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Abstract

This deliverable presents the final report on the 5G network performance evaluation within the 5G-Blueprint project, focusing on three trial locations: a cross-border site between Zelzate in Belgium and Sas van Gent in the Netherlands, the Port of Antwerp in Belgium, and Vlissingen in the Netherlands. The document outlines the chosen key performance indicators (KPIs) for technical evaluation, the testing methodology involving Points of Control and Observation (PCOs), and the categorization of measurements into foreground and background network measurements. The evaluation, conducted through active test campaigns, utilizes an advanced set of tools to ensure statistical significance. The report provides an overview of the 5G network architecture, deployment details, and results of the performance evaluation for each trial site. Notable findings include successful cross-border teleoperation with a handover interruption time below 150ms, efficient 5G slicing at the Port of Antwerp, and the impact of slicing on mitigating performance issues in the Dutch trial site's non-standalone (NSA) network compared to the standalone (SA) network. The comprehensive evaluation offers insights into meeting use case and enabling function requirements across diverse scenarios.

Keywords: 5G, evaluation, network slicing, KPIs, seamless roaming, methodology, interruption time, trials, 5G NSA, 5G SA, evaluation tools

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Disclaimer

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Dissemination Level		
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DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

OTHER: Software, technical diagram, etc

EXECUTIVE SUMMARY

The scope of this deliverable is to provide the final report on the 5G network performance evaluation for all the trial locations that have been defined in the context of the 5G-Blueprint project. The aim is to evaluate the performance of the different 5G network deployments and investigate whether they are able to fulfill the use case and enabling function requirements. Within 5G-Blueprint, three trial locations have been identified, namely the cross-border trial site located between the towns of Zelzate in Belgium and Sas van Gent in the Netherlands, the Belgian trial site located at the Port of Antwerp and the Dutch trial site located at Vlissingen.

The deliverable starts by listing the considered 5G network key performance indicators (KPIs) and their definition. These KPIs have been carefully selected by the consortium in an iterative manner resulting in a consolidated list and they have been used for the technical evaluation of the 5G network performance.

Furthermore, the testing methodology is described. In that direction, initially the Points of Control and Observation (PCOs) in an end-to-end manner have been identified, starting from standard and established conformance and interoperability testing methodologies. Hence, based on the location of the PCOs, the type of measurements can be either application-level or network segment measurements. Application-level measurements refer to end-to-end measurements focusing on the performance that is perceived by the users and the applications, while the network segment measurements focus on functional 5G network parts. The measurements are categorized based on the requirement of injecting data in the network to evaluate certain KPIs, resulting in two types: 1) foreground network measurements for which data is injected into the system under test to measure certain KPIs, 2) background network measurements, for which passive logging of metrics is required.

The network evaluation was conducted during several active test campaigns that were held at the different trial sites during a substantial number of testing days. To organize and structure the field tests, a template document was created to keep track of contextual information, such as date and time, test location, high-level 5G network details, participants on-site, weather conditions, etc. For both testing, logging, post-processing the logged data and visualizing the results, an advanced set of tools were built and used. Each KPI has been evaluated several times to ensure statistical significance.

Subsequently, the deliverable gives an overview of the 5G network architecture used, including Radio Access Network (RAN) and core aspects for each one of the trial sites. Moreover, it gives the details of the 5G network deployments, incorporating relevant RAN and core information. Additionally, the results from the 5G network performance evaluation are described in detail for all the defined trajectories and locations of interest within each one of the three trial sites.

In Section 4 the evaluation at the cross-border site is presented, where the identified network KPIs have been measured for both Mobile Network Operators (MNOs), KPN and Telenet. In addition to that, the handover interruption time has been evaluated. The results showed that the requirements for teleoperation in a cross-border scenario can be met by the deployed 5G networks and the advancements implemented within 5G-Blueprint to enable seamless handover. The handover interruption time was proven to be less than 150ms. The evaluation procedure indicated that good coverage conditions, uplink-oriented network configuration and use of active antennas at the base stations could significantly improve the overall Quality of Service (QoS) and Quality of Experience (QoE) for the teleoperation use case.

In Section 5, the deliverable focuses on the Belgian trial site and the evaluation of the 5G standalone (SA) network deployed by Telenet at the Port of Antwerp. During the evaluation, tests have been performed both on the water both in the port and on the Schelde river, as well as on the road along the port. In addition, tests were conducted at a second region including the Roossens Transport premises and a milk run from Roossens Transport to Medrepair, which is a terminal nearby. 5G network slicing has been evaluated for three different defined slices on top of the Telenet 5G network, namely eMBB, URLLC and Live Streams. The results from the KPIs evaluation showed that the deployed 5G network is capable to satisfy the defined requirements from the use cases and the enabling functions at the Port of Antwerp, as well as around the Roossens Transport premises. Poor performance was observed at the milk run from Roossens Transport towards the Medrepair due to the very challenging environment resulting in poor coverage in that area. This is a result of the presence of massive number of containers, numerous large trucks driving around and the elevation of the roads. However, that part of the milk-run was considered less important and did not affect the evaluation of the use cases and enabling functions. Traffic prioritization through slicing has been evaluated showcasing how slices (e.g., URLLC) can be more resilient to background traffic, which is of high importance for teleoperation.

In Section 6, the deliverable discusses the evaluation of the 5G network deployments by KPN at the Dutch trial site in Vlissingen. There, several identified locations and milk runs have been tested. These locations include the Verbrugge Terminals covered by a 5G SA deployment from KPN, as well as the Kloosterboer terminals, the MSP Onions premises and two milk-runs (from MSP Onions to Kloosterboer terminals and from Verbrugge Terminals to Central Gate) all covered by the 5G non-standalone (NSA) production network of KPN. On top of the 5G SA network at Verbrugge Terminals, the performance of 5G slicing has been evaluated for eMBB and URLLC slices. The results showed that URLLC slice offers improved overall latency over eMBB and that the latency is more resilient to background traffic. In addition, all the KPIs showed that the performance of the network is in line with the requirements imposed by the use cases and enabling functions. The evaluation of the 5G NSA network along the milk run trajectories, MSP Onion terminal and Kloosterboer terminals in Vlissingen showed lower performance compared to the SA network at the Verbrugge terminal. For instance, the average one-way latency recorded at the SA network was two times lower than the one achieved at the NSA. Nevertheless, an aspect that may impact the performance is that the NSA network was a production network, meaning that it was open to other subscribers of KPN. It was shown that 5G slicing is a technology that can mitigate this impact and offer the performance guarantees that are required for teleoperation.

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ABBREVIATIONS

Acronym	Description
AMF	Access and Mobility Management Function
DUT	Device Under Test
eMBB	enhanced Mobile Broadband
FAR	Forwarding Action Rule
GNSS	Global Navigation Satellite System
GTP-U	GPRS Tunneling Protocol User Plane
H-AMF	Home Access and Mobility Management Function
H-SMF	Home Session Management Function
H-UPF	Home User Plane Function
HPLMN	Home Public Land Mobile Network
KPI	Key Performance Indicator
MNO	Mobile Network Operator
NF	Network Function
NGAP	Next Generation Application Protocol
NR	New Radio
NSA	Non-Standalone
OWL	One-way latency
PDR	Packet Delivery Rate
PLMN	Public Land Mobile Network
PPS	Pulse Per Second
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RTT	Round Trip Time
SA	Standalone
SM	Session Management
SMF	Session Management Function
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communications
V-AMF	Visited Access and Mobility Management Function
V-SMF	Visited Session Management Function

V-UPF	Visited User Plane Function
VPLMN	Visited Public Land Mobile Network

1 INTRODUCTION

This deliverable constitutes the final report on the comprehensive evaluation of 5G network performance within the context of the 5G-Blueprint project, with a primary focus on three designated trial locations: the cross-border site between Zelzate in Belgium and Sas van Gent in the Netherlands, the Belgian trial site situated at the Port of Antwerp, and the Dutch trial site located at Vlissingen. The overarching goal is to assess the efficacy of various 5G network deployments in meeting specified use cases and enabling function requirements. The document initiates by defining the chosen 5G network key performance indicators (KPIs) derived through a consortium-driven iterative process. These KPIs form the basis for the subsequent technical evaluation of 5G network performance.

The testing methodology is built upon the definition of Points of Control and Observation (PCOs) in an end-to-end approach, drawing from established conformance and interoperability testing methodologies. The subsequent categorization of measurements into application-level and network segment measurements is described, distinguishing between end-to-end assessments focused on user and application experience and functional evaluations of 5G network components. This categorization further leads to the differentiation between foreground network measurements, involving data injection for specific KPI evaluation, and background network measurements, relying on passive logging of metrics.

The execution of the network evaluation is performed through multiple active test campaigns conducted at diverse trial sites over numerous testing days. To ensure qualitative organization and documentation of field tests, a template document is introduced, capturing contextual information such as date, time, test location, 5G network details, participants, and weather conditions. Advanced tools are employed for testing, logging, post-processing, and visualizing results, with each KPI subjected to repeated evaluations to ensure statistical significance.

Following this, the document provides an overarching view of the 5G network architecture, encompassing Radio Access Network (RAN) and core aspects for each trial site, coupled with detailed information about the 5G network deployments. Subsequently, it delves into the specifics of the 5G network performance evaluation for the defined trajectories and locations of interest within each trial site, starting with the cross-border site, progressing to the Belgian trial site at the Port of Antwerp, and concluding with the Dutch trial site in Vlissingen. Each section outlines the unique aspects of the evaluation, emphasizing the nuances of network deployment and the corresponding evaluation outcomes.

The remainder of the document is organized as follows. In Section 2, a definition of the used KPIs is given. Next, the methodology and tools to measure the KPIs are described in Section 3. Section 4 presents the 5G architecture and deployment at the cross-border site and discusses the evaluation results of the conducted 5G tests, including the assessment of the seamless cross-border handovers and their interruption times. Similarly, the Belgian (Port of Antwerp) and the Dutch (Vlissingen port area) trial sites are analyzed in Sections 5 and 6 respectively. Finally, conclusions and lessons learned are listed in Section 7.

2 DEFINED 5G NETWORK KEY PERFORMANCE INDICATORS (KPI)

To assess the performance of the deployed 5G networks at the different trial sites, several network KPIs have been defined within the context of 5G-Blueprint WP5. An iterative process of defining, prioritizing, and selecting the relevant KPIs to be evaluated, resulted in a consolidated list of networking KPIs, which are listed in Table 1, that have been used for the technical evaluation of the 5G network performance. Three types of KPIs have been outlined: general KPIs (KPI_{1_x}), modem stats (KPI_{2_x}) and handover KPIs (KPI_{3_x}). Several tools have been used to measure these KPIs during active measurement campaigns, which are described in Section 3.

ID	KPI	Description	Measurement
KPI_{1_1}	TCP DL	Max user experienced TCP downlink rate	Measured with the IPerf tool the achieved TCP downlink (1 stream) observed at the UE (Mbps) with 1s interval
KPI_{1_2}	TCP UL	Max user experienced TCP uplink rate	Measured with the IPerf tool measuring achieved TCP uplink (1 stream) observed at the server with 1s interval
KPI_{1_3}	UDP DL	Max user experienced UDP downlink rate	Measured with the IPerf tool the achieved UDP downlink (1 stream) observed at the UE (Mbps) with 1s interval
KPI_{1_4}	UDP UL	Max user experienced UDP uplink rate	Measured with the IPerf tool the achieved UDP uplink (1 stream) observed at the server (Mbps) with 1s interval
KPI_{1_5}	RTT	RTT is measured between the UE and Core server or 8.8.8.8	Measured by sending pings with 1s interval between the UE and the server (ms)
KPI_{1_6}	OWL	One way latency is measured between the UE and the IMEC IPerf server	Measured latency by sending UDP packets (10Hz) from the UE towards the server (ms) using time synced end points
KPI_{1_7}	Reliability	Reliability is measured between the UE and the IMEC IPerf server	Measuring the PDR (Packet Delivery Rate) and mapping it to several latency thresholds. Reliability is defined in 3GPP as capability of transmitting a given amount of traffic within a predetermined time duration. It is defined as the PDR for a certain latency threshold, where packets that arrive later than this threshold are considered as lost.

KPI_{1_8}	PDR	Packet Delivery Rate measured between the UE and the IMEC IPerf server	Measured the PDR by sending UDP packets (10Hz) from the UE towards the server (ms)
KPI_{2_1}	RSRP	RSRP (Reference Signal Received Power) value	RSRP value from the modem via AT serial commands with 1s interval
KPI_{2_2}	RSRQ	RSRQ (Reference Signal Received Quality) value	RSRQ value from the modem via AT serial commands with 1s interval
KPI_{2_3}	RSSI	RSSI (Received Signal Strength Indicator) value	RSSI value from the modem via AT serial commands with 1s interval
KPI_{2_4}	Cell ID	Cell ID value	Cell ID value from the modem via AT serial commands with 1s interval
KPI_{2_5}	MNC	Mobile Network Code value	MNC value from the modem via AT serial commands with 1s interval
KPI_{2_6}	MCC	Mobile Country Code value	MCC value from the modem via AT serial commands with 1s interval
KPI_{3_1}	E2E Handover interruption time (cross border)	Time duration for which a terminal cannot exchange packets with another end point (terminal or server) due to cross border handover procedure.	Actively measured by sending huge number of packets from terminal to server and measuring the max inter-packet arrival time at the server when cross border handover is happening.
KPI_{3_2}	Core handover interruption time (cross border)	Time duration of the cross-border handover procedure happening in the core networks on the 5G control plane.	The time between the UE abandoning its connection at the serving cell, and the tunnels being configured to forward data in the target network

Table 1: Evaluated end-to-end KPIs

3 METHODOLOGY AND TOOLS

Within WP5 of the 5G-Blueprint project, the focus lies on the evaluation and analysis of the technical network performance achieved in the 5G networks from an end-to-end perspective, providing insights on the expected performance towards the teleoperation use cases and its enablers being designed, developed, implemented, and evaluated in WP4, WP6 and WP7.

Starting from standard and established conformance and interoperability testing methodologies, one of the first steps is to identify the potential location of Points of Control and Observation (PCOs) [1] in the system under test where measurements will be taken.

Based on the location of the PCOs, the type of measurements that have been performed can be differentiated as follows [1] [2]:

1. Application-level measurements

   These end-to-end measurements focus on the performance that is perceived by the users and its applications, and as such the logging of the data is being conducted at the application level, both at the client side (UE/OBU) and the application server. For these measurements, the considered PCOs (Points of Control and Observation) are located in these entities. This evaluation is done as part of WP7.

2. Network segment measurements

   These measurements are obtained by using logging data in the functional 5G network segments, for which the PCOs can be located at the end points and intermediate network segments at the transport layer or access layer. These measurements can be end-to-end or taken in a single network entity.

All the measured KPIs (see Table 1) are considered as network segment measurements (end-to-end and at the transport level), apart from the *modem statistics* (KPI_{2_x}) which are access layer measurements and the *core handover interruption time* (KPI_{3_2}), which is computed at the 5G core network entity.

[1] A Point of Control and Observation is a point in the system under tests at which an observation is recorded both for foreground and background measurements.

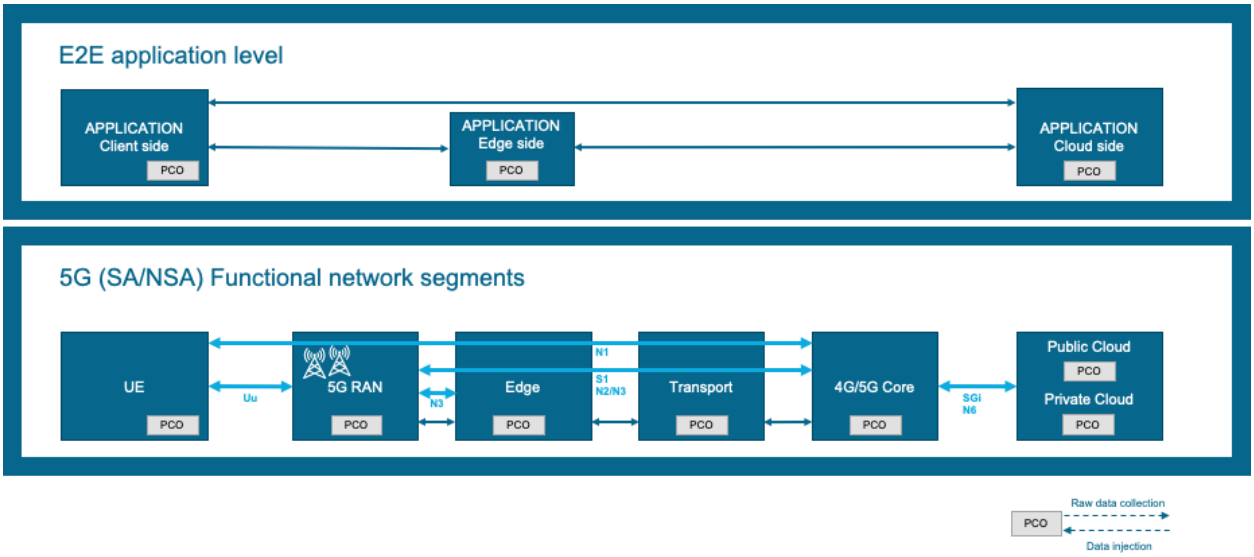


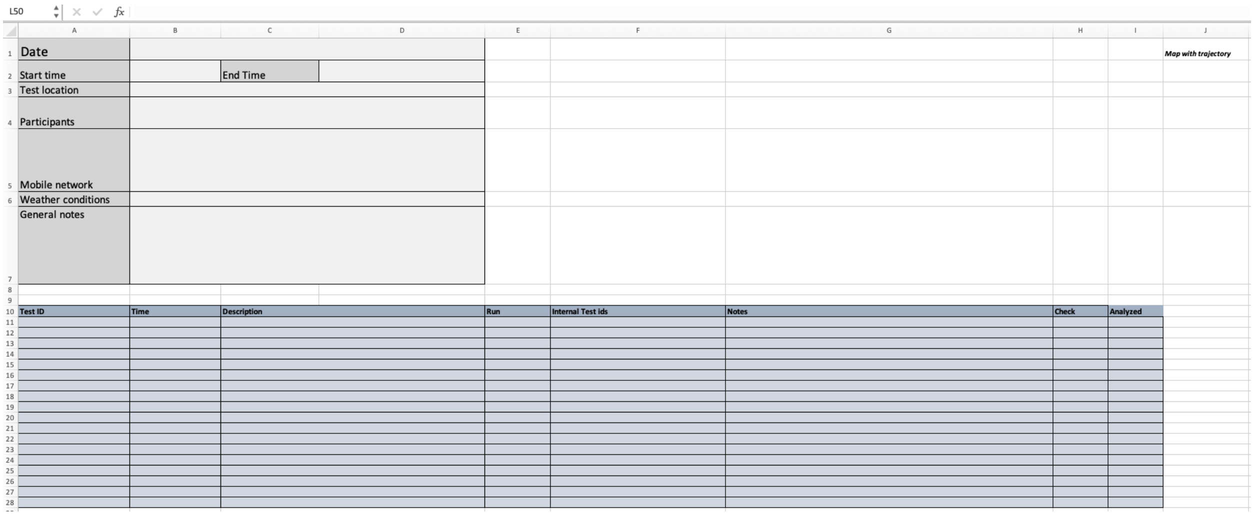
Figure 1: 5G system under test

Likewise, the measurements can be categorized based on the requirement of injecting data in the network to evaluate certain KPIs. That results in two types:

1. **Foreground network measurements:** the result of a measurement for which data is injected (using specific evaluation tools, e.g. IPerf, …) into the system under test to measure certain KPIs.
2. **Background network measurements:** the result of a measurement of the system under test by passively logging metrics from the system or data transferred by the applications running over the system. Examples: data logged from the UE (such as RSRP, RSRQ), packet traces at the PCOs (e.g. using TCPdump, Wireshark), …

As such, KPI_{1_x} and KPI_{3_1} are examples of foreground metrics and KPI_{2_x} and KPI_{3_2} are examples of background metrics.

The network evaluation was conducted during several active test campaigns that were held at the different locations during a substantial number of testing days. To organize and structure the field tests, a template Excel document was created to keep track of contextual information, such as date and time, test location, high level 5G network details, participants on site, weather conditions, etc. (See Figure 2). Details of each test were filled during the day, to keep track of start time, end time, description test id numbers, runs and annotations. Moreover, these completed forms provided an overview and guideline during the post processing of all the data afterwards.



Date			
Start time		End Time	
Test location			
Participants			
Mobile network			
Weather conditions			
General notes			

Map with trajectory

Test ID	Time	Description	Run	Internal Test Ids	Notes	Check	Analyzed

Figure 2: Field test form template

To execute the 5G-Blueprint network field tests, the IMEC BMW test car was used. The IMEC test car contains several network measuring equipment to assess the performance of the 5G networks under test according to the consolidated list of KPIs. The measuring equipment consisted of the following hardware:

- Gigabyte Brix PC and/or Intel NUC embedded PCs
- Mikrotik 4G router for remote management and data logging
- 5G UEs for 5G performance measurement
    - Fibocom FM150 5G modem
    - Quectel RM502Q
    - Sierra Wireless 5G router
    - OnePlus Pro 10 Smartphone
    - H155 5G router
    - 5G Oppo Smartphone
    - Netgear 5G Nighthawk
- Adafruit USB GNSS (Global Navigation Satellite System) receiver with PPS (Pulse Per Second) for accurate time syncing and positioning
- MobileMark 5G Magmount vehicle antennas
- Separate car battery and Victron Multiplus power unit

Figure 3: IMEC BMW test car with measuring equipment

At the backend side, an IMEC IPerf server was provisioned in the IMEC data center in Antwerp, including a GNSS receiver with PPS to support accurate time syncing. This server was also used for one-way latency measurements. For particular tests, an IPerf server inside the MNOs network was used. This one did not have accurate GNSS time syncing and, as a result, was not used for one way latency tests.

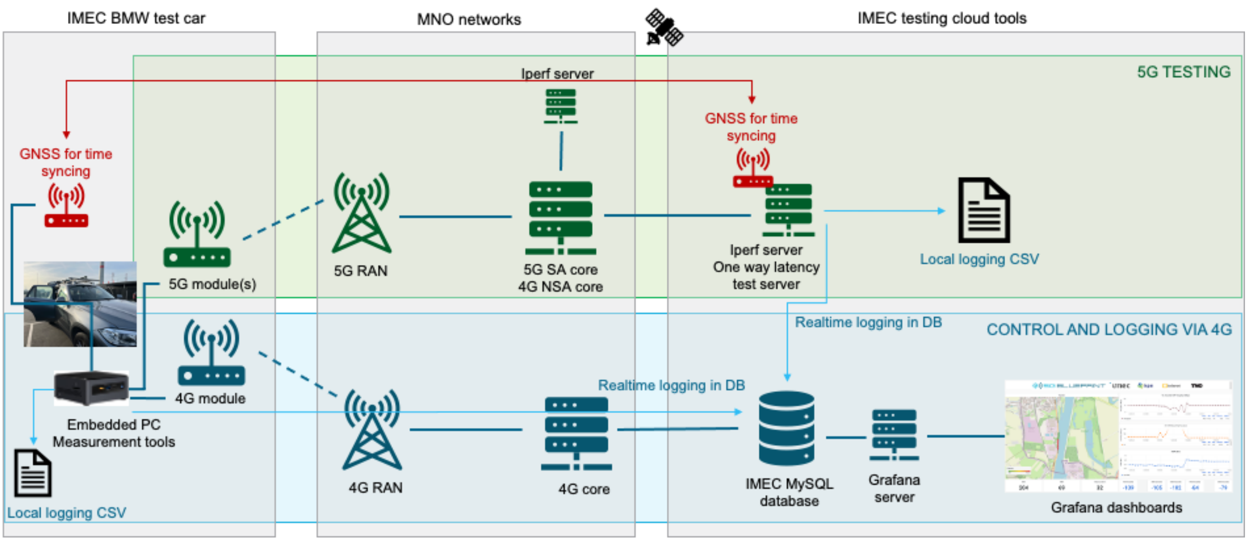


Figure 4: E2E network test methodology

An advanced set of tools were used to perform the measurements and evaluation of the list of networking KPIs according to the defined test plan. On top of some well-known open-source network measurement tools (such as IPerf and ping), IMEC developed its proprietary tools to allow for real-time logging of the tests in a structured way. Moreover, some in-house developed tools were implemented to measure one-way latency, packet delivery rate (PDR) and reliability.

The IMEC tools support both offline local logging, as well as real-time storing over 4G of logdata into a central MySQL database, to speed up the post processing analysis. The latter avoids manual copying and importing of csv file from the end-devices and IPerf server. Well-defined cvs log formats were created for all metrics that are logged offline. Furthermore, within the database, several tables were created to store all logdata in a structured way.

To visualize the logged data from the tests that resides in the database, Grafana dashboards were implemented. Using Grafana, several statistics taken from the measured logdata are calculated and can be presented to the user in a graphical (in graphs and maps) and interactive/intuitive way, allowing the selection of e.g. test ids, start and end times, etc… For the final demo event, also a dashboard was created to display dynamically and in real-time the current attached network and the interruption time that took place during a seamless handover (see Figure 5).

Figure 5: Current network and interruption time dashboard

For some of the KPIs (one-way latency, PDR, reliability), dedicated Python post-processing scripts were written by IMEC to retrieve the data from the database, make the necessary calculations and visualize the results in graphs. This is shown in Figure 6.

It should be noted that for the modem statistics (KPI_{2_x}), always the Quectel RM502 device was used during the measurements, because this device was supported by our testing scripts to retrieve the modem information via AT commands. However, on the 01/12/2022, also modem statistics were retrieved from a Fibocom modem (scripts were adapted for this) to have a comparison between the Quectel and the Fibocom. For the other KPI measurements, several types of 5G modems were used (Quectel, Fibocom, Sierra Wireless and Huawei)

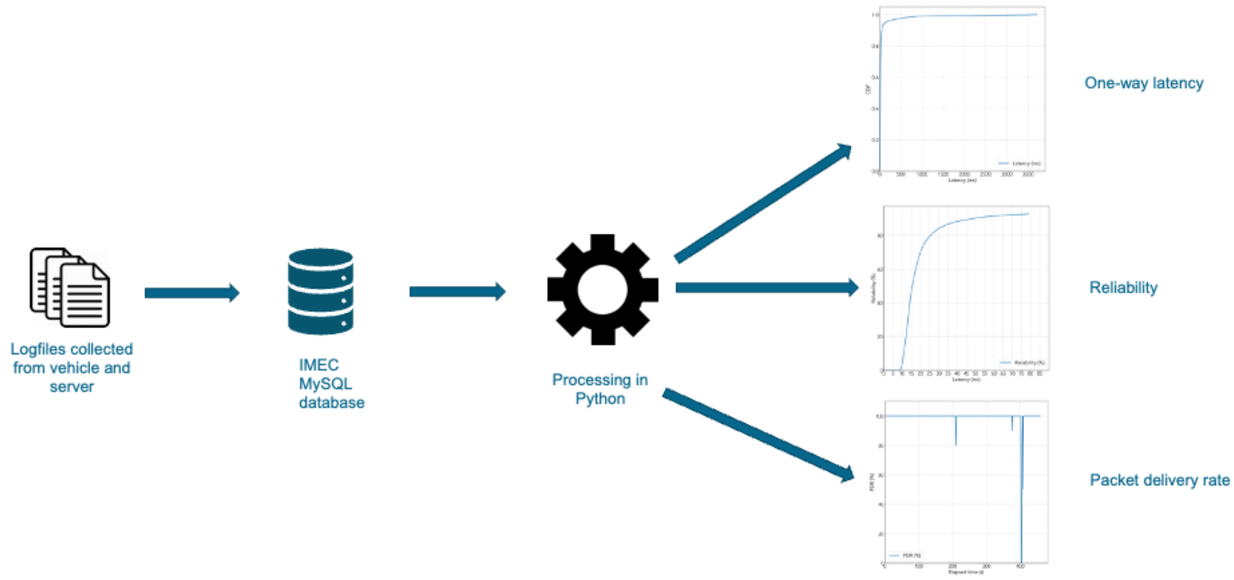


Figure 6: Postprocessing logdata with Python for a subset of KPIs (OWL, PDR and reliability)

4 CROSS BORDER SITE

4.1 5G Network Architecture

The architecture of the 5G Blueprint setup deployed at the border is shown in Figure 7. It consists of two identical roaming-enabled 5G SA cores, two gNBs, and multiple UEs (e.g., Quectel, Sierra Wireless, or Netgear 5G modem, or a smartphone). Note that although the picture shows KPN as HPLMN (and Telenet as VPLMN), the two deployed cores are identical, and that, consequently, the role of the PLMN (home or visited) would depend on the SIM card that is inserted into the UE (for example, the UE in Figure 7 has a KPN SIM card). Seamless handover was implemented and tested for both directions and SIM cards belonging to different PLMNs (e.g., Telenet, KPN).

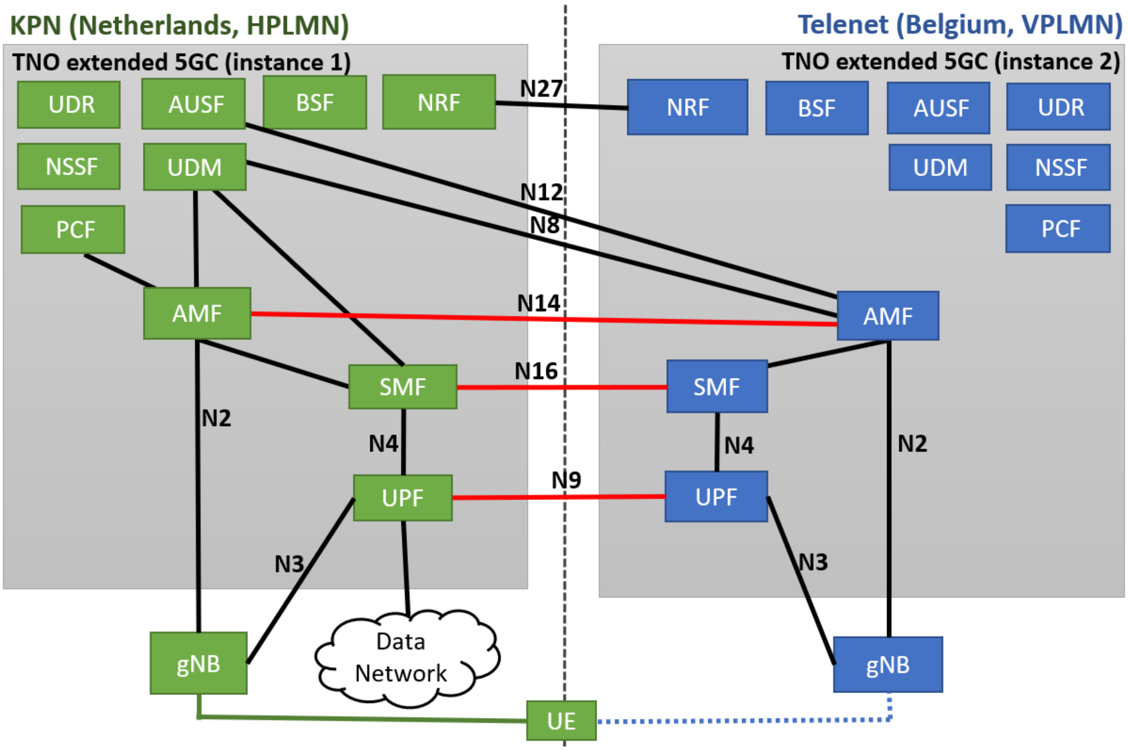


Figure 7: Architecture of the 5G deployments

4.1.1 Radio Architecture – Belgian Site (Telenet)

During the testing phase of 5G Blueprint, it was noticed that there was a low uplink capacity for the cross-border use cases.

In order to improve the uplink, Telenet has added a temporary mobile site, located close to the border and in reach of the gNB of KPN. This gNB is not part of the production RAN of Telenet and is only connected to the TNO core for the seamless roaming use cases.

For EF3, the production site in the center of Zelzate was chosen. The RAN network is similar to the RAN network in the Port of Antwerp, and is shared for the stand-alone and non-standalone networks.

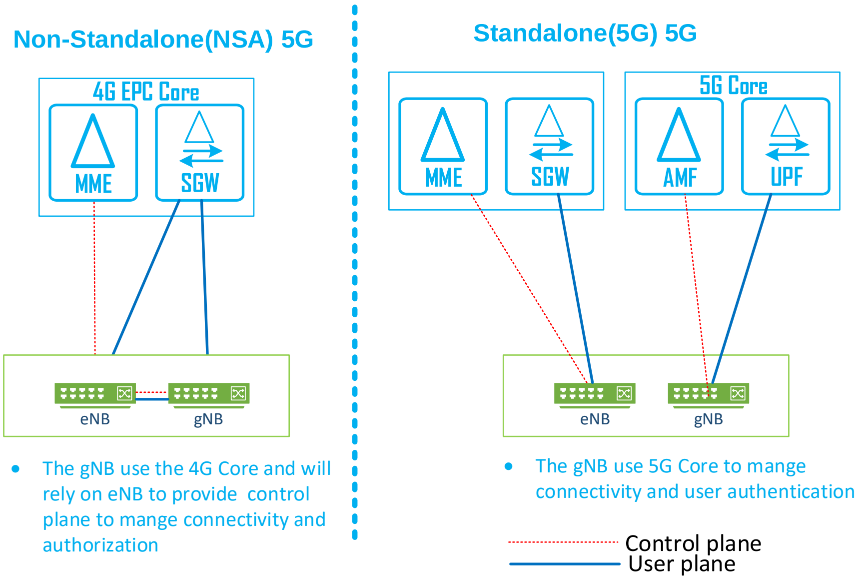


Figure 8: Telenet radio architecture at the border area

4.1.2 Radio Architecture – Dutch Site (KPN)

KPN has deployed a temporary 5G radio network at the border in Sas van Gent on a production location. The production site gave room to use the existing antenna and cabinet to setup the test network. For the test network our “test operator code” was used: 20469. The site was connected to an SA core, located in Eindhoven via the KPN transmission network.

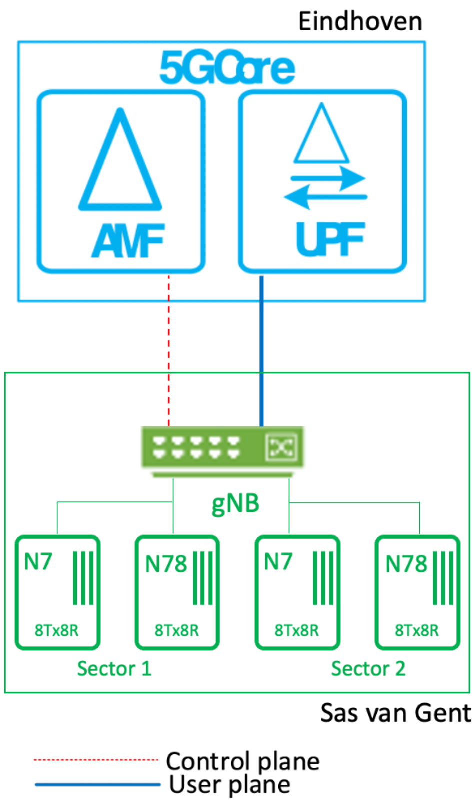


Figure 9 KPN Radio architecture at border area

4.1.3 Core Architecture – Belgian/Dutch Site

Two identical 5G SA cores, consisting of multiple Network Functions (NFs), shown in Figure 7, were deployed at the Dutch and Belgian sites. The only difference between the two cores was in their configuration. Namely, the PLMNID that was configured for them (20469 for KPN and 20620 for Telenet) and the subscribers (and corresponding SIM cards) that were provisioned depended on the country in which they were deployed.

To enable seamless roaming, the 5G SA cores combine procedures from the 16th Release of the 3GPP specifications (Home-Routed Roaming and N14 Handover) with the procedure proposed in clause 4.23 from 3GPP T.S. 23.502. The red lines in the figure show the interfaces (N9, N14 and N16) that have been developed by TNO during the project to obtain this goal.

To further reduce downtime, the original call flow (T.S. 23.503, clause 4.23) was further modified by transferring additional information on the UE context between PLMNs in the handover preparation phase, which allows removing two inter-PLMN messages between SMFs in the execution phase and reduces downtime. Namely, by transferring the SM context ID in the preparation phase, the N4 session modification procedure in the UPF of the HPLMN can be triggered by a pre-existing earlier message between the AMFs and does not require a message exchange between SMFs (which, as inter-PLMN messages, introduce a more significant latency penalty compared to intra-PLMN messages). Removing those messages allows us to perform the N4 session modification and restore connectivity sooner, ultimately reducing downtime.

Moreover, in the preparation phase, the uplink rules in the V-UPF are already provisioned to forward data, causing the uplink to work from the moment the UE is synchronized to the new cell in the VPLMN.

Figure 10 and Figure 11 illustrate the difference in downtime for both the uplink and downlink, without and with the proposed optimizations, respectively.

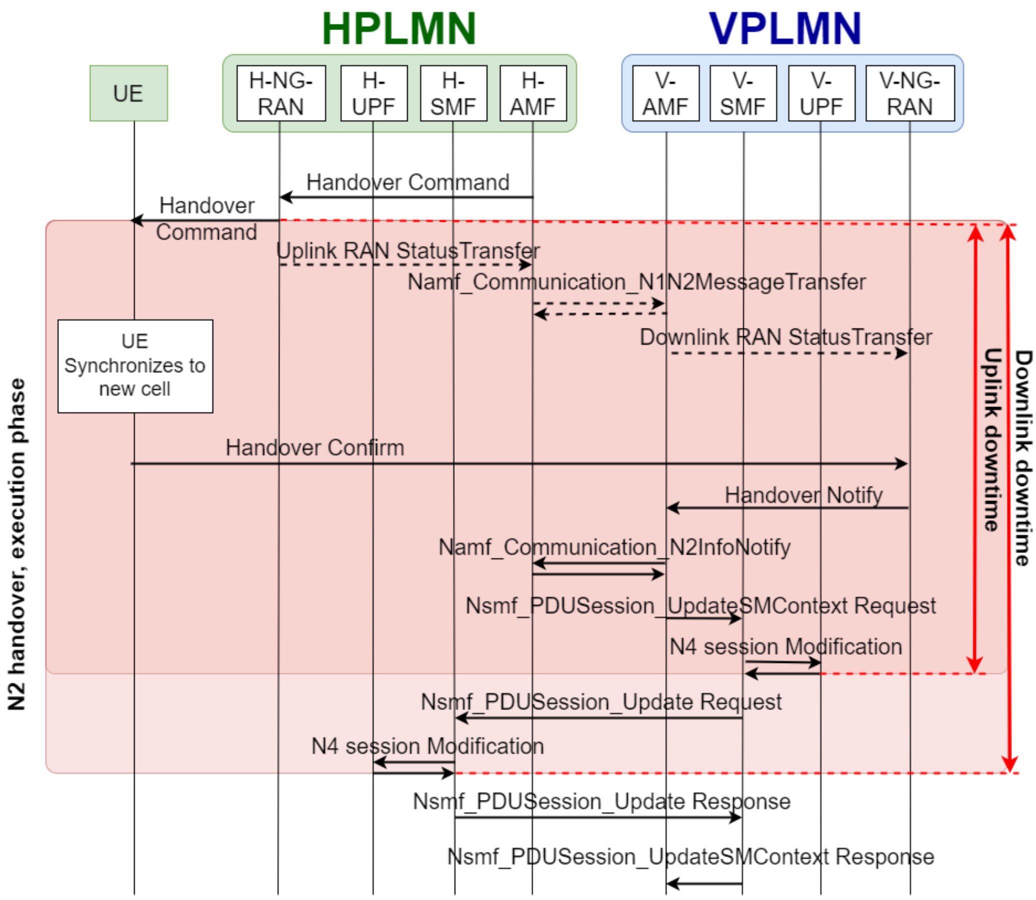


Figure 10: Original procedure as described in T.S. 23.502, clause 4.23.

Figure 10 shows the execution phase for the N2 handover procedure as described in the 3GPP standards in T.S. 23.502, clause 4.23. After the UE synchronizes to the new cell, and sends the Handover confirm message to the VPLMN, the V-AMF informs the V-SMF and H-AMF of this. V-SMF subsequently changes the associated Forwarding Action Rule (FAR) in the V-UPF for the uplink data to Forward. Next, the V-SMF informs the H-SMF and instructs it to change the downlink FAR to forward data to the N9 interface instead of the N3 interface. After this message, both uplink and downlink are re-established.

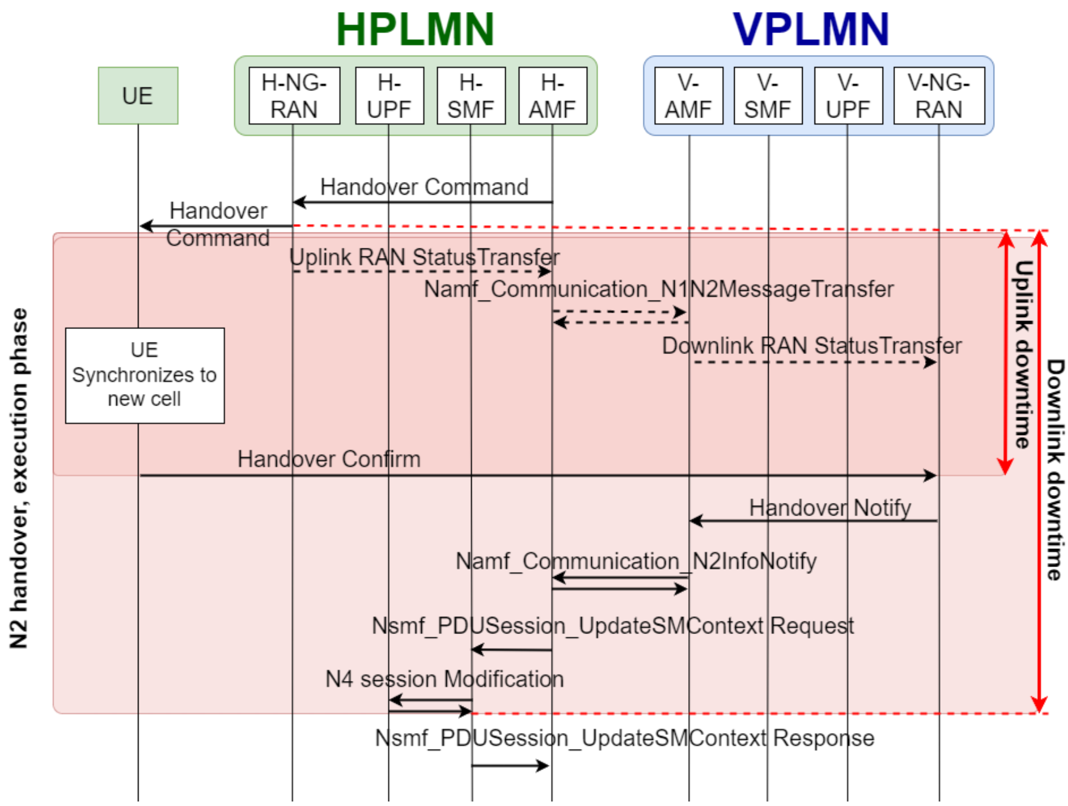


Figure 11: Optimized procedure as described in Section 6.1.3.

Figure 11 shows the optimized procedure as described in this section. After the UE synchronizes to the new cell, and sends the Handover confirm message to the VPLMN, the uplink data is already processed properly (as the uplink FAR was set to Forward in the preparation phase). Next, similar to the original procedure, the V-AMF informs the H-AMF that the handover was successful. Then, different from the standardized procedure, the H-AMF immediately informs the H-SMF which then directly changes the downlink FAR to forward data to the N9 instead of the N3 interface.

4.2 5G Network Deployment

Physically, the two roaming-enabled 5G SA cores were deployed at two different locations (one from KPN, and one from Telenet) and connected via an VPN. This is illustrated on Figure 12.

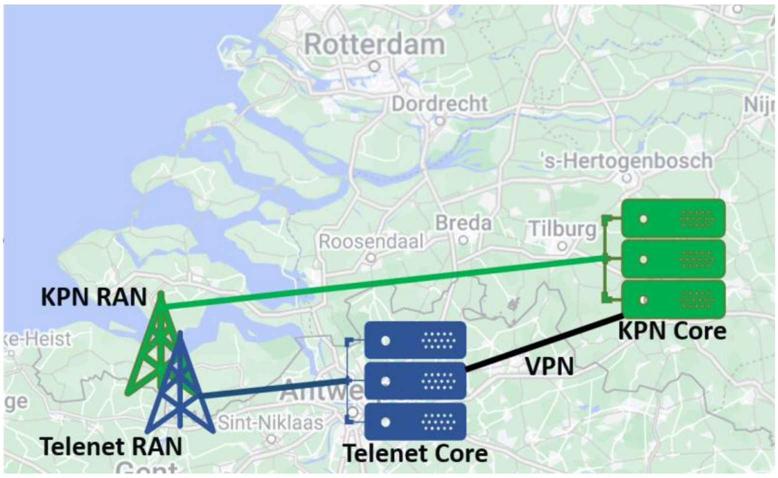


Figure 12: Physical deployment of the 5G SA networks

4.2.1 Radio Deployment – Belgian Site (Telenet)

Radio deployment at the Belgian site of the cross-border area is twofold:

1. Production site in the center of Zelzate, connected to the stand-alone and the non-standalone core
2. Mobile site at the border with the Netherlands, connected to the TNO core

1. Technical details of the actual deployment in the center of Zelzate:

- All 3 slices are available:
  - 5g-internet: the default slice
  - Live-stream: slice to prioritize video streaming
  - URLLC: slice with ultra reliable and low latency
- Center frequency: 3700 MHz
- Bandwidth: 50MHz
- Technology: 5G NR TDD
- Brand: Ericsson
- Transmission bandwidth: 1Gbps

2. Technical details of the mobile site at the border with The Netherlands:

- Center frequency: 3700 MHz
- Bandwidth: 50MHz
- Technology: 5G NR TDD
- Brand: Ericsson
- Transmission bandwidth: microwave

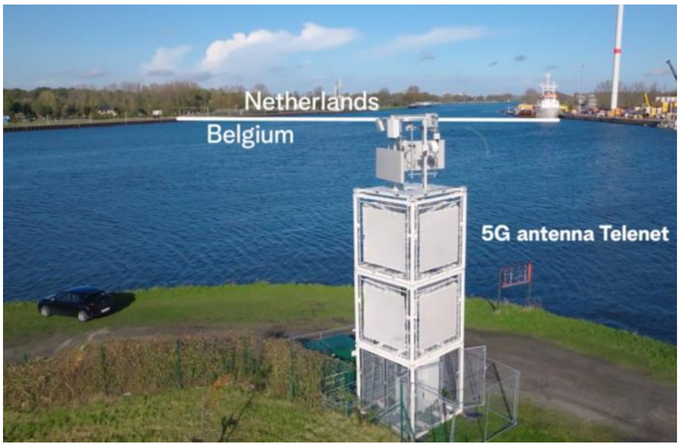


Figure 13: Mobile base station of Telenet at the border

4.2.2 Radio Deployment – Dutch Site (KPN)

At the Dutch part a production site has been reused. In the cabinet an extra BBU has been placed. In the tower 4 extra radio’s are attached to the production antenna at about 50 meters height.

Figure 14: Photo's of the Dutch site at Sas van Gent

In total two sectors have been deployed with each 2 bands (N7 and N78). The sector pointing towards Burem had to be limited in power to prevent distortion to the systems their using the same bands.

4.2.3 Core Deployment – Belgian/Dutch Site

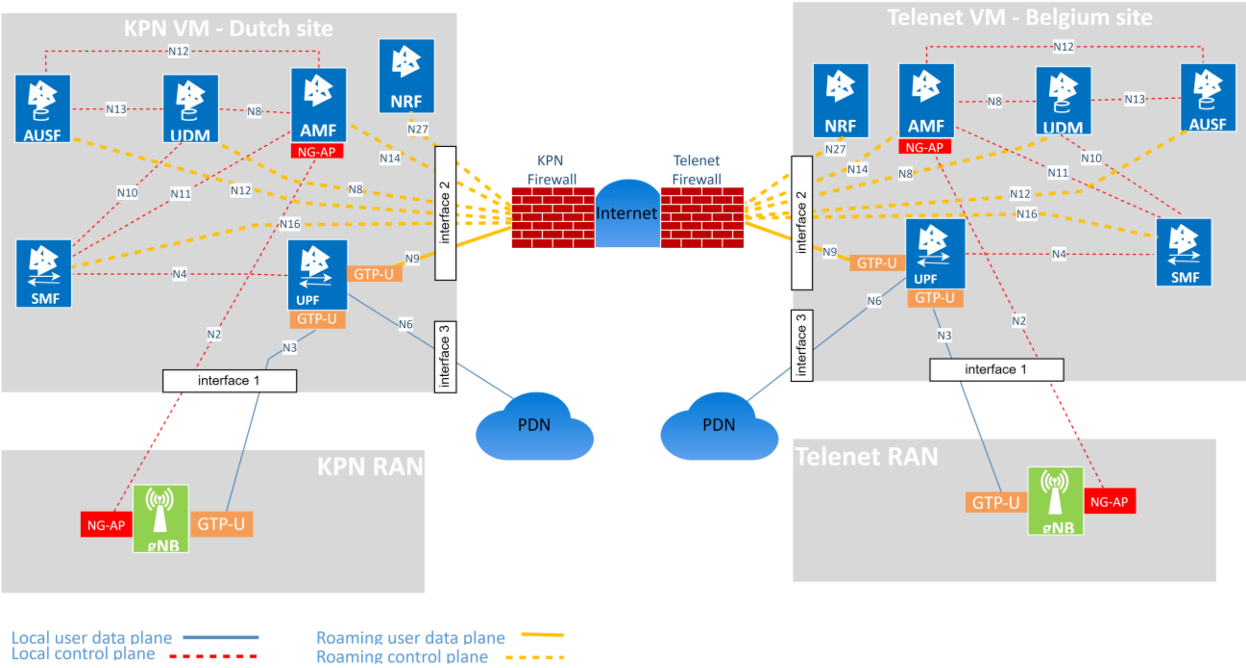


Figure 15: Interfaces between the 5G SA cores and the radio deployments.

Each roaming-enabled 5G SA core, as described in Section 6.1.3, was deployed in a virtual machine (VM) with three interfaces, as illustrated in Figure 15:

1. Radio interface (interface 1 in Figure 15). Over this physical interface communication, the 5G SA core was connected to its corresponding gNB. Therefore, it was used to transport the N2 (NGAP protocol) and N3 (GTP-U) traffic from the gNB to the 5GC NFs.
2. Inter-core interface (interface 2 in Figure 15). Over this physical interface, all the communication between the two 5G SA cores was exchanged. This traffic included all the control traffic needed to establish and maintain the roaming sessions (N14, N16, N27, N12, N8, etc.) as well as the UE's data traffic (GTP-U) traffic between the V-UPF and the H-UPF (N9 interface). Additionally, this interface was used to sync the clocks of the two VMs.
3. External interface (interface 3 in Figure 15). Over this physical interface, users' data was sent to the external PDNs (e.g., external servers for each of the use cases).

Note that due to the space constraints, the Figure 15 only displays a subset of the NFs running in each 5G SA core.

4.3 5G Network Evaluation

4.3.1 Cross-border Evaluation at the Lab

The proposed solution was first build and validated in a lab setup at TNO which consists of two machines, each running the TNO extended 5G SA core, two off-the-shelf gNBs: Ericsson (provisioned by Telenet) and Huawei (provisioned by KPN), and a 5G User Equipment (e.g., Quectel or Sierra Wireless 5G modem, or a smartphone). Two attenuators are used to attenuate the signals from the gNBs. This way, we mimic cross-border scenarios (e.g., a car moving away from the coverage area of MNO1 to the coverage area of MNO2).

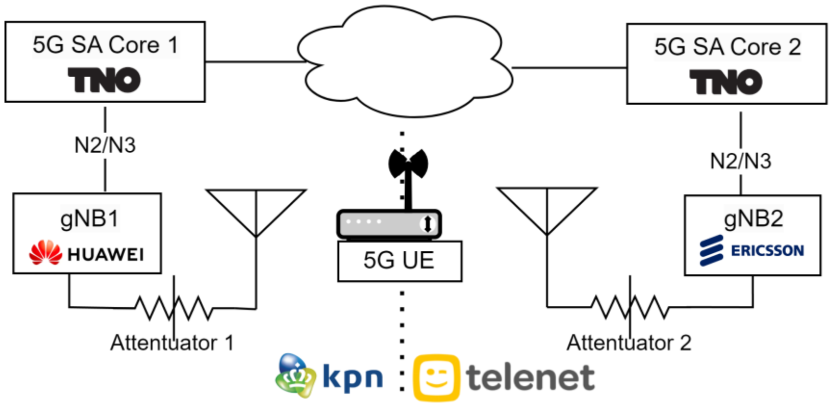


Figure 16: TNO lab setup

Our results show that the usage of Seamless 5G SA roaming significantly reduces the average downtime: **from 14s** (which was the minimum achieved in 5G-MOBIX) **to around 100ms** (see Table below).

Mean UL downtime	Mean DL downtime
92 ms	95 ms

Table 2: Downtime measured in the lab during roaming

Further, we evaluated the effect of our proposed optimizations by comparing the obtained uplink/downlink downtimes to our implementation of the existing 3GPP specifications (procedure in clause 4.23 from 3GPP T.S. 23.502) while varying the latency value (0ms and 20ms latency) between the two cores to assess its effect on the downtime (see Table).

When the latency between the cores is less than a millisecond, the optimized procedure is marginally faster than the original procedure: 92 and 95 milliseconds up-link downtime respectively. We can observe a similar pattern for the down-link downtime: 95 and 98 milliseconds respectively. As we introduce delay between the networks, this difference becomes larger. Indeed, after introducing a 20 milliseconds delay (both ways) between the two cores, we see that both the up-link and down-link differences have grown to more than 40 milliseconds.

Latency between cores	Used procedure	Prep. phase duration	Avg. UL downtime	Avg. DL downtime
No latency	Unoptimized	22ms	97ms	98ms
	Optimized	29ms	92ms	95ms
20ms latency	Unoptimized	105ms	137ms	159ms
	Optimized	108ms	93ms	115ms

Table 3: Preparation phase and downtimes during roaming for different latencies between the cores

4.3.2 Cross-border Evaluation at the Border Site

In this section, the results are presented from the cross-border network evaluation that has been conducted in the cross-border area near Zelzate (BE) and Sas Van Gent (NL). During the project, several days have been scheduled to perform a wide range of tests to assess the network performance of the MNOs networks in the area and to measure the handover interruption time generated when handing the UE over from one country to the other. When performing acceptance tests on the networks, some issues were identified at the site related to some external illegal interference source, that had to be tackled. Furthermore, the tests revealed that the initial network performance at the border location was not sufficient for the use case demonstration, which led to the deployment of a mobile Telenet base station, instead of using the fixed base station located in the center of Zelzate (see Section 4.3.2.1).

In Table 4, a list is provided with all the dates that IMEC performed tests in the area. Apart from these testing days, the individual MNOs and TNO did more acceptance tests during the rollout of the networks.

Date	Location	UE type	KPN gNB location	Telenet gNB location	Notes
02/05/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet gNB at Zelzate center	Noticed that interference source was present
04/05/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet gNB at Zelzate center	Noticed that interference source was present
08/05/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet gNB at Zelzate center	Noticed that interference source was present
19/07/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet gNB at Zelzate center	Interference source removed
12/10/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet mobile gNB near port Zelzate	Interference source removed
27/11/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet mobile gNB near port Zelzate	Interference source removed
30/11/23	Sas Van Gent - Zelzate	Quectel RM502Q	KPN gNB at Sas van Gent - Suikerdijk	Telenet mobile gNB near port Zelzate	Interference source removed
22/11/23	Sas Van Gent - Zelzate	Peplink modem	KPN gNB at Sas van Gent - Suikerdijk	Telenet mobile gNB near port Zelzate	Performance evaluation at the Belgian side on the water

Table 4: Overview of test days at the cross-border area performed by IMEC

4.3.2.1 Issues with KPN and Telenet network performance at cross-border area

When the first evaluation was performed at the cross-border area during May 2023, several KPIs were evaluated as part of the acceptance tests and measurements performed by IMEC using the evaluation tools. The RSRP, RTT, and downlink throughput that were measured, were in line with the expectations (see Figure 17). Note that the downlink throughput was UDP with 50 Mbps sent at the transmitter. However, it was observed that the uplink throughput was low, for both the Telenet and KPN network, as is depicted in Figure 18, with an average of 5 Mbps at KPN side, while Telenet showed some higher peaks (up to 20 Mbps) but in general very low (below 2.5 Mbps). After some further investigation, an interference source was identified coming from the North, as is show in Figure 20. This was further investigated by the Dutch regulator (RDI) and finally, an illegal transmitter was identified and shut down.

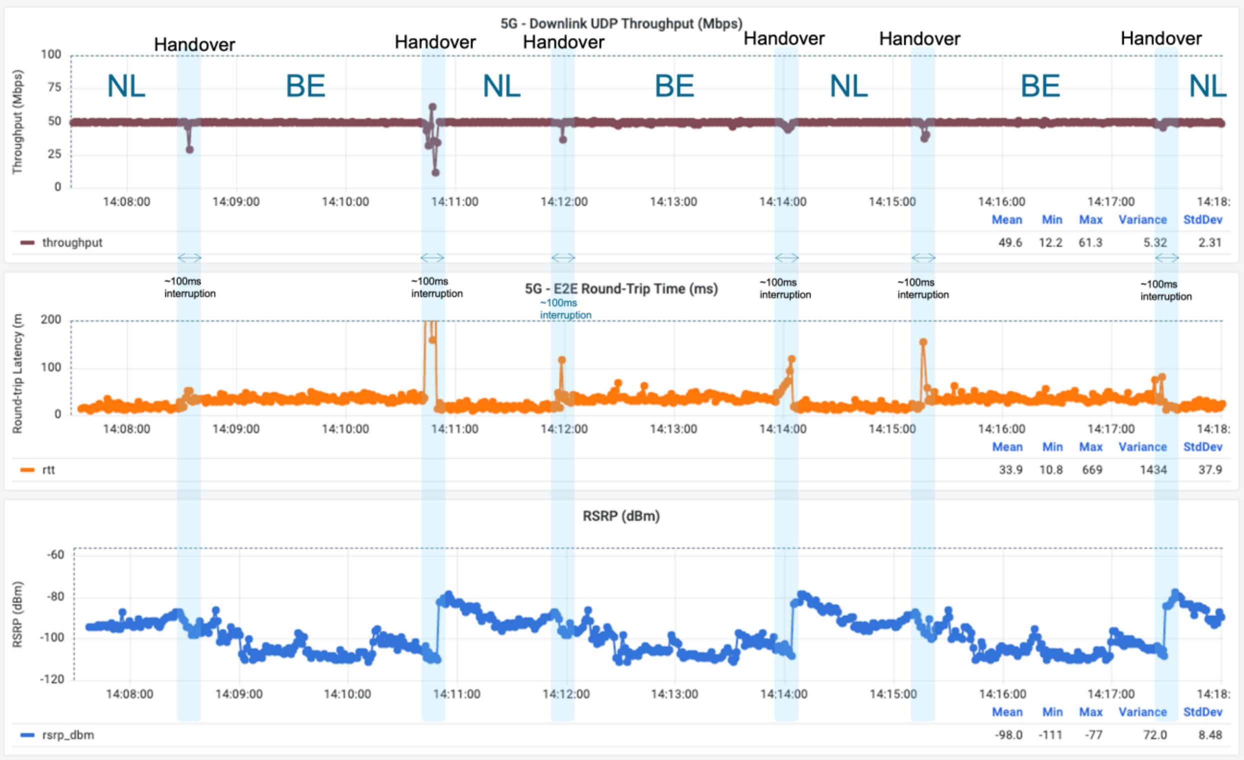


Figure 17: Evaluation 5G cross-border performance in May 2023

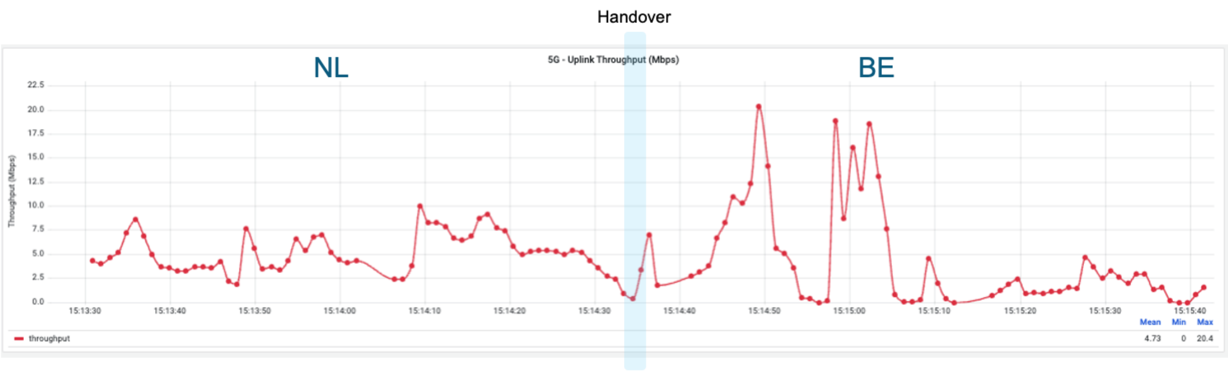


Figure 18: Uplink throughput cross-border performance test in May 2023

Figure 19: Handover location during uplink throughput cross-border performance test in March 2023

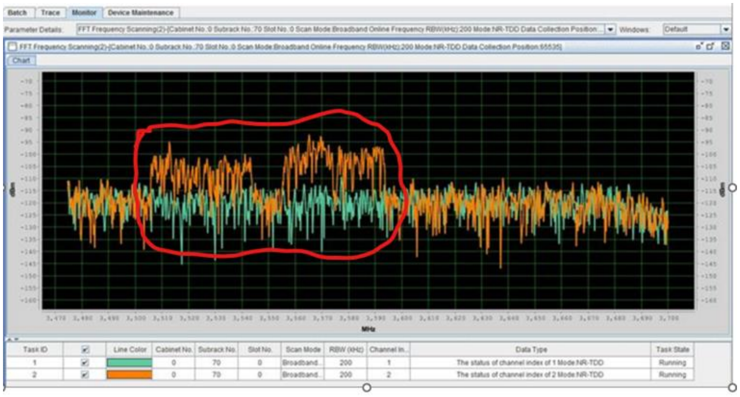


Figure 20: Interference source detected at the cross-border area.

After eradicating the external interference source, the performance at the cross-border area was evaluated again on 19/07/23.

During these tests, the uplink throughput at the Zelzate parking was in line with the expectations, around 40Mbps using the gNB at the Zelzate center (see Figure 21). However, when the UDP uplink throughput was measured at the border, it was still very low for the Telenet gNB (see Figure 22). Based on these measurements, it was decided to deploy a mobile gNB form Telenet, closer to the border, near the small harbor (see Figure 23).

Figure 21: Telenet uplink UDP throughput at Zelzate parking on 19/07/23

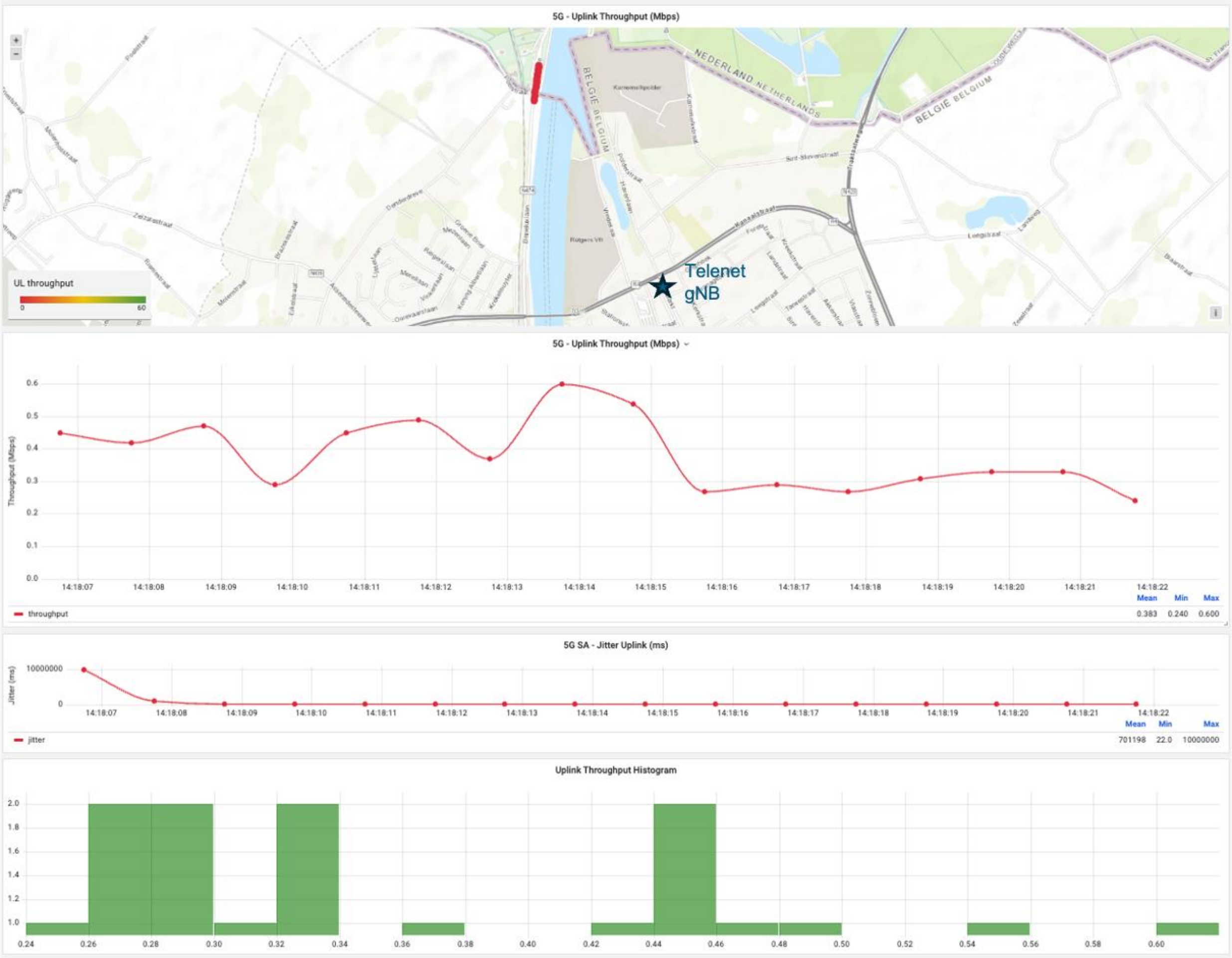


Figure 22: Telenet uplink UDP throughput at the border on 19/07/23

Figure 23: Telenet 5G-SA gNB locations

Regarding the KPN SA network, also several measurements were performed. Close to the gNB (to the South), the performance was in line with the expectations, being around 20Mbps (as can be observed in Figure 24). However, as soon as we moved away from the gNB, the uplink started to drop significantly (see Figure 25).

Figure 24: KPN uplink UDP throughput near the gNB on 19/07/23

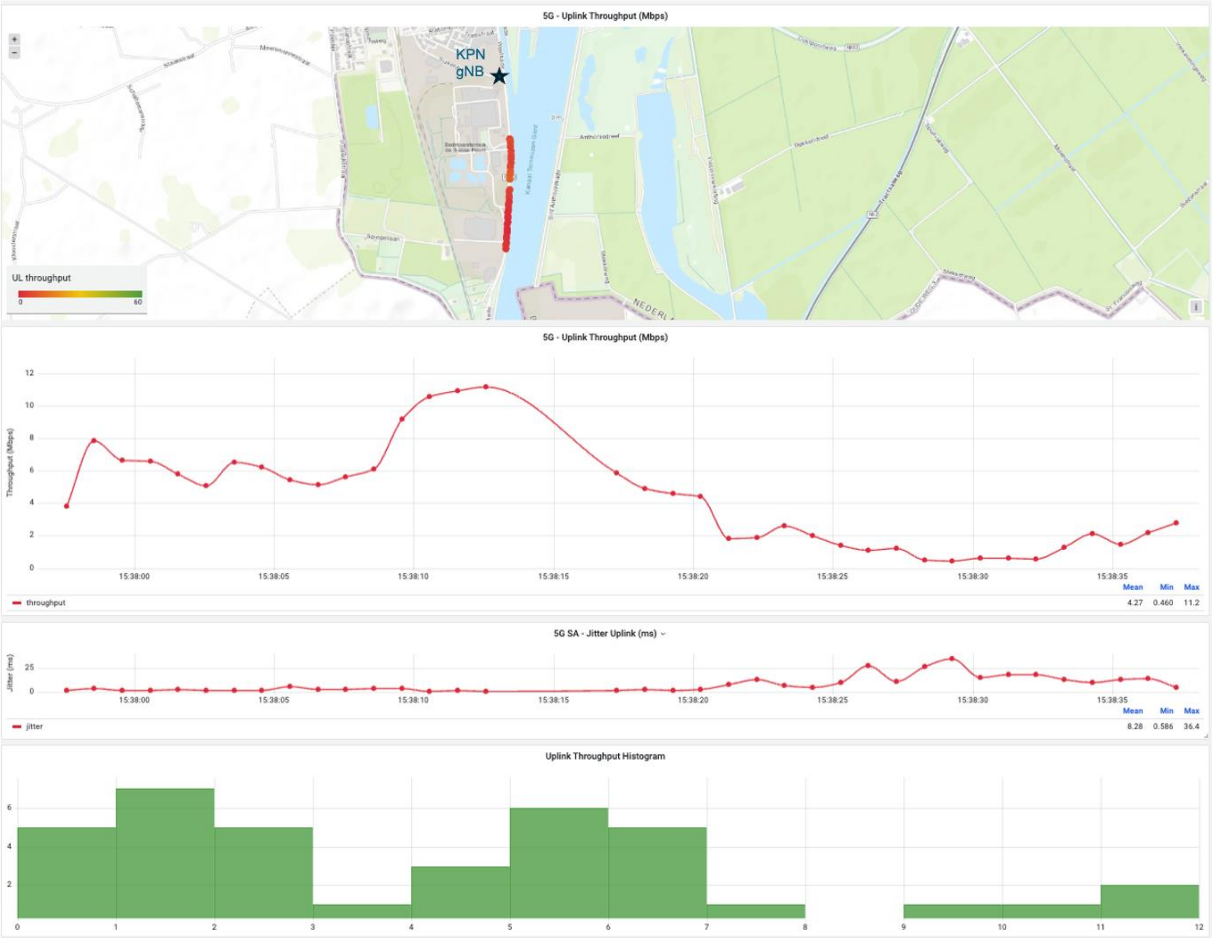


Figure 25: KPN uplink UDP throughput towards the border on 19/07/23

Based on the outcome of these tests, KPN did some troubleshooting (identified and replaced some failing equipment) to enhance the performance of their network.

These modifications led to the final architecture and deployment of the network by KPN and Telenet (deploying the mobile gNB), which was then used during the final demonstration and evaluation within the 5G-Blueprint project.

4.3.2.2 Final cross border evaluation on the road

Attached cell id and signal strengths

During the cross-border evaluation, many test runs were conducted when measuring performance KPIs and interruption times. During each test run, background metrics were logged from the 5G modem, such as RSRP, RSRQ, cell id with a 1-second interval. As an example, in this section, the results of an indicative test are presented. In Figure 26, the attached cell ids are shown on a map during a run from the South (BE) to the North (NL). It can be observed that during this run, three consecutive handovers took place. This is normal behavior since the handover is triggered by signal strength thresholds for the UE RSRP values, that have been configured in the network. Because of the dynamic nature of the wireless environment, the RSRP values of the UE can vary and sometimes, multiple handovers are triggered in one run. However, this is not always the case, and for example in Figure 29, an example run is shown from the North (KPN) to the South (Telenet), where only one handover happened. The RSRP values of these runs are shown in Figure 27 and Figure 30 respectively. In Figure 28 and Figure 31 these results are presented as a time series on which also the handover points are shown.

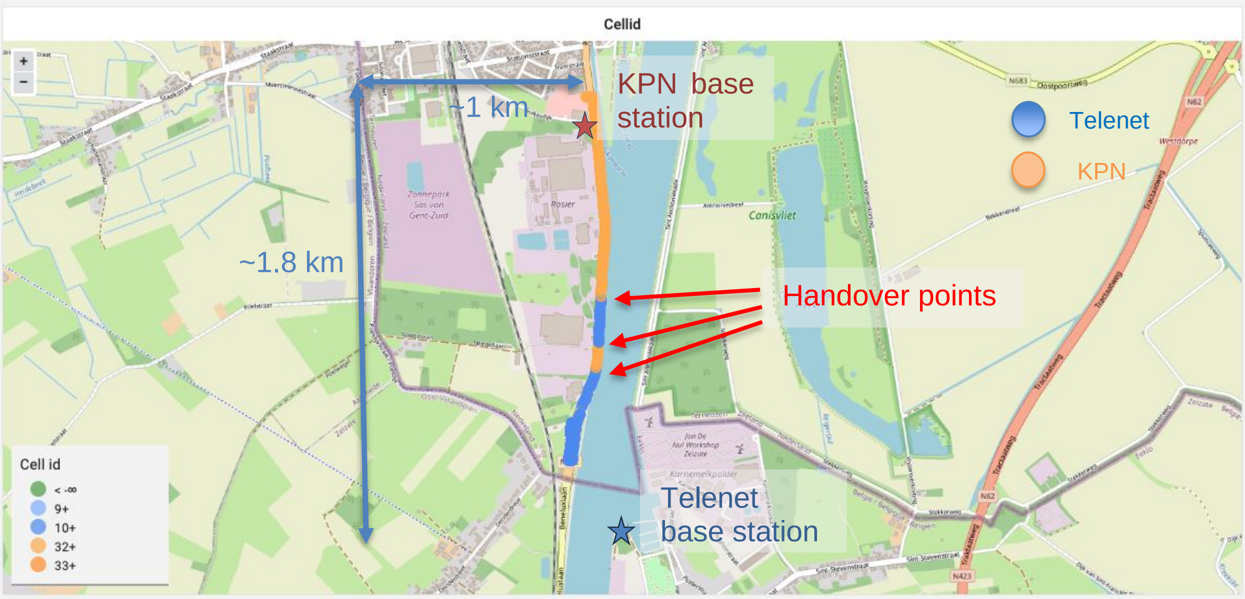


Figure 26: 5G SA attached cell ids during an indicative test at the cross-border site (South to North)

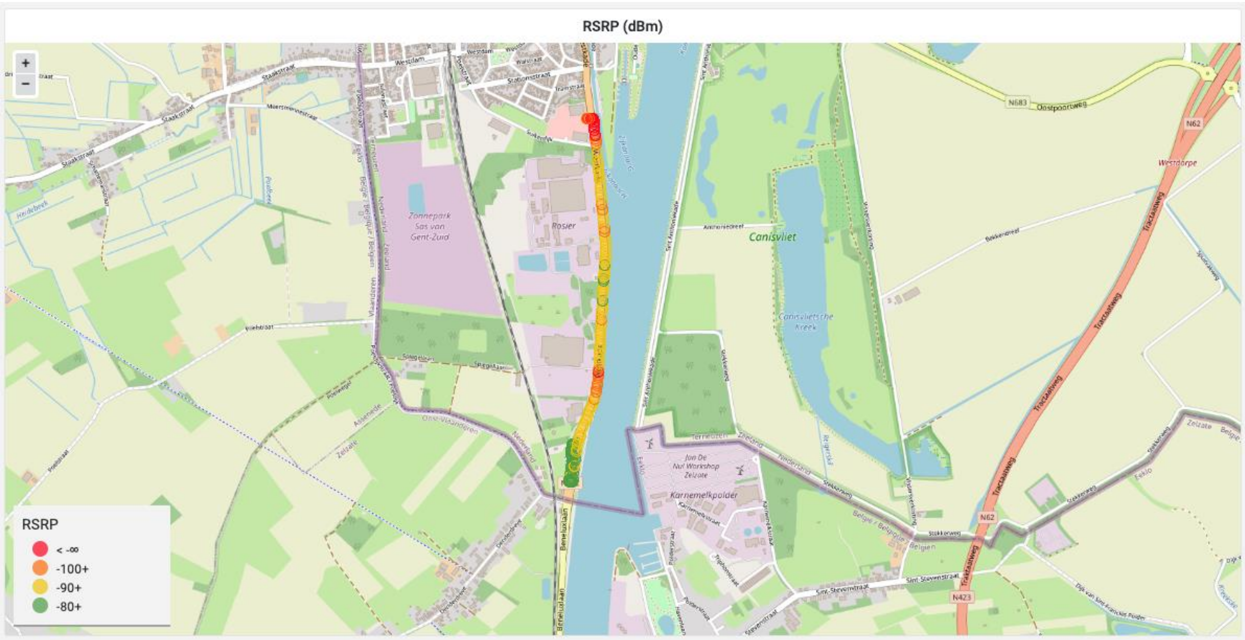


Figure 27: 5G SA RSRP values during an indicative test at the cross-border site (South to North)

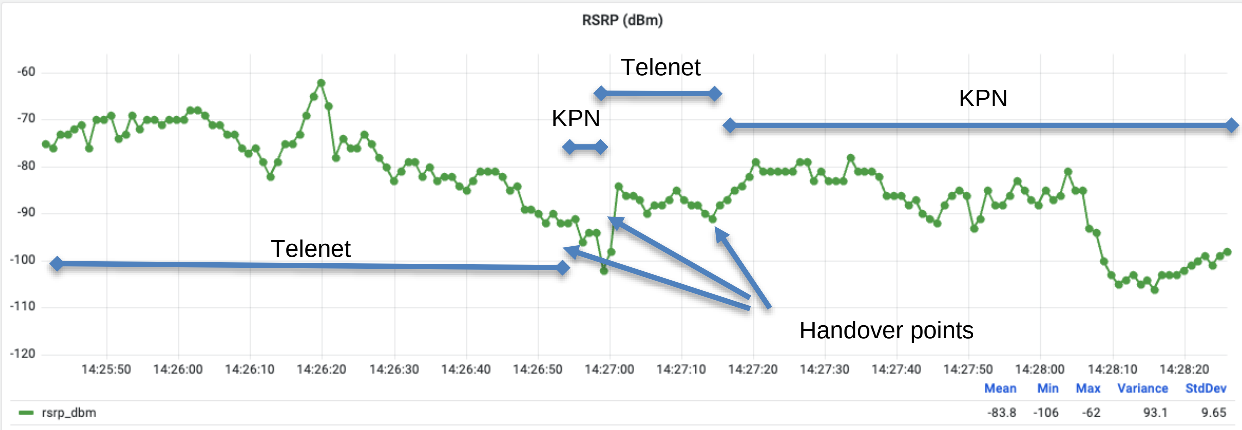


Figure 28: 5G SA RSRP values during an indicative test at the cross-border site (South to North)

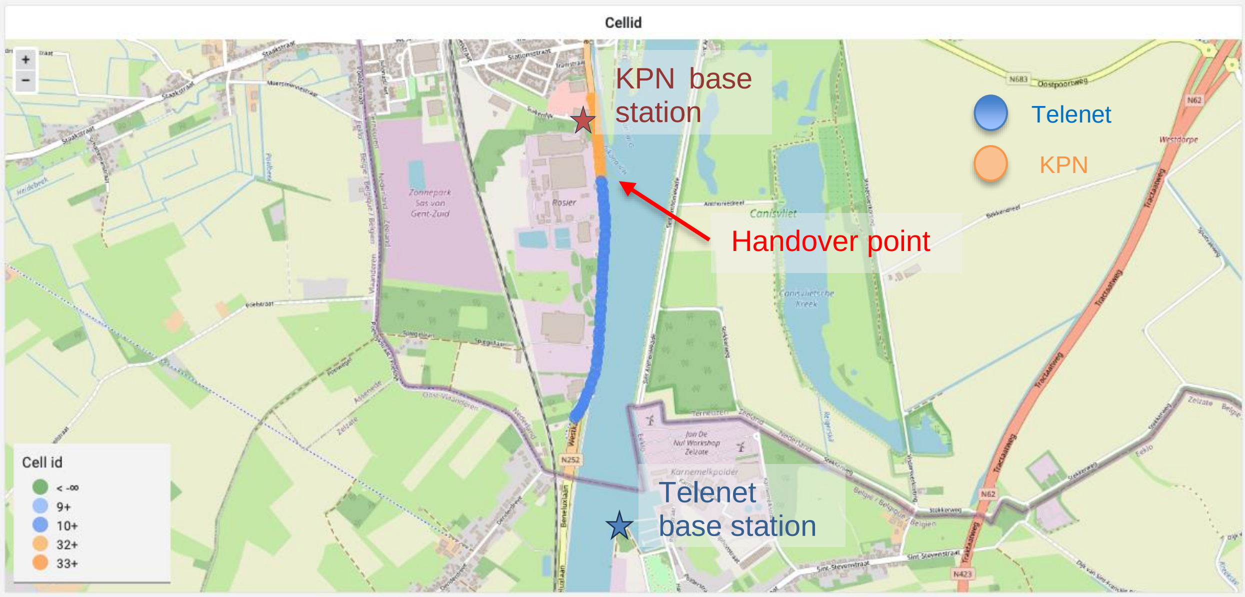


Figure 29: 5G SA attached cell ids during an indicative test at the cross-border site (North to South)

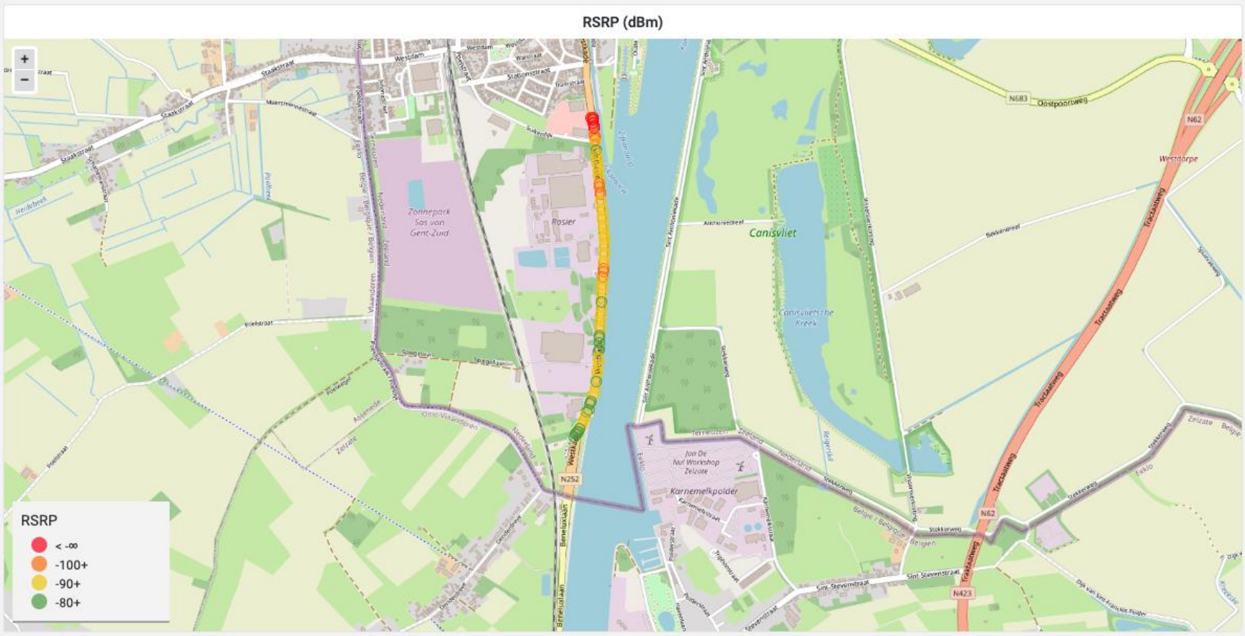


Figure 30: 5G SA RSRP values during an indicative test at the cross-border site (North to South)

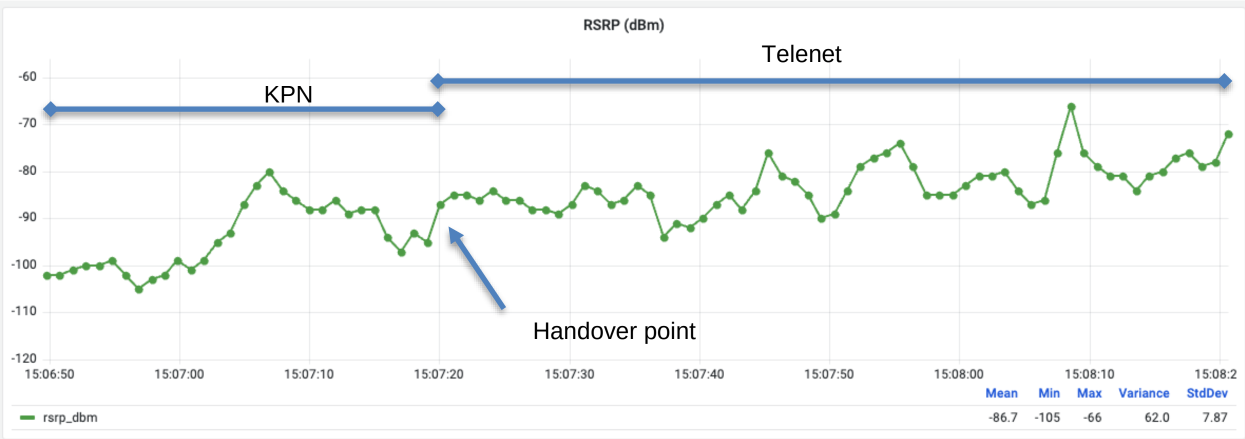


Figure 31: SA RSRP values during an indicative test at the cross-border site (North to South)

TCP downlink rate

Figure 32 presents the heatmap of the TCP downlink throughput values along the cross-border trajectory for an indicative test during which, the route was covered from Belgium (South) to the Netherlands (North).

Figure 32: 5G SA TCP downlink rate heatmap during an indicative test at the cross-border site

For the same test, the throughput in relation to time graph is shown in Figure 33. As it can be observed, the DUT (Quectel RM502Q) was initially connected to the Telenet network, and three seamless handovers have been performed between the Telenet and KPN networks before ending up to the KPN network. It should be emphasized that the three consecutive handovers are not ping-pongs, but regular handovers caused by the signal fluctuation at the cross-border area. This is to be expected as the signal in real world conditions may be affected by various factors such as trees, trucks, and other obstacles that could cause reflections or blockages. The handover points are also shown in Figure 33. The respective handover interruption times in chronological order are as follows:

- Handover interruption time from Telenet to KPN: 152ms
- Handover interruption time from KPN to Telenet: 108ms
- Handover interruption time from Telenet to KPN: 100ms

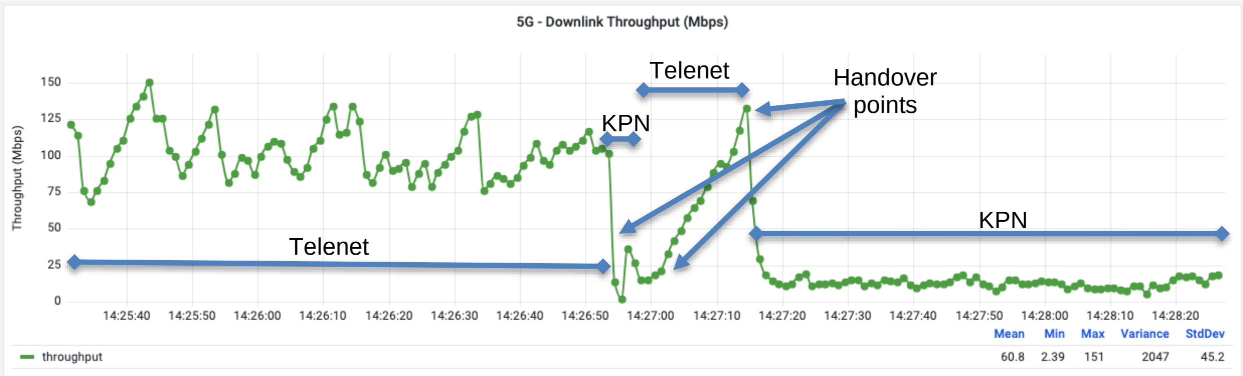


Figure 33: 5G SA TCP downlink rate graph during an indicative test at the cross-border site

Moreover, the TCP downlink throughput when connected to Telenet is higher than the respective throughput when connected to KPN. This is because the KPN gNB was using passive antennas, while the Telenet gNB had active antennas. Moreover, KPN was using 40MHz of bandwidth compared to Telenet that was using 50MHz.

Figure 34 shows the CDF plot for the TCP downlink throughput over both the KPN and Telenet networks for all the relevant tests that have been performed at the cross-border trajectory. It should be noted that the 95th percentile is 166Mbps, while the 75th percentile equals to 109Mbps.

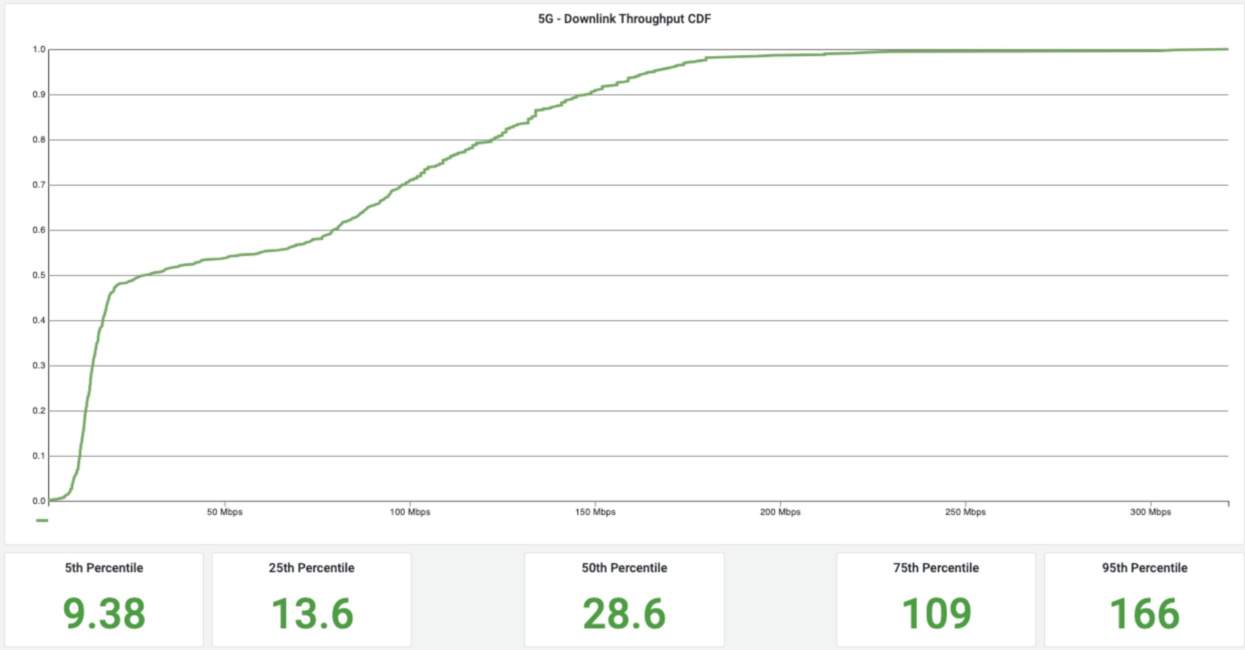


Figure 34: 5G SA TCP downlink rate CDF and percentiles for all the respective tests at the cross-border site

TCP uplink rate

Figure 35 shows the heatmap of the TCP uplink throughput along the cross-border trajectory for an indicative test. That particular test started from the Netherlands (north) with the DUT (Quectel RM502Q) being connected to the KPN network and while driving towards Belgium (south) three handovers were performed. These points are shown in Figure 36 where the throughput in relation to time is shown. The recorded handover interruption times are as follows:

- Handover interruption time from KPN to Telenet: 114ms
- Handover interruption time from Telenet to KPN: 103ms
- Handover interruption time from KPN to Telenet: 103ms

For the same reasons as the ones explained in the TCP downlink case, the observed Telenet TCP uplink throughput is higher than KPN. As it can be seen on the map shown in Figure 35, the most north part of the trajectory faces the lowest throughput performance. This is because the gNB antennas face towards south and hence the northern part of the trajectory is at the cell's edge.

Figure 35: 5G SA TCP uplink rate heatmap during an indicative test at the cross-border site

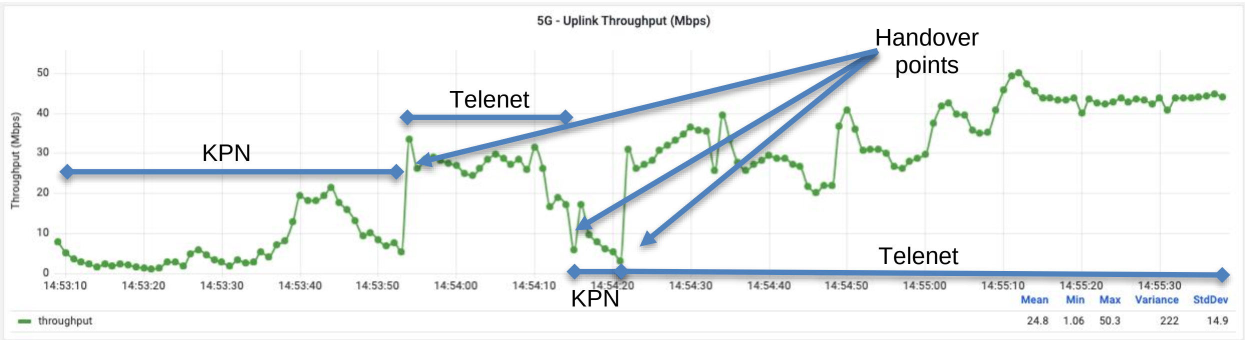


Figure 36: 5G SA TCP uplink rate graph during an indicative test at the cross-border site

Figure 37 presents the CDF plot for the uplink TCP throughput on both the KPN and Telenet networks for all the tests that have been done at the cross-border trajectory. The very low throughput values are caused by the northern part of the trajectory, where the DUT is at the cell's edge. Nevertheless, the median value is 24.3 Mbps, while the 95th percentile is 51.5 Mbps. The fact that the median value is still quite high is because for the tested trajectory the UE is mostly connected to the Telenet network. This range of values can meet the requirements for the teleoperation, as defined in Deliverable 5.1 [3].

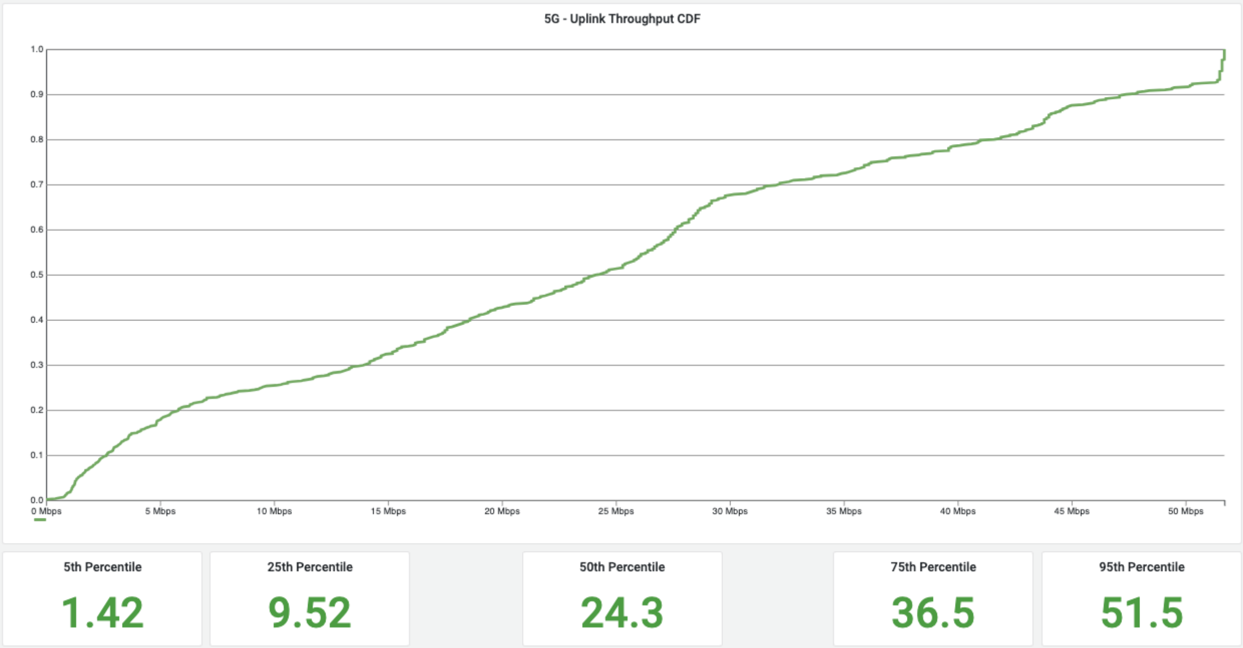


Figure 37: 5G SA TCP uplink rate CDF and percentiles for all the respective tests at the cross-border site

UDP downlink rate

Similar to the TCP downlink case, Figure 38 shows the heatmap of the UDP downlink throughput achieved along the cross-border trajectory during an indicative test, while driving from Belgium (South) to the Netherlands (North). Hence, initially the DUT (Quectel RM502Q) was connected to the Telenet network and it performed one seamless handover to the KPN network. The recorded handover interruption time was 136 ms.

Figure 38: 5G SA UDP downlink rate heatmap during an indicative test at the cross-border site

Figure 39 presents the graph of the UDP downlink throughput in relation to the time and shows the moment of the handover from Telenet to KPN. As it is shown in the figure, the average throughput equals to 132Mbps, the minimum recorded values were 31.9Mbps and the maximum value was 170Mbps.

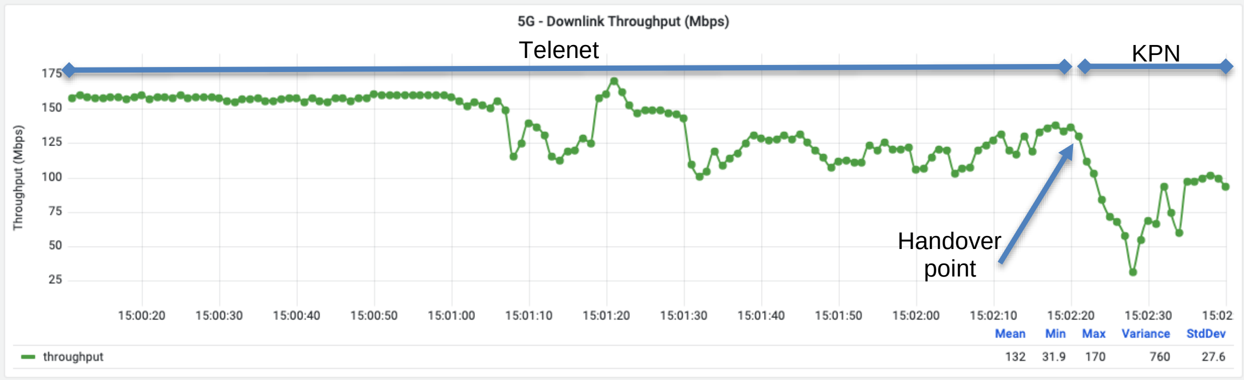


Figure 39: 5G SA UDP downlink rate graph during an indicative test at the cross-border site

Finally, Figure 40 shows the CDF graph from all the UDP downlink throughput tests performed at the cross-border region. Selective percentiles of interest are indicated at the bottom of the figure. Indicatively, the 95th percentile equals to 162Mbps.

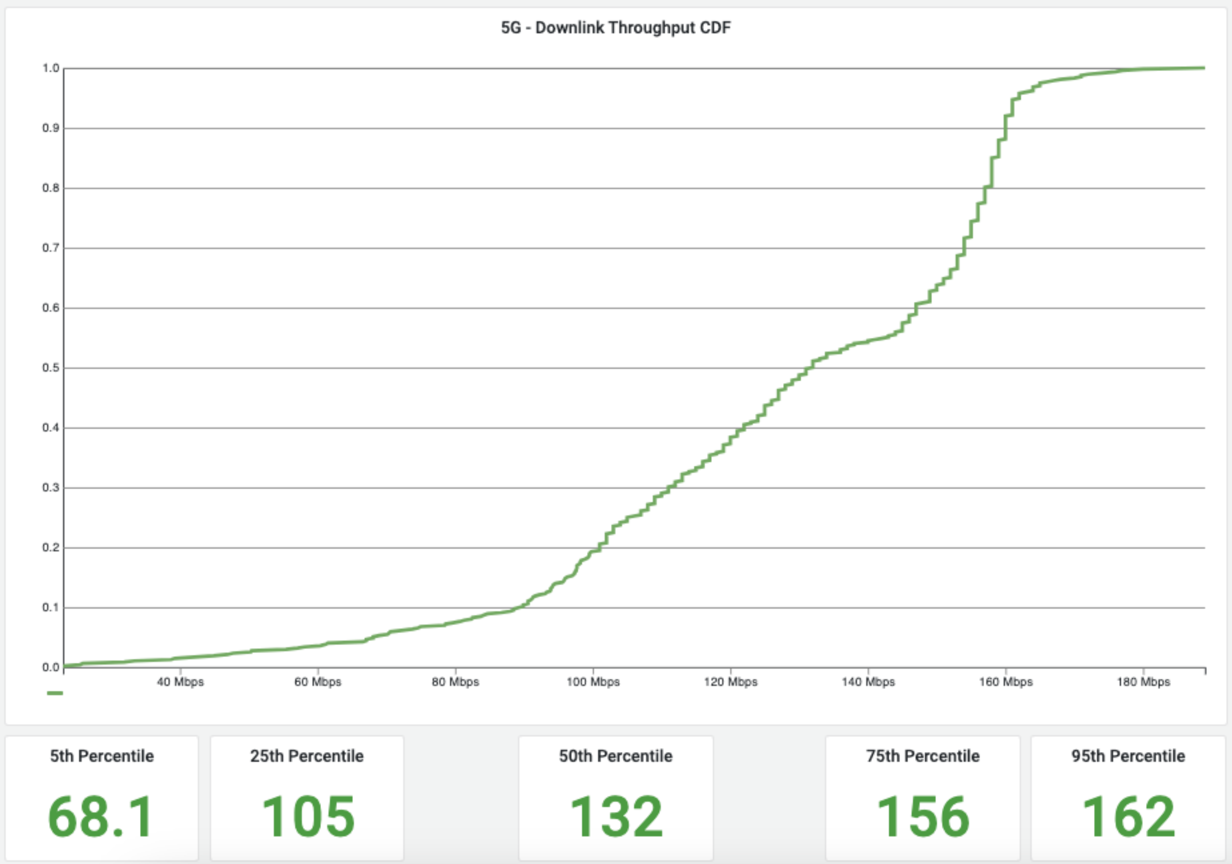


Figure 40: 5G SA UDP downlink rate CDF and percentiles for all the respective tests at the cross-border site

UDP uplink rate

The heatmap of the UDP uplink throughput for a representative test is shown in Figure 41. During that test, the trajectory was covered from south (Belgium) to north (the Netherlands). Thus, the DUT (Quectel RM502Q) was initially connected to Telenet and while driving it performed one seamless handover to KPN. The handover interruption time was 114ms.

Figure 41: 5G SA UDP uplink rate heatmap during an indicative test at the cross-border site

Figure 42 shows the throughput graph in relation to time and the moment when the handover was performed. As it is shown, the average throughput value was 26Mbps, the maximum values were 52.4Mbps and the minimum value was 1.19Mbps. However, this minimum value was only at the end of the test, as also shown in the graph, where the vehicle was at the KPN cell's edge.

Hence, we can conclude that the UDP uplink performance can meet the requirements for the teleoperation, as defined in Deliverable 5.1 [3]. In commercial deployments targeting teleoperation, these values can be further increased by optimal network deployment with multiple consecutive base stations, use of active antennas, etc.

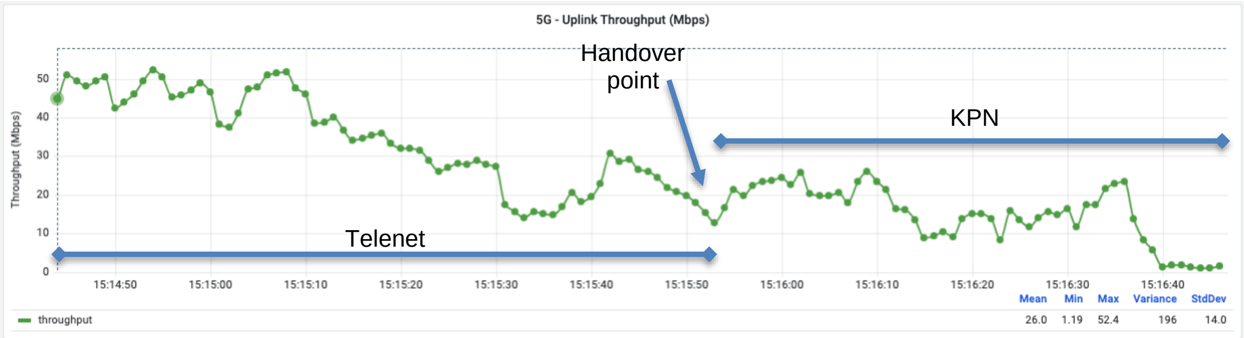


Figure 42: 5G SA UDP downlink rate graph during an indicative test at the cross-border site

Figure 43 presents the CDF plot for all the UDP uplink throughput tests performed at the cross-border trajectory. As it is shown, the 50th percentile equals to 23.6Mbps, while the 95th percentile is 50.8Mbps.

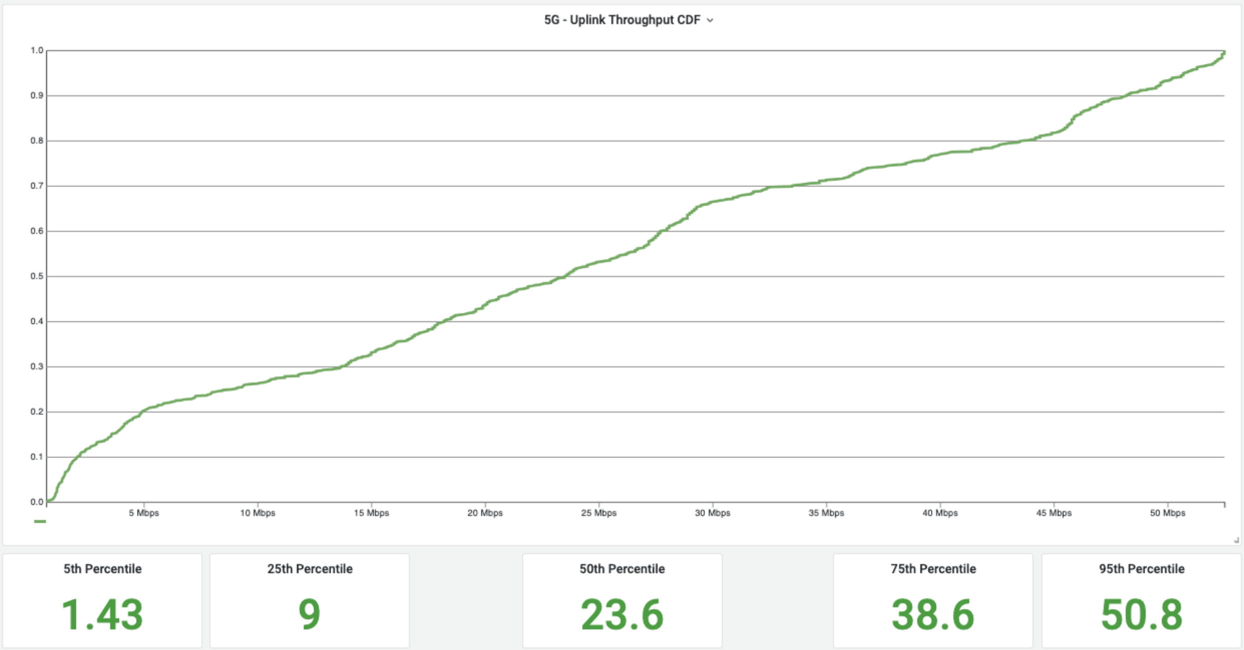


Figure 43: 5G SA UDP uplink rate CDF and percentiles for all the respective tests at the cross-border site

Round-Trip Time

This sub-section discusses the results of the RTT obtained while driving along the cross-border trajectory. Figure 44 presents the heatmap for an indicative test and while driving from Belgium (south) to the Netherlands (north). The inter-message interval was 1000ms. During that test, one seamless handover was performed from Telenet to KPN and the corresponding handover interruption time was 97ms.

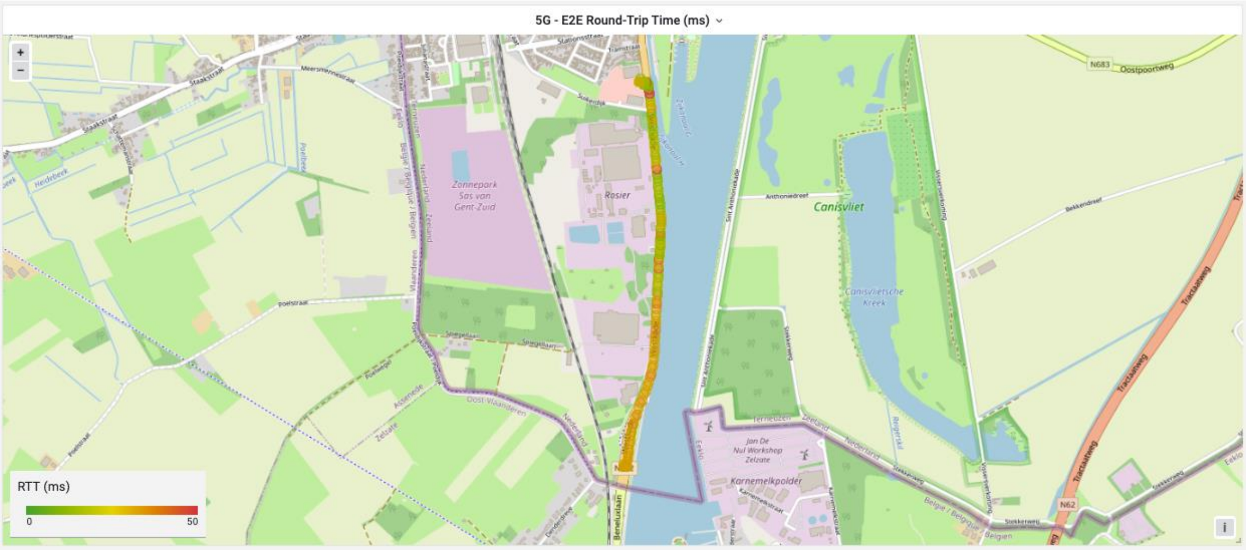


Figure 44: 5G SA RTT heatmap during an indicative test at the cross-border site

Figure 45 shows the RTT graph in relation to time for that particular test and indicates the handover point from Telenet to the KPN network. As it is shown, the average RTT value equals to 25ms.

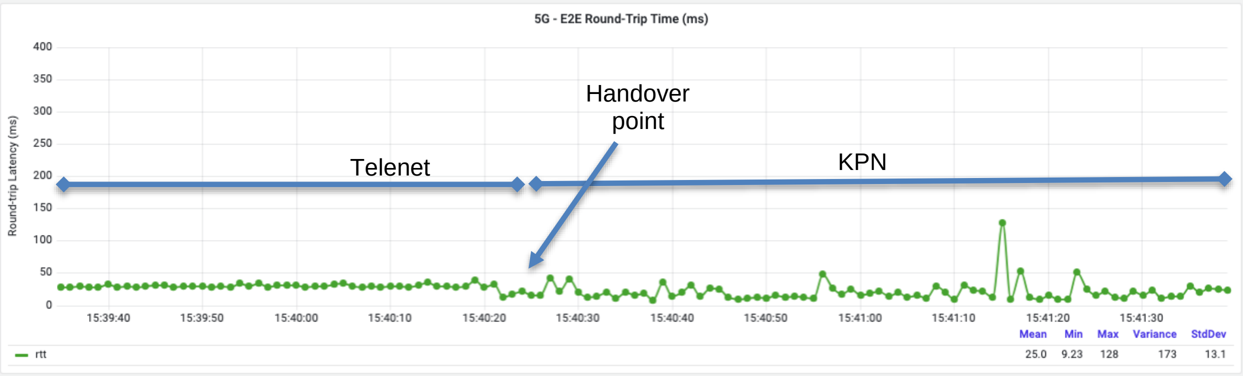


Figure 45: 5G SA RTT graph during an indicative test at the cross-border site

Figure 45 illustrates the CDF graph for all the RTT tests performed at the trajectory highlighting selected percentiles of interest. As it is shown, the 50th percentile is 24.7ms, while the 95th percentile is 40.1ms. These values are sufficient to meet the teleoperation requirements as defined in Deliverable 5.1 [3].

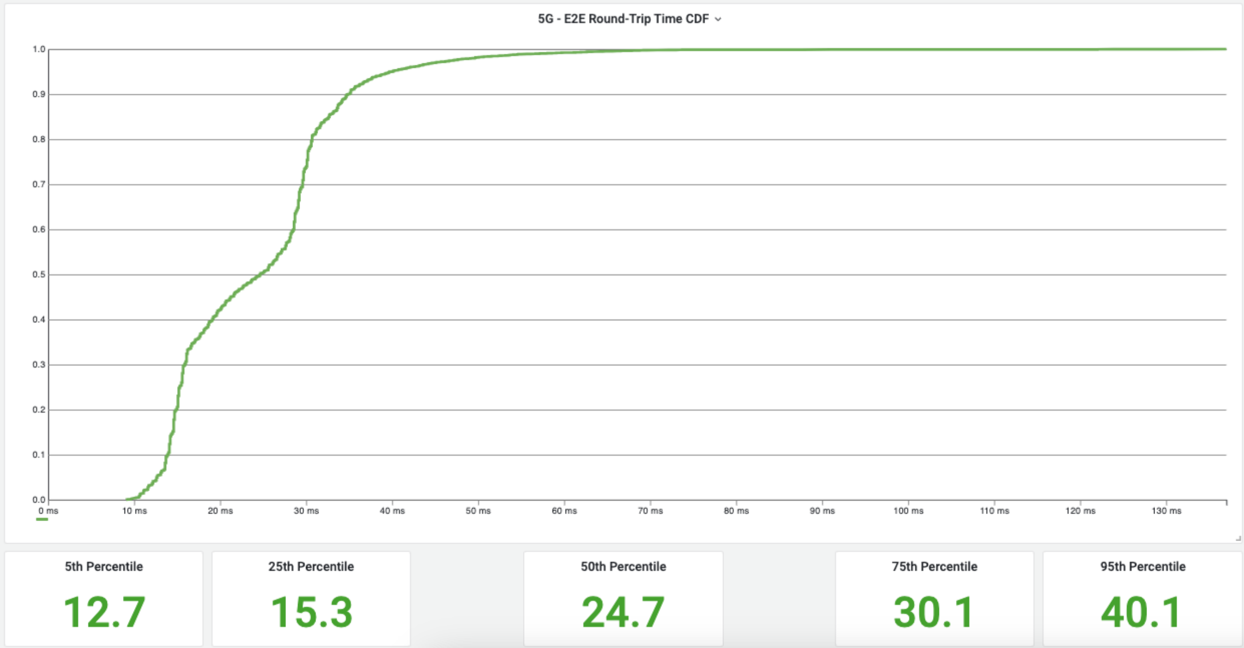


Figure 46: 5G SA RTT CDF and percentiles for all the respective tests at the cross-border site

Summary

In Table 5, a summary is provided of the results from the 5G SA network performance evaluation that was conducted at the cross-border area.

<table>
<tr><td colspan="7">On-site 5G network evaluation</td></tr>
<tr><td>Location</td><td colspan="3">Cross border area between Belgium and Netherlands (Zelzate – Sas Van Gent)</td><td>Location type</td><td colspan="2">Road - car</td></tr>
<tr><td>Network operator</td><td colspan="3">RAN: KPN – Telenet
Core: TNO</td><td>Network type</td><td colspan="2">5G SA</td></tr>
<tr><td>Network slice config</td><td colspan="3">eMBB</td><td>UE type</td><td colspan="2">Quectel RM502Q</td></tr>
<tr><th>KPI</th><th>Min</th><th>5th perc</th><th>Median</th><th>95th perc</th><th>Max</th><th>Average</th></tr>
<tr><td>RSRP (dBm)</td><td>-114</td><td>-103</td><td>-86</td><td>-69</td><td>-61</td><td>-86.3</td></tr>
<tr><td>TCP DL (Mbps)</td><td>2.39</td><td>9.38</td><td>28.6</td><td>166</td><td>321</td><td>63.7</td></tr>
<tr><td>TCP UL (Mbps)</td><td>0</td><td>1.42</td><td>24.3</td><td>51.5</td><td>51.7</td><td>24.1</td></tr>
<tr><td>UDP DL (Mbps)</td><td>23</td><td>68.1</td><td>132</td><td>162</td><td>189</td><td>128</td></tr>
<tr><td>UDP UL (Mbps)</td><td>0.71</td><td>1.43</td><td>23.6</td><td>50.8</td><td>52.5</td><td>24.2</td></tr>
<tr><td>RTT (ms)</td><td>9.09</td><td>12.7</td><td>24.7</td><td>40.1</td><td>137</td><td>24.4</td></tr>
</table>

Table 5: Summary of 5G SA Cross-border network performance evaluation

Handover Interruption time

This subsection will discuss the measurements regarding the network downtime, as measured at the border site. The network downtime is defined as follows:

The network downtime is the time between the last packet the UE could possibly send at the source network, and the first packet the UE could possibly send at the target network (that would arrive properly at the DN). For our purposes, this comes down to the time between the UE abandoning its connection at the serving cell, and the tunnels being configured to forward data in the target network. Timestamps for these events were acquired by directly logging them in the TNO core software.

Both the specification-adherent, as well as TNO's optimized version of the handover procedure were tested (see 4.1.3). The downtime characteristics of these two core versions can be compared in Figure 47.

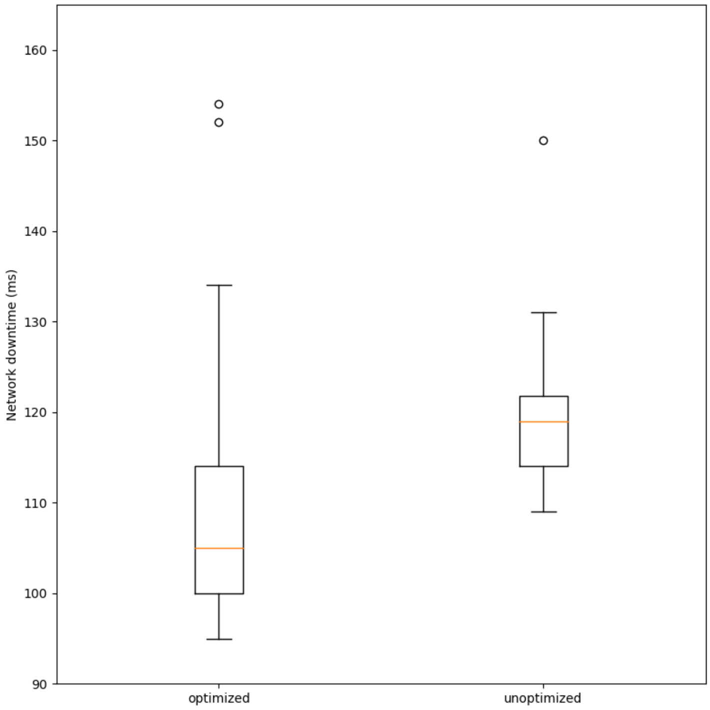


Figure 47 - boxplots of the network downtime for both the optimized and unoptimized cores

We can see a significantly lower median value in the optimized core version, as well as an IQR that is almost entirely below that of the unoptimized version. There is more variance in the optimized samples, which can be explained by the fact that testing for this version was split between two days, due to unfortunate circumstances. The outliers for both versions are roughly the same and are most likely caused by network congestion/packet loss on the control plane or possibly due to radio signal issues.

Table 6 shows the confidence intervals for various confidence levels. Again, we see a clear decrease in the network downtime when switching to the optimized version.

Confidence level	**Unoptimized interval (ms)**	**Optimized interval (ms)**
0.9	115.67 - 123.56	106.36 - 110.20
0.95	114.83 - 124.40	105.98 - 110.57

Table 6: Confidence intervals for the network downtimes for both core versions.

Table 7 shows the percentiles of the measurements. This, as well as the CDFs for both core versions in Figure 48 and Figure 49 (CDFs), give us insight in the distribution of the downtimes. We see that the optimized version has more lower values (95-110), but also has a slightly lower slope, indicating that the downtimes are less tightly packed in the lower end for the optimized version. Nonetheless, for each percentile, the downtimes of the optimized version are consistently 10-25ms lower.

Percentile	Optimized network downtime (ms)	Unoptimized network downtime (ms)
5	96.4	109.0
10	98.0	109.0
50	105.0	119.0
90	119.2	132.9
95	124.2	150.95
99	152.2	165.39

Table 7: Percentiles for the network downtimes for both core versions

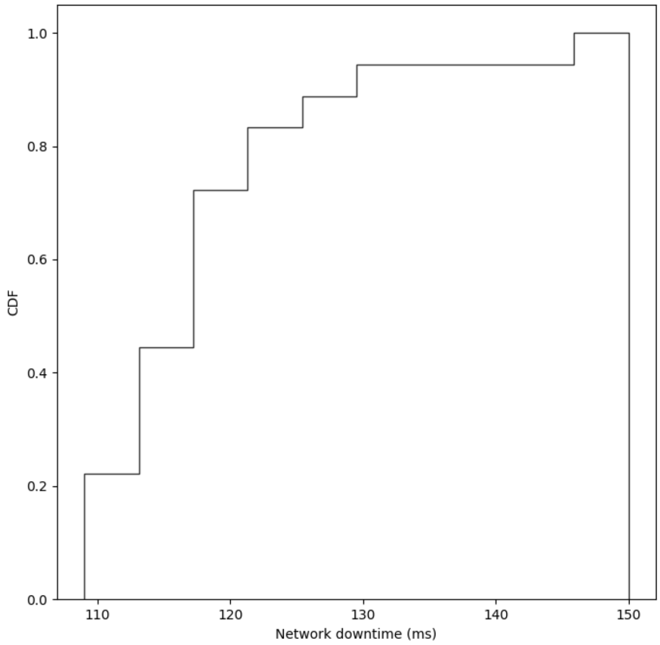


Figure 48 - CDF of the network downtime(unoptimized version)

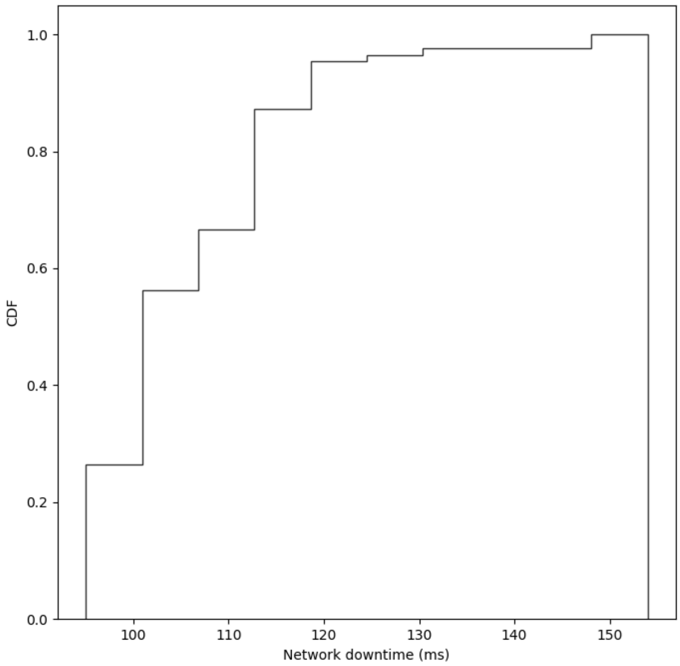


Figure 49 - CDF of the network downtime (optimized version)

It should be noted that the TNO core has two possible variations of the handover procedure:

- One where the NRF cache hits
- One where the NRF cache misses

All the figures above are based on the situation where the cache hits, meaning that the NRF does not have to discover an SMF in the target network, through the target NRF. This would incur a small delay in the network downtime (roughly 30ms). The delay could be avoided through re-use of the discoveries from the preparation phase, which was not implemented in this project. Furthermore, the cache misses occur very rarely in production scenarios. We therefore have chosen to isolate only the handovers where the NRF cache hits for our results.

4.3.2.3 Performance evaluation at the Belgian side on the water

To evaluate the performance of the 5G SA network on the Belgian side of the border, we undertook a series of network evaluation tests. These tests spanned the area from Zelzatebrug Bridge to the Belgian-Dutch border. We employed a dynamic testing approach, utilizing a boat provided by the North Sea Port. A Peplink modem, essential for the connectivity, was strategically positioned at the rear side of the boat, as shown in Figure 50. The Peplink modem established a connection with the Telenet gNB, as identified by the star symbol in Figure 50. The SIM card used for this connection was provided by TNO. To generate network traffic, we utilized the tool IPerf, initiating both TCP and UDP traffic from our device to the TNO core network. To measure the network latency, we utilized ping. To ensure the reliability of our data, we repeated each measurement twice.

Figure 50: Network evaluation trajectory and utilized equipment.

Analyzing the results of the UDP traffic tests for both downlink and uplink across two separate trials reveals several key insights into the network performance. Figure 51 shows the throughput results over the time for the different tests, and Table 8 shows statistical results. In Test 1, the downlink UDP achieved an average throughput of 328.11 Mbps indicating a robust downlink capacity. However, the standard deviation of 80.03 Mbps pointed to some variability in performance. Notably, the maximum throughput reached was 447 Mbps, while the minimum dropped to 92.3 Mbps, suggesting some fluctuations in network stability due to the other maritime traffic and loss of line-of-sight. Furthermore, the lower value in Figure 51 can be attributed to the navigational adjustments of the vessel, specifically during directional transitions. This maneuvering resulted in a temporary loss of the line-of-sight communication pathway between the modem and the gNB. The uplink in Test 1 had a lower average throughput of 47.29 Mbps, which is typical for uplink versus downlink throughput. The performance here was more consistent, as evidenced by a smaller standard deviation of 6.52 Mbps and a maximum throughput closely aligning with the 95th percentile throughput of 52.5 Mbps.

In Test 2, the downlink UDP showed a slight decrease in average throughput to 321.29 Mbps, yet this still indicated a strong performance. The variability remained similar to Test 1, with a standard deviation of 79.37 Mbps. The maximum throughput slightly surpassed Test 1, reaching 449 Mbps. The uplink UDP in Test 2 mirrored the consistency seen in Test 1, with an average throughput of 47.22 Mbps across 1213 packets and a quite similar standard deviation. The maximum throughput here was slightly lower than 52.8 Mbps, but the overall performance remained stable.

These results demonstrate a consistent pattern: the downlink performance showed higher throughput with more variation, reflecting the dynamic nature of downlink traffic, while the uplink performance was notably stable but at lower throughputs, which are sufficient for teleoperation. The slight differences between the two tests indicate the network reliability and its ability to maintain performance over multiple trials. This balance of high throughput downlink capability with stable uplink performance is crucial for the effective operation of 5G networks, especially in dynamic environments like the one tested.

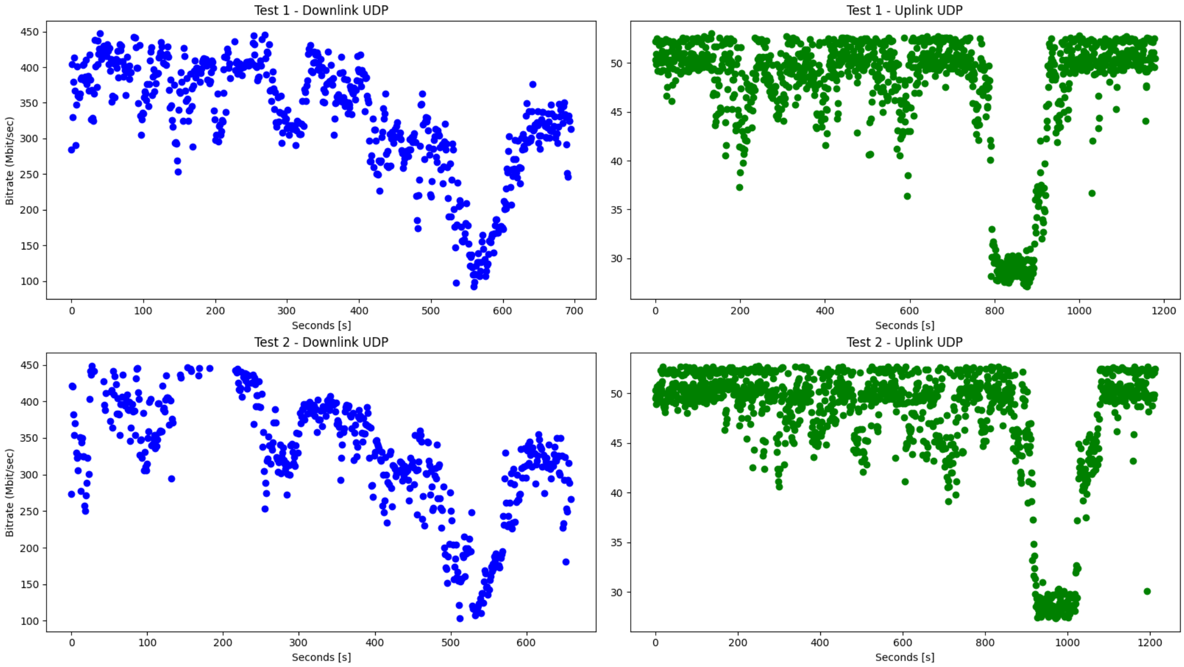


Figure 51: UDP Throughput

	Test 1 - Downlink UDP (Mbit/sec)	Test 1 - Uplink UDP (Mbit/sec)	Test 2 - Downlink UDP (Mbit/sec)	Test 2 - Uplink UDP (Mbit/sec)
mean	328.111022	47.287617	321.287091	47.221929
std	80.025839	6.524082	79.374147	6.411995
min	92.300000	27.100000	103.000000	27.300000
50th percentile	338.000000	49.700000	330.000000	49.600000
95th percentile	426.000000	52.500000	436.280000	52.500000
max	447.000000	53.000000	449.000000	52.800000

Table 8: UDP traffic statistical analysis.

The results of the TCP tests are shown in Figure 52 with a statistical analysis reported in Table 9. In Test 1, the downlink TCP throughput was 145.07 Mbps on average. This is typically lower than UDP throughput, a result of TCP's inherent mechanisms for acknowledgments and retransmissions. The standard deviation, at 49.56 Mbps, suggests a considerable variability of throughput in downlink, ranging from a high of 314 Mbps to a low of 59.2 Mbps. This range indicates potential network variability or congestion.

For uplink TCP in Test 2 we have obtained a throughput of 47.35 Mbps on average. This aligns with the expected lower throughputs for uplink, and the standard deviation of 8.66 Mbps shows a relatively consistent performance. However, the minimum throughput dropped to 16.7 Mbps, pointing to some instances of reduced performance, despite reaching a high of 70.3 Mbps.

In Test 2, the downlink TCP showed a decrease in average throughput to 125.84 Mbps with a higher standard deviation of 53.5 Mbps, indicating increased variability. The maximum throughput here was 309 Mbps, but the minimum plummeted to 17.6 Mbps, suggesting more significant network fluctuations. The uplink TCP in Test 2 had an average throughput of 46.83 Mbps. The performance was relatively stable, as seen in the standard deviation of 8.68 Mbps, similar to Test 1. The maximum and minimum throughput were 62.8 Mbps and 16.8 Mbps, respectively, mirroring the trends observed in the first test.

These TCP results, when compared with the UDP findings, illustrate a distinct pattern. TCP downlink throughput showed higher variability and a broader range between the highest and lowest throughput, highlighting TCP's sensitivity to network conditions like latency and packet loss. Uplink throughput, although lower, was more stable, which is key for reliable transmission of acknowledgments and data. The variation between Test 1 and Test 2 underlines the dynamic nature of network conditions and the importance of optimizing TCP performance in 5G networks, especially for applications requiring stable and consistent connection such as teleoperation.

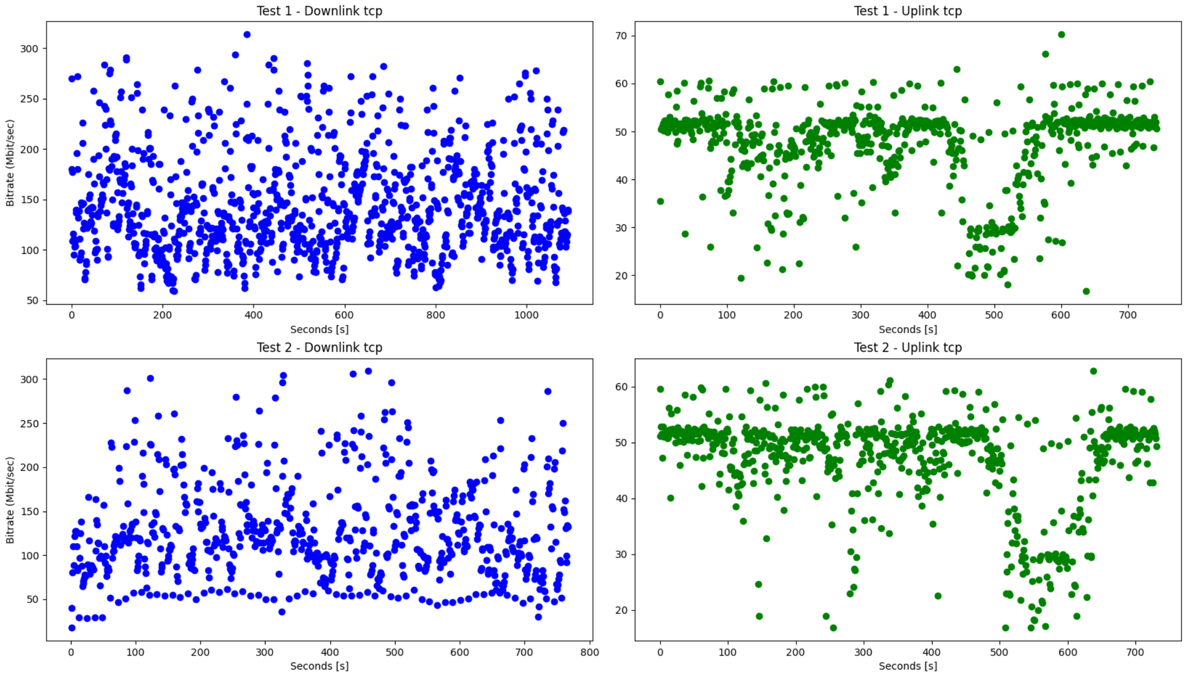


Figure 52: TCP traffic

	Test 1 - Downlink TCP (Mbit/sec)	Test 1 - Uplink TCP (Mbit/sec)	Test 2 - Downlink TCP (Mbit/sec)	Test 2 - Uplink TCP (Mbit/sec)
mean	145.066026	47.346218	125.844176	46.832525
std	49.556942	8.662647	53.499542	8.680000
min	59.200000	16.700000	17.600000	16.800000
50th percentile	135.500000	50.700000	117.000000	50.000000
95th percentile	252.000000	59.248000	233.000000	57.600000
max	314.000000	70.300000	309.000000	62.800000

Table 9: TCP traffic statistical analysis.

Building upon the TCP and UDP throughput analysis, the latency results from two rounds of testing further showcase the network performance under real-world conditions. The results are shown in Figure 53 with a statistical analysis in Table 10.

In the first round of end-to-end latency testing (round trip time measured via ping), the average value was recorded at 31.77 milliseconds, reflecting the time taken for packets to travel through the network. This average is a crucial indicator of the responsiveness of 5G SA network, particularly for real-time applications. The standard deviation was 11.86 milliseconds, indicating a considerable variation in latency values. The minimum latency was quite low, i.e., at 18.57 milliseconds, suggesting optimal network conditions. However, the maximum latency reached a significant 118.85 milliseconds, pointing to instances of considerable delay.

The second round of latency testing showed an improvement in network performance, with the mean latency dropping to 24.38 milliseconds. This decrease in average latency indicates a more responsive network in the second round. The standard deviation also reduced to 5.28 milliseconds, signifying a more consistent and stable network performance with less variation in latency. The minimum latency observed was 19.07 milliseconds, closely aligning with the first round's minimum. However, a notable improvement was seen in the maximum latency, which was reduced to 60.64 milliseconds, almost half of what was observed in the first round. These latency figures, especially the significant reduction in maximum latency between the two rounds, suggest network optimizations or less congested conditions in the second round. The lower and more consistent latency times in Round 2 are indicative of a more efficient network, essential for applications requiring real-time data transmission, such as video streaming for teleoperation. In both tests, average end-to-end latency values meet the requirements for all use cases and enabling functions (i.e., less than 35ms), which are indicated in D5.1 [3]. This improvement in latency complements the previously discussed throughput performance, providing a comprehensive view of the network's capabilities.

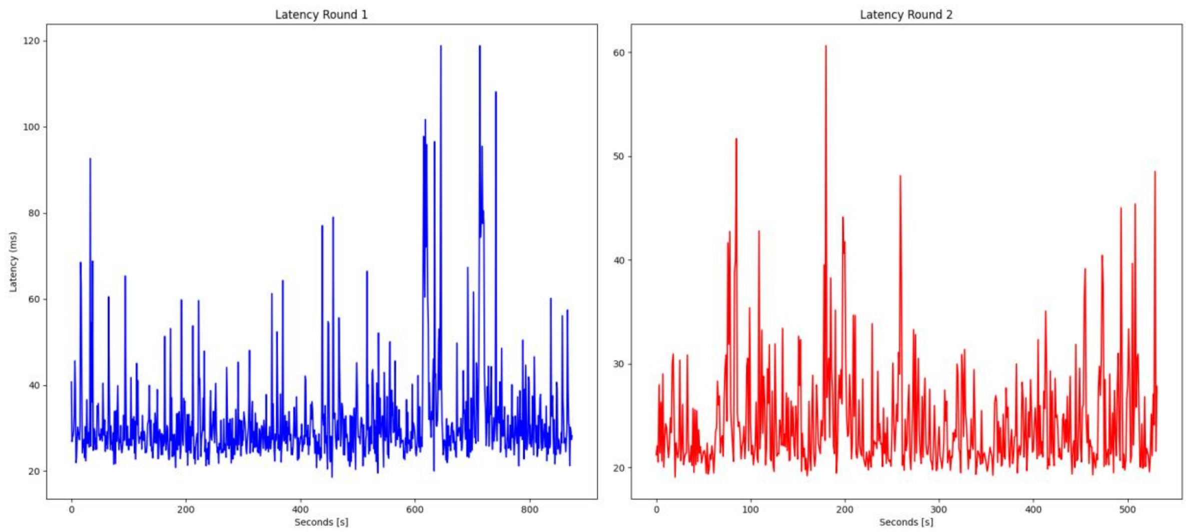


Figure 53: Latency

	Latency Round 1 (ms)	**Latency Round 2 (ms)**
mean	31.766305	24.379739
std	11.864618	5.277582
min	18.570000	19.074000
50th percentile	28.322000	22.354000
95th percentile	59.980920	36.227160
max	118.847000	60.644000

Table 10: Statistical analysis of latency

5 BELGIAN SITE

5.1 5G Network Architecture (Telenet)

5.1.1 Radio Architecture

The purpose of this section is to provide an overview of Telenet's network architecture, that has been set-up to support the 5G-Blueprint project.

Since the 5G SA production core was not in service during the 5G-Blueprint project, the RAN is both connected to the stand-alone network (Nokia CMU core) and the non-standalone network (Telenet 5G production core).

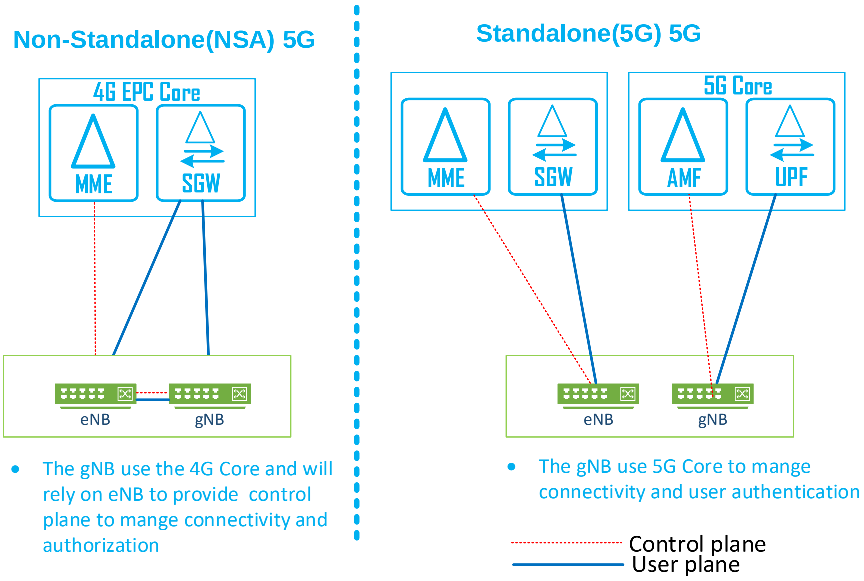


Figure 54: Telenet radio architecture at the Belgian site

5.1.2 Core Architecture

The Nokia Compact Mobility Unit (CMU) performs the mobile packet core functions of private wireless network for mobile broadband, Internet of Things, and machine-type communication (MTC) services.

The Current CMU Hardware supports either 4G or 5G radio access network connectivity. For this project, it was decided that the CMU will work as 5G SA core. In 5G SA architecture, it consists of AMF, SMF, UPF, AUSF and UDM in the same servers.

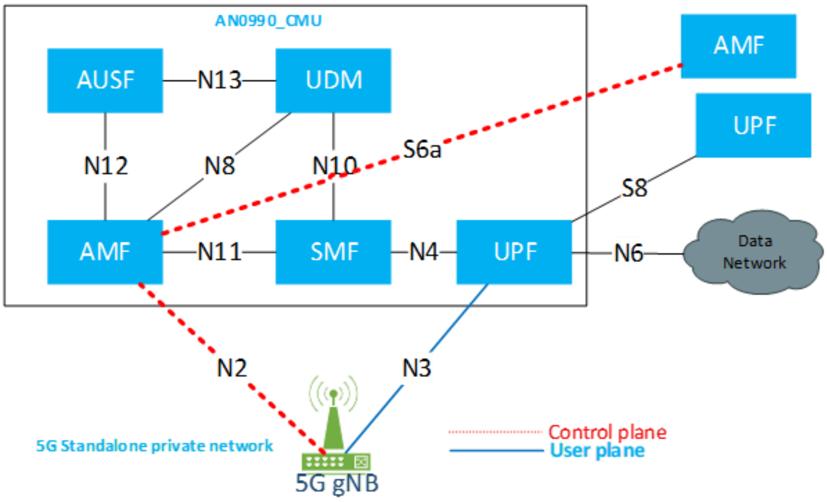


Figure 55: Core architecture at the cross-border site

In this network architecture, 5G gNB will be configured to support Multi-Operator Core Network (MOCN) solutions. Multi-Operator Core Network (MOCN) standard allows the sharing of RAN network such as eNBs/gNBs. The operators also share frequencies, Base Station (eNB/gNB) but can have its own Core Network (EPC/5GC) and Cell Coverage Area.

RAN network will be connected to the production 4G LTE core as well as to non-production Nokia CMU. The gNB will be shared by Telenet's production network and the new 5G Private network.

5.2 5G Network Deployment (Telenet)

5.2.1 Radio Deployment

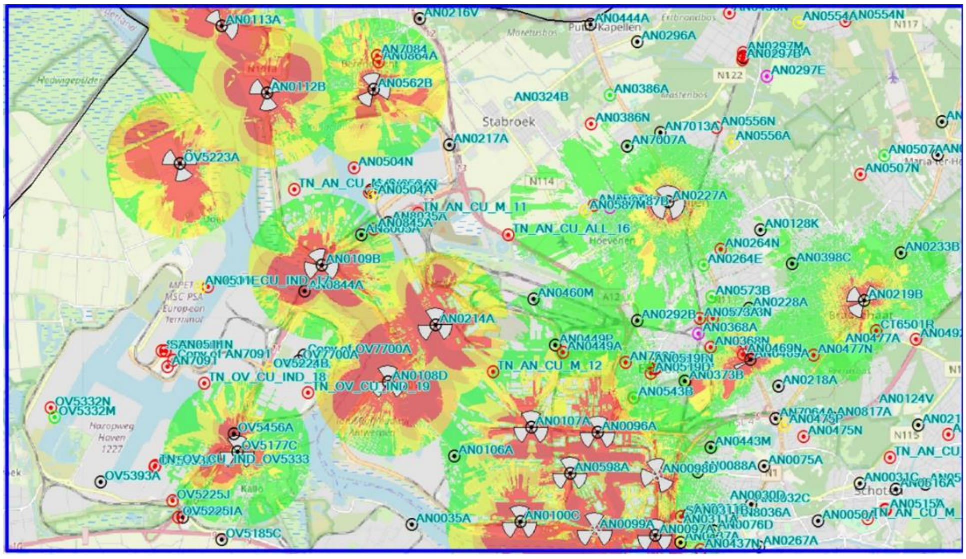
Radio deployment in the Port of Antwerp is covering a total of 7 gNBs. All the sites have 3 slices available:

- 5g-internet: the default slice
- Live-stream: slice to prioritize video streaming
- URLLC: slice with ultra reliable and low latency

Technical details on the actual deployment:

- Center frequency: 3700 MHz
- Bandwidth: 50MHz
- Technology: 5G NR TDD
- Brand: Ericsson
- Transmission bandwidth: 1Gbps

The below map shows the NR3.5 coverage area in the Port of Antwerp. The maps shows that a large area in the port of Antwerp was covered by the Telenet SA network in the context of this 5G-Blueprint project.



		Min	Max	
1	(red)	-81		Deep Indoor
2	(orange)	-85		Indoor
3	(yellow)	-93		Incar
4	(green)	-105		Outdoor

Figure 56: Telenet 5G SA planning at the Belgian site

Some pictures of the gNBs in the Port of Antwerp are shown in Figure 57.

Figure 57: Pictures of the gNBs in the port of Antwerp

5.2.2 Core Deployment

The CMU is configured as redundant mode which supports active/standby redundancy protection.

Network slices are also available on the Nokia CMU:

- 5g-internet:
  - eMBB regular
  - the default slice
- Live-stream:
  - eMBB (UL) / emBB (DL)
  - slice that is mainly used to upload video streaming
- URLLC: slice with ultra reliable and low latency, used for camera remote control

Slice Name	Silce/Service Type	Slice Differentiator	Supported DNN	5QI	Comment
S-NSSAI-1	1	1	5g-internet	8	Default
S-NSSAI-2	1	2	Live-stream	8 (default) 72 (by UDP traffic	Old 67
S-NSSAI-3	2	1	URLLC	8 (default) 65 (by destination IP)	Fake URLLC

Table 11: Network slices at the Telenet core network

5.3 5G Network Evaluation

The 5G network deployment of Telenet at the Belgian site covers the locations selected as relevant for the project's use cases, as described in Deliverable 7.2 [4], consisting of an area of approximately 225 square kilometers as shown in Figure 58. This area includes the north part of the right bank side both on the water and on the road, as well as the defined milk run trajectory at the Roossens Transport area.

The 5G network at the Belgian site is exclusively standalone 5G and has been deployed in two phases. Initially, only one gNB was deployed at the northern side of the port and it is indicated with purple color in Figure 58. This first deployment aimed to allow us to validate the initial network performance at the port. Later at the end of 2022, six (6) additional gNBs were deployed at the locations shown with orange color.

As it can be observed in the figure, the Belgian site consists of two main regions. The first one is the Port of Antwerp site that includes the right bank side of the port both on the water and on the road, as well as part of the Schelde river. The second region includes the Roossens Transport premises and a milk run from Roossens Transport to Medrepair.

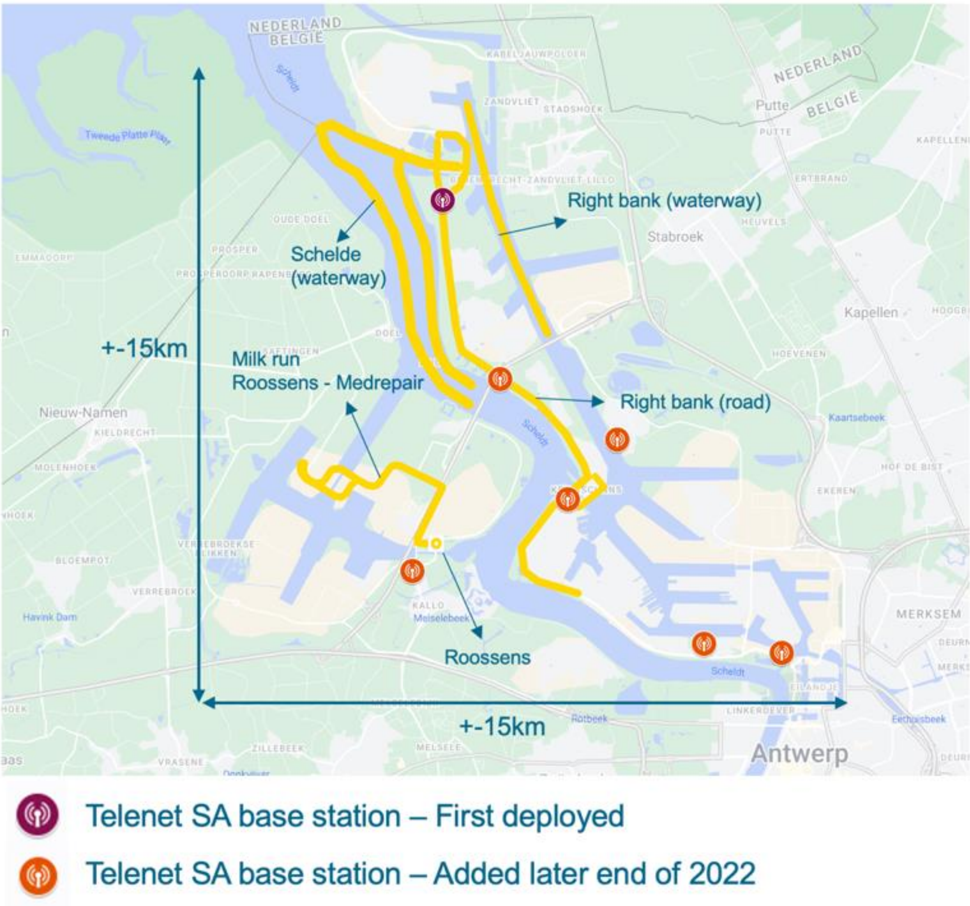


Figure 58: Telenet 5G deployment at the Belgian site

This 5G SA network deployment has been extensively evaluated for all the considered KPIs described in Section 2. In that direction, several test campaigns have been organized as shown in Table 12.

Date	Location	Slicing configuration	UE type
21/10/22	Right bank – on the road	eMBB slice	Quectel RM502Q
24/10/22	Right bank – on the road	eMBB slice	Quectel RM502Q
25/10/22	Right bank – on the water	eMBB & URLLC slices	Quectel RM502Q
26/10/22	Schelde river – on the water	eMBB & URLLC slices	Quectel RM502Q
15/02/23	Roossens Transport area and milk run	eMBB slice	Huawei 5G CPE Pro 2
29/03/23	Right bank – on the road	eMBB slice with and without background traffic	Huawei 5G CPE Pro 2
03/04/23	Right bank – on the road	eMBB, URLLC and Live Streams slices with and without background traffic	Huawei 5G CPE Pro 2

Table 12: Test campaigns for the evaluation of the Belgian site

During the whole 5G evaluation at the Belgian site over the 7 test campaigns listed in the table above, the following statistics have been derived over the collected data:

- **54220** signal strength data entries
- **15610** RTT measurement data entries
- **50** RTT test IDs, of which **30** are valuable
- **33852** iperf data entries
- **391** iperf test ids, of which **143** are valuable
- **25** one-way latency tests
- **25** reliability tests
- **25** packet delivery rate and packet-loss tests

The following subsections discuss the 5G network evaluation results for each considered location at the Belgian site, both on the water and on the road.

5.3.1 5G SA - Port of Antwerp Site

This subsection refers to the evaluation of the 5G network deployed at the first region of the Belgian site, as explained above. The evaluation has been done both on the water at the right bank side of the port, on the road across the right bank side and on the Schelde river.

It is worth to be mentioned that the region of the Belgian site is a very challenging area due to the massive metallic constructions, warehouses, enormous container parks, numerous trucks, and large cargo ships and vessels. All these create a very dynamic environment for wireless communications as the signal propagation can be blocked or reflected by these enormous constructions and moving objects.

Figure 59 shows a compilation of photos during the network evaluation while sailing at the Port of Antwerp site.

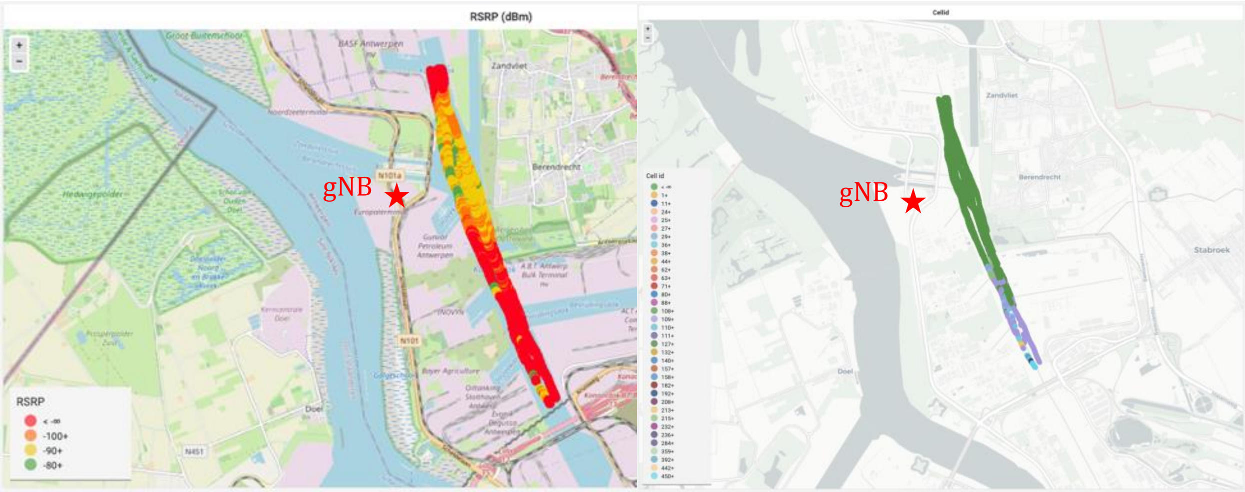
Figure 59: Test environment while sailing at the Port of Antwerp Site

5.3.1.1 5G SA on the water – Right Bank Side

This subsection presents the 5G standalone network evaluation on the water at the right bank side of the Port of Antwerp. During the evaluation, only one gNB was deployed as depicted with purple color in Figure 58. From the UE side, the IMEC evaluation equipment was installed on a boat.

Modem statistics

Figure 60 (a) shows a heatmap of the different RSRP values collected while sailing on the water several times following the identified trajectory at the right bank side. The star symbol shows the location of the gNB where the UE was connected to. As it can be observed, the signal strength is good (RSRP > -100 dbm) in the northern region of the trajectory, closer to the gNB. As the barge was sailing south, the RSRP values were decreasing resulting even to disconnection of the UE from the network. Figure 60 (b) shows the heatmap of the cell IDs to which the device was connected to while sailing across the trajectory.



(a) (b)

Figure 60: (a) 5G SA RSRP values, (b) cell ID at PoA right bank side

Figure 61 presents the CDF plot of the RSRP values from all the performed tests while sailing across the trajectory. As it can be observed, the 50th percentile equals to -95 dbm. This is to be expected as the single gNB used during the evaluation in combination with the very challenging environment could not cover the whole trajectory. Nevertheless, at the locations where the coverage is sufficient, the observed RSRP values are according to the expectations in relation to the distance between the gNB and the UE.

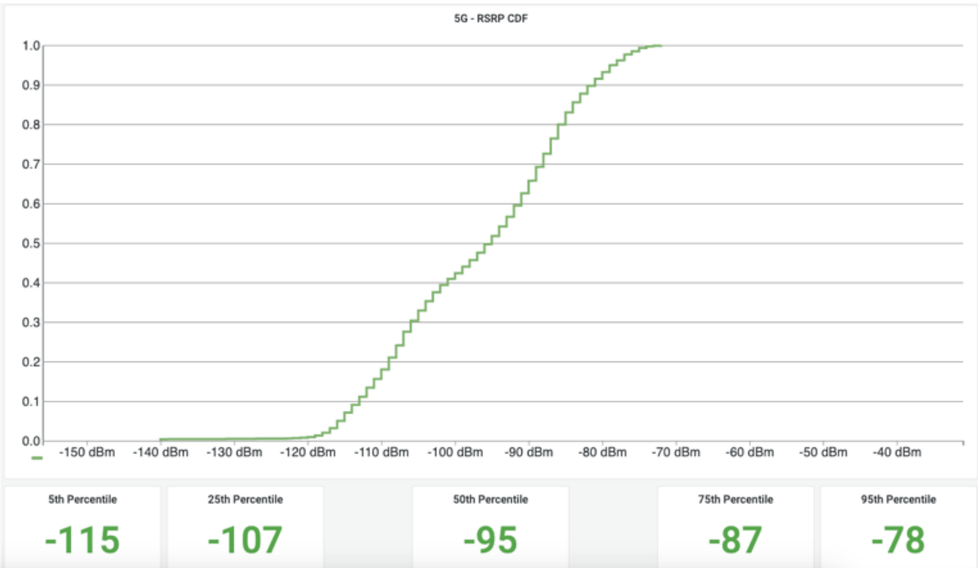


Figure 61: 5G SA RSRP - CDF graph and percentiles at PoA right bank side

TCP downlink rate

In Figure 62, a heatmap of the TCP downlink throughput values is presented along the right bank side trajectory. Moreover, Figure 63 shows the graph of the downlink TCP throughput in Mbps over time. As it can be seen and in line to the RSRP values shown above, the throughput has high values at the northern region of the trajectory which is in the proximity of the gNB. As shown in Figure 63, the maximum throughput that was observed was 411 Mbps, the mean value was 89.1 Mbps and the minimum throughput was 0 Mbps as a result of the UE being disconnected due to poor network coverage at the southern part of the trajectory.

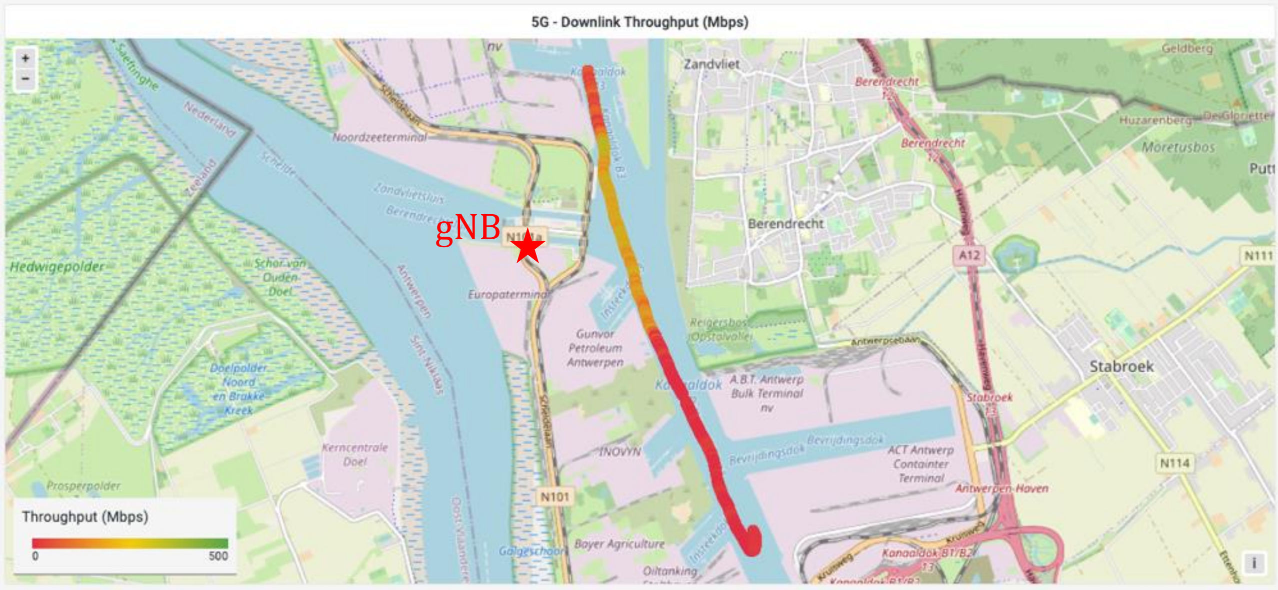


Figure 62: 5G SA TCP downlink rate on map at PoA right bank side

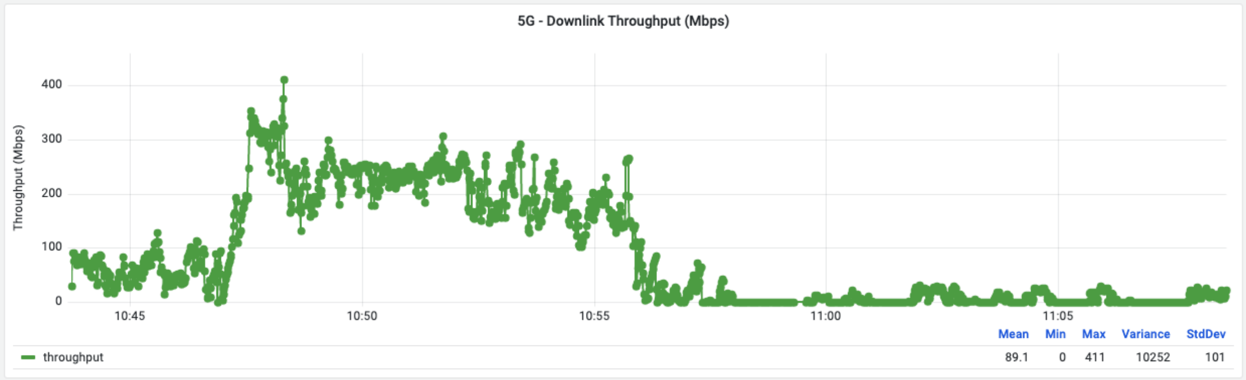


Figure 63: 5G SA TCP downlink rate – graph throughput (Mbps) vs time at PoA right bank side

The CDF graph and selected percentiles of the cumulative TCP downlink throughput values are shown in Figure 64. As it can be observed, the 95th percentile equals to 263 Mbps and the 50th percentile is 31.6 Mbps. This is in line with the CDF plot of the RSRP values shown in Figure 61 above.

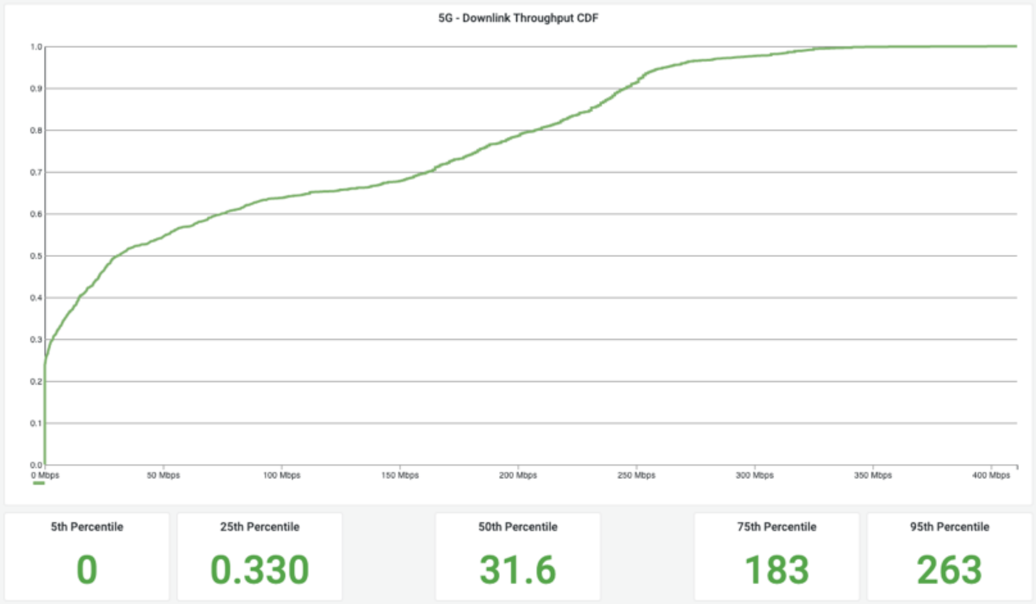


Figure 64: 5G SA TCP downlink rate - CDF graph and percentiles at PoA right bank side

TCP uplink rate

An indicative heatmap of the TCP uplink throughput is shown in Figure 65, while the corresponding graph of the throughput values in relation to time is depicted in Figure 66. It can be observed that the mean throughput is 9.14 Mbps and its maximum value is 36.5 Mbps. In addition, at the northern and southern parts of the trajectory, the TCP uplink throughput is impacted drastically since the UE moves away from the base station towards the cell edge. Especially while sailing south, the UE gets disconnected from the gNB for a couple of minutes.

Figure 65: 5G SA TCP uplink rate on map at PoA right bank side

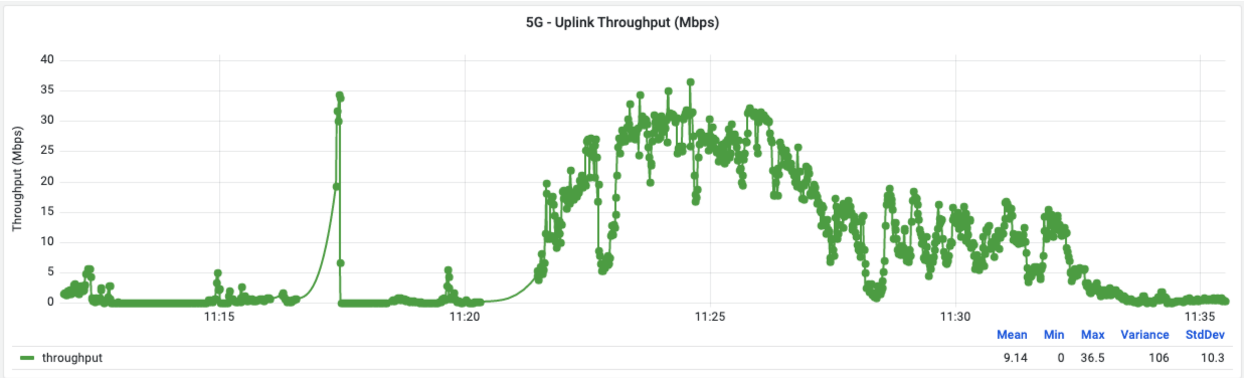


Figure 66: 5G SA TCP uplink rate – graph throughput (Mbps) vs time at PoA right bank side

Figure 67 presents the CDF graph of the uplink TCP throughput over all the tests done across the test trajectory. The relatively low value of the 50th percentile is due to the fact that a big part of the trajectory was at the cell edge or even out of coverage. However, it should be emphasized that while the UE is in the middle of the trajectory and under good cell coverage, the throughput performance satisfies the use case and enabling function requirements as defined in Deliverable 5.1 [3].

The evaluation of the TCP throughput gave insights about the cell coverage, hence this information was taken into account for the evaluation of the upcoming KPIs and the test trajectory was adjusted accordingly.

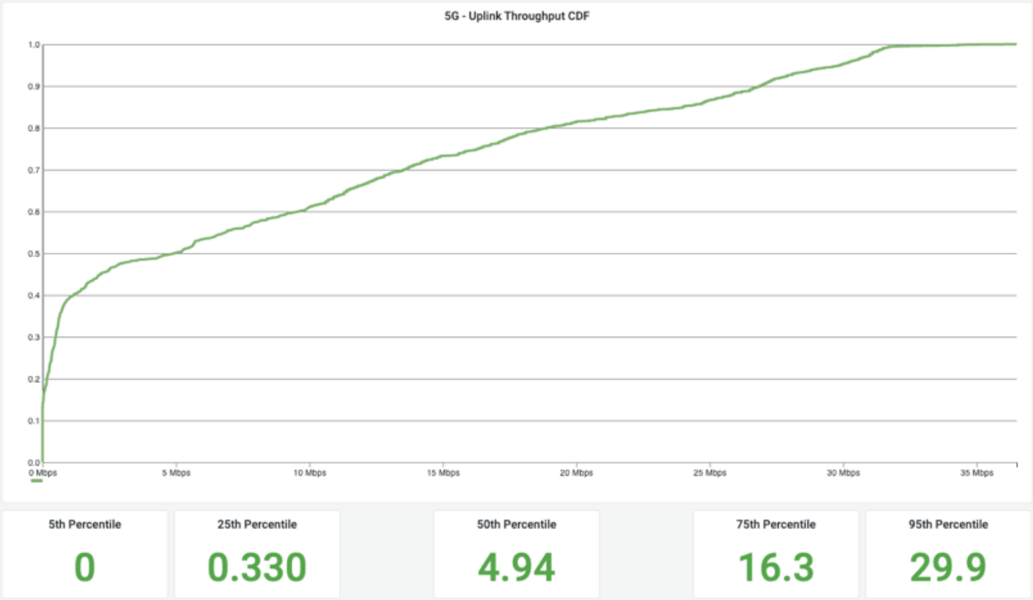


Figure 67: 5G SA TCP uplink rate - CDF graph and percentiles at PoA right bank side

UDP downlink rate

For the evaluation of the UDP downlink throughput, the test trajectory was adjusted aiming to avoid the cell edges. However, it should be emphasized that due to the challenging conditions and the traffic in the port, this was not always possible. Figure 68 shows the heatmap of the throughput, while Figure 69 shows the graph over time together with relevant statistics. As it can be seen, the maximum value is 321 Mbps and the mean value is 182 Mbps.

Figure 68: 5G SA UDP downlink rate on map at PoA right bank side

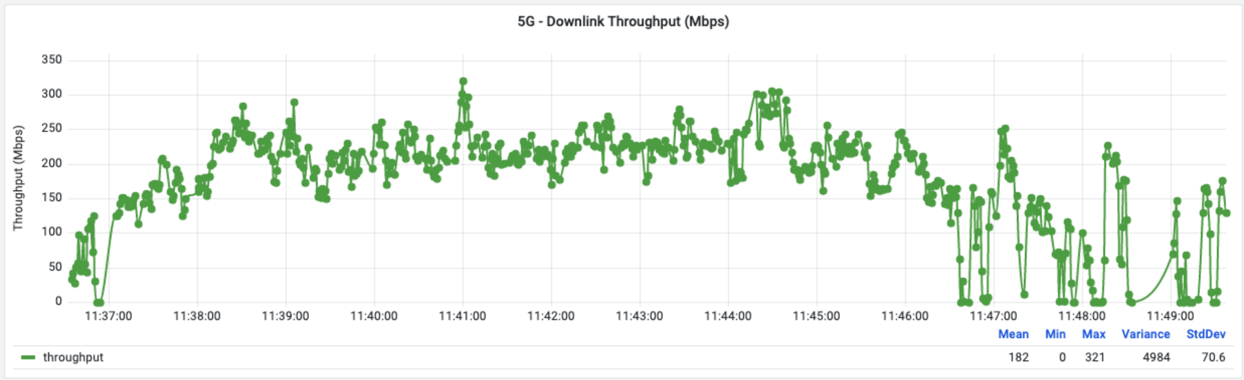


Figure 69: 5G SA UDP downlink rate – graph throughput (Mbps) vs time at PoA right bank side

Figure 70 presents the CDF graph of the downlink UDP throughput. It can be observed that even though the 95th percentile (263 Mbps) is similar to the one of the TCP downlink throughput (Figure 64), the lower percentiles are significantly better for the UDP case due to the adjusted test trajectory. Hence, the 50th percentile is 204 Mbps and the 25th percentile is 154 Mbps, indicating that the 5G performance is according to the expectations for good cell coverage conditions.

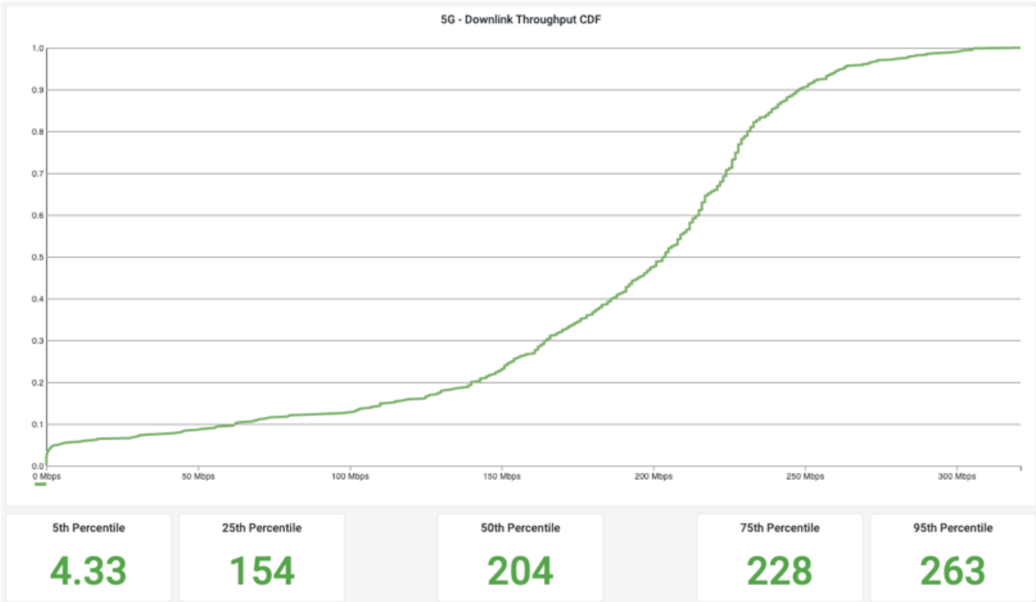


Figure 70: 5G SA UDP downlink rate - CDF graph and percentiles at PoA right bank side

UDP uplink rate

In a similar manner, UDP uplink rate has been evaluated in multiple runs. Figure 71 and Figure 72 illustrate the throughput heatmap and the graph of throughput over time respectively. As it is shown, the mean UDP uplink throughput is 12 Mbps, while the maximum recorded throughput is 32.1 Mbps.

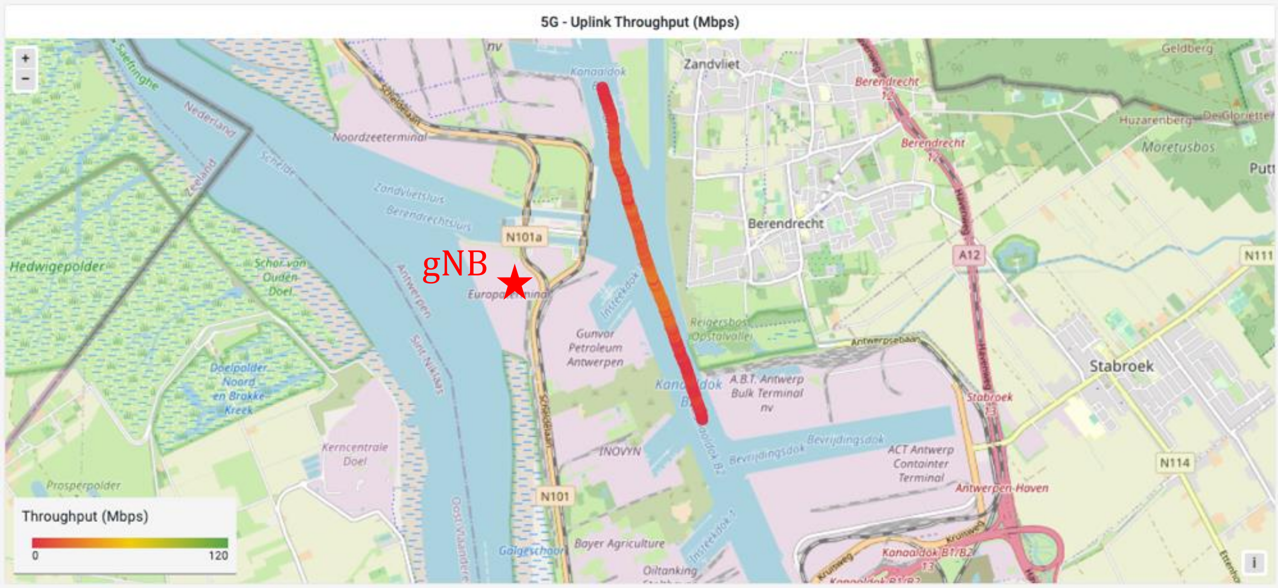


Figure 71: 5G SA UDP uplink rate on map at PoA right bank side

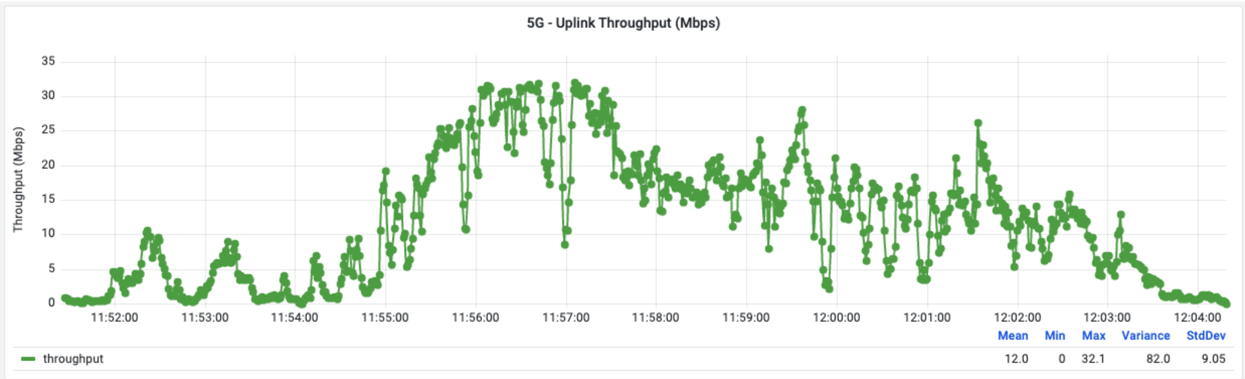


Figure 72: 5G SA UDP uplink rate – graph throughput (Mbps) vs time at PoA right bank side

Figure 73 presents the CDF of the uplink UDP throughput. The 50th percentile is 11.5 Mbps, while the 75th percentile is 11.5 Mbps and the 95th percentile is 29.5 Mbps. Similar to the downlink case, the uplink UDP throughput statistics are overall higher than the corresponding uplink TCP throughput statistics due to the updated trajectory that has been followed aiming to avoid the cell edges.

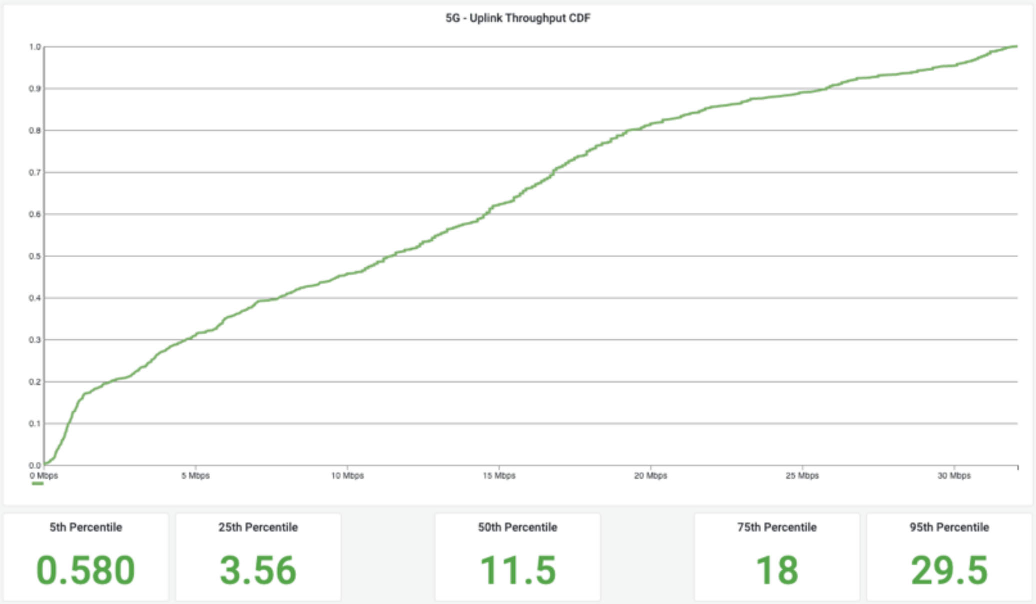
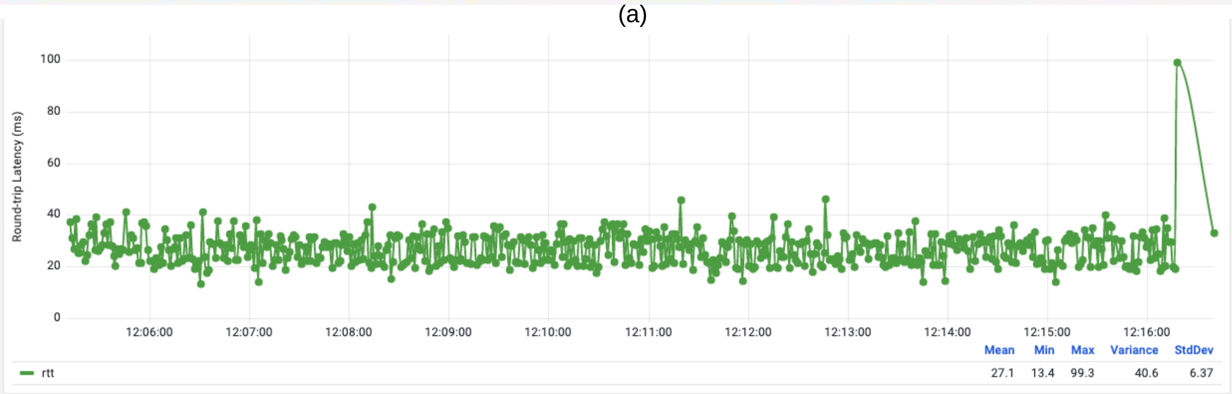


Figure 73: 5G SA UDP uplink rate - CDF graph and percentiles at PoA right bank side

Round-Trip Time

For the evaluation of the round-trip time, different slice configuration have been used. Figure 74 (a) shows the RTT heatmap while sailing at the left bank side, and Figure 74 (b) the corresponding graph of RTT over time for the same test. During that test, the device under test (DUT) uses the eMBB slice and there is no background traffic transmitted. As it can be observed, the latency values are quite constant over the whole trajectory. More specifically, the mean latency equals to 27.1 ms and the standard deviation is 6.37. The minimum round-trip latency is 13.4 ms and the maximum one is 99.3 ms, which refers to an outcast value that has been observed towards the cell edge.

(a)

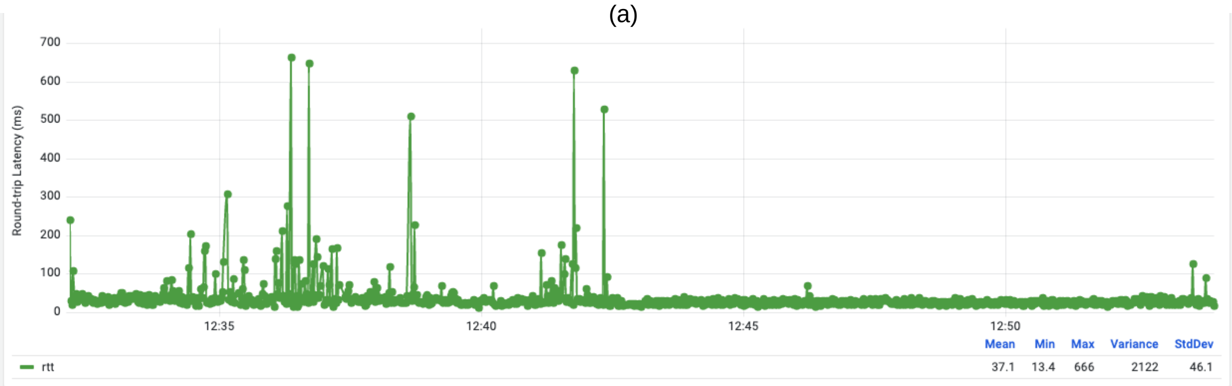


(b)

Figure 74: 5G SA RTT on (a) map and (b) graph - DUT on the eMBB slice without background traffic at PoA right bank side

Next, the trajectory was repeated but this time, background traffic was introduced so that we can evaluate the impact of heavy background traffic on the performance of round-trip latency. Hence, the DUT was again using the eMBB slice sending ICMP packets, and in addition to that another device using the URLLC slice was sending bi-directional UDL traffic using as much load as possible. Figure 75 shows the heatmap map and the graph of round-trip latency over time during an indicative example of such test. As expected, the background traffic had an impact on the recorded latency values, which have peaks that reach up to 666 ms, compared to Figure 74 where the latency values are all around the mean value of 27.1 ms. It should be emphasized that the device generating background traffic was placed next to the DUT so that both devices use the same antenna beam to send and receive data.

(a)



(b)

Figure 75: 5G SA RTT on (a) map and (b) graph - DUT on the eMBB slice with background traffic on the URLLC slice at PoA right bank side

Subsequently, we switched the used slices so that the DUTs uses the URLLC slice and the device generating both downlink and uplink background traffic uses the eMBB slice. In Figure 76, it can be seen that the background traffic introduced from 13:30 to 13:36 had an impact on the round-trip latency values on the URLLC slice. However, this was against our expectations since the traffic on URLLC slice should have higher priority than the traffic on the eMBB slice. After further investigation from Telenet, it was found out that the high priority of the URLLC slice had been configured only for downlink traffic. However, the round-trip latency uses both downlink and uplink, hence the impact from the background traffic.

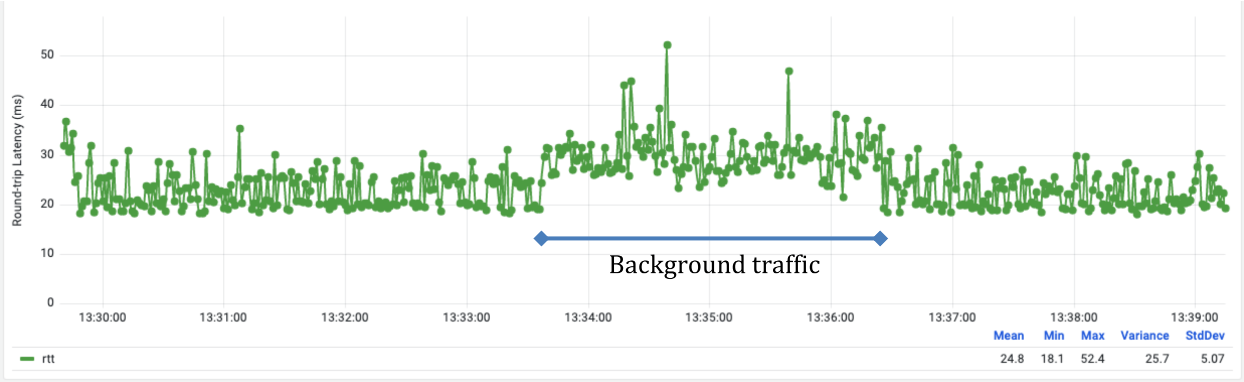


Figure 76: 5G SA RTT – DUT on the URLLC slice with downlink and uplink background traffic on the eMBB slice from 13:30 to 13:36 at PoA right bank side

Another test aimed to investigate the impact of the 5G NSA production network on the 5G SA network. Figure 77 shows the round-trip latency values over time when the DUT was using the Live Stream slice and a second device connected to the 5G NSA network was sending both downlink and uplink UDP background traffic. As shown and according to the expectations, the background traffic does not impact the latency values at the SA network, since the two networks use different frequency bands.

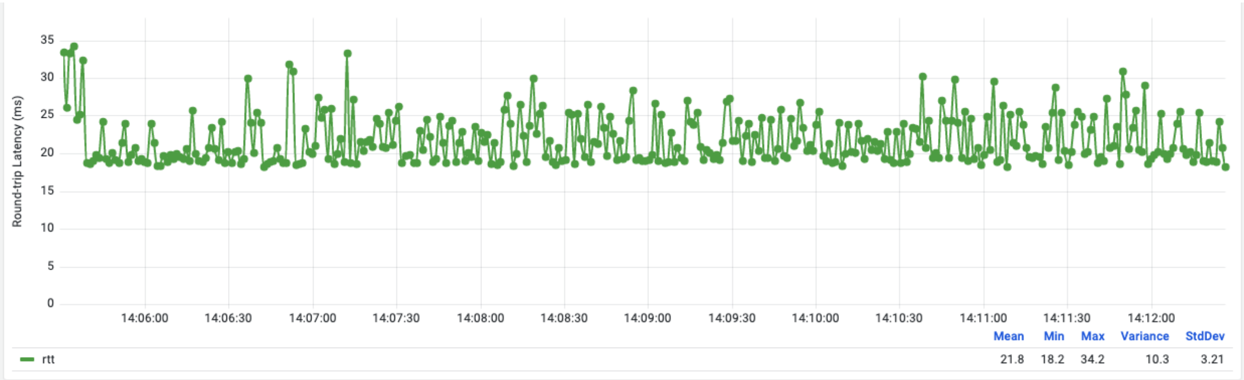
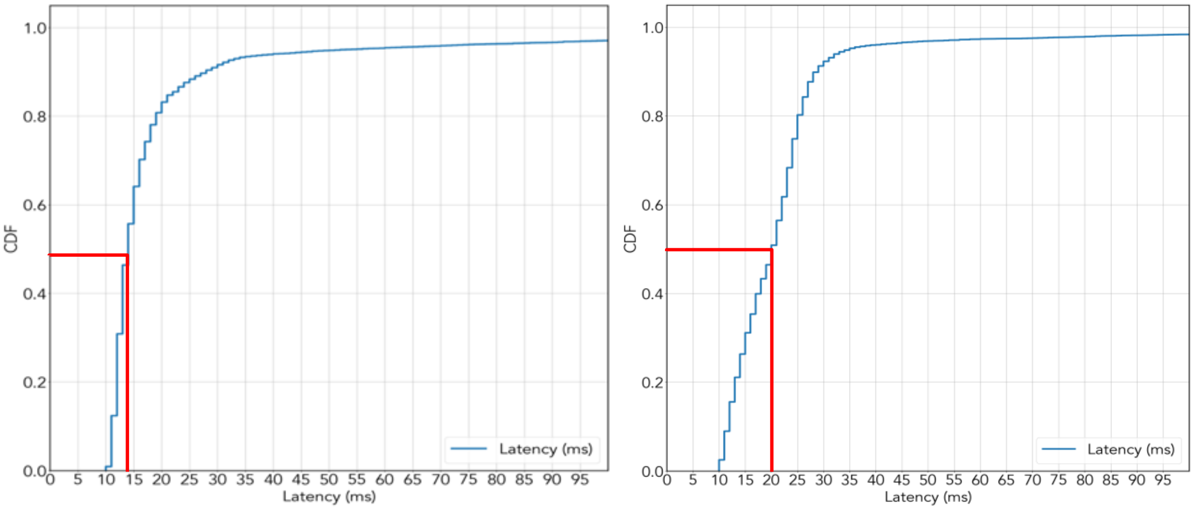


Figure 77: 5G SA RTT – DUT on the Live Stream slice with downlink and uplink background traffic on the 5G NSA network at PoA right bank side

One-way latency

The next investigated KPI refers to the uplink one-way latency. Similar to the other KPIs, the one-way latency has been evaluated during multiple runs and the impact of background traffic has been investigated. Figure 78 (a) shows the CDF graph of the one-way latency when the DUT uses the eMBB slice and there is no background traffic. The median value of the one-way latency is 14 ms. Figure 78 (b) shows the CDF graph of the one-way latency when a second co-located device using the URLLC slice transmits background downlink and uplink UDP traffic. As expected, the background traffic has an impact on the eMBB slice as eMBB has the least priority over other slices. The median value of the one-way latency increases to 20 ms.

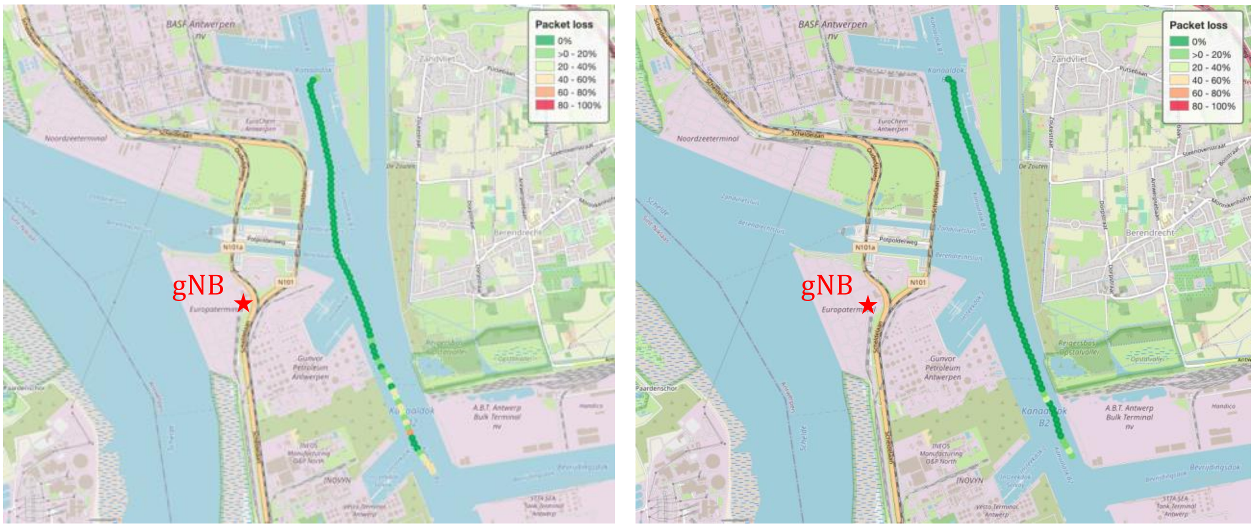


(a) (b)

Figure 78: 5G SA one-way latency - DUT on the eMBB slice (a) without background traffic, (b) with background traffic on the URLLC slice at PoA right bank side

Packet-loss

Packet-loss is another interesting KPI that has been evaluated at the right back side of the Port of Antwerp. Figure 79 shows the packet-loss when the vessel was sailing from north to south, meaning at the left side of the canal, while Figure 79 shows the packet-loss when the vessel was sailing from south to north, meaning at the right side of the canal. As it can be seen, the trajectory at the left hand side suffers from higher packet-loss compared to the trajectory at the right hand side, especially at the southern part close to the cell edge. This is due to many obstacles and constructions that result to bad line-of-sight between the gNB and the UE, compared to the right hand side where the line of sight is better.



(a) (b)

Figure 79: 5G SA Packet-loss – (a) High packet-loss due to bad Line-Of-Sight because of constructions/obstacles at the left side of the canal, (b) Better packet-loss due to improved Line-Of-Sight at PoA right bank side

Summary

In Table 13, a summary is provided of the results from the 5G SA network evaluation that was conducted at the right bank of the port area in Antwerp on a boat.

On-site 5G network evaluation						
Location	Belgium – Port of Antwerp – **Right bank**		Location type	**On the water - boat**		
Network operator	Telenet		Network type	5G SA		
Network slice config	eMBB – no background traffic eMBB – with background traffic		UE type	Quectel RM502Q		
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-140	-115	-95	-78	-72	-96.8
TCP DL (Mbps)	0	0	31.6	263	411	89.1
TCP UL (Mbps)	0	0.330	4.94	29.9	36.5	9.14
UDP DL (Mbps)	0	4.33	204	263	321	182
UDP UL (Mbps)	0	0.580	11.5	29.5	32.1	12
RTT (ms) eMBB slice without background	13.4	19.4	27.4	36.7	99.3	27.1
RTT (ms) eMBB slice with background	13.4	19.7	29.4	70.5	666	37.1

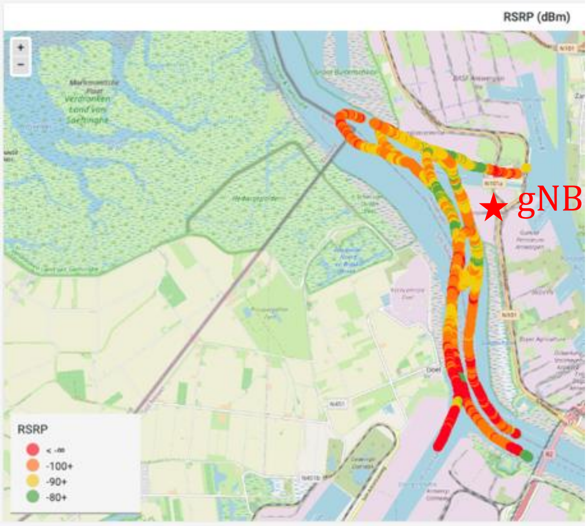
Table 13: Summary of 5G SA network performance evaluation at the right bank on the boat

5.3.1.2 5G SA on the water – The Schelde River

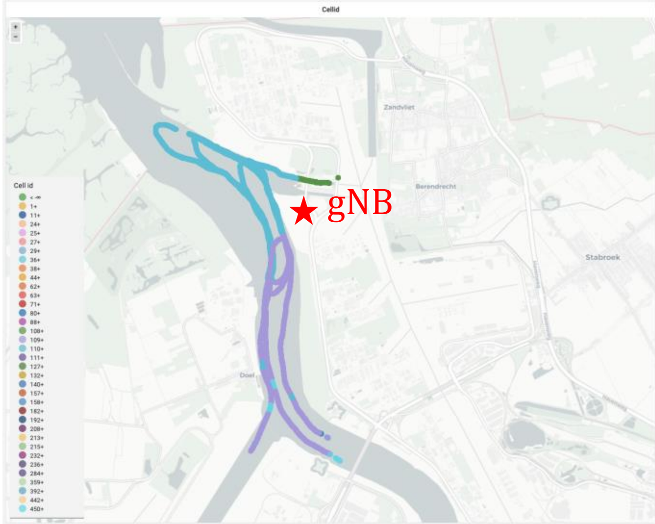
Modem statistics

After evaluating the 5G network at the right bank side of the Port of Antwerp, we started the evaluation of the counter side, meaning the corresponding part of the Schelde river parallel to the right bank side.

This trajectory is shown in Figure 80, which illustrates (a) the heatmap of the RSRP values collected during all the tests, and (b) the cell ID on which the UE was attached over the sailed trajectory.



(a)



(b)

Figure 80: (a) 5G SA RSRP values, (b) cell ID at PoA Schelde river side

Figure 81 shows the CDF plot of the RSRP values for all the tests done at the Schelde river. As it can be observed, the 5th percentile is -104 dbm, the 50th percentile is -92dbm and the 95th percentile is -79dbm. Hence, the biggest part of the trajectory is under good coverage. Only when sailing towards the cell edge, meaning towards the northern and the southern part of the trajectory the signal weakens.

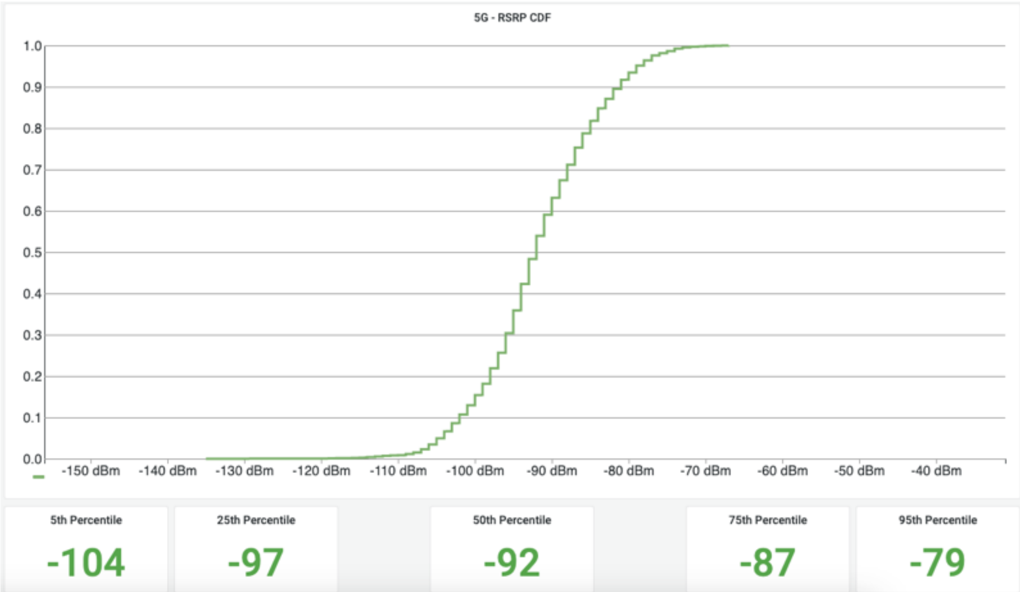


Figure 81: 5G SA RSRP - CDF graph and percentiles at PoA Schelde river side

TCP downlink rate

In Figure 82, a heatmap of the TCP downlink throughput values is presented along the Schelde river trajectory. Moreover, Figure 83 shows the graph of the downlink TCP throughput in Mbps over time. In line with the RSRP values shown above, the throughput has high values at the northern region of the trajectory which is in the proximity of the gNB. As shown in Figure 83 , the maximum throughput that was observed was 427 Mbps, the mean value was 136 Mbps and the minimum throughput was 0 Mbps as a result of the UE being disconnected due to poor network coverage at the southern part of the trajectory.

Figure 82: 5G SA - TCP downlink rate on map at PoA Schelde river side

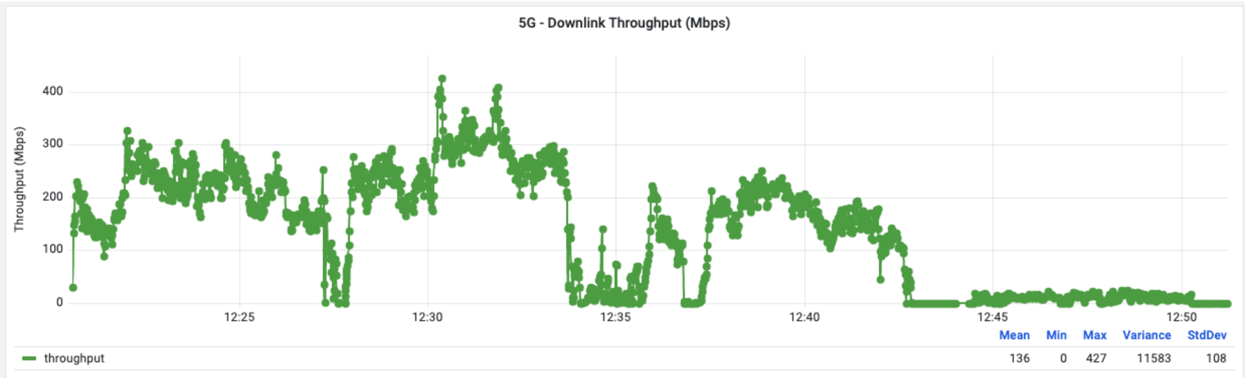


Figure 83: 5G SA TCP downlink rate – graph throughput (Mbps) vs time at PoA Schelde river side

The CDF graph and selected percentiles of the cumulative TCP downlink throughput values are shown in Figure 84. As it can be observed, the 95th percentile equals to 297 Mbps and the 50th percentile is 156 Mbps. This is in line with the CDF plot of the RSRP values shown in Figure 80 above.

Figure 84: 5G SA TCP downlink rate - CDF graph and percentiles at PoA Schelde river side

TCP uplink rate

An indicative heatmap of the TCP uplink throughput is shown in Figure 85, while the corresponding graph of the throughput values in relation to time is depicted in Figure 86. It can be observed that the mean throughput is 10.06 Mbps and its maximum value is 39 Mbps. In addition, at the northern and southern parts of the trajectory, the TCP uplink throughput is impacted drastically since the UE moves away from the base station towards the cell edge.

Figure 85: 5G SA - TCP uplink rate on map at PoA Schelde river side

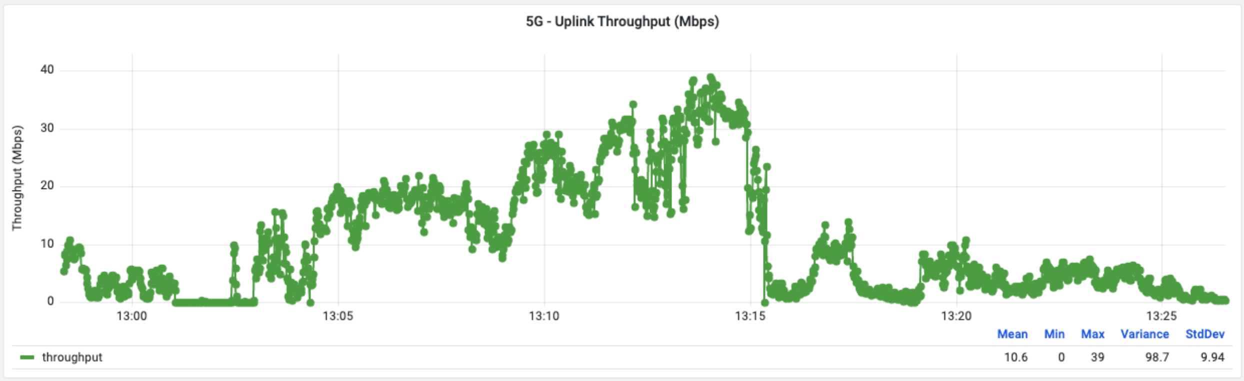


Figure 86: 5G SA TCP uplink rate – graph throughput (Mbps) vs time at PoA Schelde river side

Figure 87 presents the CDF graph of the uplink TCP throughput over all the tests done across the test trajectory. The relatively low value of the 50th percentile is because a big part of the trajectory was at the cell edge. However, it should be emphasized that while the UE is in the middle of the trajectory and under good cell coverage, the throughput performance satisfies the use case and enabling function requirements as defined in Deliverable 5.1 [3].

Figure 87: 5G SA TCP uplink rate - CDF graph and percentiles at PoA Schelde river side

UDP downlink rate

Figure 88 shows the heatmap of the throughput, while Figure 89 shows the graph over time together with relevant statistics. As it can be seen, the maximum value is 209 Mbps and the mean value is 158 Mbps.

Figure 88: 5G SA - UDP downlink rate on map at PoA Schelde river side

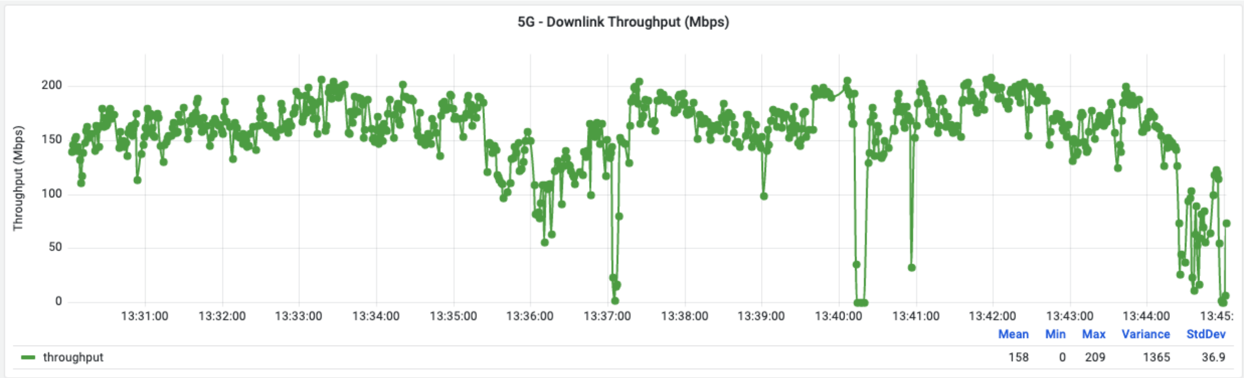


Figure 89: 5G SA UDP downlink rate – graph throughput (Mbps) vs time at PoA Schelde river side

Figure 90 presents the CDF graph of the downlink UDP throughput. It can be observed that even though the 95th percentile (198 Mbps) is lower to the one of the TCP downlink throughput (297Mbps) (Figure 84), the lower percentiles are significantly better for the UDP case due to the adjusted test trajectory. Hence, the 50th percentile is 165 Mbps and the 25th percentile is 81.5 Mbps, indicating that the 5G performance is according to the expectations for good cell coverage conditions.

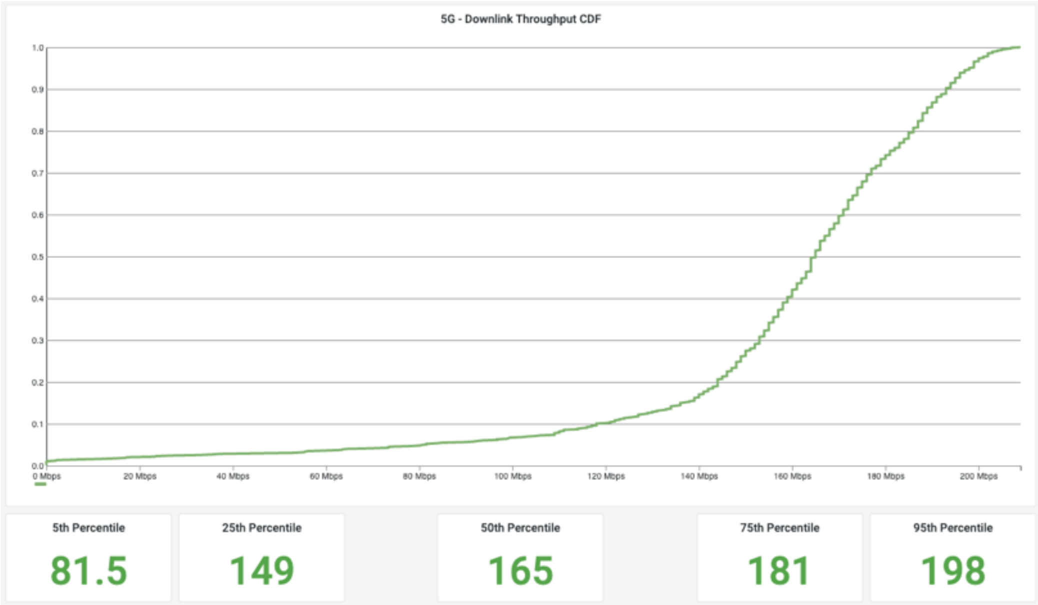


Figure 90: 5G SA UDP downlink rate - CDF graph and percentiles at PoA Schelde river side

UDP uplink rate

In a similar manner, UDP uplink rate has been evaluated in multiple runs. Figure 91 and Figure 92 illustrate the throughput heatmap and the graph of throughput over time respectively. As it is shown, the mean UDP uplink throughput is 13 Mbps, while the maximum recorded throughput is 37.2 Mbps.

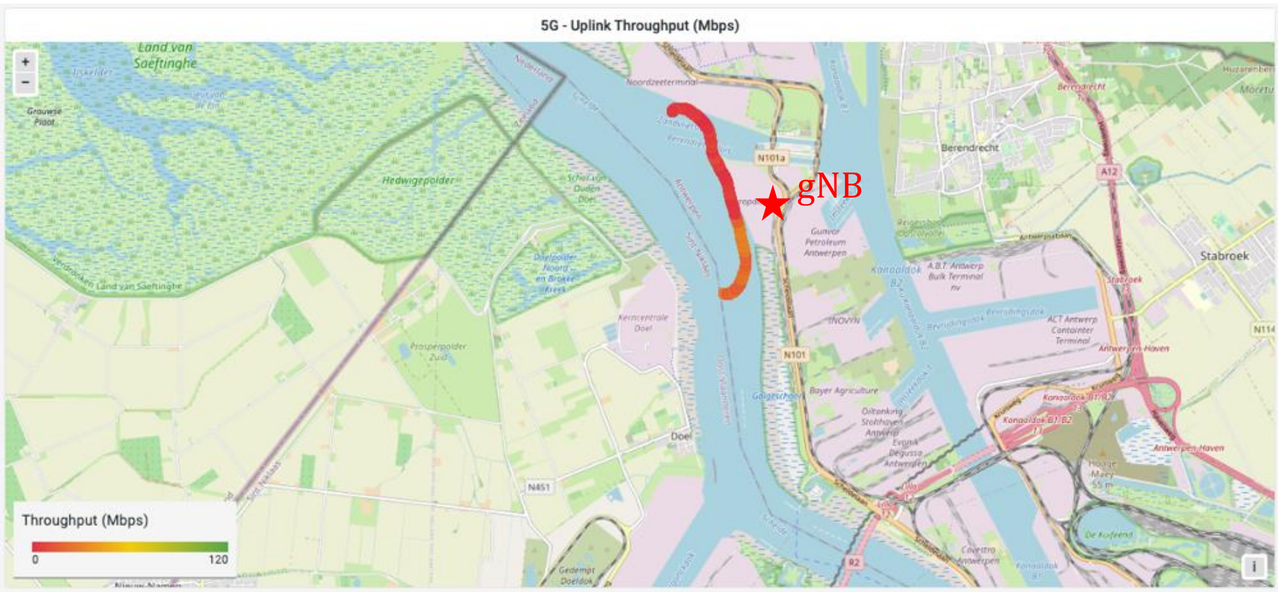


Figure 91: 5G SA - UDP uplink rate on map at PoA Schelde river side

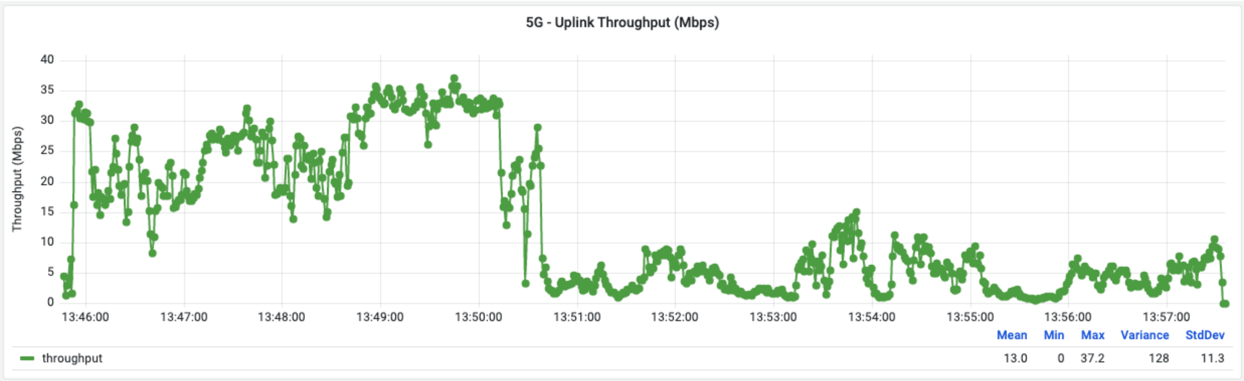


Figure 92: 5G SA UDP uplink rate – graph throughput (Mbps) vs time at PoA Schelde river side

Figure 93 presents the CDF of the uplink UDP throughput. The 50th percentile is 7.52 Mbps, while the 75th percentile is 22.8 Mbps and the 95th percentile is 33.3 Mbps. Similar to the downlink case, the uplink UDP throughput statistics are slightly higher than the corresponding uplink TCP throughput statistics due to the updated trajectory that has been followed aiming to avoid the cell edges.

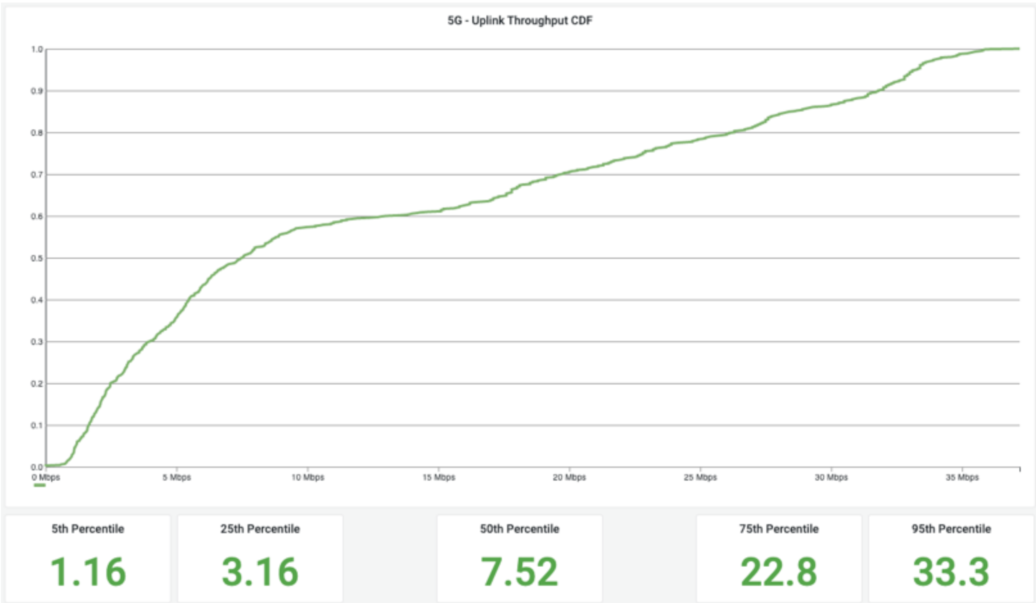


Figure 93: 5G SA UDP uplink rate - CDF graph and percentiles at PoA Schelde river side

Round-Trip Time

Figure 94 shows the RTT heatmap while sailing at the Schelde river, and Figure 95 the corresponding graph of RTT over time for the same test. During that test, the DUT uses the eMBB slice and there is no background traffic transmitted. As it can be observed, the latency values are quite constant over the whole trajectory. More specifically, the mean latency equals to 24.9 ms and the standard deviation is 19.1. The minimum round-trip latency is 18 ms and the maximum one is 359 ms, which refers to some outcast values that has been observed towards the cell edge. Figure 96 presents the CDF of the RTT. The 50th percentile is 21.6 ms, while the 75th percentile is 25.5 ms and the 95th percentile is 33.1 Mbps.

Figure 94: 5G SA RTT on map at PoA Schelde river side

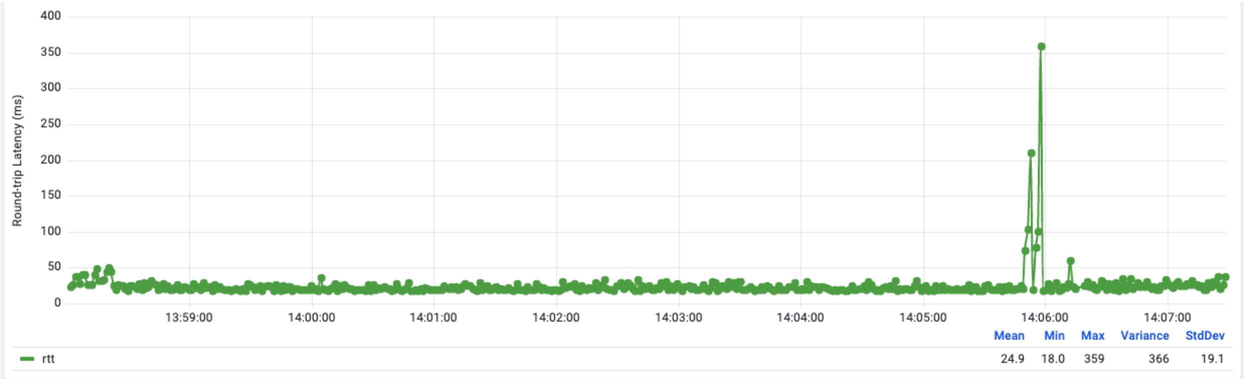
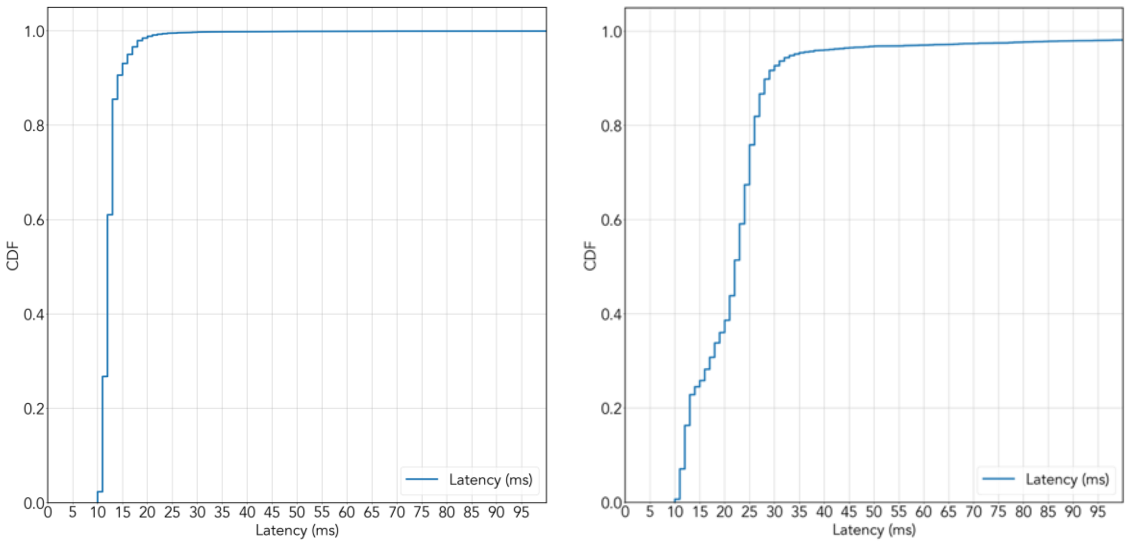


Figure 95: 5G SA RTT graph – graph RTT (ms) vs time at PoA Schelde river side

Figure 96: 5G SA RTT - CDF graph and percentiles at PoA Schelde river side

One-way latency

The one-way latency has been evaluated during multiple runs and the impact of background traffic has been investigated. Figure 97 (a) shows the CDF graph of the one-way latency when the DUT uses the eMBB slice and there is no background traffic. The median value of the one-way latency is 16 ms. Figure 97 (b) shows the CDF graph of the one-way latency when a second co-located device using the eMBB slice transmits background downlink and uplink UDP traffic. As expected, the background traffic has an impact. The median value of the one-way latency increases to 22 ms.

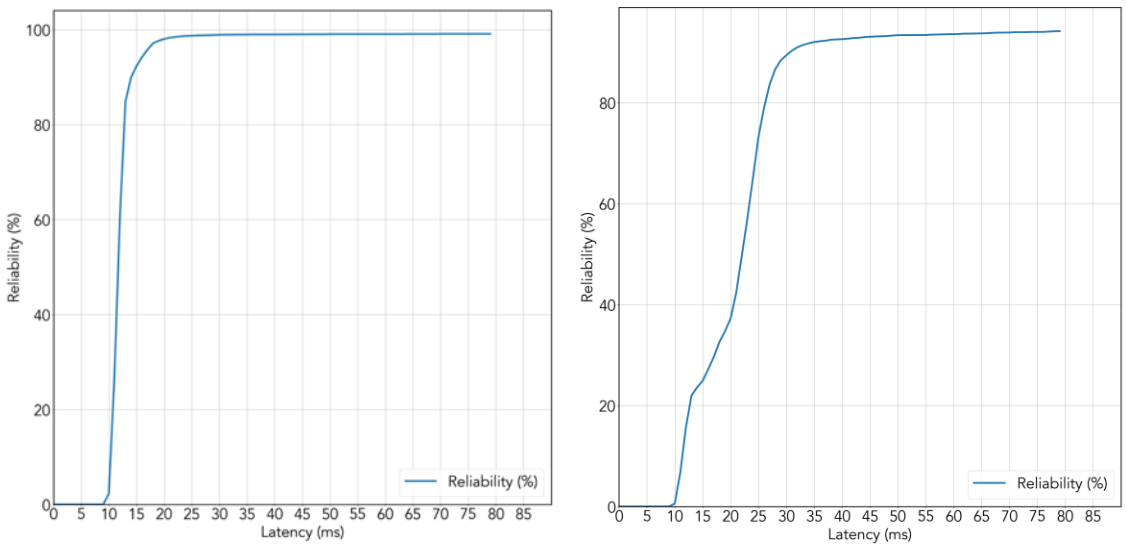


(a) (b)

Figure 97: One-way latency CDF – DUT on the eMBB slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA Schelde river side

Reliability

Reliability is another interesting KPI that has been evaluated at the Schelde river near the Port of Antwerp. Figure 98 (a) shows the reliability graph when the DUT uses the eMBB slice and there is no background traffic. Traffic is sent in the uplink. It shows that for example if the threshold is set to 25ms, around 98% of the packets are received correctly. Figure 98(b) shows the reliability graph when a second co-located device using the eMBB slice transmits background uplink UDP traffic. As expected, it has impact on the reliability. For a latency threshold of 25ms, only 70% of the packets are received correctly in time.



(a) (b)

Figure 98: Reliability CDF – DUT on the eMBB slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA Schelde river side

Packet delivery rate

Figure 99 (a) shows the packet delivery rate graph when the DUT uses the eMBB slice and there is no background traffic. It shows that only in the southern part there was a little bit of packet loss (see also Figure 100 a). Figure 99 shows the packet delivery graph when a second co-located device using the eMBB slice transmits background uplink UDP traffic. It shows that there was some more packet loss. However, it is hard to say whether it is because of the coverage in that area or due to the background traffic.

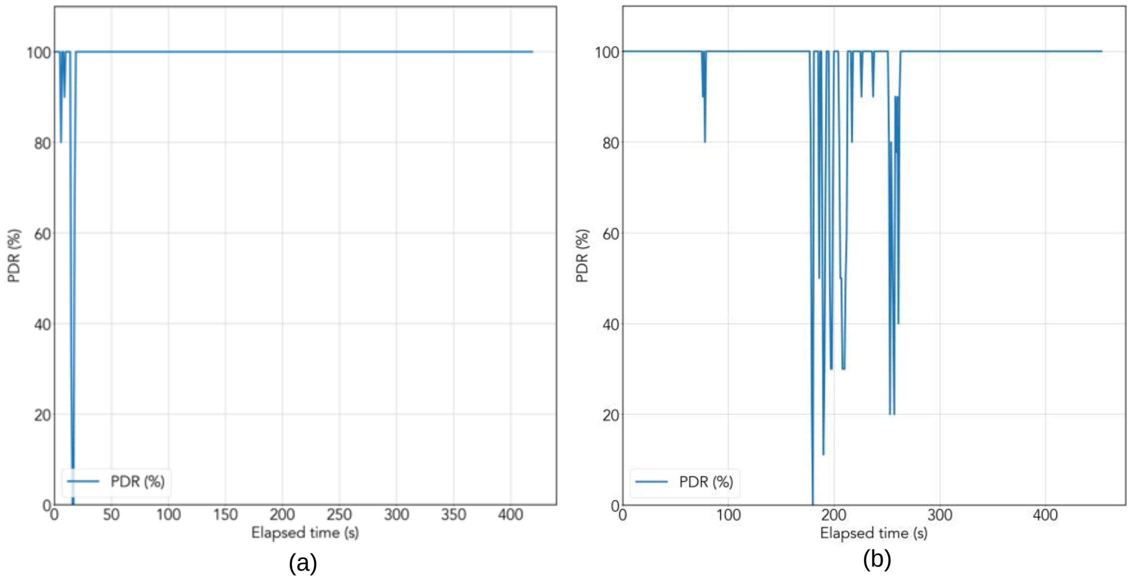


Figure 99: Packet delivery rate – DUT on the eMBB slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA Schelde river side

Packet-loss

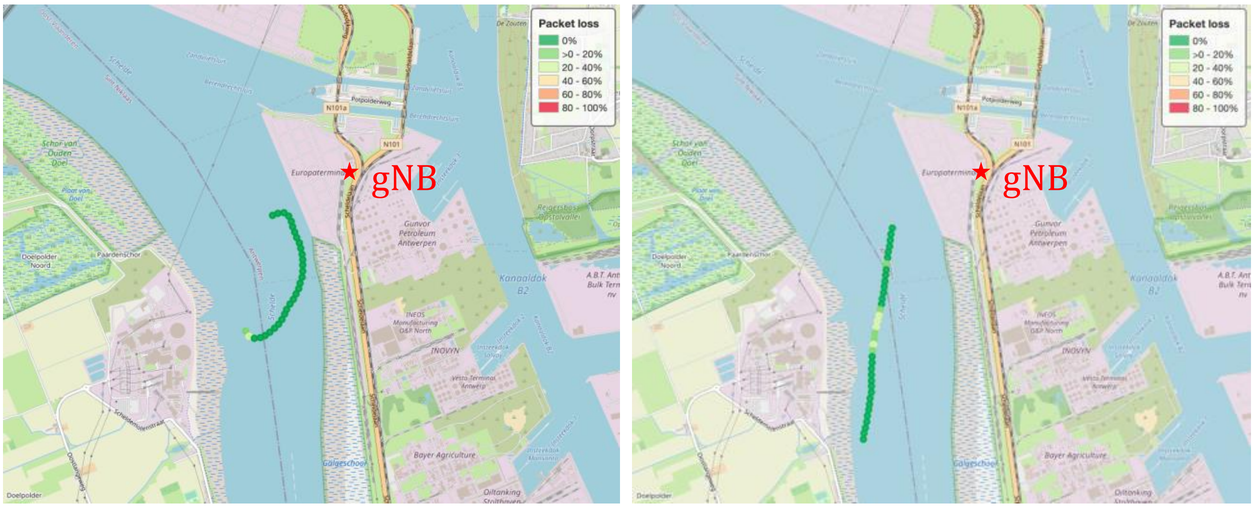


Figure 100: Packet-loss on map – DUT on the eMBB slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA Schelde river side

Summary

In Table 14**,** a summary is provided of the results from the 5G SA network evaluation that was conducted at the Schelde river in Antwerp on a boat.

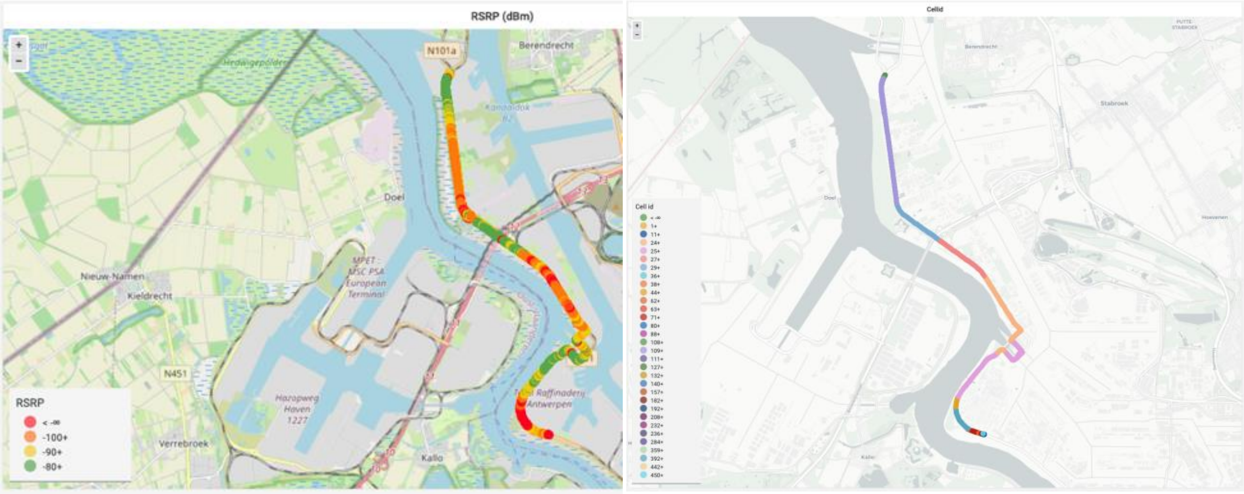
On-site 5G network evaluation						
Location	Belgium – Port of Antwerp – **Schelde**		Location type		**On the water - boat**	
Network operator	Telenet		Network type		5G SA	
Network slice config	eMBB - no background traffic		UE type		Quectel RM502Q	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-135	-104	-92	-79	-67	-91.8
TCP DL (Mbps)	0	0	156	226	427	136
TCP UL (Mbps)	0	0	6.15	31.4	39	10.6
UDP DL (Mbps)	0	81.5	165	198	209	158
UDP UL (Mbps)	0	1.16	7.52	33.3	37.2	13
RTT (ms)	18	18.7	21.6	33.1	359	24.9

Table 14: Summary of 5G SA network performance evaluation at the Schelde on the boat

5.3.1.3 5G SA on the road – In parallel to the Right Bank Side

Modem statistics

Next to the measurements that were performed on the water at PoA, more tests were executed on the road between the Right Bank and the Schelde river. For these tests, the measuring equipment was installed in the IMEC test vehicle and all seven Telenet gNBs were operational. The trajectory is shown in Figure 101, which illustrates (a) the heatmap of the RSRP values collected during all the tests, and (b) the cell ID on which the UE was attached over the droven trajectory.



(a) (b)

Figure 101: (a) 5G SA RSRP values, (b) cell ID at PoA - on the road

Figure 102 shows the CDF plot of the RSRP values for all the tests done on the road. As it can be observed, the 5th percentile is -101 dbm, the 50th percentile is -85dbm and the 95th percentile is -67dbm. Hence, the biggest part of the trajectory is under good coverage. There are a few spots where the RSRP values are a bit weaker near the cell edges. The signal strengths are in general a bit higher than observed on the water.

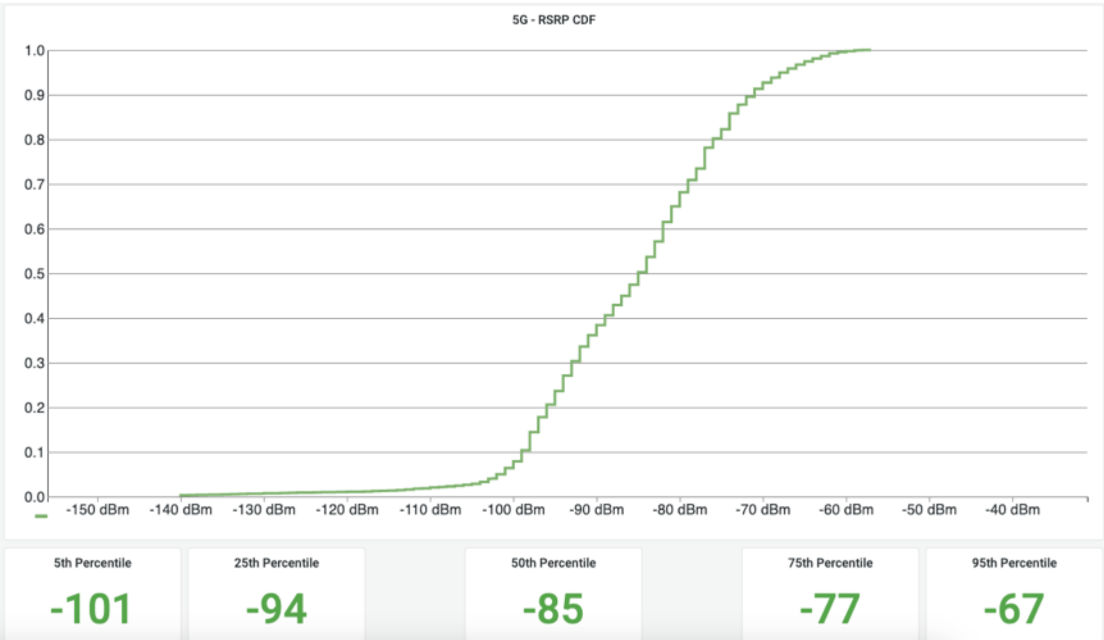


Figure 102: 5G SA RSRP - CDF graph and percentiles at PoA – on the road

TCP downlink rate

In Figure 103, a heatmap of the TCP downlink throughput values is presented along the road trajectory. In line with the RSRP values shown above, the throughput has good values along the whole trajectory with some peaks when being closer to a gNB.

Inside the blue circle on the considered trajectory is indicated an identified zone with significantly lower performance. Telenet investigated this performance degradation further and it was concluded that it was a result of cross-site interference caused by the antenna of another gNB, which was slightly tilted towards a wrong direction.

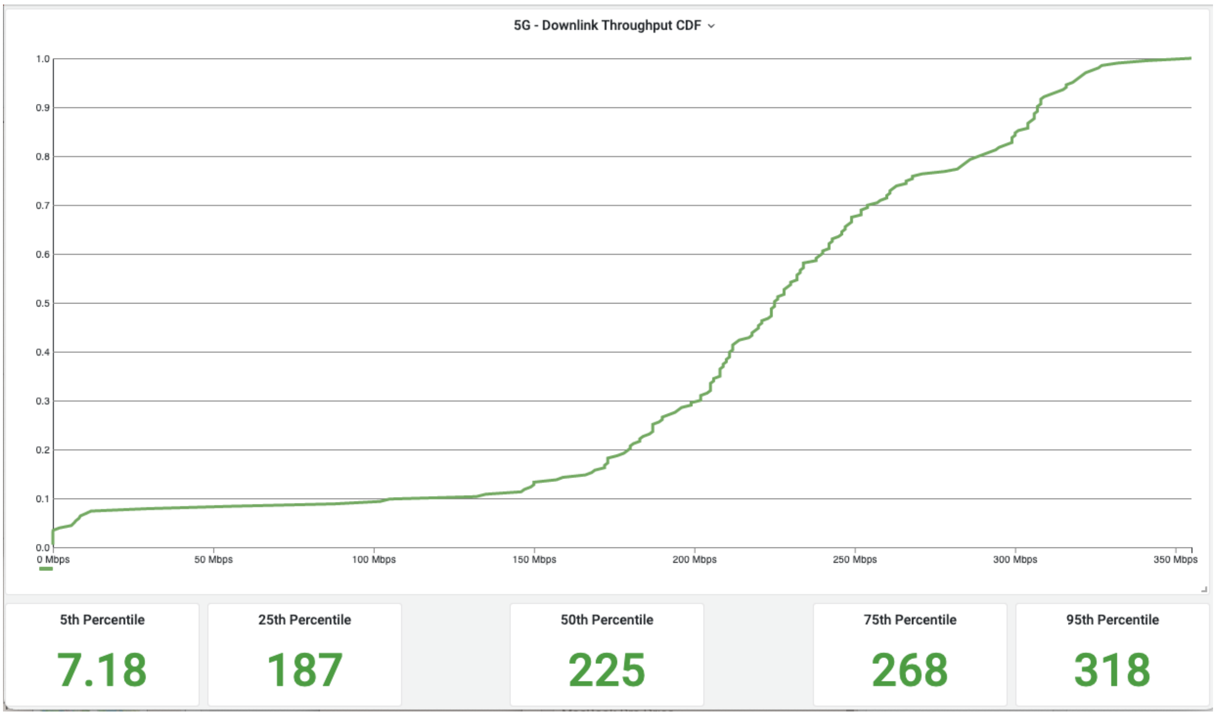
Figure 103: 5G SA TCP downlink rate on map at PoA - on the road

For the remainder of the measurements, the focus was put on a subpart of the trajectory, more towards the North.

Figure 104 shows the graph of the downlink TCP throughput in Mbps on a map and over time when the DUT was on the eMBB slice without any background traffic. In line with the RSRP values shown above, the throughput has high values at the northern region of the trajectory which is in the proximity of the gNB. At the South, there was some drop in the throughput which was caused by the misconfigured base station that caused interference as explained above. For the considered trajectory, the 95th percentile throughput that was observed was 318 Mbps, the median value was 225 Mbps and the 5the percentile throughput was 7.18 Mbps.

When load was introduced by a second UE on the eMBB slice, a clear degradation of the TCP downlink throughput was observed as shown in Figure 105. For the considered trajectory, the 95th percentile throughput that was observed was 232 Mbps, the median value was 136. However, the 5th percentile showed a clear higher value (76.7Mbps) than without the background traffic. This has to do with the fact that in the South at the moment of the measurement, the throughput seemed to be better as can be seen on the map.

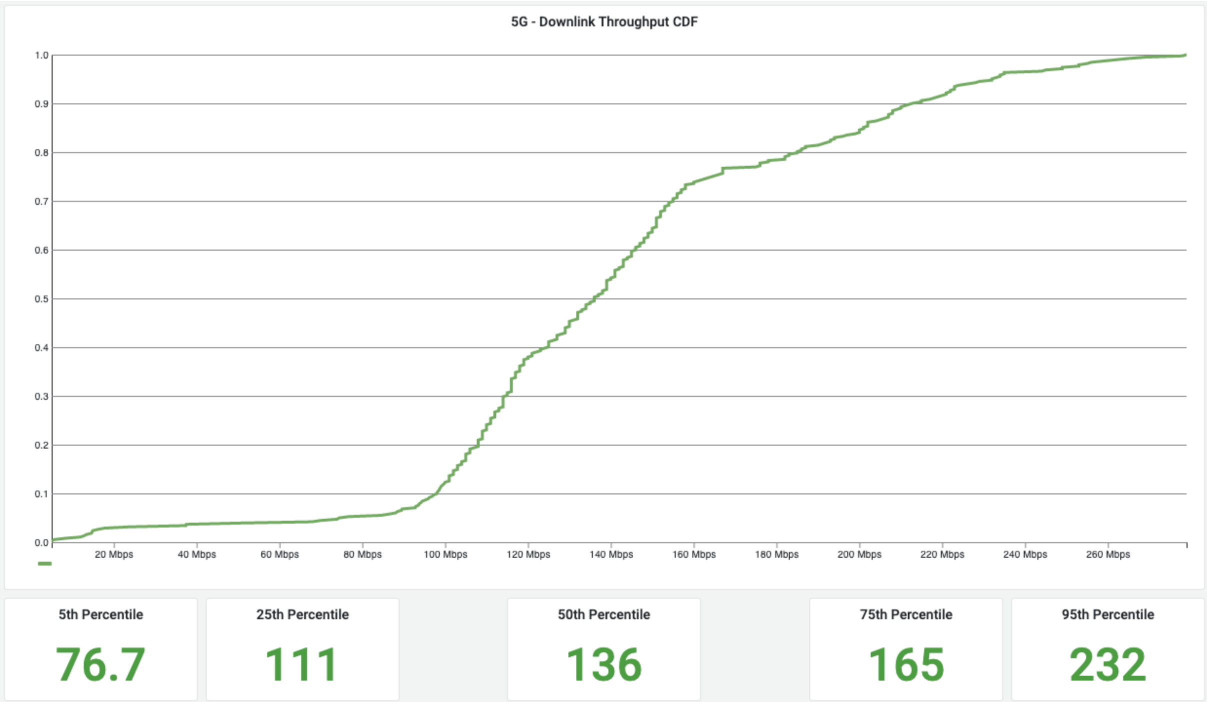
(a)



(b)

Figure 104: 5G SA TCP downlink rate – DUT on the eMBB slice without background traffic (a) on a map, (b) CDF graph and percentiles at PoA – on the road

(a)



(b)

Figure 105: 5G SA TCP downlink rate – DUT on the eMBB slice with background traffic on the eMBB slice (a) on a map, (b) CDF graph and percentiles at PoA – on the road

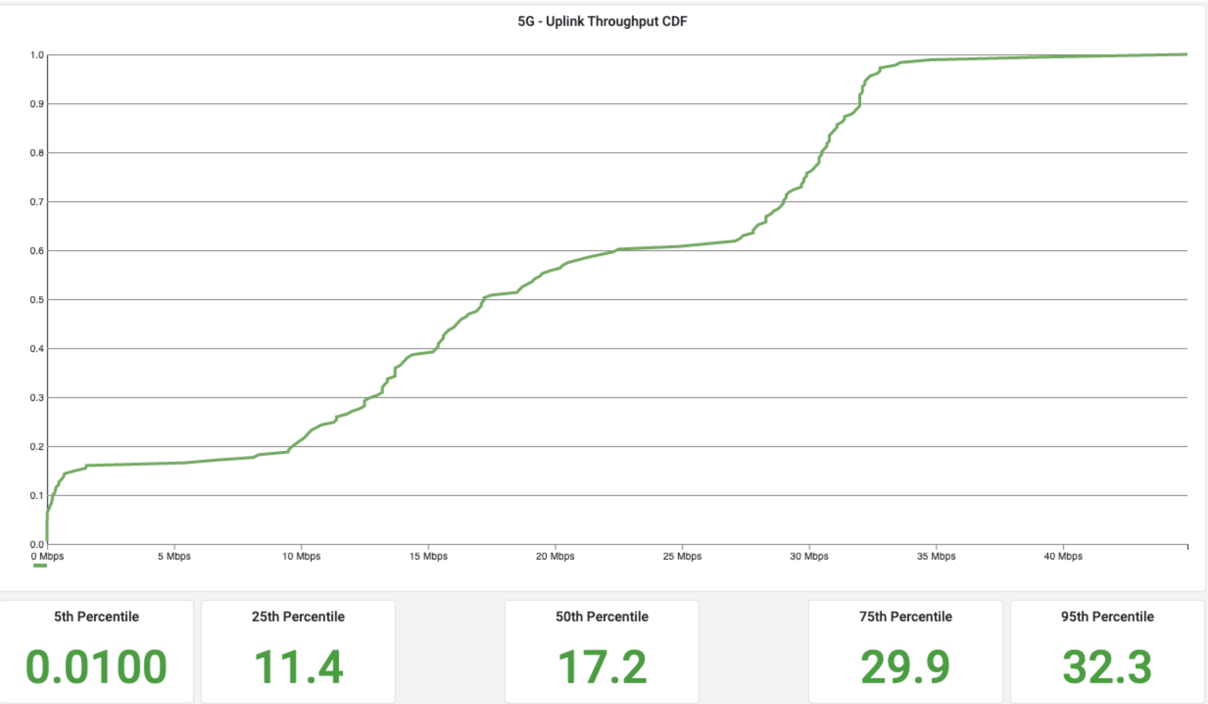
TCP uplink rate

An indicative heatmap of the TCP uplink throughput is shown in Figure 106 (a), while the corresponding CDF graph of the throughput is depicted in Figure 106 (b). It can be observed that the median throughput is 17.2 Mbps and 95th percentile is 32.3 Mbps. At the southern part of the trajectory, the TCP uplink throughput is impacted drastically.

When load was introduced by a second UE on the eMBB slice, a clear degradation of the TCP uplink throughput was observed as shown in Figure 107. For the considered trajectory, the 95th

percentile throughput that was observed was 16.1 Mbps, the median value was 10.1 Mbps.

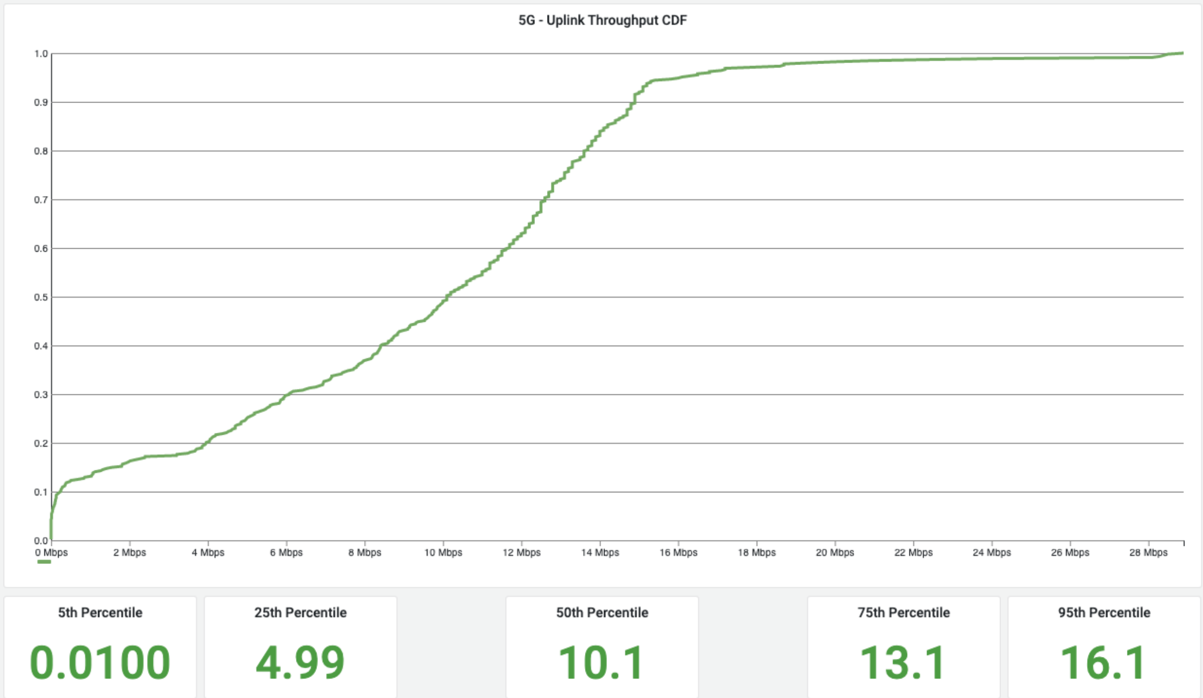
(a)



(b)

Figure 106: 5G SA TCP uplink rate – DUT on the eMBB slice without background traffic (a) on a map, (b) CDF graph and percentiles at PoA – on the road

(a)



(b)

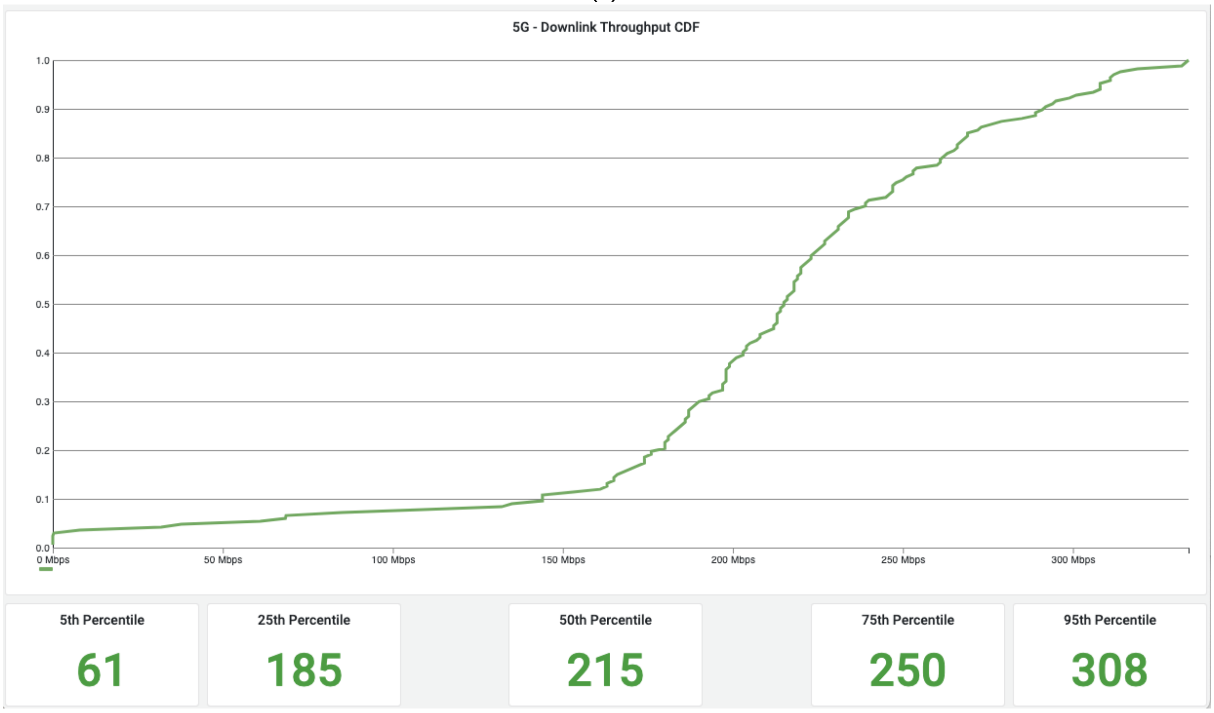
Figure 107: 5G SA TCP uplink rate – DUT on the eMBB slice with background traffic on the eMBB slice (a) on a map, (b) CDF graph and percentiles at PoA – on the road

UDP downlink rate

Figure 108 shows the graph of the downlink UDP throughput in Mbps on a map and over time when the DUT was on the eMBB slice without any background traffic. For the considered trajectory, the 95th percentile throughput that was observed was 308 Mbps, the median value was 215 Mbps and the 5the percentile throughput was 61Mbps.

When load was introduced by a second UE on the eMBB slice, a clear degradation of the UDP downlink throughput was observed as shown in Figure 109, especially in the mean value: 146Mbps. For the considered trajectory, the 95th percentile throughput that was observed was 312 Mbps. The 5th percentile was 3.45 Mbps, indicating that the throughput was quite low at some parts of the trajectory.

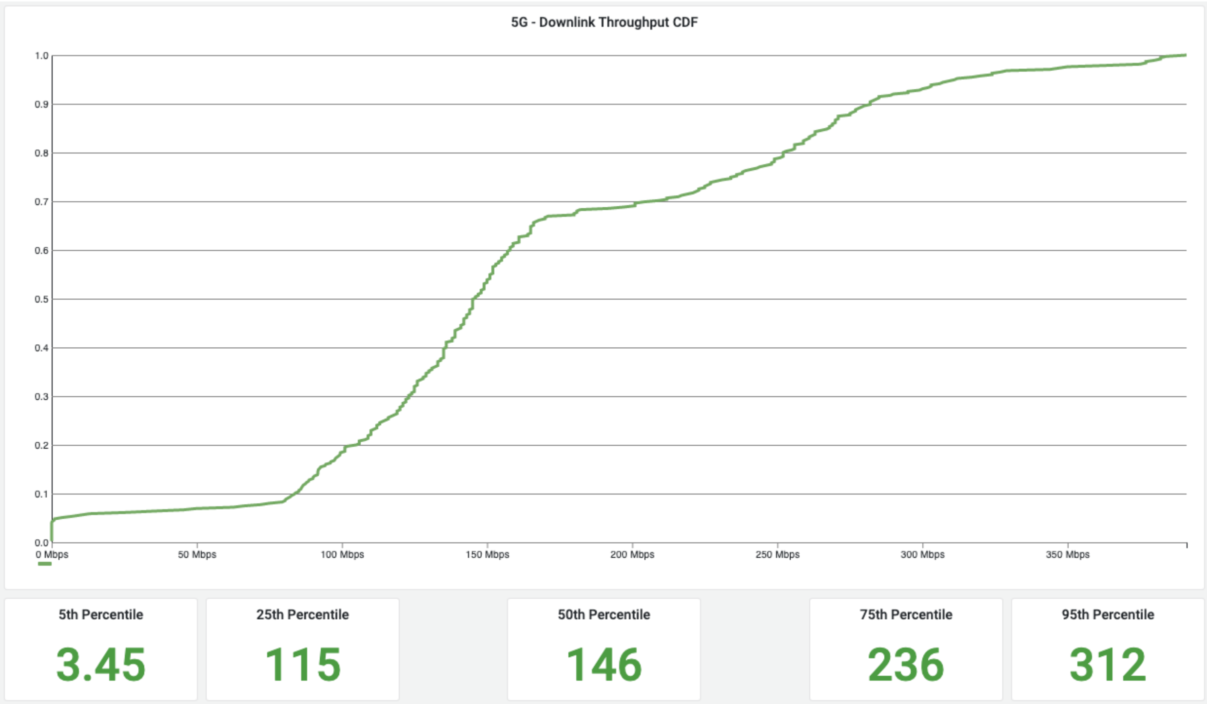
(a)



(b)

Figure 108: 5G SA UDP downlink rate – DUT on the eMBB slice without background traffic (a) on a map, (b) CDF graph and percentiles at PoA – on the road

(a)



(b)

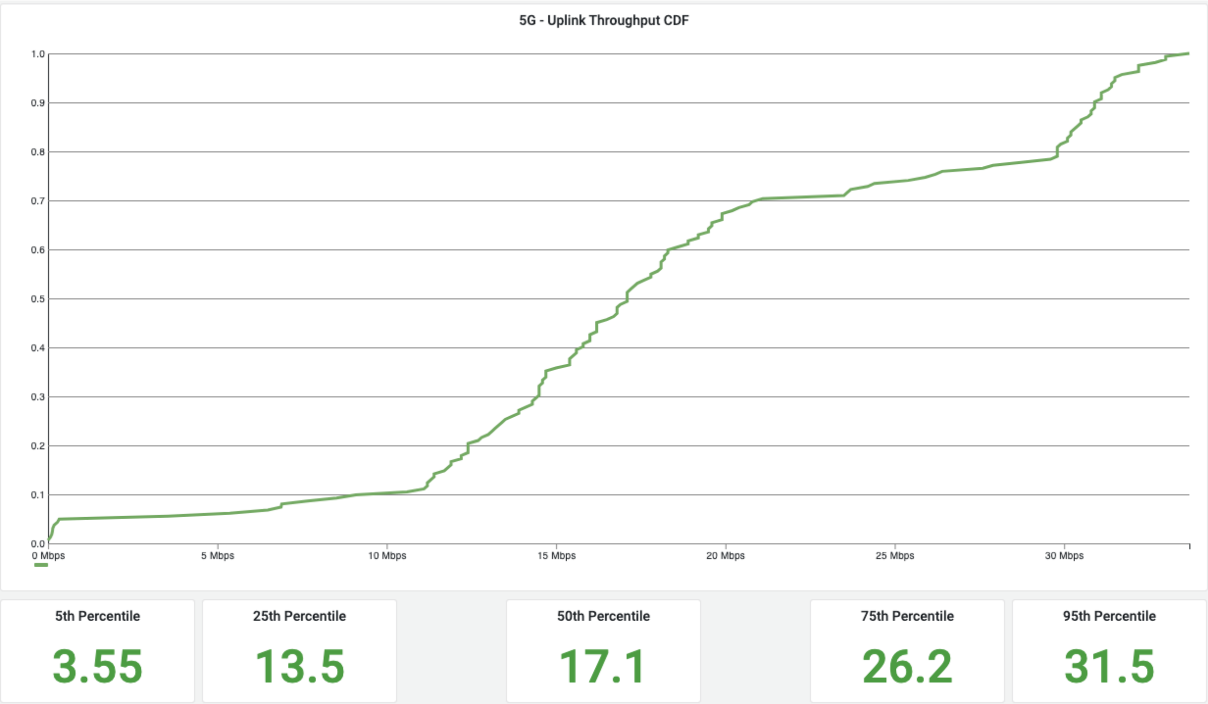
Figure 109: 5G SA UDP downlink rate – DUT on the eMBB slice with background traffic on the eMBB slice (a) on a map, (b) CDF graph and percentiles at PoA – on the road

UDP uplink rate

An indicative heatmap of the TCP uplink throughput is shown in Figure 110 (a), while the corresponding CDF graph of the throughput is depicted in Figure 110 (b). It can be observed that the median throughput is 17.1 Mbps and 95th percentile is 31.5 Mbps. At the southern part of the trajectory, the TCP uplink throughput is impacted drastically.

When load was introduced by a second UE on the eMBB slice, a clear degradation of the UDP uplink throughput was observed as shown in Figure 111. For the considered trajectory, the 95th percentile throughput that was observed was 21.5 Mbps, the median value was 13.7 Mbps.

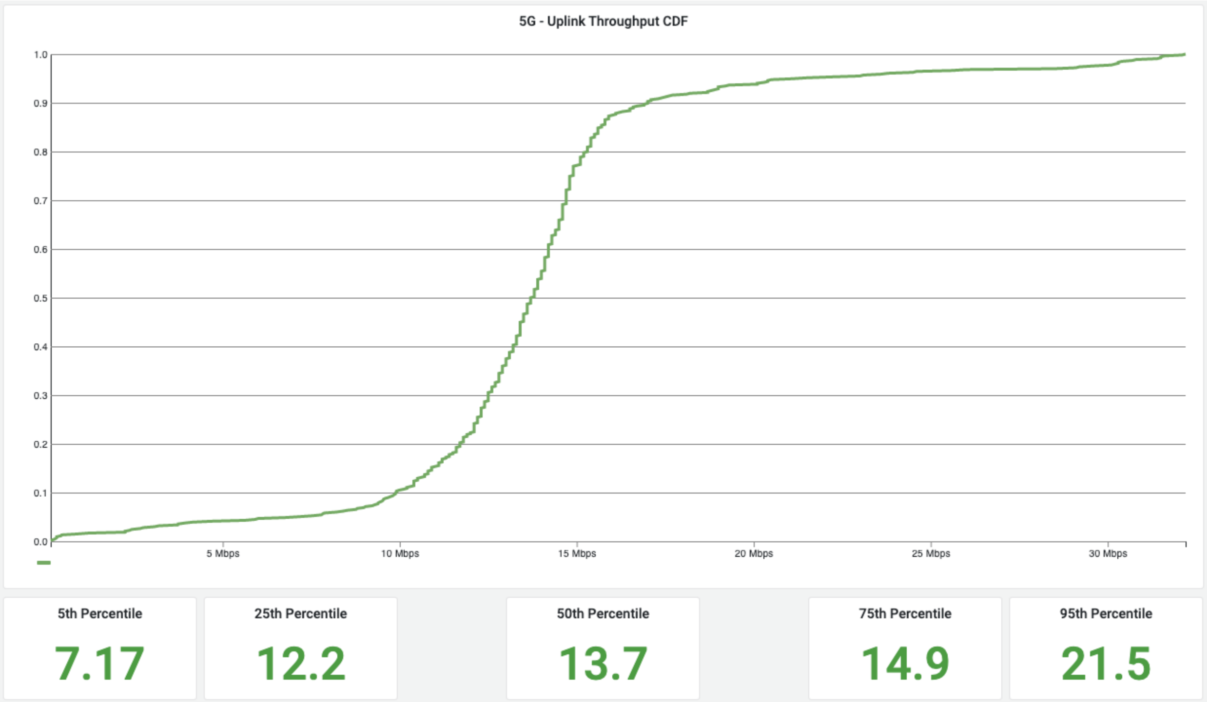
(a)



(b)

Figure 110: 5G SA UDP uplink rate – DUT on the eMBB slice without background traffic (a) on a map, (b) CDF graph and percentiles at PoA – on the road

(a)



(b)

Figure 111: 5G SA UDP uplink rate – DUT on the eMBB slice with background traffic on the eMBB slice (a) on a map, (b) CDF graph and percentiles at PoA – on the road

Round-Trip Time

In Figure 112, the RTT was measured on the URLLC slice. At some point background traffic was introduced by another UE. The figure shows that when only background traffic was transmitted in the downlink, the RTT on the URLLC does not increase. This demonstrates that the URLLC slice was not impacted by background traffic on the eMBBS slice. However, when uplink background traffic was introduced, the URLCC slice RTT traffic was impacted. The reason for this was that on the URLLC slice priority was only configured for downlink traffic. Thus, the uplink packets (of the RTT traffic) was still impacted by the background uplink traffic.

Figure 112: 5G SA RTT – DUT on the URLLC slice and background traffic on the eMBB slice at PoA – on the road

One-way latency

The uplink one-way latency CDF graphs of the URLLC slice are shown in Figure 113 (a). Without any background traffic, the median value is 11ms. When uplink background traffic is introduced, the OWL uplink latency is clearly impacted, as shown in Figure 113 (b). The median value is 23ms. The reason is that the URLLC slice priority has only been defined for downlink traffic, hence the on-way latency on the uplink is impacted by the uplink background traffic.

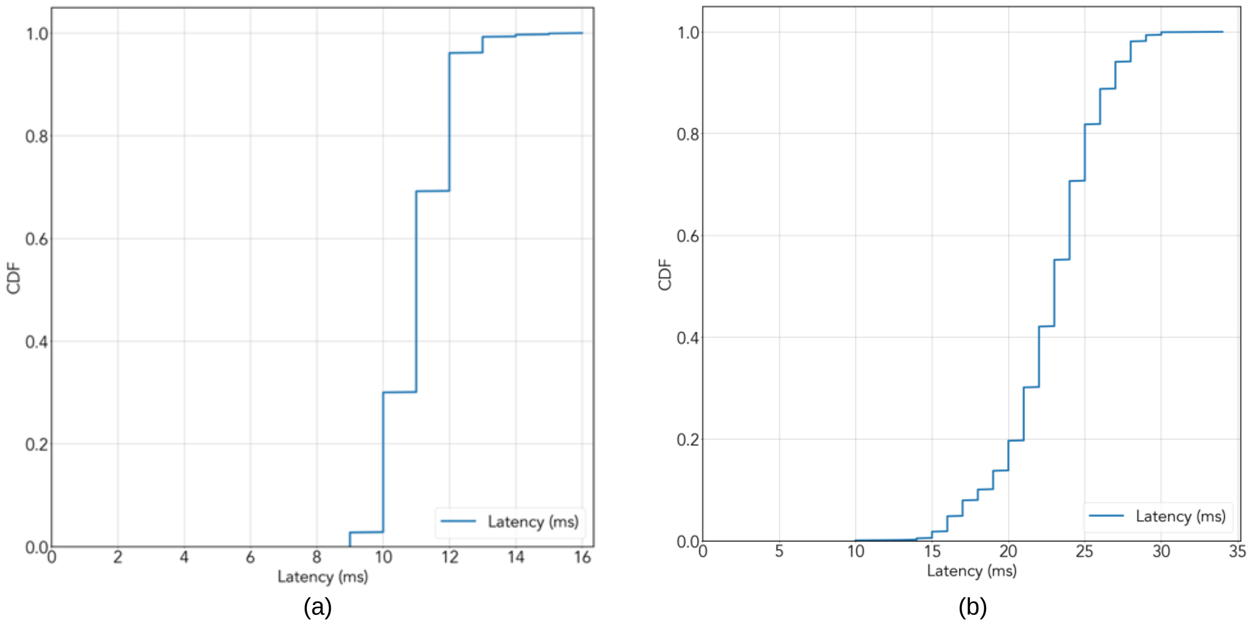


Figure 113: One-way latency CDF – DUT on the URLLC slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA – on the road

As shown in Figure 114, the impact of the uplink background traffic is clearly visible in the reliability graphs, similar as with the uplink one-way latency.

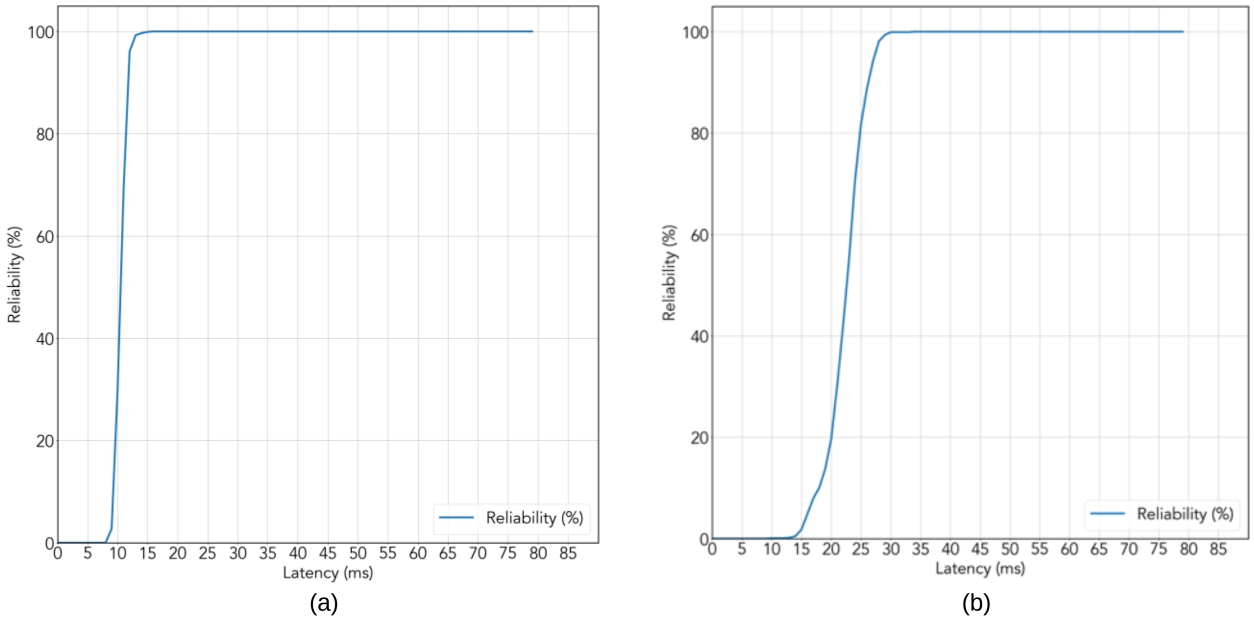


Figure 114: Reliability CDF – DUT on the URLLC slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA – on the road

Even though the one-way latency and reliability are impacted by the background traffic, the PDR remains 100% when background traffic is introduced. Note that for these measurements the packet transmission frequency is 10Hz.

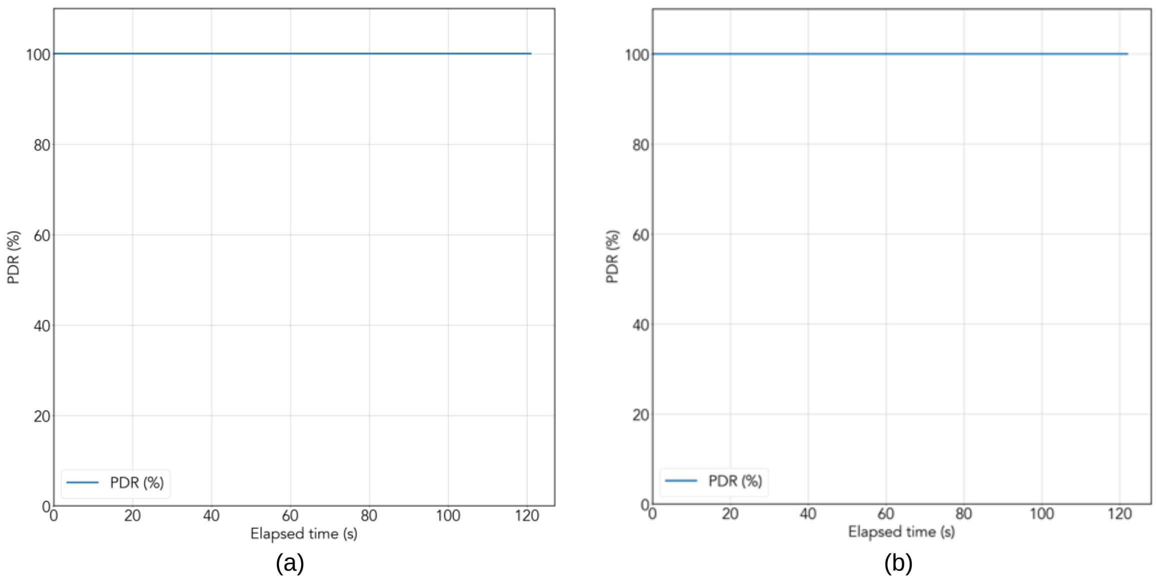


Figure 115: Packet delivery rate – DUT on the URLLC slice (a) without background traffic, (b) with background UL traffic on the eMBB slice at PoA – on the road

Summary

In Table 15, a summary is provided of the results from the 5G SA network evaluation that was conducted at the right bank in Antwerp on the road.

On-site 5G network evaluation						
Location	Belgium – Port of Antwerp – **Right bank**			Location type	**On the road - car**	
Network operator	Telenet			Network type	5G SA	
Network slice config	eMBB - no background traffic eMBB - with background traffic			UE type	Huawei 5G CPE Pro 2	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-140	-101	-85	-67	-57	-85.6
TCP DL (Mbps) eMBB slice – without background	0	7.18	225	318	355	217
TCP DL (Mbps) eMBB slice – with background	5	76.7	136	232	279	142
TCP UL (Mbps) eMBB slice – without background	0	0.01	17.2	32.3	44.9	18.7
TCP UL (Mbps) eMBB slice – with background	0	0.01	10.1	16.1	28.9	9.24
UDP DL (Mbps) eMBB slice – without background	0	61	215	308	334	210
UDP DL (Mbps) eMBB slice – with background	0	3.45	146	312	391	166
UDP UL (Mbps) eMBB slice – without background	0	3.55	17.1	31.5	33.7	18.7
UDP UL (Mbps) eMBB slice – with background	0.14	7.17	13.7	21.5	32.2	13.8
RTT (ms) eMBB slice – without background	17	17.6	19.1	30.3	3055	30

Table 15: Summary of 5G SA network performance evaluation at the right bank on the road

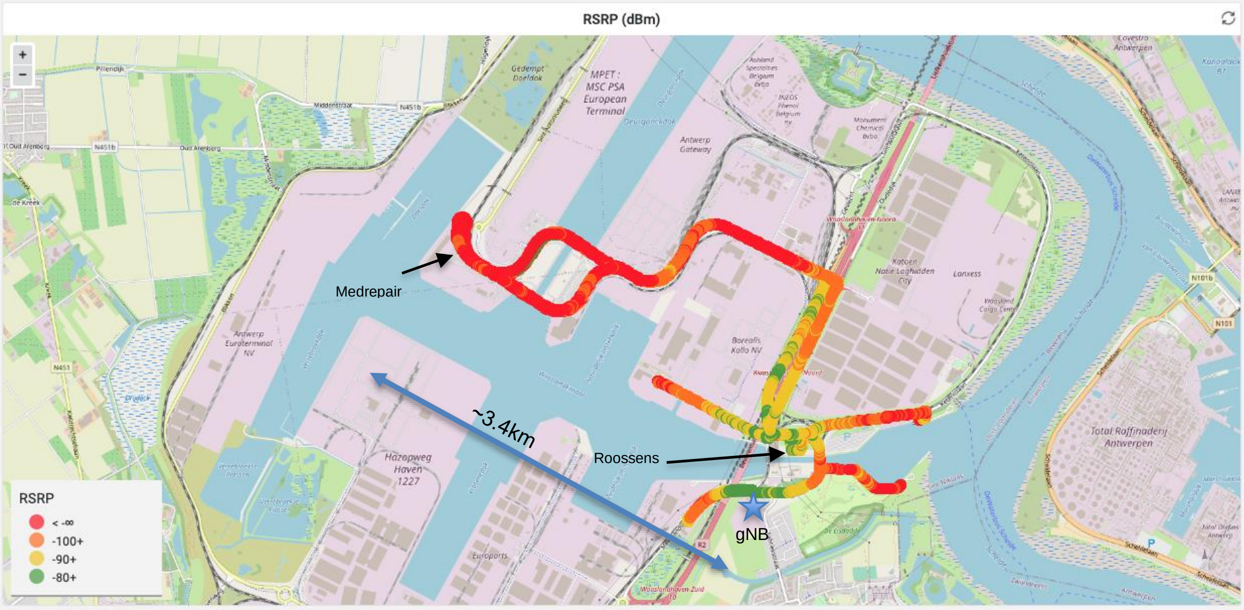
5.3.2 5G SA - Roossens Transport Site (IMEC)

To evaluate the network performance at and near the Transport Roossens site, several network measurements were conducted along a predefined trajectory between Roossens and Medrepair (a nearby terminal), as indicated on the map in Figure 116. It must be noted that the environment in this area seemed very challenging for the propagation of wireless signals due to the presence of a massive number of container, many large trucks driving around, the elevation of the roads (road going into a kind of valley), etc..

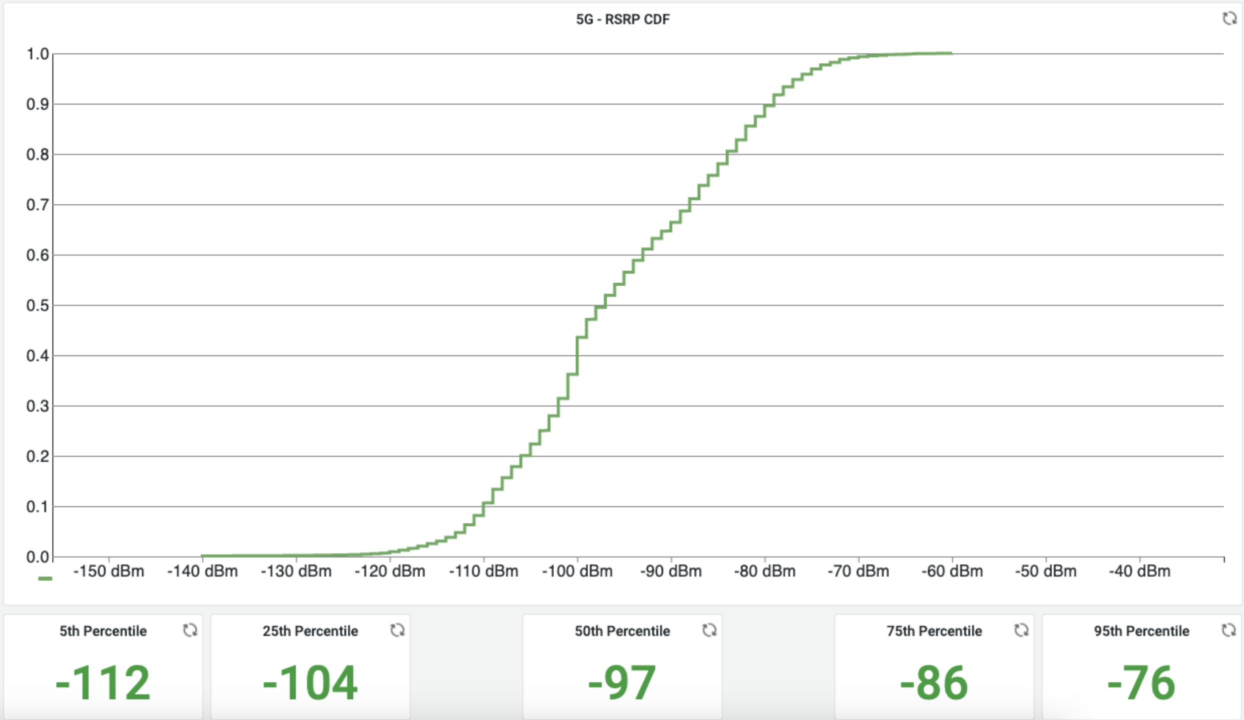
Figure 116: 5G Roossens Transport area

Modem statistics

Signal strength measurements were conducted of the area around the Roossens Transport site, including the trajectory between Roossens and Medrepair which is of interest for the milk-run use case. Figure 117 (a) shows that the area close to the gNB, including the Roossens site has good signal quality. When driving towards the north-northeast, the signal starts to decrease. On that road, when driving on the east side, the signal was a bit worse than when driving on the west side. However, when after the turn going towards the west the signal became quickly very weak due to the increasing distance towards the gNB, the massive number of containers blocking the signal and the lower elevation of the road. Only one cell was providing coverage to this area, as is shown in Figure 118.



(a)



(b)

Figure 117: 5G SA RSRP (a) heatmap over the considered trajectory, (b) CDF graph and percentiles at the Roossens Transport site

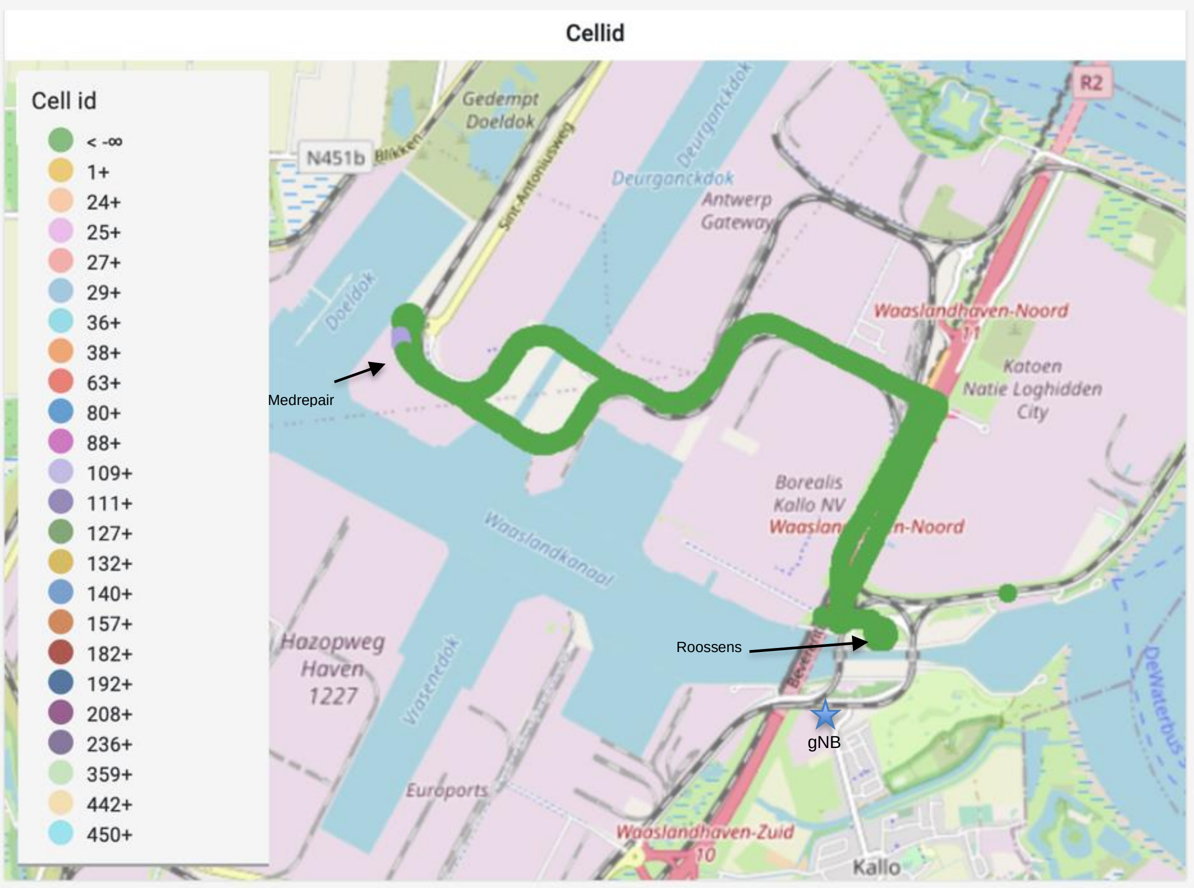
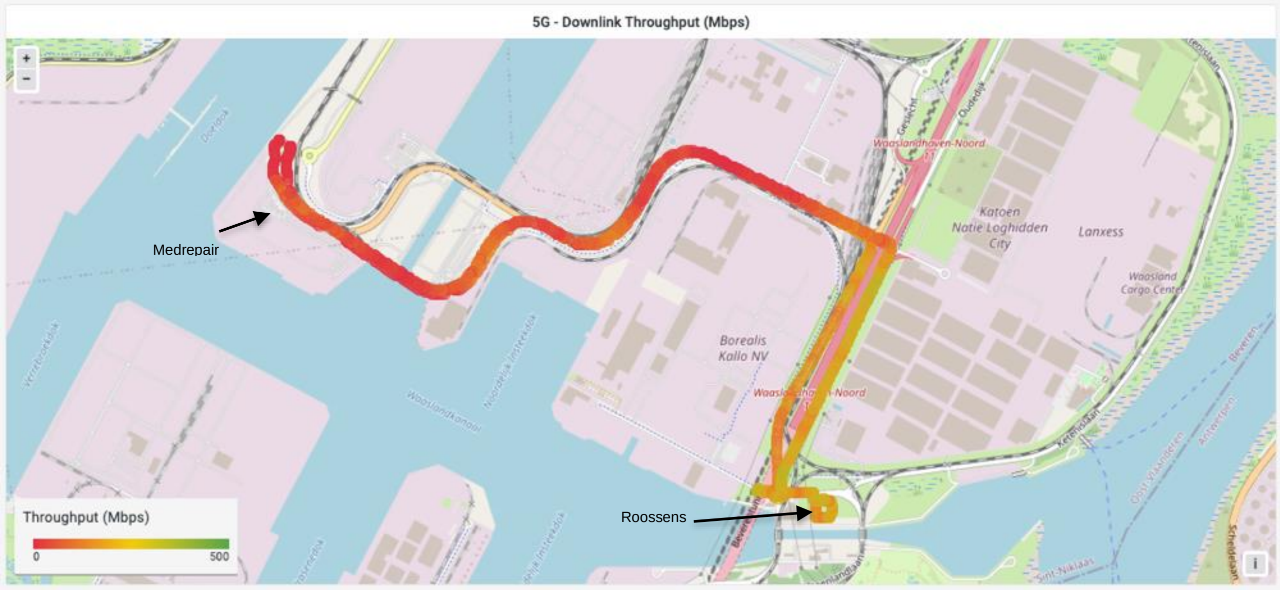


Figure 118: 5G SA used Cell ID over the considered trajectory at the Roossens Transport site

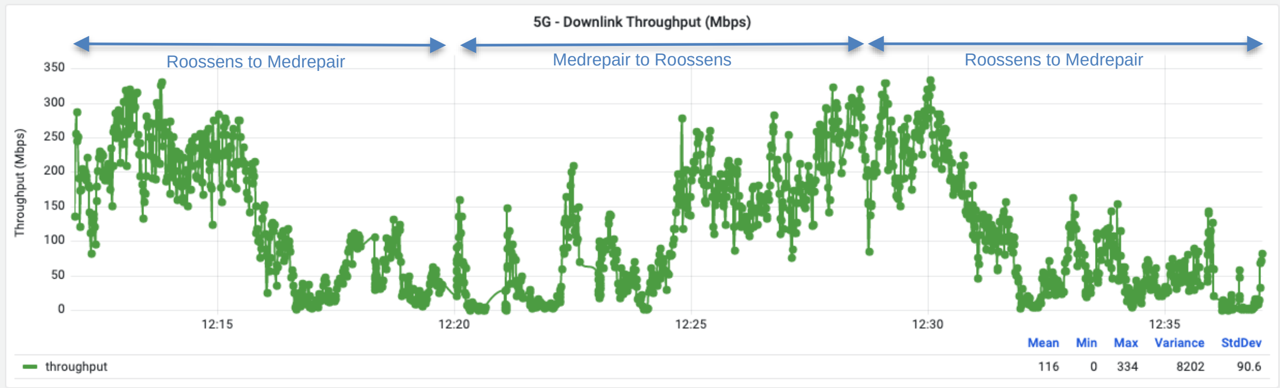
TCP downlink rate

In Figure 119 (a), a heatmap of the TCP downlink throughput values is presented along the trajectory between Roossens and Medrepair. Figure 119 (b) shows the graph of the downlink TCP throughput in Mbps over time. In line with the RSRP values shown above, the throughput has high values at the area near Roossens which is in the proximity of the gNB. The maximum throughput that was observed was 334 Mbps, the mean value was 116 Mbps and the minimum throughput was 0 Mbps due to poor network coverage at the Medrepair area.

The CDF graph and selected percentiles of the cumulative TCP downlink throughput values are shown in Figure 120. As it can be observed, the 95th percentile equals to 275 Mbps and the 50th percentile is 97 Mbps.



(a)



(b)

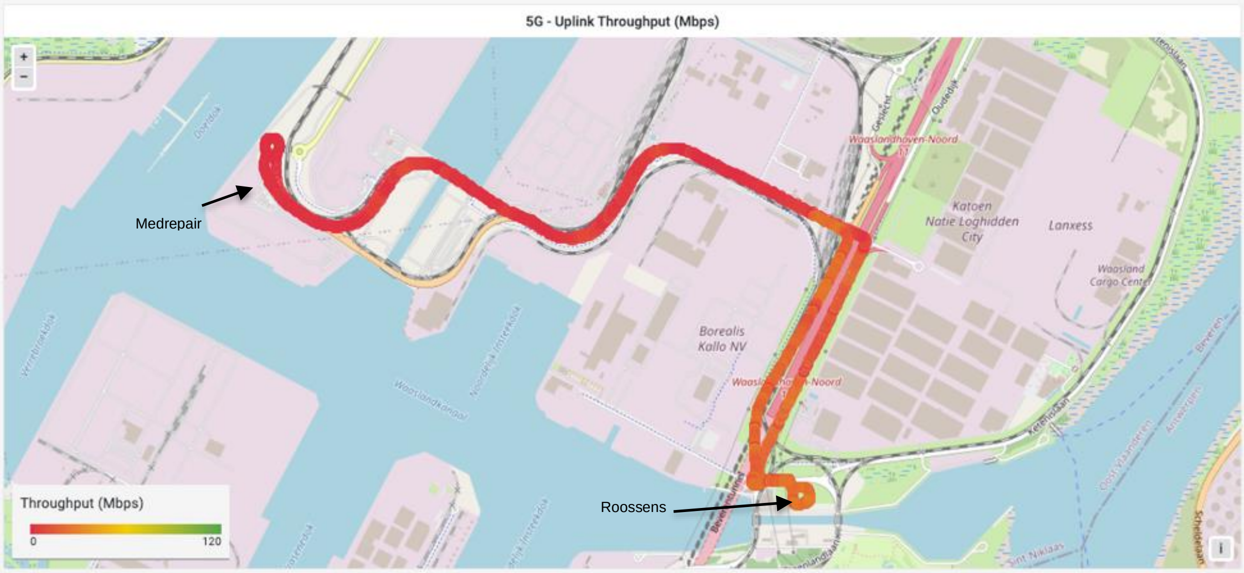
Figure 119: 5G SA TCP downlink rate (a) on a map, (b) graph throughput (Mbps) vs time (s) at the Roossens Transport Site

Figure 120: 5G SA TCP downlink rate - CDF graph and percentiles at the Roossens Transport Site

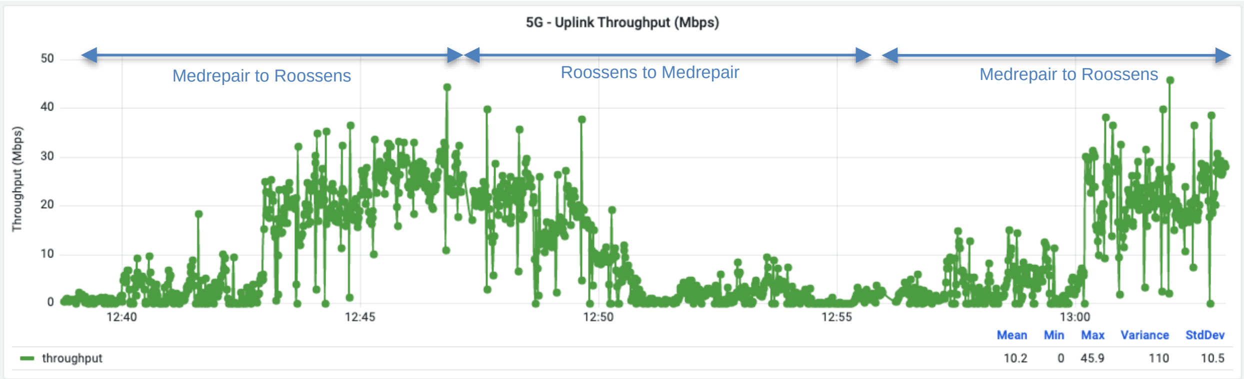
TCP uplink rate

An indicative heatmap of the TCP uplink throughput is shown in Figure 121 (a), while the corresponding graph of the throughput values in relation to time is depicted in Figure 121 (b) . It can be observed that the mean throughput is 10.02 Mbps and its maximum value is 45.9 Mbps. At the eastern part of the trajectory, the TCP uplink throughput is impacted drastically since the UE moves away from the base station towards the cell edge in combination with the harsh environment.

The CDF graph and selected percentiles of the cumulative TCP uplink throughput values are shown in Figure 122. As it can be observed, the 95th percentile equals to 28.8 Mbps and the 50th percentile is 4.76 Mbps.



(a)



(b)

Figure 121: 5G SA TCP uplink rate (a) on a map, (b) graph throughput (Mbps) vs time (s) at the Roossens Transport Site

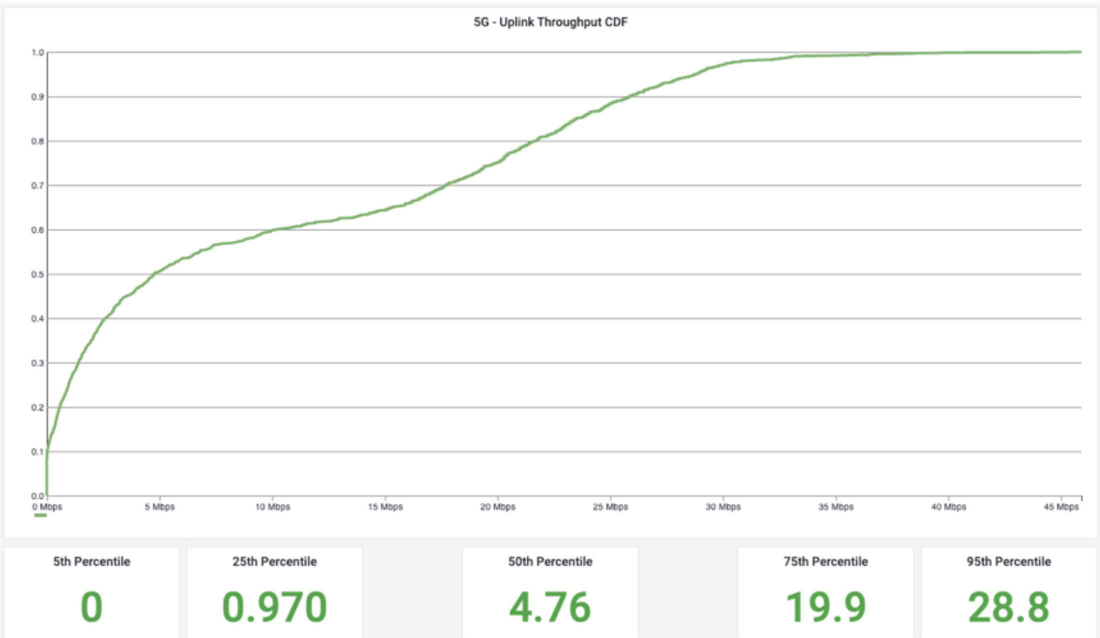
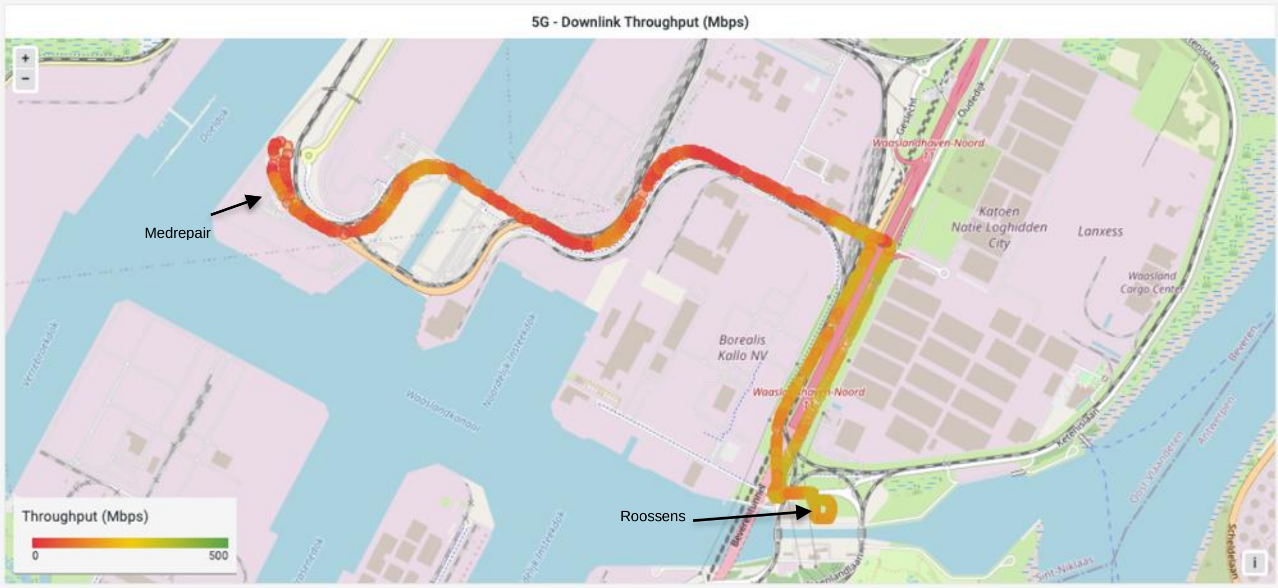


Figure 122: 5G SA TCP uplink rate - CDF graph and percentiles at the Roossens Transport Site

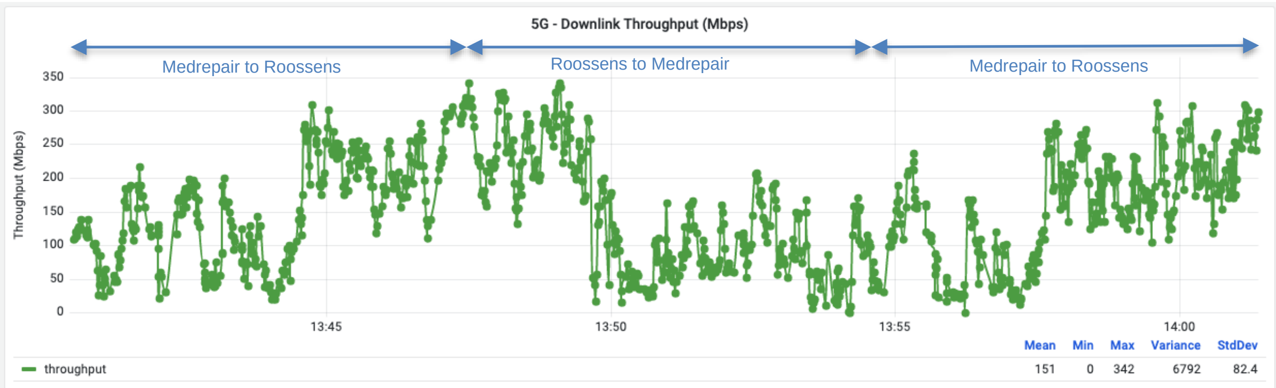
UDP downlink rate

In Figure 123 (a), a heatmap of the UDP downlink throughput values is presented along the trajectory between Roossens and Medrepair. Figure 123 (b) shows the graph of the downlink UDP throughput in Mbps over time. Similar to the TCP results shown above, the throughput has high values at the area near Roossens which is in the proximity of the gNB. The maximum throughput that was observed was 342 Mbps, the mean value was 151 Mbps and the minimum throughput was 0 Mbps due to poor network coverage at the Medrepair area.

The CDF graph and selected percentiles of the cumulative UDP downlink throughput values are shown in Figure 124. As it can be observed, the 95th percentile equals to 288 Mbps and the 50th percentile is 152 Mbps.



(a)



(b)

Figure 123: 5G SA UDP downlink rate (a) on a map, (b) graph throughput (Mbps) vs time (s) at the Roossens Transport Site

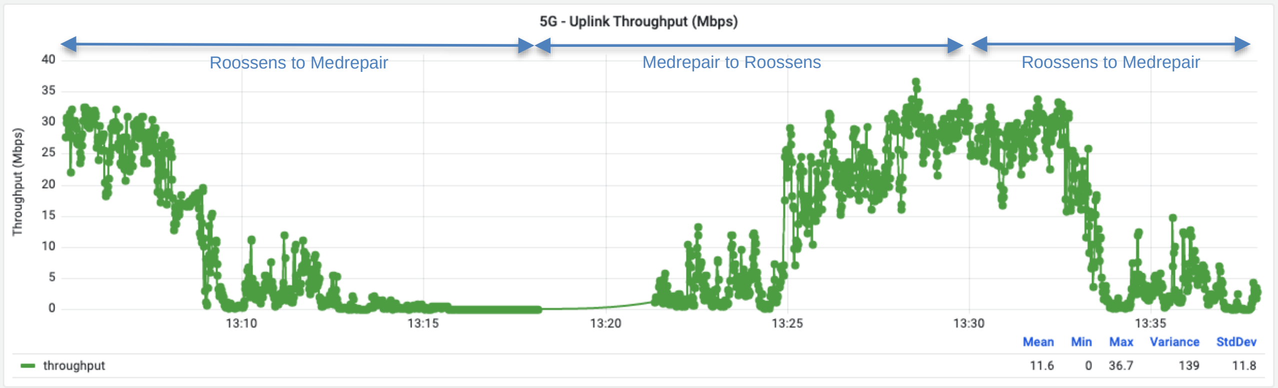
Figure 124: 5G SA UDP downlink rate - CDF graph and percentiles at the Roossens Transport Site

UDP uplink rate

An indicative heatmap of the UDP uplink throughput is shown in Figure 125 (a), while the corresponding graph of the throughput values in relation to time is depicted in Figure 125 (b). It can be observed that the mean throughput is 11.6 Mbps and its maximum value is 36.7 Mbps. At the eastern part of the trajectory, the UDP uplink throughput is impacted drastically and dropping to 0 for a significant part of the trajectory since the UE moves away from the base station towards the cell edge in combination with the harsh environment.

The CDF graph and selected percentiles of the cumulative UDP uplink throughput values are shown in Figure 126. As it can be observed, the 95th percentile equals to 30.9 Mbps and the 50th percentile is 5.33 Mbps. Note that the 25th percentile is only 0.76, indicating the low UDP uplink throughput of a large part of the trajectory.

(a)



(b)

Figure 125: 5G SA UDP uplink rate (a) on a map, (b) graph throughput (Mbps) vs time (s) at the Roossens Transport Site

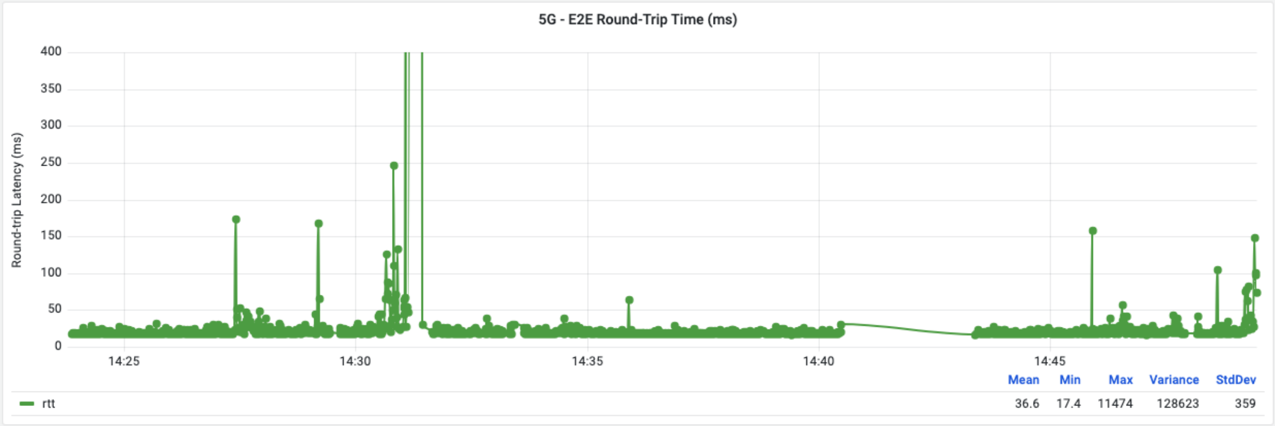
Figure 126: 5G SA UDP uplink rate - CDF graph and percentiles at the Roossens Transport Site

Round-Trip Time

Rount-trip time was measured along the trajectory between Roossens and Medrepair which is shown in Figure 127. Apart from one big peak, the RTT was quite constant around 19ms. However, near to the Medrepair site, the connection was lost for some time. This relates to the results above where very low signal strengths were observed in that area. Moreover, as it can be observed in the figure, high RTT values were observed along the trajectory going towards the west, while the maximum recorded value was 11474ms, which corresponds to the Medrepair location where the connectivity was lost.

The CDF graph and selected percentiles of the cumulative RTT values are shown in Figure 128. As it can be observed, the 95th percentile equals to 35.7ms and the 50th percentile is 19.3ms.

(a)



(b)

Figure 127: 5G SA RTT on (a) map and (b) graph at the Roossens Transport Site

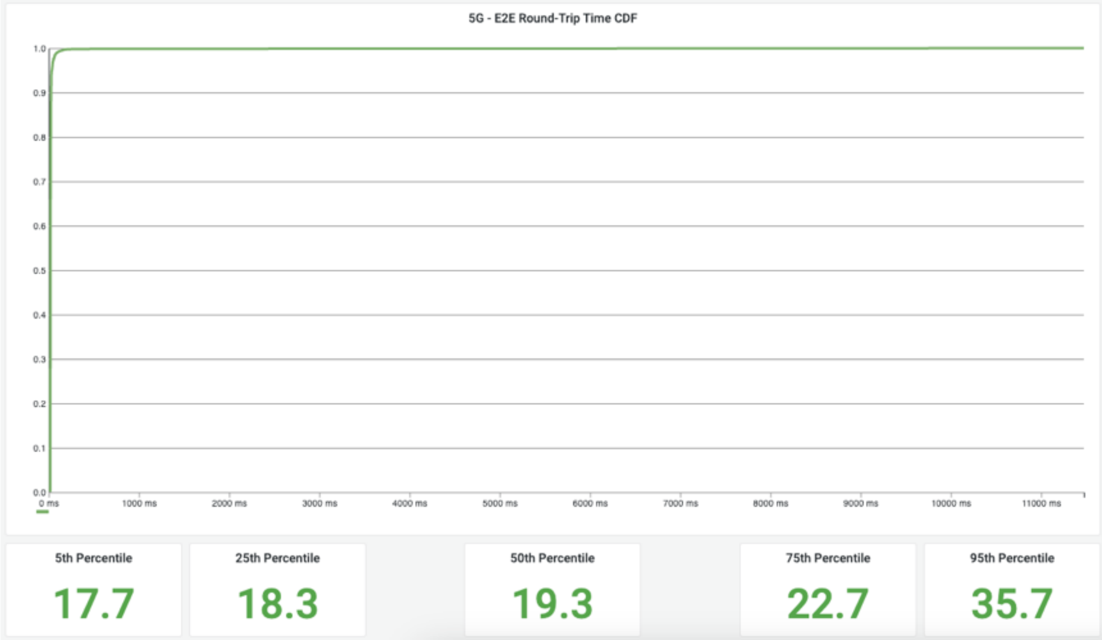


Figure 128: 5G SA RTT - CDF graph and percentiles at the Roossens Transport Site

One-way latency, reliability, packet delivery rate and packet-loss

Figure 129 shows the packet-loss on the uplink, while driving the trajectory between Roossens Transport and Medrepair during a representative test run. As it can be observed, high packet-loss is faced close to the Medrepair area and similar to the previous graphs, it can be justified by the morphology of the area, as well as the numerous obstacles between that specific location and the gNB that block the propagation of the signal.

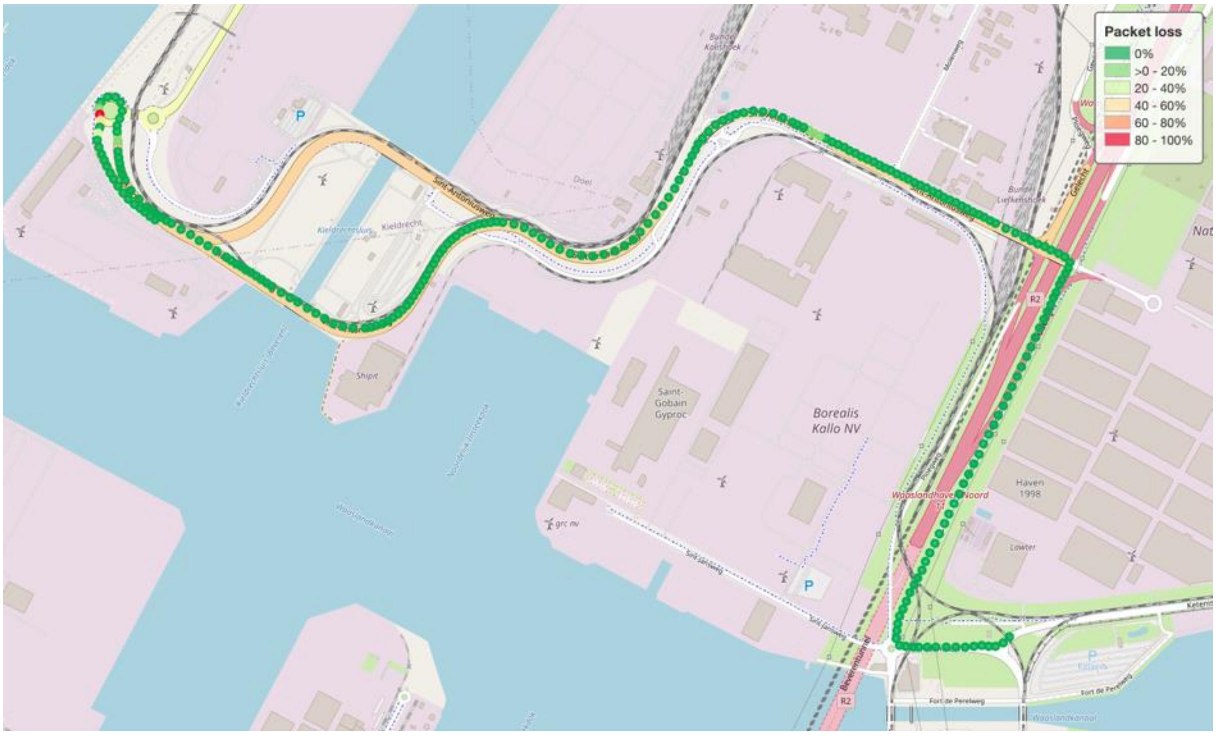
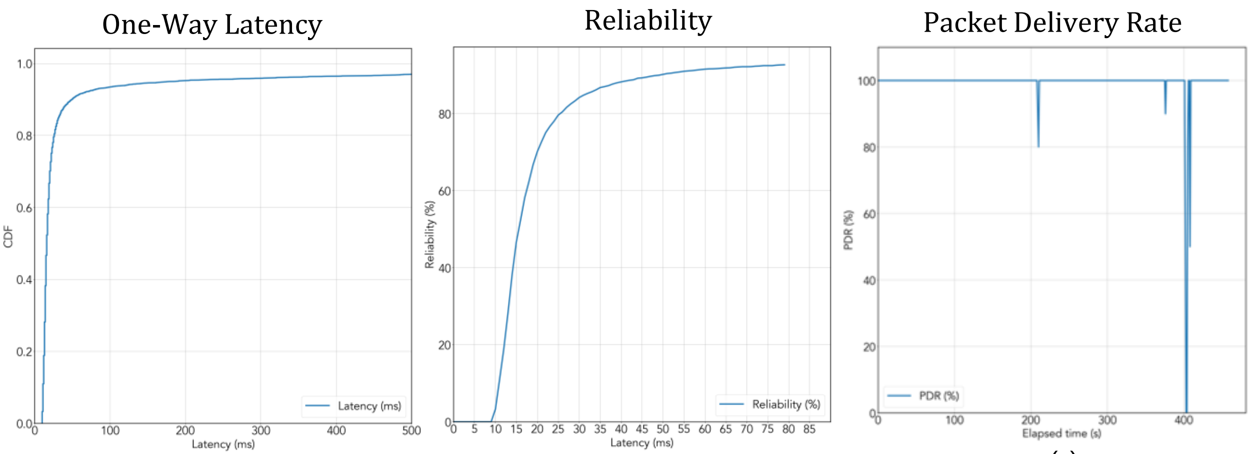


Figure 129: 5G SA packet-loss on a map at the Roossens Transport Site

Figure 130 shows (a) the one-way latency CDF plot, (b) the reliability CDF plot and (c) the packet delivery rate on the uplink, while driving the same trajectory and during the same test run as shown in Figure 129. The maximum recorded value of the one-way latency during that test is 3713ms, however, the x-axis of Figure 130 (a) has been limited to 500ms for readability reasons. From Figure 130 (b), it can be observed that reliability is also impacted by the low signal quality across the trajectory. For latency threshold of 20ms, only 70% of the packets are received correctly in time, while for threshold of 25ms, 79% of the packets are received within the desired time. Finally, for the packet delivery rate and similar to the packet-loss depicted in Figure 129, there is significant number of lost packets at the Medrepair area, which is a result of the low signal quality at that specific location, causing temporarily disconnection of the UE from the Telenet network.



(a) (b) (c)

Figure 130: 5G SA (a) one-way latency CDF graph, (b) one-way latency reliability, (c) packet delivery rate on the uplink

Summary

In Table 16**,** a summary is provided of the results from the 5G SA network evaluation that was conducted at Roossens area in Antwerp on the road.

On-site 5G network evaluation						
Location	Belgium – Port of Antwerp – **Roossens Area**			Location type	**On the road - car**	
Network operator	Telenet			Network type	5G SA	
Network slice config	eMBB - no background traffic			UE type	Huawei 5G CPE Pro 2 (RSRP measured with Quectel RM502Q)	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-140	-112	-97	-76	-60	-95.3
TCP DL (Mbps)	0	4.53	97	275	334	116
TCP UL (Mbps)	0	0	4.76	28.8	45.9	10.2
UDP DL (Mbps)	0	27.3	152	288	342	151
UDP UL (Mbps)	0	0	5.33	30.9	36.7	11.6
RTT (ms)	17.4	17.7	19.3	35.7	11474	36.6

Table 16: Summary of 5G SA network performance evaluation at the Roossens area on the road

5.4 Overview of the 5G network evaluation at the Belgian site

In the previous sections, the individual results of the 5G network evaluation at the Port of Antwerp were described for the different trajectories and KPIs. A summary of these results is presented in Table 17, containing the average values of the KPIs for both the tests on the water and the road. The first row (water, right bank side, eMBB no background traffic) indicates that the TCP throughput is substantially lower than the UDP throughput. The reason is that for TCP the trajectory was longer (going more to the south where signal was weaker).

The table also shows that using the URLLC slice is more resilient to background traffic on the eMBB slice in terms of latency. This can be observed in the RTT values for the measurements on the road. The latency increased from 19.1ms to 27.3ms for the eMBB slice when downlink background traffic was introduced. This is an increase of 43%. A similar result was seen on the water where the latency increased from 27.1 to 37.1ms, an increase of 37%. When the URLLC was used, the RTT stayed almost the same (from 18.9ms to 19.1ms).

Deployment	Test area	TCP DL (Mbps)	TCP UL (Mbps)	UDP DL (Mbps)	UDP UL (Mbps)	RTT (ms)[1]	OWL (ms)[2]
On the water	Right bank side (1 x gNB) eMBB no background traffic	89.1	9.14	182	12	27.1	14
	Right bank side (1 x gNB) eMBB with background traffic	-	-	-	-	37.1	20
	Schelde side (1 x gNB)	136	10.6	158	13	24.9	12
On the road	Right bank side (7 x gNB) eMBB no background traffic	217	18.7	210	18.7	19.1	14
	Right bank side (7 x gNB) eMBB with background traffic	142	9.24	166	13.8	27.3	25
	Right bank side (7 x gNB) URLLC no background traffic	-	-	-	-	18.9	-
	Right bank side (7 x gNB) URLLC with dowlink background traffic	-	-	-	-	19.1	-
	Roossens Transport Site (1 x gNB)	116	10.2	151	11.6	36.6	16

Table 17: Overview of the 5G SA evaluation at the Belgian site

[1] Ping to 8.8.8.8

[2] Between UE and IMEC server over internet, median values

5.5 Conclusions for Port of Antwerp area

For the Port of Antwerp area, the following conclusions can be drawn based on the network evaluation that was performed during the test campaigns:

- 5G SA network of Telenet at the water
  - Started with one gNB to validate the network performance at the port
  - Close to the gNB (good coverage conditions) the performance is in line with the requirements of the use cases and enabling functions as defined in D5.1 [3]
  - Going further south and north, the performance of the 5G network gets worse due to poor coverage in that areas. On the water, the signal is blocked by containers and other type of infrastructure along the banks of the river, which have an impact on the line-of-sight between the boat and the base station
- 5G SA network of Telenet at the road (near Roossens Transport)
  - Good performance around the Roossens Transport premises satisfying the requirements of the use cases and enabling functions as defined in D5.1 [3]
  - Worse performance of the 5G network when driving towards the west due to increasing distance from the gNB and the very challenging environment (numerous containers, road elevation) resulting in poor coverage in that area
- 5G SA network of Telenet at the road (right bank side)
  - Additional tests were done when 7 gNBs were activated
  - In good coverage conditions, the measured KPIs are in line with the requirements of the use cases and enabling functions as defined in D5.1 [3]
  - Cross-site interference was detected in a small part of the trajectory and further investigation has been performed by Telenet, concluding that the antenna had to be tilted for a few degrees
  - URLLC slice shows that latency is more resilient to background traffic, which is beneficial for teleoperation

In general, the SA network in the 3.5Ghz band has limited range (~2km) for good signal quality, which is required for good downlink and uplink throughput and ultimately for successful teleoperation of trucks and barges. Moreover, the signal propagation is affected by environmental conditions.

6 DUTCH SITE

6.1 5G Network Architecture (KPN)

6.1.1 Radio Architecture

The radio is based on a single 5G NR band, 3.5GHz.

Band	N78
Frequency	3650-3750 MHz
Bandwidth	100MHz
Frame structure	DDDSU
SSB Frequency Position	7985 (GSCN)
Transmitted power	28.9dBm

Table 18: RAN settings Vlissingen

The radio is connected to a 5G SA core system (see Figure 131

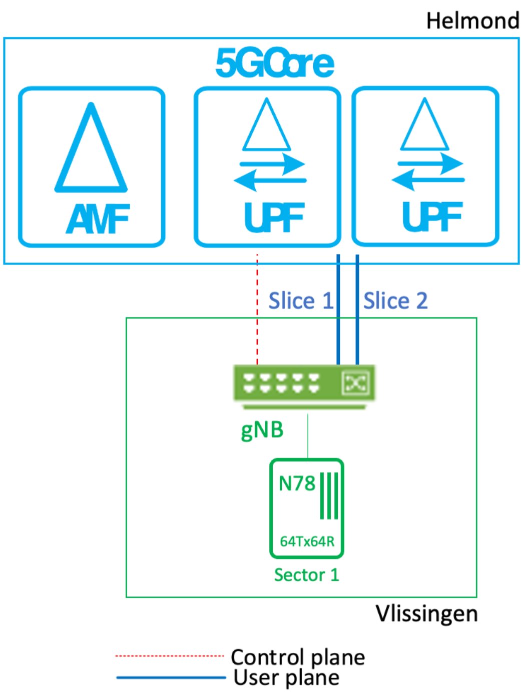


Figure 131 schematic overview of the RAN in Vlissingen

The site was configured with two slices. Minimal resource guarantees were set and 5QI86 was configured for the URLLC slice, see Table 19.

Attribute	EMBB	URLLC
SST (SD=0x000009)[1]	1 SD=0x000001)	2 (SD=0x000009)
Minimal resource guarantee	25% of RB's	50% of RB's
Slice quality of service		5QI86
APN / DNN / PDN / IP	kpn.embb.r052 kpn.v2x.r052 kpn.rtk.r052	urllc

Table 19: RAN Slicing configuration Vlissingen

The NSA network used around Vlissingen is part of the KPN production network and has the following specifications

Bands	N28, B1, B3, (on some sites: B7, B38)
Anchor band	B3
N28	2x10MHz, FDD
B1	2x20MHz, FDD
B3	2x20MHz, FDD
B38	1x30MHz, TDD
B7	2x10MHz, FDD

The production network has sites with different configurations. Some of the sites around Vlissingen are of low capacity and only use N28, B1 and B3. The medium capacity also have B7 and B38.

6.1.2 Core Architecture

The 5G core network consists of a basic set of functions, spread out over different locations (see Figure 132: Dutch 5G Core network).

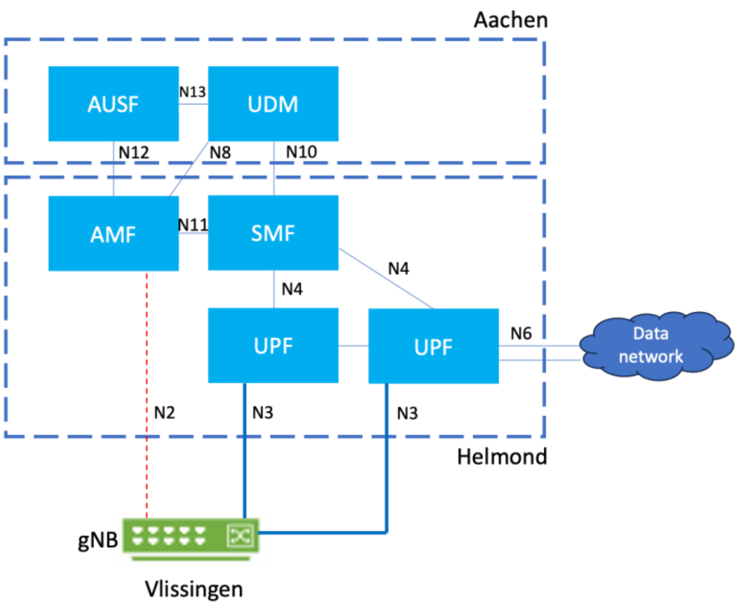


Figure 132: Dutch 5G Core network

6.2 5G Network Deployment (KPN)

6.2.1 Radio Deployment

In Vlissingen a single sector with a 64Tx64R antenna has been deployed opposite to the harbor where the use cases are deployed.

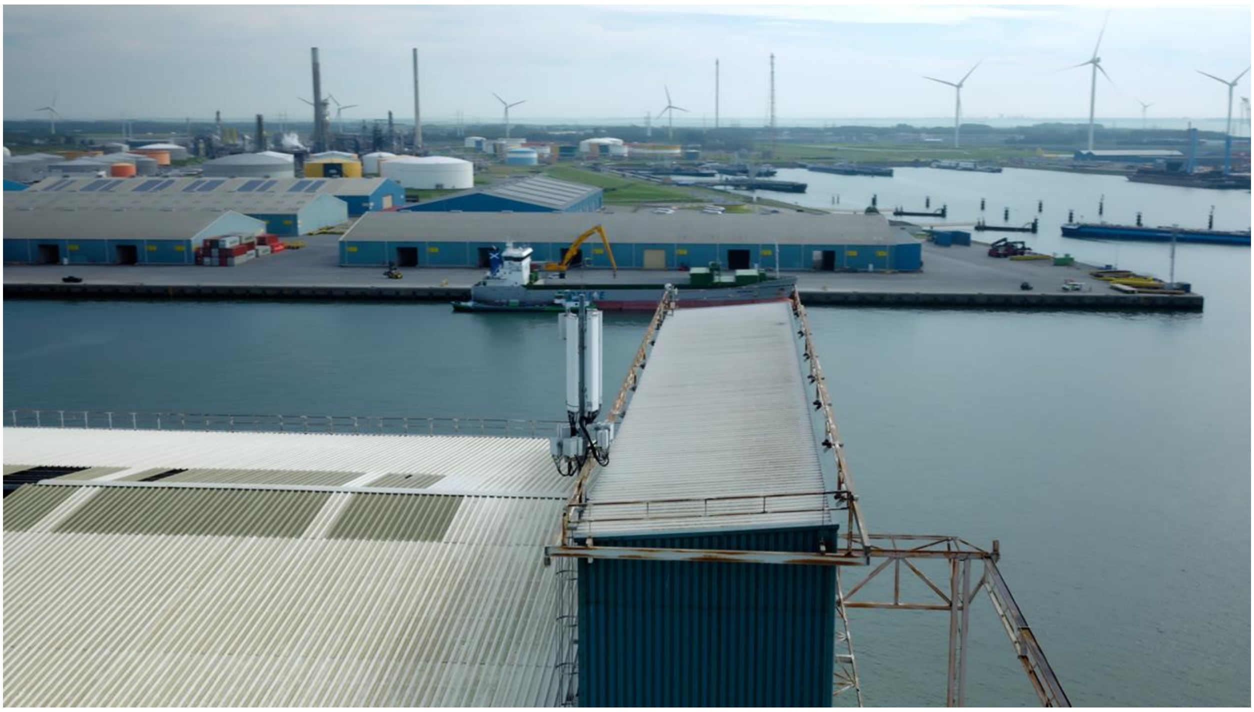


Figure 133: Antenna site in Vlissingen

The line of sight was limited to the opposite docks, a lot of the testing locations did not have line of sight towards the antenna.

For the 5G NSA tests the KPN production RAN was used. To make this possible the sites in this Vlissingen area have been swapped to 5G earlier in the planning. The NSA coverage can be found in Figure 134.

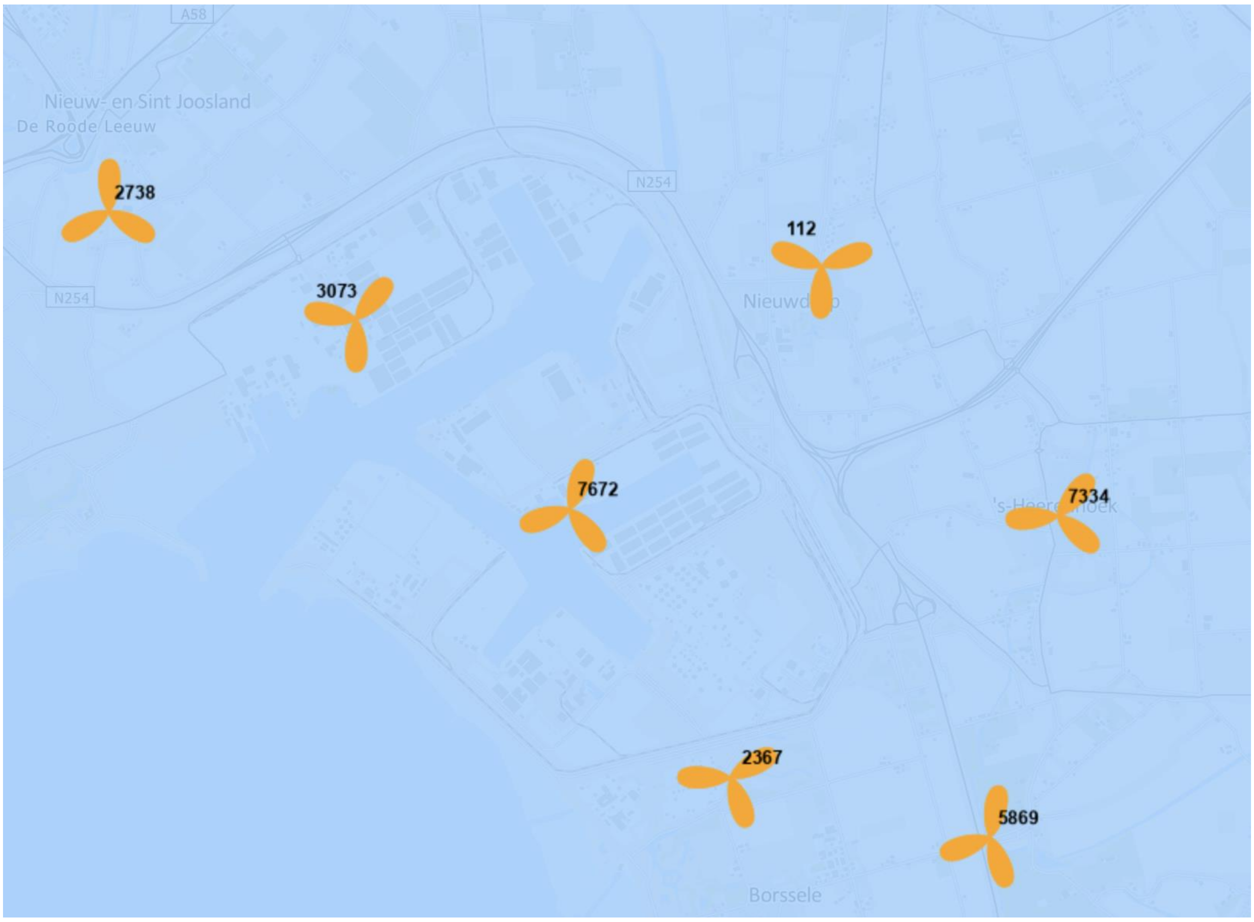


Figure 134: NSA Coverage at Vlissingen

6.2.2 Core Deployment

The core was running in a container environment and consisted of two separate core systems. This way testing could be done on one core and developments could be done on the second core. Part of the core systems were running in the Ericsson datacenter in Aachen. A flightrack in the KPN Metrocore location Helmond, provided the local core functions.

Figure 135: Flightrack at the metrocore location Helmond

6.3 5G Network Evaluation (IMEC)

In the Netherlands, both an SA and NSA deployment of KPN have been evaluated, each covering a different area. The SA deployment at the Verbrugge terminal in Vlissingen consisted of one gNB and the evaluation focused on the area inside the Scaldia terminal, which is relevant for the teleoperation of cars/trucks and skid steer use cases are relevant (see Figure 136.

Figure 136: 5G SA test area at Verbrugge Scaldia terminal

Regarding the NSA network, an evaluation has been performed at the MSP Onions and Kloosterboer terminals, as well as on the trajectories of the milk runs between MSP Onions and Kloosterboer and Verbrugge Scaldia terminal and Central Gate, which are relevant for the automated driver-in-loop docking, remote-takeover and platooning use case (See Figure 137).

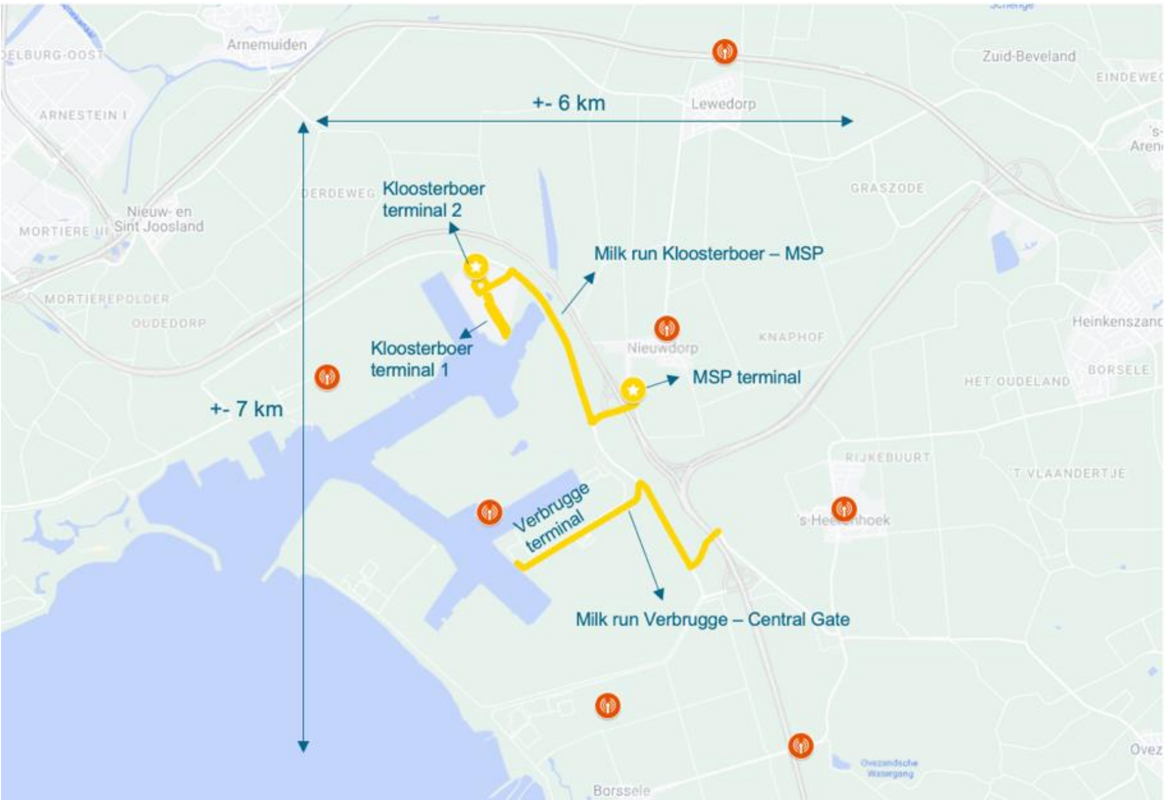


Figure 137: 5G NSA test area at Vlissingen

Date	Location	Slicing configuration	UE type
01/12/22	Verbrugge terminal	eMBB slice (5G SA)	Fibocom
14/03/23	Verbrugge terminal	eMBB slice with and without background traffic (5G SA)	Sierra Wireless + Quectel RM502Q for signal strength
24/03/23	Verbrugge terminal	URLLC slice with and without background traffic (5G SA)	Sierra Wireless + Quectel RM502Q for signal strength
12/01/23	MSP Onions, Kloosterboer and milk runs	5G NSA	Quectel RM502Q
19/01/23	MSP Onions, Kloosterboer and milk runs	5G NSA	Quectel RM502Q
24/01/23	MSP Onions, Kloosterboer and milk runs	5G NSA	Quectel RM502Q

Table 20: Test campaigns for the evaluation of the Dutch site

During the whole 5G evaluation at the Dutch site over the 6 test campaigns listed in Table 20, the following statistics have been derived over the collected data:

- **42429** signal strength data entries
- **4018** RTT measurement data entries
- **35** RTT test ids, of which **30** valuable
- **24906** iperf data entries
- **430** iperf test ids, of which **143** valuable
- **32** one-way latency tests
- **32** reliability tests
- **32** packet delivery rate and packet-loss tests

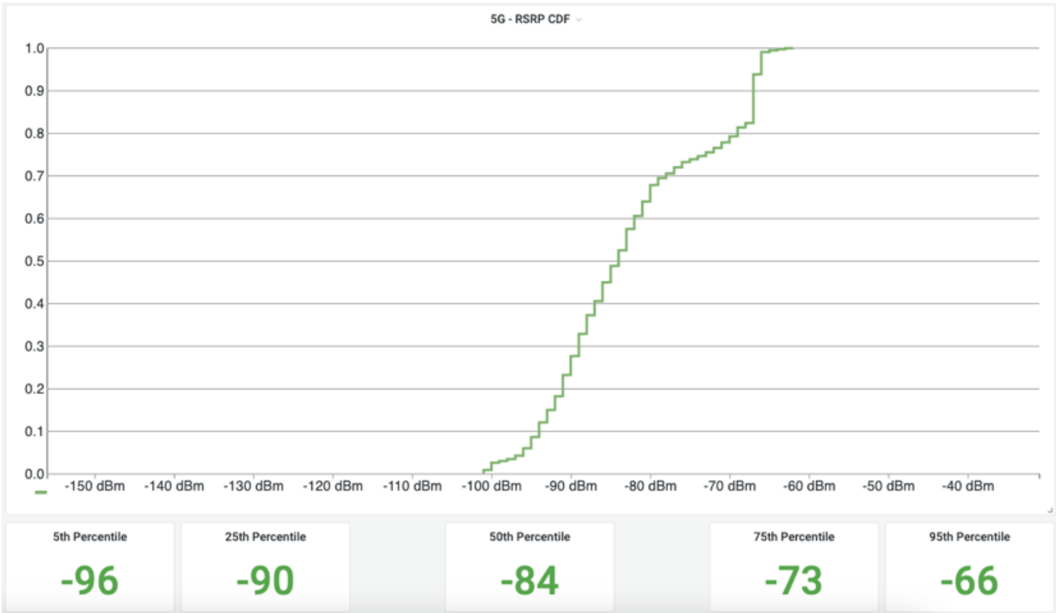
The following subsections discuss the 5G network evaluation results for each considered location at the Dutch site, both for the 5G SA and 5G NSA networks.

6.3.1 5G SA - Verbrugge Terminals Site

6.3.1.1 Testing with multiple UE devices

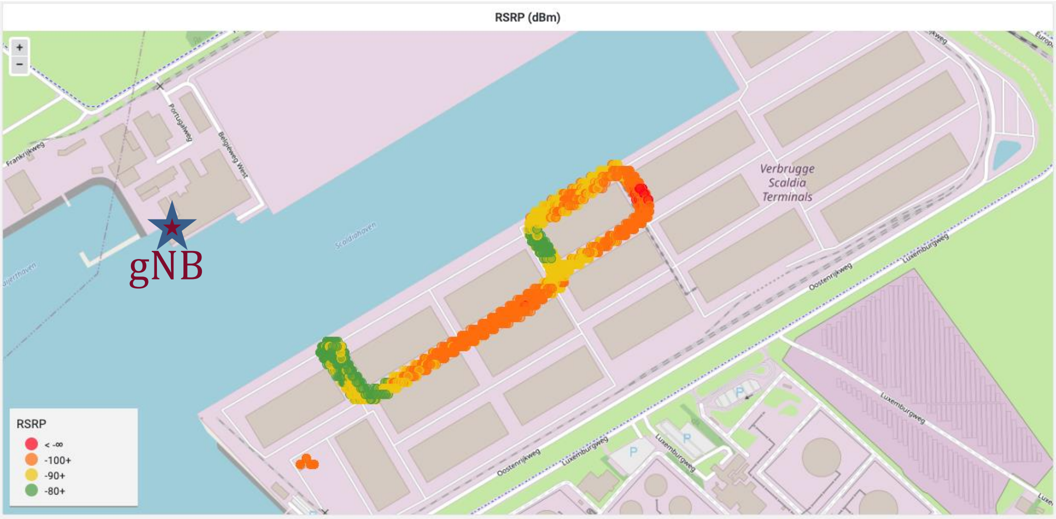
At the Verbrugge terminal, an RSRP heatmap was created for two different types of modems, namely the Fibocom and the Quectel, to get insights in the RSRP values reported by the the modems. Figure 138 (a) provides an overview on a map of the results of the Fibocom modem. The CDF plot is shown in Figure 138 (b). The heatmap clearly shows that the RSRP values are high at the west side when the modem is in line of sight of the gNB. More towards the east, the signal starts to drop. Note that also ships are docked at the quay, which can have an impact on the signal propagation. Similar results were obtained from the Quectel modem (see Figure 139), although the RSRP seemed to be slightly lower.

(a)

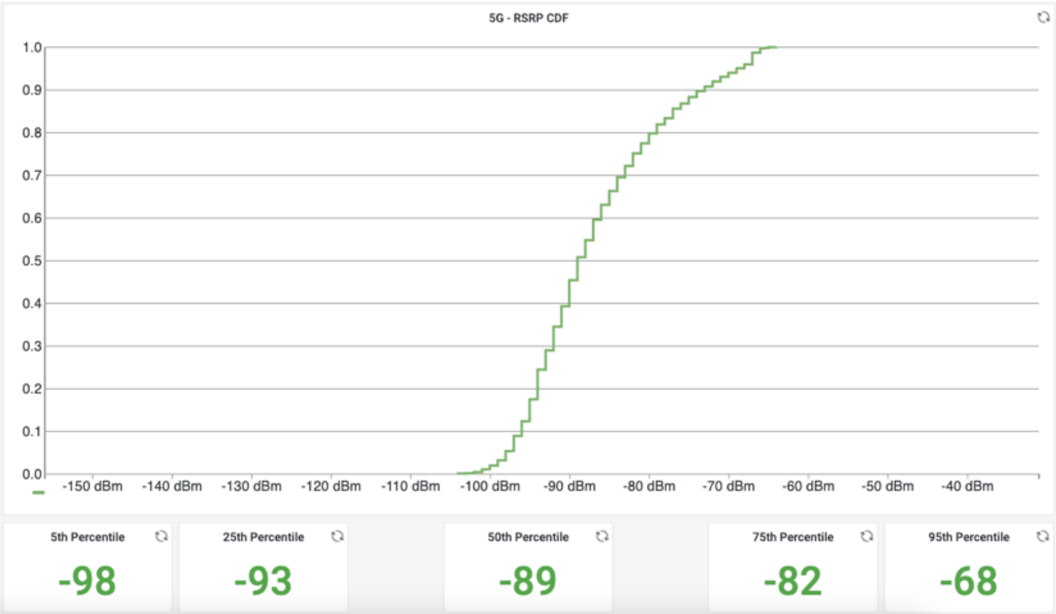


(b)

Figure 138: Tests with Fibocom module, 5G SA RSRP (a) heatmap, (b) CDF graph and percentiles at Verbrugge Terminals



(a)

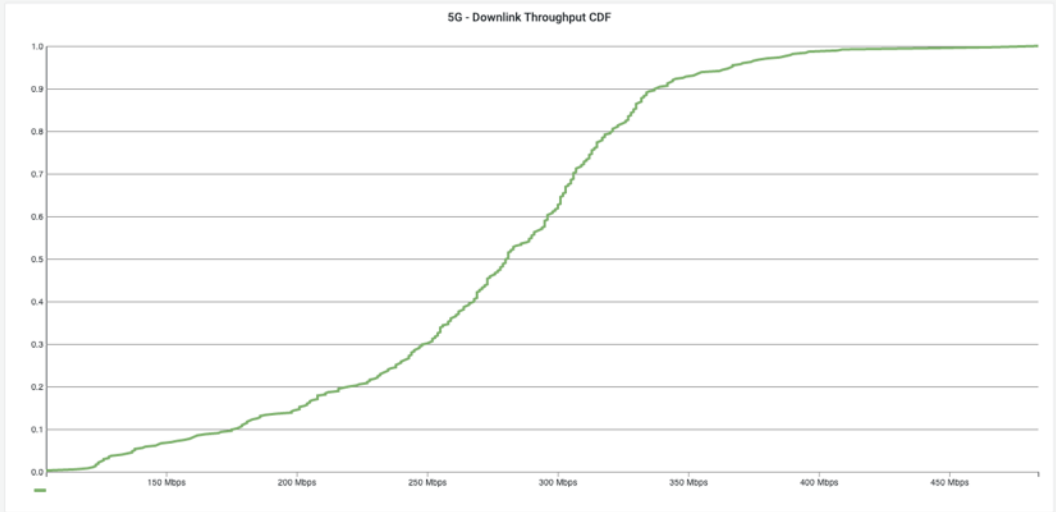


(b)

Figure 139: Tests with Quectel RM502Q module, 5G SA RSRP (a) heatmap, (b) CDF graph and percentiles at Verbrugge Terminals

Highlighting the TCP downlink throughput that was obtained by the Fibocom module and the Sierra Wireless module in Figure 140 and Figure 141, it can be observed that for the same trajectory, the Sierra Wireless module achieved relatively better results. The median value of the TCP throughput of the Fibocom was 281 Mbps while the result for the Sierra Wireless was 338 Mbps. Difference in performance between different modems are to be expected and can be a result of several parameters such as the firmware-related issues, used antennas, modem capabilities (e.g., MIMO type supported), etc.

(a)

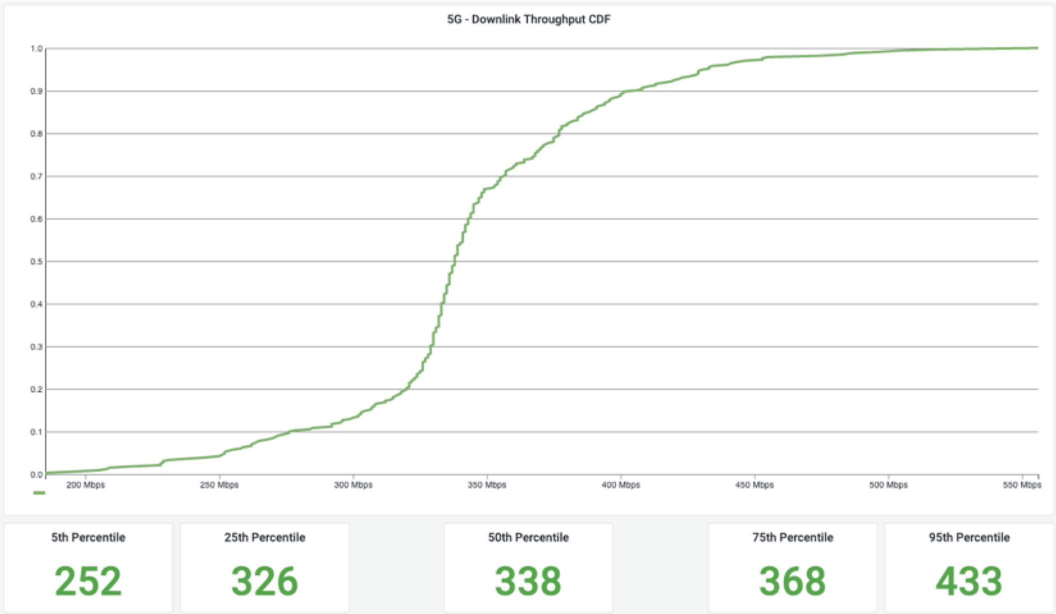


5th Percentile	25th Percentile	50th Percentile	75th Percentile	95th Percentile
138	238	281	313	367

(b)

Figure 140: Tests with Fibocom module, 5G SA TCP downlink (a) heatmap, (b) CDF graph and percentiles at Verbrugge Terminals

(a)



(b)

Figure 141: Tests with Sierra Wireless module, 5G SA TCP downlink (a) heatmap, (b) CDF graph and percentiles at Verbrugge Terminals

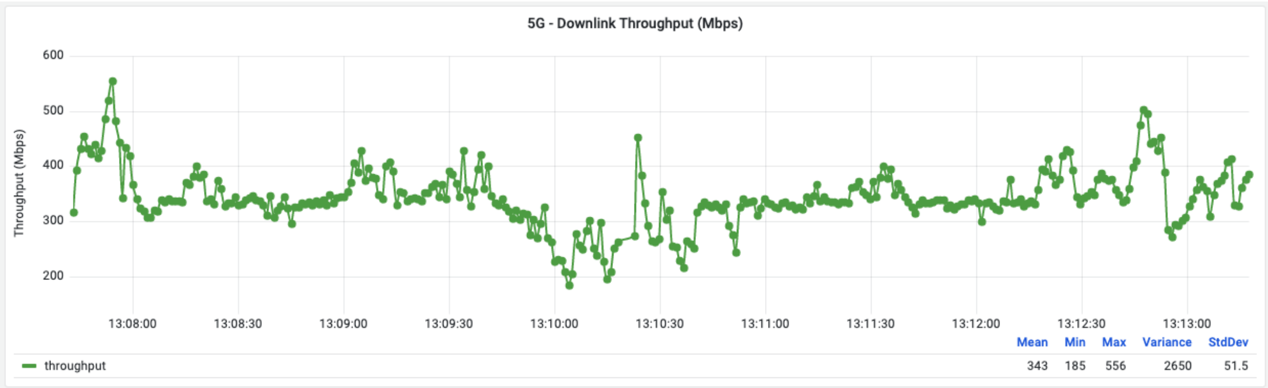
6.3.1.2 Evaluation of KPIs for different 5G network slices

In the following sections, the selected KPIs are evaluated when the DUT is connected to different 5G SA network slices of KPN, namely the eMBB and URLLC slices. Each KPI has been evaluated during multiple test-runs as shown in the test plan.

TCP downlink rate – eMBB slice

In Figure 142 (a), a heatmap of the TCP downlink throughput values on the eMBB slice is presented along Verbrugge terminal trajectory without any background traffic for the DUT (Sierra Wireless). Figure 142 (b) shows the graph of the downlink TCP throughput in Mbps over time. As it can be seen and in line to the RSRP values shown above, the throughput has the highest values at the western region of the trajectory which is in the proximity of the gNB. The maximum throughput that was observed was 556 Mbps, the mean value was 343 Mbps and the minimum throughput was 185 Mbps.

(a)

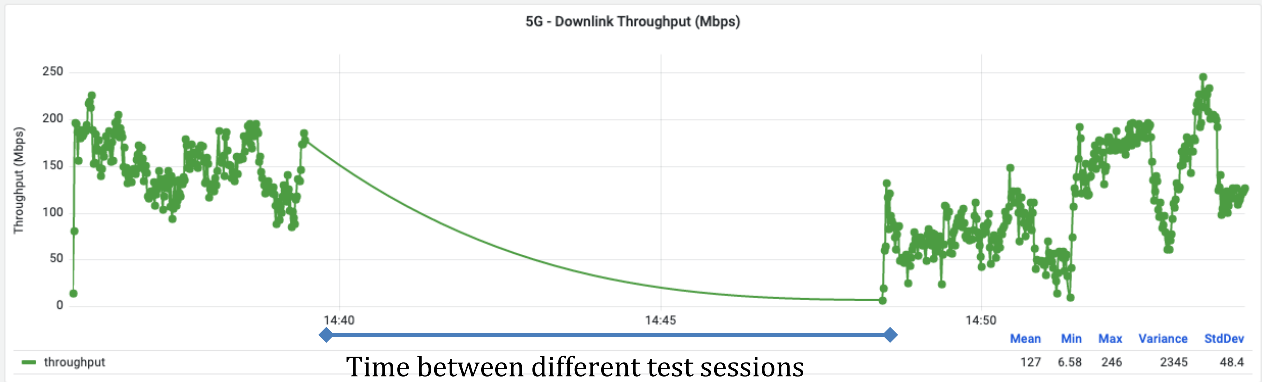


(b)

Figure 142: 5G SA TCP downlink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice without background traffic at Verbrugge Terminals

When background traffic was introduced on the eMBB slice using the Fibocom modem, the TCP downlink throughput was clearly affected. In order to ensure that both the DUT and the device generating background traffic use the same antenna beam for transmission and reception of data, both of them were placed next to each other in the test vehicle. The Fibocom device was transmitting constant background UDP traffic of 500 Mbps. The impact of the background traffic is shown in Figure 143. The maximum, mean and minimum achieved throughput was respectively 246, 127 and 6.58 Mbps. The difference between not having and having background traffic can clearly be seen in the CDF plots in Figure 144.

(a)



(b)

Figure 143: 5G SA TCP downlink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice with background traffic on the eMBB slice at Verbrugge Terminals

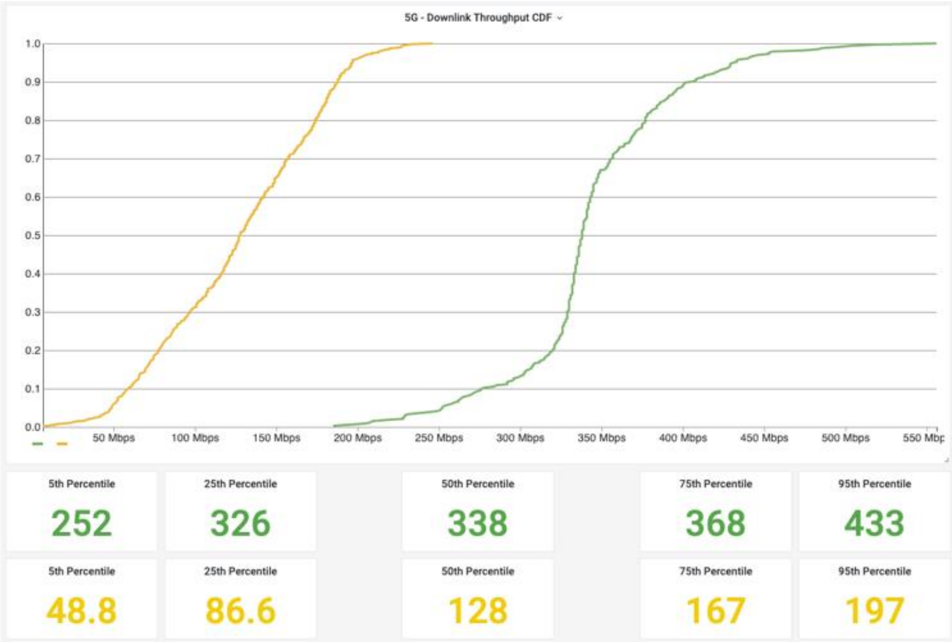
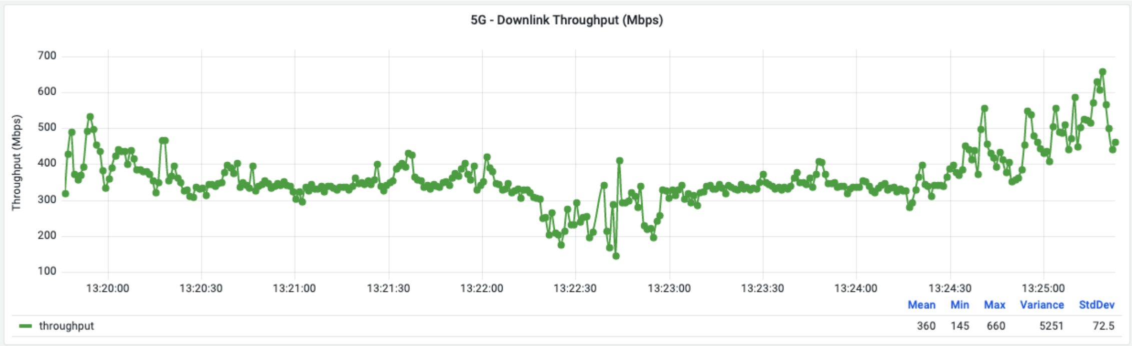


Figure 144: 5G SA TCP downlink rate – DUT on the eMBB slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

UDP downlink rate – eMBB slice

Similar to the TCP downlink rate, the UDP downlink rate is significantly impacted by background traffic when the eMBB slice is used. Figure 145 (a) shows the heatmap of the downlink UDL throughput, and Figure 145 (b) depicts the graph of the throughput values vs the time for the same tests when the DUT (Sierra Wireless module) uses the eMBB slice and there is no background traffic transmitted. As it can be observed, the maximum throughput value is 660Mbps, the mean value is 360Mbps and the minimum value is 145Mbps.

(a)

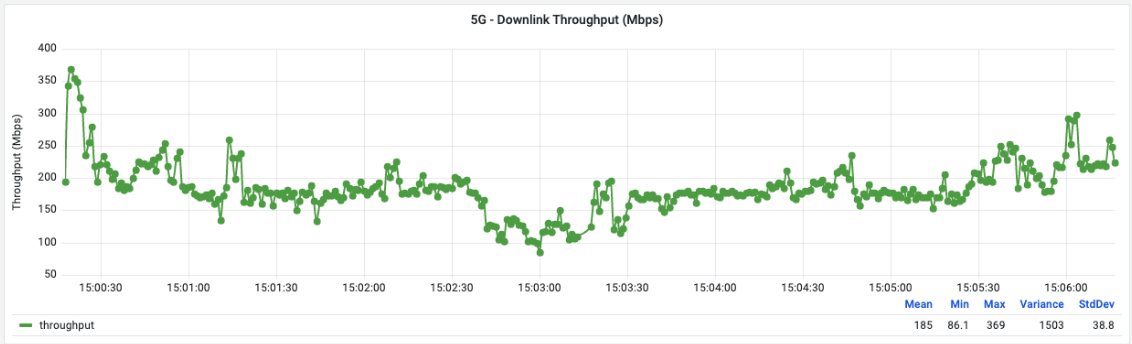


(b)

Figure 145: 5G SA UDP downlink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice without background traffic at Verbrugge Terminals

Figure 146 (a) shows the heatmap of the throughput on a map and Figure 146 (b) show the plot of the throughput over time, when the DUT is on the eMBB slice and in parallel, there is background traffic from a second device (Fibocom modem) on the same slice and next to the DUT in order to use the same antenna beam for sending and receiving data. That second device was transmitting constant UDP downlink traffic of 500 Mbps. It can be seen that the UDP downlink traffic is clearly impacted by the background traffic, as the mean value drops to 185 Mbps, while the maximum and minimum recorded values drop to 369 Mbps and 86.1 Mbps respectively. The impact can also be seen in Figure 147 that illustrates the CDF graphs of the throughput when there is and there is no background traffic. In addition, the figure emphasizes the impact based on interesting percentiles. For instance, for the 25th percentile, the throughput is up to 330 Mbps when there is no background traffic and up to 170 Mbps when there is background traffic.

(a)



(b)

Figure 146: 5G SA UDP downlink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice with background traffic on the eMBB slice at Verbrugge Terminals

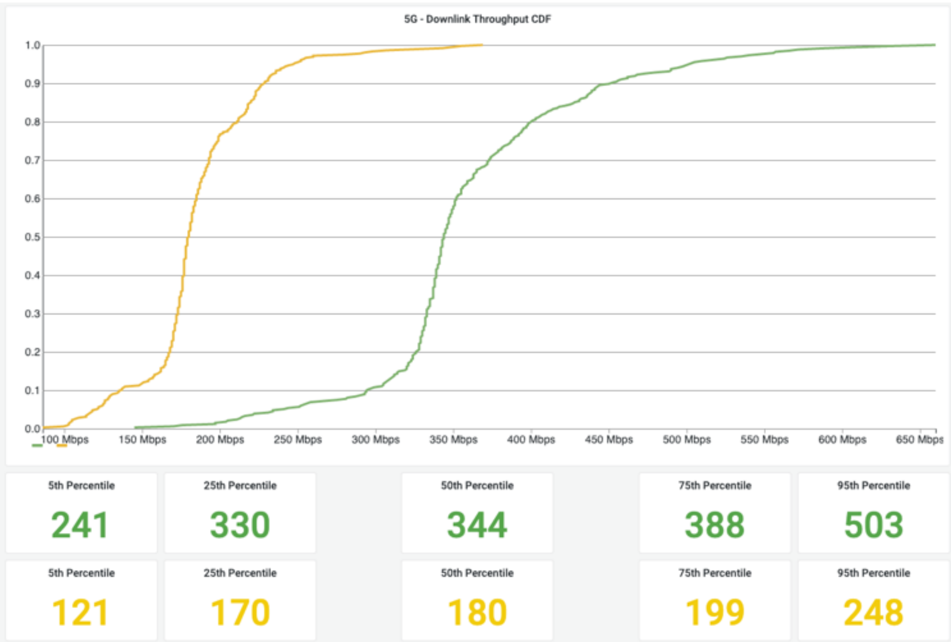
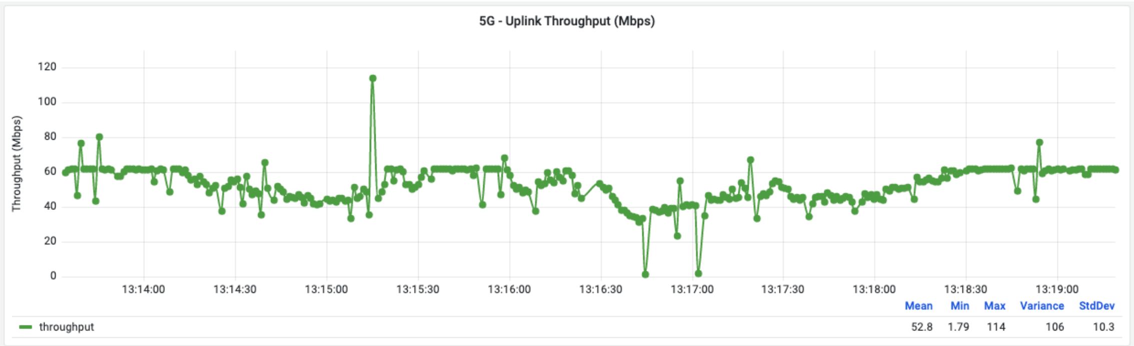


Figure 147: 5G SA UDP downlink rate – DUT on the eMBB slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

TCP uplink rate – eMBB slice

This subsection presents the evaluation of the TCP uplink rate, when the eMBB slice is used. Similar to the downlink case, the TCP uplink throughput of the DUT using a Sierra Wireless module is notably affected when background is introduced by a co-located device (Fibocom modem) transmitting as much as possible UDP uplink traffic.

(a)

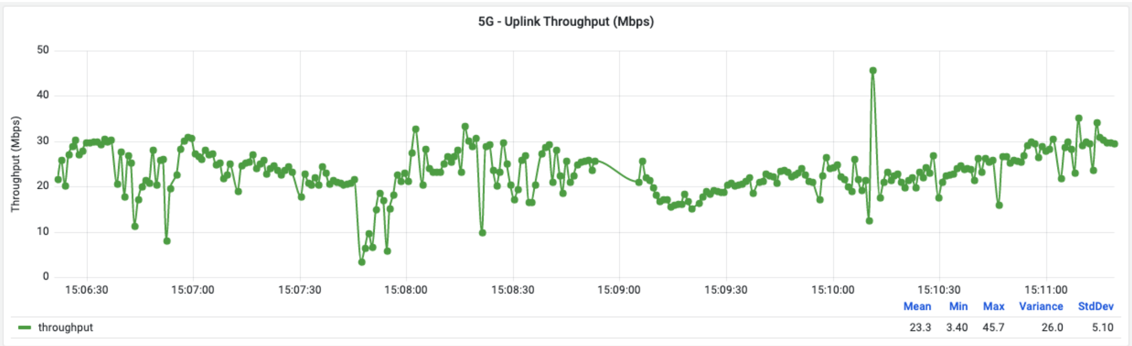


(b)

Figure 148: 5G SA TCP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice without background traffic at Verbrugge Terminals

As shown in Figure 148, the mean throughput value when there is no background traffic is 52.8 Mbps. When background traffic is introduced, the mean throughput drops to 23.3 Mbps (Figure 149). Figure 150 shows the CDF plots for the DUT uplink TCP throughput when there is no background traffic (green color) and when there is background traffic (orange color). The percentiles show the big impact of the background traffic on the throughput when eMBB slice is used. For instance, for the 95th percentile, the throughput is up to 62 Mbps when there is no background traffic, while it is up to only 30.3 Mbps when there is background traffic.

(a)



(b)

Figure 149: 5G SA TCP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice with background traffic on the eMBB slice at Verbrugge Terminals

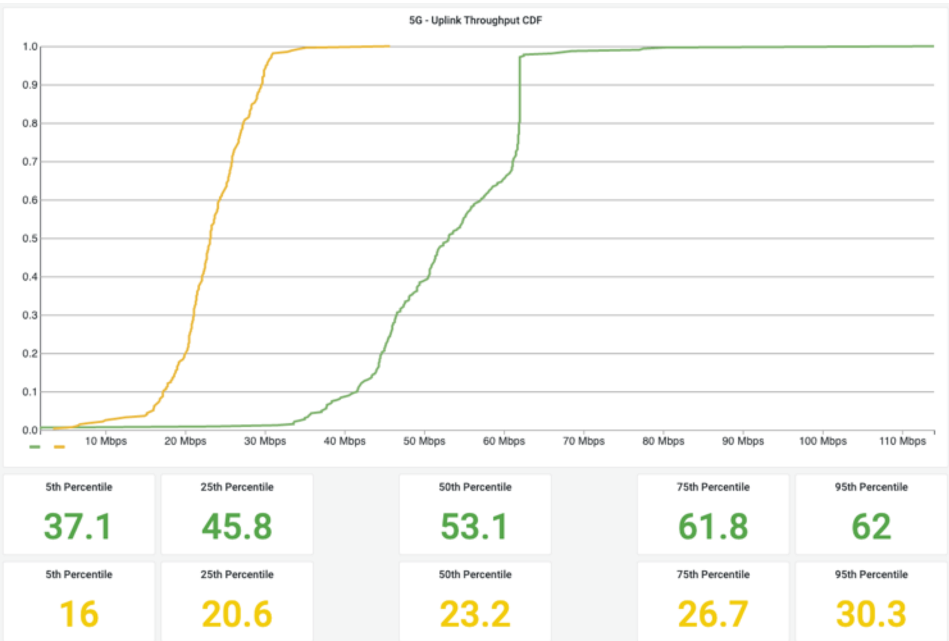
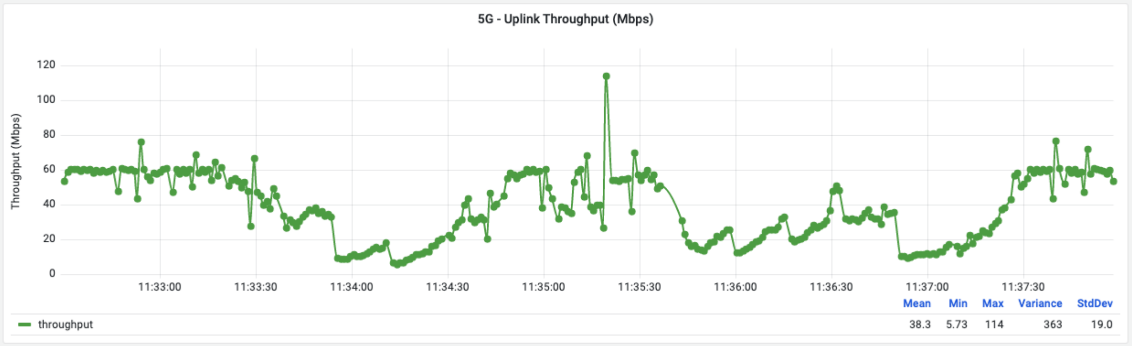


Figure 150: 5G SA TCP uplink rate – DUT on the eMBB slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

TCP uplink rate – URLLC slice

This section presents the results of the DUT (Sierra Wireless module) using the URLLC slice, which is configured to have higher priority than the eMBB slice. Figure 151 (a) shows the heatmap of the TCP uplink throughput while the test vehicle follows the trajectory in the Verbrugge terminals and there is no background traffic. Figure 151 (b) shows the graph of the throughput over time for the same test runs.

(a)



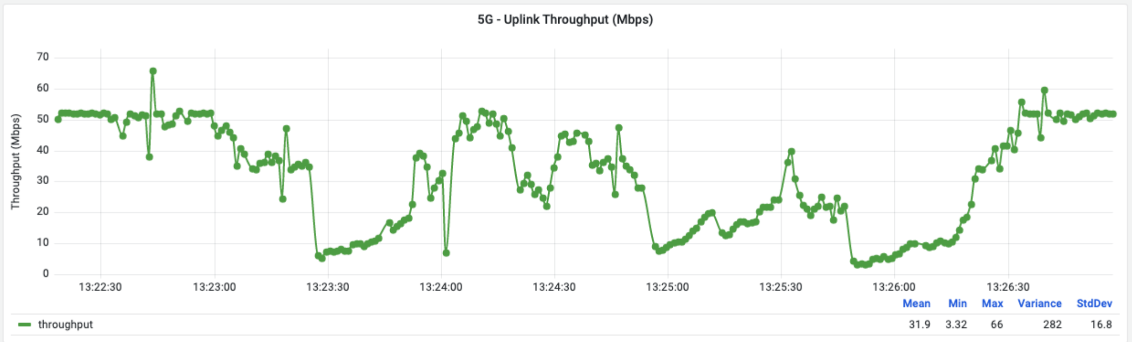
(b)

Figure 151: 5G SA TCP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the URLLC slice without background traffic at Verbrugge Terminals

Figure 152 presents (a) the heatmap of the TCP uplink throughput, and (b) the graph of the throughput over time for the same test runs, when there is background traffic introduced by a co-located device (Fibocom modem) on the eMBB slice.

As it can be observed the mean throughput is 38.3Mbps when there is no background traffic and 31.9 when there is background traffic transmitted, showcasing that the impact of background traffic on the URLLC slice is substantially less. This can be seen also in Figure 153 that shows the CDF plot of the uplink TCP throughput without background (green color) and with background (orange color) traffic. The two plots are very close to each other, and the percentiles verify that the URLLC slice is significantly less impacted by the background traffic compared to the eMBB slice.

(a)



(b)

Figure 152: 5G SA TCP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the URLLC slice with background traffic on the eMBB slice at Verbrugge Terminals

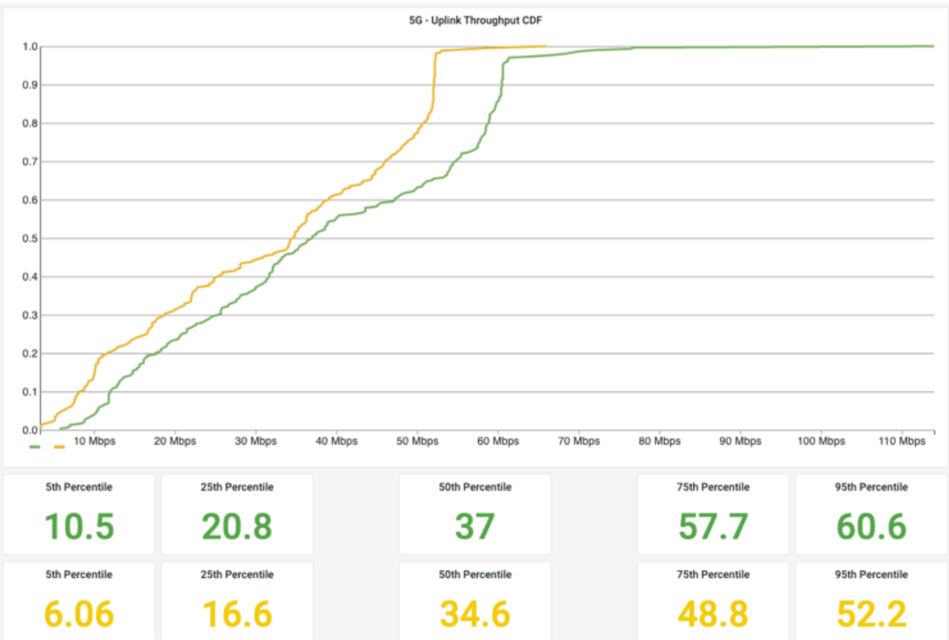
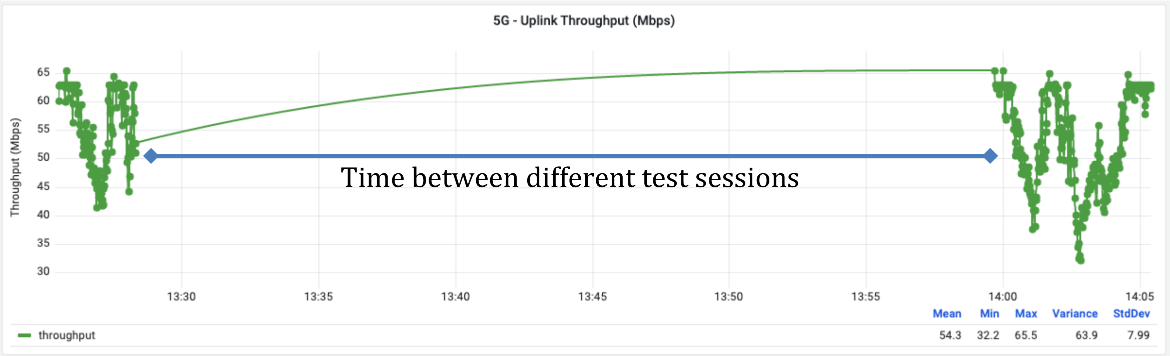


Figure 153: 5G SA TCP uplink rate – DUT on the URLLC slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

UDP uplink rate – eMBB slice

Subsequently, the UDP uplink throughput when the DUT (Sierra Wireless) is connected to the eMBB slice has been evaluated. Similarly to the previous sections, Figure 154 shows the heatmap of the throughput and the graph of the throughput over time for a series of test when there is no background traffic. On the other hand, Figure 155 presents the same graphs for the case of a co-located device (Fibocom) transmitting UDP uplink background traffic using the same eMBB slice. It can be clearly seen that the impact of the background traffic is notable, as the mean traffic drops by 53.59%.

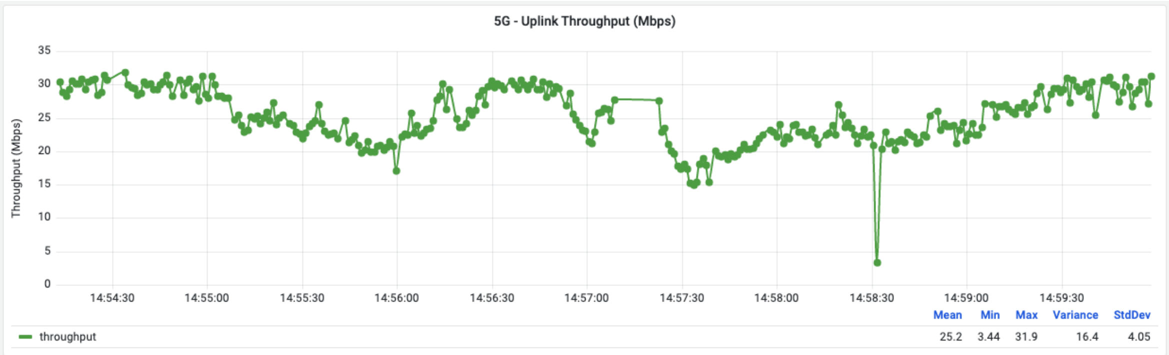
(a)



(b)

Figure 154: 5G SA UDP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice without background traffic at Verbrugge Terminals

(a)



(b)

Figure 155: 5G SA UDP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the eMBB slice with background traffic on the eMBB slice at Verbrugge Terminals

Figure 156 shows that impact using the CDF graphs when there is no background traffic (green color) and when there is background traffic (orange color). As it can be seen by the percentiles, the impact of background traffic reduces the throughput of the DUT by more than 50%.

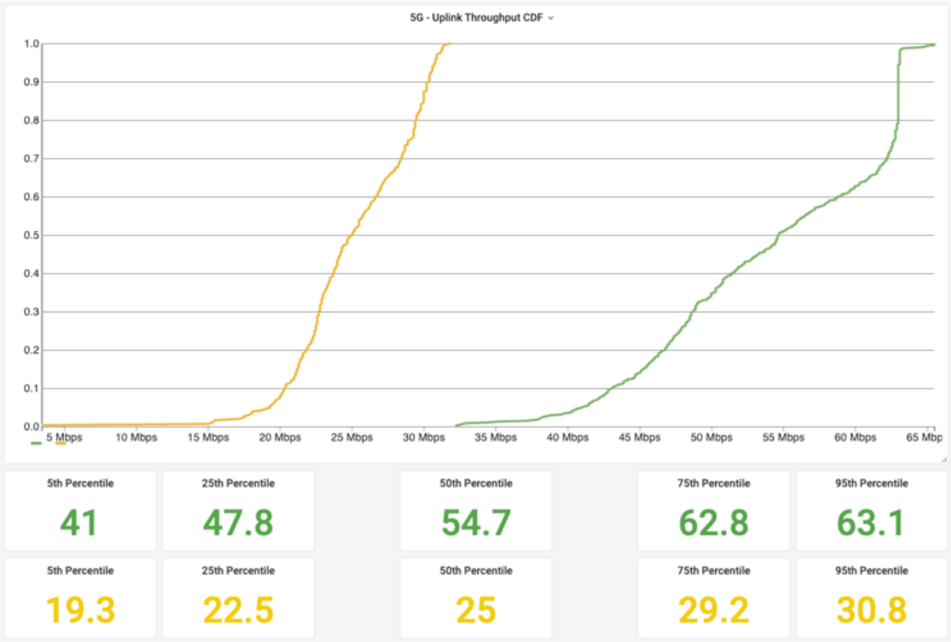
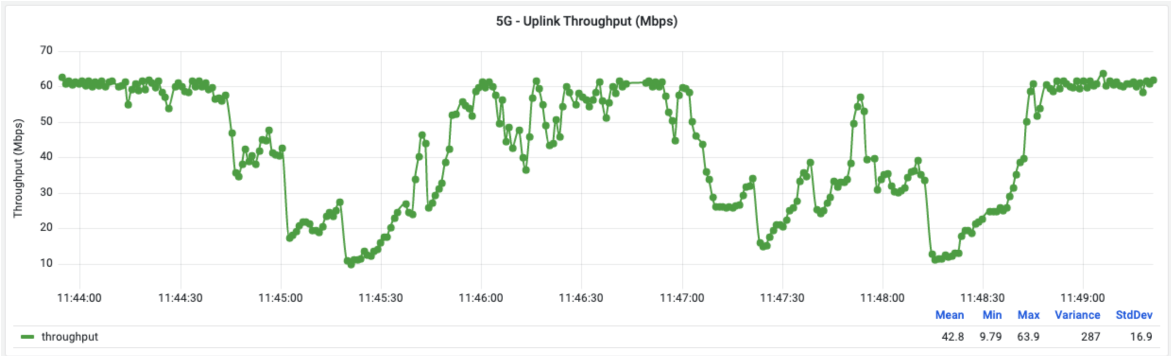


Figure 156: 5G SA UDP uplink rate – DUT on the eMBB slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

UDP uplink rate – URLLC slice

Similar to the TCP uplink scenario, this section unveils the findings from evaluating UDP uplink throughput in the context of DUT's (Sierra Wireless) connection to the URLLC slice. As previously indicated, the URLLC slice has been configured to have higher priority over the eMBB slice. In Figure 157, the throughput results from a sequence of tests without any background traffic are depicted, while Figure 158 presents the identical graphs for multiple tests conducted under the influence of background UDP uplink traffic stemming from a co-located device (Fibocom) linked to the eMBB slice. Notably, the reduction in throughput is markedly less pronounced compared to the preceding section where the DUT utilized the eMBB slice.

(a)

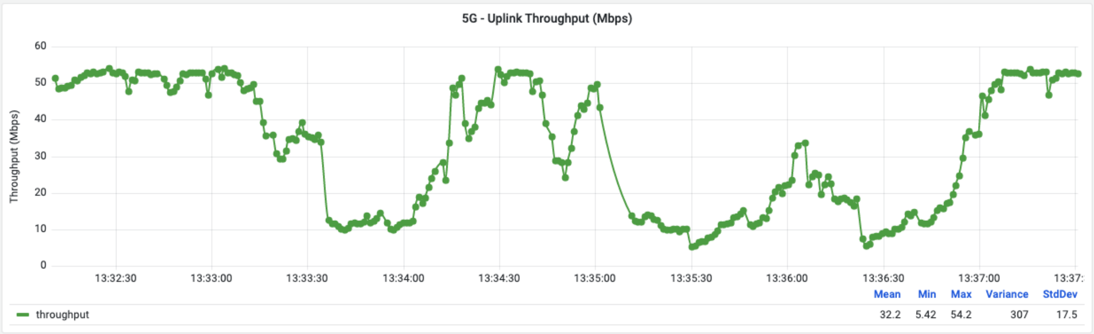


(b)

Figure 157: 5G SA UDP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the URLLC slice without background traffic at Verbrugge Terminals

Figure 159 shows the CDF plots of the uplink UDP throughput for the tests without background traffic (green color) and the tests with background traffic (orange color). Once more, the discernible trend is that the URLLC slice experiences significantly milder effects from the background traffic in contrast to the eMBB scenario discussed in the preceding section.

(a)



(b)

Figure 158: 5G SA UDP uplink rate (a) heatmap, (b) graph throughput vs time – DUT on the URLLC slice with background traffic on the eMBB slice at Verbrugge Terminals

Figure 159: 5G SA UDP uplink rate – DUT on the URLLC slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

Round-Trip Time – eMBB and URLLC slices

This segment presents a comparative analysis of round-trip latency performance under various conditions. Specifically, it evaluates the latency of the DUT (Sierra Wireless) when utilizing both the eMBB and URLLC slices. The assessment encompasses scenarios with no background traffic as well as instances where background traffic originates from a co-located device.

Figure 160 shows the CDF plots of the round-trip time for the DUT being connected to the eMBB slice. The green line depicts the latency plot in the absence of background traffic, while the orange line illustrates round-trip latency when the DUT is connected to the same eMBB slice while a co-located device (Fibocom) transmits UDP uplink background traffic using the same eMBB slice (orange line). It can be seen that the background traffic has a serious impact on the latency. Particularly noteworthy is the case of the 95th percentile, where the latency experiences an increase of nearly 80%.

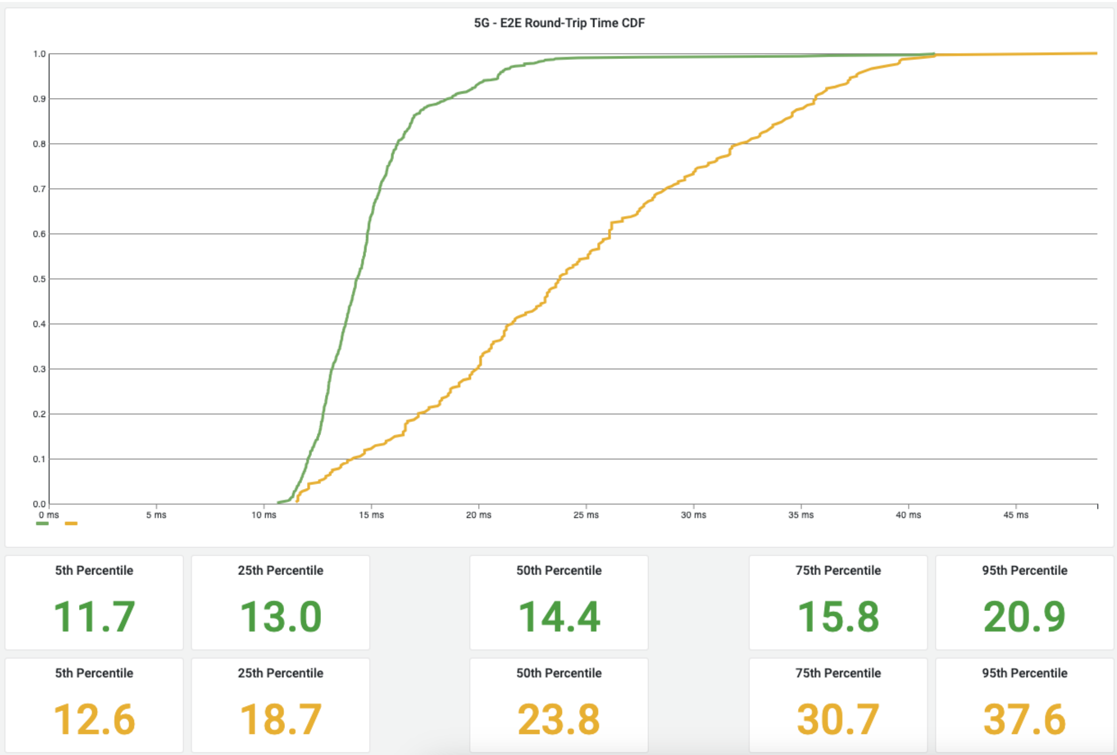


Figure 160: 5G SA RTT – DUT on the eMBB slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

In Figure 161, the CDF plots of the round-trip time for the DUT being connected the URLLC slice are shown. Similar to the previous figure, the green line presents the scenario of the round-trip latency without background traffic, while the orange line shows the plot of round-trip time under the impact of concurrent background traffic from a co-located device being connected to the eMBB slice. The plots and the corresponding percentiles showcase that the impact of the background traffic on the round-trip time performance is negligible when the URLLC slice is used.

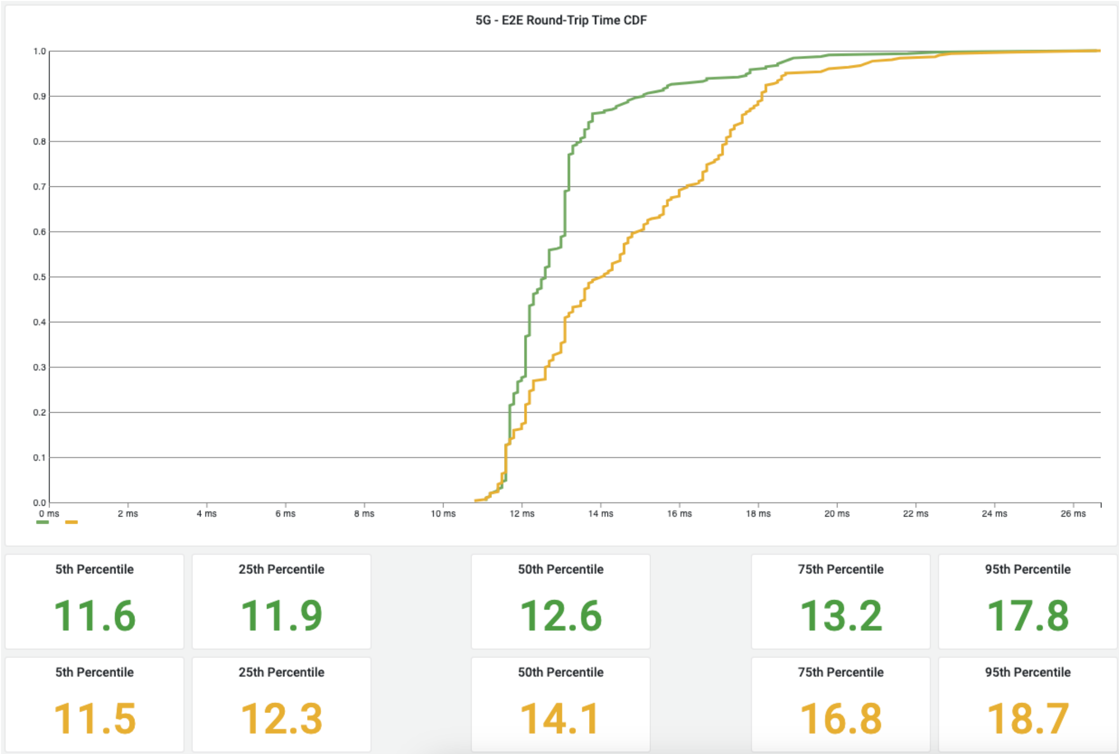


Figure 161: 5G SA RTT – DUT on the URLLC slice, without background traffic (green color), with background traffic on the eMBB slice (orange color)

One-way latency

In this section, we discuss the one-way uplink latency performance for the DUT (Sierra Wireless) being connected to the eMBB slice and the URLLC slice and for each slice, we evaluate the impact of background traffic generated by a co-located device (Fibocom) on the eMBB slice. In Figure 162, plots (a) and (c) show the CDF when the DUT is connected to the eMBB and the URLLC slice respectively, without any background traffic. As it can be observed, the one-way latency performance is quite similar in both slices. However, when uplink UDP background traffic is introduced, the traffic transmitted via the eMBB slice is impacted notably more than the traffic transmitted via the URLLC slice. This is to be expected as discussed previously due to the higher priority configured for the URLLC slice.

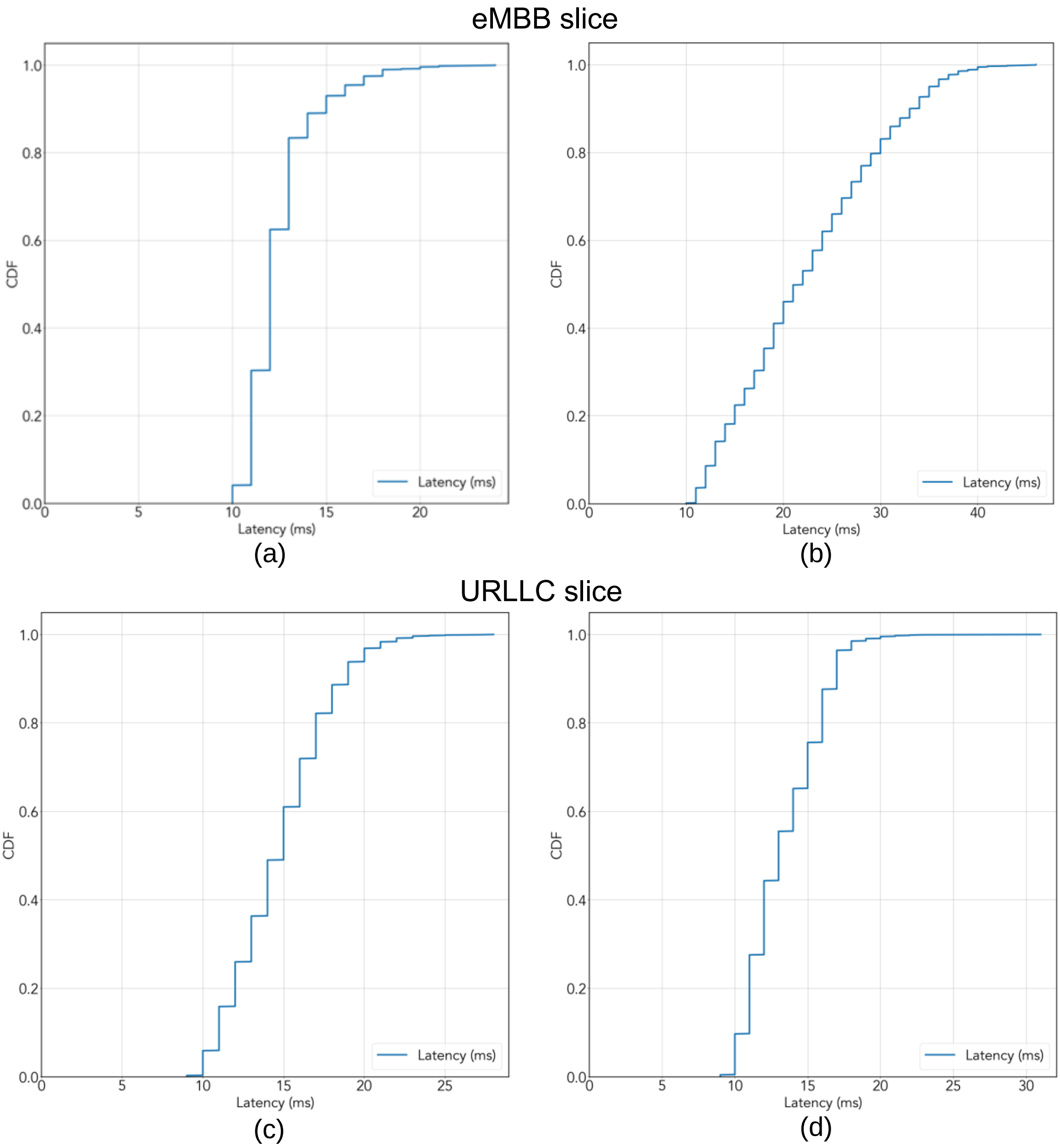


Figure 162: 5G SA one-way latency at Verbrugge Terminals – (a) DUT on the eMBB slice without background traffic, (b) DUT on the eMBB slice with background traffic on the eMBB slice, (c) DUT on the URLLC slice without background traffic, (d) DUT on the URLLC slice with background traffic on the eMBB slice

Reliability

This section delves into the assessment of reliability in the uplink concerning the DUT (Sierra Wireless), while the device is connected to the eMBB and URLLC slices. Furthermore, we explore the effects of background traffic originating from a co-located Fibocom device on the eMBB slice. In Figure 163, plots (a) and (c) unveil the CDF graphs representing the DUT's connection to the eMBB and URLLC slices, respectively, in the absence of any background traffic. As expected, the reliability appears notably comparable between the two slices. Nonetheless, upon introducing uplink UDP background traffic, a noticeable discrepancy emerges: traffic transmitted via the eMBB slice is more adversely affected compared to traffic transmitted via the URLLC slice. Hence, the reliability decreases in plot (b) compared to plot (d), which remains similar to the no background scenario depicted by plot (c). As an indicative example, the reliability for packets transmitted within 20ms is: 0.9955% for plot (a), 0.4561% for plot (b), 0.9982% for plot (c), and 0.9952% for plot (d). Similarly to the previous section, this outcome aligns with our previous discussions, given the higher priority attributed to the URLLC slice.

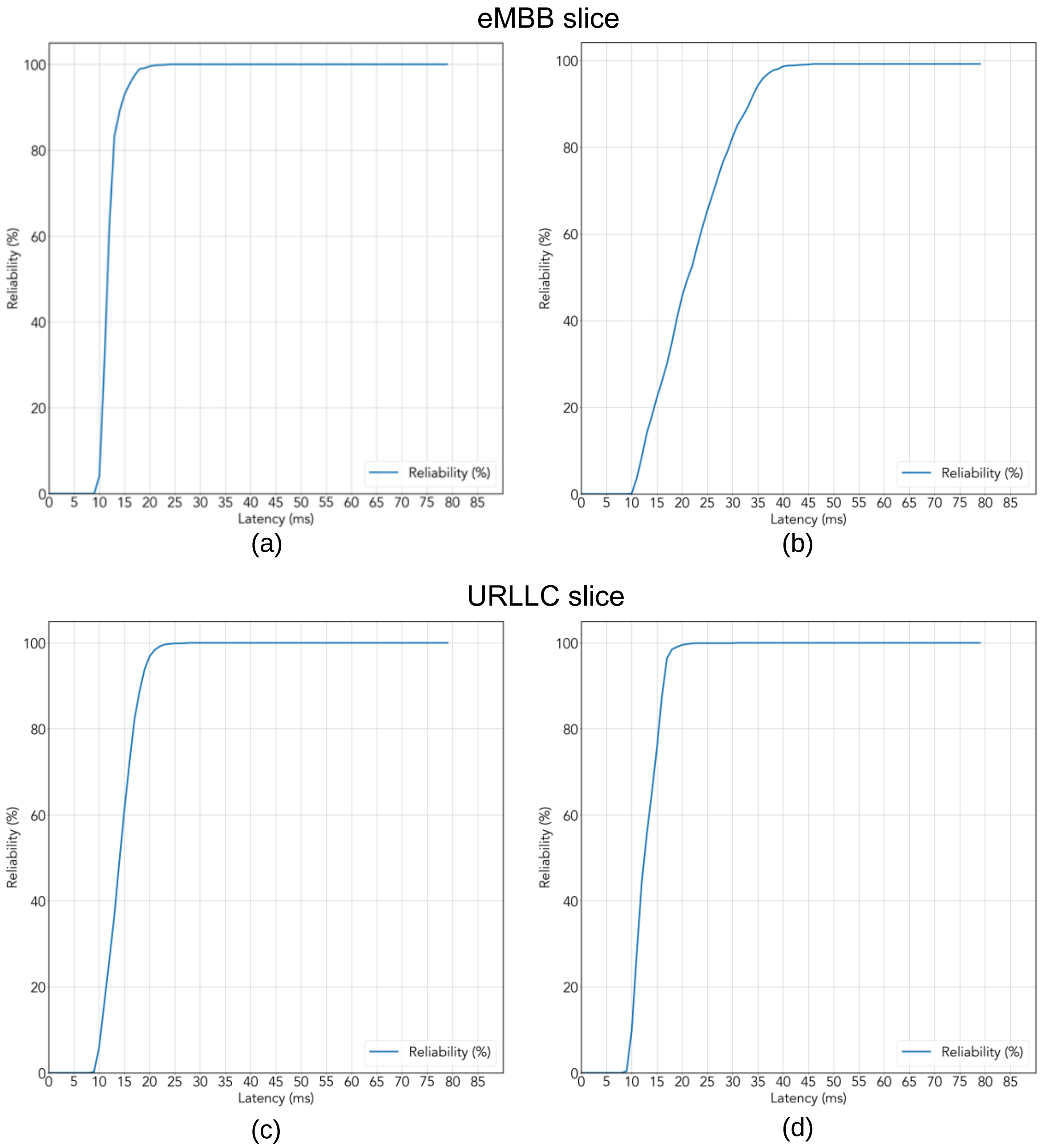


Figure 163: 5G SA reliability at Verbrugge Terminals – (a) DUT on the eMBB slice without background traffic, (b) DUT on the eMBB slice with background traffic on the eMBB slice, (c) DUT on the URLLC slice without background traffic, (d) DUT on the URLLC slice with background traffic on the eMBB slice

Packet Delivery Rate

In this section, we discuss the packet delivery rate on the uplink, when our DUT (Sierra Wireless) is connected to the eMBB and URLLC slices. In addition, we investigate the impact of UDP uplink background traffic on each slice. The background traffic is generated by a Fibocom device located next to the DUT to ensure that the same antenna beam is used for data transmission.

Figure 164 presents the PDR plot over time for indicative test runs. More specifically, plot (a) and plot (c) show the PDR over time, when the DUT is connected to the eMBB and URLLC slices respectively without the presence of background traffic. Plot (b) and plot (d) show the PDR over time for the respective slices when background traffic is sent on the eMBB slice. As can be seen, when the eMBB slice is used, the background traffic results into packet-loss reducing the PDR. Indicatively, we can see that at the 57th second of the test, the PDR drops to 80% due to packet-loss. On the contrary, when the URLLC slice is used, the PDR remains to 100% even when background traffic is transmitted.

Figure 165 shows the packet-loss on a map for the scenario that the DUT in on the eMBB slice and there is background traffic transmitted on the same slice.

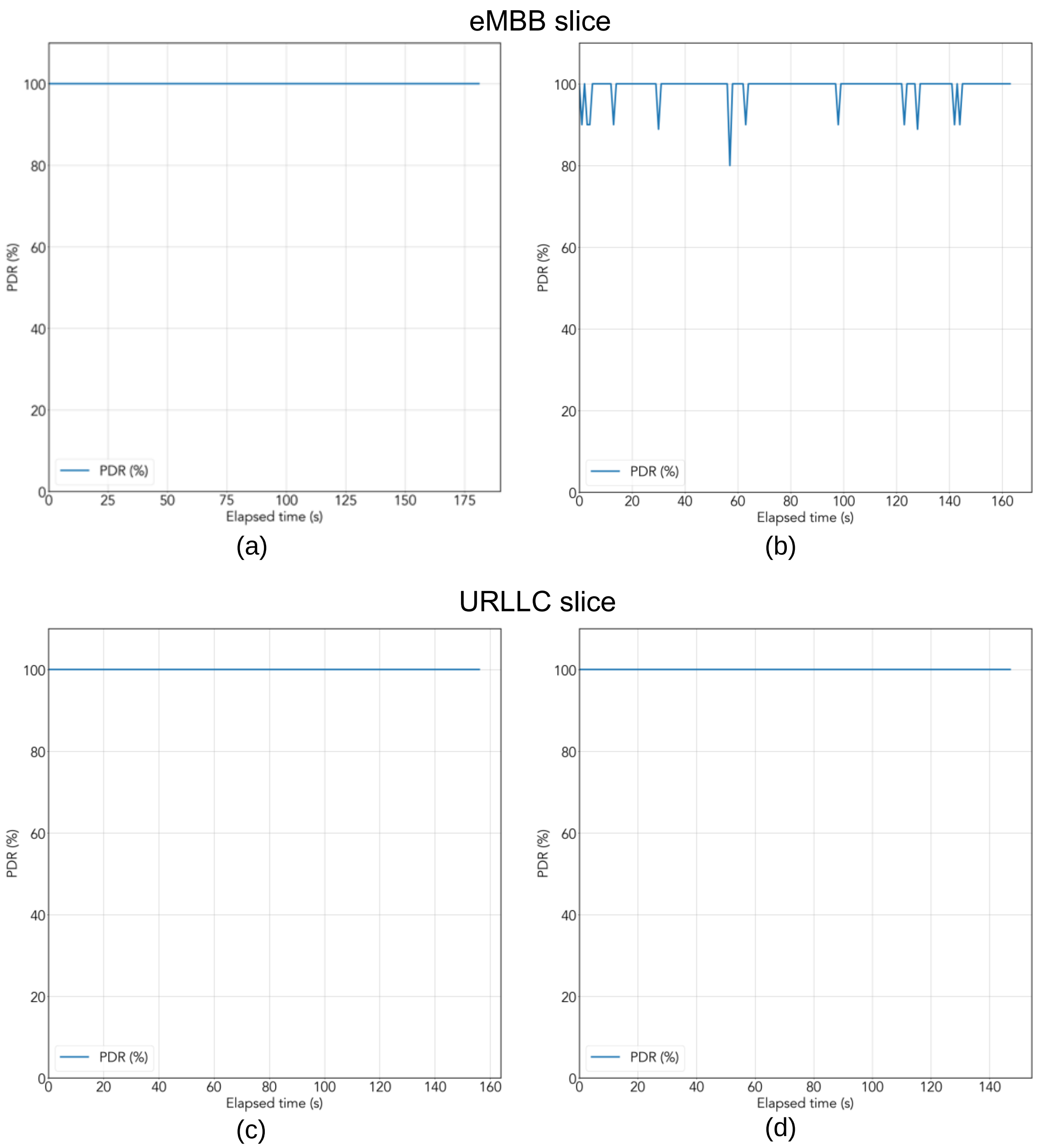


Figure 164: 5G SA packet delivery rate at Verbrugge Terminals – (a) DUT on the eMBB slice without background traffic, (b) DUT on the eMBB slice with background traffic on the eMBB slice, (c) DUT on the URLLC slice without background traffic, (d) DUT on the URLLC slice with

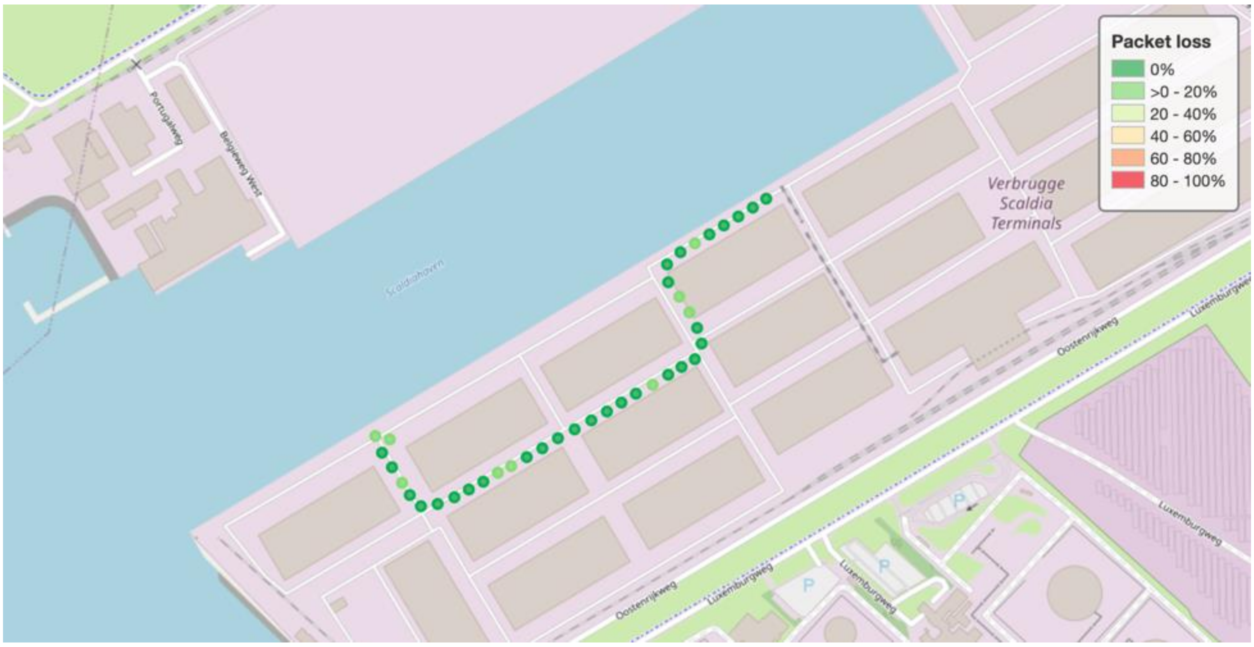


Figure 165: 5G SA packet-loss at Verbrugge Terminals – DUT on the eMBB slice with background traffic on the eMBB slice

Summary

In Table 21**,** a summary is provided of the results from the 5G SA network evaluation that was conducted at the Verbrugge terminal in Vlissingen on the road.

On-site 5G network evaluation						
Location	Netherlands – Verbrugge Terminal		Location type	**On the road - car**		
Network operator	KPN		Network type	5G SA		
Network slice config	eMBB - no background traffic eMBB – with background traffic URLLC - no background traffic URLLC – with background traffic		UE type	Sierra Wireless (RSRP measured with Quectel RM502Q and Fibocom)		
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm) – Quectel	-104	-98	-89	-68	-64	-86.6
RSRP (dBm) - Fibocom	-101	-96	-84	-66	-62	-82.3
TCP DL (Mbps) eMBB slice - Without background	185	252	338	433	556	343
TCP DL (Mbps) eMBB slice - With background	6.58	48.8	128	197	246	127
TCP UL (Mbps) eMBB slice - Without background	1.79	37.1	53.1	61.8	114	52.8
TCP UL (Mbps) URLLC slice - Without background	5.73	10.5	37	60.6	114	38.3
TCP UL (Mbps) URLLC slice - With background	3.32	6.06	34.6	52.2	66	31.9
TCP UL (Mbps) eMBB slice - With background	3.40	16	23.2	30.3	45.7	23.3
UDP DL (Mbps) eMBB slice - Without background	145	241	344	503	660	360
UDP DL (Mbps) eMBB slice - With background	86.1	121	180	248	369	185
UDP UL (Mbps) eMBB slice - Without background	32.2	41	54.7	63.1	65.5	54.3
UDP UL (Mbps) URLLC slice - Without background	9.79	13.2	45	61.6	63.9	42.8
UDP UL (Mbps) eMBB slice - With background	3.44	19.3	25	30.8	31.9	25.2
UDP UL (Mbps) URLLC slice - With background	5.42	8.93	34.6	50.9	54.2	32.2
RTT (ms) eMBB slice - Without background	10.6	11.7	14.4	20.9	41.2	15.0
RTT (ms) eMBB slice - With background	11.5	12.6	23.8	37.6	48.8	24.6
RTT (ms) URRLC slice - Without background	11.1	11.6	12.6	17.8	26.6	13.1
RTT (ms) URLLC slice - With background	10.8	11.5	14.1	18.7	26.7	14.7

Table 21: Summary of 5G SA network performance evaluation at the Verbrugge terminal on the road

6.3.2 5G NSA – Kloosterboer Terminals Site

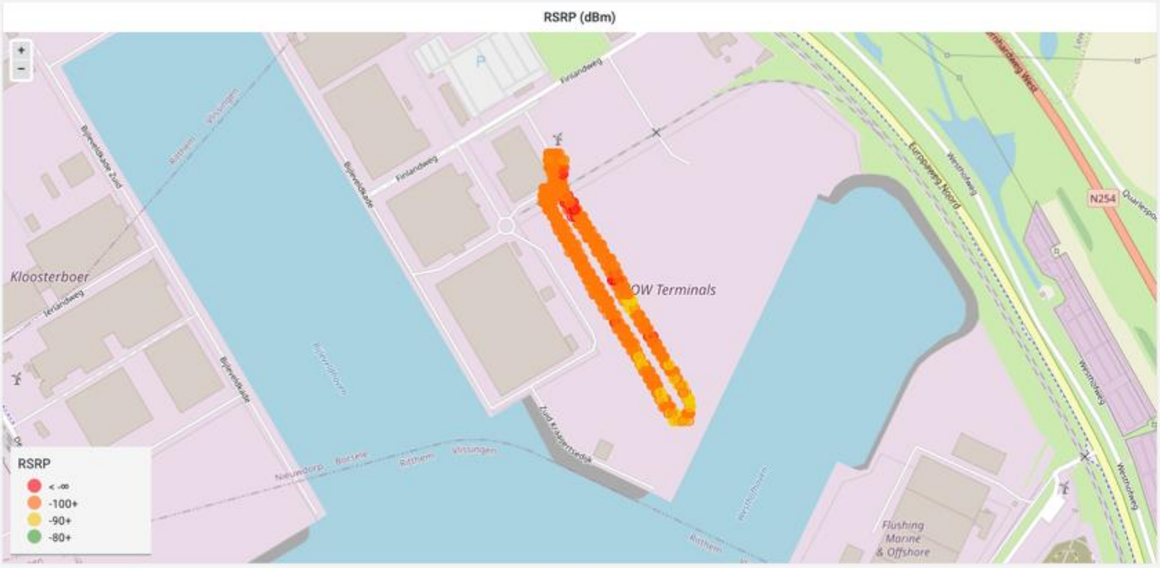
The Kloosterboer Terminals site consists of two locations, which in the context of this deliverable are referred as Kloosterboer Terminal 1 and Kloosterboer Terminal 2. Kloosterboer Terminal 1 is located at the south bank of the Scaldiahaven, while the Kloosterboer Terminal 2 is located at the north-east side of the Bijleveldhaven. The two following subsections discuss the results obtained from the evaluation of the 5G NSA network of KPN in these two locations respectively.

6.3.2.1 Kloosterboer Terminal 1

During the test campaign at Kloosterboer Terminal 1, we drove on a predefined trajectory that was selected carefully taking into account safety measures as the terminal is a busy environment where cranes constantly move massive containers. Aiming to perform the tests in a realistic environment, the selected trajectory included the main gate of the terminal as well as main corridors between the containers. For all the tests performed at the Kloosterboer Terminal 1, the Quectel RM502Q module was used at the UE side.

Modem statistics

Figure 166 presents (a) the heatmap of the RSRP values on the test trajectory, and (b) the CDF graphs of RSRP values, highlighting percentiles of high interest. As it can be seen, the 50th percentile is -97 dBm, while the 5th percentile is -100 dBm and the -95th percentile is -89 dBm, meaning that the signal power is quite similar over the whole trajectory. The higher RSRP values have been observed at the most south-east part of the trajectory and are depicted with yellow values on the heatmap. This is because that part is less being blocked by the stored containers.



(a)

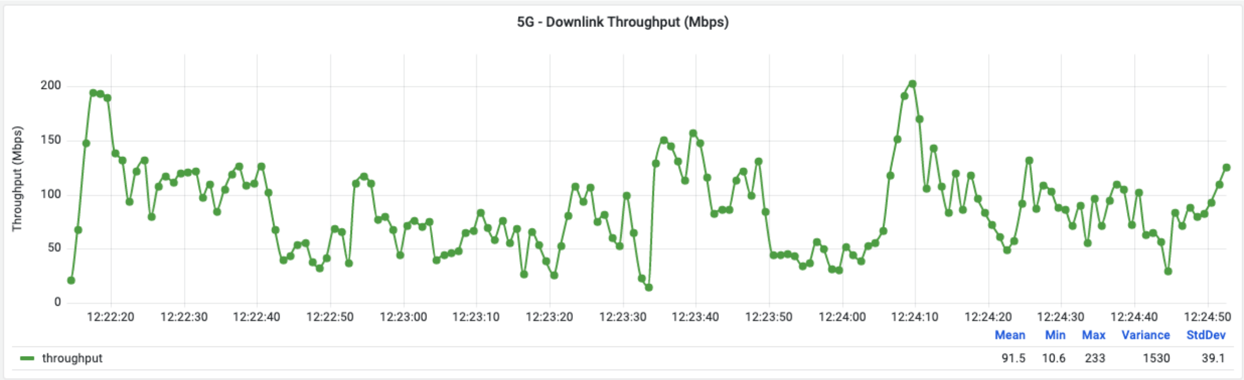
(b)

Figure 166: 5G NSA (a) RSRP values on map, (b) CDF graph and percentiles at Kloosterboer Terminal 1

TCP downlink rate

Figure 167 presents the TCP downlink rate (a) on a heatmap, and (b) on a graph in comparison to time for a series of consecutive tests. As it can be observed, the mean throughput value is 91.5 Mbps, while the minimum observed value is 10.6 Mbps and the maximum recorded value is 233 Mbps. This variation in the throughput values is a result of the very challenging environment that the selected trajectory includes. The stack of metallic containers may significantly hinder the signal propagation, impacting the throughput that can be achieved in certain locations of the trajectory.

(a)



(b)

Figure 167: 5G NSA TCP downlink rate (a) on map, (b) graph throughput vs time at Kloosterboer Terminal 1

The CDF graph of the TCP downlink rate values for all the performed tests is shown in Figure 168. Indicatively, the 50th percentile is 85.4 Mbps, and the 95th percentile is 164 Mbps.

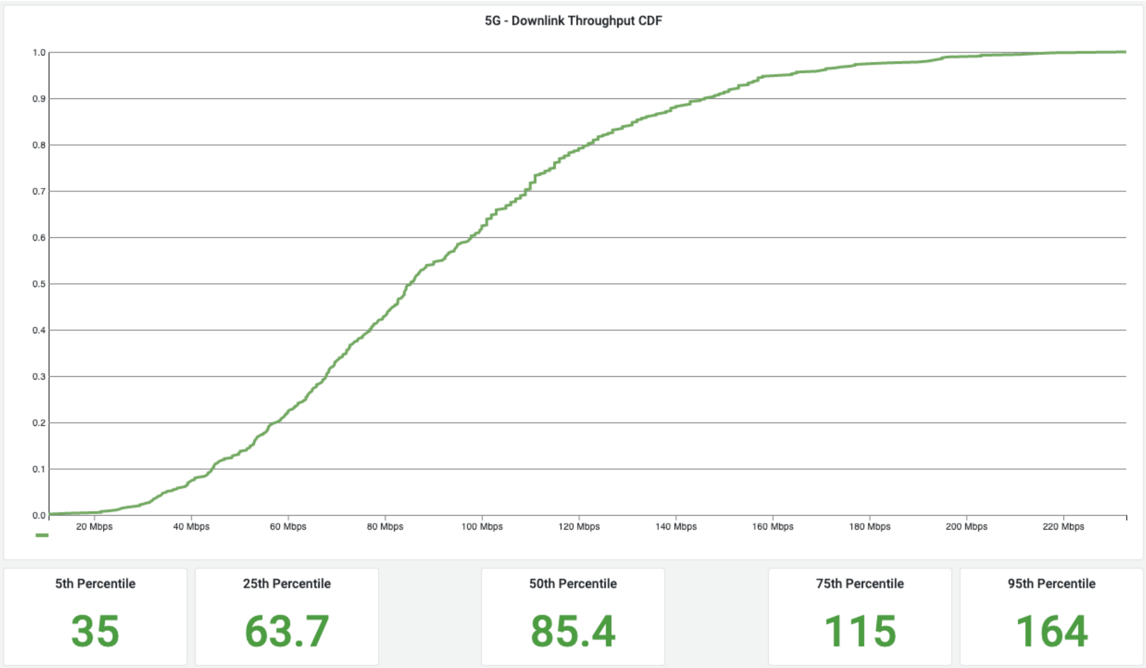
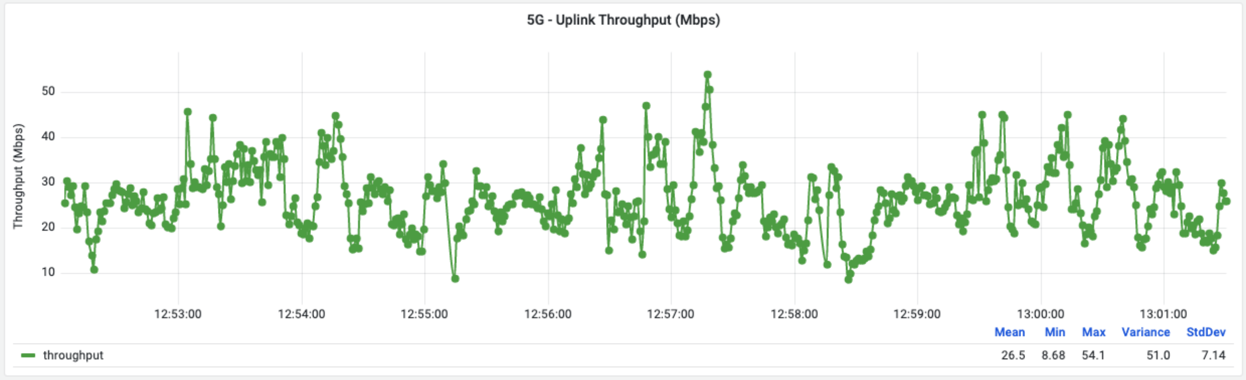


Figure 168: 5G NSA TCP downlink rate - CDF graph and percentiles at Kloosterboer Terminal 1

TCP uplink rate

Consecutively, the TCP uplink rate has been evaluated for the same trajectory, while performing multiple tests. In a similar way to the downlink case, Figure 169 shows (a) the heatmap of the throughput values over the driven trajectory, and (b) the graph of the throughput over time. From the statistics mentioned below the graph, it is shown that the mean uplink TCP throughput equals to 26.5 Mbps, while the minimum and maximum values are 8.68 Mbps and 54.1 Mbps respectively.

(a)



(b)

Figure 169: 5G NSA TCP uplink rate (a) on map, (b) graph throughput vs time at Kloosterboer Terminal 1

Figure 170 presents the CDF graph of the uplink TCP throughput values for all the performed tests. Pointedly, the 95th percentile is 39.1 Mbps and the 50th percentile is 26 Mbps.

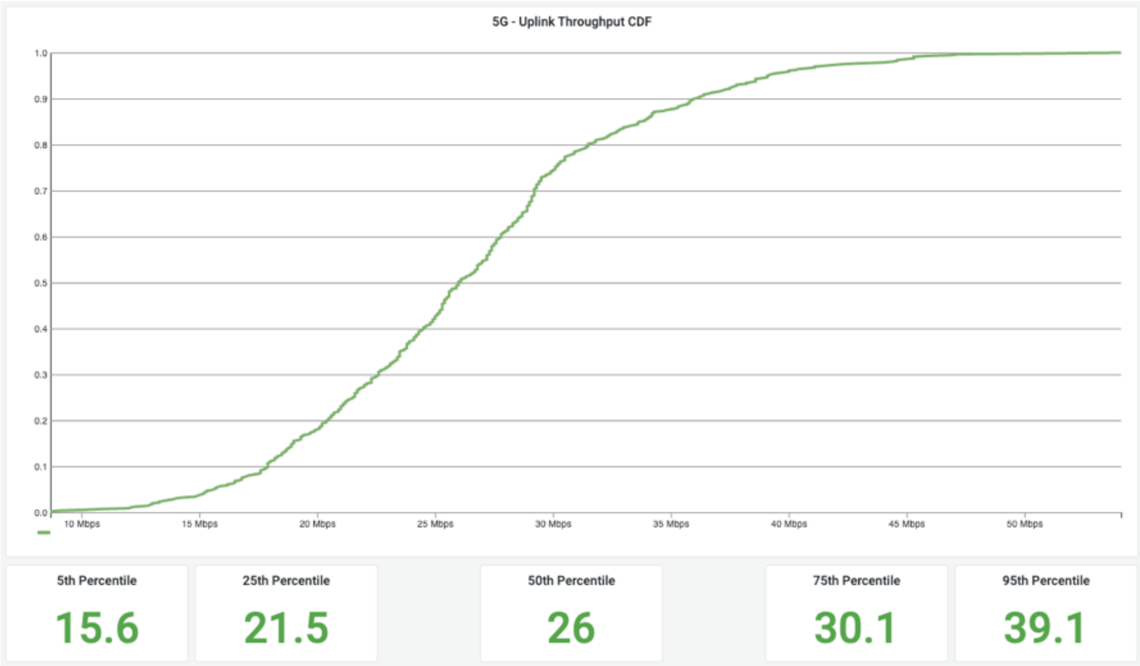
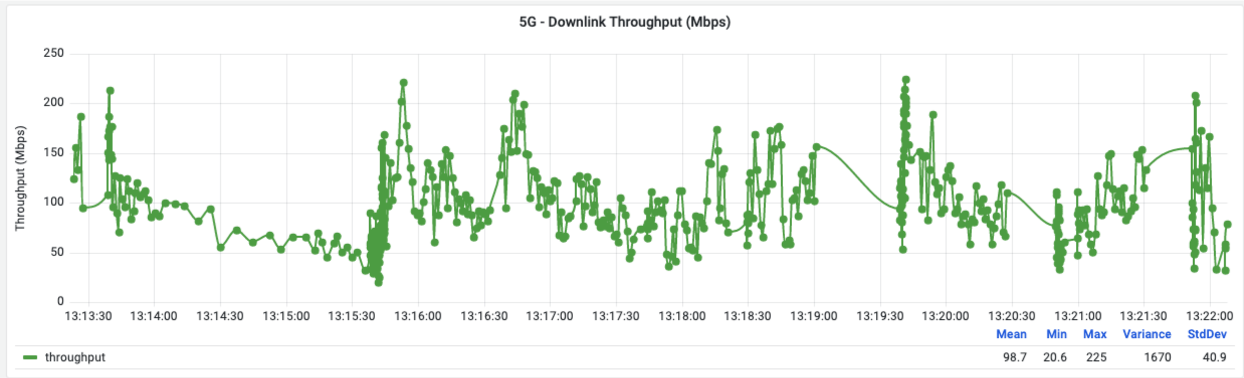


Figure 170: 5G NSA TCP uplink rate - CDF graph and percentiles at Kloosterboer Terminal 1

UDP downlink rate

This section discusses the results of the downlink UDP throughput evaluation at Kloosterboer Terminal 1. In Figure 171, we present two visualizations: (a) a heatmap depicting throughput values across the driven trajectory, and (b) a time-based graph illustrating throughput variations. Analyzing the statistics provided alongside the graph, we observe that the average downlink UDP throughput stands at 98.7 Mbps, with the lowest and highest recorded values being 20.6 Mbps and 225 Mbps, respectively.

(a)



(b)

Figure 171: 5G NSA UDP downlink rate (a) on map, (b) graph throughput vs time at Kloosterboer Terminal 1

Figure 172 shows the CDF graph of the downlink UDP throughput values for all the executed tests. Below the graph, the values of selective interesting percentiles are given. As it can be seen, the 50th percentile equals to 91.6 Mbps, the 5th percentile is 45.4 Mbps and the 95th percentile is 178 Mbps.

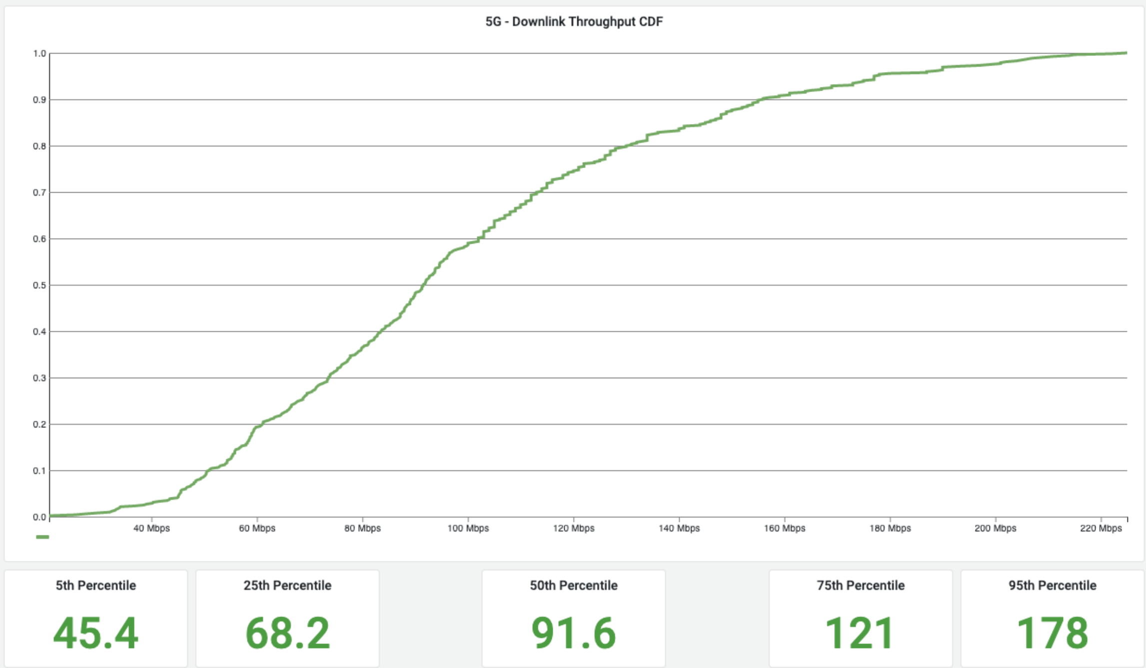
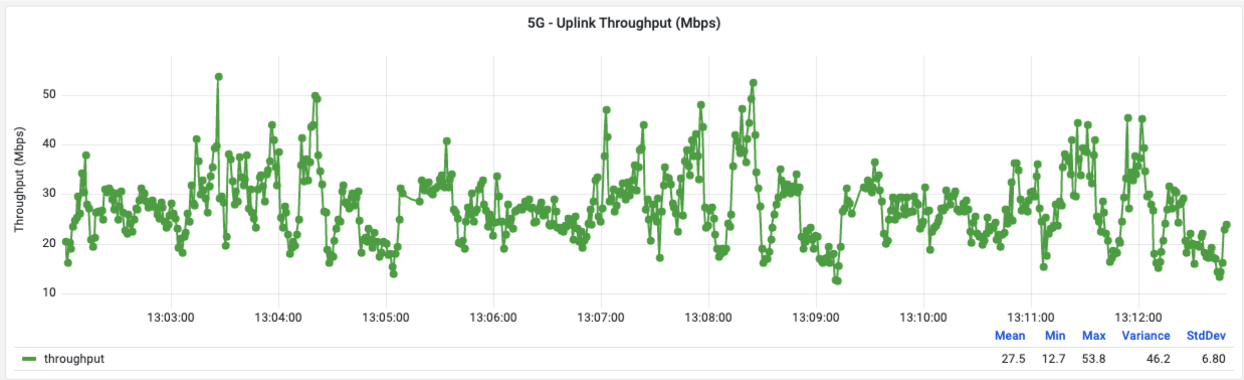


Figure 172: 5G NSA UDP downlink rate - CDF graph and percentiles at Kloosterboer Terminal 1

UDP uplink rate

Sequentially, the UDP uplink rate was assessed through a series of tests conducted on the identical trajectory. Mirroring the methodology used for the downlink scenario, Figure 173 displays (a) a heatmap illustrating throughput values along the driven trajectory, and (b) a time-based graph depicting throughput changes. Examining the statistics provided beneath the graph, we observe that the mean uplink UDP throughput is 27.5 Mbps, with the lowest and highest recorded values being 12.7 Mbps and 53.8 Mbps, respectively. It is worth to mention that these values are similar to their TCP counterparts.

(a)



(b)

Figure 173: 5G NSA UDP uplink rate (a) on map, (b) graph throughput vs time at Kloosterboer Terminal 1

In Figure 174, it can be observed the CDF plot representing the uplink UDP throughput values across all conducted tests. Below the graph, we present the values for specific percentiles of interest. Notably, the 50th percentile stands at 27.1 Mbps, the 5th percentile records 17.5 Mbps, and the 95th percentile reaches 39.8 Mbps.

It is important to mention that the overall throughput performance at Kloosterboer Terminal 1 satisfies the use case and enabling function requirements as defined in Deliverable 5.1 [3].

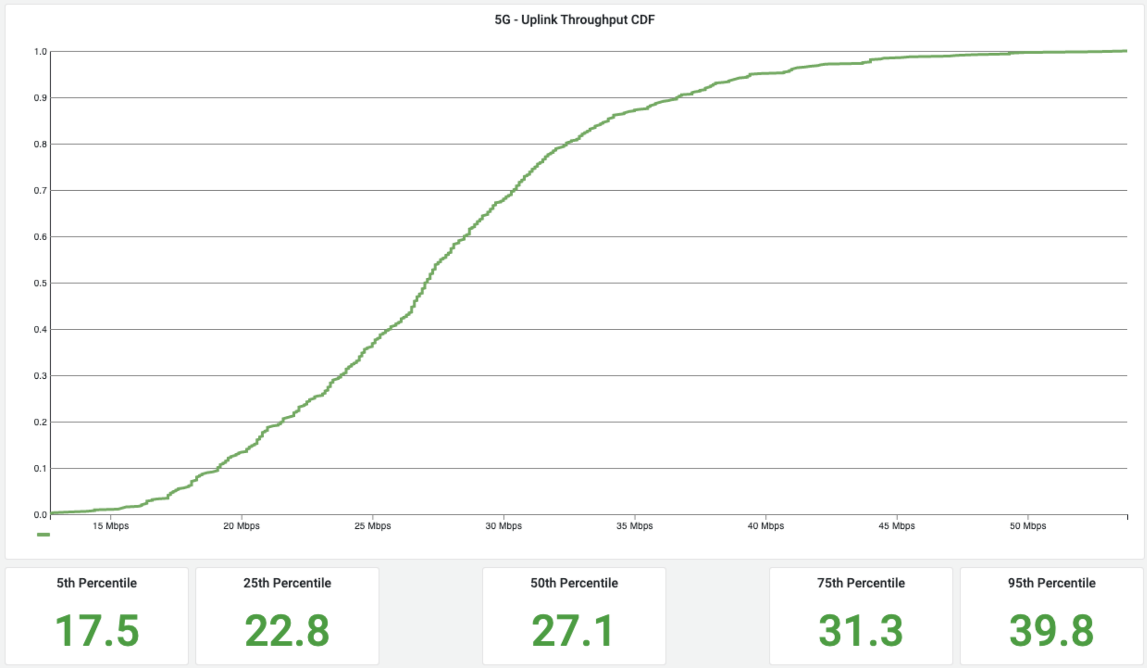
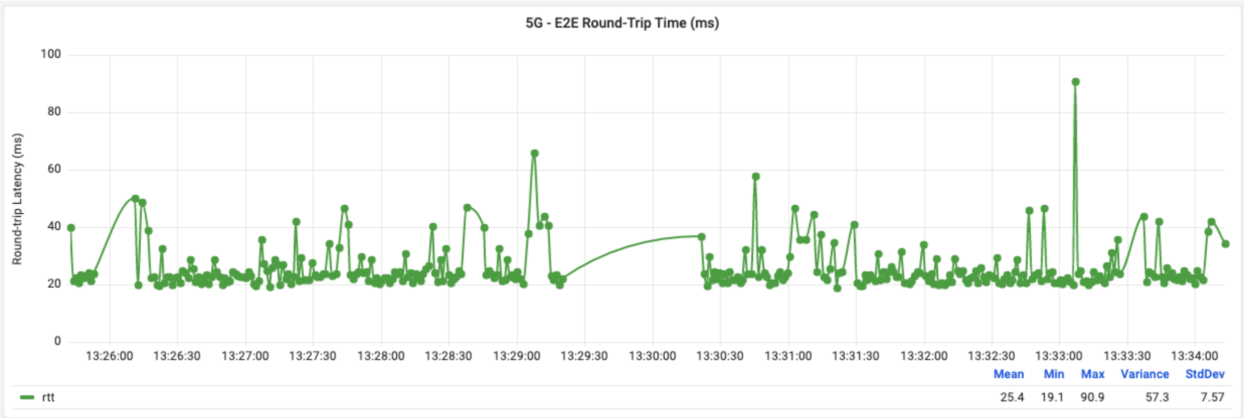


Figure 174: 5G NSA UDP uplink rate - CDF graph and percentiles at Kloosterboer Terminal 1

Round-Trip Time

This chapter discusses the results of the RTT evaluation on the KPN's NSA 5G network at Kloosterboer Terminal 1 trajectory. Figure 175 shows (a) the heatmap of RTT on the considered trajectory during multiple performed tests, and (b) the corresponding RTT values in relation to time. Any gaps on the graph (b) are result of pause time between consecutive tests. As it can be observed from the graph, the mean RTT latency is 25.4 ms. The maximum recorded latency value is 90.9 ms.

(a)



(b)

Figure 175: 5G NSA RTT (a) on map, (b) graph throughput vs time at Kloosterboer Terminal 1

Figure 176 shows the CDF graph of the RTT latency and a selection of percentiles of high interest. As it can be observed, the 50th percentile equals to 23 ms of RTT and the 95th percentile equals to 41.1 ms.

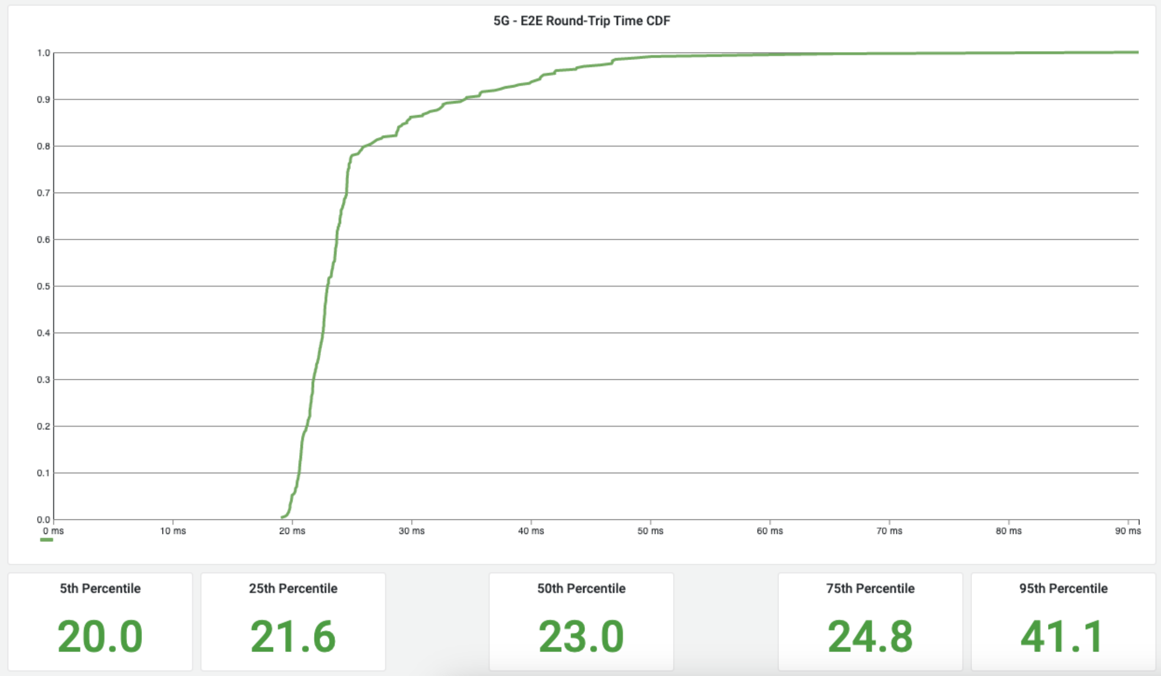


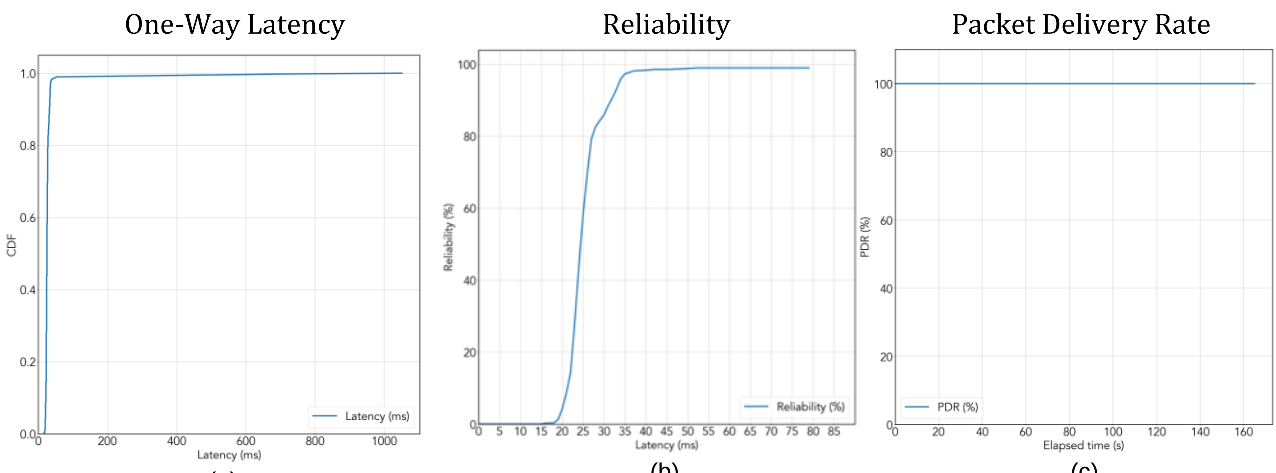
Figure 176: 5G NSA RTT - CDF graph and percentiles at Kloosterboer Terminal 1

One-way latency, reliability, packet delivery rate

Figure 177 presents (a) the CDF graph of one-way latency, (b) the percentage of reliability over time, and (c) the packet delivery rate over time. All three KPIs are measured on the uplink, meaning for packets that are transmitted by the UE to the gNB at a frequency of 10 Hz, meaning 10 packets per second.

As it can be observed, the one-way latency has a few values that exceed the 1000ms (1s). This is to be expected as the NSA 5G network of KPN is a production network and at any time, it might be used by other co-located users without having any SLA agreements. In addition, the challenging environment (stacks of containers) has a big impact on signal propagation and signal quality in general.

In the packet delivery rate graph, we can see that there is no packet loss observed. This graph is from a specific test, however it is representative for all the performed tests. However, as it can be seen in the reliability graph, the graph line does not reach the 100%, even though there is no packet loss. This is because of the way that reliability is defined, meaning the percentage of packets that are transmitted and received within a specific time frame. Hence, if a packet is received but outside the defined latency threshold, then it should be considered as lost. From collected data, it is derived that 98% of the transmitted packets are received within 37 ms.



(a) (b) (c)

Figure 177: 5G NSA (a) one-way latency, (b) reliability, (c) packet delivery rate at Kloosterboer Terminal 1

Summary

In Table 22**,** a summary is provided of the results from the 5G NSA network evaluation that was conducted at the Kloosterboer terminal 1 in Vlissingen on the road.

On-site 5G network evaluation						
Location	Netherlands – Kloosterboer Terminal 1			Location type	**On the road - car**	
Network operator	KPN			Network type	5G NSA	
Network slice config	eMBB - no background traffic			UE type	Quectel RM502Q	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-102	-100	-97	-89	-84	-95.9
TCP DL (Mbps)	10.6	35	85.4	164	233	91.5
TCP UL (Mbps)	8.68	15.6	26	39.1	54.1	26.5
UDP DL (Mbps)	20.6	45.4	91.6	178	225	98.7
UDP UL (Mbps)	12.7	17.5	27.1	39.8	53.8	27.5
RTT (ms)	19.1	20.0	23.0	41.1	90.9	25.4

Table 22: Summary of 5G NSA network performance evaluation at the Kloosterboer terminal 1

6.3.2.2 Kloosterboer Terminal 2

After concluding the evaluation at the Terminal 1 location, the selected KPIs were evaluated at Terminal 2 during multiple test rounds. However, Kloosterboer Terminal 2 is significantly busier than Terminal 1, hence for safety reasons all the tests were performed while the car was parked at a predefined location as shown in Figure 178. Similar to the evaluation at Klossterboer Terminal 1, for all the tests performed Terminal 2, the Quectel RM502Q module was used at the UE side.

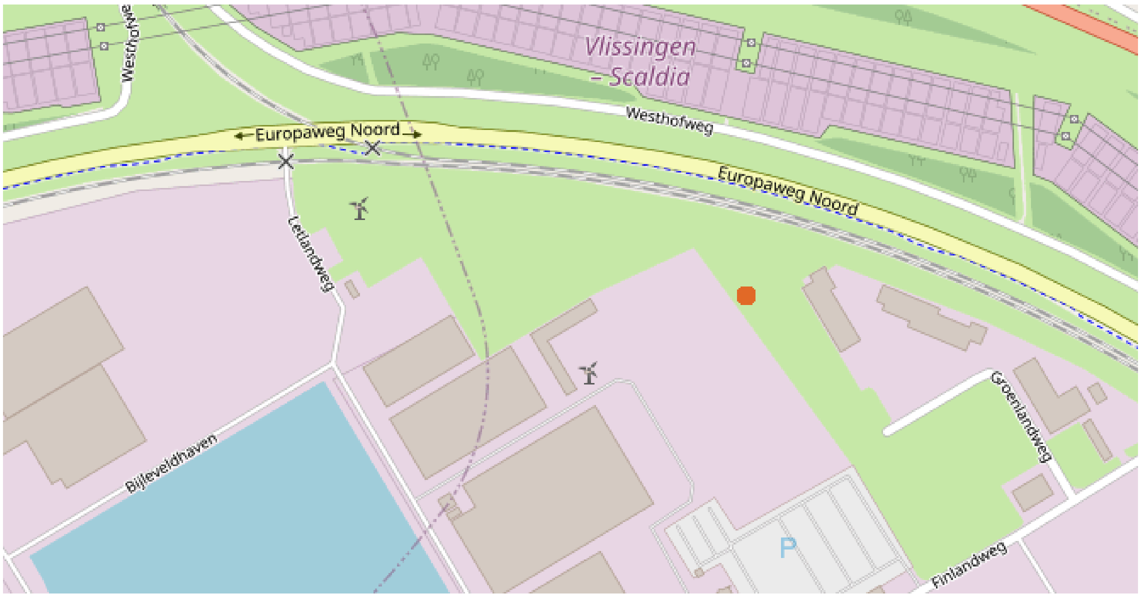
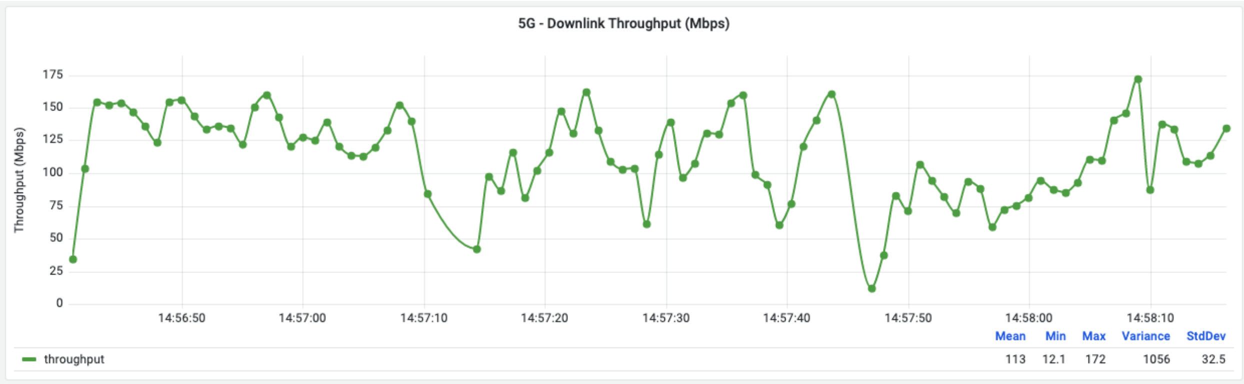


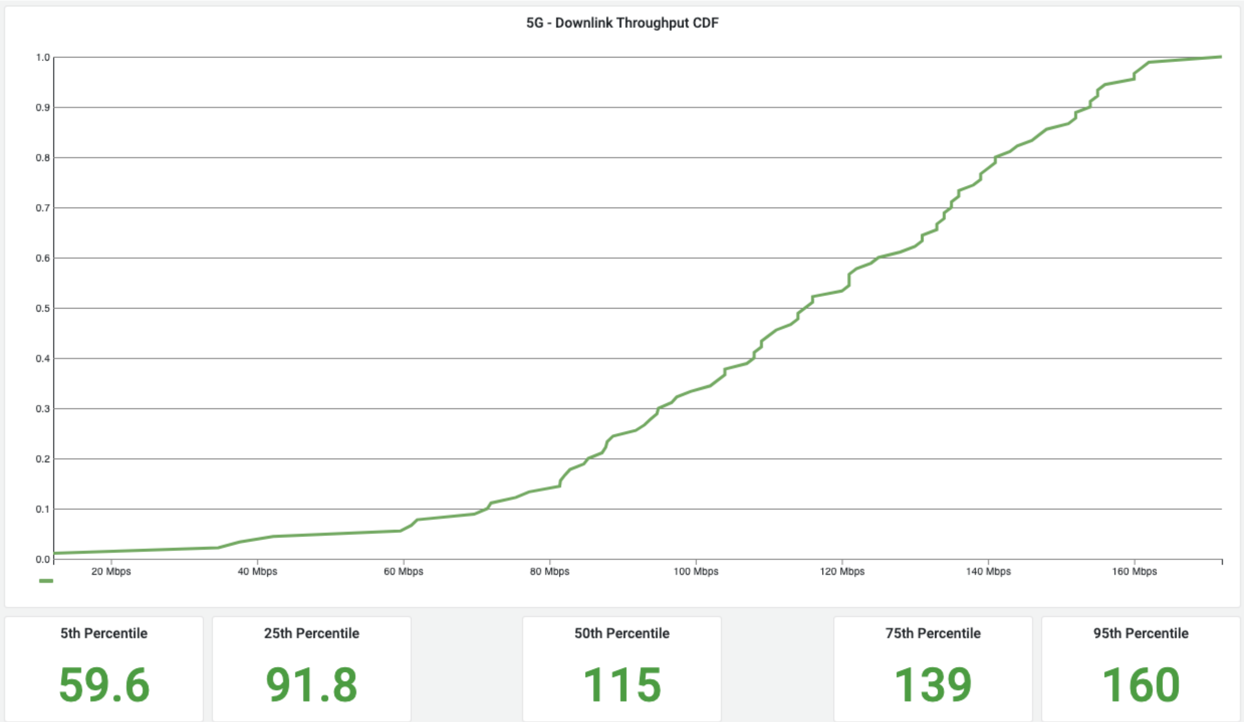
Figure 178: Kloosterboer Terminal 2 test location

TCP downlink rate

Figure 179 exhibits the TCP downlink rate through two visualizations: (a) a time-based graph, showcasing results from a series of consecutive tests and (b) a CDF graph of the corresponding throughput values, highlighting specific percentiles of interest. Notably, the mean throughput value is 113 Mbps, with the highest recorded value at 172 Mbps. Notably, the 50th percentile indicates a throughput of 115 Mbps and the 95th percentile indicates a throughput of 160 Mbps. The fluctuation in throughput can be attributed to the ever-changing environment, characterized by the continuous movement of trucks and large cranes transporting containers within the terminal.



(a)

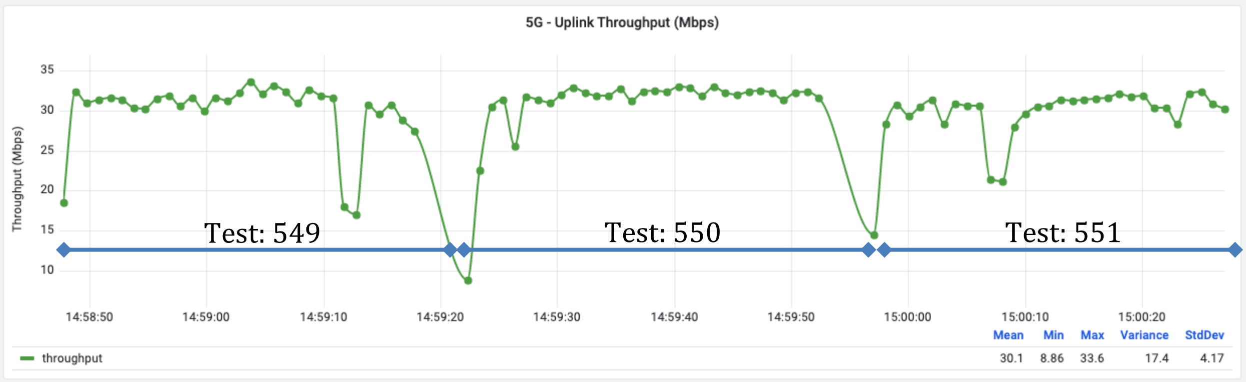


(b)

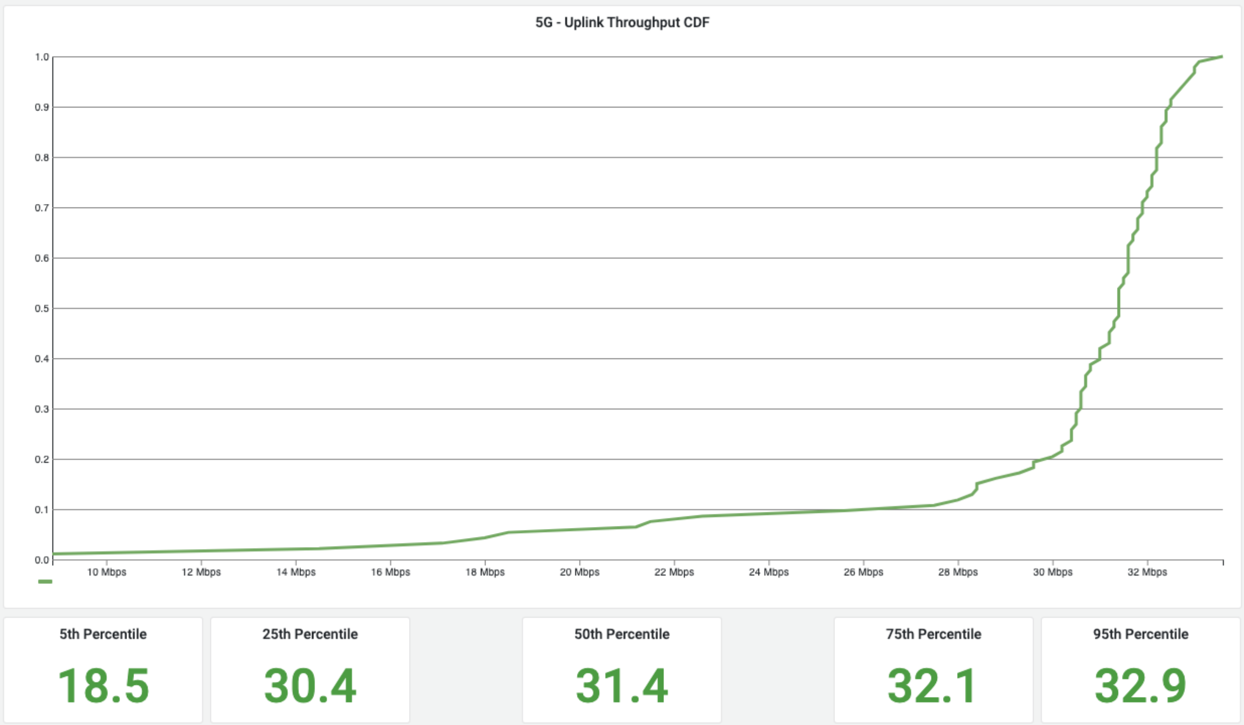
Figure 179: 5G NSA TCP downlink rate (a) graph throughput vs time, (b) CDF graph and percentiles at Kloosterboer Terminal 2

TCP uplink rate

Figure 180 presents the TCP uplink rate using two distinct visualizations: (a) a time-based graph depicting results from a series of consecutive tests, and (b) a CDF graph illustrating the corresponding throughput values while emphasizing specific percentiles of interest. Notably, the average throughput stands at 30.1 Mbps, with the highest recorded value peaking at 33.6 Mbps. It is worth noting that the 50th percentile reflects a throughput of 31.4 Mbps, while the 95th percentile indicates a throughput of 32.9 Mbps.



(a)



(b)

Figure 180: 5G NSA TCP uplink rate (a) graph throughput vs time, (b) CDF graph and percentiles at Kloosterboer Terminal 2

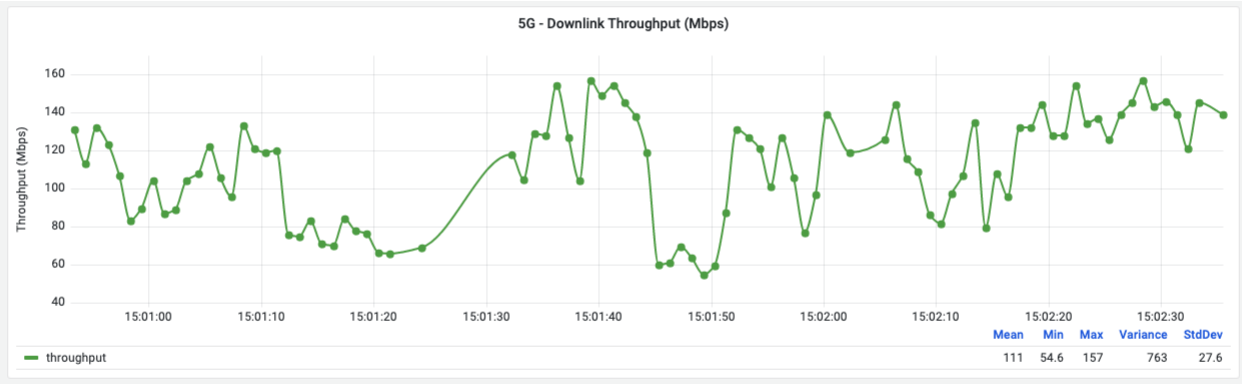
UDP downlink rate

In Figure 181, we present a comprehensive analysis of the UDP downlink rate, using two distinct visual representations to discuss further the collected data. The first visualization, depicted in (a), comprises a time-based graph, which provides a comprehensive overview of the results logged from a series of consecutive tests. The second visualization, illustrated in (b), uses the form of a CDF graph, emphasizing specific percentiles of significance.

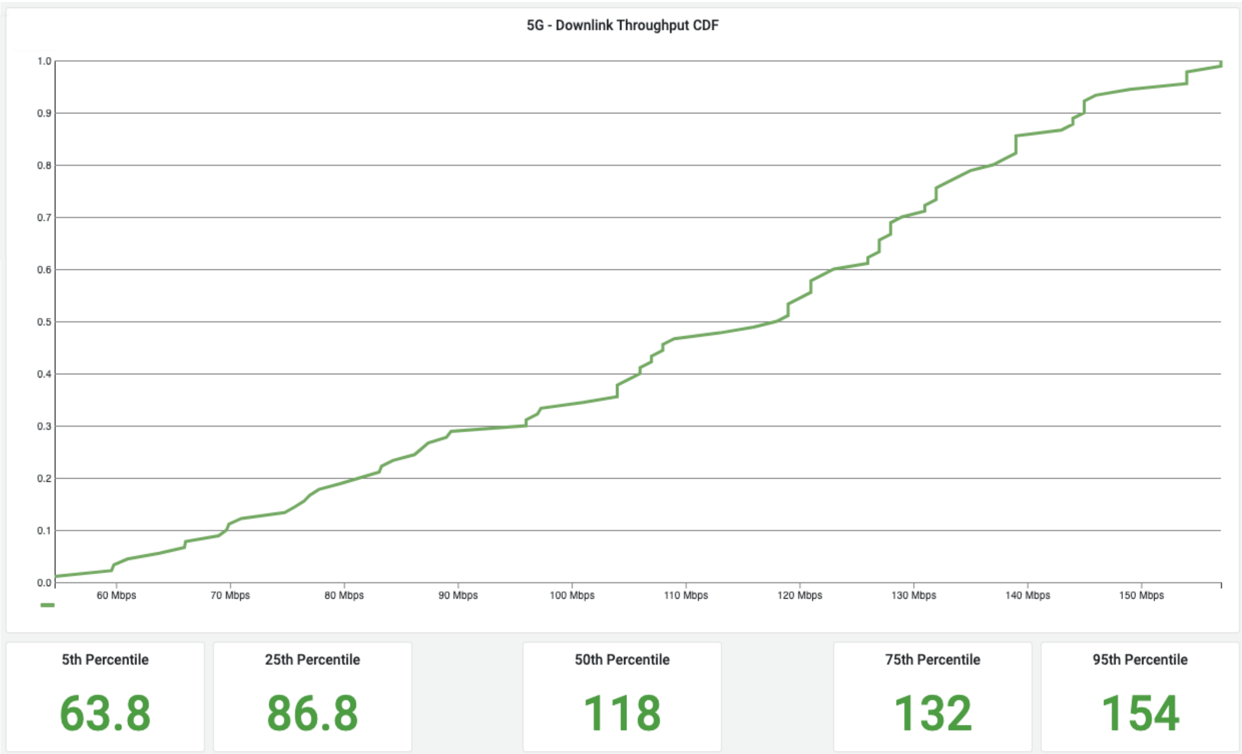
It is worth noting that the mean throughput value, as revealed by our analysis, stands at a robust 111 Mbps. Within this dataset, we have also identified notable extremes, with the highest recorded throughput value peaking at 157 Mbps.

Further data analysis indicates that the 50th percentile corresponds to a throughput rate of 118 Mbps, showcasing the median performance level. Moreover, the 95th percentile stands out with a throughput value of 154 Mbps, which represents the upper tier of performance in our measurements.

The observed fluctuations in throughput can be attributed to the dynamic and ever-changing environment in which these measurements were conducted. This environment is characterized by the constant movement of trucks and large cranes engaged in the transportation of containers within the terminal. These elements introduce variability into the network conditions, impacting the observed throughput rates and resulting in the diverse range of values captured in our analysis.



(a)



(b)

Figure 181: 5G NSA UDP downlink rate (a) graph throughput vs time, (b) CDF graph and percentiles at Kloosterboer Terminal 2

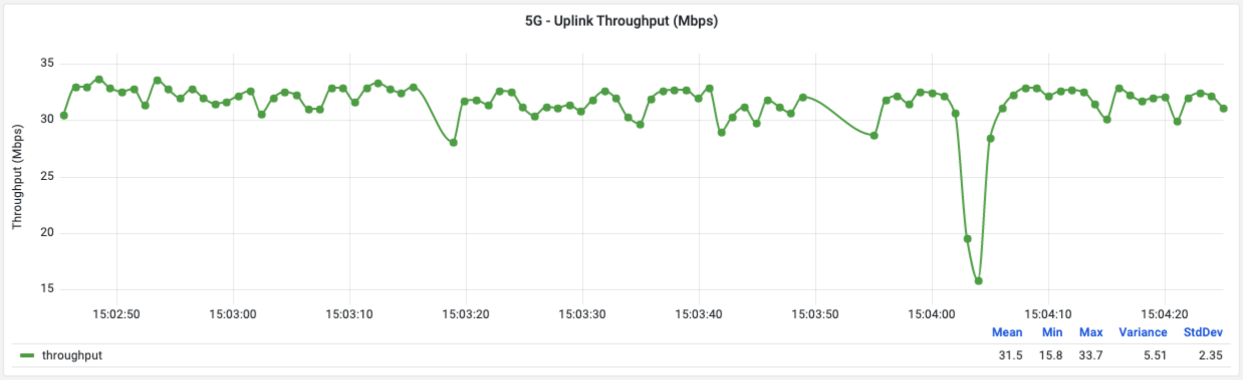
UDP uplink rate

Figure 182 provides an analysis of the collected TCP uplink rate data for the tests performed at Kloosterboer Terminal 2. Similar to the downlink analysis, we use two different ways to illustrate the data. Firstly, in figure (a), the graph shows how the throughput varies over time and over the whole series of tests. Secondly, in figure (b) the CDF graph of the same data is presented, highlighting certain important percentiles.

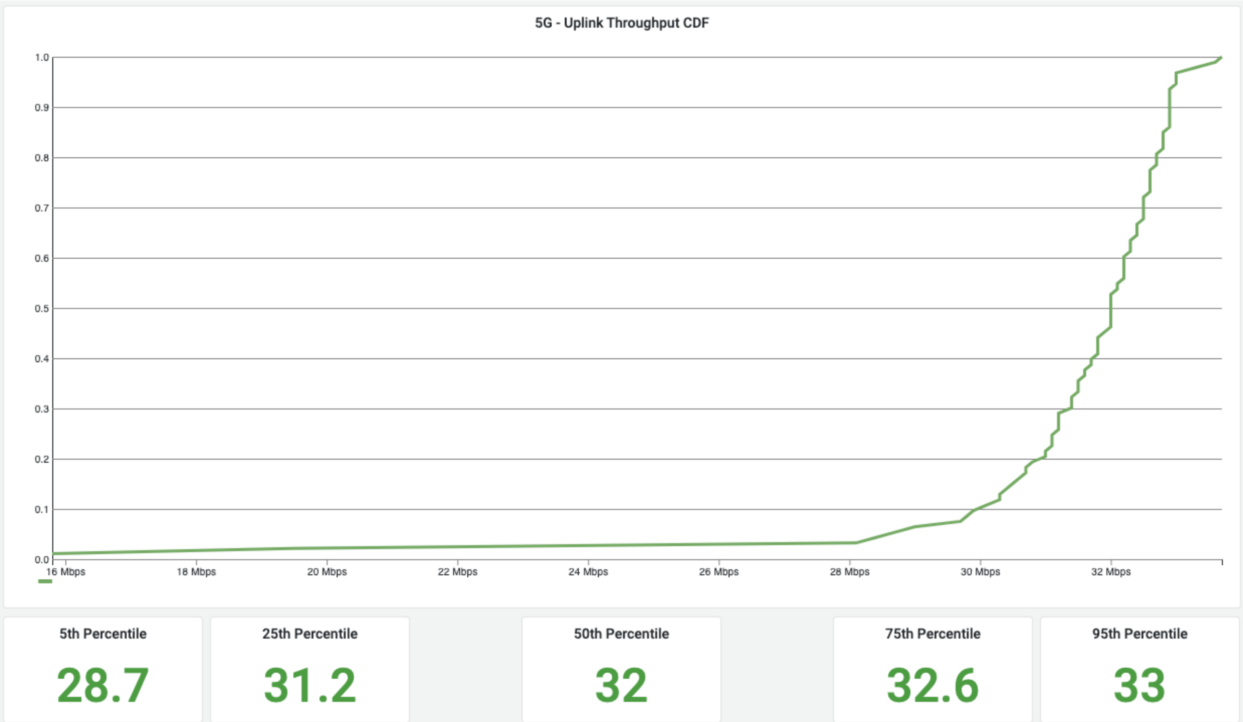
On average, the uplink throughput is 31.5 Mbps, while the maximum and minimum values are recorded to 33.7 Mbps and 15.8 Mbps respectively. However, this minimum value may be considered as an outlier as also shown by the percentiles in figure (b). As it can be observed, the 50th percentile is 32 Mbps, while the 5th percentile is 28.7 Mbps and the 95th percentile is 33 Mbps.

If we look at the middle point of all the speeds, it's around 115 Mbps, which is like the average.

It is worth to mention that the overall throughput performance at Kloosterboer Terminal 2 satisfies the use case and enabling function requirements as defined in Deliverable 5.1 [3].



(a)



(b)

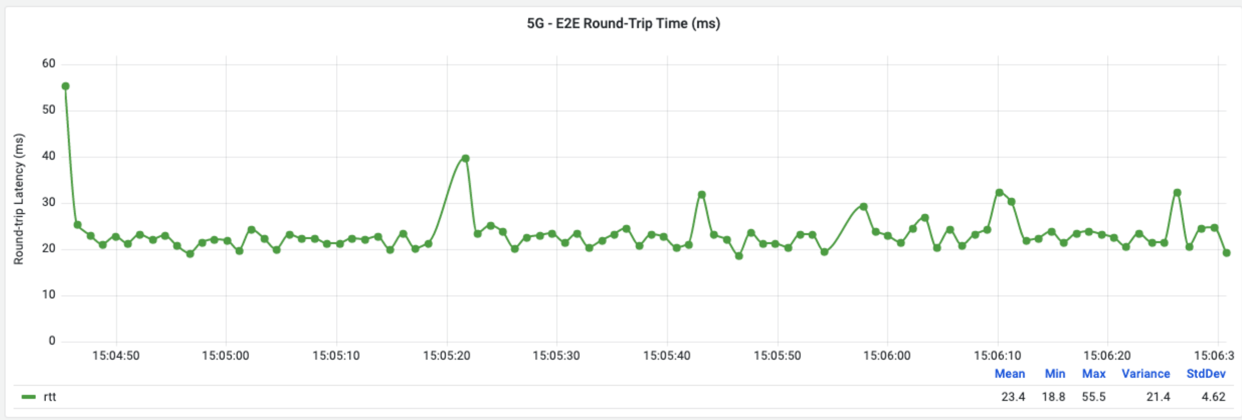
Figure 182: 5G NSA UDP uplink rate (a) graph throughput vs time, (b) CDF graph and percentiles at Kloosterboer Terminal 2

Round-Trip Time

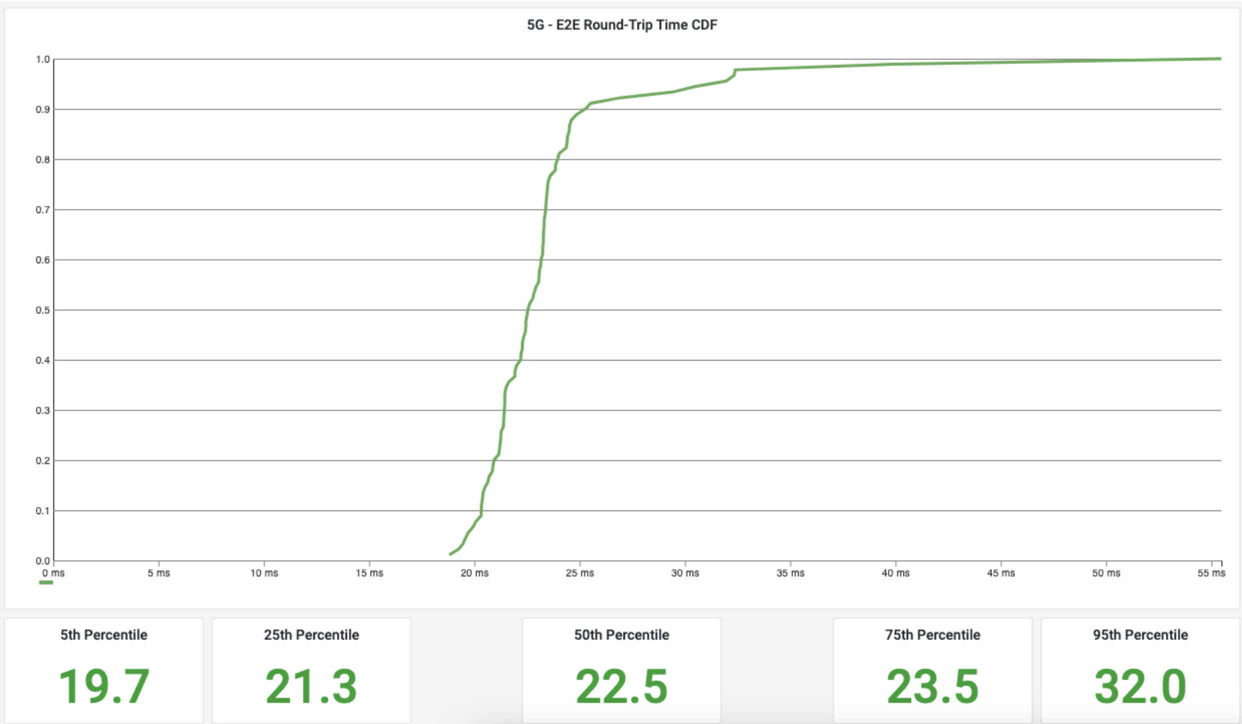
In this chapter, we examine the outcomes of the RTT assessment conducted on KPN's NSA 5G network at Kloosterboer Terminal 2. Figure 183 presents two visualizations: (a) a graph illustrating RTT values over time, and (b) the CDF graph of the RTT latency, emphasizing specific percentiles of interest. The graph in figure (a) reveals that the mean value of the RTT latency is 23.4

milliseconds, indicating the typical time it takes for data to travel round-trip. The highest recorded latency value observed is 55.5 milliseconds.

From figure (b), it can be derived that the 50th percentile, which represents the median RTT latency, stands at 22.5 milliseconds, while the 95th percentile is recorded at 32 milliseconds.



(a)



(b)

Figure 183: 5G NSA RTT (a) graph throughput vs time, (b) CDF graph and percentiles at Kloosterboer Terminal 2

One-way latency, reliability, packet delivery rate

Figure 184 illustrates three KPIs derived from uplink data transmission. Specifically, it presents (a) the CDF graph for one-way latency, (b) a representation of reliability as a percentage over time, and (c) a depiction of the packet delivery rate over time for Kloosterboer Terminal 2. These metrics are assessed in the context of data packets sent by the UE to the gNB at a rate of 10 packets per second (10 Hz).

In the CDF graph for one-way latency, it can be derived that the 50th percentile of the latency is 25 ms and the 95th percentile is 33 ms.

The packet delivery rate graph demonstrates that there is no observable packet loss. It's important to note that this graph represents a specific test but is indicative of the results across all the tests conducted. The reliability graph shows that all the transmitted packets are received within 49 milliseconds, while 95% of the transmitted packets are received within 33 milliseconds.

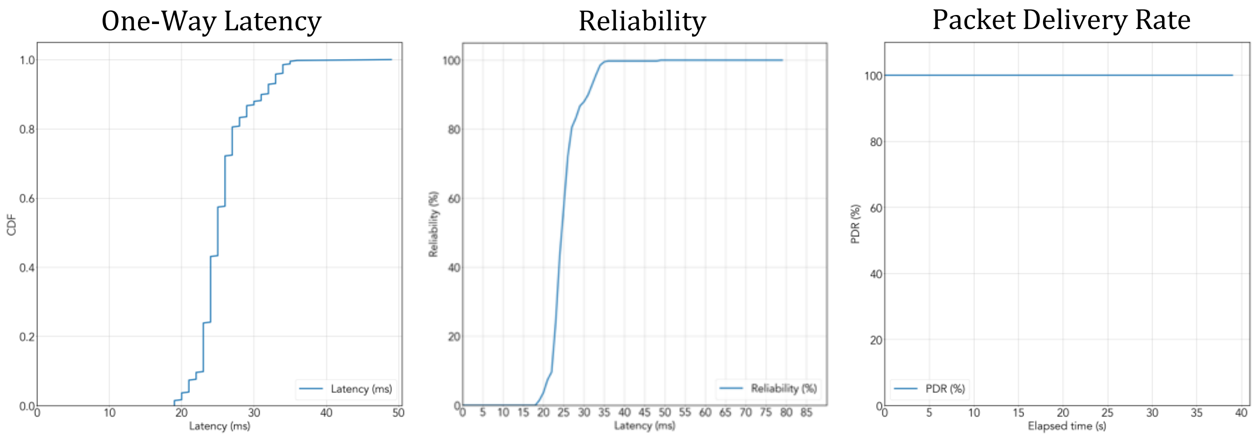


Figure 184: 5G NSA (a) one-way latency, (b) reliability, (c) packet delivery rate at Kloosterboer Terminal 2

Summary

In Table 23**,** a summary is provided of the results from the 5G NSA network evaluation that was conducted at the Kloosterboer terminal 2 in Vlissingen on the road.

On-site 5G network evaluation						
Location	Netherlands – Kloosterboer Terminal 2			Location type	**Stationary - car**	
Network operator	KPN			Network type	5G NSA	
Network slice config	eMBB - no background traffic			UE type	Quectel RM502Q	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-98	-98	-97	-97	-96	-97
TCP DL (Mbps)	12.1	59.6	115	160	172	113
TCP UL (Mbps)	8.86	18.5	31.4	32.9	33.6	30.1
UDP DL (Mbps)	54.6	63.8	118	154	157	111
UDP UL (Mbps)	15.8	28.7	32	33	33.7	31.5
RTT (ms)	18.8	19.7	22.5	32.0	55.5	23.4

Table 23: Summary of 5G NSA network performance evaluation at the Kloosterboer terminal 2

6.3.3 5G NSA – MSP Onions Site

At the MSP Onions site, located on the map in Figure 185, an evaluation of the 5G KPN NSA network was performed to measure the predefined KPIs. For these measurements the Quectel RM502Q modem was used at the UE side. The tests were conducted in a stationary way at the entrance of the MSP Onions terminal near the truck docking gates (see Figure 186).

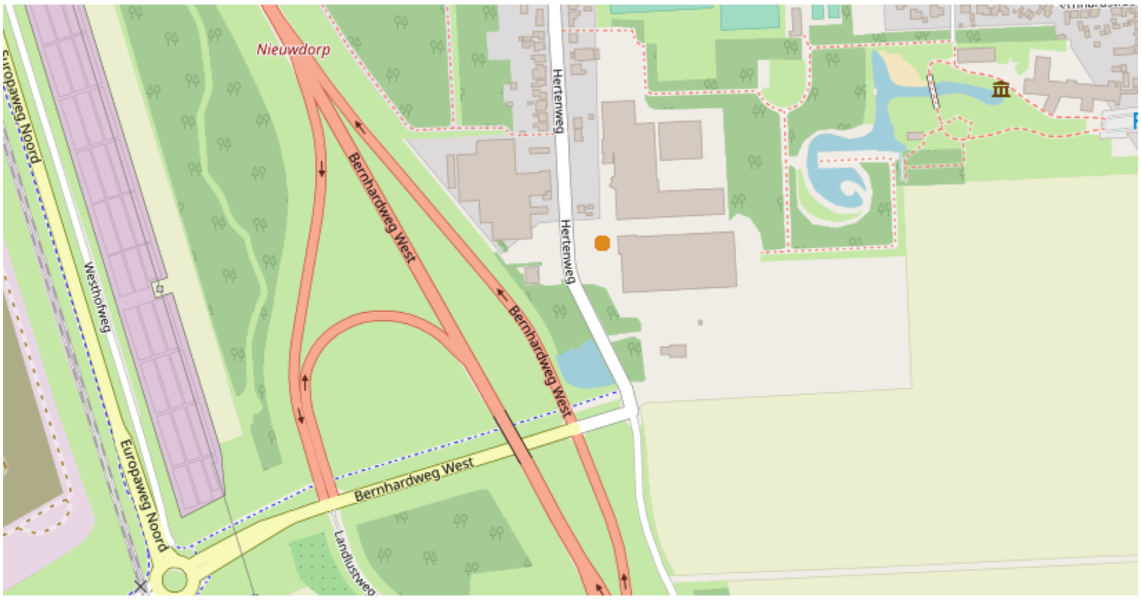
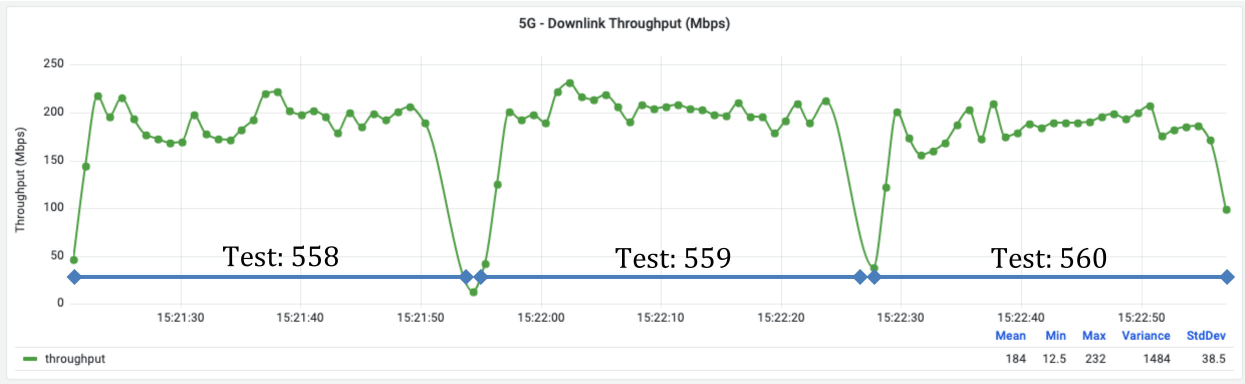


Figure 185: MSP Onions test location

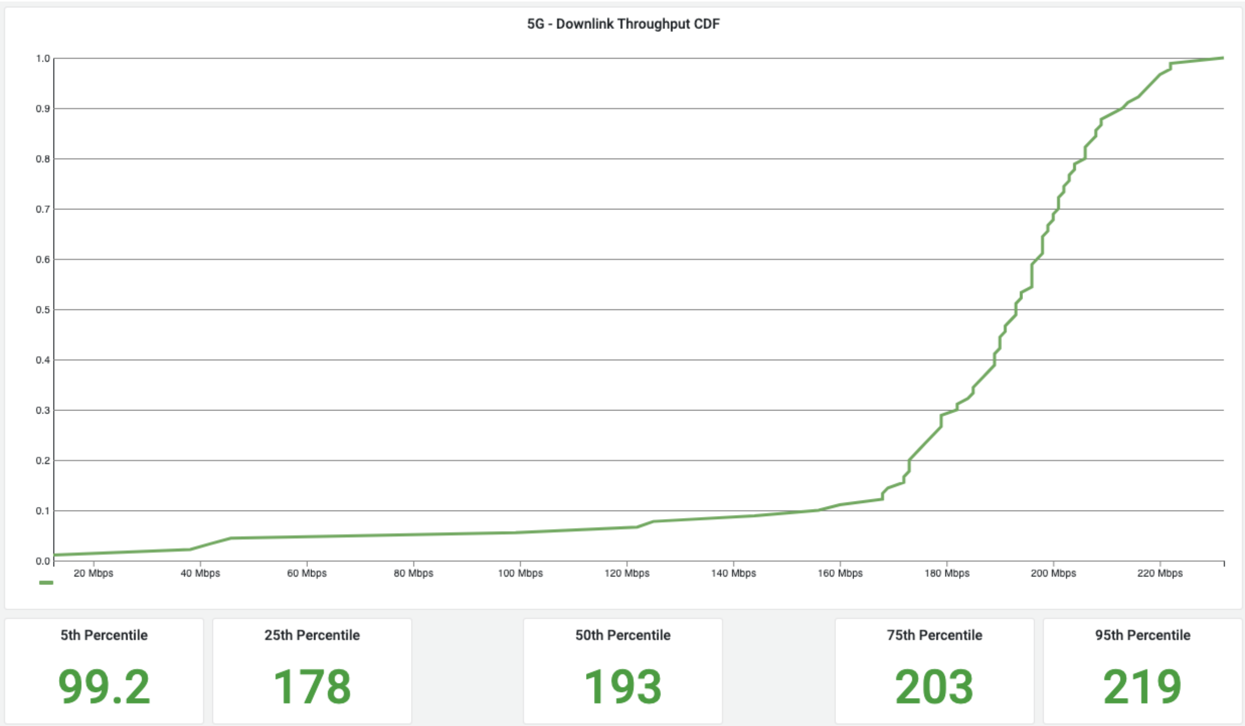
Figure 186: Picture of the IMEC BMW test car at MSP Onions

TCP downlink rate

Figure 187 (a) presents the TCP downlink rate on a graph in comparison to time for a series of consecutive tests. As it can be observed, the mean throughput value is 184 Mbps, while the minimum observed value is 12.5 Mbps, which is due to the TCP slow start at the beginning of the test. The maximum recorded value is 232 Mbps. Figure 187 (b) depicts the CDF graph of the TCP downlink rate. The 50th percentile indicates a throughput of 193 Mbps and the 95th percentile indicates a throughput of 219 Mbps.



(a)

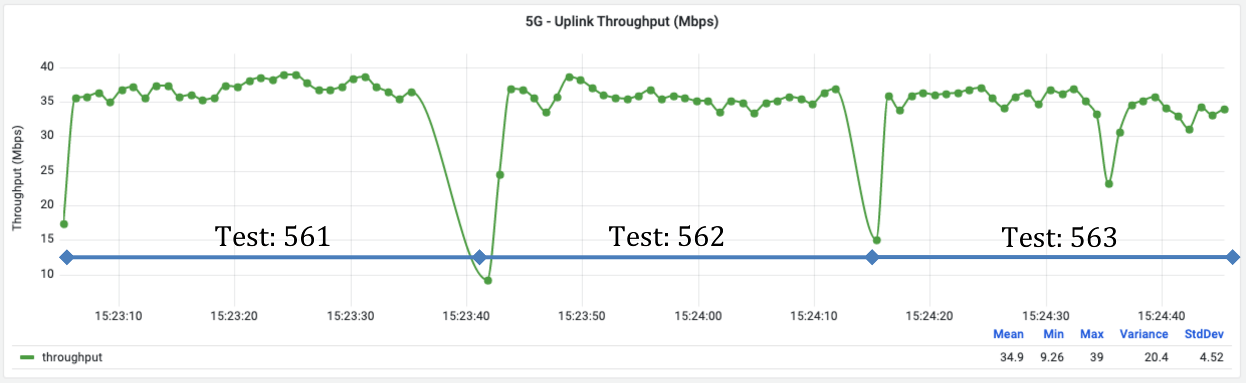


(b)

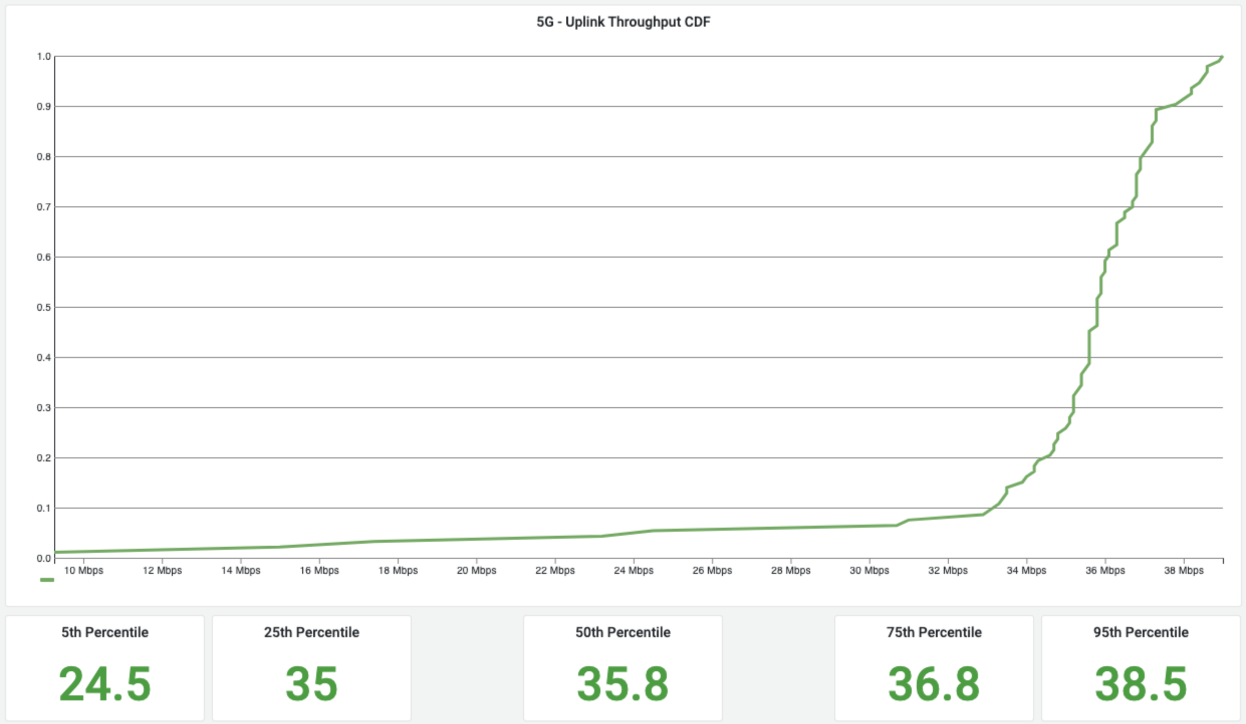
Figure 187: 5G NSA TCP downlink rate (a) graph throughput vs time, (b) CDF graph and percentiles at MSP Onions

TCP uplink rate

Figure 188 presents the TCP uplink rate: (a) a time-based graph depicting results from a series of consecutive tests, and (b) a CDF graph. Notably, the average throughput stands at 34.9 Mbps, with the highest recorded value peaking at 39 Mbps. The 50th percentile reflects a throughput of 35.8 Mbps, while the 95th percentile indicates a throughput of 38.5 Mbps.



(a)



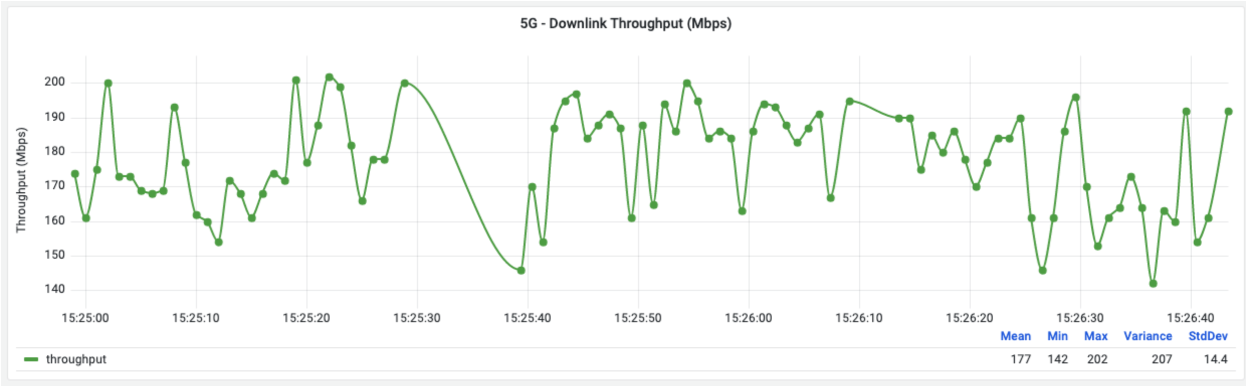
(b)

Figure 188: 5G NSA TCP uplink rate (a) graph throughput vs time, (b) CDF graph and percentiles at MSP Onions

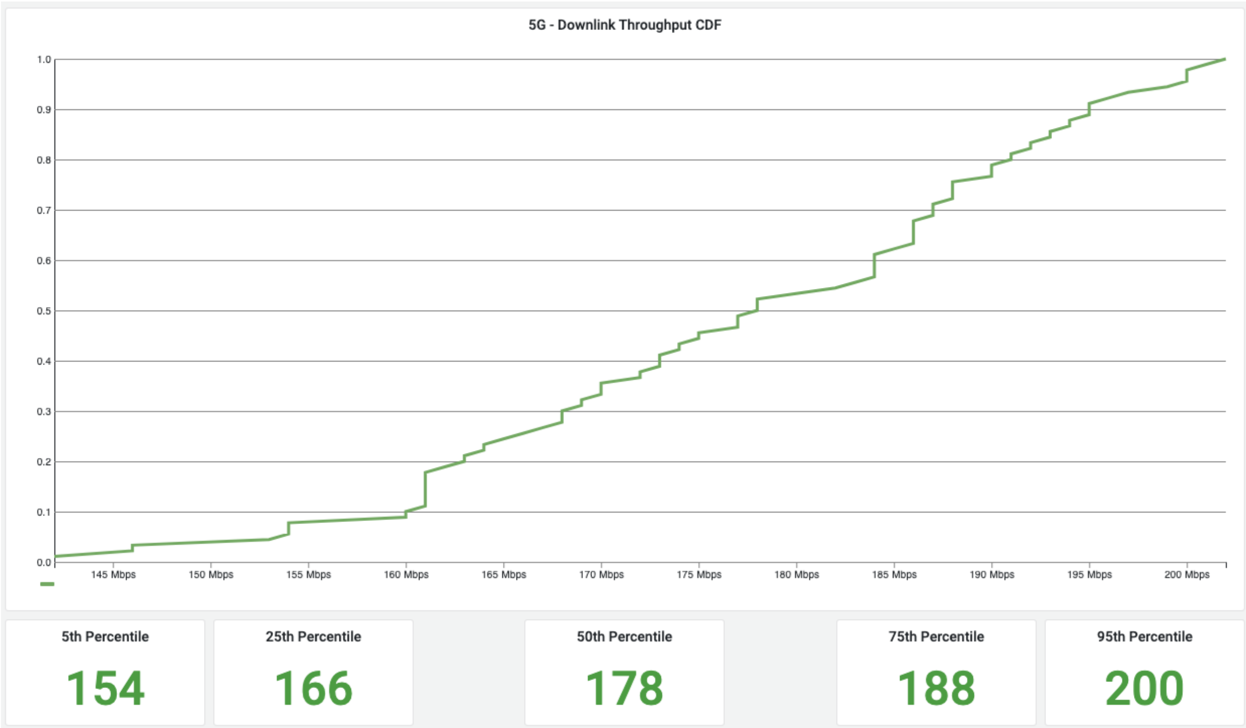
UDP downlink rate

In Figure 189, we present a comprehensive analysis of the UDP downlink rate. In Figure 189(a), it can be noted that the mean throughput value is 177 Mbps, while the max value is 202 Mbps.

Further data analysis shows that the 50th percentile corresponds to a throughput rate of 178 Mbps, which can be observed in Figure 189(b). Moreover, the 95th percentile stands out with a throughput value of 200 Mbps.



(a)

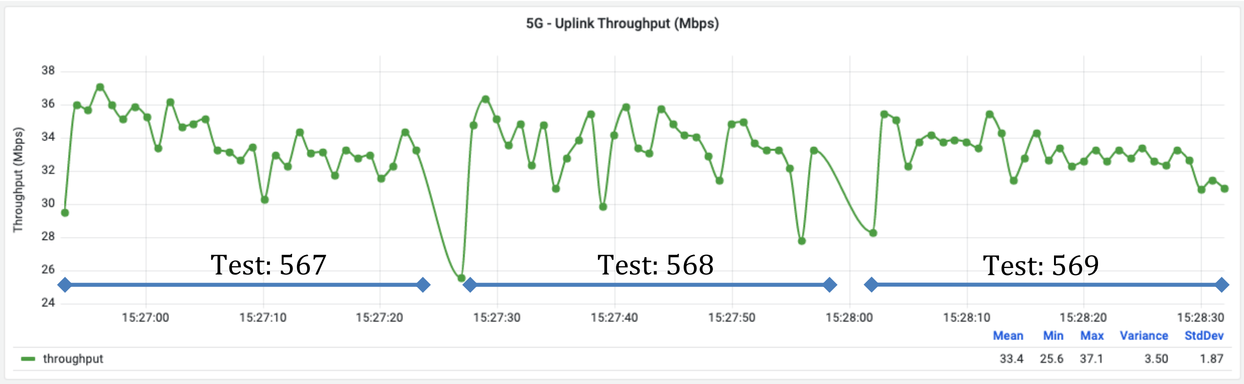


(b)

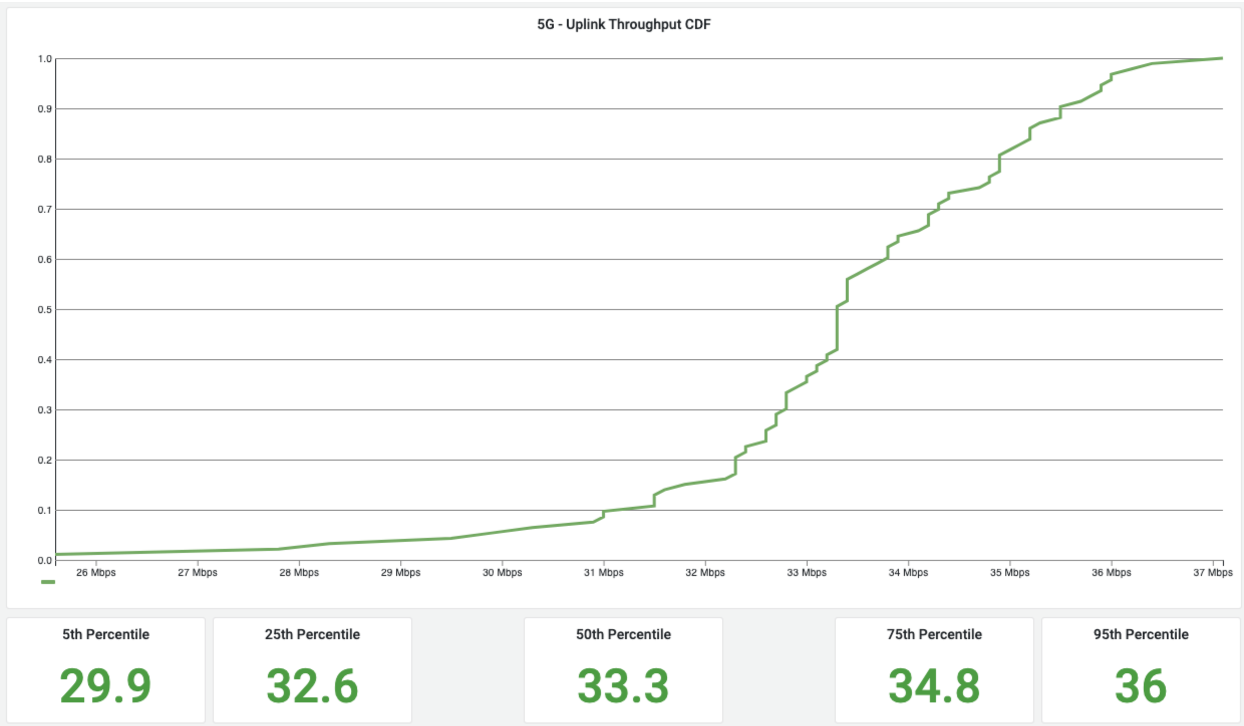
Figure 189: 5G NSA UDP downlink rate (a) graph throughput vs time, (b) CDF graph and percentiles at MSP Onions

UDP uplink rate

Figure 190 provides an analysis of the collected UDP uplink rate data for the tests performed at MSP Onions. In figure (a), the graph shows how the throughput varies over time and over the whole series of tests, indicating that the uplink throughput on average is 33.4 Mbps, while the maximum and minimum values are recorded to 37.1 Mbps and 25.6 Mbps respectively. In figure (b) the CDF graph of the same data is presented, highlighting certain important percentiles. As it can be observed, the 50th percentile is 33.3 Mbps, while the 5th percentile is 29.9 Mbps and the 95th percentile is 36 Mbps.



(a)



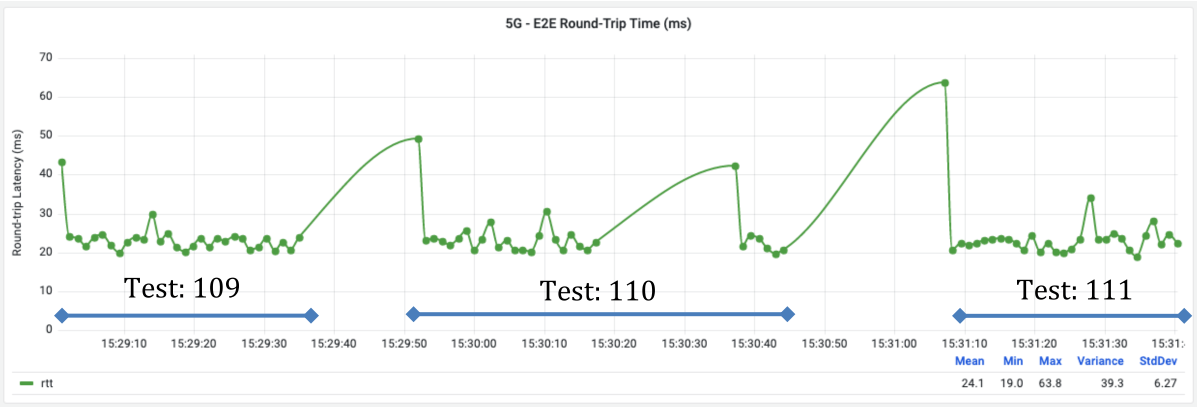
(b)

Figure 190: 5G NSA UDP uplink rate (a) graph throughput vs time, (b) CDF graph and percentiles at MSP Onions

Round-Trip Time

In this section, the outcomes of the RTT measurements are depicted. Figure 191 (a) shows that the mean value of the RTT latency is 24.1 milliseconds, indicating the typical time it takes for data to travel round-trip. The highest recorded latency value observed is 63.8 milliseconds, which seem to reflect outliers at the start of each test, due to scheduling of resource blocks, which is also exposed by the CDF graph.

From figure (b), it can be derived that the 50th percentile, which represents the median RTT latency, stands at 23 milliseconds, while the 95th percentile is recorded at 34.2 milliseconds.



(a)

(b)

Figure 191: 5G NSA RTT (a) graph throughput vs time, (b) CDF graph and percentiles at MSP Onions

One-way latency, reliability, packet delivery rate

Figure 192 illustrates (a) the CDF graph for one-way latency, (b) a representation of reliability as a percentage over time, and (c) a depiction of the packet delivery rate over time for the MSP Onions site. These metrics are assessed in the context of data packets sent by the UE to the gNB at a rate of 10 packets per second (10 Hz).

In the CDF graph for one-way latency (a), it can be derived that the 50th percentile of the latency is 22 ms and the 95th percentile is 30 ms.

The packet delivery rate graph (c) demonstrates that there is no observable packet loss. It's important to note that this graph represents a specific test but is indicative of the results across all the tests conducted. The reliability graph shows that all the transmitted packets are received within 35 milliseconds, while 95% of the transmitted packets are received within 27 milliseconds.

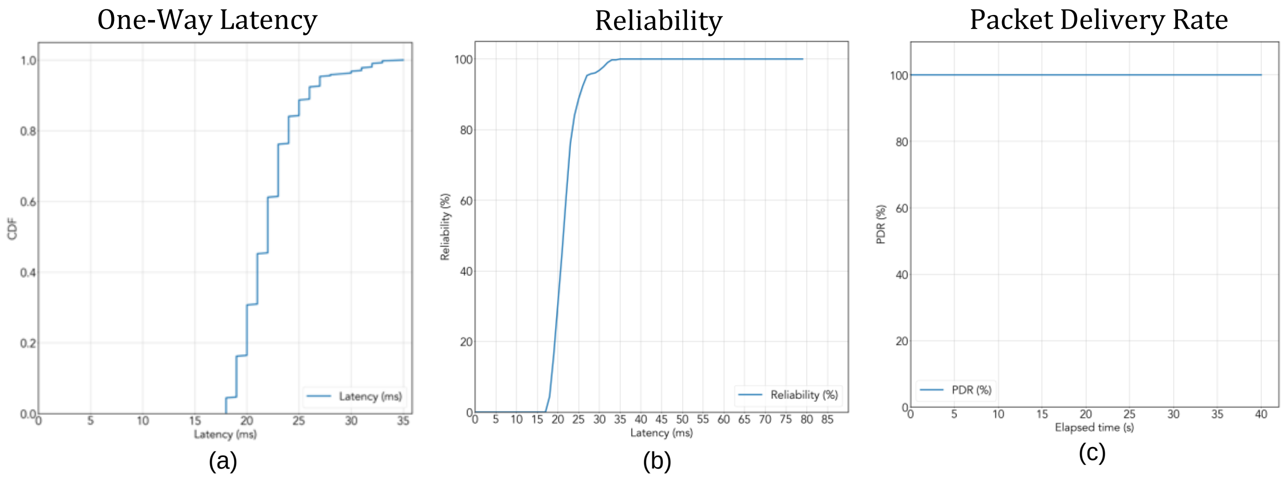


Figure 192: 5G NSA (a) one-way latency, (b) reliability, (c) packet delivery rate at MSP Onions

In Table 24, a summary is provided of the results from the 5G NSA network evaluation that was conducted at the MSP Onion terminal in Vlissingen on the road.

<table>
<tr><td colspan="7">On-site 5G network evaluation</td></tr>
<tr><td>Location</td><td colspan="3">Netherlands – MSP Onions</td><td>Location type</td><td colspan="2">Stationary - car</td></tr>
<tr><td>Network operator</td><td colspan="3">KPN</td><td>Network type</td><td colspan="2">5G NSA</td></tr>
<tr><td>Network slice config</td><td colspan="3">eMBB - no background traffic</td><td>UE type</td><td colspan="2">Quectel RM502Q</td></tr>
<tr><th>KPI</th><th>Min</th><th>5th perc</th><th>Median</th><th>95th perc</th><th>Max</th><th>Average</th></tr>
<tr><td>RSRP (dBm)</td><td>-97</td><td>-97</td><td>-97</td><td>-96</td><td>-96</td><td>-96.6</td></tr>
<tr><td>TCP DL (Mbps)</td><td>12.5</td><td>99.2</td><td>193</td><td>219</td><td>232</td><td>184</td></tr>
<tr><td>TCP UL (Mbps)</td><td>9.26</td><td>24.5</td><td>35.8</td><td>38.5</td><td>39</td><td>34.9</td></tr>
<tr><td>UDP DL (Mbps)</td><td>142</td><td>154</td><td>178</td><td>200</td><td>202</td><td>177</td></tr>
<tr><td>UDP UL (Mbps)</td><td>25.6</td><td>29.9</td><td>33.3</td><td>36</td><td>37.1</td><td>33.4</td></tr>
<tr><td>RTT (ms)</td><td>19.0</td><td>20.1</td><td>23.0</td><td>34.2</td><td>63.8</td><td>24.1</td></tr>
</table>

Table 24: Summary of 5G NSA network performance evaluation at the MSP Onion terminal

6.3.4 5G NSA – Milk Run between Central Gate and Verbrugge Terminals

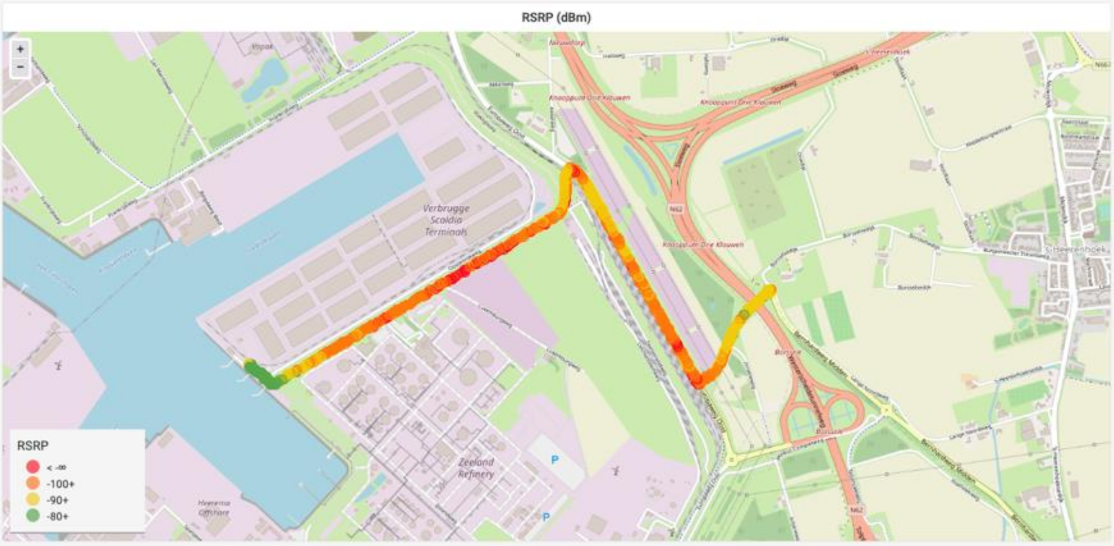
This section discusses the evaluation of the selected KPIs for all the tests performed on the trajectory (milk run) ranges between the Verbrugge Terminals and the Central Gate. Each KPI has been evaluated for multiple runs in order to ensure that the collected data have enough statistical significance. For all the tests performed across the milk run trajectory, the Quectel RM502Q module was used at the UE side.

Modem statistics

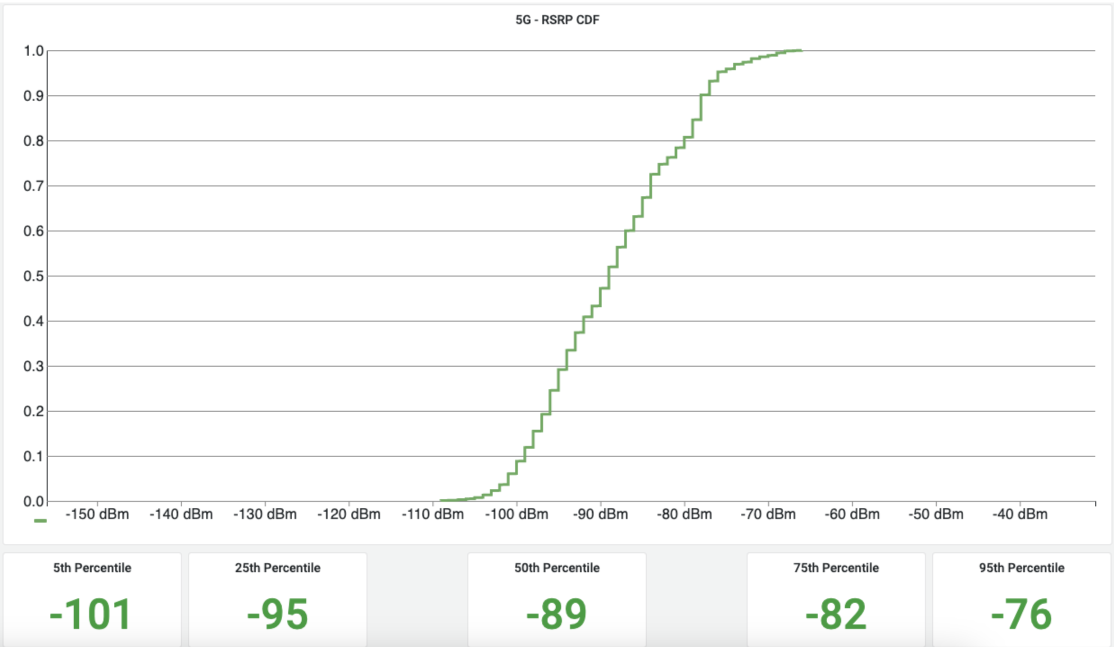
Figure 193 provides a detailed visual representation of about the conducted tests regarding RSRP values across the test trajectory. This figure encompasses two components: (a) a heatmap displaying the distribution of RSRP values along the entire test route, and (b) the CDF graph of the collected RSRP values, highlighting specific percentiles of significant interest.

Upon careful examination of the data, we observe that the 50th percentile, representing the median RSRP value, registers at -89 dBm. Meanwhile, the 5th percentile, signifying the lower end of RSRP values, is measured at -101 dBm, and the -95th percentile, representing the higher end, stands at -76 dBm.

Notably, we observe higher RSRP values concentrated in area closer to Verbugger Terminals gate (western part of the trajectory), as well as closer to the central gate (eastern part of the trajectory) and in the middle of the trajectory, indicated by green and yellow values on the heatmap. This phenomenon is attributed to consecutive handovers among different base stations deployed along the trajectory as part of the production 5G NSA network of KPN at the considered area. Overall, the recorded RSRP values indicate that the signal quality is very good (higher than -100 dBm) at biggest part of the trajectory.



(a)



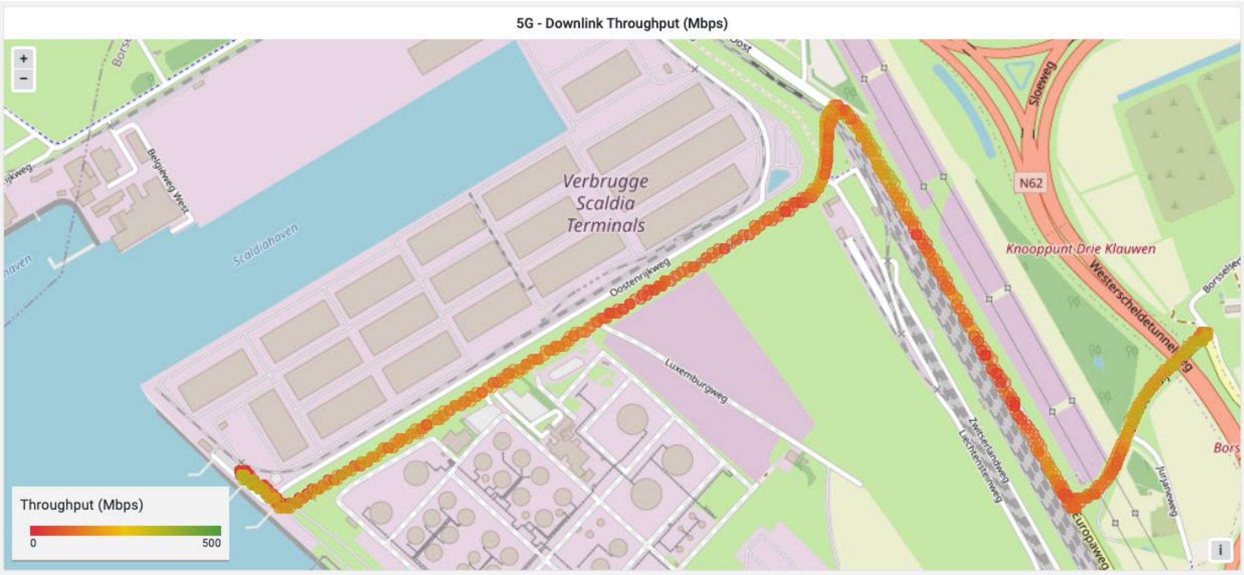
(b)

Figure 193: 5G NSA (a) RSRP values on map, (b) CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

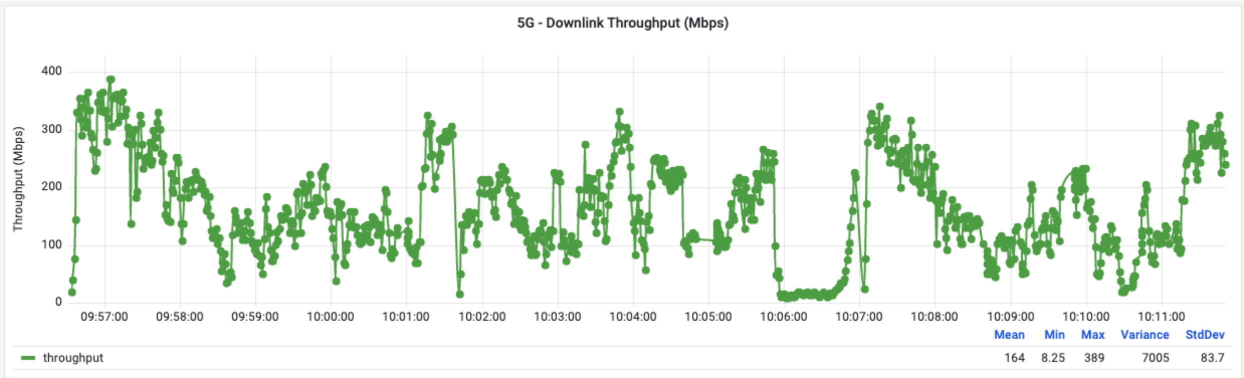
TCP downlink rate

Figure 194 offers a comprehensive depiction of the TCP downlink rate through a combination of (a) a heatmap and (b) a graphical representation that spans over time, effectively summarizing the outcomes of a series of consecutive tests.

Upon examination of the data, it becomes evident that the mean throughput value registers at a notable 164 Mbps, reflecting the average rate of data transfer. On the lower end of the spectrum, the minimum observed throughput value is measured at 8.25 Mbps. Such values were recorded in parts of the trajectory where the signal quality was also low, indicating that at these points are at closer to the cell edge. In contrast, the maximum recorded throughput value peaks impressively at 389 Mbps, underscoring the potential for high-speed data transmission in specific areas.



(a)



(b)

Figure 194: 5G NSA TCP downlink rate (a) on map, (b) graph throughput vs time at the milk run between the central gate and the Verbrugge Terminals

For a more detailed understanding, Figure 195 presents the CDF graph, offering an encompassing view of TCP downlink rate values derived from all the conducted tests. Notably, the 50th percentile, representing the median throughput value, stands at 149 Mbps, indicating the typical performance level. Furthermore, the 95th percentile, reflecting a higher level of performance, is calculated at 311 Mbps, showcasing the upper echelon of throughput achieved in our assessments.

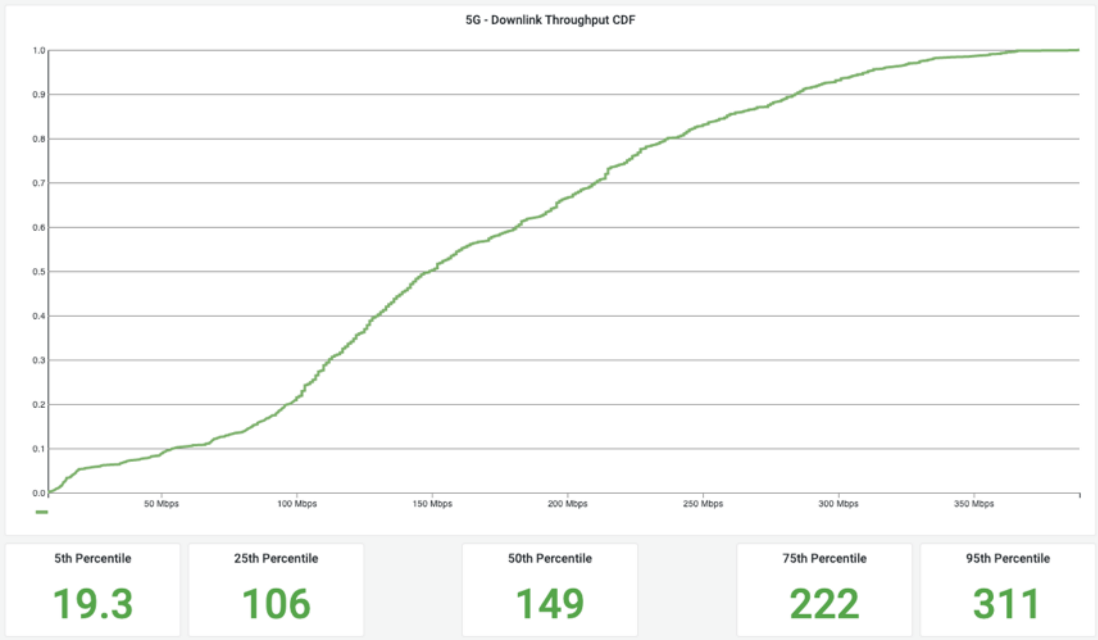


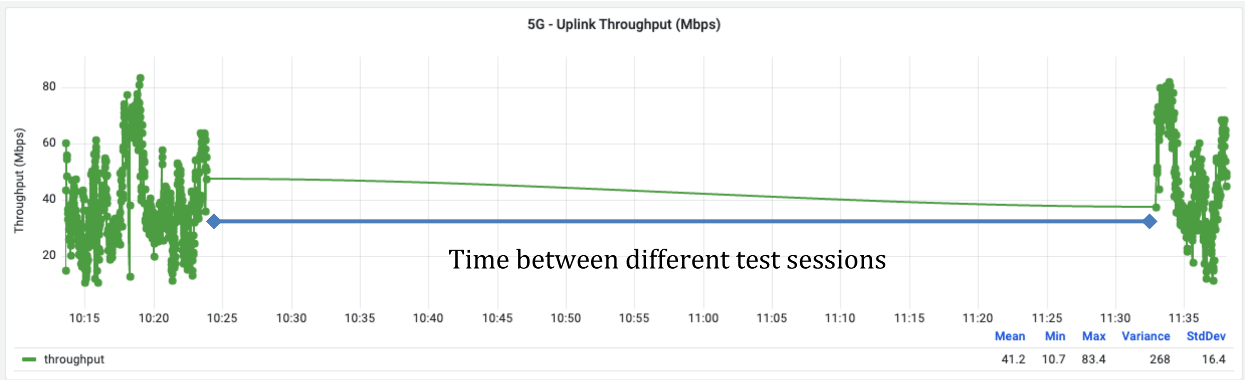
Figure 195: 5G NSA TCP downlink rate - CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

TCP uplink rate

Subsequently, a thorough assessment of the TCP uplink rate was conducted, encompassing a series of multiple tests, all conducted along the same trajectory. Following a similar methodology as employed in the downlink scenario, Figure 196 provides a comprehensive view of this evaluation, showcasing (a) a heatmap displaying the throughput values observed across the entire route, and (b) a time-based graphical representation of the throughput values throughout the tests.

Incorporating the statistics presented below the graph, we see that the mean TCP uplink throughput averages at 41.2 Mbps, offering an indication of the typical rate at which data is transmitted in the uplink direction. At the lower end of the spectrum, we identify the minimum throughput value, which registers at 10.7 Mbps, highlighting the challenges encountered in certain segments of the trajectory as they are located close to the cell edge. Conversely, at the upper limit, the maximum recorded throughput value impressively reaches 83.4 Mbps, highlighting the potential for higher-speed data transmission under specific conditions (e.g. good cell coverage).

(a)



(b)

Figure 196: 5G NSA TCP uplink rate (a) on map, (b) graph throughput vs time at the milk run between the central gate and the Verbrugge Terminals

To gain further insights, Figure 197 shows the CDF graph, aggregating the uplink TCP throughput values derived from all the conducted tests. Notably, the 95th percentile, signifying a higher level of performance, is situated at 72.7 Mbps. Moreover, the 50th percentile, representing the median throughput value, stands at 36.9 Mbps, serving as a reference point for the typical performance level in the uplink direction.

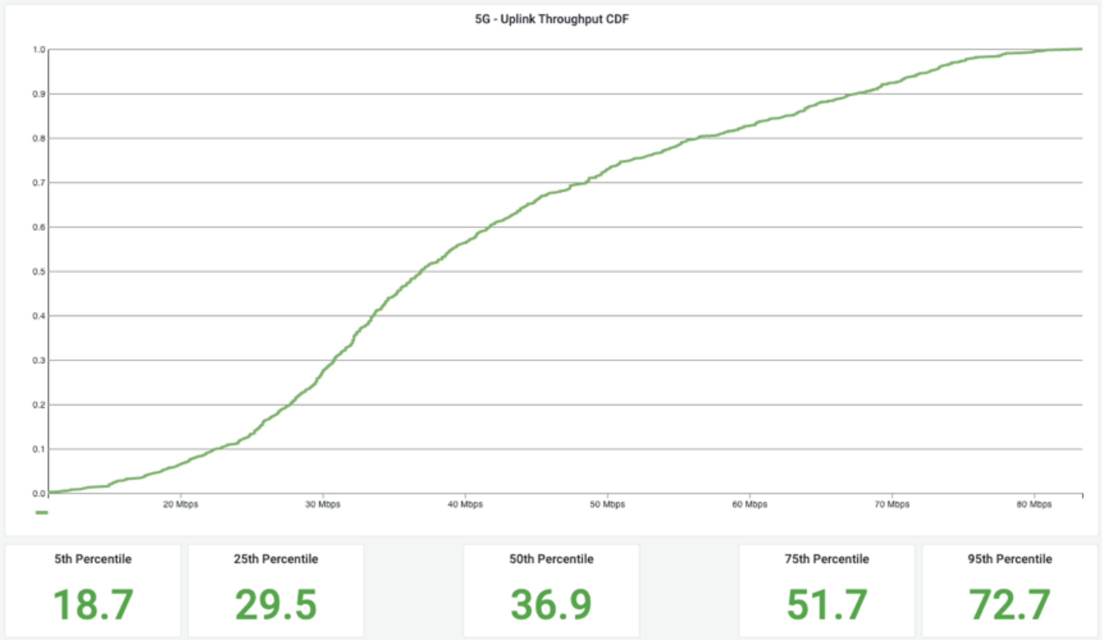
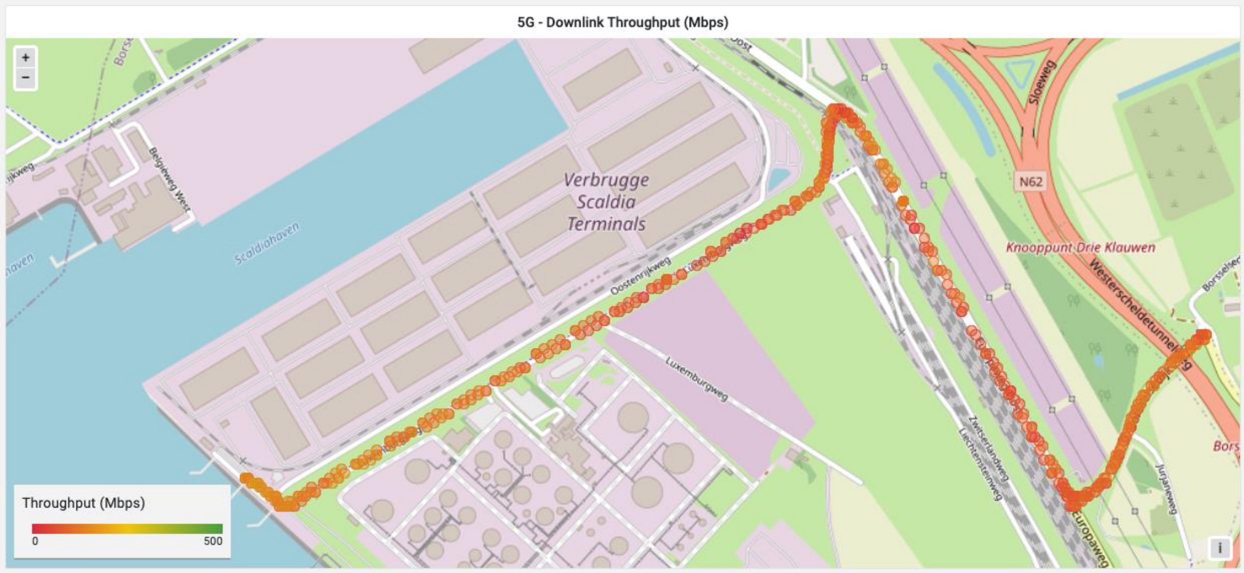


Figure 197: 5G NSA TCP uplink rate - CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

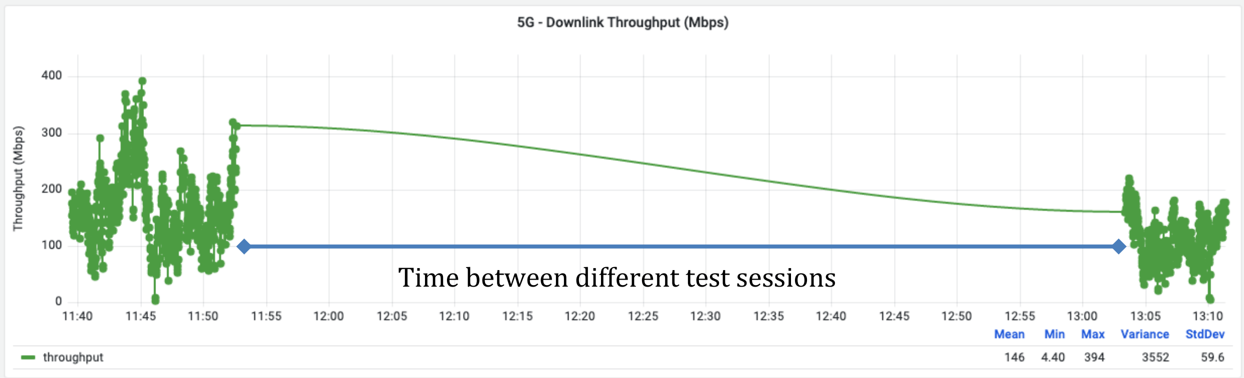
UDP downlink rate

Similar to the TCP case, Figure 198 provides an extensive representation of the UDP downlink rate, using a combination of two graphical components: (a) a heatmap and (b) a time-based graph. These visuals effectively encapsulate the outcomes of a series of consecutive tests, enabling a comprehensive understanding of the data.

From the statistics presented at the bottom of figure (b) it can be seen that the mean throughput value of UDP downlink rate reaches 146 Mbps. However, we observe the minimum recorded throughput value, which reaches a modest 4.40 Mbps at the same parts of the trajectory as for the TCP case. On the contrary, the maximum recorded throughput value reaches an impressive peak of 394 Mbps, underscoring the potential for fast data transmission in specific geographical areas with good signal strength conditions.



(a)



(b)

Figure 198: 5G NSA UDP downlink rate (a) on map, (b) graph throughput vs time at the milk run between the central gate and the Verbrugge Terminals

For a different perspective, Figure 199 presents the CDF graph, providing a comprehensive overview of UDP downlink rate values derived from the entirety data of our conducted tests on the specific trajectory. Specifically, the 50th percentile, which signifies the median throughput value, is situated at 140 Mbps, serving as an indicator of typical performance. Furthermore, the 95th percentile, reflecting a higher level of performance, is calculated at 254 Mbps, showcasing the upper tier of the observed throughput levels.

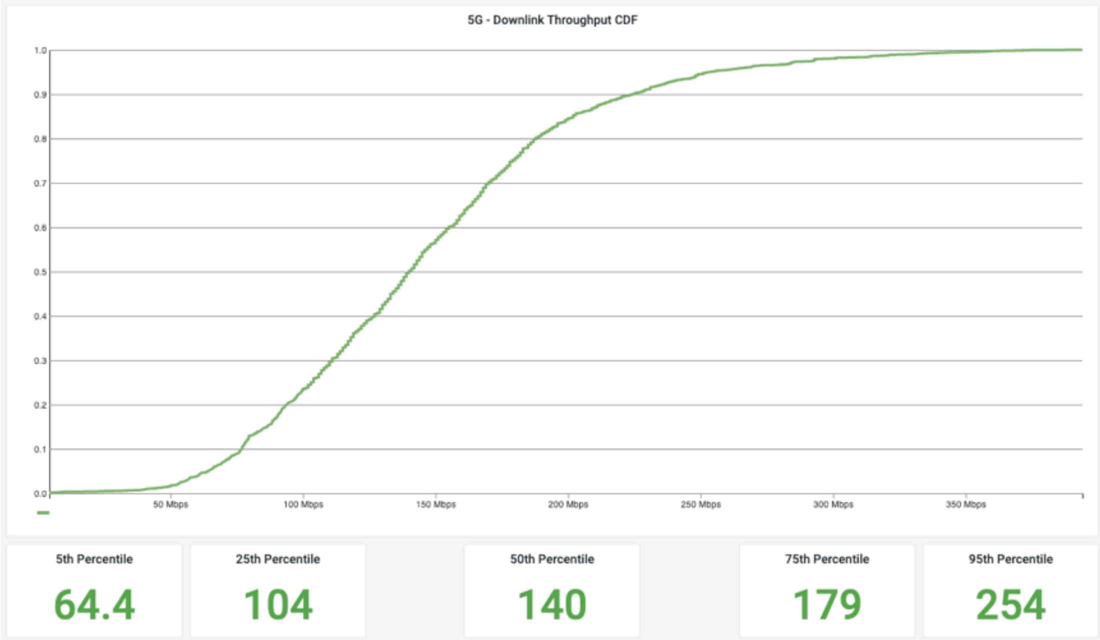


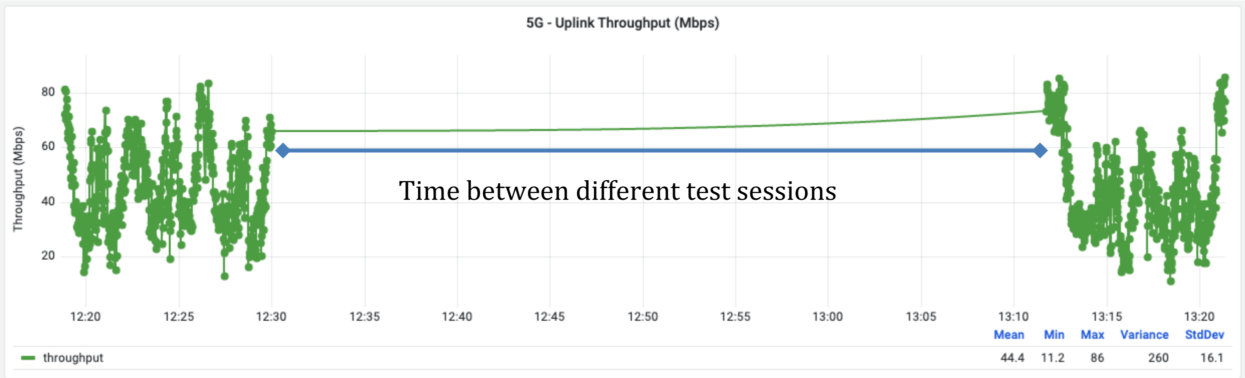
Figure 199: 5G NSA UDP downlink rate - CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

UDP uplink rate

This subsection presents a comprehensive evaluation of the UDP uplink rate, conducting a series of multiple tests along the same trajectory in order to ensure again the statistical relevance of the collected data. In Figure 200, we present the analyzed data in two representative graphs, consisting of (a) a heatmap that visually represents the throughput values observed across the entire route, and (b) a time-based graphical illustration showcasing how throughput values evolved throughout the course of the tests.

From the statistical data provided beneath the graph, we see that the mean UDP uplink throughput is 44.4 Mbps. At the lower end of the spectrum, we identify the minimum throughput value, which registers at a modest 11.2 Mbps, drawing attention to the challenges faced in segments of the trajectory, particularly those situated in close proximity to the cell edge. Conversely, at the upper limit, the maximum recorded throughput value impressively reaches 86 Mbps, highlighting the potential for higher-speed data transmission under good cell coverage conditions.

(a)



(b)

Figure 200: 5G NSA UDP uplink rate (a) on map, (b) graph throughput vs time at the milk run between the central gate and the Verbrugge Terminals

Figure 201 presents the CDF graph of the UDP uplink throughput values derived from all the conducted tests. Specifically, the 95th percentile, denoting a higher level of performance, is positioned at 75.2 Mbps, offering insight into the upper tier of throughput levels observed throughout the trajectory. Furthermore, the 50th percentile, representing the median throughput value, stands at 40.7 Mbps. As it can be observed, both UDP and TCP traffic has a similar performance at this specific trajectory and their performance mainly depends on cell coverage conditions.

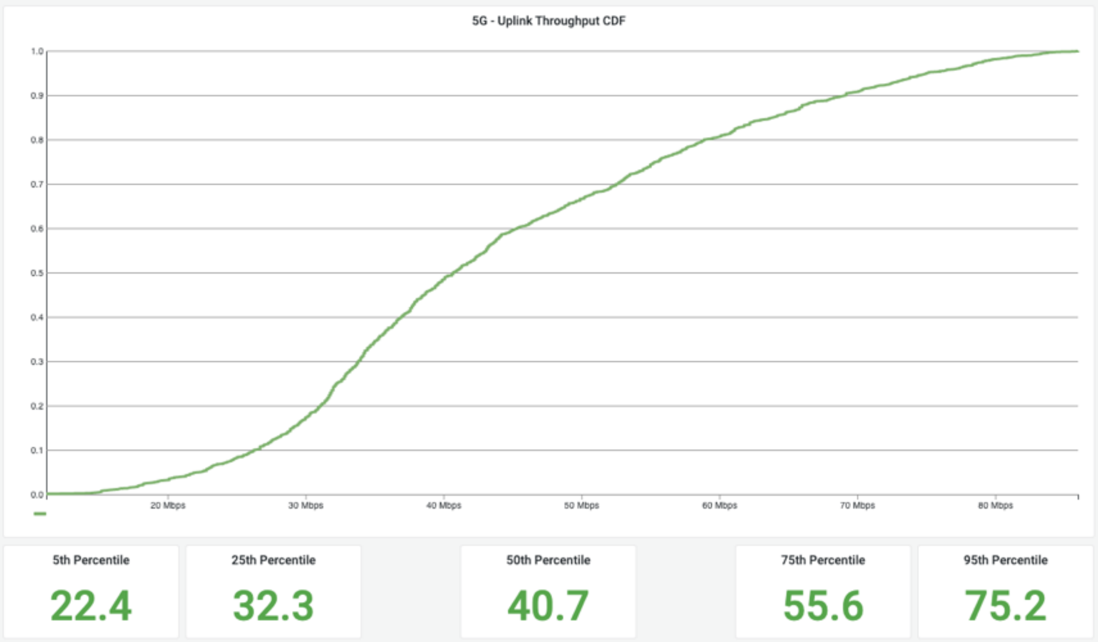
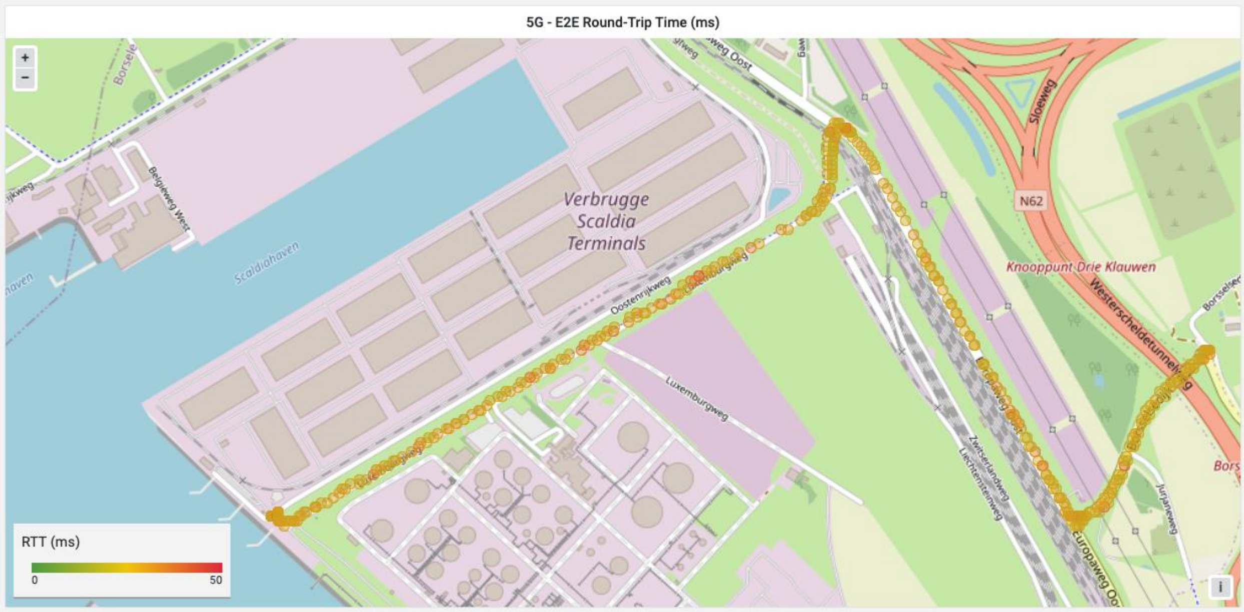


Figure 201: 5G NSA UDP uplink rate - CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

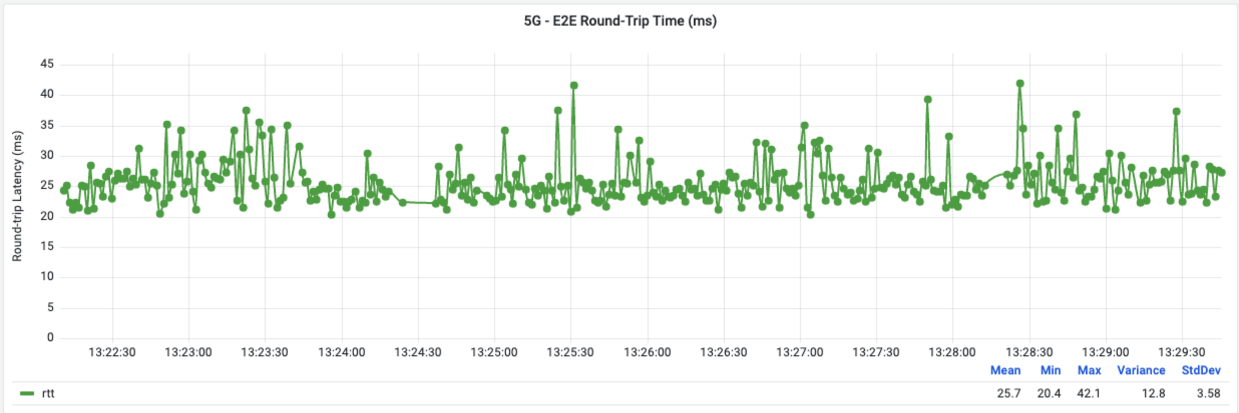
Round-Trip Time

This subsection provides an overview of the outcomes derived from the RTT evaluation conducted at the considered trajectory. Figure 202 presents (a) a heatmap showcasing the RTT values observed during a series of executed tests, and (b) a time-based presentation of the corresponding RTT values.

Examining the graph, we observe that the average RTT latency stands at a 25.7 milliseconds, symbolizing the typical time required for data to travel from source to destination and back. At the upper limit of our observations, we identify the maximum recorded latency value, which peaks at 42.1 milliseconds.



(a)



(b)

Figure 202: 5G NSA RTT (a) on map, (b) graph throughput vs time at the milk run between the central gate and the Verbrugge Terminals

In Figure 203, we present the CDF graph, which further enriches our understanding of RTT latency, also presenting percentiles of particular interest. Notably, the 50th percentile is measured at 24.9 milliseconds. Additionally, the 95th percentile, denoting a more elevated tier of latency performance, stands at 34.3 milliseconds, indicating the threshold for latency experienced in a more extensive proportion of our measurements.

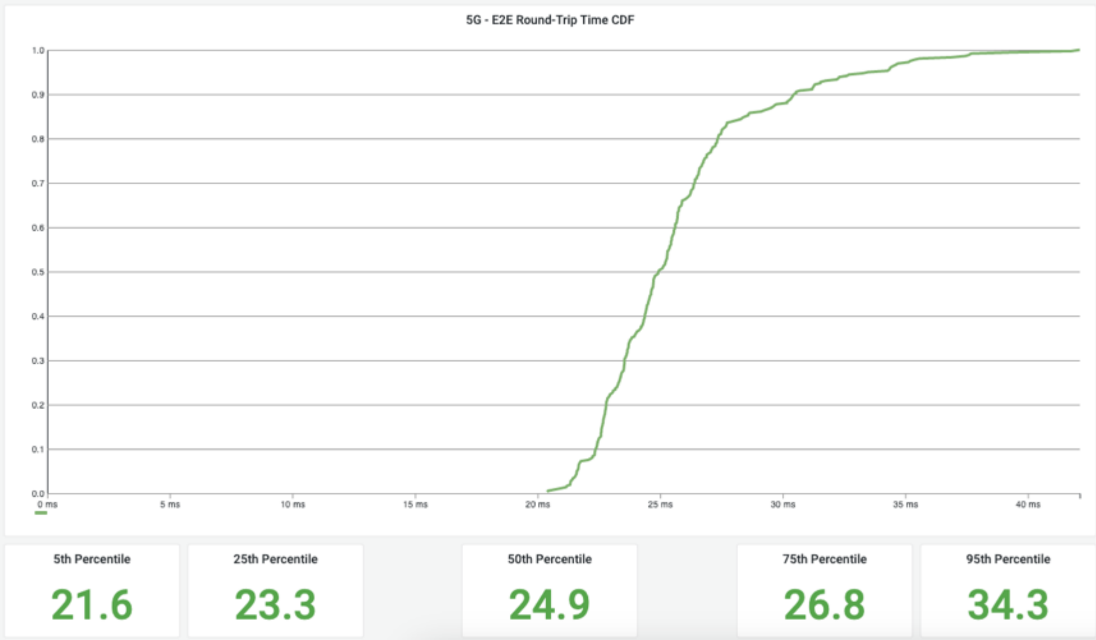


Figure 203: 5G NSA RTT - CDF graph and percentiles at the milk run between the central gate and the Verbrugge Terminals

One-way latency, reliability, packet delivery rate

Figure 204 provides a visual representation of the analysis of key performance metrics at the milk run between the Verbrugge Terminals and the Central Gate, considering data packet transmission from the UE to the gNB at a steady rate of 10 packets per second (10 Hz). This illustration encompasses (a) the CDF graph depicting one-way latency, (b) the reliability over time as a percentage, and (c) a graphical representation of the packet delivery rate over time.

From the CDF graph for one-way latency (a), it can be noticed that the 50th percentile of latency stands at 23 milliseconds, signifying the median latency experienced in our measurements. Furthermore, the 95th percentile records a latency of 33 milliseconds, while the 99th percentile stands at 36 milliseconds.

The packet delivery rate graph (c) reveals that no packet loss was observed. It is important to emphasize that while this graph refers to a specific test, it serves as a reliable representation of the overall results gathered across all conducted tests. Additionally, the reliability graph (b) illustrates that all transmitted packets were successfully received within 80 milliseconds, with an impressive 99% of the transmitted packets being received within 30 milliseconds.

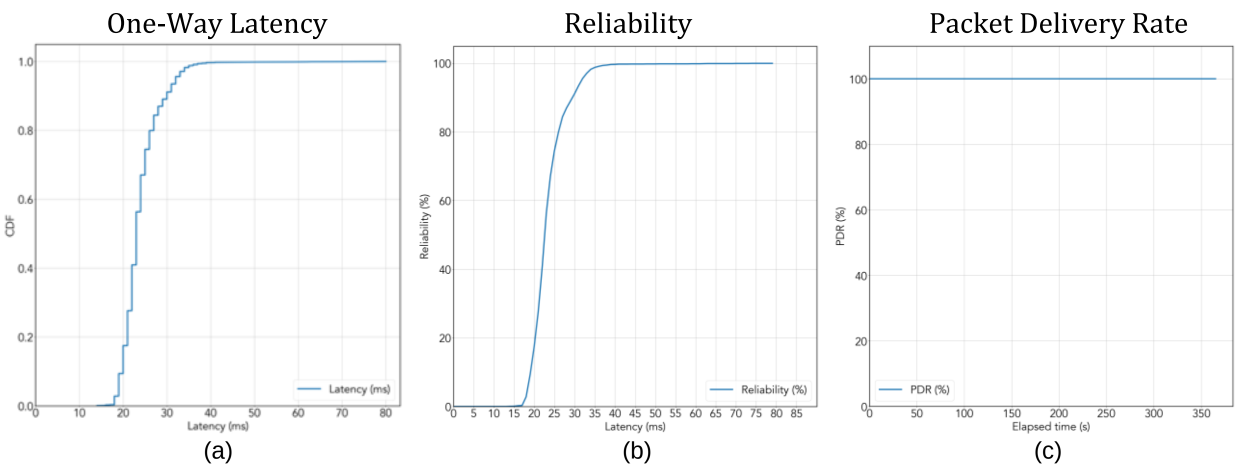


Figure 204: 5G NSA (a) one-way latency, (b) reliability, (c) packet delivery rate at the milk run between the central gate and the Verbrugge Terminals

Packet loss

As demonstrated in the previous subsection, the packet delivery rate along the evaluated trajectory remained at 100%, signifying a complete absence of packet loss. This fact is further illustrated in the subsequent map (Figure 205), which visually confirms a 0% packet loss across the entire trajectory. Each point on the map represents the packet loss observed within distance bins of 100 meters, considering packets transmitted at a frequency of 10 Hz in the uplink traffic direction.

Figure 205: 5G NSA packet loss at the milk run between the Central Gate and the Verbrugge terminal

Summary

In Table 25**,** a summary is provided of the results from the 5G NSA network evaluation that was conducted between the Central Gate and the Verbrugge terminal in Vlissingen on the road.

On-site 5G network evaluation						
Location	Netherlands – Milk run between central gate and Verbrugge terminal			Location type	**Road - car**	
Network operator	KPN			Network type	5G NSA	
Network slice config	eMBB - no background traffic			UE type	Quectel RM502Q	
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-109	-101	-89	-76	-66	-88.5
TCP DL (Mbps)	8.25	19.3	149	311	389	164
TCP UL (Mbps)	10.7	18.7	36.9	72.7	83.4	41.2
UDP DL (Mbps)	4.4	64.4	140	254	394	146
UDP UL (Mbps)	11.2	22.4	40.7	75.2	86	44.4
RTT (ms)	20.4	21.6	24.9	34.3	42.1	25.7

Table 25: Summary of 5G NSA network performance evaluation between the Central Gate and the Verbrugge terminal on the road

6.3.5 5G NSA – Milk Run between Kloosterboer Terminals and MSP Onions

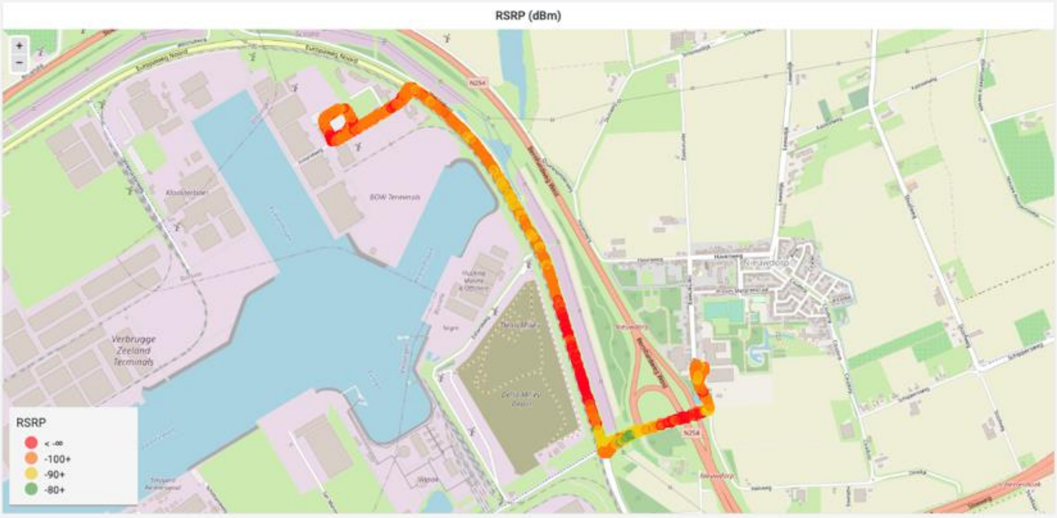
This second milk run that was evaluated from a 5G network perspective is the trajectory between the Kloosterboer Terminals and the MSP Onions site. Every specified KPI has undergone multiple assessments to guarantee that the gathered data possesses sufficient statistical significance. For all the tests performed across the milk run trajectory, the Quectel RM502Q module was used at the UE side.

Modem statistics

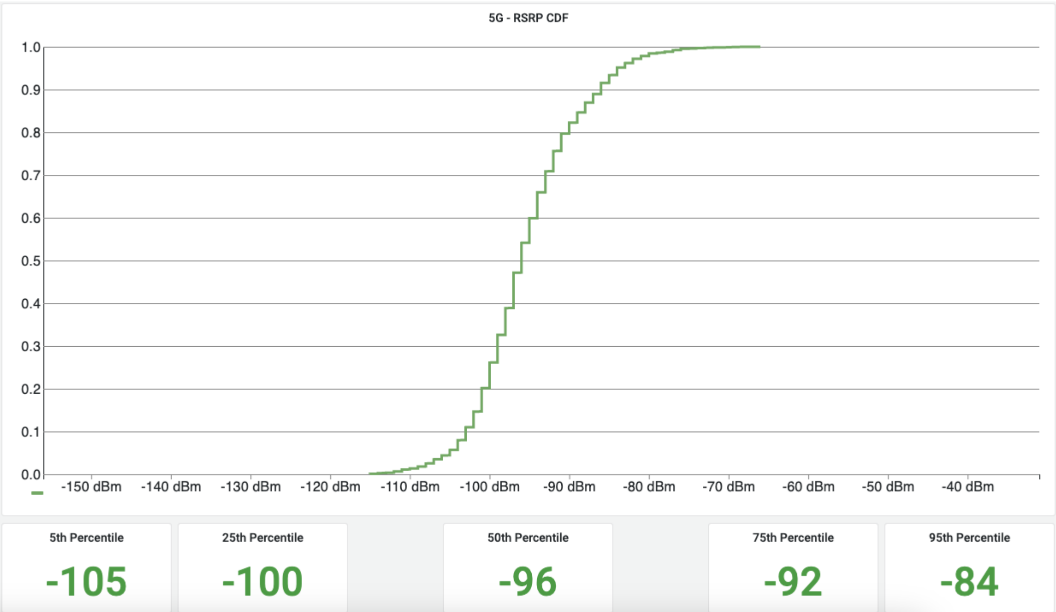
Figure 206 presents a comprehensive visual depiction of the tests conducted on RSRP values along the test trajectory. This figure has two parts: (a) a heatmap displaying the distribution of RSRP values along the entire test route, and (b) the CDF graph of the collected RSRP values.

It can be observed that the 50th percentile, representing the median RSRP value, is -96 dBm. Meanwhile, the 5th percentile, signifying the lower end of RSRP values, is measured at -105 dBm, and the -95th percentile stands at -84 dBm.

From the heatmap, it can be observed that there are two areas where the RSRP values are rather low, one at the middle southern part and one at the viaduct on the east side, crossing the main road. Also, at the Kloosterboer terminals (western part of the trajectory), some lower RSRP values were observed. In general, the recorded RSRP values suggest that for a substantial part of the trajectory the signal quality is good, with values higher than -100 dBm, however, there are some parts where the signal is weak.



(a)



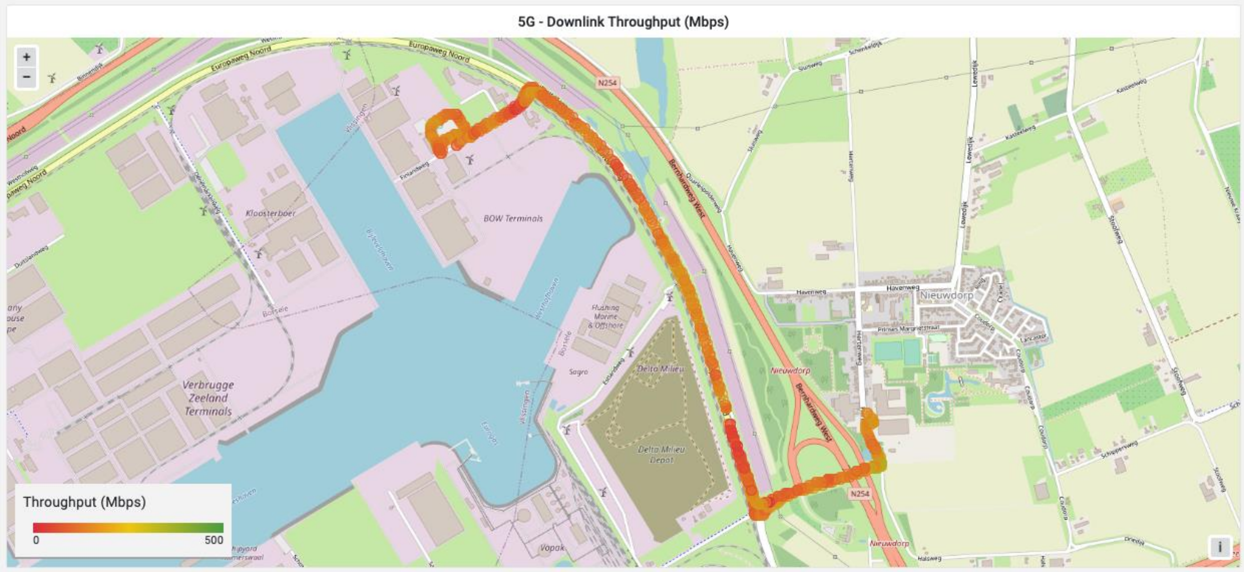
(b)

Figure 206: 5G NSA (a) RSRP values on map, (b) CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

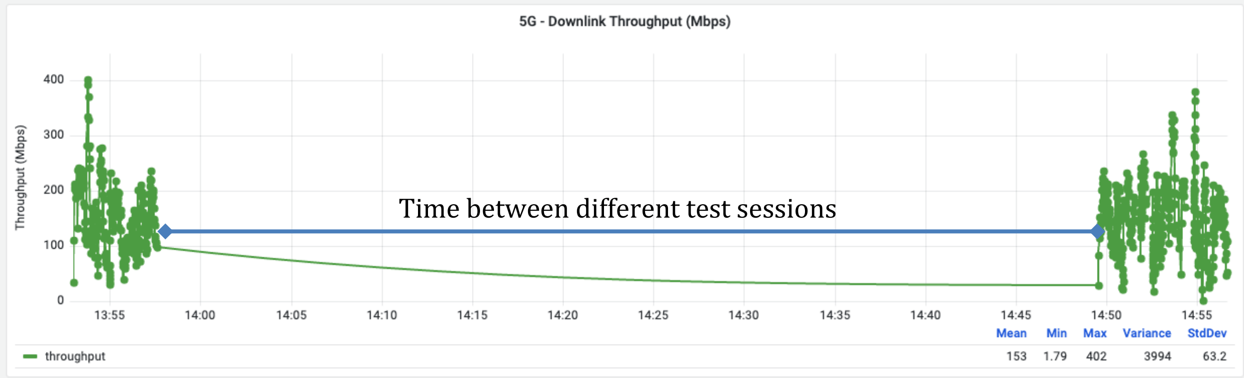
TCP downlink rate

Figure 207 offers an overview of the TCP downlink rate including (a) a heatmap and (b) a graphical representation over time, summarizing the outcomes of a series of consecutive tests.

The observed mean throughput value registers at a 153 Mbps, reflecting the average rate of data transfer. On the lower end of the spectrum, the minimum observed throughput value is measured at 1.79 Mbps. Such values are in line with the RSRP measurements and were recorded in parts of the trajectory where the signal quality was low. In contrast, the maximum recorded throughput value along the milk run trajectory was 402 Mbps.



(a)



(b)

Figure 207: 5G NSA TCP downlink rate (a) on map, (b) graph throughput vs time at the milk run between the Kloosterboer Terminals and MSP Onions

Another representation of the data is shown in Figure 208 where the CDF graph is shown., The 50th percentile stands at 151 Mbps, indicating the typical performance level. Furthermore, the 95th percentile is calculated at 248 Mbps.

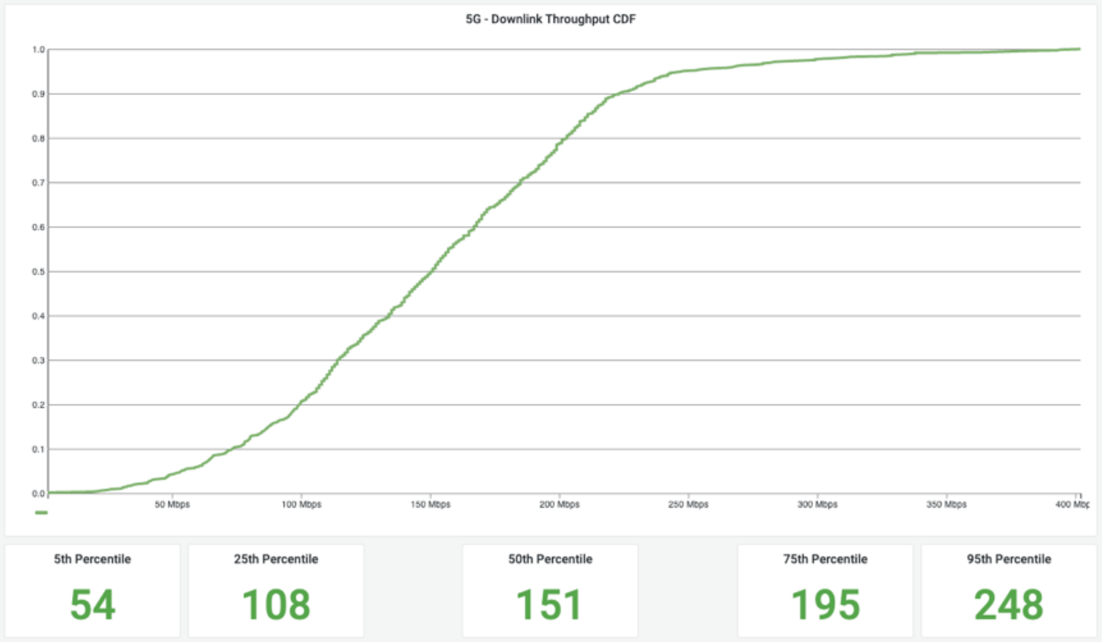


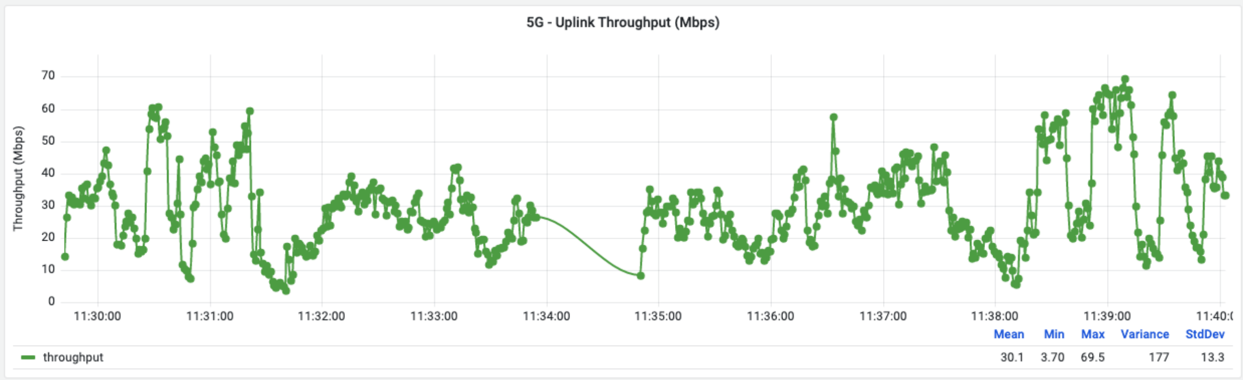
Figure 208: 5G NSA TCP downlink rate - CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

TCP uplink rate

Following this, an extensive evaluation of the TCP uplink rate was carried out through a series of multiple tests conducted along the same trajectory. Figure 209 provides a comprehensive view of this evaluation, showcasing (a) a heatmap displaying the throughput values observed across the entire route, and (b) a time-based graphical representation of the throughput values throughout the tests.

The mean TCP uplink throughput averages at 30.1 Mbps. At the lower end of the spectrum, the minimum throughput value registers at 3.7 Mbps, reflecting the low signal strengths that were observed at certain parts of the trajectory. The maximum recorded throughput value reaches 69.5 Mbps.

(a)



(b)

Figure 209: 5G NSA TCP uplink rate (a) on map, (b) graph throughput vs time at the milk run between the Kloosterboer Terminals and MSP Onions

To gain deeper insights, the CDF graph, as shown in Figure 210, aggregates the uplink TCP throughput values obtained from all the conducted tests.The 95th percentile is situated at 57.8 Mbps, while the 50th percentile is 28.6 Mbps, serving as a reference point for the typical performance level in the uplink direction.

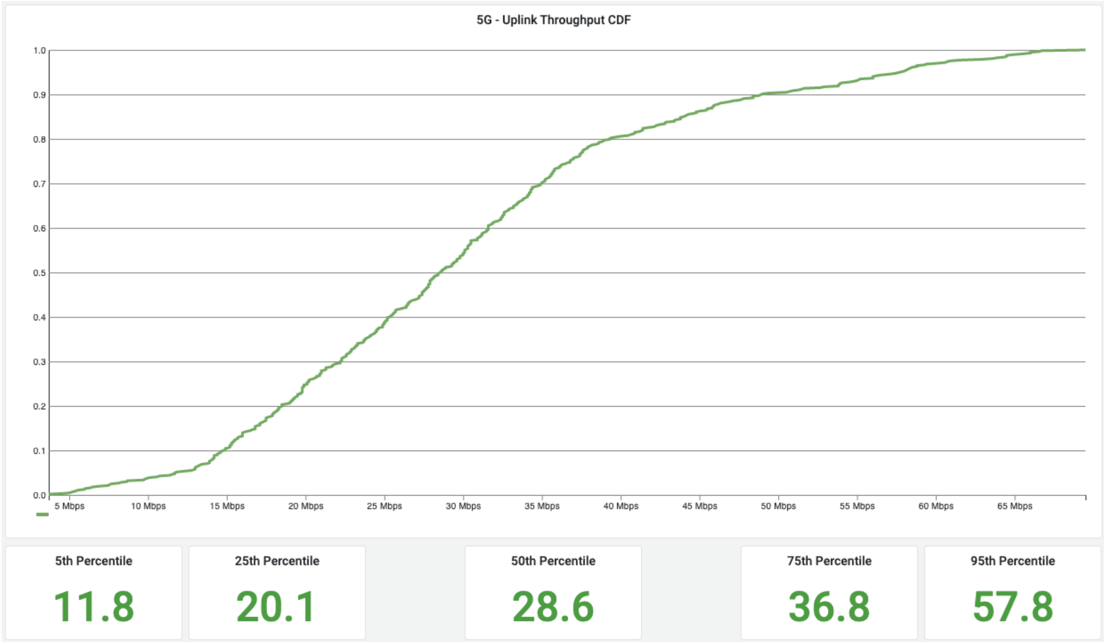
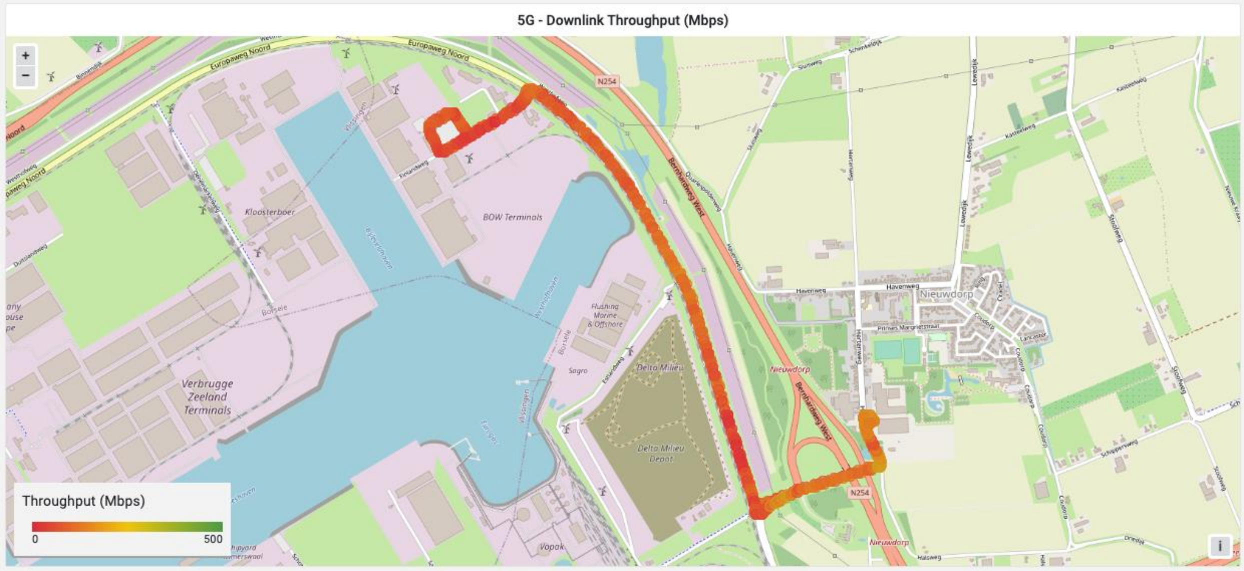


Figure 210: 5G NSA TCP uplink rate - CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

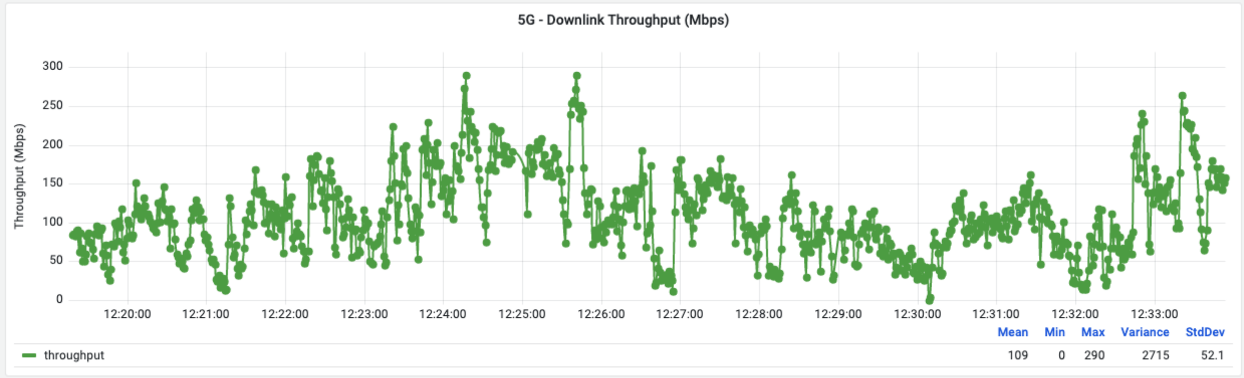
UDP downlink rate

Similar to the TCP case, Figure 211 provides a representation of the UDP downlink rate in a heatmap (a) and a time-based graph (b), including data that was measured in a series of consecutive tests.

The mean throughput value of UDP downlink rate reaches 109 Mbps. However, the minimum recorded throughput was observed to be 0 Mbps, indicating that at a certain spot, no uplink data was received during the measurement interval (this can be observed around 12:30 in the time graph). Conversely, the highest recorded throughput value peaks at 290 Mbps.



(a)



(b)

Figure 211: 5G NSA UDP downlink rate (a) on map, (b) graph throughput vs time at the milk run between the Kloosterboer Terminals and MSP Onions

Figure 212 presents the CDF graph of the UDP downlink rate values derived from the conducted tests on the specific trajectory. Specifically, the 50th percentile is around at 102 Mbps. Furthermore, the 95th percentile is calculated at 204 Mbps.

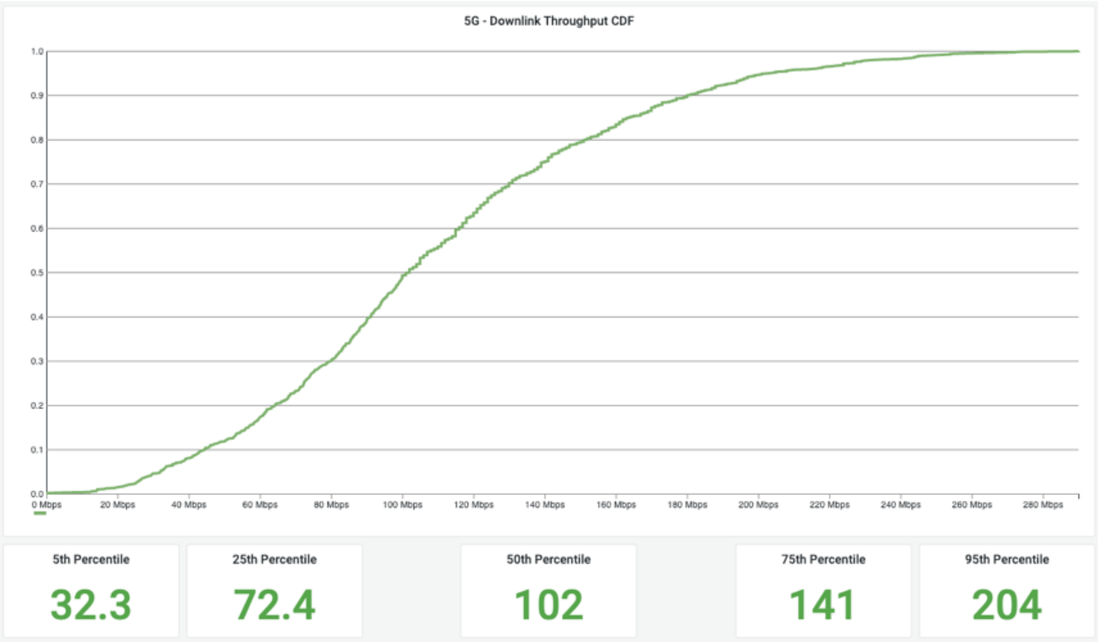
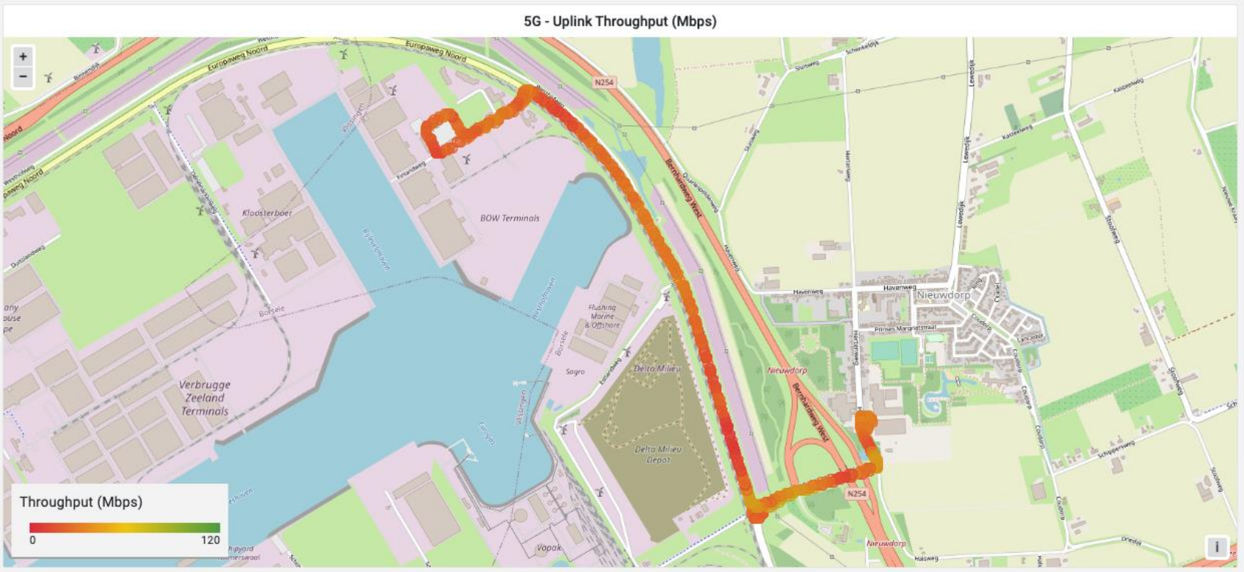


Figure 212: 5G NSA UDP downlink rate - CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

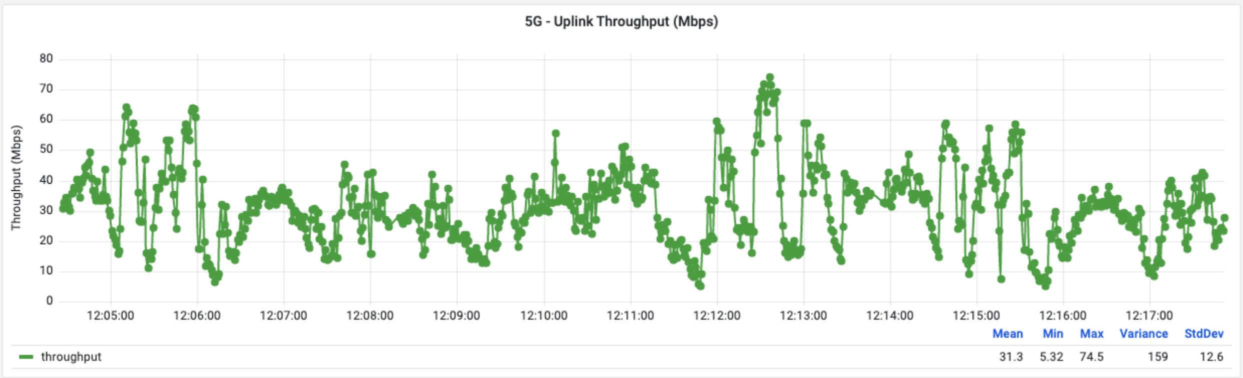
UDP uplink rate

This subsection presents an evaluation of the UDP uplink rate for the milk run trajectory. In Figure 213 , the analyzed data is represented in a heatmap (a) and a time-based graph (b).

The mean observed UDP uplink throughput is 31.3 Mbps. The minimum UDP uplink throughput value that was recorded in the area where the signal quality was low, is 5.32 Mbps. Conversely, the maximum recorded throughput value reaches 74.5 Mbps, highlighting the potential for higher-speed data transmission under good cell coverage conditions.



(a)



(b)

Figure 213: 5G NSA UDP uplink rate (a) on map, (b) graph throughput vs time at the milk run between the Kloosterboer Terminals and MSP Onions

Figure 214 presents the CDF graph of the UDP uplink throughput values derived from all the conducted tests. The 95th percentile is calculated to be 55.7 Mbps. Furthermore, the 50th percentile stands is 31.4 Mbps. As it can be observed, both UDP and TCP traffic has a similar performance at this specific trajectory and their performance mainly depends on signal quality conditions.

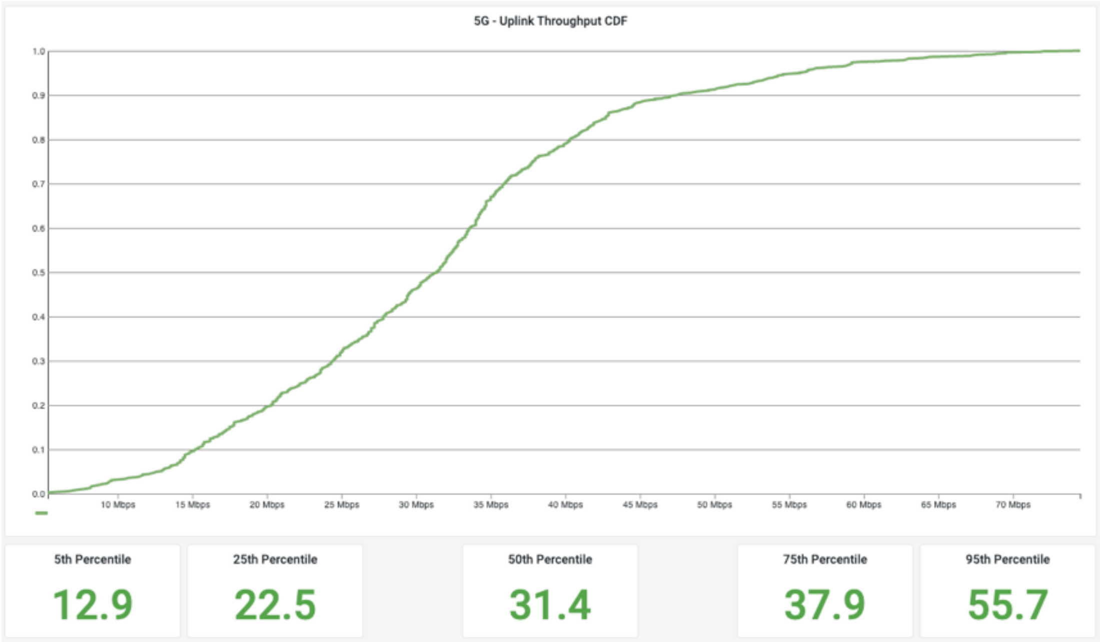


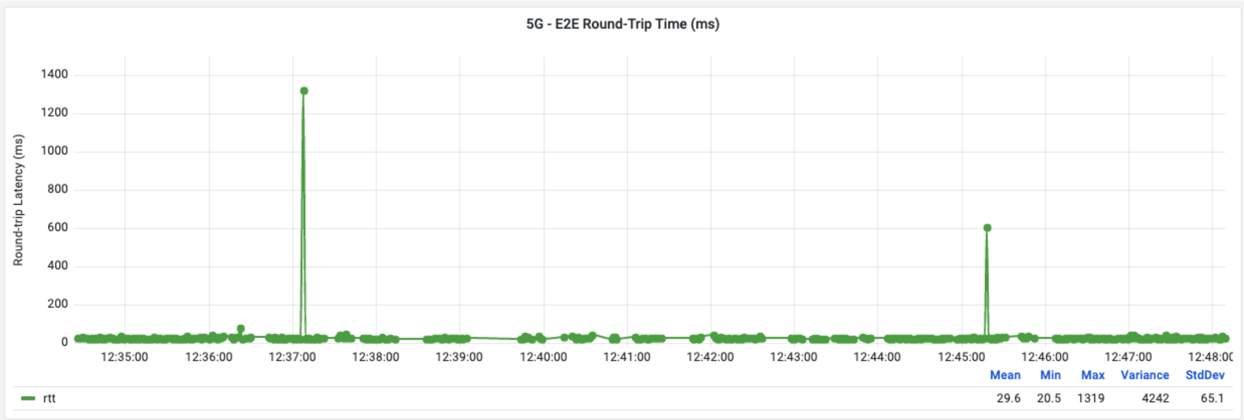
Figure 214: 5G NSA UDP uplink rate - CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

Round-Trip Time

This section offers a summary of the results obtained from the RTT evaluation carried out along the specified trajectory. Figure 215 presents (a) a heatmap showcasing the RTT values observed during a series of executed tests, and (b) a time-based presentation of the corresponding RTT values.

From the graph it can be observed that the average RTT latency is 29.6 ms. At the upper limit of our observations, the maximum recorded latency value peaks at 1319 milliseconds. In the time graph it can be seen that there were two high RTT peak during the tests. These are outliers and do not occur frequently, however it is an important observation that should be taken into account for the correct operation of the use cases.

(a)



(b)

Figure 215: 5G NSA RTT (a) on map, (b) graph throughput vs time at the milk run between the Kloosterboer Terminals and MSP Onions

In Figure 216, the CDF graph is presented. Notably, the 50th percentile is measured at 24.7 milliseconds. Furthermore, the 95th percentile registers at 34.2 milliseconds, signifying the latency threshold encountered in a larger portion of our measurements.

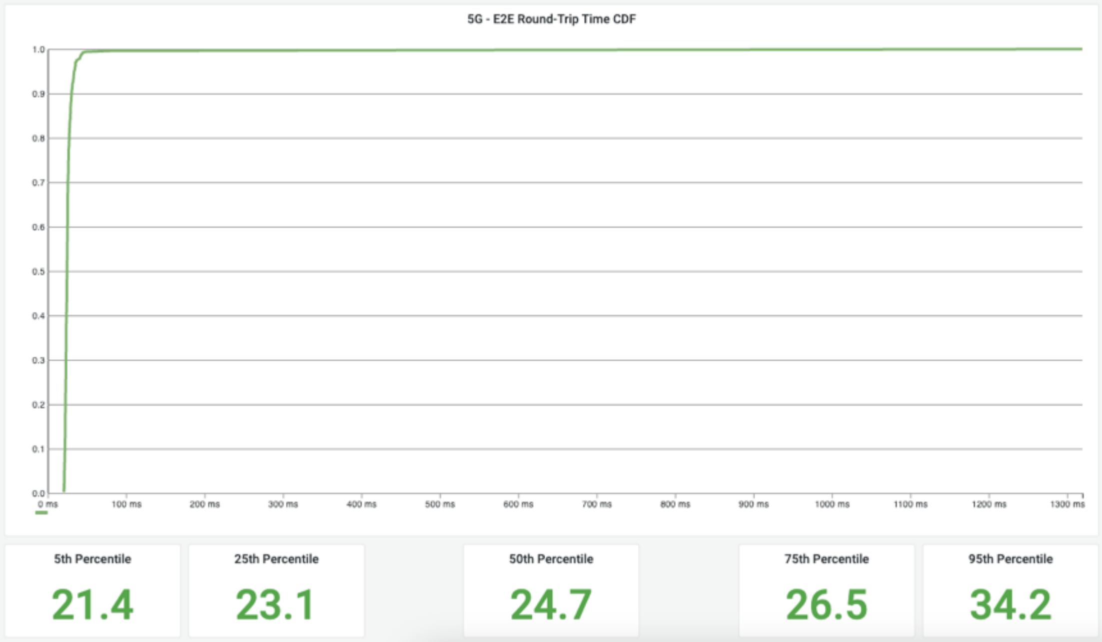


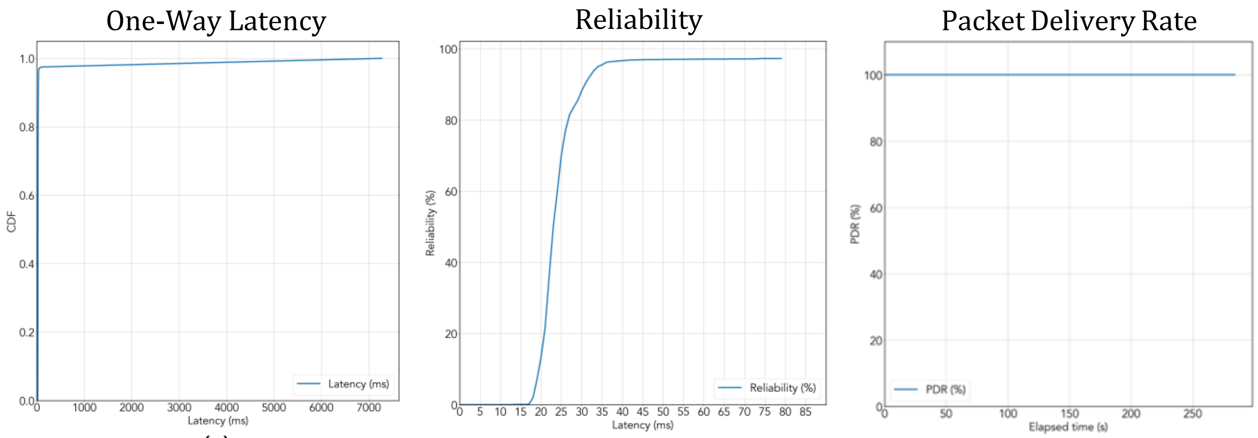
Figure 216: 5G NSA RTT - CDF graph and percentiles at the milk run between the Kloosterboer Terminals and MSP Onions

One-way latency, reliability, packet delivery rate

Figure 217 provides a representation of the analysis of one-way latency (a), reliability (b) and packet delivery rate over time (c) at the milk run between the Kloosterboer Terminals and MSP Onions. During the tests, data packets were transmitted from the UE to the gNB at a steady rate of 10 packets per second (10 Hz).

From the data used for the CDF graph for one-way latency (a), the 50th percentile of latency stands at 24 milliseconds. Furthermore, the 95th percentile records a latency of 36 milliseconds, while the 99th percentile stands at 4454 milliseconds.

The packet delivery rate graph (c) reveals that no packet loss was observed. It is important to emphasize that while this graph refers to a specific test, it serves as a reliable representation of the overall results gathered across all conducted tests. Additionally, the reliability graph (b) illustrates that 95% of the transmitted packets being correctly received within 34 milliseconds.



(a) (b) (c)

Figure 217: 5G NSA (a) one-way latency, (b) reliability, (c) packet delivery rate at the milk run between the Kloosterboer Terminals and MSP Onions

Packet loss

As demonstrated in the previous subsection, the packet delivery rate along the evaluated trajectory remained at 100% at low packet transmission frequency. This fact is further illustrated in the subsequent map (Figure 218), which visually confirms a 0% packet loss across the entire trajectory. Each point on the map represents the packet loss observed within distance bins of 100 meters, considering packets transmitted at a frequency of 10 Hz in the uplink traffic direction.

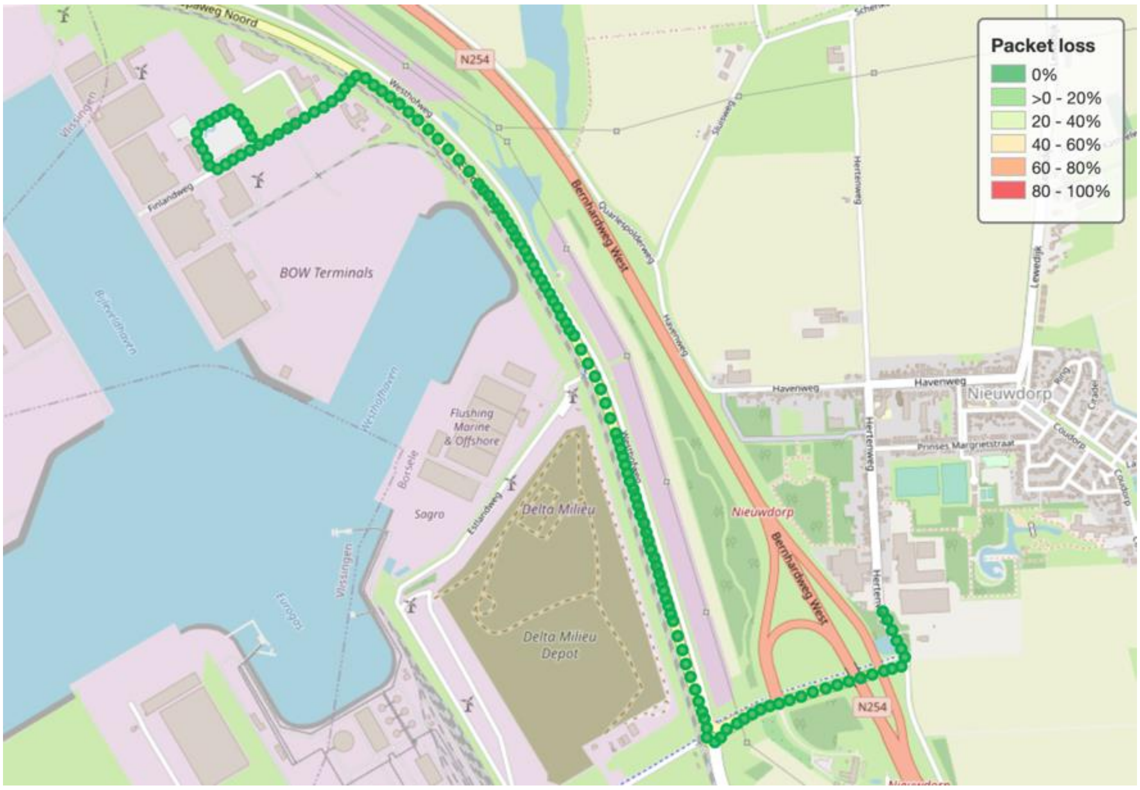


Figure 218: 5G NSA packet loss at the milk run between the Kloosterboer Terminals and MSP Onions

Summary

In Table 26, a summary is provided of the results from the 5G NSA network evaluation that was conducted betwen the Kloosterboer terminals and MSP Onions in Vlissingen on the road.

On-site 5G network evaluation						
Location	Netherlands – Milk run between Kloosterboer Terminals and MSP Onions			Location type		**Road - car**
Network operator	KPN			Network type		5G NSA
Network slice config	eMBB - no background traffic			UE type		Quectel RM502Q
KPI	**Min**	**5th perc**	**Median**	**95th perc**	**Max**	**Average**
RSRP (dBm)	-115	-105	-96	-84	-66	-95.3
TCP DL (Mbps)	1.79	54	151	248	402	153
TCP UL (Mbps)	3.70	11.8	28.6	57.8	69.5	30.1
UDP DL (Mbps)	0	32.3	102	204	290	109
UDP UL (Mbps)	5.32	12.9	31.4	55.7	74.5	31.3
RTT (ms)	20.5	21.4	24.7	34.2	1319	29.6

Table 26: Summary of 5G NSA network performance evaluation between the Kloosterboer terminals and MSP Onions on the road

6.4 Overview of the 5G network evaluation at the Dutch site

In the previous sections, the individual results of the 5G network evaluation at the Dutch trial site were described for the different trajectories and KPIs. A summary of these results is presented in Table 27, containing the average values of the KPIs for the tests on the road.

The table shows that using the URLLC slice is more resilient to background traffic on the eMBB slice in terms of latency. This can be observed in the RTT. The latency increased from 15ms to 23.8ms for the eMBB slice when downlink background traffic was introduced. When the URLLC was used, the RTT stayed almost the same (from 12.6ms to 14.1ms).

The results also show that both SA and NSA networks were able to support the teleoperation requirements. An important learning is that having good coverage is crucial to meet the performance that is required for the use cases. Near the cell edge or at “weak spots”, the performance of the networks degrades significantly which results in low throughput. To avoid that, it is recommended to evaluate the network coverage before deploying teleoperation along certain trajectories. Choosing an MNO with best coverage will lead to more optimal performance for the teleopeation use case along fixed trajectories.

Deployment	Test area	TCP DL (Mbps)	TCP UL (Mbps)	UDP DL (Mbps)	UDP UL (Mbps)	RTT (ms)	OWL*** (ms)
5G SA	Verbrugge (embb without background)	343	52.8	360	54.3	15*	13
	Verbrugge (embb with background)	127	23.3	185	25.2	23.8*	24
	Verbrugge (urllc without background)	-	38.3	-	42.8	12.6*	14
	Verbrugge (urllc with background)	-	31.9	-	32.2	14.1*	14
5G NSA	Kloosterboer 1	91.5	26.5	98.7	27.5	25.4**	25
	Kloosterboer 2	113	30.1	111	31.5	23.4**	25
	MSP Onions	184	34.9	177	33.4	24.1**	22
	Milk run (Central Gate – Verbrugge)	164	41.2	146	44.4	25.7**	22
	Milk run (Kloosterboer – MSP)	153	30.1	109	31.3	29.6**	24

Table 27: Overview of the 5G SA/NSA evaluation at the Dutch site

* RTT to core network

** RTT to 8.8.8.8

*** OWL between UE and IMEC server over internet, median values

7 CONCLUSIONS

The objective of the report was to present the results from the evaluation of the deployed networks at the three trial locations.

At the cross-border area, the results showed that the requirements for teleoperation in a cross-border scenario can be met by the deployed 5G networks and the advancements implemented within 5G-Blueprint to enable seamless handover. The handover interruption time was proven to be less than 150ms in both directions using both KPN and Telenet sim cards. Initially, it was observed that the uplink performance in some areas was not sufficient using the originally planned base stations and the network configuration. This led to the deployment of a mobile base station from Telenet on the Belgian side, closer to the border area. KPN also identified an illegal source of interference (which was tackled by contacting the Dutch regulator who took action to get it removed) and identified some failing equipment that was replaced to enhance the uplink performance. The evaluation procedure indicated that good coverage conditions, uplink-oriented network configuration and use of active antennas at the base stations could significantly improve the overall Quality of Service (QoS) and Quality of Experience (QoE) for the teleoperation use case. Some notable difference in performance between the KPN and Telenet network was observed at the cross-border site. This can most likely be explained by the fact that Telenet was using an active antenna, while KPN did not. At the Verbrugge terminal in Vlissingen (Netherlands), KPN deployed the base station with an active antenna, and there the performance was in line with what we observed at the Telenet SA network with active antenna.

As part of the scope of this project, the solutions presented in this document focused on minimizing the handover interruption given that both MNOs and their corresponding cross-border radio cells are pre-selected and known beforehand. Furthermore, the base stations from the two pre-selected MNOs were configured as neighbour cells with fine-tuned signal strength thresholds. These thresholds had to be determined upfront by conducting signal strength measurements on the field.

Based on the experience gained in the project to develop and achieve seamless roaming in a cross-border scenario, the follow lessons learned are highlighted:

- <u>Optimization</u>: The optimized version of the core tested shows that preparing the PDU session as much as possible beforehand further reduces the downtime. This means that fewer messages are exchanged between home and visited networks during the network interruption, thereby potentially reducing QoS requirements between the MNOs in terms of bilateral Service Level Agreement (SLA).
- <u>Networks selection</u>: Instead of pre-selecting the target MNO at the border, a fine-grained network selection among available MNOs that includes per-UE priorities, service availability, and home MNO preferences/agreements should be further researched.
- <u>End-to-end latency</u>: after the UE being handed over to the target MNO across the border, it might be desirable to switch the data traffic to a local edge server running the required tele-operation service to avoid longer delays due to home-routing roaming. To this end, further investigation is needed towards using Local Breakout Roaming (LBO) and Session and Service Continuity (SSC) mode 3.

Regarding the trial site in Belgium, the evaluation of Key Performance Indicators (KPIs) revealed that the deployed 5G network successfully meets the defined requirements for use cases and enabling functions at the Port of Antwerp and around the Roossens Transport premises. However, suboptimal performance was noted during the milk run from Roossens Transport to Medrepair due to a challenging environment characterized by poor coverage. This issue is attributed to a significant number of containers, numerous large trucks in motion, and elevated roads in the area. Despite the observed limitations in this specific segment of the milk run, it was deemed less critical and did not impact the assessment of use cases and enabling functions. It is expected that deploying extra base stations according to optimal planning will solve the coverage issue and will result in better performance to support the TO trucks on this milk run. In general, when deploying teleoperation on a specific milk run route, it is therefore advised that the network coverage along the trajectory from the different MNOs is carefully evaluated upfront to reveal “weak spots” and choose the operator that possibly does not have these low coverage zones along the trajectory. We observed that the real usable cell size at the 3.5Ghz band seems to be ~2km. This also applies to the milk run testing that was done in the Vlissingen test site. The evaluation also included an examination of traffic prioritization through slicing, illustrating how slices, such as URLLC (Ultra-Reliable Low Latency Communications), can exhibit greater resilience to background traffic. This resilience is particularly crucial for teleoperation scenarios.

Concerning the Dutch trial site, the findings indicate that the URLLC slice demonstrates lower overall latency compared to eMBB, and this latency is more resilient in the presence of background traffic. Furthermore, all Key Performance Indicators (KPIs) confirm that the network's performance aligns with the stipulated requirements for use cases and enabling functions. An assessment of the 5G NSA network in Vlissingen reveals a lower performance compared to the SA network. Specifically, the average one-way latency on the SA network was observed to be twice as low as that on the NSA network. However, it's noteworthy that the NSA network operated as a production network, open to other KPN subscribers, potentially impacting its performance. It was demonstrated that 5G slicing is a technology capable of mitigating such impacts and ensuring the necessary performance guarantees for teleoperation.

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[4] 5GBlueprint, “D7.2 - Platform Integration and Minimum Viable Platform,” 2022.