



Immersive Situational Awareness for Robotic Assistance of First Responders Enabled by Reliable 6G Multi-X Communications

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Abstract—The teleoperation of robotic systems relies heavily on the perception of the robot’s environment and, therefore, expects reliability and low latency from wireless networks. The convergence of digital and physical worlds envisioned by the upcoming 6G standard is expected to enable use cases that provide immersive sensory experiences. This work focuses on one such case: immersive situational awareness for first responders. It proposes a system architecture based on the multi-link concept that combines multiple network links into a single link, thus combining their strengths to meet the reliability and responsiveness requirements of the application. The proposed architecture is implemented in a demonstration scenario. The results show improved connectivity robustness and confirm the importance of multi-X communications for future communication standards.

Video Abstract—Demonstration video available online at: <https://tiny.cc/6GEMRescueRoboticsDemo>.

I. INTRODUCTION

To inform their decision-making during rescue missions, first responders must collect and analyze data from the mission scene. The gathering of data during robotic missions often relies on wireless networks, either for the remote control of teleoperated robots or data acquisition from autonomous ones. Low latencies and high throughput are expected from network infrastructure for reliable robot use and situation assessment. Furthermore, the next mobile communication standard is expected to facilitate augmented and mixed-reality applications and enable novel and efficient man-machine interfaces that presenting the data from machines seamlessly [1]. We envision, as shown in Fig. 1, immersive situational awareness powered by next-generation communication standards as an application for first responders using immersive insights from the robot’s perspective using Virtual Reality (VR), which has been shown to improve situational awareness acquisition [2][3]. To meet the strict demands in network latency and throughput of this application, we rely on the multi-link concept [4] to leverage multiple network technologies simultaneously.

The contributions of this work can be summarized as follows:

- **System architecture proposal** for multi-robot and multi-link (multi-X) immersive situational awareness.
- **Demonstration of multi-X-enabled** immersive situational awareness in an exploration scenario.

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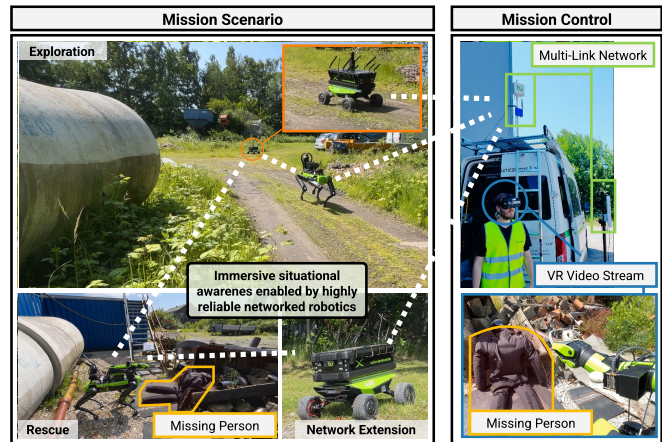


Fig. 1. Envisioned approach: Leveraging seamlessly coordinated access to multiple networks to enable robust immersive perception of robots’ surroundings during robotic missions.

The remainder of the paper is structured as follows: The multi-X-enabled architecture is presented in Sec. II, followed by a demonstration of immersive situational awareness provisioning in a search and rescue scenario in Sec. III.

II. MULTI-X-ENABLED IMMERSIVE SITUATIONAL AWARENESS

The architecture of the proposed multi-X approach is presented in Fig. 2 and revolves centrally around the Multi-Link used to provide a robot fleet with multiple network links in a mix that increases the overall network resilience. The different aspects of this architecture are discussed in this section.

A. Multi-Link

First, the key point of the multi-X communication concept, the multi-link solution SEAMLESS [4], is discussed. As single-link solutions are prone to interference and changing network conditions, SEAMLESS aggregates multiple communication technologies for reliability and robustness. From an application layer point of view, SEAMLESS provides a regular network interface which supports Internet Protocol (IP) network traffic. This virtual network interface is linked to scheduling logic that chooses between individual links based on predefined metrics. Various other scheduling logics are available.

This paper focuses on the *Priority Quality* scheduler with the Received Signal Strength Indicator (RSSI) as the quality

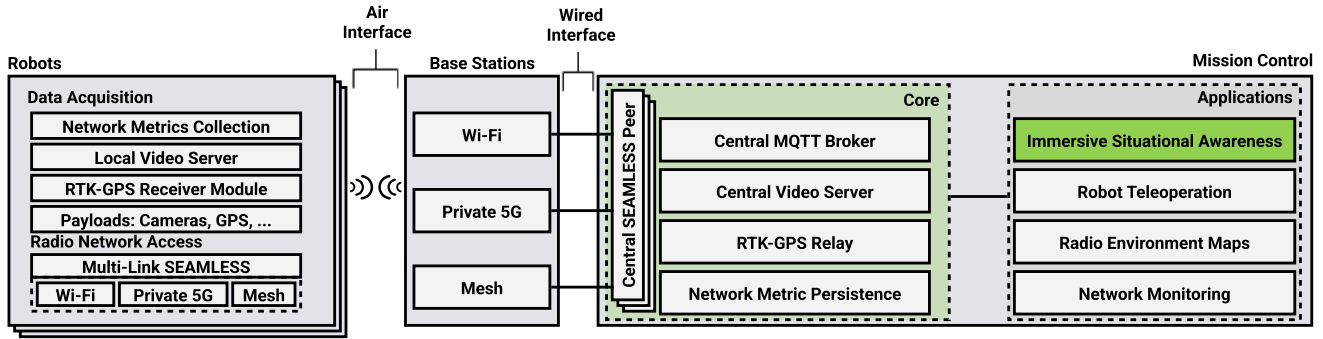


Fig. 2. System architecture of the proposed multi-X-enabled robotic immersive situational awareness approach. The coordinated combination of multiple network links for accessing the robots in the field enhances network performance and enables the immersive situational awareness application.

indicator. This scheduler considers the signal strengths of the communication technologies and switches between the links in a priority order based on predefined thresholds, making SEAMLESS suitable for both stationary and mobile applications contrary to other existing multi-link approaches. Therefore, SEAMLESS is a central enabler for multi-X robotic rescue missions.

B. Multi-Network

The multi-link is provisioned with a combination of centralized and decentralized technologies that leverage their strengths to mitigate each other's shortcomings and achieve greater robustness. Wi-Fi and private 5G are used as primary links. These can achieve high bandwidths if sufficient signal strength and minimal interference are provided, but are limited in range. Private 5G offers an additional layer of robustness against third-party interference through its band licensing requirements. Mesh provides a flexible and extensible connectivity range at the cost of limited bandwidth. Therefore, it is configured as a backup link.

C. Multi-Robot

The robot team deployed for this demonstration is presented in Fig. 3 and features the following:

- Xplorer: exploration robot equipped with various camera sensors.
- Rescuer: robot with a robotic arm to handle manipulation tasks which may arise during the exploration scenario.
- Xtender: robot equipped with mesh nodes that can provide extended network range.

All robots are equipped with the multi-link provisioned with the network combination described previously and Global Positioning System (GPS) modules with Real-Time Kinematic (RTK) support for precise position estimation.

III. DEMONSTRATION SCENARIO

Building on the multi-X-enabled infrastructure presented in Sec. II-C, a demonstration was carried out as a search and rescue mission powered by immersive situational awareness in the outdoor test field of the German Center for Rescue Robotics (DRZ). Immersive insights were provided through

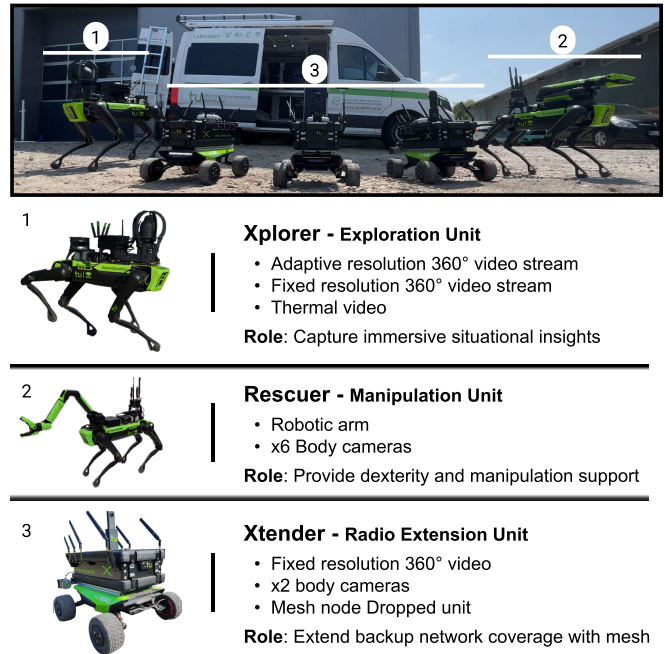


Fig. 3. Overview of robots and roles within the fleet. The Xplorer and Rescuer are actively involved in rescue missions through exploration and manipulation, while the Xtenders are responsible for enlarging the coverage area using the backup mesh connectivity.

a 360° video stream from the Xplorer. The primary setup parameters are listed in Tab. I. For the *Priority Quality* scheduler of SEAMLESS, the multi-link solution we used, the signal quality thresholds were determined before the demonstration scenario as the lowest signal strengths at which stable video transmission was still possible with the equipment used. The RSSI was used for Wi-Fi and the Reference Signal Received Power (RSRP) for private 5G. The robotic fleet, equipped with the described multi-network provisioned multi-link, was deployed over the scenario, as shown in Fig. 4.

The Xtenders were stationed at the different corners to ensure link redundancy in case of eventual Wi-Fi connectivity loss. The other robots could then freely roam the enclosed region with at least two active network connections at all

TABLE I
PARAMETERS OF THE EVALUATION SETUP

Parameter	Value
Video throughput	ca. 15 Mbps
Wi-Fi RSSI Threshold	-70 dBm
Private 5G RSRP Threshold	-105 dBm
Priority Quality Order (SEAMLESS)	Wi-Fi, 5G, Mesh

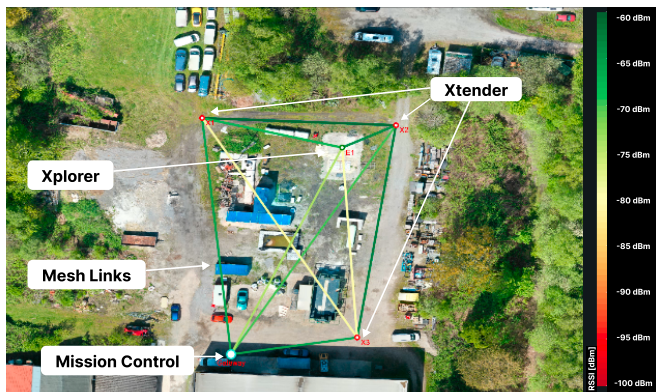


Fig. 4. Deployment of the multi-robot setup during the demo scenario. The Xtenders were set at the corners to provide backup connectivity over mesh if needed.

times. The recorded Radio Environmental Maps (REMs) for Wi-Fi and private 5G in Fig. 5 show the limited Wi-Fi connectivity range, which only covers a small region around the access point, while the private 5G base station's range reaches the scenario bounds.

During the demonstration, the Xplorer used Wi-Fi while close to the mission control and switched to private 5G when the Wi-Fi's RSSI was lower than the defined threshold in the farther scenario regions. This can be confirmed by the measured throughput of the different technologies on the Xplorer in Fig. 6. Signal strength was used as quality indicator to perform suitable handovers and ensure steady throughput for the immersive video streams.

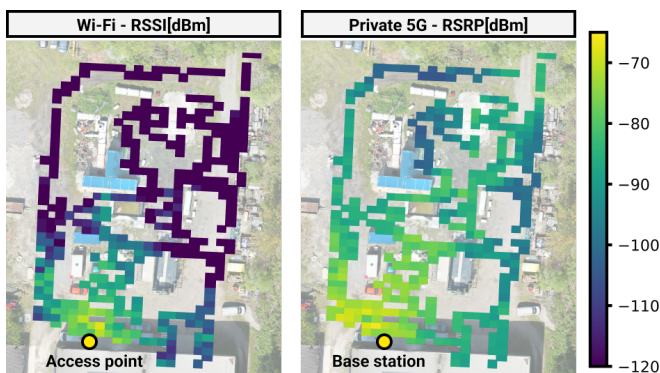


Fig. 5. Radio Environmental Maps for Wi-Fi and private 5G over the exploration scenario.

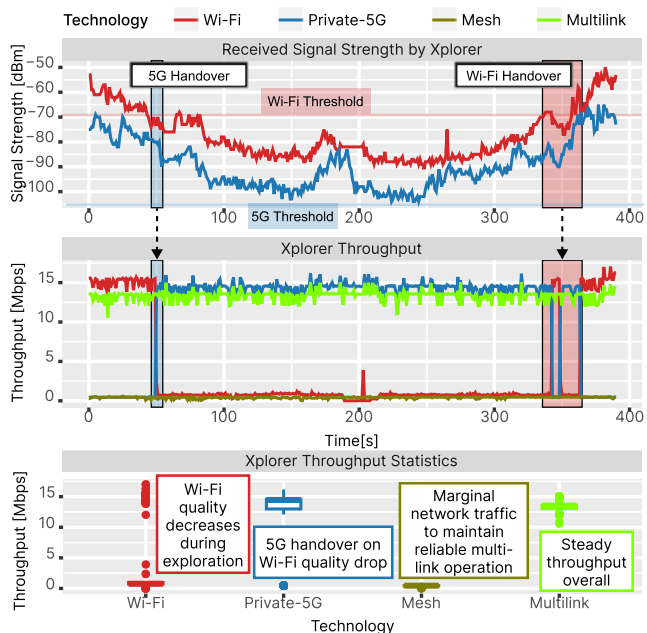


Fig. 6. Throughput of the 360° video stream from the Xplorer robot. An uninterrupted 360° stream was achieved during the exploration through suitable handovers between the network technologies.

IV. CONCLUSION

In this work, we demonstrated the realization of immersive situational awareness for first responders powered by a multi-link-based communication architecture. This poses the multi-X concept as an enabler of novel VR-based applications as envisioned for the upcoming development of the 6G standard.

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