Enhancing 5G-enabled Robots Autonomy by Radio-Aware Semantic Maps

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***Abstract*— Future robotics systems aiming for true autonomy must be robust against dynamic and unstructured environments. The 5th generation (5G) mobile network is expected to provide ubiquitous, reliable and low-latency wireless communications to ground robots, especially in outdoor scenarios. Empowered by 5G, the digital transformation of robotics is emerging, enabled by the cloud-native paradigm and the adoption of edge-computing principles for heavy computational task offloading. However, wireless link quality fluctuates due to multiple aspects such as the topography of the deployment area, the presence of obstacles, robots' movement and the configuration of the serving base stations. This directly impacts not only the connectivity to the robots but also the performance of robot operations, resulting in severe challenges when targeting full robot autonomy. To address such challenges, in this paper, we propose a framework to build a semantic map based on radio quality. By means of our proposed approach, mobile robots can gain knowledge on up-to-date radio context map information of the surrounding environment, hence enabling reliable and efficient robotics operations.**

I. INTRODUCTION

Indoor mobile robots are traditionally controlled by means of local wireless networks (WLAN), e.g., WiFi, Bluetooth. Nevertheless, in outdoor scenarios, the WLAN connectivity is not always available, and requires the setup of costly ad-hoc networks to ensure connectivity. In such scenarios, mobile networks can be exploited to connect the robots and coordinate their operation tasks thanks to its almost ubiquitous coverage. The adoption of the 5G and 5G-Advanced networks in the robotic domain, especially in outdoor scenarios, is expected to bring significantly decreased deployment and operation costs, improve robot autonomy and their tasks performances, and enable new robotic applications, benefiting from the ultra-high data rate and low latency wireless communications offered by 5G to the ground robots. PPDR (Public Protection Disaster Relief) is one of the examples of the outdoor robotic exploration use cases, where a team of networked robots coordinates to explore an unknown environment collaboratively. Such scenarios require an accurate estimation of the position of a robot and the characteristics of the environment at the same time, i.e., inferring the relative robot location given a map of the environment, while building a map of the environment given a set of measurements taken at subsequent robot locations [1]. Building real-time knowledge from the environment is considered fundamental for the robots to become truly autonomous, as it enables motion, navigation and path planning based on robot localization and other measured environment-related context information, in order to, e.g., avoid obstacles or minimize the energy consumption via the shortest path selection. The environment measurements are traditionally tackled by means of multiple sensors, such as video cameras, lidar, radar, tactile sensors, which are computationally and energy-demanding. Given the limited energy and computing availability on the robots, it will be meaningful to off-load the computation to the edge or cloud computing facilities, where the robots will stream their sensor data to the edge or cloud facilities and retrieve only the result of the related computations, e.g., a 2D/3D map of the surrounding environment [2].

Fig. 1: Robotnik's Summit-XL in outdoor scenario

In mobile network scenarios, the robots performing the exploration task (or any other tasks involving the exploration of an area) would benefit from good radio link propagation conditions, which ensure faster and more resilient upload of the collected sensor information, as well as saving the energy needed for transmitting data in poor channel conditions, or re-transmitting in case of wireless link signal drops. However, in the robotic domain, so far the robots have no direct ways or standards for exploiting radio quality information, neither in navigation and path planning, nor in general decision-making tasks.

In this paper, we propose a framework to build a semantic quality map based on radio quality information of the 5G

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networks at the edge (close to the robots), and provide it to all the robots in the exploration area through ROS (Robot Operating System), hence improving the overall robot cooperative exploration and energy efficiency. The main contributions of this work are summarized as follows:

- Develop a method to collect and process real-time information on the radio link quality of an area, as to generate a radio quality map;
- Build a 2D semantic map for navigation, considering the experienced QoS for the robot applications
- Develop a ROS package to generate and collect radio signal information depending on the real-time robot position. We make it publicly accessible to foster research on related topics. [1]
- Design and implement a ROS-based simulation environment, providing an in-depth evaluation of our proposed framework.

The remainder of the paper is structured as follows. Sec. II summarizes related works in the field. Sec. III introduces the main problem addressed throughout this article. Sec. IV describes the main architectural components and functionalities of the proposed solution, detailing a pipeline process for translating the quality of signal metrics into semantic data that can be used by robots. Sec. V showcases the proposed framework and discusses the main benefits. Finally, Sec. VI concludes this paper.

II. RELATED WORKS

The combination of cloud-connected intelligence and robotics offers global libraries on knowledge sharing and enables augmented human–robot interactions as part of robotic services. In this context, however, the wireless radio quality heavily affects remote robot operation, which demands for non-line of sight (NLOS) communication to fully exploit the robot capabilities in deployment scenarios, e.g., autonomous exploration and monitoring. In this context, 5G mobile networks can support the development of new robotic services, by providing semi-ubiquitous low-latency communication and high bandwidth availability. The quality of a radio channel can be affected by a variety of factors, including the distance between the sender and the receiver, the presence of obstacles, the type of radio frequency being used, and interference. These and similar aspects have been carefully investigated in the literature. For example, in [3] the authors propose to combine the orchestration logic from the network infrastructure and the robot domains, addressing the problem from an optimization perspective and proposing an architectural framework to achieve the overall solution. Similarly to our proposed architecture, the authors of [4] propose a multi-provider platform targeting 5G-enabled drone services supported by a 5G standalone mobile infrastructure, to optimize the navigation of drones over optimally covered areas. The potential of robotic autonomous operations by utilizing the cloud's massive computation power and global knowledge can be enhanced by shifting part of the cognitive capabilities from robots to the cloud. Many works have been delivered in this field, such as [5]and [6], taken from EU projects like RoboEarth[2] and KnowRob [3], respectively. In [7] the authors address the motion energy minimization problem subject to quality of service (QoS) constraints in mm-Wave communication scenarios. The proposed algorithm uses intelligent reflective surface (IRS) and radio map to avoid obstacles and poorly covered areas, assuming the whole processing is performed at the edge of the network. Computation offloading is a promising solution to extend the capacity of robots in computation-intensive applications. In [8], the authors propose a multi-robot coordination scheme exploiting multi-hop communication to enhance connectivity in intermittent connectivity scenarios.

Nevertheless, none of the above works considered radio quality map information nor how to embed this into a semantic map for robot tasks planning, nor disclose methods to effectively build and transfer to the robots such information.

III. PROBLEM STATEMENT

Robot communication must be robust over unstructured and dynamic environments. Given the effort in building knowledge about an unknown environment, it is essential to enhance coordination and collaboration among the robots by sharing the information learned by each robot with others in the same exploration area to improve their context awareness, e.g., detected obstacles or objects. This would allow robots to save time and resources by avoiding cold-start exploration tasks and, at the same time, collect a more comprehensive (aggregated) environment map exploiting historical information, as well as the information of radio quality, and environment context data explored by multiple robots in the area. More importantly, unaware robots may travel to an uncovered area, and lose connectivity towards their controlling entity and/or computing platform [9], significantly affecting their operations. Therefore, autonomous robots should be able to learn about the surrounding environment and adapt their operation tasks according to the context environment. The adoption of a semantic map can support such a process, potentially improving fault detection, monitoring, localization and path planning during search and rescue operations, hence reducing the overall task completion time and energy costs.

In recent years, mobile robots have gained a significant level of autonomy due to advancements in localization, mapping, and navigation algorithms. However, these algorithms often require high computational power and processing time, which can limit the robot's autonomy in real-world applications. Offloading these processes to external servers can increase the robot's autonomy, as it can reduce the computational load on the robot's onboard processor and allow for faster processing times. Therefore, to achieve efficient offloading of robotics based applications to edge/cloud

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[1] Online available: https://github.com/5G-ERA/RadioQualityMap

[2] RoboEarth Accessed on February 2023, Online Available at http://roboearth.ethz.ch/

[3] KnowRob Accessed on February 2023, Online Available at http://knowrob.org/

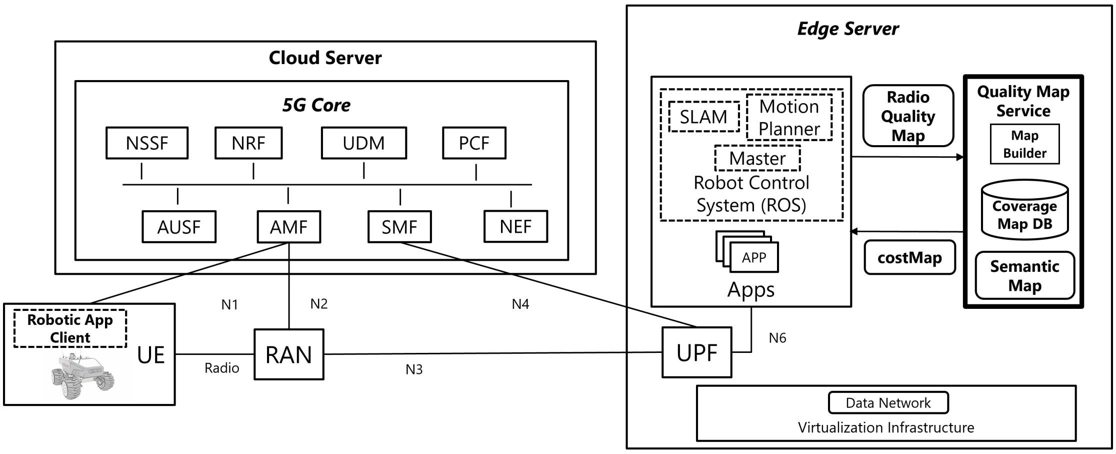

Fig. 2: Architecture overview.

platforms, there must be some guarantee of a good and stable connectivity or a plan to maintain such a desired metrics. In this context, it clearly appears that Quality of Service (QoS) metric is becoming of key importance in robotics, and that it should be considered during the navigation and planning phase. Open-source robotic software generally does not consider or lacks Quality of Service (QoS) considerations, assuming ubiquitous and constant networking connectivity. For example, the ROS framework started to consider QoS metrics only along the ROS 2 release, still neglecting the presence of mobile network transport protocol and infrastructures. Therefore, in this paper, we advocate for the adoption of 5G radio quality signal maps, which indicate the 5G link QoS, and then translate them into a semantic map, which indicates the expected QoS by the robotic applications, for performing path planning and robot navigation tasks, as a way to improve robot autonomy in 5G-enabled scenarios.

We evaluate the potential benefits derived from this approach by setting up a preliminary test [4], comparing the CPU consumption of a mobile robot when allowed to offload computing tasks through a 5G link, and when such an option is not available. Fig. 3 depicts several hardware metrics, including CPU consumption, current, and battery charge level, taken from a Robotnik's RB1-Base mobile robot.[5]. In the considered scenario, the RB1-Base robot autonomously navigates in a static and indoor environment. Within this time, the robot i) processes on board all the ROS-related tasks necessary for navigation and sensing, or ii) offloads such processing to a nearby computing platform, switching on/off the corresponding ROS nodes every 5 minutes. From the plot, it can be noticed that the average CPU utilization reduces from $\approx 90\%$ to $\approx 60\%$ when offloading to the edge platform, even in this simple scenario. In turn, this fact positively influences the battery and current consumption, finally

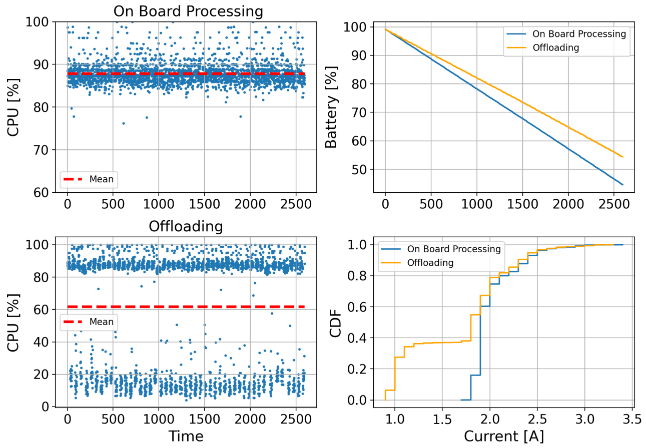

Fig. 3: Comparison of robot metrics in presence and absence of offloading capabilities.

extending the operational time of the robot. This motivates our work, highlighting once again how radio channel quality is fundamental to enable task offloading from the robots to edge/cloud platforms, bringing significant benefits to robotic use-cases.

IV. THE 5GERA APPROACH

In Fig. 2 we depict the reference high-level system architecture, which comprises a 5G network and an edge platform (based, e.g., on the ETSI MEC [10]), as well as a robotic application managing 5G-enabled robots and their respective functionalities (Sensing, navigation, etc.). The 5G network includes data plane elements, i.e., User Plane Functions (UPFs), as well as control plane functionalities such as routing, authentication and mobility management by means of standardized entities such as Session Management Function (SMF), Authentication Server Function (AUSF) and Access and Mobility Management Function (AMF). The robot applications are deployed as virtual/container-based images at the edge/cloud platform premises. By running these applications at the edge of the 5G network, we ensure low latency (due to proximity), high bandwidth, and assessment of up-to-date location and radio network information. Connectivity

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[4] The data collection has been performed by Robotnik Automation and Fondazione Bruno Kessler (FBK), in the context of Decentralised technologies for orchestrated Cloud-to-Edge Intelligence (DECENTER) EU Horizon 2020 project (grant agreement no. 815141)

[5] RB1-Base mobile robot, Online Available `https://robotnik.eu/es/productos/robots-moviles/rb-1-base/`

between the User Equipments (UEs) i.e., the robots, and its control logic, i.e., remote operator or control system in ROS, is provided by the 5G network data plane exploiting a dedicated UPF deployed within the edge platform premises, which acts as Protocol Data Unit (PDU) session end-point for the mobile tunneling protocol (GTP protocol).

A. Build and implementation of 5G Radio Quality Map

The 5G radio quality map is computed by means of mobile network-based information, as well as other possibly available sensor data provided by the robot applications running within the edge platform. Accurate monitoring of the wireless channel quality is crucial in mobile network environments, as to adapt radio signal characteristics to the available settings. From a wireless communication perspective, upon primary synchronization, the UEs perform physical layer measurements and feedback on their output to the serving base station. Such information is used both at Layer 1 (Physical - PHY) to cope with fast-fading wireless channel variations, at Layer 2 (Medium Access Control - MAC) to decide resource allocation and scheduling and at Layer 3 (Radio Resource Control - RRC) to take decisions on, e.g., handover and/or cell reselection. In the context of this work, we will focus on the latter aspect, as it represents the most meaningful information for robot controllers and applications. In particular, the Reference Signal Received Power ($RSRP$) in 5G New Radio (5GNR) provides a cell-specific metric that allows UEs to rank the power coming from multiple nearby base stations. It is defined as the linear average over the power contributions (in Watt) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. However, multiple base stations deployed in the same area and/or additional UEs may cause communication interference. To consider this aspect, the Reference Signal Received Quality ($RSRQ$) can be defined as [11]

$$RSRQ = N_{prb} \frac{RSRP}{RSSI}, \tag{1}$$

where N_{prb} indicates the number of resource blocks (RBs) over the measured bandwidth, and $RSSI$ is the Received Signal Strength Indicator, which can be defined as total power obtained by the UE on the entire frequency band, including the power of main signals, co-channel non-serving signals, adjacent-channel interference, and thermal noise on the specified frequency band. In this sense, the RSRQ provides information about interference and desired signal strength and will be considered as the key radio quality metric in the following of this paper. Such information is collected from the robots, and shared by means of ROS topics towards the edge platform, as later detailed in Sec.V.

B. Translating Radio Quality Map into a Semantic map

Fig. 4 illustrates the designed pipeline for building a Semantic Map from the 5G radio quality map. The RSRQ metrics indicating the measured radio quality reported from the robots will be continuously collected and stored in a Map Database, and processed to build the radio quality map. Such information together with additional ROS topics and statistics reflecting the QoS metrics, e.g., latency, packet loss, and throughput etc., can be extracted and processed as input of building the Semantic Map following an RGB semantic schema. The translation from the 5G radio quality map to the semantic map can be achieved in mutiple ways, depending on the key performance metrics and required QoSs of the robot's operational tasks. For example, the semantic map can be presented as a matrix of the probability of achieved robot task performance such as latency, data streaming quality, task failures, achieved reliability. The translation from radio quality map to such semantics can be done, for instance, by means of classification or profiling of these achieved performances, which may adopt machine learning approaches or prediction frameworks. Optionally, the QoS requirements specific to the target robotic application can be used to characterize the system behavior and configurations. In this way, the system can learn about how 5G network quality affects robot performances, enabling a more informed and optimized decision process on how to optimize networking resources and energy [3]. It is also worthy to mention that the instantaneous and punctual robot measurement feedback may be affected by random wireless fluctuations. Therefore, as depicted in Fig. 4, adopting also the historical data stored in the database to further enrich the radio quality map or the semantic map, will make the entire process less prone to erroneous estimations. In the next, the outcome of the semantic will be further exploited as a costmap to perform decisions on the robot operation and navigation tasks. Such an exploitation will be explained in the following Sec. IV-C.

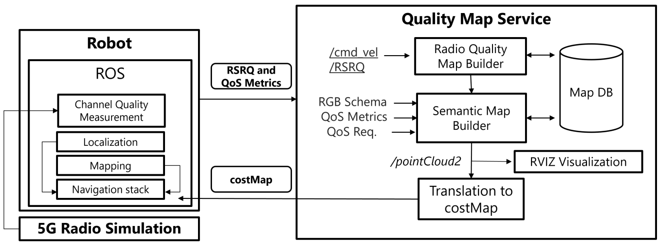

Fig. 4: Pipeline overview.

C. Exploitation of Radio-aware Semantic Map

Robotic navigation is a combination of processes that provide the mobile robot with the ability to establish its own position and orientation within an environment and go from an initial position to a target position, avoiding obstacles when following the safest and optimal path. To enable the robot to move autonomously between given positions, accurate localization, efficient path planning and adequate path tracking are required. *Global maps* are representations of the entire environment and are useful for long-term planning and decision-making, while *local maps* are representations of the immediate surroundings of the robot, and are typically generated in real-time from sensor data as an effective way for obstacle avoidance and short-term planning [13]. The integration of these two maps provides robots with a balance of global understanding and local adaptability. The

TABLE I: RSRP to RSRQ and Semantic Mapping. Adapted from [12]

RSRP	RSRQ	Signal Strength	Semantic Description	RGB Color Mapping
≥ -80 dBm	≥ -10 dB	Excellent	Strong signal for maximum data rates.	Dark green (0,128,0)
-80 to -90 dBm	-10 to -15 dB	Good	Good signal for average data rates.	Light green (124,252,0)
-90 to -100 dBm	-15 to -20 dB	Poor	Marginal data rates with possible communication drops.	Red (255,0,0)
≤ -100 dBm	≤ -20 dB	No signal	Disconnection.	Dark red (128,0,0)

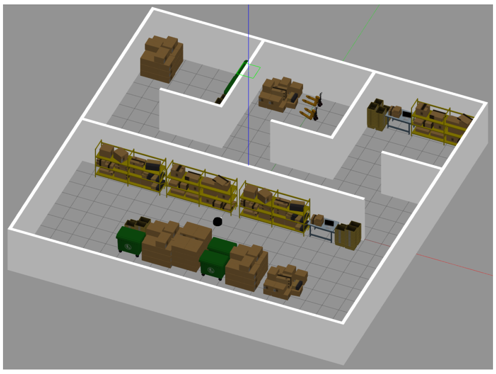

Fig. 5: Simulation environment

path planning accuracy grows with the knowledge of the navigation environment, and more efficient if the obstacles in the environment are static as they can be used as reference points, or *landmarks*, when planning the robot mobility [14]. Robots can use their sensors (i.e. 2D/3D LIDAR, RGB cameras, etc.) to gain knowledge of the surrounding environment, as well as implement localization algorithms to determine the position and orientation in the environment [15]. In this context, the exploitation of a semantic map with the 2D/3D navigation processes can enhance the robot's autonomy by bringing new parameters to the navigation stack, allowing robots to take informed decisions and improving their capability to perceive and navigate, e.g, avoid areas with poor signal quality, therefore resulting in safer offloading capabilities. Costmaps are commonly used to represent the environment around the robot and guide its motion planning [7]. Costmaps assign a cost value to each cell in the map proportional to the traversal difficulty of that cell. Such values are considered by path planning algorithms, e.g., A* Algorithm, Dijkstra, Artificial potential field etc., and as a result, by the whole robot navigation stack. The path planning algorithms use cost functions that combines different inputs/factors into a single metric that is used to evaluate the desirability of different paths. Thus, as depicted in Fig.4, we envision the semantic map information embedded in the robot's navigation stack as a costmap. The costmap obtained by the synchronization of the quality signal map with the 2D/3D navigation can be used to adjust the corresponding algorithms' weights. Such weights are used to adjust the contribution of each factor to the cost function, allowing the robot to prioritize exploration over connectivity depending on the specific task or environment [8], such as avoiding areas with poor 5G signal.

V. PERFORMANCE EVALUATION

In order to evaluate the performances of our proposed approach, we develop a simulation environment using ROS-based software and Gazebo, adopting the Summit XL as mobile robot [6]. The final code and its implementation are made publicly available to foster research on this topic, and favor reproducibility. In particular, we consider an indoor scenario of 20m×20m, as depicted in Fig. 5. We assume the presence of three 5G base stations providing cellular connectivity to a ground robot in the proximity of the exploration area, marked as green circles in the picture. We set the base stations with 20MHz bandwidth, and assume omnidirectional antennas. The transmission power of each base station is fixed to 5 dB to impose average channel conditions and simulate long-distance communication. Nevertheless, the latter represents a tunable parameter that can be modified to address a variety of scenarios. The perimeter and internal walls of the warehouse are set to enforce 15dB and 5dB signal attenuation, respectively [16]. We develop a ROS package to generate and collect radio signal information depending on the robot's position in a generic virtual environment. In particular, without loss of generality, we consider an area $A \times B$ meters, and subdivide it into a grid $\mathcal{G} = \{g_{a,b}, \forall (a,b) \in (A,B)\}$, where A and B are its geometric dimensions expressed in meters, and $g_{a,b}$ are single cell elements which provide the robot with an RSRQ value $RSRQ_{a,b}$ during its operational phase. Such value is obtained by exploiting and extending the work of [17], which allows simulating the SINR and RSRQ values of a parametric mobile network environment, accounting for heterogeneous base station deployments both in terms of number of RAN nodes and their radio configuration, as well as the presence of obstacles, e.g., walls, during the radio signal propagation. Starting from our test scenario, we consider the warehouse scenario depicted in Fig.5, and generate an RSRQ map as depicted in Fig. 6 (left side). From the picture, it can be clearly noticed the impact of walls on the radio channel propagation and perceived quality when compared to the obstacle-free propagation in the outdoor area. Along its exploration task, the robot experiences different $RSRQ_{a,b}$ values, which are collected and transmitted to the edge-deployed Quality Map service. By gathering such information, the service generates a 2D radio quality map, which is converted to a 2D semantic map. In this scenario, we define the semantic as the achievable data rates and link connectivity as relevant QoS metrics for the robot tasks, which are mapped to the radio signal quality. For example, RSRQ values larger than -15dB would allow for good signal and data rates. We adopt the `ros-semantic-mapper` [18] to enforce this policy in the simulation. The resulting 2D map resembles a heatmap with a color schema matching different radio quality values as depicted in Fig. 6 (right-side), while the semantic color schema is summarized in Table I. We adopt `/pointCloud2` topics

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[6] Online available: `https://github.com/RobotnikAutomation/summit_xl_sim`

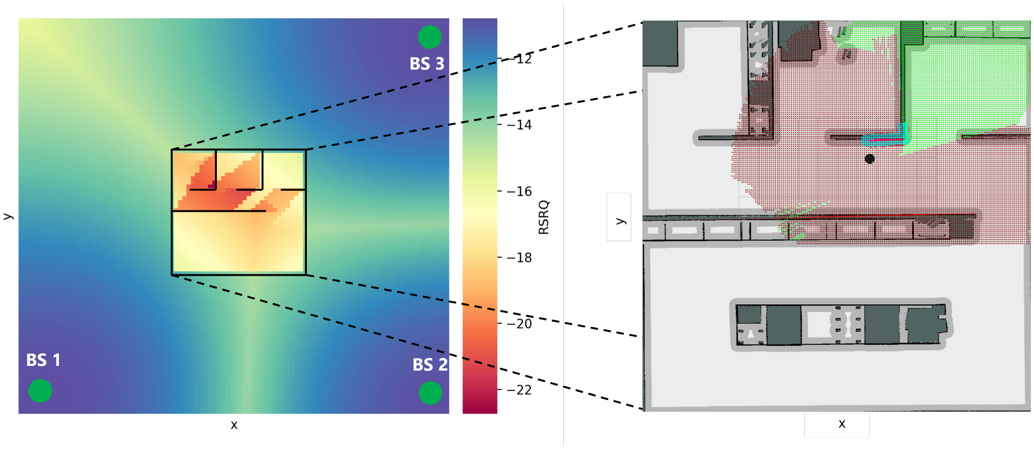

Fig. 6: Radio quality signal map and resulting semantic map.

for RVIZ visualization. From our test scenario, we can see that the top right room is well covered by the Base station number 3, and therefore when exploring that area, the robot reports good channel quality. Conversely, the presence of additional walls in the central room as well as in the corridor affects the signal propagation, limiting the perceived radio quality. Within those areas, marked in red in the picture, the robot should adopt mitigation actions to compensate for the reduced offloading capabilities, e.g., process tasks locally. After exploration or by exploiting historical information from past robot deployments, the semantic map can be consumed by the navigation stack of the robot to infer the best routes along the environment. At the same time, the robot can safely offload computational work to the cloud knowing beforehand, up to certain degrees of reliability, the achievable QoS performances.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we introduced a novel framework to seamlessly build radio quality maps when adopting 5G-enabled robots and mobile network infrastructure, and embedded such information into a semantic map to enhance the autonomy of robotic operations. The proposed approach brings several benefits to the 5G-enabled robotics domain, specifically: i) increased resiliency against 5G coverage issues in mission-critical operations, ii) increased energy efficiency and thus extend the mobility range of robots, and iii) better robot navigation planning by adding the 5G connectivity quality as a key parameter to be considered.

As for future work, we plan to integrate the proposed QoS-aware semantic approach into the ROS navigation stack, as to achieve the complete solution.

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