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Published in:
IEEE 94th Vehicular Technology Conference (VTC2021-Fall)

DOI (link to publication from Publisher):
10.1109/VTC2021-Fall52928.2021.9625208

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Raunholt, T. M., Rodriguez, I., E. Mogensen, P., & Larsen, M. (2021). Towards a 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots. In *IEEE 94th Vehicular Technology Conference (VTC2021-Fall)* Article 9625208 IEEE. https://doi.org/10.1109/VTC2021-Fall52928.2021.9625208

Towards a 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots

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Abstract—**As the use of robots increases in industrial environments, there is a need for enhanced centralized cloud management to improve coordination and planning capabilities. This paper explores the suitability of different 5G schemes for migrating robot intelligence to the cloud by communicating the I/O systems of an AMR with a cloud path planner. The paper includes the analysis of the TCP-based I/O-planner communication and puts it in perspective of 5G mobile edge cloud technology. The observed Mbit/s throughput and statistical uplink/downlink splits of the communication indicate that 5G is a suitable technology to reliably operate the planner. This was further validated by 5G emulation, performing a navigation test and a docking station tests, where the cloud-based system operated over the different 5G configurations achieved a performance and accuracy similar to that from the original on-board local planner.**

I. INTRODUCTION

The integration and coordination of robots within the industrial work space is one of the main trends within the current advances towards Industry 4.0 (I4.0). In current industrial environments, internal transportation of goods is typically dominated by human interactions, either manually or aided by mechanical help, which constitutes a significant cost. It is estimated that 52.1% of the cost associated with warehouse operations is the pay of human labor [1]. In an effort to reduce costs, new innovations have made transportation robots a viable alternative to manual labour. However, this technology requires additional support when deployed to acquire the same efficiency. The needs varies depending on the robot, but common for them all is the need for guidance in finding paths throughout the work environment. Currently, automated guided vehicles (AGV) and autonomous mobile robots (AMR) are the most commonly used robot types. The former uses an implementation of pre-marked paths embedded in the floor or reflective surfaces for location, while the latter uses a pre-generated map and permanent structures to traverse the environment [2].

Currently, AMRs are controlled from centralized fleet manager (FM) entities that allow to allocate specific missions to a given robot by directly configuring its final destination point (or also a route composed of several intermediate points) and the specific actions to be done upon arrival (i.e. rotating to a particular direction or docking to a given station). However, current AMRs determine their exact live navigation path using their local on-board planner and do not share input/output (I/O) and other sensor information with other robots. This can cause a robot to plan through a path that unbeknownst to itself is blocked, even if it has been pre-detected already by other robots. This problem can be mitigated by moving some of the intelligence of each individual robot, e.g. the planner capabilities, to the centralized cloud unit, creating a virtual shared world based on streamed I/O data from all robots, which would allow for optimization of the overall fleet route planning. Further, the cost of each the robots could be reduced, as the necessary on-board computation power will be reduced.

The I/O-planner communication is more demanding than the general AMR-FM one [3]. Thus, in order to ensure a reliable AMR cloud path planning operation, the wireless data transmitted between the robot I/O and the path planner needs to be taken under strict time requirements, as communication delays may result in a significant delay of operations of the robot (and of the overall production in the long run), or in activation of safety systems, in worst case. Therefore, wireless technologies applied to the I/O-based control of mobile robots should allow for ultra-reliable low-latency communication (URLLC). In this paper, we will set the focus on 5G, as its operation over licensed spectrum, improved scheduling mechanisms and mobility handling procedures guarantee a contained quasi-deterministic control-loop latency, better than Wi-Fi [3].

Current works on centralized planning of paths for mobile robots present different visions. Some dismiss the idea, suggesting to keep a local planner as it allows for better scalability and robustness compared to a centralized planner [4]. Others, develop the idea, by proposing algorithms which improves upon optimized task distribution or path generation. This is the case in [5], where a single centralized planner controls multiple robots completing different warehouse-related goals. Despite these works put their focus on communication-related aspects, they do not present any viable explanation, as to which wireless communication technology or necessary communication requirements, are needed to support a reliable performance of their planning solutions. In this respect, [6] shed some light on the throughput requirements to operate a small fleet of custom-built robots. This paper aims at filling this communication-related knowledge gap, by looking into the communication requirements of current commercial industrial robots, and exploring the feasibility of utilizing 5G for providing centralized I/O-based cloud planning. The possibility

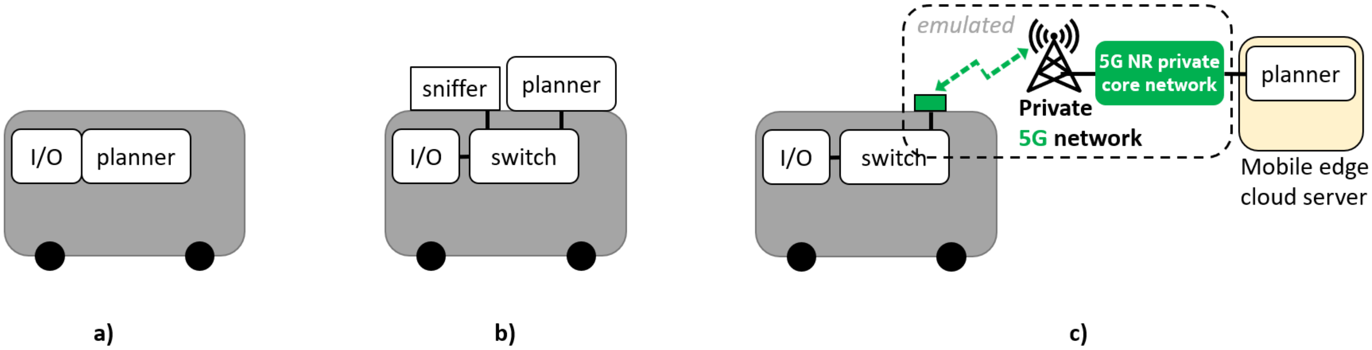

Fig. 1. General AMR planner architectures: a) current on-board planner, b) split planner, and c) 5G mobile edge cloud planner.

of changing the control communication architecture, splitting and migrating the functionalities of the on-board planner to the cloud, is investigated, implemented, and evaluated by emulation of different 5G configurations for two specific situations: overall navigation of the robot and docking to a fixed station.

The content of this paper is structured as follows. Section II presents an overview of the current communication requirements for an on-board internal planner and elaborates on the feasibility of the 5G cloud-based architectural split. Section III describes the different configurations of the emulated 5G implemented in the live testing. Section IV describes the test setups and methodology used to evaluate the effects of the different 5G configurations. In Section V, the results of the tests are presented and discussed. Finally, Section VI presents the conclusions and future works.

II. DATA TRAFFIC ANALYSIS OF THE SPLIT PLANNER

To obtain a comprehensive view of the amount of information that a cloud-planner is expected to handle, the on-board planner from a MiR200 [7] was split into two fully separated functional hardware and software parts: one handling the on-board I/O connections and the other handling the planner processing tasks. This is illustrated in Fig. 1, which depicts the architectures of: a) the current on-board planner, b) the split planner, c) and the envisioned 5G mobile edge cloud planner.

The current robot uses robot operating system (ROS) [8] for internal communication, providing the support for low-level system control and communication between processes on different systems. Such communication works by generating 'publishers', which publish topics, with each topic having a predefined message type to be transmitted. These topics are then received by 'subscribers', which have pre-existing knowledge about the message types and structures. A centralized ROS master is in charge of keeping a lookup table, which is used to determine individual connecting, when new subscribers or publishers connects. ROS uses TCP packets when communicating internally to ensure reliability and quality of service [9]. The planner is uninterruptedly communicating with I/O, to issue the proper location, velocity and heading commands for reliable operation of the AMR.

To determine the current communication pattern of the planner, which we aim at migrating to the cloud, a data traffic analysis was performed locally within the target robot. In order to do that, two subscribers were created on an external device with data traffic logging capabilities (sniffer) to capture data sent and received by the planner. See Fig. 1.b for a reference. The separation of subscriber is due to the fact that transmissions may differ significantly between received (uplink, UL) and transmitted (downlink, DL) from the planner. The sniffer logs all packets being transmitted over the I/O-planner Ethernet interface, and statistics about packets sizes and inter-packet arrival times are computed. No analysis is performed over the information contained in each message, as it can be considered as irrelevant for the purpose of this paper.

During the data traffic measurement collection, the robot was instructed to execute normal operations, which included moving between multiple points with automatic reconfiguration of its path due to dynamic obstacles. The introduction of dynamic obstacles increases the communication exchanges between the I/O and the planner to ensure safe operations of the robot, while also illustrating the upper-bound of the expected data traffic in the cloud planner configuration. The test was run for 5 minutes, resulting in, approximately, 300.000 packets being available for statistical analysis.

The measurements revealed that the average traffic is 458.3 packets/s or 1.3 Mbit/s for UL (between the I/O and the planner) and 476.7 packets/s or 1.9 Mbit/s for DL (between the planner and the I/O). As illustrated in the statistical distributions in Fig. 2, there is a significant number of 64-bytes packages. These are mainly acknowledgment messages from the TCP communication utilized by ROS, and are to be expected. Overall, they constitute 43% of the UL communication. There are other 4 different relevant packet sizes identified in UL: 78-, 158-, 271-, 788- and 1514-bytes, which are responsible for the remaining 3%, 12%, 6%, 17% and 5% of the communication, respectively. For DL 64-bytes packets are also dominant, contributing to 45.3% of the traffic, with the remaining significant communication being based on 4 other different packet sizes: 78-, 148-, 445- and 1514-bytes, which are responsible for 7%, 21%, 3.4% and 7.7% of the downlink communication, respectively.

The CCDF of the packet inter-arrival time is displayed in

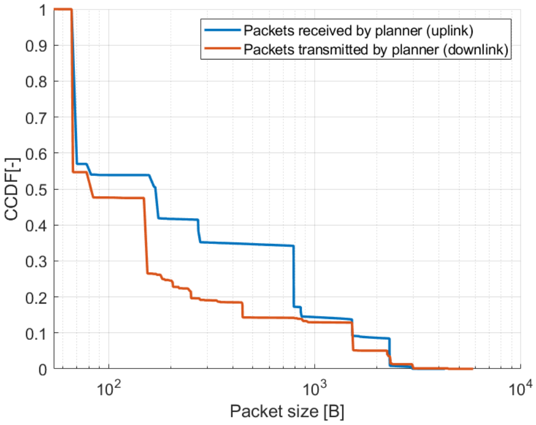

Fig. 2. CCDF of different packet sizes observed in the communication between the I/O and the planner.

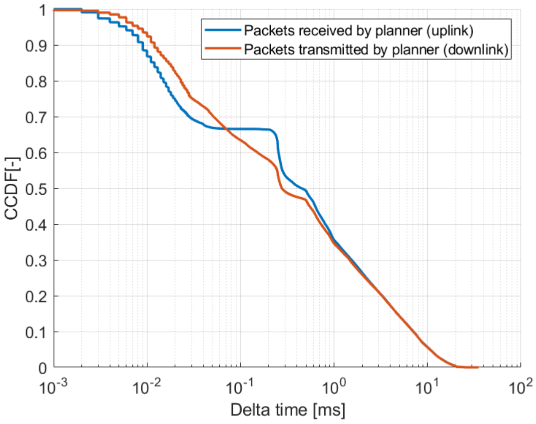

Fig. 3. CCDF of inter-arrival time of packets observed in the communication between the I/O and the planner.

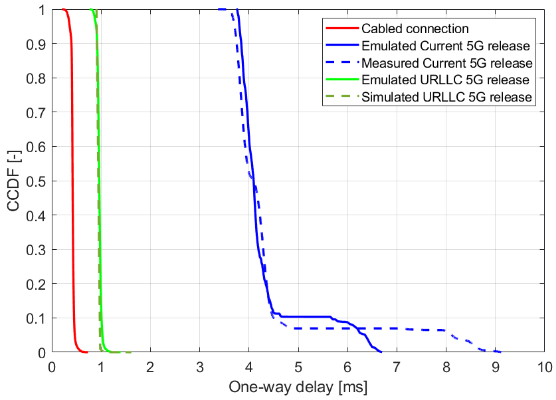

Fig. 4. Reference communication delays and validation of the 5G-emulated delay distributions for the current release and URLLC release. The on-board cabled planner link performance is also plotted as a reference.

Fig. 3, revealing that packets can be transmitted as fast as 0.001 ms for both UL and DL direction. On average, packets are received every 0.445 ms in UL, and 0.277 ms in DL. The maximum separation between consecutive packets was found to be approximately 20 ms.

As a reference, the general AMR-FM communication targeted for mission-control is based on shorter packets of 4-kilobytes in DL (from FM to AMR) and 100-bytes in UL (from AMR to FM), on average, which are received/sent with a frequency of 1 s (average throughput of 32 kbit/s) [10]. Thus, this empirical analysis confirms that the I/O-planner communication is more demanding than the AMR-FM one.

III. 5G MOBILE EDGE CONFIGURATIONS

Wireless connectivity is a key aspect in the development of I4.0. In particular, 5G has a strong potential to support a wide variety of use cases, specially those requiring URLLC and mobility support, as it is the case with the cloud control of AMRs targeted in this paper. As the control-loop latency is required to remain as low as possible, private 5G networks, where the cellular core network is placed next to the radio access are ideal candidates to operate this use case, allowing to have a reliable high-throughput connection between the cloud and the robot, enabling the possibility of migrating some of the control intelligence to the mobile edge cloud (see Fig. 1.c as a reference).

Current initial releases of private 5G are well capable of supporting the Mbit/s traffic flows observed in the previous analysis. There should be no problem in supporting the observed packet size distributions and inter-arrival time distributions [3] - although there is some room for protocol optimization, this will be left out of this study to focus on the performance of the current planner implementation. In order to evaluate the performance of the planner over private 5G mobile edge technology, two 5G configurations are selected:

1) Current 5G release: the AMR is connected to an edge cloud server directly accessible from the private core network through a dedicated 5G channel. The communication latency values are in the order or 4 ms on average, which halves those ones observed in private 4G networks, and are approximately 15 ms better than to those experienced in public networks [3].
2) URLLC 5G release: the AMR is connected over the same network infrastructure reported for the current release, but uses enhanced scheduling access with URLLC support features, specifically designed for the operation of industrial use cases. In this case, latency values are reduced to 1 ms on average, starting to be comparable to those experienced over cabled connections [11].

As a reference, a statistical comparison between the different communication delays expected with the 5G-based cloud configurations as compared with the on-board cabled system is presented in Fig. 4. This plot will be further explained in Section IV.

IV. 5G MOBILE EDGE CLOUD PLANNER TEST SETUP

The initial evaluation of the performance of the split cloud planner over 5G technology is done by the help of a 5G emulator. This emulator is a customized piece of equipment that introduces specific delays to a certain communication link, resembling the performance of an individual 5G connection.

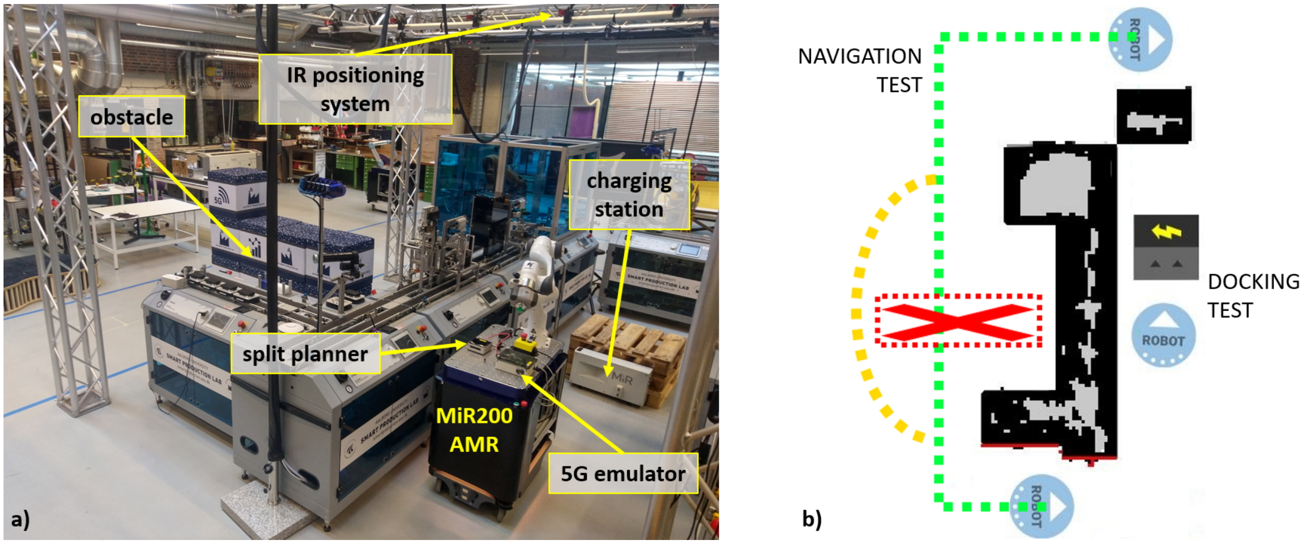

Fig. 5. Overview of the: a) test setup including the AMR, the networking elements, charging station, and other industrial elements, and b) test environment, illustrating the trajectories for the navigation test and the location of the charging docking station for the docking test.

The emulator receives packets which are withheld for a predetermined delay. This delay is obtained from the uniform sampling of a specific delay distribution loaded into the emulator. The emulator was configured with distributions matching the two 5G setups described in Section III (current 5G release and URLLC 5G release). The latency values from the current release were empirically obtained from the measurements in [3], while the ones from the URLLC release were obtained via simulations [11] as no technological implementation was still available for our use. The delay value added to each packet is adjusted in intervals of 100 ms. Ideally, it should be adjusted in a per-packet basis, but this was not possible due to computational limitations. This causes some artificial burst intervals to the latency, but as illustrated in Fig. 4, this has a negligible effect in the long run, as the delay distributions of the emulated 5G configurations are in very good agreement with the original input delay distributions for over 90% of the time. As a further reference, the figure also displays the delay experienced by the on-board planner when operated over a cabled connection. This reference case, presents an average delay of 0.3 ms.

The emulator is placed in-between the I/O and the planner, following the architecture in Fig.1.c, by applying a specific 5G performance to the link. Fig. 5.a presents an overview of the test setup. With this configuration two different AMR performance test were performed:

- Navigation test: the robot is instructed to move between two points as illustrated in Fig. 5.b, where in the absence of an obstacle, the robot will ideally follow the green line between the two points. As the direct path is blocked by the box marked with the red cross, it will force the robot to plan a new path through the open space. The expected alternative path is marked with yellow in the drawing. This test will be repeated 40 times, to generate statistical relevance. The objective of this test is to analyze the overall path navigation execution time for the different 5G configurations and compare it with the baseline cabled planner.
- Docking test: the robot is instructed to execute a docking maneuver to its charging station, located 1 meter in front of it. This test is repeated 15 times for each 5G configuration and compared with the reference cabled planner. The objective of this measurements is to compute the approach accuracy obtained for the different configurations. An OptiTrack IR camera system [12], allowing for mm precision, will be used to accurately measure the position of the AMR during the test.

V. RESULTS

Table I summarizes the results of the navigation test. As the 5G configurations introduce increased communication delays as compared to the cabled planner configuration, it was expected that the total execution time was increased as well. When applying the current 5G release configuration, an increase of 17 seconds in total execution time is experienced with respect to the reference cabled planner configuration. With the URLLC 5G release, a smaller increase of 12 seconds is observed. It can be concluded that 5G latency, despite of being increased as compared to a cabled connection, does not adversely impact the operations of the robot. The increase in total execution time between is bounded between 1.1% and 1.5%, which is significantly lower than the one form other expected operational delays, such as waiting time between

TABLE I
EFFECT OF THE DIFFERENT PLANNER COMMUNICATION SCHEMES ON THE AMR NAVIGATION (TOTAL EXECUTION TIME FOR 40 REPETITIONS)

Configuration	**Total execution time**	**Delay increase in %**
Cabled planner	18 m 24 s	-
Current 5G release	18 m 41 s	1.5
URLLC 5G release	18 m 36 s	1.1

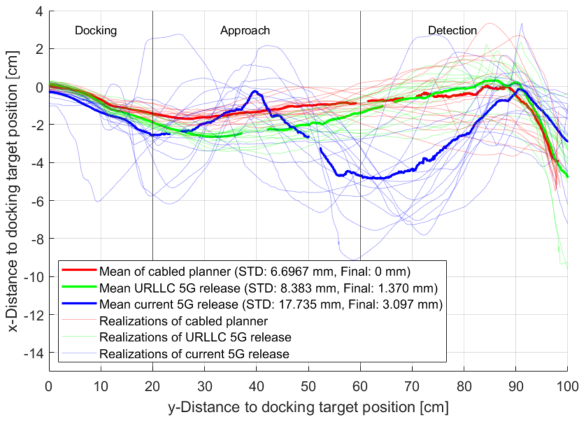

Fig. 6. Location of AMR during the different docking tests for the different planner communication configurations.

TABLE II
EFFECT OF THE DIFFERENT PLANNER COMMUNICATION SCHEMES ON THE AMR DOCKING ACCURACY (AVERAGE RESULTS FOR 15 REPETITIONS)

Configuration	Docking accuracy	Docking STD
Cabled connection	0 mm	10.26 mm
Current 5G release	3.09 mm	11.48 mm
URLLC 5G release	1.37 mm	8.88 mm

missions or stops to avoid collision with other robots.

Fig. 6 illustrates the results obtained in the docking test. The figure describes the 3 different phases the robot goes through during the test. In the first 40 cm, the AMR tries to locate the marker on the docking station. In the next 40 cm, the robot approaches the target maker while it tries to configure its location for the final docking procedure. The last 20 cm, represent the docking operation. For each of the configurations, an average trajectory is computed from the different realizations of the test. The thick red line, illustrates the average trajectory obtained with the cabled planner configuration. This is, moreover, used as a reference for the final docking position target located at the origin at coordinates (0,0). The thick blue line and green thick line represent the average trajectories for the current 5G release and URLLC 5G release, respectively. The thin lines illustrates each of the individual realizations. The variations of the lines represent the uncertainties in the trajectory of the AMR during the docking test. The uncertainties are found to be proportional to the delays of the I/O-planner communication. As displayed in the figure, the variations of the cabled planner configuration are the lowest with an accuracy standard deviation (STD) of 0.66 cm. For the 5G configurations, the current 5G release achieves an accuracy STD of 1.77 cm, while with the URLLC 5G release, an accuracy STD of 0.83 cm is experienced. Despite of the slightly increased inaccuracies with the 5G configurations, the average accuracy of the final docking position was 0 mm for the cabled planner with an STD of 10.26 mm, 3.09 mm for current 5G release with and STD of 11.48 mm and 1.37 mm with an STD of 8.88 mm for URLLC release. These values are summarized in Table II. These results support the fact that the current AMR navigation and docking control based on the split planner could be reliably operated in 5G mobile edge cloud configuration.

VI. CONCLUSION

This paper analyzed the internal path planner communication requirements from a MiR AMR, allowing for the necessary insight into the requirements to be fulfilled by a 5G system to replace the current cabled on-board planner with a wireless cloud version. It was found that, split planner functionalities considering streaming of data between the I/O interfaces of a robot and a cloud planner will result in a communication scheme with an average throughput of 3.2 Mbit/s, where 43% of packages in uplink and 45.3% in downlink direction will have a size of 64-bytes.

Such communication patterns are theoretically supported by 5G. The emulation test results illustrated in this paper, demonstrate how a cloud planner based on 5G technology will be capable of achieving a navigation performance and docking accuracy similar to that of the original on-board local planner, not affecting notably the normal operations of the robot. An increase of 1.5% in navigation execution time, and an average docking accuracy of 3 mm accuracy were observed in worst case. These values are acceptable for reliable operation of the AMRs and validate the possibility of migrating robot intelligence and computing power to the cloud.

For future work, integration with operational 5G networks and live trials of the presented 5G mobile edge cloud planner concept will be considered. Further, system scalability tests and planner protocol enhancements will be performed to optimize the communication and operational performance of the AMR 5G mobile edge-cloud planner platform.

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