed construction site. For this purpose, the robotic system drives around the site and streams the high-resolution 360° camera video feed live to the operator. The average data rate of the video stream is about 50 Mbps. A top view of the area and the corresponding robot trajectory are mapped in Fig. 8, together with the operator view and possible Non-Line-of-Sight (NLOS) situations.

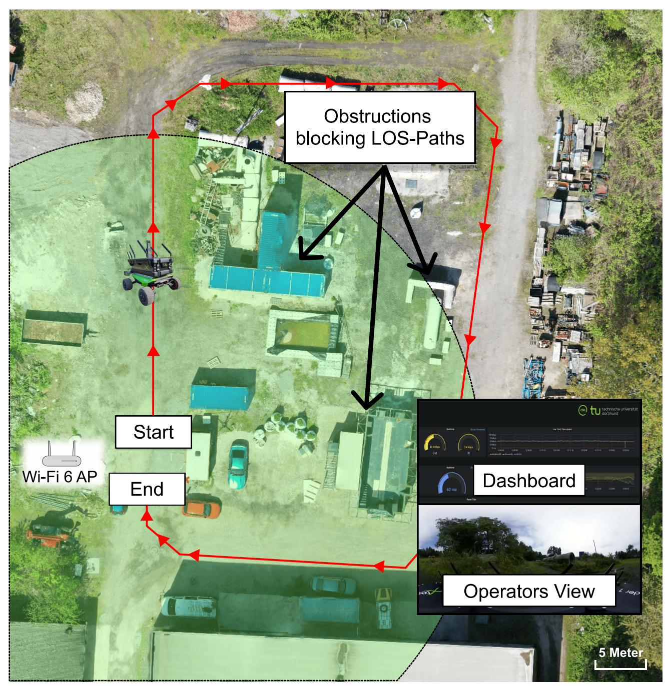

Fig. 8. Experiment in the DRZ outdoor scenario using a locally deployed Wi-Fi 6 AP network and a public 5G infrastructure. A reproducible trajectory was chosen with multiple NLOS situations.

The scenario is based on a possible first responder deployment. In contrast to the indoor scenario, only a single Wi-Fi 6 AP deployed by the rescue forces is available. So, the risk of a connection interruption due to a handover can be excluded. The RSSI threshold is selected to be −80 dBm based on the indoor base-line experiments findings and public 5G infrastructure is again used as a fallback. Fig. 9 is structured similarly to the indoor scenarios. As indicated by the expected behavior, the correct operation of the scheduler at −80 dBm can be seen. The implemented time-to-trigger-based hysteresis catches most of the handover processes. However, there is still potential for optimization in situations like around 80 s since the connection switches to Wi-Fi 6 for a short time despite directly dropping below the threshold again. Furthermore, another challenging moment can be noticed at 100 s, where an unpredictable drop in throughput of the public 5G network occurs together with a short but steep rise in latency. In both cases, the video decoder comes into play and compensates for the constraints, resulting in smaller stutters in the otherwise smooth and reliable video stream. Nevertheless, potential future improvement for SEAMLESS can be derived from this to handle such situations more efficiently. The full video of the experiment can be found here[1].

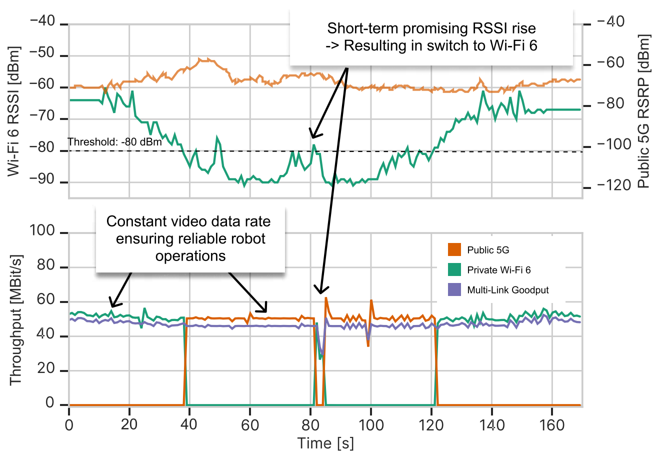

Fig. 9. Radio link aware multi-link measurements in the DRZ scenario transmitting a high-resolution 360° video feed with an average data rate of 50 Mbps. The multi-link Wi-Fi handover threshold is set to −80 dBm. A screen capture of the operator's video can be found here[1].

V. Conclusion

This paper presents the novel multi-link approach SEAMLESS with full IP layer support and extensible scheduling logic. An open radio metric interface was implemented to make radio metrics accessible for scheduling decisions. A dual evaluation of the proposed solution was conducted, featuring an indoor inspection scenario and an outdoor SAR scenario. The presented results demonstrate the validity and potential of the proposed approach, yielding increased performance and reliability in communications for SAR robotic missions. In future work, extending the existing approach in the case of predictive scheduling and scheduler optimizations is possible. Furthermore, the implementation and the extensive comparison of different multi-link scheduling approaches can be conducted.

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