# Field report on experimental comparison of a WiFi mesh network against commercial 5G in an underground disaster environment

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***Abstract*— Mobile robots in disaster scenarios such as tunnels, mines, or collapsed structures face communication challenges for reliable video streaming to remote control centers. Commercial fifth-generation (5G) networks provide low latency and high bandwidth, especially in urban areas, but ad hoc WiFi networks with static and robotic nodes can provide a solution to attenuation in occluded areas. This paper offers a field experiment report from a search and rescue (SAR) exercise where we tested a WiFi mesh network against commercial 5G in tunnels 184 m long, 6 m wide, and 4 m high. Two operator streamed video to the Internet through a mesh that consisted of two static nodes and two mobile nodes on unmanned ground vehicles (UGV). Latency was measured for both operators for different video resolutions, as well as for a 5G customer-premises equipment (CPE) on-board a scout-UGV. The paper discusses experimental results and lessons learned.**

***Keywords: Disaster Robotics; Distributed Robot Systems; Search and Rescue; Mesh Networks; 5G; Underground Scenarios***

## I. Introduction

Underground environments are relevant to emergency response missions [1] due to the occurrence of accidents in mines [2], [3], caves [4] or tunnels [5], but also in the case of collapsed structures [6]–[8]. Working in an underground environment poses particular challenges to emergency teams and equipment, including communications [9], [10]. As in most emergency response missions, coordination among different actors involved plays a key role in underground scenarios [11]. Effective communication allows coordinated command and control, ensuring that decisions are transmitted and executed efficiently [12], [13]. Keeping an updated picture of the scenario is required to identify hazards and changes, and thus adapt plans and actions to the actual problems [14], [15]. The use of multi-robot systems [2], or even cloud robotics approaches including IoRT (Internet of Robotic Things) [16], can boost the performance of human-robot cooperative teams [16], [17], particularly if a communications system with low latency and high bandwidth is available. In this context, smartphones are becoming a powerful IoRT enabling technology [18], providing not only built-in sensing and processing, but also communications for cloud and edge computing.

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Cellular networks are widely available, and the new fifth-generation (5G), aims to provide low latency and high bandwidth, and it can be a valuable resource for emergency response missions, since the 5G standard also allows for standalone, private networks than can run independently of commercial operators [19]. However, attenuation issues can render cellular networks impractical in underground environments, where adaptive mobile relays can provide a feasible alternative for reliable communications [20]. In particular, the nodes in mesh networks [21] can relay data to other nodes in the network, creating a decentralized and self-configuring network [22].

Nodes of the network can be either static or mobile [23], [24]. Mobile nodes can be attached to human team members, but also to unmanned ground vehicles (UGVs) [14]. Different technologies are available to create such mesh networks, like IEEE 802.15.4 (ZigBee), LoRa, Bluetooth or IEEE 802.11, in its several variations. A review of these protocols is beyond the scope of this paper, being available in [25]–[28]. Actual field experiments are needed to evaluate the performance of robot missions in tunnels and underground disaster scenarios [29].

This work offers a field experiment report from a search and rescue (SAR) exercise in a catastrophic scenario involving a vehicle embedded in a dual-tunnel 184 m long, 6 m wide, and 4 m high (see Fig. 1). The wrecked vehicle is just in front of an inner opening (internal door), which connects both tunnels (A and B) right in the middle of the dual-tunnel. We evaluate and compare the behavior of two wireless networks inside the underground scenario: a novel WiFi mesh network based on UGVs with two different roles (scout and repeater) and a 5G commercial network. Two human agents (HA) streamed video to the Internet through the mesh network, composed of static and mobile nodes. Key performance indicators (KPI), such as latency and packet loss, were measured for both HAs for different video resolutions, and for a 5G customer-premises equipment (CPE) on-board the scout-UGV. Both networks have been tested in a prepared disaster scenario in an experimental terrain at the University of Malaga.

The rest of the paper is structured as follows. Sect. II gives a brief overview of the proposed mesh network. Sect. III describes the experimental setup to compare the proposed networks. Sect. IV discusses the experimental results. Finally, Sect. V is devoted to the concluding remarks and lessons learnt.

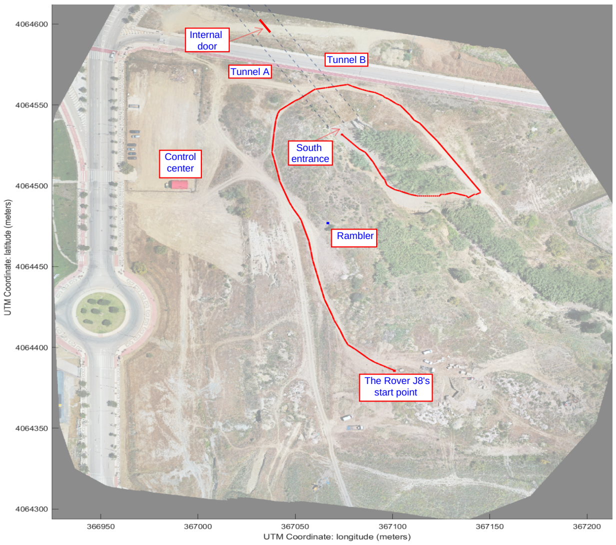


Fig. 1: Orthophoto showing the trajectory followed by Rover J8 to reach the south dual-tunnel entrance. Rambler remains static once the master is linked to some WiFi mesh node.

## II. System overview

The proposed system is based on WiFi, particularly on IEEE 802.11s, a standard that allows wireless nodes to be interconnected in a mesh network. All the devices were compatible with 802.11mc, which includes Round-Trip Time (RTT) and Fine Time Measurement (FTM) technologies, useful for accurate time-of-flight measurements of radio signals between devices and access points. These functionalities could be helpful to detect and locate victims in SAR situations [30]. Although these features were not used in the experiments described in this article, they add potential new uses to this 802.11 variant, so devices to be part of our mesh network were selected to be compatible with 802.11mc.

In this case, the mesh network is composed of four WiFi mesh routers, developed by Google (Menlo Park, California, EEUU), that are Multi-User Multiple-Input Multiple-Output (MU-MIMO) nodes: two are static, and two are mobile. Both static relay nodes should be placed at the south entrance to guarantee line of sight (LoS) into the dual-tunnel.

The mobile mesh nodes were placed on two UGVs: Rambler (repeater-UGV) and Rover J8 (scout-UGV). Rambler is a 4-wheeled skid-steering mobile robot with active suspension, weighing 370 kg, designed and built by the Robotics and Mechatronics Lab of the Univesity of Malaga [31]. Rover J8, developed by Argo (Kitchener, Ontario, Canada), is an electric off-road 8×8 UGV designed for outdoor navigation, with a weight of 1090 kg, and it has been modified by our Lab to include autonomous features [32]. Both UGVs are integrated as robotic agents in SAR-FIS, a management platform for distributed robotic systems in emergency missions, including path planning [33]. In addition, two human agents (from now on, HA1 and HA2) operated two smartphones (UE1 and UE2, respectively) while moving through the dual-tunnel. They streamed video

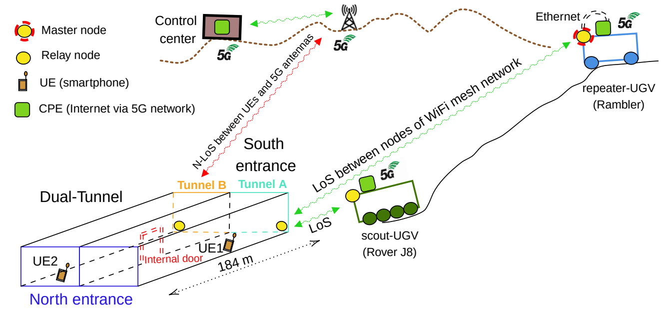


Fig. 2: Scheme of a WiFi mesh network providing Internet to a disaster underground scenario using two UGVs

to a remote control center where images were monitored in real-time, and KPIs were processed and stored.

First, the repeater-UGV (in this case, Rambler) must move to an area where it has good coverage to guaranty good latency and throughput for the 5G router it carries (CPE Pro 2 H122-373) developed by Huawei (Shenzhen, Canton Province, People's Republic of China): a mobile router (with SIM card) with 5G and WiFi 6 (802.11ax) connection. Rambler also carries the master node of the WiFi mesh network. This node creates its WiFi network but does not have an Internet connection. Thus, we connect the master node to the 5G CPE via Ethernet cable, acting as an Internet extender. However, the master distributes Internet through a wireless network independent of the CPE's WiFi network, i.e., the master node creates and manages a WiFi mesh network that is extensible through relay nodes: two static at the tunnel south entrance, at a fix distance from Rambler, and one mobile node carried by Rover J8, thus changing its position relative to the rest of the mesh nodes.

The Rover J8's role is to introduce a relay node into the tunnel as it moves from its south entrance to the end. In addition, the scout-UGV carries a CPE to test the 5G commercial network inside the tunnel. In this case, the CPE is not connected via Ethernet to the mesh node because its purpose is giving Internet access to the dual-tunnel via 5G. Thus, the scout-UGV extends two different networks inside the tunnel: the WiFi mesh network and the CPE's 5G network.

All the operation was coordinated and supervised from the control center (red tent in Fig. 1) using walkie-talkies, the Uv-5r model by Baofeng (Nan'an, Fujian, China). The experiment supervisor makes use of a 5G CPE similar to those on UGVs, and can receive and send commands, such as ping tests, to the deployed UEs (connected to the WiFi mesh network) and to Rover J8's computer (connected to the Rover J8 CPE's network), as they are all included in a Virtual Private Network (VPN), which is based on ZeroTier.

## III. Experiments

The experiments were performed in the outdoor test ground of the Laboratory and Area for Experimentation on New Technologies for Emergencies and Catastrophes (LAENTIEC), in the University of Malaga (Spain). This test ground covers over 90 000 $m^2$ of unstructured natural terrain with different altitudes, including two parallel sewer tunnels 184 m long. Both tunnels A and B are 6 meters wide and 4 meters high. The tunnels are internally connected by a rectangular door-like opening at half their length (internal door). The test ground was set up as a simulated disaster site, with rubble mounds and a crushed vehicle to mimic the conditions of emergency missions.

The experiments took place during an annual Workshop organized by the Chair of Security, Emergencies and Disasters at the University of Malaga (UMA), held on June 9, 2023. Fig. 1 shows an aerial view of the experimental setup.

Before the experiment started, the static relay nodes were deployed in the outer corners of the south entrance of tunnels A and B (see figures 1 and 2). Rambler was also set up and placed in a position `(36.71668869, -4.48848178)` where the master node had LoS with both static relay nodes. They were at a distance of approximately 62 m from Rambler, which is a feasible distance to interconnect two mesh nodes stably, according to preliminary tests. These three static mesh nodes remained in their positions for the whole exercise.

HA1 and HA2 carried two smartphones (UE1 and UE2, respectively), and they had to connect them to the WiFi mesh network when it was available. Both operators were instructed to move through the tunnels while streaming video (using the Android app called IP Webcam) at three different resolutions: 352x288, 640x360, and 640x480 pixels. Rover J8 was teleoperated in LoS using a radio link to get to the tunnel from another location (see Fig. 1, joining the human operators once they were already inside the tunnel.

The system setup consisted in several steps:

1. HA1 and HA2 approach the tunnels and place the static relay nodes with LoS with the inside of tunnels A and B, and LoS with the master node (in Rambler). They can confirm that the LoS is good thanks to the status LED on these Google devices. Then, they notify, using the walkie-talkie, that the mesh network is ready.
2. HA1 and HA2 enter tunnel A through its south entrance and connect their smartphones (UE1 and UE2) to the WiFi mesh network, as soon as it is available. They verify with the control center that communications through the VPN are working correctly.
3. HA1 and HA2 go through tunnel A up to the internal door, cross it, and go back through tunnel B to the south entrance of the dual-tunnel, in order to make a first test about throughput. Once they knew the required bandwidth (Mbps), the supervisor requests that they keep transmitting simultaneously, and proceed to enter through tunnel B.

The designed experiment was performed according to the following items, where the most important events are highlighted in Table I.

a) HA1 and HA2 walk up to the internal door through tunnel B, switching the video resolution and streaming it to the control center, where a remote operator reports on video smoothness.
b) Rover J8 is requested once HA1 and HA2 are close to the internal door.
c) Rover J8 moves manually controlled with a joystick in the test ground from the Rover J8's start point to the south entrance of the dual-tunnel (see its trajectory in Fig. 1).
d) Rover J8 arrives at the tunnels' south entrance and enters A.
e) Rover J8 meets the human agents inside tunnel A, and stands 2 meters from the internal door.
f) HA1 and HA2 walk together to the north entrance of tunnel A. The remote supervisor reports about smooth video streaming and decide switching resolution.
g) HAs arrive at the north entrance of tunnel A. Then, HA2 moves to tunnel B through the north entrances, while HA1 stands at the north entrance of tunnel A. At this point, both HA begin to detect certain latency problems.
h) Rover J8 is required to advance to a position near the north entrance of tunnel A to improve the HAs' cover, while HA1 and HA2 move randomly between the second section (from the internal door to the north entrance) of both tunnels.
i) Rover J8 and the human operators get back to the south entrance of tunnel A, along this tunnel. This part of the exercise can be seen in the sequence of frames in Fig.3.

## IV. RESULTS AND DISCUSSION

This section first describes the actual development of the exercise. Then, we analyze key performance indicators, and finally we offer a discussion of lessons learned.

### *IV-A. Development of the exercise*

The exercise lasted approximately 21 minutes, excluding networks and agents deploy, i.e., from the moment the HAs enter tunnel B (at 13:34:49, local time) to the moment Rover J8 exits tunnel A (at 13:54:58). A detailed event log for the experiment is presented in Table I.

### *IV-B. Key performance indicators*

This SAR exercise aimed to measure four KPIs to compare the behavior inside an underground tunnel of our WiFi mesh network against a commercial 5G network, including packets transmitted, packets received, RTT, i.e., latency, and throughput. At the same time, two smartphones carried by two HAs streamed video at different resolutions to a remote control center.

These KPIs were measured for UE1 and UE2, as well as for the CPE on-board Rover J8. All relevant events in terms of performance are highlighted in Fig. 4, 5, and 6) with a vertical dashed line.

### *IV-C. Discussion*

From the analysis of the event log, and the latency figures, some results can be highlighted (see Table II):

- Latency raised in UE1 and UE2 as the human operators moved along the tunnels, reaching an average value of 457.46 and 334.07 ms for RTT during the time they

TABLE I: Event log for the exercise considering agents inside the tunnels: HA1, HA2, and Rover J8.

| Time | Device | Highlighted events during the course of the experiment's items |
|---|---|---|
| 13:34:49 | UE1 | HA1 sets a resolution of 640x360, and walks along tunnel B close to the inner wall of the dual-tunnel, followed by HA2. For $2'17''$, UE1 moves up to it reaches the internal door, crosses it and looks back to the south entrance. |
| | UE2 | HA2 sets a resolution of 352x288 for UE2, and walks following HA1. Then, he also cross the internal door to tunnel A and points with his camera to the south entrance of tunnel A. |
| 13:37:06-13:39:44 | CPE | The scout-UGV arrives to the dual-tunnel and enters the tunnel A. |
| | UE1 | HA1 stands next to the wrecked vehicle (embedded in the wall), to make way for Rover J8. A latency peak can be seen in Fig. 4 and 5 (central area of blue period), due to this. |
| | UE2 | HA2 stands under the internal door's frame, losing LoS with respect to any node of the mesh network. He does this, to let the Rover J8 through. A latency peak can be seen in Fig. 4 and 5 due to the agent hiding behind the vehicle. |
| 13:39:40 | CPE | The scout-UGV completes its first movement since entering tunnel A. At this point, it stops, two meters from the internal door. This position was considered adequate to cover the rest of the tunnel, where UEs have worst KPIs, considering only the static relay nodes. |
| | UE1 | HA1 starts walking from the internal door to the north entrance of tunnel A. He walked $26''$ towards the end of the tunnel A, while showing with his smartphone camera the robot standing in the middle of the tunnel A. The video smoothness is goot at the control center, before changing the resolution to a higher one. |
| | UE2 | This operator walks alongside HA1, while transmitting video to the control station, showing HA1 (moving) and Rover J8, which remains static in the center of the tunnel. The transmitted video is smoothly viewed at the control center, from where a request is received to increase the resolution by one step before continuing to walk towards the end of the tunnel A. |
| 13:40:06 | UE1 | HA1 changes resolution to 640x480. Rover J8 is in the center of tunnel A providing better KPIs, especially throughput, as the node it carries improves the coverage of the tunnel, specifically in its end. |
| | UE2 | HA2 changes resolution to 640x360. |
| 13:43:22 | UE1 | HA1 reaches the north entrance of tunnel A and moves his UE (which continues to transmit in 640x480 resolution) showing his surroundings, including HA2 |
| | UE2 | HA2 reaches the north entrance of tunnel A, close to HA1, and moves his UE (which continues to transmit in 640x360 resolution) showing his surroundings, including HA1. |
| 13:44:07 | UE1 | HA1 changes resolution to 640x360. |
| | UE2 | HA2 changes resolution to 640x480. |
| 13:49:52 | CPE | The scout-UGV has moved, stuck to the outer wall of tunnel A (west side), and has now stopped 20 metres from the north entrance, where both HAs are. However, HAs have been moving through tunnel B. |
| | UE1 | HA1 is showing how Rover J8 stops after advancing a few meters from the internal door, to improve the coverage of both UEs, while they stay at the north entrance of tunnel A, transmitting video at the highest possible resolution (he tests 640x640) but the execise supervisor request to reduce the throughput since the bandwidth does not seem to support that resolution, along with what the other agent was already transmitting. HA1 quickly establishes the above resolution (640x480). |
| | UE2 | HA2 is in tunnel B now, having exited tunnel A through its north entrance, and is now transmitting video to the control station from the north entrance of tunnel B without Los to the Rover J8's node. The video flow is not as smooth, but it is correctly maintained without too many cuts, thanks to the existing node at the beginning of this tunnel. However, because the partner raised its resolution as well, the joint throughput was not well supported by the mesh network. |
| 13:50:01 | UE1 | HA1 moves away from the scout-UGV and goes outside through the north entrance of tunnel A. Subsequently, it passes to the parallel tunnel (B), where HA2 is already located. HA1 approaches HA2 to check together if the video resolution configured is being well received at the control center, after the preliminary issues. |
| | UE2 | HA2 remains 15 meters away from the north entrance of tunnel B, transmitting video. He waits for the arrival of HA1 to check the resolutions and set up a new one. It is time to decide if it is possible to go up one more step, or if it is advisable to go down one more step. |
| 13:50:20 | UE1 | HA1 changes resolution from 640x480 to 352x288, and maintains it until the end of the experiment. |
| | UE2 | HA2 changes resolution from 640x480 to 640x360, and maintains it until the end of the experiment, as the engineer at the control center comments that the bandwidth in the dual-tunnel seems to be exceeded by the data rate generated by the HAs. |
| 13:52:50 (see Figure 3) | CPE | Rover J8 starts its movement from the north entrance of tunnel A towards the south entrance of same tunnel. It will complete its journey in $2'10''$ (from 13:52:50 until 13:55:00), having HAs behind it from the middle of the tunnel, escorting them to leave tunnel A by its south entrance. |
| | UE1 | HA1 starts walking from the internal door of the dual-tunnel, following Rover J8 to leave tunnel A, while streaming video. |
| | UE2 | HA2 starts walking from the internal door of the dual-tunnel, following the scout-UGB to leave tunnel A, while streaming video. |
| 13:54:00 (see Figure 3) | CPE | Rover J8 has approximately 46 metres to go to the south entrance of tunnel A (it is just between the internal door and the south entrance). |
| | UE1 | Ha1 is close to the internal door but attached to the outer wall of tunnel A. |
| | UE2 | HA2 is just at the central door, also walking throughout tunnel A. |
| 13:54:45 (see Figure 3) | UE1 | HA1 remains attached to the inner wall of tunnel A. He stays behind the Rover J8's operator, for safety reasons, at a distance of approximately 10 metres from the scout-UGV. |
| | UE2 | HA2 remains attached to the outer wall of tunnel A. This agent stays behind the Rover J8's operator, for safety reasons, at a distance of approximately 14 metres from the robot. |
| 13:54:58 (see Figure 3) | CPE | Rover J8 leaves the dual-tunnel. |
| | UE1 | HA1 stands at the south entrance showing the remote control center how the Rover J8 is leaving the site through the gully. |
| | UE2 | HA2 stands at the south tunnel entrance showing the remote control center how the scout-UGV is leaving the site through the gully. |

were on north entrance, and without Rover J8. However, RTT had an average of around 186 ms for the rest of the experiment, which can be practical for many applications.

- Video streaming was received on the control center at the different resolutions tested. Reception was smooth, except when HAs were at the end of tunnel A or B, transmitting at resolution 640x480, and Rover J8 was still in the central position of tunnel A.
- Latency was high for the CPE onboard Rover J8 for the whole experiment, with latency values well over seconds.
- Latency improved for both UE1 and UE2 when Rover J8 entered the tunnel, due to the mobile mesh node.
- Mesh network nodes made use of a 5 V, 3 A wireless battery, which enabled a very efficient deployment. They supplied the mesh nodes for the preparation and execution of the exercise (1 hour), without any problem.

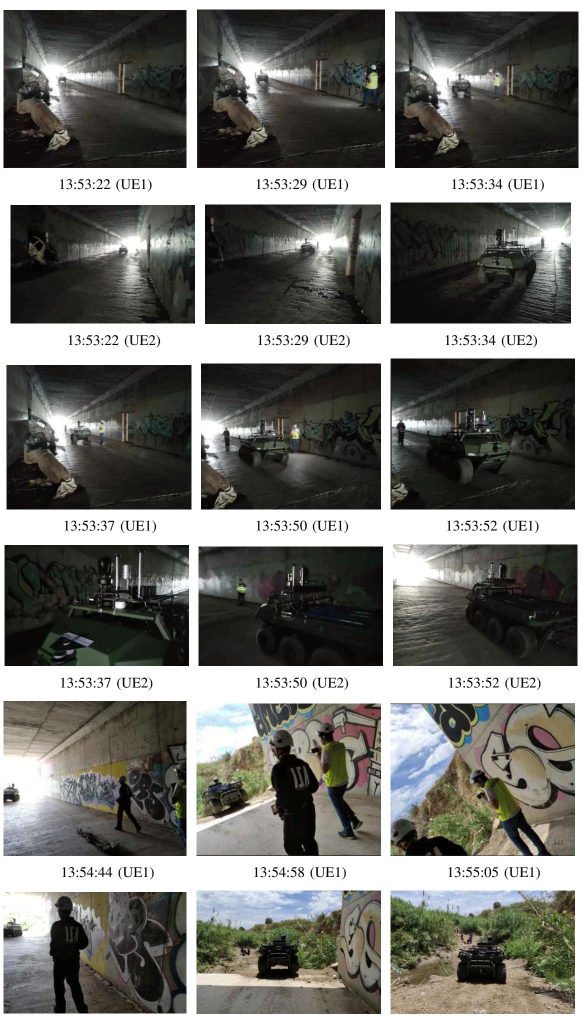


Fig. 3: Sequence of frames received at the control center from each UE during the Rover J8 tunnel exit path.

## V. Conclusions

This paper presents a field experiment report on a search and rescue (SAR) exercise. The experiment involved testing a WiFi mesh network against a commercial 5G in 184-meter-long tunnels. Two human agents (HAs) streamed video to the Internet through the mesh. The configuration of the presented mesh is novel as the extension of the network is done with two unmanned ground vehicles (UGVs) with different roles: a repeater-UGV, with good coverage, which carries the mesh master node, and a scout-UGV, which explores the area until it reaches the tunnel, providing coverage to the users inside the tunnel. Thus, the network is deployed from an outdoor area to an indoor area, thanks to the mobile relay node on-board the scout-UGV, getting the repeater-UGV to maintain LoS with the scout-UGV.

Results show that this configuration is helpful to improve the key performance indicators (KPIs) of the static mesh network and provides coverage with the ability to stream video from two HAs in disaster area where the 5G network is not functional, which was demonstrated by introducing a 5G CPE on-board the scout-UGV into the tunnel. Video at 640x480 resolution has been transmitted smoothly to a remote control station, and the mesh network achieved latency of less than 200 ms throughout the dual-tunnel. Thus, the WiFi mesh network opens up possibilities for future remote tele-operation of the UGV, allowing visualization of streaming video from its cameras via the Internet.

Future research will focus on optimizing the mesh network's efficiency inside tunnels, considering different network configurations to achieve higher bandwidth. Multilateration algorithms will be incorporated to utilize FTM technology, aiding in estimating relative distance between all mesh nodes, from the outdoor position of the repeater-UGV to the interior positions of the other mesh nodes. The study could also analyze techniques for autonomous UGV navigation indoors, providing coverage and Internet access to underground users, merging FTM and UWB technologies to detect and locate potential victims indoors and outdoors.

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## References

[1] T. Rouček, M. Pecka, P. Čížek, T. Petříček, J. Bayer, V. Šalanský, D. Heřt, M. Petrlík, T. Báča, V. Spurný, F. Pomerleau, V. Kubelka, J. Faigl, K. Zimmermann, M. Saska, T. Svoboda, and T. Krajník, "DARPA Subterranean Challenge: Multi-robotic Exploration of Underground Environments," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 11995 LNCS, pp. 274–290, 2020.

[2] R. R. Murphy, J. Kravitz, S. L. Stover, and R. Shoureshi, "Mobile robots in mine rescue and recovery," *IEEE Robotics and Automation Magazine*, vol. 16, no. 2, pp. 91–103, 2009.

[3] J. Zhao, J. Gao, F. Zhao, and Y. Liu, "A Search-and-Rescue Robot System for Remotely Sensing the Underground Coal Mine Environment," *Sensors*, vol. 17, no. 10, p. 2426, oct 2017.

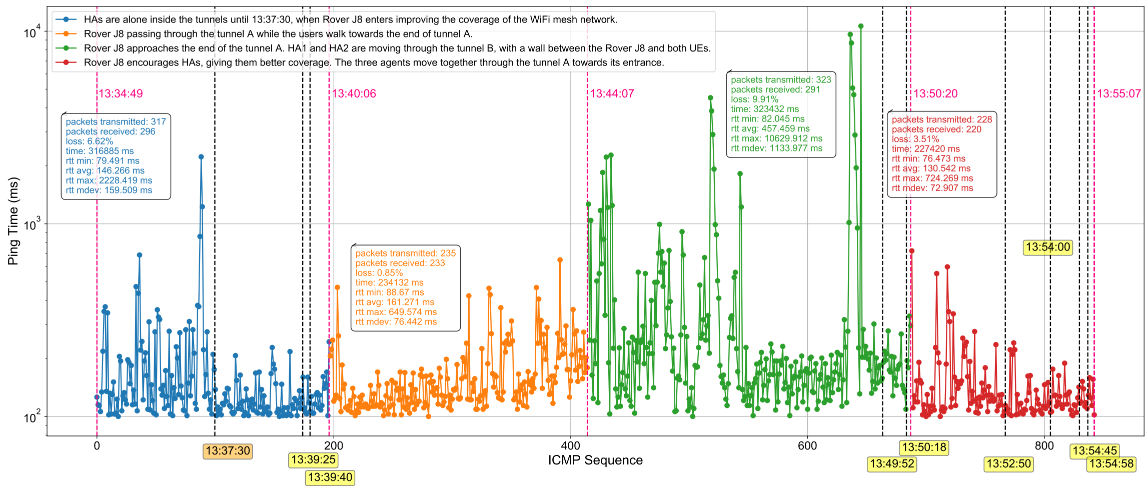


Fig. 4: latency (ms) from control center to the UE1

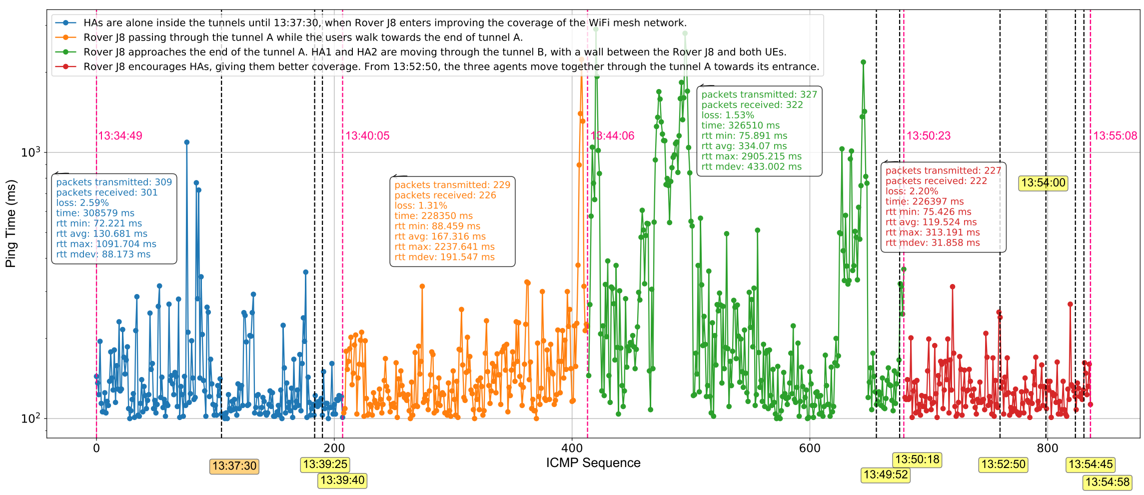


Fig. 5: latency (ms) from control center to the UE2

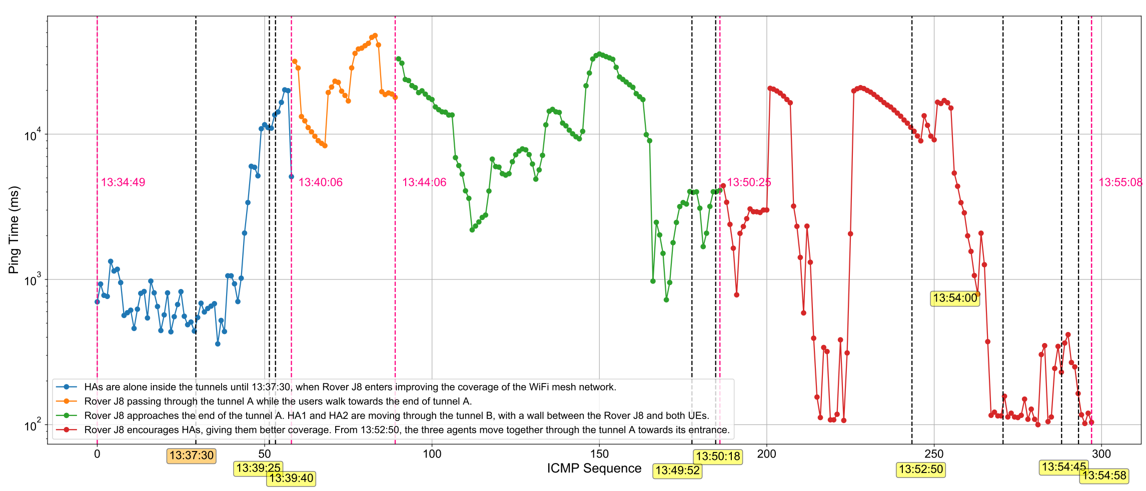


Fig. 6: latency (ms) from control center to the Rover J8's CPE

TABLE II: Information from the latency tests

| UE | Period (hh:mm:ss) | Packets Transmitted | Packets Received | Packet Loss ( %) | Time (ms) | RTT Min (ms) | RTT Avg (ms) | RTT Max (ms) | RTT Mdev (ms) |
|---|---|---|---|---|---|---|---|---|---|
| smartphone 1 | 13:34:49-13:40:06 | 317 | 296 | 6.62 | 316885 | 79.49 | 146.26 | 2228.41 | 159.51 |
| | 13:37:30-13:44:07 | 235 | 233 | 0.85 | 234132 | 88.67 | 161.27 | 649.57 | 76.44 |
| | 13:44:07-13:50:20 | 323 | 291 | 9.90 | 323432 | 82.04 | 457.46 | 10629.91 | 1133.97 |
| | 13:50:20-13:55:07 | 228 | 220 | 3.51 | 227420 | 76.47 | 130.54 | 724.27 | 72.90 |
| smartphone 2 | 13:34:56-13:40:05 | 309 | 301 | 2.58 | 308579 | 72.22 | 130.68 | 1091.70 | 88.17 |
| | 13:40:05-13:44:06 | 229 | 226 | 1.31 | 228350 | 88.46 | 167.32 | 2237.64 | 191.54 |
| | 13:44:06-13:50:23 | 327 | 322 | 1.52 | 326510 | 75.89 | 334.07 | 2905.21 | 433.00 |
| | 13:50:23-13:55:08 | 227 | 222 | 2.20 | 226397 | 75.42 | 119.52 | 313.19 | 31.86 |
| Rover J8's CPE | 13:37:30-13:40:06 | 154 | 59 | 61.68 | 155015 | 360.14 | 3187.94 | 20182.63 | 5085.17 |
| | 13:40:06-13:44:06 | 221 | 31 | 85.97 | 224104 | 8329.17 | 23836.36 | 47741.68 | 11949.57 |
| | 13:44:06-13:50:25 | 324 | 97 | 70.06 | 328106 | 721.26 | 12164.28 | 35629.51 | 9827.40 |
| | 13:50:25-13:55:08 | 214 | 147 | 31.30 | 215185 | 69.09 | 4583.79 | 20894.63 | 6873.22 |


[4] F. Arzberger, J. Zevering, A. Bredenbeck, D. Borrmann, and A. Nuchter, "Mobile 3D scanning and mapping for freely rotating and vertically descended lidar," *SSRR 2022 - IEEE International Symposium on Safety, Security, and Rescue Robotics*, pp. 122–129, 2022.

[5] M. Leingartner, J. Maurer, A. Ferrein, and G. Steinbauer, "Evaluation of sensors and mapping approaches for disasters in tunnels," *Journal of Field Robotics*, vol. 33, pp. 1037–1057, 12 2016.

[6] W. Wang, W. Dong, Y. Su, D. Wu, and Z. Du, "Development of Search-and-rescue Robots for Underground Coal Mine Applications," *Journal of Field Robotics*, vol. 31, no. 3, pp. 386–407, may 2014.

[7] G. J. M. Kruijff, F. Pirri, M. Gianni, P. Papadakis, M. Pizzoli, A. Sinha, V. Tretyakov, T. Linder, E. Pianese, S. Corrao, F. Priori, S. Febrini, and S. Angeletti, "Rescue robots at earthquake-hit mirandola, italy: A field report," *2012 IEEE International Symposium on Safety, Security, and Rescue Robotics, SSRR 2012*, 2012.

[8] T. Linder, V. Tretyakov, S. Blumenthal, P. Molitor, D. Holz, R. Murphy, S. Tadokoro, and H. Surmann, "Rescue robots at the collapse of the municipal archive of cologne city: A field report," *8th IEEE International Workshop on Safety, Security, and Rescue Robotics, SSRR-2010*, 2010.

[9] H. Tian and W. Yang, "Research on emergency rescue communication and exploration system underground," *Proceedings of 2011 IEEE International Conference on Service Operations, Logistics and Informatics, SOLI 2011*, pp. 443–446, 2011.

[10] W. Tang, C. Xue, C. Li, and Q. Zhu, "Towards coordinated multi-robot exploration under bandwidth-constrained conditions," in *IEEE International Symposium on Safety, Security, and Rescue Robotics*, 2022, pp. 180 – 187.

[11] J. Gu, P. Xue, S. Lin, and G. Zhang, "Architecture for Disaster Relief Networks in Underground Coal Mines: A Survey."

[12] J. Jensen and S. Thompson, "The Incident Command System: a literature review," *Disasters*, vol. 40, no. 1, pp. 158–182, jan 2016.

[13] M. Malešič, "Disaster response from a comparative perspective," *International Journal of Disaster Risk Reduction*, vol. 48, p. 101621, sep 2020.

[14] J. Bravo-Arrabal, P. Zambrana, J. Fernández-Lozano, J. Gomez-Ruiz, J. Serón, and A. García-Cerezo, "Realistic deployment of hybrid wireless sensor networks based on zigbee and lora for search and rescue applications," *IEEE Access*, 2022.

[15] Y. S. Dohare, T. Maity, P. S. Das, and P. S. Paul, "Wireless Communication and Environment Monitoring in Underground Coal Mines – Review," *IETE Technical Review*, vol. 32, no. 2, pp. 140–150, 2015.

[16] J. Bravo-Arrabal, M. Toscano-Moreno, J. Fernandez-Lozano, A. Mandow, J. A. Gomez-Ruiz, and A. García-Cerezo, "The internet of cooperative agents architecture (X-IoCA) for robots, hybrid sensor networks, and MEC centers in complex environments: A search and rescue case study," *Sensors*, vol. 21, no. 23, p. 7843, 2021.

[17] A. Botta, J. Cacace, R. De Vivo, B. Siciliano, and G. Ventre, "Networking for cloud robotics: The DewROS platform and its application," *Journal of Sensor and Actuator Networks*, vol. 10, no. 2, p. 34, 2021.

[18] A. Jiménez-González, J. R. Martinez-De Dios, and A. Ollero, "Testbeds for ubiquitous robotics: A survey," *Robotics and Autonomous Systems*, vol. 61, no. 12, pp. 1487 – 1501, 2013.

[19] R. El Hattachi and J. Erfanian, "Ngmn 5G white paper," *NGMN Alliance, February*, 2015.

[20] E. Feo-Flushing, L. M. Gambardella, and G. A. Di Caro, "On using mobile robotic relays for adaptive communication in search and rescue missions," in *International Symposium on Safety, Security and Rescue Robotics*, 2016, pp. 370 – 377.

[21] A. Yarali, B. Ahsant, and S. Rahman, "Wireless mesh networking: A key solution for emergency  rural applications," *Proceedings - 2009 2nd International Conference on Advances in Mesh Networks, MESH 2009*, pp. 143–149, 2009.

[22] D. Benyamina, A. Hafid, and M. Gendreau, "Wireless mesh networks design - A survey," *IEEE Communications Surveys and Tutorials*, vol. 14, no. 2, pp. 299–310, 2012.

[23] C. A. Socarrás Bertiz, J. J. Fernández Lozano, J. A. Gomez-Ruiz, and A. García-Cerezo, "Integration of a mobile node into a hybrid wireless sensor network for urban environments," *Sensors*, vol. 19, no. 1, p. 215, 2019.

[24] J. Bravo-Arrabal, J. Fernandez-Lozano, J. Serón, J. A. Gomez-Ruiz, and A. García-Cerezo, "Development and implementation of a hybrid wireless sensor network of low power and long range for urban environments," *Sensors*, vol. 21, no. 2, p. 567, 2021.

[25] M. I. Hussain, N. Ahmed, M. Z. I. Ahmed, and N. Sarma, "Qos provisioning in wireless mesh networks: A survey," *Wireless Personal Communications*, vol. 122, pp. 157–195, 1 2022.

[26] M. R. Ghori, T. C. Wan, and G. C. Sodhy, "Bluetooth low energy mesh networks: Survey of communication and security protocols," *Sensors 2020, Vol. 20, Page 3590*, vol. 20, p. 3590, 6 2020.

[27] J. R. Cotrim and J. H. Kleinschmidt, "Lorawan mesh networks: A review and classification of multihop communication," *Sensors 2020, Vol. 20, Page 4273*, vol. 20, p. 4273, 7 2020.

[28] A. Cilfone, L. Davoli, L. Belli, and G. Ferrari, "Wireless mesh networking: An iot-oriented perspective survey on relevant technologies," *Future Internet 2019, Vol. 11, Page 99*, vol. 11, p. 99, 4 2019.

[29] H. Miura, A. Watanabe, S. Suzuki, and M. Okugawa, "Field experiment report for tunnel disaster by investigation system with multiple robots," in *International Symposium on Safety, Security and Rescue Robotics*, 2016, pp. 276 – 277.

[30] C. S. Álvarez Merino, E. J. Khatib, H. Q. Luo-Chen, and R. Barco, "Victim detection and localization in emergencies," *Sensors 2022, Vol. 22, Page 8433*, vol. 22, p. 8433, 11 2022.

[31] Y. Zennir, S. Allou, and J. J. Fernandez-Lozano, "Fault-tolerant path-tracking control with pid controller for 4ws4wd electric vehicles," *Lecture Notes in Electrical Engineering*, vol. 682, pp. 931–945, 2021.

[32] A. Mandow, J. Seron, F. Pastor, and A. Garcia-Cerezo, "Experimental validation of a robotic stretcher for casualty evacuation in a man-made disaster exercise," *2020 IEEE International Symposium on Safety, Security, and Rescue Robotics, SSRR 2020*, pp. 241–245, 11 2020.

[33] M. Toscano-Moreno, A. Mandow, M. A. Martínez, and A. García-Cerezo, "DEM-AIA: Asymmetric inclination-aware trajectory planner for off-road vehicles with digital elevation models," *Engineering Applications of Artificial Intelligence*, vol. 121, 5 2023.