Data Offloading for Mobile Unmanned Systems –
Evaluation of Throughput and Latency in a Private 5G Network

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Summary: This paper investigates data offloading for mobile unmanned systems in private 5G networks. The presented evaluation is based on real-world measurements in a modernized industrial facility, using an unmanned ground vehicle. Our results indicate that the service requirements for uplink and downlink throughput are mostly met, while latency is still partially an issue for real-time data offloading and online processing.

Keywords: Unmanned Systems, Mobile Robotics, Data Offloading, 5G Private Networks, Real-World Measurements

1. Introduction & Motivation

With its promise of low latency and high throughput, 5G New Radio (NR) yields exciting potential for the future of industry, mobile robotics, and unmanned systems. This paper targets especially the use case of data offloading for online processing. Thereby, a fast, wireless network, e.g., 5G, is used to transport sensor data to a server, which then conducts resource-intensive calculations and returns the results in real-time. Such an approach can save space, weight, energy, and cost by replacing CPU and GPU capabilities of mobile systems with edge-near cloud solutions. One prominent use case is the calculation of precise Visual Simultaneous Localization and Mapping (VLSAM) combined with a high-resolution Light Detection and Ranging (LiDAR). An exemplary system setup for this approach is shown in **Figure 1**, where the collected LiDAR data of an Unmanned Ground Vehicle (UGV) is offloaded via the 5G NR system to a Data Processing Server (DPS) for online processing and an associated Network Attached Storage (NAS) for further data analysis. While data offloading seems very promising, sufficient wireless throughput and low latency is critical to ensure real-time capability. Thus, since the network conditions are the limiting factor, this paper investigates the concept by presenting and analyzing measurements of private 5G network throughput and latency in a challenging real-world environment.

2. Related Work & Contribution

Since the introduction of 5G NR, several performance measurements and evaluations have been published. Especially prominent is the early work by Rappaport et al. [1]. Newer results are presented by Ghourtani et al. [2], whereas a comprehensive survey on 5G channel measurements and models is presented in [3], which references the most important publications in the field. A comprehensive survey on edge computing and data offloading in general was published by Qui et al. [4]. 5G-specific literature on the topic is presented by Pham et al. [5] and Di Lorenzo et al. [6].

This paper contributes to this field by giving novel insights into the current state-of-the-art of 5G NR performance and service requirements compliance [7], with the goal to increase the scientific community's assessment of its potential for data offloading. One unique characteristic of the presented results is the deployment of a commercial-grade 5G NR system, produced by Ericsson, in a large, modernized industrial indoor facility. Such an environment yields much potential for automation and mobile robotics, yet it is very challenging for wireless communication, due to the facility's size and steel construction. In comparison, most analyzed data sets mentioned in the survey by Wang et al. [3], were collected in labs or smaller facilities, often using prototypical network infrastructure.

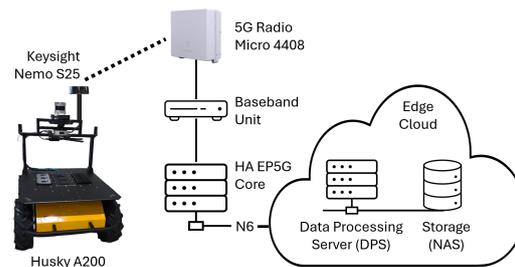To support future research, all data is made available under: https://doi.org/10.5281/zenodo.18465652

Fig. 1. Overview of the used network architecture for UGV data offloading via 5G NR to an edge-near cloud.

3. System Setup

This section summarizes the system setup, including the test area, the used UGV, and the 5G NR network system.

3.1. Test Area

The private 5G campus network of the Faculty of Management, Culture and Technology of the Osnabrück University of Applied Sciences is hosted in a modernized industrial facility. Originally, the area was a central railway repair workshop, which was converted into a university campus. Within the large hall, several buildings were constructed to house labs, seminar rooms, and offices. Due to the still existing large steel structures, which are characteristic of such workshops, the environment is rather challenging for radio signal propagation and network deployment. **Figure 2** shows an image along the long central axis of the main hall and a floorplan, which also includes the buildings within the hall.

3.2. Unmanned System Platform

A Clearpath Robotics Husky A200 UGV was selected as the reference system. The Husky A200 was chosen because it is a widely available off-the-shelf platform and deploys several sensor types, which are interesting for data offloading. These sensors include especially a multi-layer 3D LiDAR, a stereo and depth camera, an RTK system, and several IMUs.

To conduct the 5G network throughput measurements, a Keysight Nemo Handy [8] was attached to the Husky at 1 m above floor height. The Nemo Handy is essentially a Samsung Galaxy S25, which is flashed with a custom Keysight firmware and application. Together with the Nemo Outdoor Playback data analysis software, this enables reliable, professional network measurements, especially for 5G private networks.
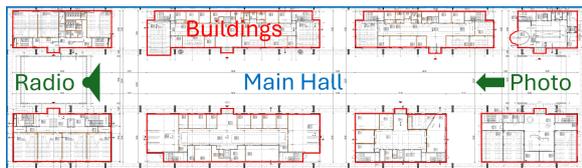

Fig. 2. Test area and floorplan Campus Lingen, photo taken along length axis (green arrow), cf. https://www.hs-osnabrueck.de/en/study/student-life/campus/

3.3. 5G Network System

To enable efficient data offloading in a private 5G network, the unmanned system must be connected with the Data Processing Server (DPS) and the Network Attached Storage (NAS) via the local 5G infrastructure, as illustrated in **Figure 1**. The used system is an Ericsson Private 5G (EP5G) network, which is operated on the 3.7-3.8 GHz frequency band (n78). For the conducted measurement campaign, a single Ericsson Micro Radio 4408 was deployed. While our full-scale 5G network is planned to use multiple radio units for optimal coverage, the choice of a single radio for this evaluation was made to simplify the experiment parameters, create challenging link conditions, and avoid cell handovers. The radio dot was attached to a large tripod on a balcony within the central hall of the facility, cf. **Figure 2**, at a height of 11.275 m above the pavement. The heading was aligned along the length axis of the building, looking down at 35°. The wattage was set to 4x250 mW. To avoid any impact from virtualization, a dedicated bare metal server was used as DPS, which is connected via an N6 interface. A condensed summary of the network system is shown in the following **Table 1**.

Table 1. Configuration 5G NR Network.

Component	Product	Configuration / Connection
Core Hardware	DELL Server R640	2x SFP28, 25 GbE with OM3, l=5m
Core Software	Ericsson EP5G	Release 25.81
Baseband Unit	BBU 6651	TDD Pattern: 2-DDSU / 2-10:2:2
Radio	Ericsson Mirco Radio 4408	4x250 mW, Fiber OS2 9/125, l=200m
Data Processing Server	DELL PowerEdge R6515	Ubuntu Server 24.04 LTS, 1xSFP28, 25 GbE with OM3, l=5m
Switching	FS S5850-48B8C-PE	FS OS 7.4.8, 48x SFP28 + 8x QSFP28

4. Measurements & Evaluation

The main research question of the presented evaluation is whether the data offloading demand can be satisfied by the 5G network. Therefore, measured data rate demands of the UGV will be presented, analyzed, and compared to the statistical distribution of the measured 5G throughput. The evaluation also analyzes latency measurements to assess if the 3GPP latency service requirements [7] are met and if the delays are low enough to enable real-time operation.

4.1. Data Offloading Demand UGV

To quantify the data rate, which an unmanned system demands to offload to a processing server, a two-minute test drive was conducted with the reference UGV. Thereby, a ROS 2 bag of all relevant sensor data is saved and later analyzed. The resulting data rate demands are presented in **Table 2**.

Table 2. Measured RoS2 data rates of reference UGV (Clearpath HUSKY A200), cf. **Sec. 3.2**

Data Source	Product	Data Rate [Mbit/s]
Stereo RGB Camera	Stereolabs ZED 2i	10.958
Depth Camera	Stereolabs ZED 2i	5.481
Multi-Layer 3D-LiDAR	Ouster OS1 32 Gen2 (1024 points @20 Hz)	12.523
IMU	Fixposition Vision Sensor Fusion RTK2	0.509
Combined	all above	**29.471**

It has to be noted that we only consider the payload data rates here. Usually, the DPS would run a ROS 2 subscriber or a streaming service, such as Apache Kafka, to offload the data. Thus, additional network and control overhead would occur. Since the amount overhead depends heavily on the protocols, we note an evaluation of network overhead for future work.

4.2. 5G Throughput & Latency

Detailed 5G throughput and latency measurements were conducted using the Nemo Handy [8], which was attached to the UGV at a height of 1 m above the floor, cf. **Section 3**. For the throughput measurements, an iperf3 server was hosted on the DPS, while an iperf3 client ran in TCP mode on the Nemo Handy. The latency (one-way delay) is approximated using half the Round-Trip Time (RTT) of ICMP Pings from the UGV to the server. The results of these measurements are visualized on the maps in **Figures 3-5**. The following evaluation analyzes the statistical distribution of the data. Therefore, **Figures 6**, **7**, and **9** show Empirical Cumulative Distribution Functions (ECDFs) and regular Boxplots of the data.
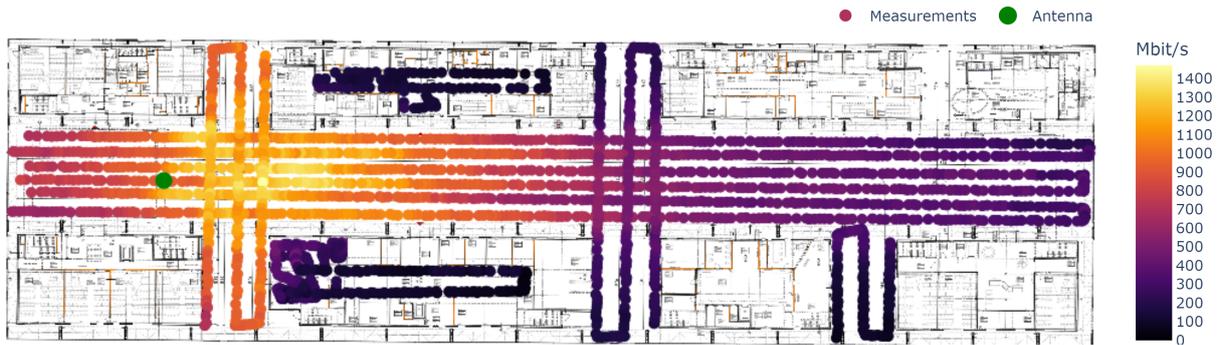

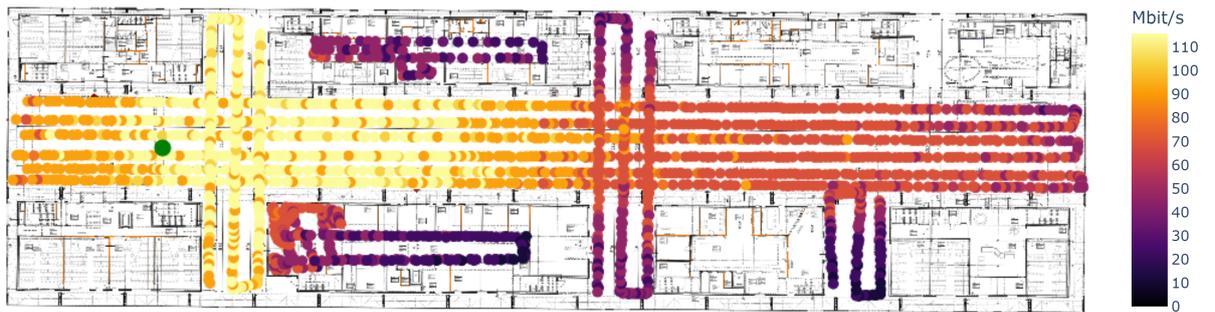**Fig. 3.** Measured iperf3 TCP Throughput 5G Downlink in Mbit/s.

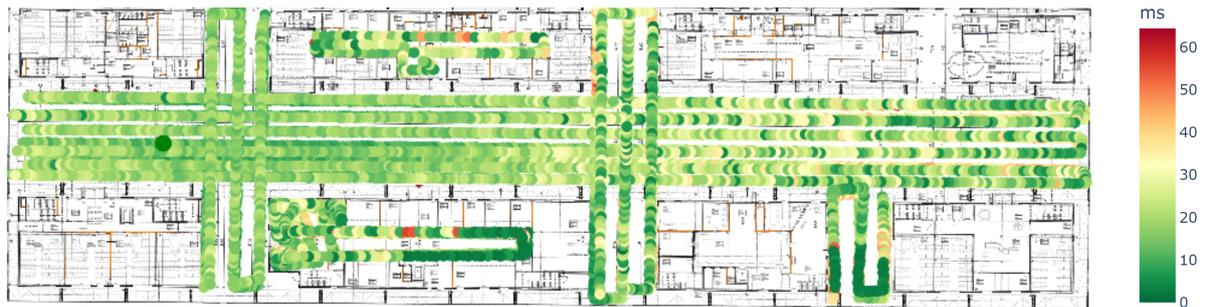**Fig. 4.** Measured iperf3 TCP Throughput 5G Uplink in Mbit/s.

Fig. 5. Measured latency (one-way-delay) in ms, using ICMP Ping RTT/2.

Downlink Throughput: Due to the focus on data offloading for online processing, our evaluation mainly analyzes the uplink and latency measurements. Thus, in short, here are the condensed findings regarding downlink throughput distribution, which is shown in **Figure 6**:

- The median downlink throughput in the hall is 599.8 Mbit/s, with a lower quartile of 378.5 Mbit/s and an upper quartile of 958.6 Mbit/s.

- In the buildings, a median of 145.2 Mbit/s was achieved, with a lower quartile of 111 Mbit/s and an upper quartile of 247 Mbit/s.

- The medians and lower quartiles reside far above the UGVs' combined data rate demand of 29 Mbit/s, cf. **Table 2**. While usually the uplink throughput to a server is critical for data offloading, this high downlink throughput enables fast machine-to-machine streaming via 5G.
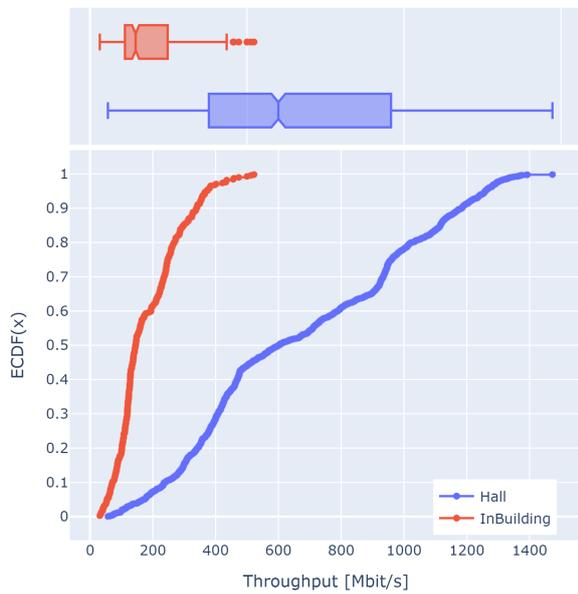

Fig. 6. ECDF and Boxplot of measured iperf3 TCP Throughput 5G Downlink in Mbit/s.

Uplink Throughput: Sufficient uplink throughput is the critical key for real-time data offloading and online processing. The uplink throughput distribution of the 5G measurements is shown in **Figure 7**, which shows:

- The median downlink throughput in the hall is 80.4 Mbit/s, with a lower quartile of 68.8 Mbit/s and an upper quartile of 114.6 Mbit/s.

- In the buildings, the median is at 45.9 Mbit/s, with a lower quartile of 23.0 Mbit/s and an upper quartile of 57.8 Mbit/s.

Compared to the measured data rate demands, cf. **Table 2**, which are represented by the vertical lines in **Figure 7**, the following key takeaways can be identified:

- The IMU and depth camera data rate demand can be always satisfied.

- In the main hall, the LiDAR and RGB camera demand is satisfied in 99.9 percent of positions and still in 94 percent in the buildings.

- The combined data rate demand is satisfied in 96 percent of measurement positions in the hall and in 71 percent of positions in the buildings.

One interesting finding is the stepped nature of the uplink throughput, seen in **Figure 7**. The reason for these steps is the automatic selection of the used Modulation and Coding Scheme (MCS) in the 5G NR waveform. This explanation is in line with the findings of Rappaport et al. [1] and Ghourtani et al. [2]. Given the fundamental inverse-square law of wireless communication, the reception power sinks drastically with distance. Thus, the Signal-to-noise and inter-ference Ratio (SNIR) decreases, which results in an increased Block Error Rate (BLER). This finally forces the NR waveform to select a more robust MCS, sacrificing throughput for robustness. To further investigate this phenomenon, **Figure 8** shows the correlation between throughput and Euclidean distance to the radio for the main hall measurements.
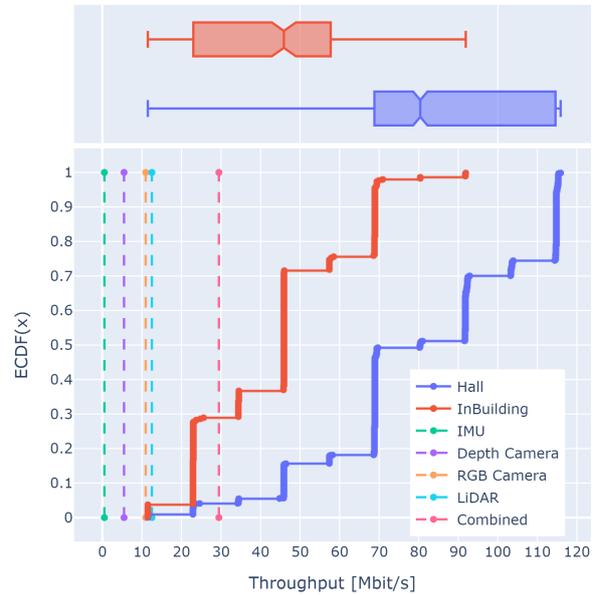

Fig. 7. ECDF and Boxplot of measured iperf3 TCP Throughput 5G Uplink in Mbit/s.
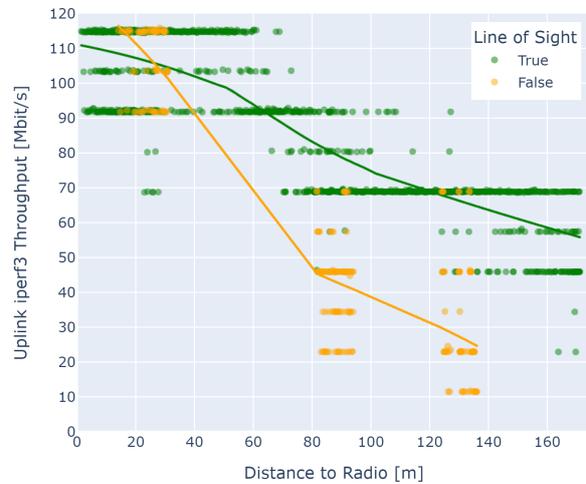

Fig. 8. Correlation uplink throughput to distance, colored by existence of line of sight. Main hall measurements only.

The data points in the buildings have no line of sight (LOS) by default, and, thus, are excluded here. The points are colored depending on the existence of a LOS, which was calculated using simple 3D models of the buildings in the main hall. For future work, it is very interesting to create a more precise 3D model, which also includes smaller obstacles, like the steel beams and trees, which are visible in the photo in **Figure 2**. Notice, since fitting a function for TCP throughput over distance is a complex task, the depicted trendline simply uses the Locally WEighted Scatterplot Smoothing (LOWESS) to visualize the trend. The trendlines not only highlight the expected throughput decline with increasing distance, but the slope difference also clearly indicates a stronger decline if the LOS is blocked. In general, electromagnetic waves can overcome a blocked LOS by transmitting through an obstacle or bending around it using diffraction. Since the buildings are made of reinforced concrete and the frequency of 3.8 GHz is rather high, transmission and diffraction are unlikely. Thus, a possible explanation is the impact of multipath reflections within the hall, especially at the roof, which spans across the whole facility.

Latency: While uplink throughput is usually the critical key performance indicator for data offloading, real-time systems also require low latency. This is especially important if time-critical functions shall be calculated by the data processing server, e.g., VSLAM. **Figure 9** shows the latency distribution in ms, approximated using half the RTT of ICMP Pings from the UGV through the 5G infrastructure to the server and back. The vertical lines indicate the 3GPP service requirements for the low-latency, high-reliability scenarios, cf. [7, Table 7.2.2-1]. Analyzing the data, which is shown in **Figure 9**, highlights the following key takeaways:

- In the main hall, the median latency is 19 ms, with a lower quartile of 26 ms and an upper quartile of 13.5 ms.
- The median latency only slightly increases to 21 ms in the buildings, but a higher variance leads to a lower quartile of 11.4 ms and an upper quartile of 32.375 ms.
- The targeted 60 ms 3GPP service requirement for Process Automation would be always achieved. This also applies to the 100 ms latency target for remote operation of Underwater UAVs, discussed in our DAUS 2025 paper [10].
- The 30 ms latency requirement for Intelligent Transport Systems is achieved in 83 percent of positions in the hall, and 70 percent in the buildings.
- For Discrete Automation, the ambitious goal of 10 ms latency can only be satisfied in 13 percent of data samples in the hall and in 22 percent in the buildings.
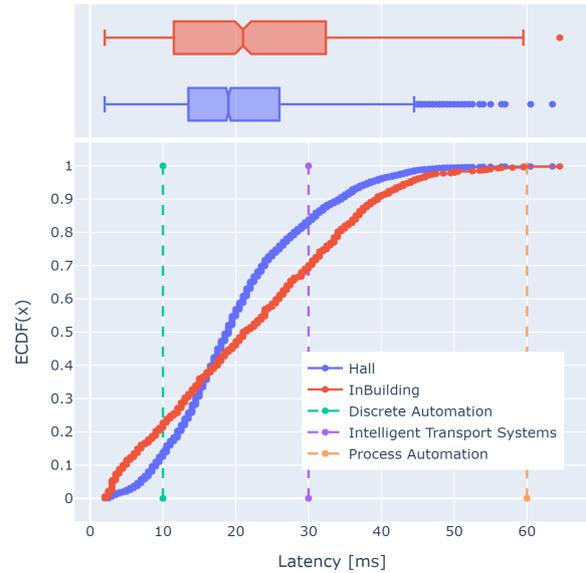

Fig. 9. ECFD and Boxplot of measured latency (one-way delay) in ms, using ICMP Ping RTT/2 approximation, the vertical lines represent the 3GPP 5G latency service requirements, cf. [7, Table 7.2.2-1].

5. Conclusion & Future Work

As shown by the presented evaluation, based on real-world measurements, the 5G service requirements for uplink and downlink throughput are mostly met, while latency is still partially an issue for real-time data offloading and online processing. The most important numbers for this use case are the presented median uplink throughputs of 80.4 Mbit/s in the hall and 45.9 Mbit/s in the buildings. Given some variance, this leads to a 96 percent satisfaction of the UGVs data offload demand in the hall and 71 percent in the buildings, cf. **Figure 7**. The service requirements regarding latency instead are only satisfied partially, e.g., the 30 ms latency requirement for Intelligent Transport Systems is only achieved 83 percent of time in the hall and 70 percent in the buildings cf. **Figure 9**.

For future work, we plan to extend the measurements to our full network configuration with multiple radios, thus, also evaluating the impact of handovers. Also, it is very interesting to create a high-resolution 3D model of the test area and use our measurements to evaluate the accuracy of modern Ray Tracing-based 5G signal propagation simulators, such as NVIDIA Sionna RT [11]. This approach would enable novel capabilities for unmanned systems, such as site-specific, communication-aware path planning, which is especially challenging in multi-robot scenarios.

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