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LANTERN: Enabling Seamless Relay-Based Network Expansion in Search and Rescue Environments using an Open Multi-Radio Relay

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***Abstract*— Reliable communication is critical for robotic teleoperation in Search and Rescue missions, particularly in challenging environments such as street canyons, underground garages, and industrial halls. While mesh networks, operating within unlicensed frequencies, extend range through multi-hop connectivity, they face interference, frequency competition, and reduced data rates per hop. Cellular technologies offer a promising alternative by leveraging dedicated frequency bands. However, standard-compliant Integrated Access and Backhaul (IAB) solutions are limited by hardware compatibility restrictions that result in vendor lock-in. This paper introduces LANTERN, an open multi-radio relay system that builds on the established SEAMLESS Multi-Link protocol, enabling interoperability across diverse communication technologies, including cellular and mesh networks. This architecture ensures reliable operation even in complex environments by combining established systems with modern ones without requiring substantial infrastructure changes. Initial validation experiments using a homogeneous 5G over-the-top relay demonstrate seamless transitions between the umbrella and relay networks, enabling uninterrupted immersive robotic teleoperation during mission-critical operations. In addition, a second case study demonstrates the functionality of heterogeneous relaying between a cellular umbrella and a mesh network, while highlighting potential future improvements to enhance handover and link usage when dealing with heterogeneous technologies.**

I. Introduction

Reliable communication is essential for robotic teleoperation during Search and Rescue missions, particularly in complex environments such as street canyons, underground garages, or industrial halls. Immersive teleoperation, which enables operators to control robots with high precision and situational awareness, places additional demands on communication systems due to its reliance on high data throughput and low-latency connections. Traditional solutions, such as Wi-Fi or mesh networks operating in the public Industrial, Scientific and Medical Band (ISM) band, extend range through multi-hop connectivity but face significant challenges, including interference, frequency competition, and reduced data rates per hop. Cellular technologies offer promising advantages by providing dedicated frequency ranges that mitigate these issues while ensuring reliable performance; however, standard-compliant so-called Integrated Access and Backhauls (IABs) are limited by vendor lock-in due to hardware compatibility restrictions. To address these limitations and meet the demands of immersive teleoperation in mission-critical scenarios, this paper introduces an open multi-radio relay architecture called LANTERN.

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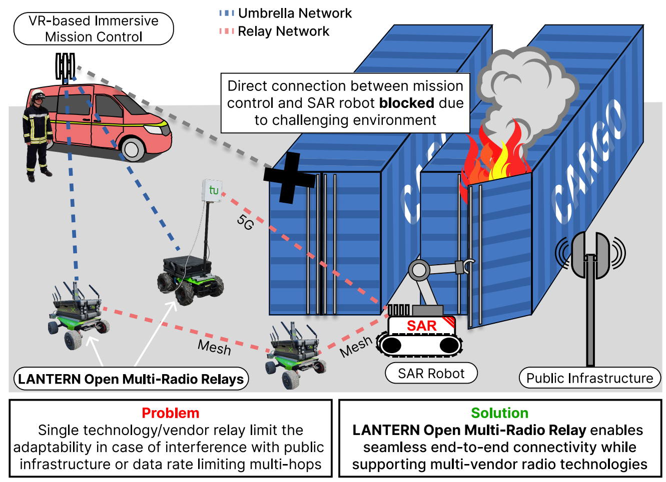

Fig. 1. Visualization of a typical robotic search and rescue mission, highlighting the challenges arising due to NLOS conditions and interference by public infrastructure. Additionally, the flexibility of the proposed LANTERN open multi-radio relay is highlighted.

Built upon the SEAMLESS Multi-Link protocol, which was introduced in prior work [1], this over-the-top architecture seamlessly integrates diverse communication technologies, such as multi-vendor cellular network components, with, e.g., mesh networks, into a single, cohesive platform without requiring low-level integration. This seamless integration ensures reliable performance and allows operators to reuse established technologies alongside newer ones. For example, homogeneous 5G relays similar to the concept of IABs are possible while not relying on a single manufacturer. Additionally, unlicensed mesh networks can be integrated with licensed cellular systems to form a flexible communication framework, thereby avoiding performance degradation caused by airtime sharing among numerous mesh nodes, a common issue in traditional mesh setups. The LANTERN open multi-radio relay system offers a key advantage in its adaptability, allowing for hardware selection to be tailored to meet specific mission requirements. This means that high-performance components can be used in scenarios where energy efficiency is less critical, while compact and power-efficient devices can be deployed in the mobile relay system, as illustrated in Fig. 1.

The structure of this paper is as follows. The next chapter will discuss the related work regarding IABs, over-the-top radio relay concepts, and the use of mesh networks. Then, Sec. III will delve into the proposed architecture of the LANTERN open multi-radio relay and discuss its design decisions. In Sec. IV, the first of two case studies will be performed, consisting of a detailed validation experiment for a homogeneous cellular 5G over-the-top relay. Sec. V will present a concise case study for a heterogeneous setup consisting of a cellular umbrella network and a mesh relay in an underground scenario. The paper will conclude with a summary and an outlook in Sec. VI.

II. Related Work

Radio relaying is widely adopted in robotics to extend communication range, particularly in constrained environments such as underground scenarios. Unlicensed solutions, such as Wi-Fi and mesh networks, are frequently used by robotic teams to expand their operational area [2]. However, these systems tend to suffer from reduced throughput as the number of hops increases [3]. Licensed wireless technologies, especially 5G, offer more robust and high-performance communication compared to unlicensed mesh networks, particularly in underground search and rescue (SAR) contexts [4]. To extend the coverage of 5G networks, Integrated Access and Backhaul (IAB) has been introduced. IAB enables the integration of relay nodes (RNs) into existing 5G infrastructure, allowing backhaul and access traffic to share the same radio resources [5]. Recent research has begun to explore mobile IAB solutions. For example, the authors of [6] use IAB nodes to interconnect drone swarms using the same frequency band. Additionally, the integration of IAB with Non-Terrestrial Networks (NTN) is gaining traction. Studies such as [7] and [8] investigate the use of satellite-based IAB to expand 5G coverage in maritime and remote environments. IAB solutions typically require tight integration between the core and access networks. To address this, [9] proposes a novel multihop relay architecture for LTE and 5G that introduces Proxy-eNB/gNB (P-eNB/P-gNB) components. These separate radio and core functions, enabling plug-and-play mobile relaying over multiple hops using only standard interfaces. Additionally, in Vehicular-2-Vehicular (V2V) and Vehicular-2-X (V2X) contexts the Device-2-Device (D2D) communication can be used to relay connectivity between User Equipments (UEs), but again require the implementation by the manufacturer [10]. Further, research is conducted in extending the D2D communication in the unlicensed spectrums [11] by either direct radio access or established unlicensed technologies like IEEE802.11z [12]. Other works have explored more flexible, over-the-top approaches. For example, [13] presents a multi-radio 5G/Beyond-5G (B5G) relay architecture that, unlike 3GPP IAB, leverages standard IP interfaces and full UE stacks at each relay. This allows for greater flexibility and modularity. However, seamless, over-the-top relay systems capable of integrating heterogeneous radio technologies without core network dependencies remain an active area of research.

III. Architecture of the LANTERN Open Multi-Radio Relay

The following chapter deals with the considerations taken into account and the implementation of the proposed LANTERN open multi-radio relay. The architecture discussed in the following is illustrated in Fig. 2. The core contribution includes the combination of an Over-the-top (OTT) connector, which enables the integration of diverse communication technologies into the relay platform, such as 5G and Mesh networks, together with the established SEAMLESS protocol, which facilitates seamless transitions between networks. In general, the OTT connector considers all communication technologies as a basic Internet Protocol (IP)-based network. Accordingly, both the relay and umbrella network always consist of complete network stacks tailored to their respective technologies, including core functionalities and radio access mechanisms. For example, in cases where a 5G network is used as the relay, the relay node includes the complete 5G protocol stack, comprising both basestation (gNB) and core network. Using commercially available end-user devices, such as 5G UEs or dedicated mesh nodes, the OTT connector establishes a connection between relay and umbrella network by performing corresponding routing tasks and Network Address Translation (NAT) using a Virtual Private Network (VPN)-based approach. Therefore, a direct IP connection can be established between the rescue robot and mission control via the LANTERN open multi-radio relay platform. However, without the radio networks being directly interconnected at a native level, user terminals cannot hand over seamlessly between umbrella and relay networks. At this point, the SEAMLESS Multi-Link Protocol takes effect. By equipping the rescue robot with a dedicated interface for each network technology (e.g., one UE for a 5G umbrella network and one for a mesh relay network), the SEAMLESS protocol can maintain simultaneous connections to all networks involved, enabling lossless switching between them and thereby ensuring uninterrupted operation at higher application layers, as shown in [1]. A significant benefit of this architecture is its flexibility, allowing the robot to use the umbrella network directly while in reach, which results in, e.g., lower latencies. Additionally, it can directly switch to the relay network as soon as the connection to the umbrella network becomes too weak. Furthermore, it offers

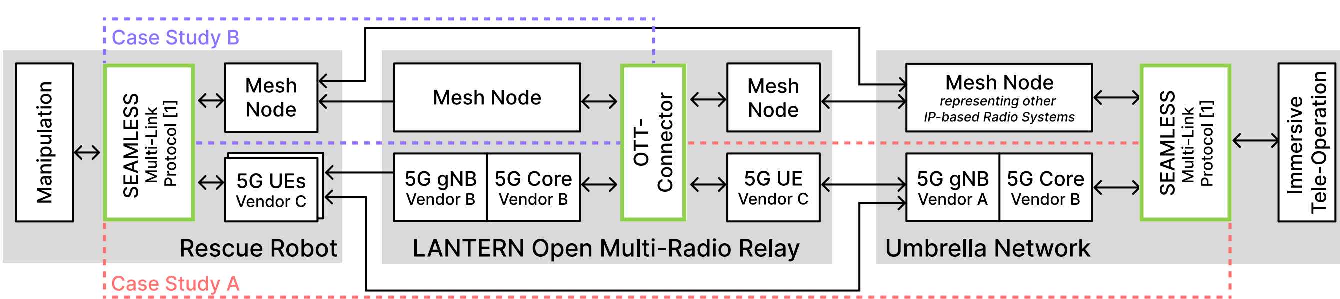

Fig. 2. Architecture of the proposed LANTERN open multi-radio relay enabling multi-vendor radio technologies as well as seamless roaming between umbrella and relay network.

adaptability to various existing communication systems and the ability to reuse established technologies alongside newer ones. This flexibility also enables operators to integrate legacy unlicensed solutions, such as mesh networks, with licensed technologies like 5G, without requiring substantial overhaul efforts. The architecture also yields benefits for homogeneous relay scenarios, such as both a 5G umbrella network and a 5G relay, by enabling the selection of appropriate hardware tailored to each use case. As the relay works OTT for each application scenario, suitable hardware can be selected based on specific requirements, for instance, leveraging high-performing but bulky hardware for an umbrella network while employing compact solutions from a different manufacturer for the relay platform.

IV. Case Study A: Evaluation of an Homogeneous 5G Over-the-Top Relay

In the following chapter, the first of two case studies is conducted, focusing on a homogeneous 5G over-the-top relay. For this setup, both the umbrella network and the relay network are full 5G stacks from different vendors. The rescue robot is equipped with two 5G UEs to connect to both networks. First, the experimental setup and the hardware configuration of all systems are described. The following results are then discussed. The validation was conducted in an outdoor laboratory environment. The area is located within an enclosed courtyard surrounded by buildings, which significantly affect radio propagation.

A. Experimental Setup

For experimental validation, an telco-grade private 5G system was chosen as the umbrella network, operating at a center frequency of 3775 MHz with 50 MHz bandwidth. The relay platform utilized a compact private 5G system configured at 3725 MHz with 40 MHz bandwidth. Since this relay network was not time-synchronized with either the umbrella network or a nearby public network located at the lower limit of the available 100 MHz spectrum, a 5 MHz guard band was applied to both systems.

To accommodate the predominantly uplink data traffic from robotic systems (e.g., video and sensor data), the chosen Time Division Duplex (TDD) pattern represented the most uplink-focused configuration possible: DSUUU for the umbrella network and DSUU for the relay network. Both were configured to operate at low power levels of 10 dBm (10 mW) to simulate greater distances within the confined testing environment. The specifications and configuration parameters of the umbrella and relay networks are summarized in Tab. I. The umbrella network was mounted

TABLE I
Configurations of the umbrella and Relay-Cell

Feature	Umbrella	Relay
Transmit Power	10 dBm	10 dBm
Bandwidth	50 MHz	40 MHz
Carrier Frequency	3775 MHz	3725 MHz
TDD Pattern	DSUUU	DSUU
Hardware	Telco-grade Private 5G	Compact Private 5G

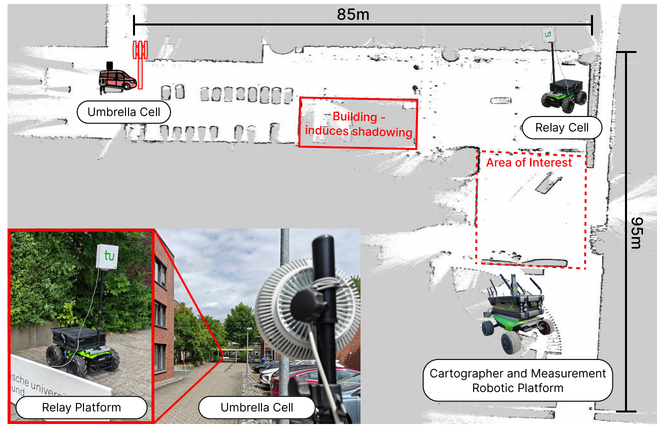

Fig. 3. LIDAR-based map of the validation environment. Additionally, impressions of the used robotic and hardware systems are displayed.

on a tripod at a height of 2 m, representing ground-based deployment typical for Search and Rescue (SAR) forces. For mobility and flexibility, the relay network was mounted on an Agilex Scout robotic platform. The robot carrying the relay system included a weatherproof enclosure housing all key components: a 5G core network, an embedded system hosting the OTT Connector, and an RM520N 5G modem connected to outward-facing antennas for backbone communication with the umbrella network. The relay system had a low power draw of less than 100 W, enabling fully self-contained operation. The measurement and cartographing robot used in this scenario was an Agilex Scout Mini, a high-speed, four-wheel-drive mobile platform representing a general rescue robotic system. The enclosure mounted on top housed an embedded system running the SEAMLESS Multi-Link Protocol for communication link selection, equipped with two Quectel RM520N modems, one connecting to the umbrella network and the other to the relay network. A Velodyne VLP-16 360-degree LiDAR sensor was also mounted for environmental perception, enabling SLAM. The resulting map shown in Fig. 3 covered an area of 85 × 85 m at a 0.05 m resolution. To maximize radio communication distances within granted permissions, the umbrella network was placed in the upper-left corner of the map. A building near the center caused considerable shadowing, creating NLOS conditions and poor coverage due to shadowing. To address these, the relay network was strategically deployed in the upper-right corner of the environment to extend coverage into NLOS areas.

B. Validation of the Homogeneous 5G Relay

After completing the mapping process in subsection V-A, we conducted connectivity-focused measurements to evaluate the coverage and performance of the LANTERN open multi-radio relay. Fig. 4 shows REMs that visualize the distribution of RSRP for the umbrella network, relay network, and their combined effect. Signal strength is represented by a color gradient, ranging from −60 dBm (red) to −140 dBm (dark blue). In the first REM, the umbrella network in the upper-left corner provides sufficient coverage in Line-of-Sight (LOS) areas, with RSRP decreasing as distance increases. At the relay network location in the upper-right corner, RSRP values around −100 dBm are achievable. However, be-

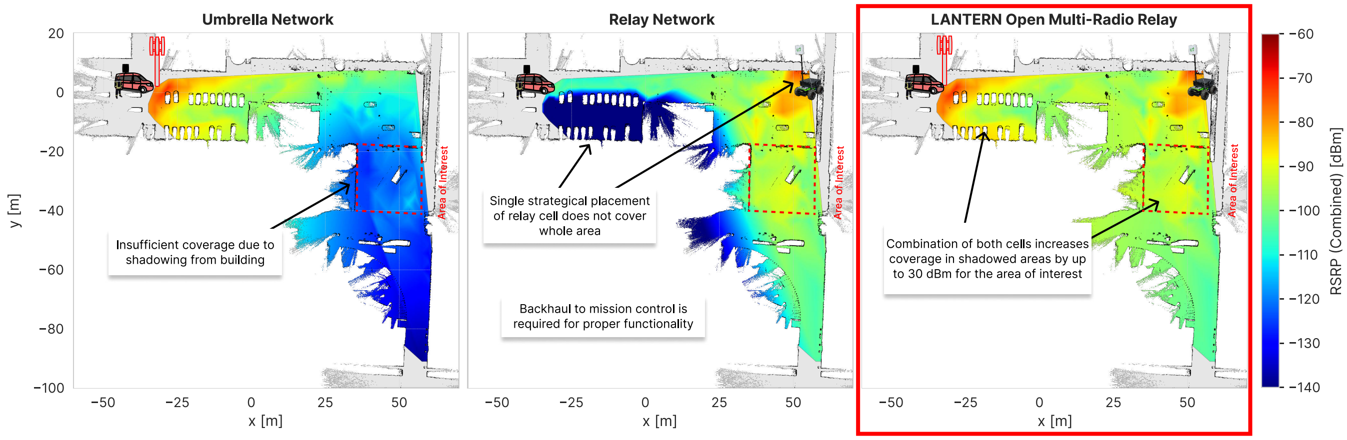

Fig. 4. REM of the RSRP for the umbrella and relay network individually, as well as the combined coverage achieved with the LANTERN Open Multi-Radio Relay System. Note: The REMs are interpolated based on an empirical measurement campaign.

hind the central building's shadowed region, signal strength drops below −110 dBm, indicating insufficient coverage. The second REM in Fig. 4 shows the RSRP distribution for the relay network, placed in the upper-right corner of the map to improve coverage in NLOS areas. However, its reach is limited by shadowing from the same building, affecting the area afore served by the umbrella network. As a result, neither cell alone can provide complete coverage from mission control to the complete mission area. The third REM illustrates the combined RSRP distribution of both cells, demonstrating that their integration significantly improves overall coverage. Previously underserved shadowed areas now receive sufficient signal strength, enabling near-complete and reliable coverage across the 85 × 85 m courtyard environment. This highlights the effectiveness of using a relay-based approach to mitigate NLOS limitations caused by shadowing. The next step involved conducting an in-depth study to evaluate the availability of a realistic payload. For this purpose, the robot transmitted a data stream with a data rate of 20 Mbit/s, representing a challenging high-resolution constant data rate video stream, to Mission Control. During the experiment, Mission Control steered the robot toward the designated area of interest. The analysis focused on two key aspects. First, as illustrated in Fig. 5, the link selection was evaluated. The results show that when a threshold of −100 dBm for the umbrella network was reached due to NLOS conditions, the SEAMLESS protocol seamlessly switched from the umbrella network to the relay network. This behavior enabled reliable communication even within areas of interest that were otherwise out of range for direct umbrella network coverage as further shown in Fig. 6, highlighting the seamless transition between cells over a selected time range. The upper graph displays the data rate received at mission control during operation, while the middle section indicates the link decision at any given time. The third section shows the measured Round Trip Time (RTT) during the transmission. Notably, despite switching between networks, there were no drops in data rate, enabling continous operations in search and rescue missions aligning with the results in [1]. Further, short back and forth switches between both networks are visible for the period of the focused link change indicating fluctuations in the RSRP of the anchor cell. When connected to the umbrella network, the RTT only consists of the RTT of the umbrella network with a mean of 16.15 ms (± 3.64 ms). For the relay network, the RTT of both cellular networks add up, resulting a mean of 33.94 ms (± 5.51 ms).

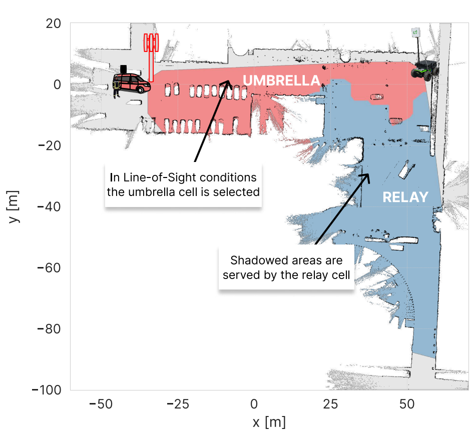

Fig. 5. Map displaying the link selection of the SEAMLESS Multi-Link Protocol for each area (Umbrella: Red, Relay: Blue). Note: The Map is interpolated based on an empirical measurement campaign.

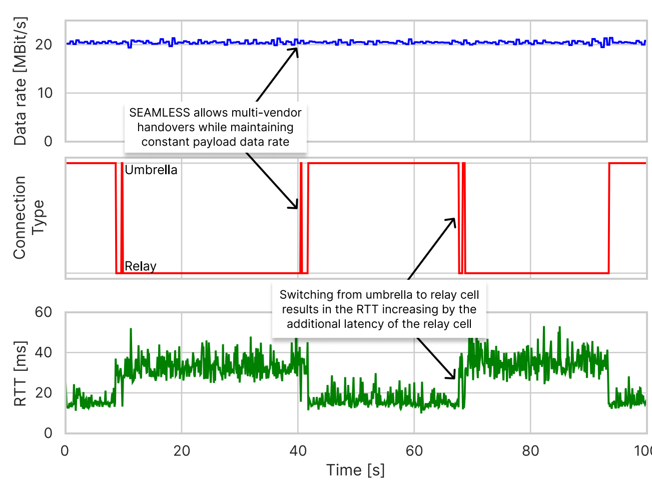

Fig. 6. Application data rate and link selection over a selected time period, showing that the link switch do not impact the transmission. Further, the end-to-end latency adds up in case of the relay connection.

V. Case Study A: Evaluation of an Heterogeneus Cellular-2-Mesh Relay

The following chapter presents the second case study, focusing on a heterogeneous relay setup. In contrast to the homogeneous use of two 5G cells, this case study utilizes a 5G network as an umbrella network and an ISM-based mesh system as the relay network to highlight the general functionality of heterogeneous relay links. Additionally, the second case study involves a simulated exploration mission within a tunnel system; therefore, the results presented are an excerpt of the mission. First, the scenario and experimental setup are explained again.

A. Experimental Setup

The second case study took place in an underground tunnel system at TU Dortmund University, serving as a simulation area for an exploration mission and a search for a missing person. A possible hazardous substance leak was assumed, which is why the exploration was to be carried out by teleoperated robotic systems. A Boston Dynamics Spot quadruped robot was used as the robotics platform for the exploration. It was equipped with the manufacturer's proprietary SpotCam camera unit, which supports a 360° camera as well as pan-tilt zoom and infrared camera. In terms of communication technology, the robot was equipped with a 5G modem (identical to Case Study 1) and an ISM-based mesh unit. An Agilex Scout Mini platform was used to support the exploration robot, taking on the role of the LANTERN relay. This time, however, the use case differs from a technology-homogeneous relay. In this use case, 5G serves as the umbrella network, and the relay link is mapped via a direct mesh connection. In this case, the umbrella network was mapped by the compact private 5G system, which is ideal for use in the tunnel system due to its small form factor. Its configuration is identical to that in Sec. IV. However, the transmission power was increased to 23 dBm instead of 10 dBm, and the bandwidth was increased to 50 MHz instead of 40 MHz. The mesh nodes were configured to the regulatory maximum of 20 dBm at a center frequency of 2412 MHz. The bandwidth was set to 5 MHz. Fig. 7 shows a lidar scan of the tunnel system in question, together with impressions of the deployment simulation. First, the tunnel system consists of long (200 m in the case of the lidar scan) straight sections with large metallic pipes on both sides. In

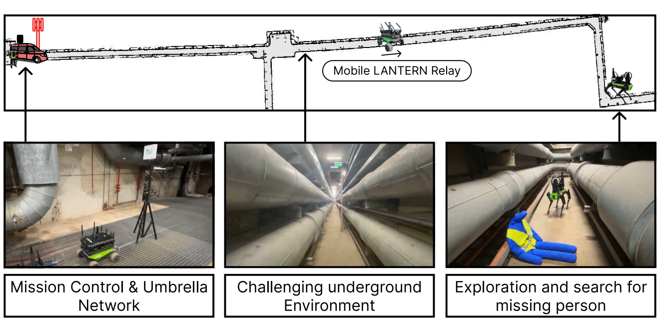

Fig. 7. LIDAR-based Map of the underground scenario, in which an exploration robot is supported by a mobile LANTERN relay. The tunnel system consists of narrow paths with metallic tubes on both sides, challenging radio propagations.

addition, there are branches (center and right), which lead to very challenging communication conditions due to the interruption of LOS paths. Likewise, the large metal pipes affect multipath propagation, resulting in strong attenuation jumps. In this scenario, the exploration robot must now advance from the left side (mission control) to the dummy doll marked on the right. The Agilex Scout Mini Platform supports the LANTERN relay concept by moving behind the exploration robot. The video stream from the SpotCam is transmitted as the application, which automatically adjusts the data rate through WebRTC bandwidth estimation techniques.

B. Validation of the Heterogeneus Relay

When discussing the results, it is important to note that the teleoperation of the exploration robot was successful up to the dummy. However, there were occasional drops in video quality and brief stuttering of the video stream. Communication was also briefly interrupted after the exploration robot went around the first bend, resulting in an NLOS situation with both the Umbrella network and the LANTERN relay. Once the LANTERN relay caught up with the exploration robot and LOS was restored, the mission could continue. To analyze the effects described above in more detail, we will now examine the link switch decisions and the exciting area of switching between NLOS and LOS. First, we examine the selected link of the SEAMLESS protocol in Fig. 8. Notably,

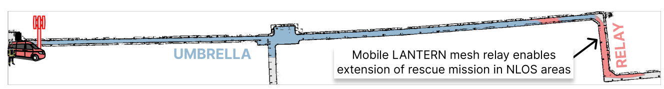

Fig. 8. Map of the used link for the LANTERN relay for the underground scenario, highlighting that the LANTERN relay enables communication in NLOS condition. Note: The REM is interpolated based on an empirical measurement campaign.

as expected, a switch to the relay is necessary after the first curve. However, a second switch also occurs before the curve. To understand why, we take another detailed look at the RSRP of the umbrella network, which is used as a kicker metric for the SEAMLESS protocol. Together with the active link decision and the data rate of the video stream (note: logarithmic scale), this is shown in Fig. 9 for the selective section around the handover. Firstly, concerning the video data rate, it can be observed that this fluctuates in accordance with the bandwidth estimation mechanisms. Between 0 s and 150 s in particular, drops in the data rate from approx. 25 Mbit/s to 10 Mbit/s can be observed. These correspond to drops in the RSRP and are attributable to destructive interference due to multipath propagation through the narrow path and reflective metallic pipes. At 160 s, the RSRP falls below 100 dBm for the first time due to these fluctuations, causing a premature link change to the mesh network. Due to the lower capacity of the mesh network and the distance to the LANTERN relay, the video stream reduces its data rate significantly to 1 Mbit/s. At 180 s, the RSRP then rises above 100 dBm again, causing the SEAMLESS protocol to switch back to the umbrella network. Due to the higher capacity, more resources are available again. The video encoder gradually increases its data rate accordingly.

At 230 s, the exploration robot moves behind the curve, resulting in the aforementioned brief connection interruption due to NLOS conditions (RSRP drops over 15 dBm). As LANTERN Relay constantly catches up to the robot, the data rate can be increased again and ranges to 4 Mbit/s in the following sequence.

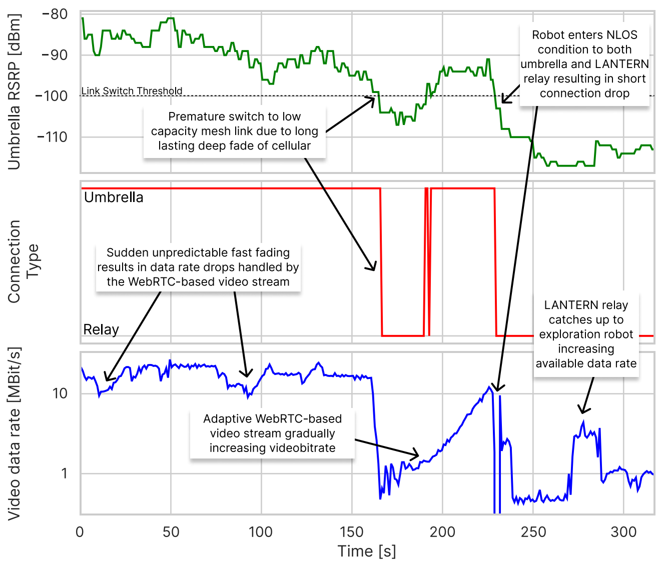

Fig. 9. Application data rate, link selection and cellular RSRP of the underground scenario over a selected time period, demonstrating general functionality of the LANTERN relay while highlighting potential improvements regarding data rate adaption and link selection mechanisms.

While this case study showed the general functionality of the open-radio LANTERN with heterogeneous communication technologies, the harsh radio conditions of the tunnel environment show substantial key takeaways for future research. First, adaptive application data rates, such as those used by the WebRTC video stream, are essential to handle deep fades and varying data rate capacities between heterogeneous links. Second, advanced link selection mechanisms are necessary to prevent premature link switches, which lead to unnecessarily reduced data rates. In [14], a first concept for the combination of both mechanisms is given for the adaptation of a live video stream and link selection using data rate predictions. However, it is currently limited to the parallel usage of cellular networks and therefore has to be extended to include relays and heterogeneous setups in general.

VI. Conclusion and Outlook

In this paper, insights into the development and validation of the LANTERN open multi-radio relay, allowing the combination of heterogeneous communication technologies and preventing vendor lock-in, were presented. The first of two case studies focused on applying the architecture to a homogeneous over-the-top 5G relay, improving network coverage while allowing manufacturer independence. Furthermore, the validation results highlight the SEAMLESS multi-link protocol [1] as a key enabler of the LANTERN relay for uninterrupted transitions between the umbrella and relay networks, ensuring continuous robot operation. In a second case study, a heterogeneous variant of the architecture, consisting of a cellular umbrella network and mesh relay network, successfully enabled the exploration of an underground scenario, while highlighting the overall requirement for adaptive application data rates and the research perspective for more sophisticated link switch mechanisms (e.g., machine-learning based [15]).

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