Design and Implementation of a 5G-Connected Edge-Cloud Platform for Autonomous Mobile Robots Route Planning

Communication Technology,
- Aalborg University -

Master thesis

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Abstract:

With the increased connectivity of Industry 4.0, and the focus on industrial robots therein, AMR robots are one of the main tools for achieving increased productivity. Currently AMR robots only relay on its own sensors to gather information regarding the working environment, with limited information shared between the robots. However, if information sharing was increased, to create a virtual reality, the robots could plan their paths with additional efficiency, increasing the overall planning efficiency. This study investigates the possibility of moving the planner from individual robots to a centralised edge cloud planner with the help of 5G. To determine feasibility of the proposed solution, the impact of 5G delays in communication between a robot and a separated external planner was investigated by emulation.
Furthermore, an analysis of the communication between the robot and planner have been conducted with the purpose of determining and improving the connection by batching small packets, while upholding time requirements. To conclude if the results achieved is reflective of reality, a test with a a private 5G network with local core was conducted. When applying an emulated latency of current 5G connections and the enhanced scheduling of 5G with URLLC support a small increase in execution of 0.154‰ and 0.108‰ observed.
Further investigation of the communication between robot and planner revealed a significant amount of small packets from TCP connection. Through small window batching of these, were the PPS reduced by 7%. When applying the batching and expected result from emulation, the feasibility of safe operation over 5G was theoretically validated. However, when this was tested over an operational 5G connection, some gaps in operation were discovered. Individual TCP streams timed out, which caused the robot to operate in suboptimal conditions. Therefore, further debugging is needed. It is believed that it is possible to achieve an operational 5G-based edge cloud planner with slight adjustments to the connection.

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STUDENTERRAPPORT

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Design og implementering af en 5G-tilsluttet Edge-Cloud-platform til autonome mobile robotters ruteplanlægning

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Abstract:

Med den øgede konnektivitet i Industri 4.0 og fokus på industrirobotter er AMR-robotter et af de vigtigste værktøjer til at opnå øget produktivitet. AMR-robotter deler kun begrænset information mellem robotterne. Men hvis informationsdelingen blev øget for at skabe en virtuel virkelighed, kunne robotterne planlægge deres baner med større effektivitet og dermed øge den samlede planlægningseffektivitet. I denne rapport undersøges muligheden for at flytte planlæggeren fra individuelle robotter til en centraliseret edge cloud-planlægger ved hjælp af 5G. For at fastslå gennemførligheden af den foreslåede løsning blev virkningen af 5G-forsinkelser i kommunikationen mellem en robot og en separat ekstern planlægger undersøgt ved hjælp af emulering.
En analyse af kommunikationen mellem robotten og planlæggeren med henblik på at bestemme og forbedre forbindelsen ved at samle små pakker i stakkevis, samtidig med at tidskravene overholdes. For at konkludere, om de opnåede resultater afspejler virkeligheden, blev der gennemført en test med et privat 5G-netværk med lokal kerne. Ved anvendelse af en emuleret latenstid for de nuværende 5G-forbindelser og den forbedrede planlægning af 5G med URLLC-understøttelse blev der observeret en lille stigning i udførelsen på 0,154 ‰ og 0,108 ‰. En yderligere undersøgelse af kommunikationen mellem robotten og planlæggeren afslørede en betydelig mængde små pakker fra TCP-forbindelsen. Ved at samle disse i små vinduer blev PPS reduceret med 7%. Ved anvendelse af batching og det forventede resultat fra emulering blev muligheden for sikker drift over 5G teoretisk valideret. Da dette blev testet over en operationel 5G-forbindelse, blev der imidlertid opdaget nogle huller i driften. Individuelle TCP-strømme gik ud i tid, hvilket fik robotten til at operere under suboptimale forhold. Derfor er der behov for yderligere fejlfinding. Det menes derfor, at det er muligt at opnå en operationel 5G-baseret edge cloud-planner med mindre justeringer af forbindelsen.

Preface

This study was written as a Master thesis spanning 3 and 4 semester from 2nd September 2020 and ended 3rd June 2021. The Master is in Communication Technology with specialisation in Network and Distributed Systems, at Aalborg University.

This project was made in collaboration with MiR, Odense.

The author would like to thank the supervisors of this project, Professor Preben Mogensen and Assistant Professor Ignacio Rodriguez from Aalborg University and Morten Larsen from MiR for their assistance, supervision and guidance thought the project.

Citation are noted with square brackets (Example: [1]), it should be noted that papers are cited separately in their own bibliography.

Contents

Chapter 1

Extended Summary

In current industrial environment the use of logistic robots for internal transportation have increased in recent years. This follows with the increased interest for Industry 4.0(I4.0), in which a main focus is on automation and information sharing between individual manufacturing machines, robots, and management systems. Currently this is achieved with the use of wi-fi. However, with the increasing demand for high throughput and low latency for time critical appliances are improvements necessary to ensure reliable operations. Newer iterations of cellular communication are becoming more prevalent as it allows for support of massive internet-of-things(m-IoT), ultra-reliable low latency communication. Therefore, is the use of 5G becoming an increasing interest for use as wireless medium.

The most commonly used types of robots for internal logistics are autonomous mobile robot (AMR) and Automated Guided Vehicle (AGV). The latter uses located markers in the environment to determine its location. This can be reflective surfaces, lines marked on the floor or electromagnetic stripes in the floor. These robots are limited in their range and can take significant effort to alter the paths. An AMR will use a pre-generate map of static objects (i.e. walls or production machines) to create a global plan of movement. When executing operations will an AMR detect dynamic obstacles and re-plan its path to avoid collision.

The AMR is the type of robot that stands to most directly benefit from an increase information sharing, this is due to the information gather on dynamic objects are not exchanged among robots. Two AMR robots with the same map and destination will plan the same path. If one of the robots discovers the path is blocked by a dynamic object, will it replan its own path, but not share the information regarding the dynamic obstacle with the other robot. The other robot will have to discover the blocked path on its own. If the information was shared between the robots, would the second robot be able to replan its path before it met the dynamic obstacle.

With 5G edge cloud solutions providing increased planning capabilities compared to currently used solutions at the cost of increased latency, have the following problem statement have been constructed for this project:

"It is possible to successfully integrate an 5G edge cloud planner, without significant reduction of the efficiency of an AMR"

To investigate this hypothesis, the following research questions (RQ) are defined:

RQ1: What data is transmitted between the robot and planner?

RQ2: Will the robot experience a significant reduction in performance when using a centralized planner operating over 5G?

RQ3: Can the data flow between robot and planner be improved?

RQ4: What hidden difficulties arises when testing and validating a cloud planner over on a 5G network?

As an internal step to investigate the problem statement, was it necessary to separate a robot from its planner. To do this were the planner separated from a MiR 200 robot. The integrity of the system had in initial test been determined to be as efficient as an onboard planner, when connected directly with an Ethernet cable. Furthermore, the measurements of packet sizes and time between packets were determined for analyses. This follows the initial steps seen in paper 1 "Towards a 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots". In which, it was revealed that the majority of packets transmitted were TCP acknowledgements (acks). 43% of packets transmitted from the planner are acks, while they constitute 45.3% of packets from the robot. This reveals the answer to the first RQ, as the communicating between the planner and robot consisting of multiple TCP connections.

To investigate if the TCP connection were affected by an increased delay were a delay box, placed in-between the planner and robot. This allowed the robot to experience 5G by emulating the delays. Two tests were conducted in an environment meant to accommodate normal operations with dynamic planning. The first of the test were a navigation test, with the robot being instructed to move between two points in the environment, with and dynamic object placed in its path. Additionally, a docking test was preformed, where the robot was placed 1 meter in front of station. The robot then executed a docking operation.

RQ 2 were answered by both the docking and navigation test, with the latter revealing an increase in execution time of 0.154‰, when utilizing the network configuration with the highest round-trip time. It was furthermore discovered in the docking test that a standard deviation of 11.48 mm was observed for the same network configuration. As both test point to the same conclusion which answers RQ 2, as the change to a 5G connection from a wired configuration is possible, with negligible impact on operations. Additional information regarding docking and navigation test can be found in 3.5.3 and 3.5.2 respectably.

As it is theoretically possible to have a centralized planner, were the possibility of reducing the packets transmitted investigated in the paper 2 "Implementation and Experimental Validation of an Optimized 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots". It was discovered that there were there a significant amount of small packets. These packets will instead of being transmitted individually be batch together. This was done to reduce the amount of packets send, which allows for increased scalability. When batching two requirements were set that allowed for transmission of the gathered packets. This first were a size requiting, if the next packet gather will make the buffer of stored packets exceeds 1500 bytes, which is the MTU of 5g packet, will the packet be transmitted. The other requirement was a time restriction, this were done to avoid a period of low traffic that would cause the buffer to slowly fill up, but exceed the time requirements of the first packets in the buffer. It was discovered that a hold back time of 2 ms were able to achieve results. This answers RQ 3, as the improvement of the flow between planner and resulted in a reduction of packets transmitted by 7% compared to a hold back of 1 ms

When testing the centralized planner over an 5g connection with batching in the network, was it discovered that significant gaps in the communication occurred. A gap of 60 s accrued every 100 s for TCP conversations with large packets. This caused the robot to be unable to navigate through the environment, as it greatly affected the communication of the laser scanners on the robot, making the robot "blind" while driving. Additional information regarding operations over 5G can be found in 3.5.5. This answers RQ4, as test have revealed additional investigation of the robot and network is necessary.

When returning to the problems statement, with the information acquired thought the RQ can it be determined, it is theoretically possible to operate and AMR with an 5G edge cloud planner. To achieve an operational connection over a 5G network, it is necessary to tune network configurations to mitigate connection loss.

Chapter 2

Papers

2.1 Paper 1

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

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

Taus Raunholt[1], Preben Mogensen[1], Ignacio Rodriguez[1], and Morten Larsen[2]

Abstract— **As the use of robots increases in industrial environments, there is a need for centralized cloud management to improve coordination and planning capabilities. This paper explores the suitability of different 5G schemes for communication between an AMR and a cloud planner by emulating different 5G configurations in an operational test environment. The paper includes the analysis of the TCP-based planner communication and puts it in perspective of 5G mobile edge cloud technology. The observed Mbit/s throughputs 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 performing a navigation test and a docking station tests, where the 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 labour [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, an AMR determines its path using a local planner and does not share share 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 planner capabilities from each individual robot to a centralised cloud unit, creating a virtual shared world, 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.

In order to ensure a reliable AMR cloud planner operation, the wireless data transmitted between the robot and the 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 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 centralised 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 centralised 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 utilising 5G for providing centralized cloud planning. The possibility 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 emulating 5G delays for different 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 5G implemented in the live testing. Section IV describes the test setups and methodology used to evaluate the effects of

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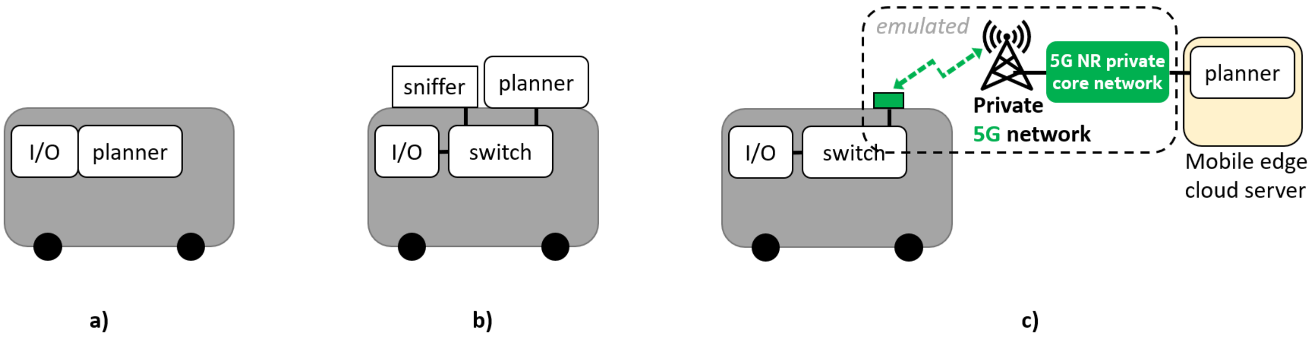

Fig. 1. General AMR planner architectures: a) current on-board planner, b) split planner, and c) 5G mobile edge cloud planner.

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 input/output (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 centralised 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) and transmitted (downlink) 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.

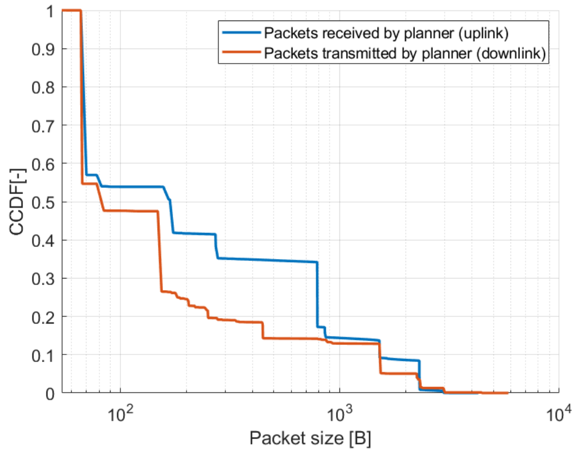

Fig. 2. CCDF of different packet sizes observed in the communication between the I/O and the planner.

The analysis revealed that the average traffic is 458.3 packets/s or 1.3 Mbit/s for uplink (between the I/O and the planner) and 476.7 packets/s or 1.9 Mbit/s for downlink (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 acknowledgement messages from the TCP communication utilised by ROS, and are to be expected. Overall, they constitute 43% of the uplink communication. There are other 4 different relevant packet sizes identified in uplink: 78-, 158-, 271-, 788- and 1514-

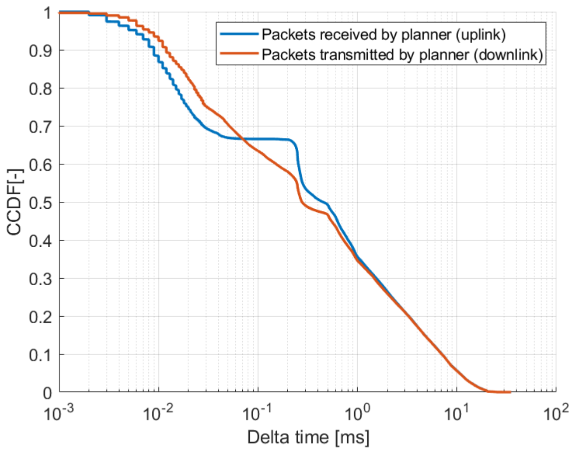

Fig. 3. CCDF of inter-arrival time of packets observed in the communication between the I/O and the planner.

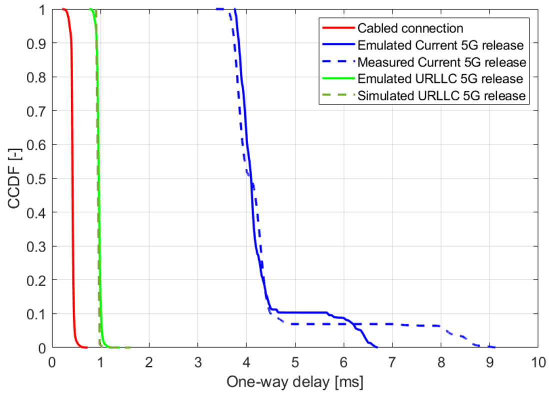

Fig. 4. Validation of 5G-emulated communication delay distributions for the current release and URLLC release. The cabled planner link performance is plotted as a reference.

bytes, which are responsible for the remaining 3%, 12%, 6%, 17% and 5% of the communication, respectively. For downlink 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. 3, revealing that packets can be transmitted as fast as 0.001 ms for both uplink and downlink direction. On average, packets are received every 0.445 ms in uplink, and 0.277 ms in downlink. The maximum separation between consecutive packets was found to be approximately 20 ms.

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 [10].

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.

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 [10] 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

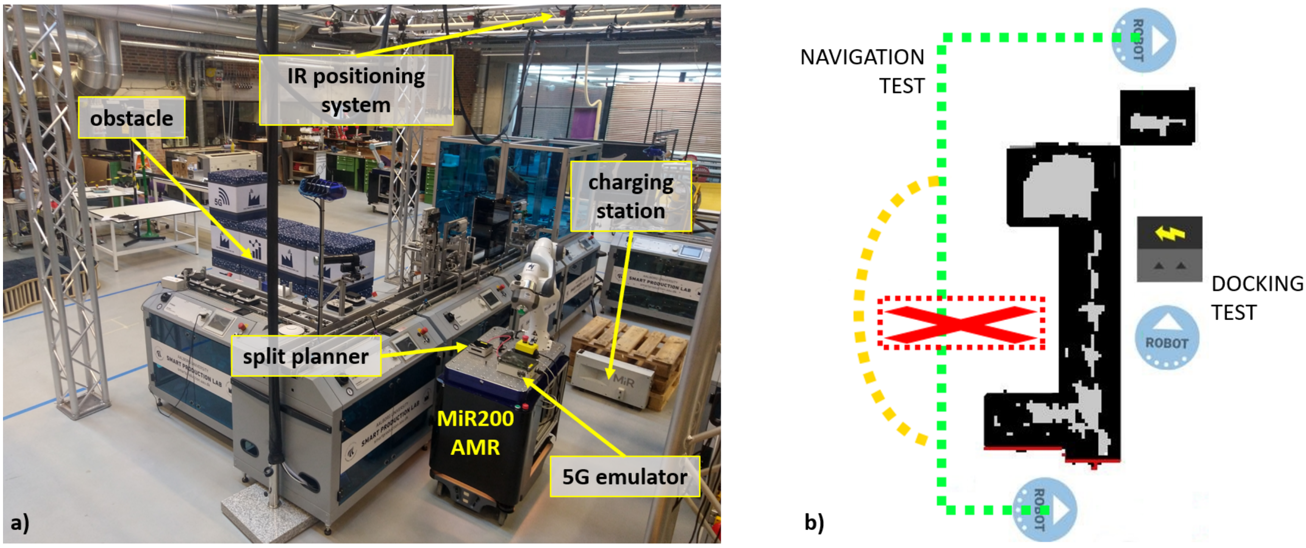

Fig. 5. Overview of the: a) test setup including the AMR, the networking elements, charging station, and other industrial elements, and b) test environment, illustrating the trajectories for the navigation test and the location of the charging docking station for the docking test.

original input delay distributions for over 90% of the time. As a further reference, the figure also displays the delay experienced by the 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, applying 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 manoeuvre 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 [11], 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

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	0.154
URLLC 5G release	18 m 36 s	0.108

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 11 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 0.108‰ and 0.154‰, which can be considered negligible or significantly low than other expected operational delays, such as waiting time between 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

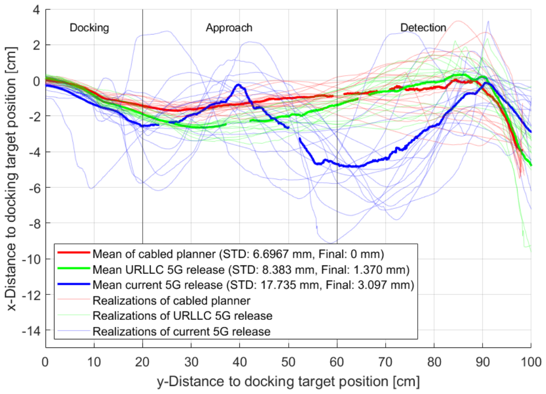

Fig. 6. Location of AMR during the different docking tests for the different planner communication configurations.

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

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. CONCLUSIONS

This paper analyzed the internal planner communication requirements from a MiR AMR, allowing for the necessary insight into the requirements to be fulfilled by a 5G wireless system to replace the current planner system with a cloud version cabled communication between a robot and cloud planner. It was found that, split planner functionalities 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 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 those of the original on-board local planner, not affecting notably the normal operations of the robot. An increase of 0.154‰ in navigation execution time, and an average docking accuracy of 3 mm accuracy were observed in worst case. As this values are negligible for reliable operation of the AMRs, it is expected that 5G will be capable of operating reliably these industrial use case.

For future work, integration and live trials of the presented 5G mobile edge cloud planner concept will be considered. Further, planner protocol enhancements will be performed to optimize the communication performance of the 5G cloud planner.

REFERENCES

[1] E. Frazelle, *World-class warehousing and material handling*, 2nd ed. McGraw-Hill Education, 2016.
[2] R. Michel, "AGVs gain in FLEXIBILITY & applications," *Modern Materials Handling*, vol. 75, no. 11, pp. 40–47, 2020.
[3] I. Rodriguez *et al.*, "5G Swarm Production: Advanced Industrial Manufacturing Concepts enabled by Wireless Automation," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 48–54, 2021.
[4] D. Claes, F. Oliehoek, H. Baier, K. Tuyls *et al.*, "Decentralised online planning for multi-robot warehouse commissioning," in *International Conference on Autonomous Agents and Multiagent Systems*, 2017, pp. 492–500.
[5] C. Amato, G. Konidaris, G. Cruz, C. A. Maynor, J. P. How, and L. P. Kaelbling, "Planning for decentralized control of multiple robots under uncertainty," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2015, pp. 1241–1248.
[6] A. Singhal, P. Pallav, N. Kejriwal, S. Choudhury, S. Kumar, and R. Sinha, "Managing a fleet of autonomous mobile robots (AMR) using cloud robotics platform," in *European Conference on Mobile Robots (ECMR)*, 2017, pp. 1–6.
[7] Mobile Industrial Robots (MiR). MiR200. [Online]. Available: https://www.mobile-industrial-robots.com/en/solutions/robots/mir200/
[8] Open Robotics. Robot Operating System (ROS). [Online]. Available: https://www.ros.org/
[9] Y. Pyo, H. Cho, R. Jung, and T. Lim, *ROS Robot Programming*, 1st ed. ROBOTIS Co., Ltd., 2017.
[10] G. Pocovi, H. Shariatmadari, G. Berardinelli, K. Pedersen, J. Steiner, and Z. Li, "Achieving Ultra-Reliable Low-Latency Communications: Challenges and Envisioned System Enhancements," *IEEE Network*, vol. 32, no. 2, pp. 8–15, 2018.
[11] OptiTrack. Flex 3. [Online]. Available: https://www.optitrack.com/

2.2 Paper 2

Implementation and Experimental Validation of an Optimized 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots

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Implementation and Experimental Validation of an Optimized 5G Mobile Edge Cloud Planner for Autonomous Mobile Robots

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***Abstract*—**

I. Introduction

In industry 4.0 (I4.0) is communication between the individual manufacturing machines, robots, and management systems relent on Ultra-reliable low-latency communication (URLLC) [1]. It is therefore necessary to ensure the wireless technology used, is capable of supporting the high throughput and reliability constraints. Wi-Fi have been the main technology used for industrial communication. With newer iterations having increased focus on lower battery consummation to improve compatibility with Internet-of-Things (IoT) requirements [2]. For time critical communication have use of Wi-Fi recently been outperformed by the 5. generation (5G) of cellular communication. This is due to the development use cases used for 5G, which specifically include the use of URLLC and massive IoT (mIoT), the latter of which is expected to support up to 300.000 unites [3]. The increased amount of information gather, allows for cloud solutions for increased accessibility and centralisation of processing power. Although multiple facets of a production benefits from implementation of I4.0, will this paper focus on logistics robots. As the use of robots for transpiration of goods in warehouses environment have been increasing in resent years [4].

Multiple types of logistics robots are prevalent in industrial environment, out of which autonomous mobile robots (AMR), stands to benefit significantly by the implementation of I4.0. AMR uses a pre-generated map, based on permanent structures (e.g. walls or shelves), to locate itself in the environments. This map does not include dynamic object (e.g. personal or pallets), which the robot avoids based on sensory input. Information regarding blocked paths identified by an individual robot is not shared among the others [4]. As robots planning from the identical map with the same endpoint, will plane the same route. Will they both spend time to discover a block path, which could have been mitigated if information sharing between the robots was possible. It is therefore relevant to identify the possibility of moving planning from individual robots to a centralised planner, located at the cloud. A centralised planner allows for a virtual world, in which each robot can optimize there path to improve overall planning of a fleet.

Multiple papers have discussed the demands, needed in the wireless communication for I4.0. In [2] [5] [6] [7] different aspects of I4.0 are investigated to identify the requirements need to fully enable cloud control systems. It is proposed the use of 5G will be capable of improving the communication between robots and cloud, allowing it to support the URLLC needed for safe operations. A proof of concept has been created to demonstrate a robot arms ability to balance a ball, while communicating over 5G with the controller, seen in [1]. The robot used a simple control loop to explore the effect of offloading time critical computation over 5G. Preliminary work on the topic has been done in [8], which uses an industrial MiR robot. The robot were instructed to dock to a charging station and execute a set operations, while communication between planner and robot were affected by emulated 5G delay. This will be used as a basis in this paper to improve upon discoveries made, Furthermore will this paper will follow the examples set in [8] and use a industrial robot to determine if moving the planner from the robot to an edge cloud, using an 5G connection effects operations. As discovered is it necessary to modify the flow of packets to ensure a 5G network is not congested by the communication used by the robot. This paper will therefore be investigate the possibly of moving the planner of a MiR robot to the edge cloud over a 5G connection. Furthermore this paper will explore the combination of individual frames to reduce the overall packet transmitted over 5G to an edge cloud planner .

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II. Gathering of packets in 5G

A MiR robot uses robot operating system (ROS) [9] for internal communication. ROS is a common operating software for low-level system control and internal communication. It uses TCP to transmit predetermined payload between devices including communication with the planner. As the separation of planner and robot have been described previously in [8], will this paper not describe the details there off. Initial measurements of the communication between the planner and robot reveals an total of 69 conversations. Each of there conversation are individual TCP connections, which while under the influence of a batching algorithms still creates multiple small packets. As the "small packet problem" first described in [10] still arises, can an additional batching be applied to all conversations for reduced PPS. Table I, shows the transmitted packets per second(PPS) and the corresponding percentage of packets only consisting of acknowledgement or selective acknowledgement. As the destination of all packets send are identical with only the port differing, can the batching

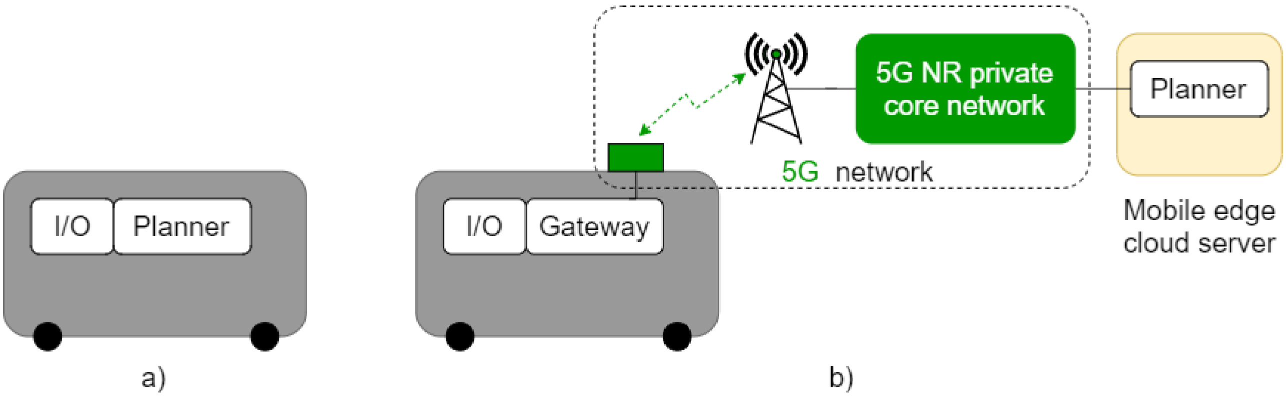

Fig. 1. Generalised AMR architecture: a) currently used configuration, b) 5G enabled edge cloud planner

TABLE I
SMALL PACKET PROBLEM IN COMMUNICATION BETWEEN ROBOT AND SEPARATED PLANNER

	Edge cloud planner	MiR robot
PPS	458.3	476.7
SACK/ACK	51.7%	45.8%

of packet be applied post transmission.To gather the packes, it is requires any previous messages not already send, to be buffered along with any packets received. The buffer is to be transmitted when any new packet received exceeds the maximum transmission unit (MTU). As this can cause the system to have an inflated latency is an additional requirement necessary. An time limitation based on the earliest packet in the buffer. This allows the buffer to be transmitted early even if it is not full.
To separate the packets on a receiving will the header of the first packet in the receiving buffer be read. The length of this packet can be determined and removed from the buffer. If the size of the buffer is longer than the length of the removed packet, does the buffer contain more packets. The next packet can then be read and removed, this process is repeated until the all packets are removed from the buffer. This process of transmitting and receiving packets are depicted in Fig. 2.

Increasing the time interval, is expected to have a demonising return, as the buffer will in increasing instances be transmitted due to meeting the MTU size. Multiple time interval will be investigated to determine an approximate value, which yields an optimal value, for the robot used. This values will be used in future test to determine its affect in comparison to a wired planner and a 5G connected planner without any modifications to the connection.

III. 5G Mobile Edge Cloud Planner Test Setup

The performance evaluation of the 5G enabled edge cloud planner, is done using a customised gateway with a 5G modem. The gateway allows for bridging over wireless

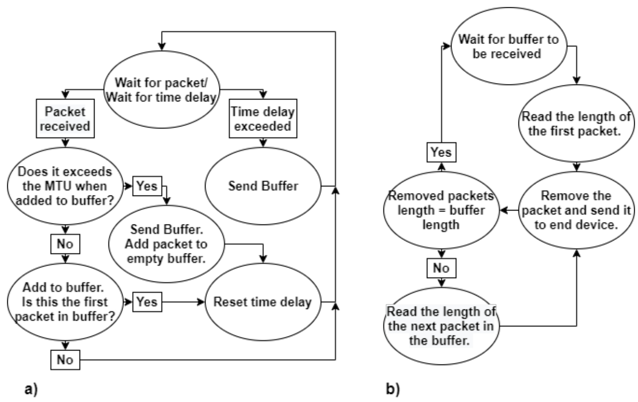

Fig. 2. Flowchart illustrating a) transmitting logic for batching, and b) logic for separating packets.

technologies, by encapsulating packet received on an enabled interface. The gateway will furthermore be executing the batching of packets as described in as described in section II. The 5G connection used is a private local network with configurations seen in Table II The core used is a stand alone(SA) 5G core, this allows the system to utilise the advanced functionalities found in 5G, such as ultra low latency. This is in contrast to non-SA which uses a 4G core but with improvements from the 5G specifications such as the increased spectrum [11]. The core is located in AAU smartlab with the antennas, which allows for low latency due to the small geographical distance the signal needs to travels.

Table II summarises the configurations of the 5G network. An overview of the test setup is presented on figure 3.a. which depicts the test environment.

Two performance test will be conducted to determine the effects of a 5G edge cloud planner:
Navigation test: instructing the robot to move between to points, illustrated on figure 3.b. The robot will follow the path marked in green. Its path is blocked by the objects marked with the red cross, it will therefore need to modify the planned path. This path marked with yellow is the new

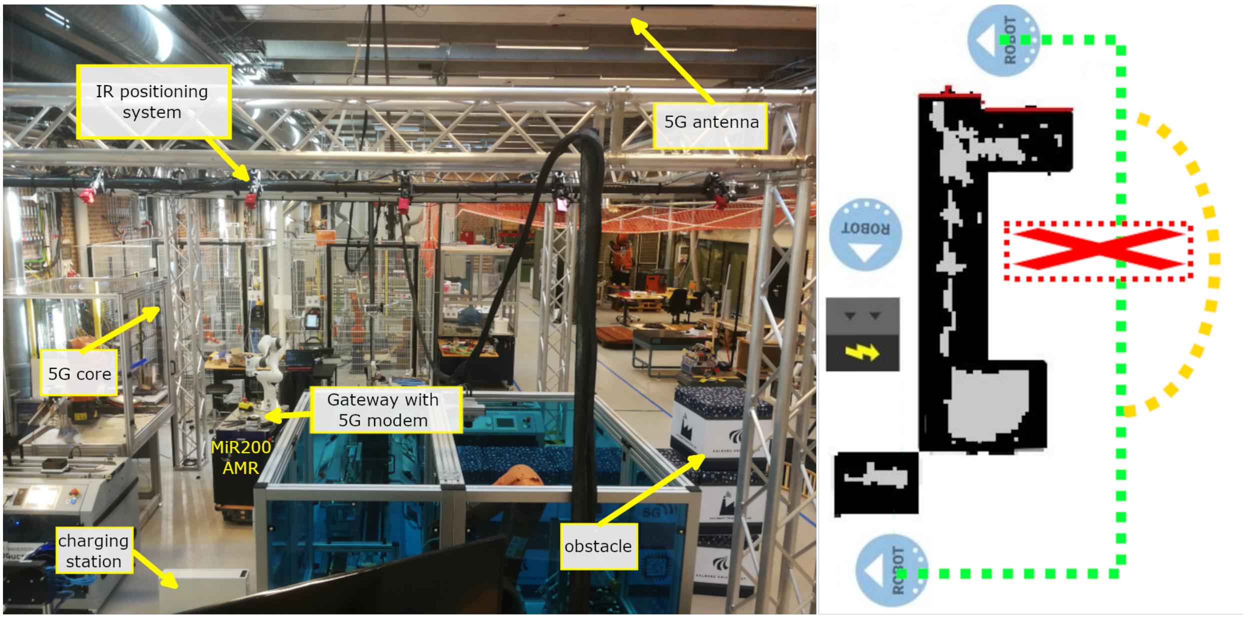

Fig. 3. Overview of the: a) test setup including the AMR, the networking elements, charging station, and other industrial elements, and b) test environment, illustrating the trajectories for the navigation test and the location of the charging docking station for the docking test.

TABLE II
CONFIGURATIONS USED IN THE 5G NETWORK.

5G CONFIGURATIONS	
Frequency	3.7 GHz
Bandwidth	100 MHz
Subcarrier spacing	30 KHz
Block error rate	10%
Proactive scheduling	1 ms
UL-DL scheduling	3/7 TDD

path the robot will follow, when it has detected the blocking objects. For statistical relevance will this test be repeated 40 times, with 3 configurations: an wired planner, a 5G edge cloud planner and a 5G edge cloud planner with batching. The path executions time over 5G compared to the baseline gather from the on board planner, will allow for analyses of execution time.

Docking test: Positioning the robot 1 meter in front of a charging station, while tracking its location with an Opti-Track IR camera system [12] for mm accuracy. The robot will be instructed to locate and dock to the charging stations. This docking manoeuvre will be preformed 15 times, for a connected on board planner. an 5G edge cloud planner and 5G edge cloud planner with improved communication. The accumulated accurate of each configuration will be compared to identify any performance differences between the different configurations.

IV. Results

V. Conclusions

References

[1] F. Voigtländer, A. Ramadan, J. Eichinger, C. Lenz, D. Pensky, and A. Knoll, "5g for robotics: Ultra-low latency control of distributed robotic systems," in *2017 International Symposium on Computer Science and Intelligent Controls (ISCSIC)*, 2017, pp. 69–72.
[2] A. Varghese and D. Tandur, "Wireless requirements and challenges in industry 4.0," in *2014 International Conference on Contemporary Computing and Informatics (IC3I)*, 2014, pp. 634–638.
[3] M. Kottkamp, A. Pandey, D. Raddion, A. Roessler, and R. Stuhlfauth, *5G New Radio: Fundamentals, procedures, testing aspects*, 4th ed. Rohde&Schwarz GmbH & Co. KG, 2019.
[4] R. Michel, "AGVs gain in FLEXIBILITY & applications," *Modern Materials Handling*, vol. 75, no. 11, pp. 40–47, 2020.
[5] I. Rodriguez *et al.*, "5G Swarm Production: Advanced Industrial Manufacturing Concepts enabled by Wireless Automation," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 48–54, 2021.
[6] A. Vick, V. Vonásek, R. Pěnička, and J. Krüger, "Robot control as a service — towards cloud-based motion planning and control for industrial robots," in *2015 10th International Workshop on Robot Motion and Control (RoMoCo)*, 2015, pp. 33–39.
[7] M. Aleksy, F. Dai, N. Enayati, P. Rost, and G. Pocovi, "Utilizing 5g in industrial robotic applications," in *2019 7th International Conference on Future Internet of Things and Cloud (FiCloud)*, 2019, pp. 278–284.
[8] T. Raunholt, P. Mogensen, I. Rodriguez, and M. Larsen, "Towards a 5g mobile edge cloud planner for autonomous mobile robots," *International Conference on Intelligent Robots and Systems*, 2021, in consideration.
[9] Open Robotics. Robot Operating System (ROS). [Online]. Available: https://www.ros.org/
[10] "Congestion Control in IP/TCP Internetworks," RFC 896, Jan. 1984. [Online]. Available: https://rfc-editor.org/rfc/rfc896.txt
[11] Hannes Ekström. (2019, JUL) Non-standalone and Standalone: two standards-based paths to 5G. [Online]. Available: https://www.ericsson.com/en/blog/2019/7/standalone-and-non-standalone-5g-nr-two-5g-tracks
[12] OptiTrack. Flex 3. [Online]. Available: https://www.optitrack.com/

Chapter 3

Worksheets

3.1 5G

Target of 5G

With each passing generation has mobile technologies sought to improve different aspects of wireless transmissions. This can be seen in the introduction of digital transmission in 2G, the implementation of High speed packet access (HSPA) in 3g or the change to orthogonal frequency-division multiplexing (OFDM) in 4G [1, p.2]. Each improvement has created higher efficacy and improved end user experience by increasing data rates and quality of service (QoS). This is reflected in the desired target use cases of 5G, with an increased interests in IoT devices which needs a highly reliable wireless technology that can also supply low latency with a high capacity. To avoid creating a entire new protocol from nothing 5G builds upone the previous generation of 4G LTE technology, with improvements and changes made to the standards that allows the 5G development uses cases, described later, to be fulfilled.

The current leap forward to the next generation will be one that enables impotent technologies, such as self driving cars, remote surgery or improved cellphone communication. The former of which can utilise 5G to better enable vehicle to vehicle(v2v) communication, which will allow self driving cars to better keep track of each other allowing for platooning and extend the range vehicles can share information. [2]. While the latter will allow

To accommodate the cases describe above have 3 development use cases been described by the 3GPP group, which has been a leading force in creating requirements for mobile technologies. These use case is designed to simplify the technical specifications for 5G and is as following:

- High data rate service
- Massive internet of things
- Ultra reliable low-latency services

High data rate or enhanced mobile broadband (eMBB), describes the desire to gain a higher throughput from an end users perspective. This use case have been described in every generation and will be measured in comparison to 4G. [1, p.4]

Massive internet of things or massive machine-type communication (mMTC), focuses on improving current IoT implementations[3, p.11]. This includes reducing the power consumption of the transmitters and device cost, to allow its implementation of 5G into almost every machine. [1, p.4]

Ultra Relabel low-latency Communication (URLLC), is the final use case and focuses on the need for quick and reliable communication in critical components, such as health monitoring[1, p.4] or traffic safety[3, p.11]

Real world deployments scenarios might not fall directly into any of these categories, but as the use cases aim to create a bases for more technical specifications does this not effect the new generation.

Operational frequency of 5G

As each new generation of mobile communication has build upon structures of the previous generation, it also follows that the frequencies used will be reused. 5G uses the same frequencies as 4G, and follows the established paired bands described in 3.1, this frequency range is referred to as FR1. This allows 5G to utilised frequency division duplex(FDD) when communication in most of FR1. To support the requirements set for the use case eMBB, will additional frequencies be added to 5Gs operational range. These frequencies are from 24GHz - 52.6 GHz and is refereed to as Frequency range 2 (FR2)[1]. As of release 15 of 3GPPs specification 3 frequencies in has been specified, as non of these bands has a paired band to spilt a up/down link connection with does they utilise time division duplex (TDD).

Duplex schemes

5G is capable of using two duplex schemes, this being frequency division duplex(FDD) which is commonly used in FR1 as it has been extensively used in 4G. It works by paring two diffident frequencies together and using one of the frequencies as an uplink, while the other handles downlink. This allows the 5G to have full duplex. In FR2 paired spectrum are uncommon, therefore another duplex scheme is necessary. For this time division duplex(TDD) is used. Instead of using a separate frequency to gain full duplex, does TDD split one band into uplink and downlink slots. While this is only half duplex, it still addresses the need for a duplex scheme that allow both uplink and downlink. Furthermore, 5G allows for dynamic TDD. This allows 5G to change the uplink-downlink allocation. If a large data packet needs to be transferred and the end device is not required to respond during the transmission does dynamic TDD reallocate uplink slots for downlink. The opposite is also true if a large file is moved from an end device to the base station. [1, p.63-p.65]

Subcarriers spacing

To support the different deployment scenarios does 5g support additional sub-carrier spacing compared to 4g, which only support one at 15 kHz[3]. The new subcarrier spacing all increase the spacing, which allows for a reduced transmission time of each character, granting an increase for the overall throughput. As 5g shares transmission frequencies with 4g are each new subcarrier a multiple of the previous spacing, this can be seen in table 3.1,

Subcarrier spacing (kHz)	15	30	60	120	240
Symbol duration (µs)	66.7	33.3	16.7	8.33	4.17
Cyclic prefix duration (µs)	4.7	2.3	1.2	0.59	0.29
Max. nominal bandwidth (MHz)	50	100	100(FR1) 200(FR2)	400	400
Max. fast Fourier transform size	4096	4096	4096	4096	4096
Symbols per slot	14	14	14	14	14
Slots per subframe	1	2	4	8	16
Slots per frame	10	20	40	80	160

Table 3.1: Subcarrier spacing with numerology[3]

To ensure that a frame are identical regardless of frequency is a 5G frame always 10 ms. Each frame is is divide into 10 subframe of 1 ms each, a subframe is the further divided into slots of 14 OFDM character. This allows higher sub carrier spacing to transmit with a higher throughput as multiple slots can be fitted in to a subframe. This can also be seen on figure 3.1, where the possible slots for different frequencies can be seen.[1]

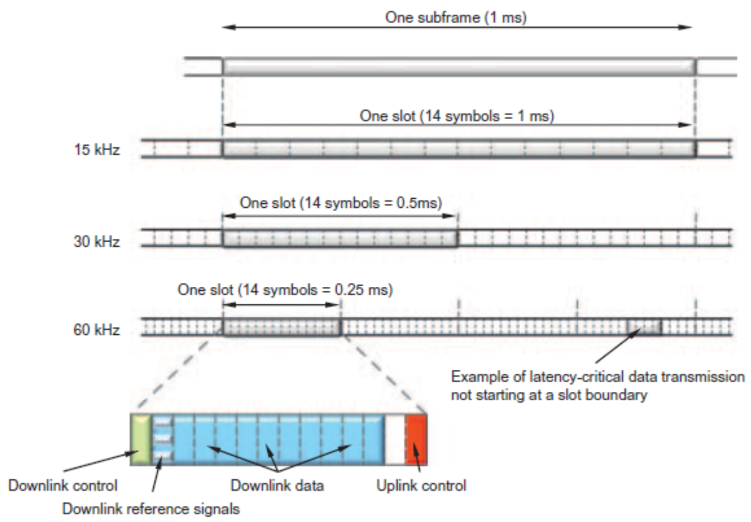

Figure 3.1: 5G subframes at different subcarrier spacing[1]

3.2 ROS

Robot operating system(ROS) is a commonly used middleware software for robots. It provides support for low-level device control and communication between processes. The latter of which works by creating publishers, which publish topics, that a subscriber can listen to. To control the publishers and subscribers a master is in charge of controlling the directing message groups for topics. ROS utilises TCP communication to ensure integrity of communication between end devices. This constitutes significant problems when moving to the wireless domain. Multiple version of ROS exist each designed to focus on different releases of Ubuntu.

Common applications in ROS is to control the odometry of the robot, in combination with information regarding I/O communication. This allows a centralised unit to control the robot by subscribing to relevant topics, and publish control information to relevant topices[4].

As ROS utilises tcp communication is the transition to wireless domain problematic. As a wired connection have theoretically 0 dropped packets, is communication not required to incorporate retransmission logic. When moving it to the wireless domain, will this cause problems as packets can be lost during wireless communication. As default configurations for TCP allows for basic transmission is usable over a wireless connection. It does however need configuration to achieve acceptable preference. To reduce time between transmission of packets that have been dropped, will the configuration for tcp retransmission from last ack be reduced. The default configuration for this setting is set to 30 seconds, as the laser sensor information will change dramatically in this time frame will it be reduced to 2 seconds. This is done using the following command:

```
$ sudo sysctl net.netfilter.nf_conntrack_tcp_timeout_last_ack=2
```

Listing 3.1: Chancing the delay from last ack to new transmission of packet.

3.3 Robot/planner split

As a robot traverses its environment, will it detect dynamic objects(ie. people or pallet) , and dynamically alter its path to avoid collisions. The information necessary to do this is on a MiR robot mainly gather in the laser scanners. This information is shared with the planner through ROS. As all communication in this is done internally, is location of dynamic objects not shared. A second robot with the same configuration will plan throughout the dynamic object blocking the path. This can course the second robot to make a path that is impossible to execute. If the information was share between the robots, can the second robot plan a path that avoids pathes blocked by dynamic objects.

To separate the planner from the robot, is it necessary to determine the functionalities that needs to be move. The main functionality that needs to be move is the global planning. Furthermore sensor information needed for lotion and movement in the endowment is needed for dynamic planning and re planning needs to be transmitted. Communication from sensors are time critical with short interval in which the information is relevant. If sensor information is not transmitted and packets are dropped, is it necessary for quick retransmission. If this is not achieved the information becomes invalid as the robot has already moved and a new measurements are necessary.

Initially the non time critical information such as maps can be transferred to the planner. As the maps are not expected to be change during normal operations, will they be consider to be static. Time critical information such as I/O data from laser sensors, need to be constantly update to ensure safe operations. Furthermore odometry information needs to be transmitted from the planner back to the robot.

3.4 Configuring MTU on gateway when using 5G

As ROS can transmit larger tcp packets, is it necessary for the gateways to be able to accept these packets. The MTU does therefore need to be set large enough to accommodate these packets, which for the use of a MIR robot is 6000. This is explored in [5], in which an analyses of the communication between planner and robot is presented. The correct configuration of MTU is also impotent when transmitting over the 5G interface. As the 5G modem and core will reject any packets larger than 1500 bytes, will the MTU of theses interface be set to 1500. As the defult configuration is set to 1500, is it only necessary to change the MTU of the interface connected to the network.
Chaining the MTU will be done using using the commands seen below: Commands executed on the gateway connected to the robot.

```
$ sudo ip link set dev enp0s25 mtu 6000
```

Listing 3.2: Chancing the MTU from 1500 to 6000 to accept larger packets.

As the 5G interface and interface connected to the planner are both children of a different interface, does the parent interface MTU need to be change. This will automatically change the MTU of all children to the same size. As this will cause problems with the 5G network, will its MTU be changed back to 1500.

```
$ sudo ip link set dev enp196 mtu 6000
```

Listing 3.3: Chancing the parent interface to accept packets of size 6000.

```
$ sudo ip link set dev 5Gcore mtu 1500
```

Listing 3.4: Chancing the MTU of the 5G interface to transmit packets of max 1500.

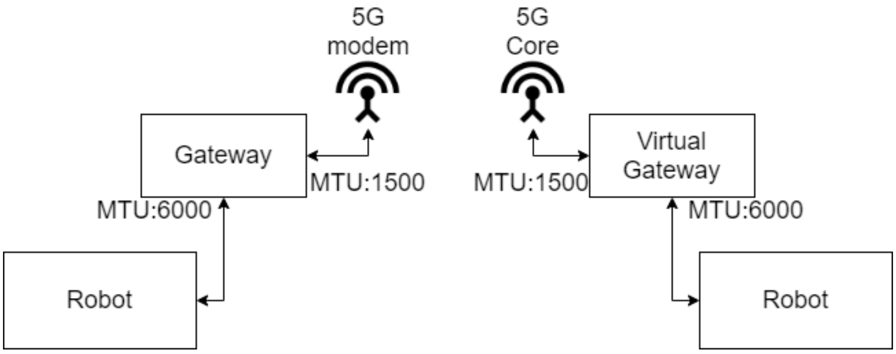

Figure 3.2: MTU sizes on the different gateway interfaces.

3.5 Test Journals

3.5.1 Test Journal - Traffic model from remote observation.

Purpose of the Test

To generate a traffic model of information exchanged between the planner and robot is it necessary to observe this communication. This will reveal how often the system is communication with the planner and the necessary throughput of the connection if it is to communicate over 5G .

Theory

As the robot is using Robot operating system(ROS) to communicate internally is it relevant to discover how this communication is done. ROS is a commonly used middleware software for robots. It provides support for low-level device control and communication between processes. For the focus of this test only the latter is relevant to further discuss. ROS works by generating publishers which publishes topics, with each topic having a predefined message type that is transmitted. The topics are then received by subscribers that can interpret the message that have been send. To keep track of the different publishers and subscriber, is a master necessary. To generate a traffic model is the information in each message irrelevant, as it is not necessary to repeat the information, but only the data on the network. Therefore to capture the data a subscriber is created to receive both data transmitted and received from the planner. Furthermore the new subscriber is located at in a separate computer to avoid additional adding interference from normal operations.

Test Setup

For the test a Intel NUC with ROS installed was installed on top of a MiR 200 robot equipped with a top module. As this module does not contribute to the communication between the robot and planner does it only server to improve the work environment for the test. An image of the test setup can be seen in figure 3.4. The NUC was connected to the robot through a ethernet cable, this gives the NUC access to the internal router in the MiR robot. Furthermore power were provided also provided from the robot.

To separate the data transmitted and received data of the planner was the test run 2 time each with a duration of 5 minutes to gather sufficient data to establish patters in the received information. The Intel NUC was instructed to first subscribe to the same topics as the planner to gain a copy of the information received by the planner. The robot was instructed to drive between two point in an test environment seen in figure 3.5, with dynamic obstacles in the form of human movement. This ensures the planner is operating as if in an industrial environment. Afterwards the test was run with the Intel NUC subscribing to all topics published by the planner.

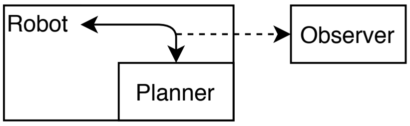

Figure 3.3: Simplified flow diagram of internal connection for test setup

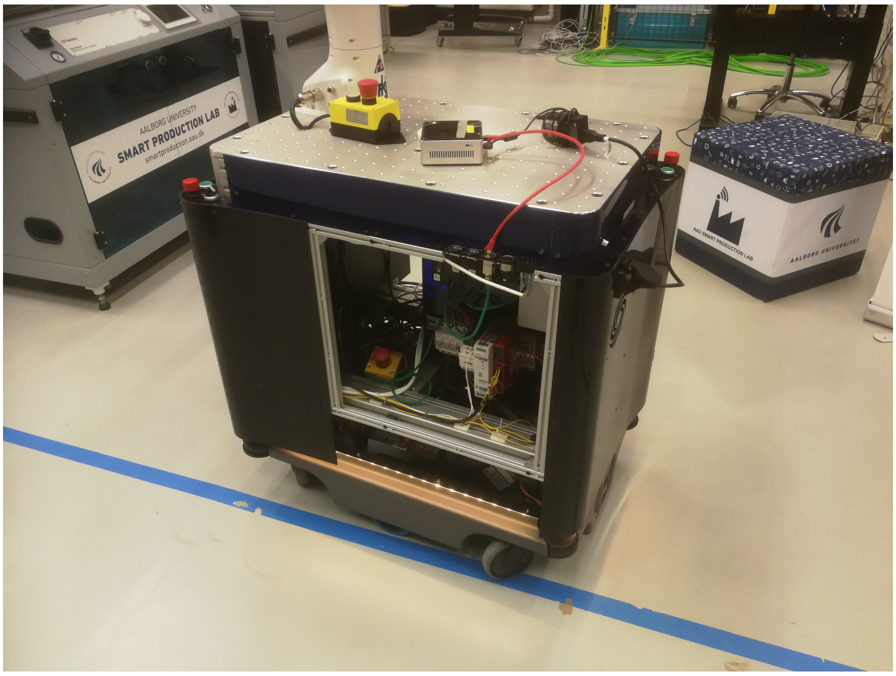

Figure 3.4: MiR robot with top module.

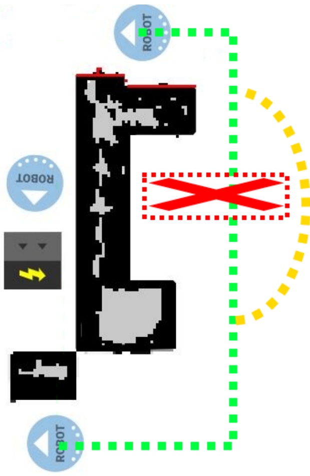

Figure 3.5: Test environment, with planned path marked in green, alternative path marked in yellow and red illustrating the dynamic object.

Results

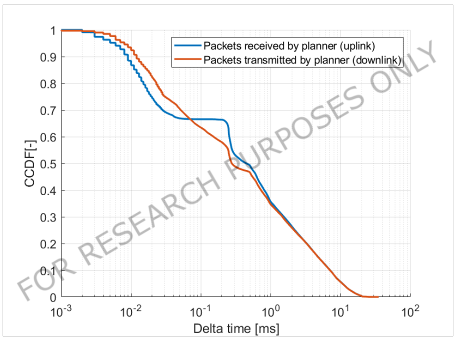

Figure 3.6: Time between packets

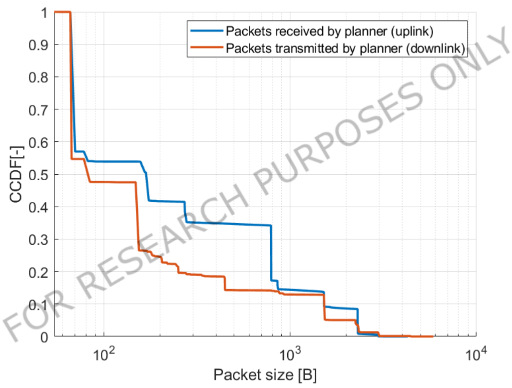

Figure 3.7: CCDF of packets transmitted.

3.5.2 Test Journal - Navigation test

Purpose of the Test

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.

Theory

As the AMR will try to move between the two points. Will it plan, using the global planner, a path through the environment. This path is not effected by dynamic objects, as the AMR needs to plan around these are the are encountered. Both during normal operations and when replanning the path due to dynamic objects does the AMR communicate with the planner. If this connection is disturbed, will the AMR stop moving. The extends to delays if an significant amount if packets are lost. It is therefore necessary to test if the AMR will stop moving if the important packets, such as information to avoid activating the emergency stop, are delayed. Furthremore, the delay the AMR experiences, when first communicating with the AMR, will be explored by looking into the increase in execution time between different configurations.

Test Setup

For this test, a separate device running the planner was connected to the AMR. In between the AMR and separate planner, is a delay box placed, which will emulated the delays of 5G. A top module were connected to the AMR, but as it were not active during the test, it is expected that it therefore does not contribute to the tests.

The test environment is illustrated in Fig.3.9, where the planned path is marked with green. But as a dynamic object, marked with red, is placed on this path, will the AMR be expected to move along the yellow path. This replaning of its path is expected to be effected by delay, and will therefore more clearly illustrate the effect of delay on a system.

Three different configurations will be tested, a cabled planner, Current 5G release and URLLC 5G release. A CCDF of these configurations can be seen in figure 3.8, where the configurations with the corresponding CCDF of the emulated delay in the delay box.

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

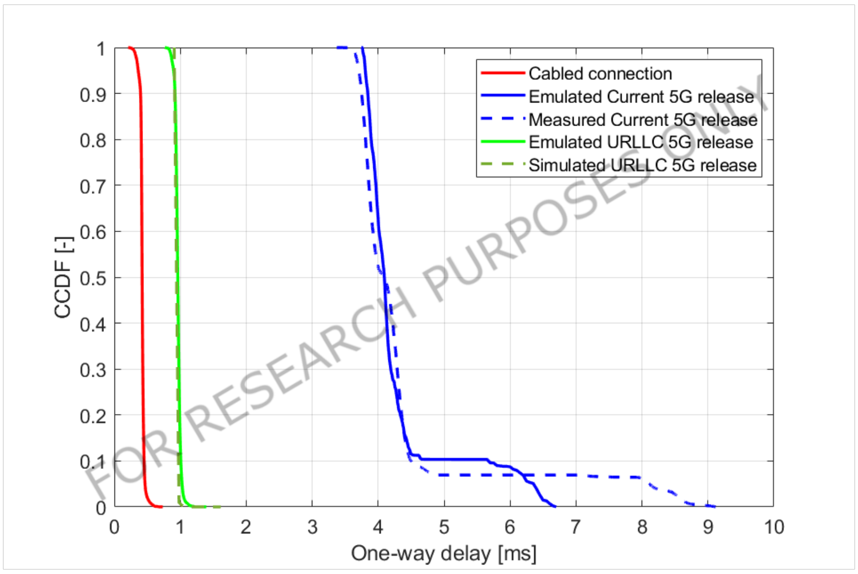

Figure 3.8: CCDF of 5G configurations and there emulated CCDF in the delay box.

ones observed in private 4G networks, and are approximately 15 ms better than to those experienced in public networks [6].

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 [7].

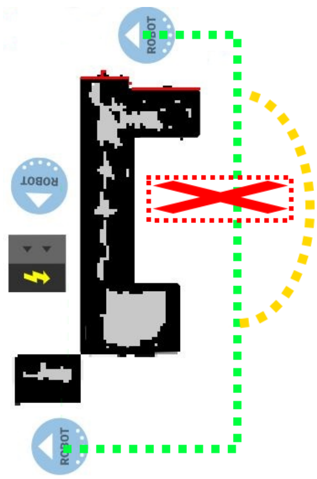

Figure 3.9: Test environment, with planned path marked in green, alternative path marked in yellow and red illustrating the dynamic object.

Results

Table 3.2: 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	0.154
URLLC 5G release	18 m 36 s	0.108

Table 3.2 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 11 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 0.108‰ and 0.154‰, which can be considered negligible or significantly low than other expected operational delays, such as waiting time between missions or stops to avoid collision with other robots.

3.5.3 Test Journal - Docking test

Purpose of the Test

The objective of this test is to compute the approach accuracy obtained for the different configurations.

Theory

As the AMR is set to dock to a charging station, will it not plan a global path, but use relative move. As these moves are determined based on feedback on sensors, will a delay between the planner, which issues the move commands, and the sensors cause the AMR to constantly sway from side to side to locate the marker on the docking station.

Test Setup

For this test, a separate device running the planner was connected to the AMR. In between the AMR and separate planner, is a delay box placed, which will emulated the delays of 5G. A top module were connected to the AMR, but as it were not active during the test, it is expected that it therefore does not contribute to the tests.

The test environment is illustrated in Fig.3.11.

Three different configurations will be tested, a cabled planner, Current 5G release and URLLC 5G release. A CCDF of these configurations can be seen in figure 3.10, where the configurations with the corresponding CCDF of the emulated delay in the delay box.

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 [6].
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 [7].

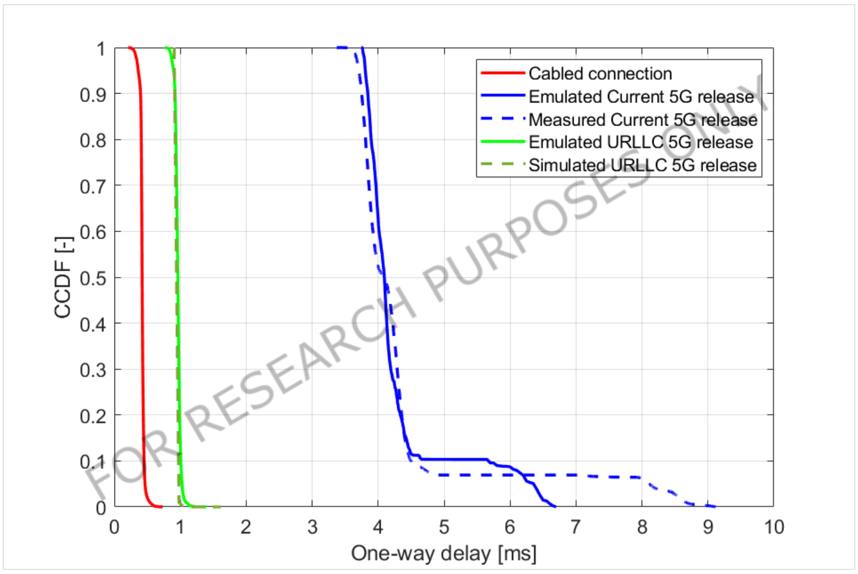

Figure 3.10: CCDF of 5G configurations and there emulated CCDF in the delay box.

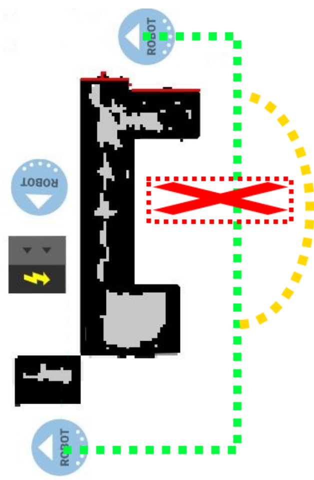

Figure 3.11: Test environment, with the docking test located at the middle left in the illustration.

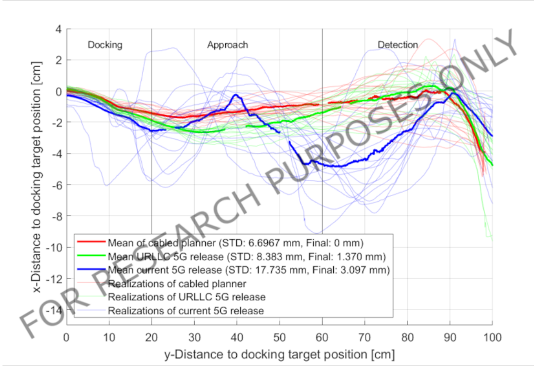

Figure 3.12: Location of AMR during the different docking tests for the different planner communication configurations.

Table 3.3: 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

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 3.3.

3.5.4 Test Journal - Test of batching

Purpose of the Test

To determine the most reasonable hold back, needed for optimal communication when using batching.

Theory

As a significant amount of packets transmitted between the robot and planner is in the form of small tcp ack packets, can these be reduced to improve performance over wireless medium. As multiple smaller packets takes resources, which is better allocated to larger packets. It is beneficial to collect smaller packets to be transmitted as one big packet. An emulation of the improvement of batching can be seen in 3.13. A limitation of this emulation is ability to only send packets when a new is received.

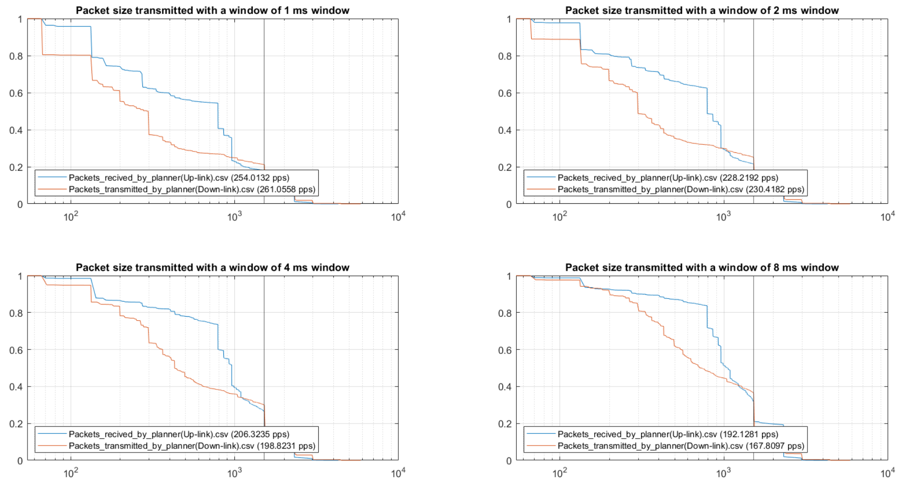

Figure 3.13: The expected results by batching with different hold back times.

Test Setup

The robot is set to passively transmit data, while communicating to the planner over 5G. The gateway used will be set to batch all incoming packets.

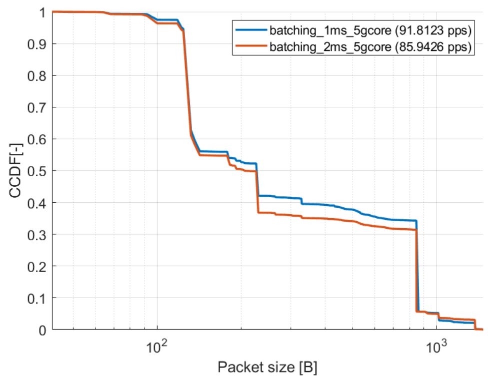

Figure 3.14: CCDF of transmitted packets between gateways

Results

[h] As the result show, can a small bathing window reduce the amount of packets transmitted by 7% Due to new configurations on the robot used, were a detraction in stability of communication, it was therefore not possible to conduct a full and test with batching latency higher than 3 ms. If increasing the delay was possible is it expected to improve the batching capabilities. Further working in this in this needs to investigate the reason for instabilities and the optimal hold back.

3.5.5 Test Journal - Stability of planner/robot connection over 5G

Purpose of the Test

The object of this test is to determine the stability of a centralised planner, when communicating over a 5G connection.

Theory

As previous test have indicated no failings in the communication between the planner and robot is it not expected to any difficulties arises.

Test Setup

For this test, will the robot be set up and not instructed to do anything. It is expected that the passive information flow between the planner and robot is sufficient to determine any initial problems with the connection.

Results

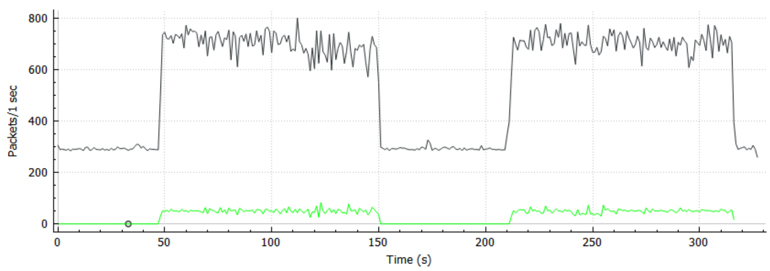

Figure 3.15: Packet transmitted between the planner and robot, with total amount of packets show in black and packets regarding laser scanner in green.

As it can be seen from the figures does the connection experience a drop in connection. It can be under further investigation can it be seen that the laser sensors loses connection with the planner. The connection is lost for 60 s until it reconnect. This disconnect happens every 100 s. When compared to tcp setting does this fit the frequency if retransmissions attempts of *tcp_retries* were set to 9.

3.6 Dealy box

To test if a system is effected by the inclusion of delay between critical components, will a delay box be used. The use of which allows for control over the delay applied to a connection. This creates an controlled environment in which the delay can be fine tuned, and the effects can be be observed. The dealybox is constructed using a raspberry pi 3b with 2 additional USB to Ethernet adapters. One of the Ethernet adapters and the default Ethernet connection on the raspberry pi is used for bridging. This allows the delaybox, when connected inbtween to devices or parts of the network, to become transparent. The bridge is set up using the following commands:

```
$ sudo brctl addbr br0
$ sudo brctl addif br0 eth0 enx00e04c686510
$ sudo ip link set br0 up
```

Listing 3.5: Chancing the MTU of the 5G interface to transmit packets of max 1500.

With the bridge set up, can delay now be applied to each interface. Netem [8] is utilised for this as it allows network emulation. By applying a set delay to one of the interfaces used for bridging can this emulate the distribution of a wireless connection. As stated in its own documentation can netem emulate different distributions, but to ensure identical operations to emulated technology is a set of samples from a real life measurement used. A wrapper function in the gateway reads the samples and picks two at random to apply to the each interface on the bridge. After a set duration of 100ms will the program reconfigure the delay, by randomly selecting two new delays from the samples to apply to the interfaces. Bursts of messages will have the same delay added to them, but the overall distortion will approach what is to be expected in the simulate wireless network. While this creates skewed results when executing a small test, will it avoid achieving delays otherwise impossible for the technology emulated.

3.7 Gateway

To enable bridging functionalities over wireless networks will a customize piece of software be used. Devices running the software will be referred to as gateway(GW). To modify communication between two devices from a wired connected connection to the wireless domain, is it necessary to adapt configurations on the end devices. This can be in the configuration of new modems to allow for a connection to be established. However, it is not always possible to do these modifications. To circumvent this problem will the wireless communication be move to an external device. This devices will be the GW and will be received packet from an Ethernet connection. The packets are in the GW encapsulate and transmitted over a wireless medium to a receiving GW. The receiving GW will the decapsulate the packets and send the packets on an Ethernet interface to the end device. This allows the gateways to be invisible for the end devices as they only receive Ethernet packets. This grants the same functionalities as bridging, but with the include used of a wireless network. Furthermore the GW include functionalities to destinies MAC addresses, allowing for multiple GW to be connected together, with different wireless technologies. As this aspect of the GW is not used in this project, will it not be discussed. When accommodating packets larger than the MTU of a given wireless technology, is fragmentation done automatically in the gateway. This is because the encapsulated packets are seen as raw data which can be fragmented during transmission. When using the gateways can the transmission time dramatically increase as transmission over a wireless domain has an increase latency compared to wired connections. It is therefore still necessary to ensure timeouts does not happen on the end devices. If a timeout is set lower than the expected round trip time for the wireless technology used, will the end device keep retrying to transmit data, while not accepting packets received by the wireless device.

For this project will the hardware used to run the GW software will be an intel NUC, with a 5G modem. The receiving GW will be run on a virtual machine connected to the 5G core.

3.8 Batching

A MiR robot uses robot operating system (ROS) [4] for internal communication. ROS is a common operating software for low-level system control and internal communication. It uses TCP to transmit predetermined payload between devices including communication with the planner. As the separation of planner and robot have been described previously in [5], will it not be described in detail. Initial measurements of the communication between the planner and robot reveals an total of 69 conversations, with a packet distribution illustrated in Fig. 3.16. Each of there conversation are individual

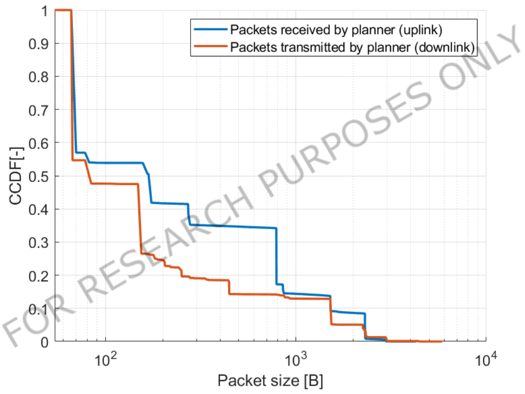

Figure 3.16: CCDF of distribution of packet sizes from communication between separated planner and robot.

TCP connections, which while under the influence of a batching algorithms still creates multiple small packets. As the "small packet problem" first described in [9] still arises, can an additional batching be applied to all conversations for reduced PPS. Table 3.4, shows the transmitted packets per second(PPS) and the corresponding percentage of packets only consisting of acknowledgement or selective acknowledgement. As the des-

Table 3.4: Small packet problem in communication between robot and separated planner

	Edge cloud planner	MiR robot
PPS	458.3	476.7
SACK/ACK	51.7%	45.8%

tination of all packets send are identical with only the port differing, can the batching of packet be applied post transmission.To gather the packes, it is requires any previous messages not already send, to be buffered along with any packets received. The buffer is to be transmitted when any new packet received exceeds the maximum transmission unit (MTU). As this can cause the system to have an inflated latency is an additional requirement necessary. An time limitation based on the earliest packet in the buffer. This allows the buffer to be transmitted early even if it is not full.

To separate the packets on a receiving will the header of the first packet in the receiving buffer be read. The length of this packet can be determined and removed from the buffer. If the size of the buffer is longer than the length of the removed packet, does the buffer contain more packets. The next packet can then be read and removed, this process is repeated until the all packets are removed from the buffer. This process of transmitting and receiving packets are depicted in Fig. 3.17.

Depending on the hold back time and the set buffer size can the delay be expected

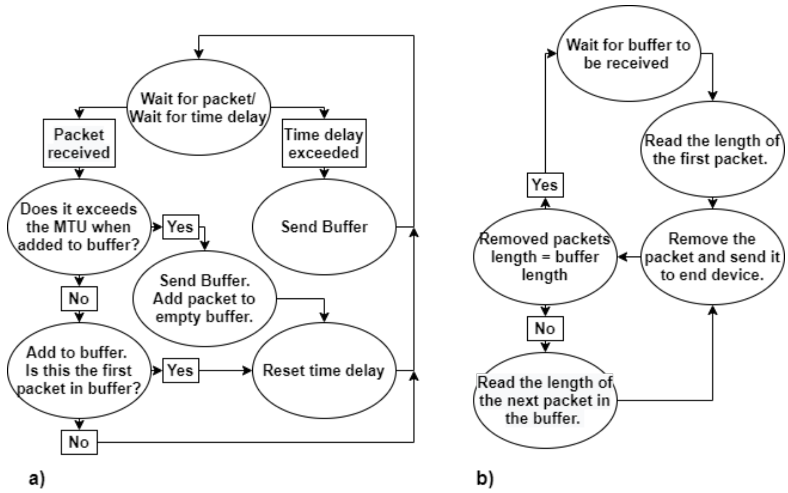

Figure 3.17: Flowchart illustrating a) transmitting logic for batching, and b) logic for separating packets.

to increase. This delay needs to be optimized to ensure optimal amount of packets are batched together, while ensuring the delay does not effect safe operations of the robot. It is therefore necessary to identify which hold back time is optimal to allow for maximum MTU while not adversely affecting the communication.

3.9 Network sniffer

To determine the communication on a wired connection, without interfering with the device connected, will the network sniffer be used. This customized device is designed to be placed on an existing connection, and record the communication for later analyses. The network sniffer is a raspberry with an additional Ethernet adapter added. When the network sniffer is placed on an connection, is a bridge interface created between the two Ethernet ports. This allows the raspberry to become invisible for devices connected to the network. To capture traffic on the connection is TCPDUMP used [10]. TCPDUMP creates a copy of information received from the network interface card. This information is then saved, and can later be retrieved for analyses. As the sniffer is additional device the data needs to pass through, will it slightly increase the transmission time for packets on the network.

Bibliography

[1] E. Dahlman, S. Parkvall, and J. Sköld, *5G NR: The Next Generation Wireless Access Technology*, 1st ed. Academic Press, Inc., 2018.

[2] A. Molinaro and C. Campolo, "5g for v2x communications," *5G Italy White eBook*, 2019.

[3] M. Kottkamp, A. Pandey, D. Raddion, A. Roessler, and R. Stuhlfauth, *5G New Radio: Fundamentals, procedures, testing aspects*, 4th ed. Rohde&Schwarz GmbH & Co. KG, 2019.

[4] Open Robotics. Robot Operating System (ROS). [Online]. Available: https://www.ros.org/

[5] T. Raunholt, P. Mogensen, I. Rodriguez, and M. Larsen, "Towards a 5g mobile edge cloud planner for autonomous mobile robots," *International Conference on Intelligent Robots and Systems*, 2021, in consideration.

[6] I. Rodriguez, R. S. Mogensen, A. Schjørring, M. Razzaghpour, R. M. Cuevas, G. Berardinelli, R. O. Adeogun, P. H. Christensen, P. E. Mogensen, O. Madsen *et al.*, "5G Swarm Production: Advanced Industrial Manufacturing Concepts enabled by Wireless Automation," *IEEE Communications Magazine*, vol. 59, no. 1, pp. 48–54, 2021.

[7] G. Pocovi, H. Shariatmadari, G. Berardinelli, K. Pedersen, J. Steiner, and Z. Li, "Achieving Ultra-Reliable Low-Latency Communications: Challenges and Envisioned System Enhancements," *IEEE Network*, vol. 32, no. 2, pp. 8–15, 2018.

[8] The linux foundation. netem. [Online]. Available: https://wiki.linuxfoundation.org/networking/netem

[9] "Congestion Control in IP/TCP Internetworks," RFC 896, Jan. 1984. [Online]. Available: https://rfc-editor.org/rfc/rfc896.txt

[10] The linux foundation. tcpdump. [Online]. Available: https://www.tcpdump.org/