Strengthening Multi-Robot Systems for Search and Rescue: Co-Designing Robotics and Communications Toward 6G

Juan Bravo-Arrabal, Ricardo Vázquez-Martín, J. J. Fernández-Lozano, and Alfonso García-Cerezo

Abstract

This paper presents field-validated Search and Rescue (SAR) use cases that demonstrate how the co-design of mobile robots and communication systems can support an edge–cloud architecture built on 5G Standalone (SA). The main goal is to enable effective cooperation among multiple robots and professional first responders in realistic, infrastructure-challenged environments. Our deployments include Hybrid Wireless Sensor Networks (H-WSNs) for risk and victim detection, smartphones integrated into the Robot Operating System (ROS) as edge devices for mission requests and path planning, real-time Simultaneous Localization and Mapping (SLAM) offloaded to Multi-access Edge Computing (MEC), and Uncrewed Ground Vehicles (UGVs) for casualty evacuation under different navigation modes. These experiments, conducted in collaboration with professional first responders, highlight the need for intelligent network resource management to balance low-latency and high-bandwidth traffic. Network slicing emerges as a key enabler for ensuring that critical emergency services remain available under adverse communication conditions. The paper distills architectural requirements, lessons learned, and open challenges that future 5G-Advanced and 6G technologies must address to strengthen emergency response capabilities.

Introduction

In recent decades, new technologies have increasingly been used to support and enhance rescue operations, thereby improving safety and efficiency in emergency response. In this context, robots play a key role in collecting data from disaster environments, searching for victims, conducting structural inspections, providing medical assistance and intervention, recovering victims, extending the operational reach of rescue teams, and performing other logistical tasks [1]. Recent efforts also explore low-latency onboard perception for reactive Search and Rescue (SAR) drones, radiation-tolerant remote operation systems, and swarm-based autonomous strategies for locating hidden emitters, further expanding the range of robotic capabilities considered for emergency response.

For safety reasons, teleoperation has been used in robot deployments in disaster situations. However, achieving full autonomy remains a significant challenge due to the complexity of emergency scenarios. As a result, semi-autonomous tasks are often preferred, where robustness and coordination among multiple multimodal robots and human teams are the main objectives. Advances in large language model (LLM)-enabled voice interaction for UGVs [2] and ultra-compact aerial systems for rapid response highlight the diversity of emerging SAR applications.

In addition, building an Internet of Things (IoT)–edge–cloud continuum remains challenging, but it could greatly benefit SAR operations [3]. Progress in standardized testbeds for teleoperation and multi-terrain evaluation [4] and relay-based multi-radio network extension further illustrate the increasing importance of communication robustness in emergency robotics.

Semi-autonomous robotic tasks that require interactions among robots, the environment, and response teams depend on high-quality wireless communication systems for effective collaboration and coordination toward shared goals. 5G technology delivers reliable wireless connectivity with low latency, essential for demanding applications such as remote sensing and mapping, while also enabling edge computing capabilities. Furthermore, 5G features can provide a resilient network infrastructure, enabling the deployment of crowdcells in disaster areas where catastrophic events typically destroy communication systems.

This article summarizes our field experience integrating communication systems and mobile robots in realistic SAR exercises conducted with professional responders. Unlike urban SAR deployments that may rely on existing 5G/6G infrastructure, our work focuses on infrastructure-denied scenarios where communication and robotic systems must be jointly designed and deployed. The presented use cases fall into two categories: those that extend first-responder perception and decision-making, and those that support physical tasks such as casualty evacuation. For each case, we outline mission objectives, participating stakeholders, robotic platforms, and the specific role of communication technologies, together with observed operational outcomes and

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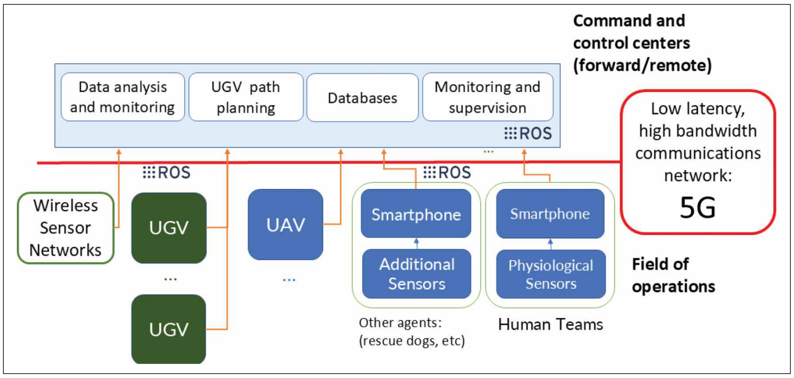

FIGURE 1. Simplified architecture of the multi-robot SAR coordination system.

challenges. The article concludes with identified limitations, lessons learned, and recommendations for improving communication reliability in emergency operations.

The remainder of the paper is organized as follows. Section II describes our approach to communication and robotic systems, Section III summarizes field use cases, Section IV discusses results and challenges, and Section V provides concluding remarks.

An Approach to Communications and Robotic Systems for Emergency Missions

Collaboration with professional first responders is a cornerstone of our approach, ensuring that our developments address real operational needs. This collaboration is structured around the annual Workshop on Emergencies, JEMERG,[1] organized by the Chair for Security and Emergencies at the University of Málaga. Since 2006, JEMERG has brought together around 200 participants from multiple emergency services in realistic field exercises, incorporating human factors such as procedures, workload, and stress, while revealing practical limitations that are often invisible in laboratory settings.

Consequently, our methodology is driven by use cases co-designed with first responders, focusing on how technological solutions fit into existing organizational structures and operational protocols. This creates a continuous development loop in which feedback from the field guides improvements and eases later adoption.

A central requirement identified by responders is timely access to reliable information. Our first step was therefore to deploy Wireless Sensor Networks (WSNs): static sensors placed at strategic locations monitor environmental variables (e.g., temperature and gas concentration) to detect risks, while Hybrid WSNs (H-WSNs) based on technologies such as LoRa and ZigBee combine static and mobile nodes. Mobile nodes mounted on robots, rescue dogs, and crewed vehicles extend coverage and keep environmental data up to date. In parallel, Bluetooth Low Energy (BLE) scanners onboard robots enable victim detection by sensing personal electronic devices and geo-tagging these detections via the Global Navigation Satellite System (GNSS), allowing rescue teams to prioritize high-probability areas.

The integration of mobile robots into WSNs highlighted the potential of connected systems and motivated the adoption of high-bandwidth, low-latency technologies such as 5G. Within a national pilot project led by Vodafone and Huawei, we developed and tested 5G-enabled solutions in realistic exercises. 5G allowed extensive information sharing and new use cases, but also required a holistic architecture to integrate ground and aerial robots, crewed vehicles, WSNs, human responders, and control centers. This led to the Internet of Cooperative Agents (X-IoCA) architecture [5], which unifies these components and introduces Multi-access Edge Computing (MEC) centers for efficient data sharing, computation, and coordination in complex environments. As illustrated in Figure 1, emergency response is treated as a collective mission performed by a heterogeneous team of agents exchanging information, with communications as a central enabler for remote casualty extraction, edge-based mapping, real-time responder stress monitoring [6], and cooperative robotic missions.

Field-Validated Use Cases in Connected SAR Robotics

The Robotics and Mechatronics Group, together with the Institute of Mechatronics of the University of Málaga (IMECH.UMA), established the Laboratory and Area for Experimentation in New Technologies for Catastrophes (LAENTIEC). Dedicated to advancing disaster robotics and emergency-response technologies, LAENTIEC provides a 90000m^2 outdoor test area with diverse terrain, a river bed, and dual tunnels for realistic experimentation. It hosts the JEMERG initiative, enabling the validation of emerging robotic and communication technologies under conditions representative of natural and human-made catastrophes.

The following use cases demonstrate the integration of mobile robots and first responders as cooperative agents in disaster scenarios, highlighting the importance of tailored application design and robust communication strategies.

Perception and Localization via Hybrid WSN

Mobile nodes can function as both Concentrator Nodes (CNs) and End Devices (EDs), i.e., edge devices. Any mobile SAR agent (e.g., firefighting brigades, military units, or mobile robots) has a certain payload capacity to deploy WSN nodes, thereby extending network coverage and enhancing the efficiency of risk detection and victim localization.

Figure 2 depicts a framework for mobile robot interaction with its operational environment through various H-WSNs, including Bluetooth Low Energy (BLE), LoRa, and Zigbee radios, complemented by WiFi-based mesh links (802.11s).

Robots carry nodes of each technology during navigation, integrating themselves in star, mesh, and peer-to-peer network segments. Human teams can additionally deploy static EDs grouped into Sensory Groups (SGs) in areas of interest, including locations without Line of Sight (LoS). These SGs measure environmental variables and detect relevant gradients (such as temperature, gas, humidity, radiation, or noise), actively contributing to the construction of shared situational awareness. Each SG includes a GNSS module and

[1] JEMERG: Jornadas de Seguridad, Emergencias y Catástrofes.

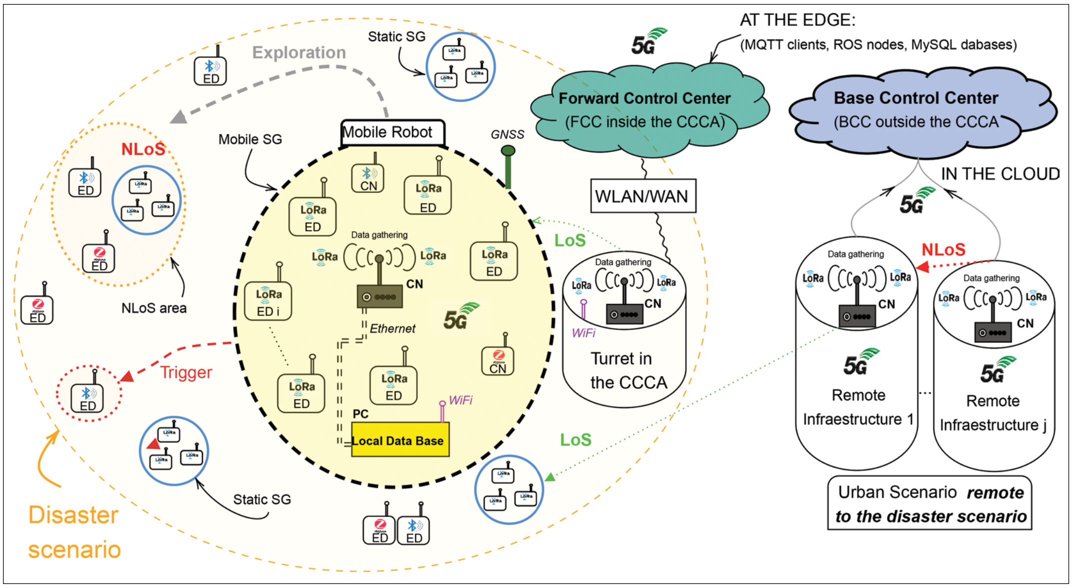

FIGURE 2. Framework for mobile robot interaction in SAR scenarios, including H-WSNs.

periodically transmits its position and readings to the Forward Control Center (FCC) via LoRa gateways. When any SG reading exceeds a predefined safety threshold, the SG issues an alarm to the FCC, which assigns the nearest UGV to inspect the area. In this way, robots provide mobility and access to areas that are difficult or hazardous for human teams, acting as sensing units, edge-processing nodes, communication relays, or coverage extenders [7].

If an SG does not exceed any alarm threshold, regular low-rate telemetry is still transmitted; data transmission is never fully suspended. However, if an SG stops transmitting—due to sensor failure, communication degradation, power loss, or physical destruction—the system generates a data-gap alert. This absence of data is itself meaningful: data MULEs (Mobile Ubiquitous LAN Extensions) are then instructed to approach the area, perform an in-situ inspection, and collect environmental data for later offloading to local or cloud databases. This mechanism ensures continuity of situational awareness even when parts of the sensor infrastructure fail.

A major concern in disaster scenarios is the loss of the core communication infrastructure. In our architecture, such a failure is considered a temporary but expected condition. During this period:

- Robots retain full local autonomy (navigation, SLAM, obstacle avoidance, and local decision-making).
- Each robot carries its own LoRa gateway, BLE scanner, 802.11mc anchor, and ZigBee coordinator, enabling the autonomous formation of local star, mesh, or P2P networks without depending on Internet access.
- Edge devices store data locally and synchronize opportunistically when connectivity is restored (dew–edge–cloud progression).
- Local services (LLM-based high-level commands, path planning, and risk reasoning) can still be executed onboard, but without cooperative reasoning or shared situational awareness.

Zigbee and Wi-Fi mesh networks enhance environmental perception and coverage extension. UGVs and Uncrewed Aerial Vehicles (UAVs) maintain local storage and synchronize with central databases whenever a communication opportunity arises, enabling delay-tolerant but reliable information flow to the Command, Control, and Communication Area (CCCA).

Robots also operate as data MULEs, collecting data from disconnected regions and offloading it later [8]. This property ensures that data consistency and cross-team awareness are preserved even during long communication outages.

A modified LoRaWAN approach was validated, where packets transmitted by SGs can be received simultaneously by multiple CNs [8]. When CNs are placed on urban rooftops, localization services remain feasible even under non-line-of-sight (NLoS) conditions [9]. These CNs may be connected to the Internet via 5G or satellite links, providing cloud access to remote FCCs, while local LoRa communication continues uninterrupted during infrastructure loss.

Victim detection has also been explored through passive scanning of BLE signals from both UGV and UAV platforms [10], analyzing parameters such as Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), device manufacturer data, and the dynamic or static nature of detected Medium Access Control (MAC) addresses. These indicators help infer the presence of potential victims in the field at a coarse spatial scale. An ESP32-based BLE scanner is embarked on each search agent—both first responders (human rescuers) and second responders (mobile robots)—so that BLE detections are made opportunistically while they perform their primary tasks (inspection, exploration, or victim assistance).

In representative field exercises, semi-hidden victims (mock victims carrying ESP32-based beacons under vegetation) were detected by UGVs of 0.82 m height at distances of approximately 15 m during their approach, while navigating at ground speeds around 1 m/s. UAVs overflying the same areas of interest were able to detect

FIGURE 3. Autonomous victim evacuation: after executing the planned path, the UGV reaches the extraction point and waits for the helicopter [11].

the same BLE transmitters from altitudes below 22 m above ground level, with teleoperated flight speeds always kept below 9 m/s. These values confirm that BLE-based detection is effective at short range (tens of meters) in cluttered outdoor environments, provided that platform speed and altitude are adapted to the scanning periodicity and signal strength.

Potential limitations include:

- short effective range (on the order of tens of meters, depending on obstacles),
- false alarms from non-victim devices,
- MAC address randomization affecting long-term tracking.

To mitigate these limitations, our design incorporates multi-parameter filtering (RSSI stability, manufacturer data extraction, motion patterns) and cross-validation with other sensing modalities. BLE-based victim detection is conceived as the opportunistic detection of wearable devices (smartphones, earphones, smartwatches) that people already carry. In our experiments, this behavior was emulated with ESP32-based beacons configured with fixed, non-randomized MAC addresses, acting as stable identifiers for mock victims. Devices carried by responders and robots use a set of pre-registered identifiers; therefore, any detected BLE source that does not match this predefined set can be treated as an unknown device of interest, and thus a potential victim. This approach avoids dependence on bespoke hardware while ensuring that BLE detection remains lightweight and easily integrable into responders' equipment.

Detection events (device identifier, RSSI, timestamp, and agent pose) are published by each ESP32 scanner to a mission Message Queuing Telemetry Transport (MQTT) broker; when connectivity is available, this broker synchronizes the incoming data with a remote server at the command and control center, where detections from all agents are fused and stored for further analysis. The accuracy of the mobile agents' geolocation (GNSS or real-time kinematic GNSS, RTK-GNSS) is essential to reliably georeference BLE detections, especially for fast-moving platforms such as UAVs, since pose estimates must be updated at high frequency to correctly associate each detection with the robot's position at the time of reception. In a real deployment, the system would focus on a predefined set of mission-provisioned BLE identifiers, using them as short-range presence cues that complement other sensing modalities, while avoiding indiscriminate tracking of arbitrary public devices and allowing the associated data streams to be protected through standard encryption and access-control mechanisms. In this sense, BLE provides reliable binary information about the presence or absence of tagged devices in a local area, rather than precise standalone victim localization.

Results from our H-WSN deployments demonstrate that the value of connected networks in SAR missions lies not in high bandwidth, but in resilient connectivity, low latency, and the ability to support distributed coordination. The progressive integration of 5G—and, eventually, 6G—will further improve synchronization, scalability, and robustness, enabling more efficient and intelligent H-WSNs in challenging, dynamic environments.

Casualty Extraction Using Smartphones as Edge Devices

This use case provides first responders with a time-critical tool to request a UGV or UAV for missions such as casualty extraction, medical assistance, or equipment delivery. Using a smartphone, the responder sends a request that includes their current location; the FCC computes a feasible path and transmits it to the robot, which then autonomously follows the route to the extraction point (Figure 3).

The scenario was developed as a cooperative training exercise with a combat medical unit of the Spanish Army (Tercio "Alejandro Farnesio" 4° of the Spanish Legion) and has been repeated in several JEMERG editions. In these realistic one-shot runs, the Rover J8 UGV transported two casualties on commercial stretchers, while the UMA-ROS-Android app and a path planner within the SAR-IoCA architecture handled the request and routing logic [11]. In early trials, the UGV was teleoperated along the extraction route because of its limited autonomous speed, whereas in the most recent exercise it completed the evacuation path fully autonomously at higher, yet still safe, speeds.

This experiment was also conducted in a different scenario, utilizing a remote Base Command and Control Center (BCC) to autonomously deploy a UGV in an urban SAR scenario at a distance of 440 km [12]. The robot successfully received and executed the planned paths over commercial networks, but the communication performance differed markedly between setups. In the first experiment, using 5G near the operation area, uplink throughput exceeded 110 Mbps with low latencies of 10–12 ms, enabling real-time teleoperation with simultaneous transmission of LiDAR for SLAM, multiple ROS topic subscriptions, and dual onboard video streams. In the remote experiment, only 4G connectivity was available, with latencies of 18–21 ms and a maximum throughput of 40 Mbps, sufficient for streaming the Rover J8 cameras and LiDAR point clouds but leaving little margin for additional data. These results confirm the feasibility of long-distance remote operation while highlighting the limitations of commercial coverage in SAR missions and the need for ad-hoc or rapidly deployable networks to ensure reliability in disaster scenarios.

In conflict zones, communication infrastructures are frequently targeted and deliberately disabled, aiming to isolate affected areas. Similarly, natural disasters such as earthquakes, hurricanes, or floods often damage critical infrastructure, while extended power outages further accelerate network degradation. These failures significantly compromise emergency response efforts, especially in SAR missions, where reliable connectivity is vital.

To mitigate these challenges, 5G network slicing enables the creation of virtual network segments tailored to the latency, bandwidth, and reliability needs of emergency services. This ensures that, even under infrastructure disruption or heavy network load, critical SAR operations retain dependable communication links and can share scarce resources with other connected agents.

In our experiments, the Hierarchical Dynamic Layers (HDL) Graph SLAM[2] algorithm was used to generate 6-DOF real-time maps by fusing LiDAR and GNSS data from the robot. SLAM was executed under two configurations: *Cloud* and *Edge*. In the Cloud configuration, raw LiDAR packets and GNSS measurements were uploaded through 5G to a MEC server, where the map was constructed and shared with other agents. This reduced onboard computation but required substantial uplink bandwidth. In the Edge configuration, the SLAM pipeline was executed directly on the robot's Jetson AGX Xavier, processing live LiDAR and GNSS streams in real-time; only the resulting map was uploaded to the cloud. A ROS-bag was recorded in parallel only for logging and offline analysis. CPU usage remained around 45% on average, indicating that onboard processing did not represent a bottleneck. End-to-end latency within the standalone 5G cell—measured through Internet Control Message Protocol (ICMP) pings exchanged between UEs in both slices—remained below 19 ms, indicating that the network contribution to the Cloud SLAM loop remained compatible with real-time updates. During JEMERG XV (2021), the Rover J8's router SIM was assigned to a prioritized slice configured to use up to 80% of the 5G SA cell capacity whenever real-time SLAM offloading required it, while the remaining 20% slice was shared by smartphones and additional robots. Figure 4 summarizes the traffic evolution during the two *Cloud* SLAM runs, showing uplink and downlink Radio Link Control (RLC) throughput in the 5G cell together with the FCC upload and download rates, i.e., the uplink and downlink throughput generated by the router located at the FCC. The figure also marks the activation of network slicing, the 80%/20% resource split, a map reset between runs, and the start of a new map generation phase.

The relatively high aggregate throughput observed in the cell was not due to SLAM alone: it also included simultaneous camera streams and traffic from other devices connected to the network. However, these additional flows were not prioritized; the 80% slice protected the Rover J8 traffic whenever the robot needed guaranteed uplink capacity for real-time SLAM offloading. This configuration guaranteed uplink

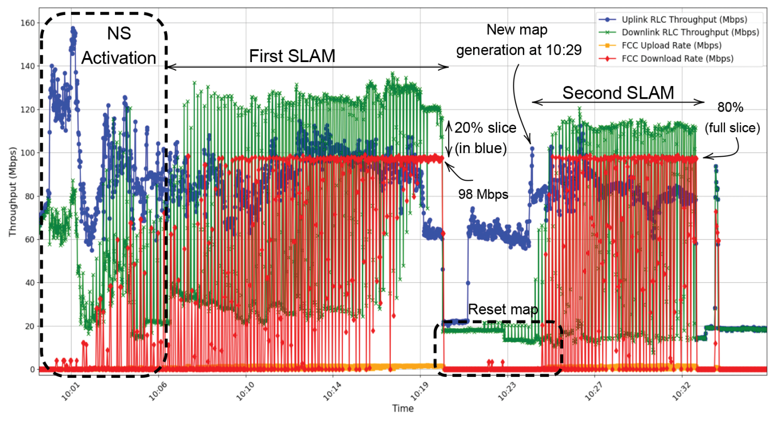

FIGURE 4. Traffic evolution within the 5G SA cell during the two Cloud SLAM runs offloaded to the MEC, showing uplink/downlink RLC throughput, the uplink/downlink throughput generated by the FCC router, network slicing activation, the 80%/20% slice distribution, and the map reset/regeneration events between runs.

availability even under heavy load and enabled peak throughputs close to 100 Mbps in the robot slice, with sub-20 ms latency and strong resource isolation—performance that would not be achievable with LTE or 4G networks under comparable conditions.

The Cloud experiment illustrates the network demands of the LiDAR pipeline itself: approximately 2.2 MB/s of raw LiDAR packets were uploaded from the robot to the MEC, while operator workstations received fully processed 3D point clouds at around 16 MB/s, together with 0.75 MB/s of SLAM-related topics. During the generation of the largest map chunks, the robot produced up to 6.58 MB/s ($\approx$ 53 Mbps) of map-related data in the prioritized slice. Processed clouds are significantly larger than raw packets because each LiDAR point includes XYZ coordinates, intensity values, and timestamps. These application-level rates should therefore be interpreted together with the higher aggregate cell throughput shown in Figure 4. Which also includes concurrent non-prioritized traffic from other mission devices.

In the Edge configuration, the Jetson AGX Xavier eliminated the need to upload raw LiDAR packets, transmitting only the resulting map to the MEC. In contrast, a Jetson Nano used as a reference saturated all CPU cores at 100% and could not complete SLAM in real-time, demonstrating the necessity of either offloading to the MEC or using high-end onboard hardware. Both Cloud and Edge executions achieved successful loop closure and produced consistent 3D maps. The Cloud SLAM run lasted approximately 30 minutes, whereas the Edge SLAM run lasted around 27 minutes.

Network slicing also ensured fair resource allocation, allowing the Rover J8's router SIM to perform additional task—such as high-frequency GNSS streaming or onboard camera video upload—without compromising SLAM performance. Since ROS communication is subscriber-driven, traffic was generated only when topics were actively consumed, helping maintain efficient bandwidth usage even under high load.

The key performance indicators (KPIs) discussed in this section correspond to field trials carried out in 2021 on a private 5G SA core

[2] https://github.com/koide3/hdl_graph_slam

FIGURE 5. Rover J8 coming out of a tunnel in *follow-me* mode.

provided by Vodafone, which enabled controlled evaluation of slicing, latency, and throughput. Implementation details of the SLAM offloading architecture and network configuration are available in [10]. Modern cloud–edge compression frameworks such as *Cloudini*,[3] designed for fast LiDAR point cloud compression, could further enhance future studies.

Multi-Robot Cooperative Exploration and Casualty Extraction in Communication-Denied Areas

This use case validated an implementation of the IoCA architecture in a SAR mission by testing the entire multi-robot system over 5G communications under real-time, high-bandwidth, and low-latency requirements. The participating agents included human responders such as firefighters, military units, and police officers, as well as robotic units such as UGVs and UAVs, and canine rescue teams [13]. The validation was carried out during a realistic disaster response exercise that formed part of the annual JEMERG full-scale event [5]. The simulated mission was conducted under realistic conditions following strict timing constraints and safety protocols coordinated by the exercise director and the organization staff.

The mission was an emergency response to a disaster caused by an earthquake, which created fires and left victims trapped inside crushed vehicles in a storm-water drainage tunnel with challenging access. Other participants included the Provincial Fire Department of Málaga and the Spanish Military Emergency Unit (UME). The mission protocol was established in collaboration with the participant organizations to facilitate cooperation among heterogeneous robotic teams.

The use of the SAR-IoCA architecture facilitated the coordination of three UGVs and one UAV with the human rescue teams. The UAV was used to map the environment, creating a Digital Elevation Model (DEM) and an orthophoto of the operation area. These maps serve two purposes: to help the human rescue teams assess the disaster and to support path planning for cooperative robotic agents. At the FCC, human coordinators are responsible for making decisions about the deployment of rescue and robotic teams based on data received from the field through the different H-WSNs and video streams transmitted via ROS. Both the UAV and UGVs used their onboard sensors to detect risks and potential victims.

The Rover J8 UGV requires special attention because of its high bandwidth demands for sensor-data transmission. The vehicle streams 4K video from an onboard smartphone together with LiDAR point-cloud data to the FCC. However, when the robot enters communication-denied areas—where even GNSS may fail—the SAR coordinator at the FCC can no longer access the camera feeds. In such cases, a UME responder (see Figure 5) must press *the follow me* button located on the front of the UGV. In addition, the smartphone application can automatically reduce the resolution of the transmitted video or control when video is transmitted, serving as a redundant vision system if the robot's onboard systems fail. This highlights the advantage of integrating a smartphone into ROS as a plug-and-play edge device that operates independently of the robot's own systems.

A coordinated effort is then made to extract and evacuate casualties. This process of exploration and response to identified risks and victims continued as long as required by the mission to ensure the safety of the emergency area. The mission was completed successfully, with victims found and evacuated in the designated area as a result of the joint operation of a fire brigade team, a military emergency team, and our systems (comprising the UGVs, UAV, FCC, and BCC). The mission lasted one hour and fourteen minutes.

The specialist rescue teams involved in the realistic exercises were satisfied with the overall results. The MEC centers played a significant role by providing smooth audiovisual feeds, enhanced through aerial and ground exploration of the environment. This included the teleoperation of the UGVs and the effective identification of victims.

Discussion and Lessons Learned

Emergency response inherently requires coordinated action among humans, robotic platforms, and communication systems. Our field experience demonstrates that robotics and communications cannot be treated as separate capabilities: in infrastructure-denied environments, effective operation depends on a co-designed architecture in which sensing, control, data exchange, and network behavior are jointly considered. From this perspective, every robot and responder edge device becomes a networked *thing*—that is, an *agent* in the sense used by the Internet of Cooperative Agents (IoCA) architecture: a mobile entity equipped with perception, memory, processing capability, and the ability to act autonomously or semi-autonomously within the mission.

5G Standalone connectivity has been a key enabler in this transition. High-throughput, low-latency links improve teleoperation, allow real-time transmission of sensor data such as LiDAR point clouds, and enable offloading computation—e.g., SLAM—to Multi-access Edge Computing (MEC) nodes. These capabilities expand the design space for energy-constrained robots and unlock new behaviors that are impractical with onboard

[3] https://github.com/faconti-davide/cloudini

processing alone. Our deployments align with industrial IoT and Ultra-Reliable Low-Latency Communications (URLLC) enhancements introduced in 3GPP[4] Releases 16–17, especially network slicing and reducedcapability devices, which support heterogeneous H-WSNs and mission-specific traffic isolation.

Beyond perception, advanced communication enables richer forms of human–robot teaming in which robots do not merely act after human responders, but operate before, alongside, or in coordination with them. In this sense, robots can function as second responders—not as a second wave in time, but as complementary agents that extend the reach, safety, and effectiveness of the SAR mission. Depending on the scenario, they may enter hazardous areas ahead of humans to prevent additional casualties, operate in parallel to perform reconnaissance or structural inspection, or support ongoing operations by transporting equipment and evacuating victims. Dedicated 5G applications enable responders to request robotic assistance, share their location, and trigger autonomous behaviors in real-time, creating a tightly integrated interaction loop. These mechanisms remain effective even in remote or infrastructure-denied areas when complemented with NTN backhaul, ensuring resilient connectivity beyond terrestrial coverage. Multi-robot missions further benefit from centralized coordination at the FCC, which aggregates data from heterogeneous agents and orchestrates teleoperation or autonomous motion across the fleet.

Secure and reliable communication remains fundamental. Our deployments combine encrypted tunnels, authenticated network access, and edge-level redundancy to protect mission-critical information. When 5G infrastructure is available, these measures are complemented by native 3GPP security mechanisms and slice-level isolation, which help mitigate long-standing concerns of emergency services regarding commercial networks. Crowdcells additionally provide local connectivity when external infrastructure is damaged, enabling continuity of operations.

From a backhaul perspective, the architecture is designed to operate at several levels of connectivity. When a 5G or LTE core remains reachable, crowdcells or portable base stations can use terrestrial, microwave, or satellite backhaul to restore end-to-end connectivity and enable features such as network slicing for SAR traffic. In the complete absence of backhaul, operation falls back to H-WSNs and local mesh segments supported by robots and static nodes, with data stored at the edge and synchronized opportunistically when connectivity returns. This yields a graceful degradation model rather than a hard dependency on 5G slicing.

In connected multi-robot systems, we also observed that the choice of ROS 2 middleware (RMW) has a non-negligible impact on performance, particularly in 5G/6G-enabled SAR missions, where mobility, variable link quality, and heterogeneous network paths are common. Data Distribution Service (DDS) implementations such as CycloneDDS, Fast DDS, RTI Connext, and GurumDDS differ in latency, robustness under mobility, discovery mechanisms, and computational footprint. Lightweight subsets such as MicroDDS remain appropriate for embedded IoT and H-WSN nodes. More recently, Zenoh has emerged as an alternative RMW with very low latency, built-in routing, and seamless operation across network address translation (NAT) boundaries, wide-area networks (WANs), 5G SA cells, crowdcells, and MEC backends, making it attractive for multi-network robotic missions. In our practical deployments, this middleware layer was complemented with a lightweight tooling workflow that automates RMW selection, DDS peer-list management, and machine-specific Cyclone DDS configuration generation for multi-host ROS 2 setups, including Docker-only host.[5] Although Zenoh does not yet match the full quality-of-service (QoS) coverage of DDS, its robustness in heterogeneous networks aligns well with the connectivity patterns observed in real SAR deployments. Middleware selection must therefore be treated as a design parameter that shapes the reliability of distributed perception, mapping, and coordination.

Our field deployments reveal several challenges that become even more acute in remote, maritime, or mountainous SAR operations, where robots and IoT devices face intermittent connectivity and heterogeneous network segments. Key limitations include the need for reliable links in safety-critical missions, stronger sensing capabilities for victim and hazard detection, more intuitive human–robot interfaces, and a natural integration between robotic behavior and communication systems.

6G has the potential to address many of these gaps. The evolution toward 5G-Advanced already anticipates important improvements, such as enhanced URLLC, precise positioning, and low-power devices suitable for dense H-WSNs. Future 6G systems extend these capabilities with integrated sensing and communication (ISAC), allowing the network itself to act as a distributed sensor; predictive, adaptive connectivity management to adjust robotic behavior based on expected link conditions; and dynamic resource allocation to guarantee bandwidth and reliability when and where required.

In line with current IMT-2030 targets, 6G URLLC aims at sub-millisecond user-plane latencies (down to 0.1–1 ms) and reliability levels approaching 10^{-5}–10^{-7} or beyond for critical traffic, which matches the reaction-time requirements of SAR teleoperation and coordinated multi-robot control [14]. For sensing, 6G deeply integrates wireless perception with communication, enabling high-accuracy positioning and richer environmental awareness for robotic teams. In parallel, aerial-image understanding can complement onboard sensing by providing disaster-area recognition from UAV imagery [15]. High-bandwidth links will support advanced perception offloading, while improved telepresence and natural-language interaction may reduce operator workload. In addition, 6G-native support for networked digital twins will enable continuously updated virtual replicas of robots, environments, and communication infrastructure, further enhancing situational awareness and what-if analysis during SAR operations. Finally, 6G seeks to enhance interoperability across terrestrial, aerial, and non-terrestrial segments, enabling smoother

[4] 3GPP is the standardization partnership responsible for 5G system specifications, including Releases 16–19, where URLLC, network slicing, reduced-capability devices, non-terrestrial network (NTN) integration and 5G-Advanced features are defined.

[5] Repository: https://github.com/jbravoMlg/ros2-peers-sync

coordination among heterogeneous robotic teams and human responders.

Conclusion

This work has presented the experience and lessons learned by the Robotics and Mechatronics Lab at the University of Málaga in emergency robotics, highlighting the inseparable roles of robotics and communications. Our field deployments confirm that the successful use of advanced robotic systems in infrastructure-denied environments hinges on robust, adaptive communication architectures. In this context, the co-design of robotic platforms and communication networks is not a secondary technical detail, but a prerequisite for moving beyond controlled demonstrations and simulations toward real operational deployments in emergency response.

Realizing this transition calls for sustained and coordinated efforts—such as permanent testbeds and observatory-like programs—that support continuous validation, iterative refinement, and regular interaction with first responders. While 5G connectivity has already enabled new capabilities and use cases, important challenges remain, and progress depends on preserving this holistic, practice-oriented approach.

Ultimately, tightly integrating robotics and communications is essential to deliver deployable solutions that can effectively save lives and mitigate the impact of emergencies in real scenarios. In terms of situational awareness and the Internet of Robotic Things (IoRT), this means evolving from isolated robotic deployments toward resilient, standards-aligned systems of systems capable of operating reliably even in remote, heterogeneous, and communication-challenged environments.

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