

# Further Development of a Measurement Method assessing the Coverage Quality of a private Standalone 5G network.

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## Abstract

This paper demonstrates the methods that have been adopted and developed to measure the coverage quality of a private, standalone 5G network. Using the specific example of the private 5G network at the University of Cottbus-Senftenberg, this article presents the application of this method, from hardware to algorithms. The results show the relationships found between input factors such as variations in the physical context and in the network, and key performance indicators such as throughput and round-trip time.

## 1 Introduction

In recent years, the fifth-generation new radio (5G NR) mobile communication technology has been widely adopted across numerous industrial applications. Although there are some efforts to evaluate and characterize the status or quality of the network (see [1], [2]), evaluating a 5G stand-alone (SA) private network under the effects of variations in physical and network parameters remains to be explored. In particular, studies on mobile vehicles with 5G connectivity are limited (see [3]) because the current 5G public infrastructure is still limited. A further challenge in evaluating the performance of the 5G network for vehicles lies in the numerous input factors and their combinations. On the other hand, performance measurements involve selecting key performance indicators (KPIs) from a non-negligible list. For this reason, to obtain a sensible performance evaluation of the correlations between input factors and KPIs, the use of metadata analysis tools is crucial. The characterization of the 5G network also depends on the operator's configuration. In this work, we focus on the enhanced mobile broadband (eMBB) service, the most common service today [1].

The contribution of this work is the study of a 5G SA performance through a measurement campaign using 5G-enabled vehicles (on ground and in air) and the further analysis between relevant KPIs with respect to mobile characteristics like spatial position and velocities of vehicles, as well as the dependence under different data-related parameters like throughput and packet size.

## 2 Hardware used

For this Measurement Campaign a quadricopter unmanned aerial vehicle (UAV) and a cargo bike have been used as moving platforms. For our experiments we used the 5G SA private network provided at the Brandenburg University of Technology, Cottbus-Senftenberg (BTU-CS). The 5G network works indoors (in some Hallways) and outdoors. It supports the radio signals in the n78 frequency band with the eMBB service.

### 2.1 5G-Connected Devices

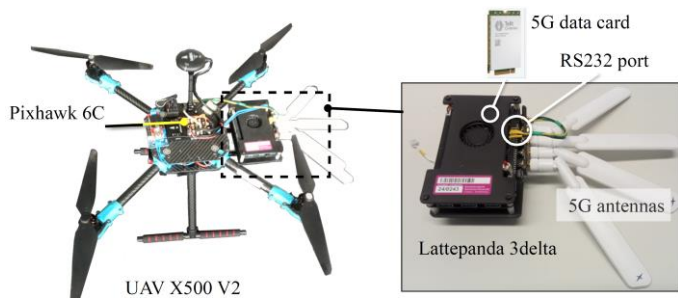
The measurement campaign is also designed to compare the performance of 5G SA-compatible hardware, either on mobile platforms or as a server. All devices are equipped with dedicated SIM cards and have the option of a fixed IP address. The SIM8200EA-M2 5G Hat from Waveshare is intended for a placement atop a Raspberry Pi 4 and based on the Qualcomm Snapdragon X55 platform. It offers compatibility with SA, NSA, 5G, 4G, and 3G, operates across multiple frequency bands including n78 (3.3 to 3.8 GHz), and supports eMBB. For more technical information, see [4] Another model, also from Waveshare, features the newer RM520N-GL 5G module, available as a hat for a Raspberry Pi 4 or as a dongle [5]. The Samsung Galaxy Tab S9 5G is included in the campaign for its broad network compatibility, specifically its support for 5G SA n78, although detailed information on its integrated 5G module is not provided [6]. The Telit FN990 data card, a compact board with an M.2 connection, is also utilized on the UAV; it supports 5G sub-6 GHz, SA and NSA operations, connects to the 5G core network, and is also compatible with band n78 [7].

### 2.2 5G-enabled UAV

The Telit FN990 data card is connected to the Lattepana 3Delta processor, which has a 4-core, 11th generation processor running up to 2.9 GHz and 8 GB of RAM. The Lattepana and FN990 antennas are attached to the rear of the UAV as a payload. The UAV is based on the X500 V2 frame and uses a Pixhawk 6C as its flight control unit. An additional power converter supplies the Lattepana with 12V. Additionally, the Lattepana 3Delta, which uses Ubuntu 22.04, is connected to the flight controller via the RS232 port for reading the UAV GPS and sensors, (see **Figure 1**).

### 2.3 5G-enabled Cargo Bike

The Raspberry and 5G Hat casing is mounted on the left side of the Cargo Bike with removable attachments, using a banded metal sheet to pinch the rim, (See **Figure 2**).



**Figure 1** UAV adaptation with 5G data card. Author: Rolando Cortés-Martínez.



**Figure 2** Driver point of view of the 5G-Hardware installed on the Cargo Bike. Author: Johan Levon.

A touchscreen installed on the handlebars serves as a human-machine interface. The 4 Antennas of the 5G Hat are between 70 and 96cm above the Ground Level.

The Galaxy Tab S9 was fixed facing the sky with the back double sided taped to the right side of the sitting surface of the cargo Bike. The integrated Antennas are at a height of 60cm above ground level.

### 3 Testing Methodology

The GPS position and its Coordinated Universal Time (UTC) are recorded every second. Algorithms test the latency and throughput of the connection to the 5G Network every 3 to 10 Seconds also with UTC. Both the positioning and performance are combined with UTC Timestamp. At the end we get a Map Showing the Performance corresponding to the localization on the Campus.

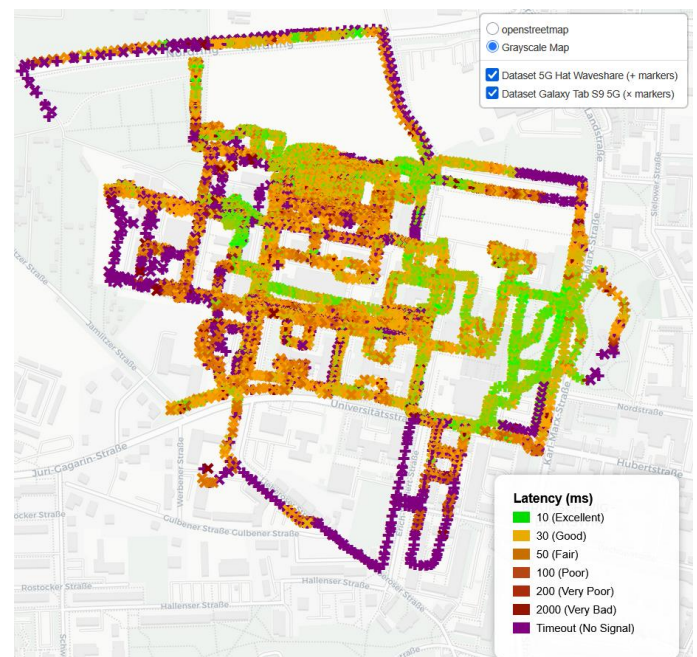
For the UAV recordings, the flights are carried out manually in public areas maintaining low speed, less than 3m/s, and in supervised automatic mode under empty-from-people conditions in the sport fields in the BTU installations. A total of 10 flights were recorded with different mission objectives. We tested different flight fixed altitudes of 5 m, 10 m and 20 m, but also a variable altitude from 0 m to 80 m with a constant elevation velocity. Another considered variable is the velocity, which was established at 1 m/s, 3 m/s, 5 m/s and 10 m/s. Finally, the orientation of the UAV (yaw angle  $\psi$ ) is constantly varying as the target way points are continuously updated. It is important to note that although for the missions definition we have fixed some variables, for the analysis of the data we use all the recorded information (e.g., UAV at ground level).

### 3.1 Monitoring the Position through GPS-Signal

For the Cargo Bike, although it is possible to replace one antenna with a GPS Module on the 5G Hat. It was decided to use the Tablet as GPS-GNSS Receptor for positioning. Giving the technology of the tablet, the proximity to Buildings and that the Cargo Bike was moving during the measurement, the expected Precision for the positioning lays between 3 and 10m.[8]. On the other side, an already integrated GPS module was used to measure the position in the UAV case. The accuracy of the position is higher with the drone, given his flying height of 10-80 meters above ground level, laying between 1 and 5 meters.

### 3.2 Measurements

A first data collection for coverage evaluation using the Round Trip Time (RTT) KPI was carried out with the Cargo Bike in combination with the two mounted 5G devices. Significant connectivity differences have been noted.[9] **Figure 3** shows the quality of the connection to the 5G network depending on the location.

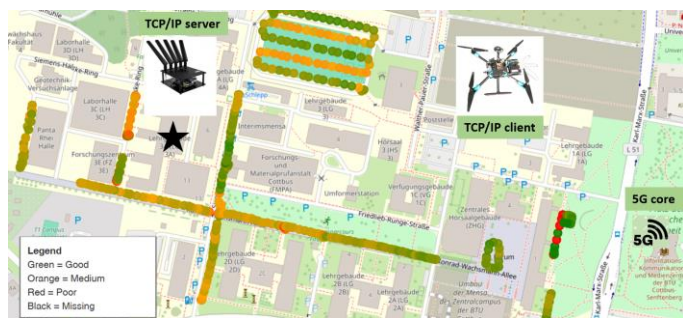


**Figure 3** 5G network coverage heat map with all the Data measured with the Cargo Bike. This interactive map is available on the iCampus Website [10]. Author: Johan Levon

To improve data collection, the iperf3 protocol was chosen. For simple ping tests, the fixed IP address of the 5G core router 192.168.88.100 is defined as the reference to ensure that all future measurements are comparable.

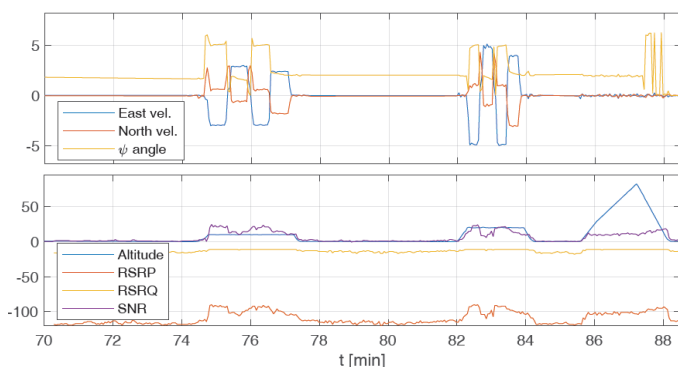
For the UAV the parameter and KPI measurements consists of the Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal to Noise Ratio (SNR), Yaw angle, the position of the UAV (latitude, longitude, and relative altitude), and velocities of the UAV (north velocity and east velocity). Additionally, the UAV captures the iperf3 measurements like the received data packages, throughput and RTT. For these tests we use the following configuration: TCP/IP protocol, port 5201 (single client connected to the server), 1 second *Duration* of the transmissions, 4 streams, infinity bandwidth, and 128 KB for the packet size. The latter value corresponds to the maximum size for TCP packages,

which is suitable for obtaining maximum values for throughput and at the same time we test the network and buffer near to the limits. We perform variations in speeds and altitudes in the sport field test flights while in the rest of the campus area we maintain fixed secure conditions (see **Figure 4**).



**Figure 4** Campus 5G mapping for the UAV at 20m altitude.

As part of the flights carried out in the sport fields, **Figure 5** shows an exemplary extract of the flights carried out. In this example, the UAV performs a zigzag trajectory with fixed altitudes of 10m in  $t = (74, 77)$  min, another altitude of 20 m in  $t = (82, 84)$  min and a growing altitude up to 80 m in  $t = (85, 88)$  min. While the altitude is fixed at 10m or 20m the UAV surveys a series of way points at maximum nominal velocity of 3m/s and 5m/s, respectively. The directional angle yaw is also shown.



**Figure 5** Extract UAV flight measurements campaign 2025.

## 4 Results and Data Analysis

This section describes the exploratory data analysis of the 5G signal measurements. The data consisted of two separate data sets, measured from the client and from the edge side simultaneously. As a first step, the two data sets were merged, synchronized based on the time stamps. Since the synchronization of the time stamps from the two measurements were not perfect, a 3 second tolerance was applied that assumed data points captured within the tolerance measure the identical signal occurrence. Upon closer investigation this assumption proved to be accurate.

The merged dataset contained missing values, which severely impacted the possibility to analyze it, this required the imputation of the dataset. Imputation is the process of estimating and filling in the missing values based on the available data. It is generally possible to produce a complete dataset without introducing significant bias or distortion.

Simple imputation methods such as filling missing values with the mean or the median of the column ignore the correlation between the features. In this study, the Iterative Imputer from iCCC2026 - iCampus Cottbus Conference 2026

scikit-learn was used, that provides a more sophisticated and multivariate approach. Here, each missing value of a feature was modelled as a function of the other features in a round-robin fashion. The iterative imputation process consists of the following steps:

- Initially the missing values are filled with the means of available values of that feature
- For each feature that has missing values, the remaining features are used to predict the missing values by using Bayesian Ridge regressor
- The process is continued for all features with missing values repeatedly, until a convergence is reached.

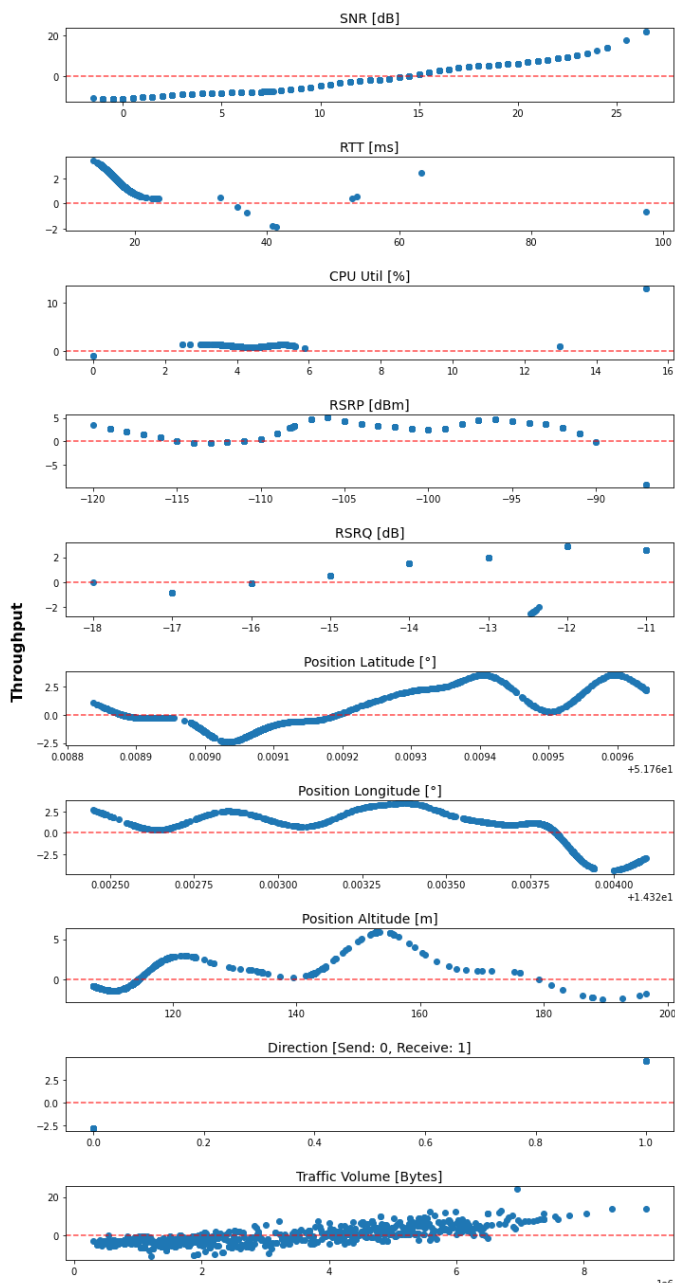
This method effectively uses the full feature covariance structure to produce more accurate estimates for missing values of throughput (Mbps), RTT (ms), CPU Util (%), RSRP, RSRQ, SNR, *position.lat*, *position.lon*, *position.alt*, *Direction* and *Bytes*.

In the last step, the Linear Generalized Additive Models (GAMs) was used to visualize the detailed correlation of separate variables with each other. Within the framework of this study, the *Throughput* was chosen as the main variable of interest, other variables were varied individually while keeping the rest constant to determine their impact on *Throughput*. GAMs are a powerful class of models that balance the interpretability of linear models with the flexibility to capture non-linear relationships. They are well-suited for analyzing complex, non-linear dynamics often observed in 5G network performance metrics.

A Linear GAM expresses the expected value of the target variable  $Y$  (in this case *Throughput*) as a sum of smooth, non-linear functions of the individual predictor variables (SNR, RTT, etc.), instead of a simple linear combination. Since relationships are additive across the functions in linear GAM, there are no interaction terms between the predictors, making the contribution of each feature easily discernible. Linear GAM has advantages for the 5G data analysis, such as interpretability, flexibility and robustness.

- Interpretability: Since the model is a sum of univariate functions, the impact of each feature on the target variable can be visualized and interpreted independently, providing clear insights into the non-linear operational dynamics of the 5G network.
- Flexibility: The smooth functions (in the internal components of GAM) allow the model to accurately fit complex, non-monotonic relationships between network parameters without requiring manual feature engineering.
- Robustness: They are generally more robust to outliers and misspecification than purely parametric models.

By using GAMs, the non-linear relationship between, for example, the RSRP and the resulting *Throughput* can be modeled precisely, offering a more realistic representation of network behavior than a simple linear regression. **Figure 6** shows the Partial Dependence Plots (PDP) of the network features on the *Throughput*, it consists of 10 different plots, each showing the individual impact of a network parameter on the *Throughput*. The X-axis represents the range of the predictor variable; the Y-axis represents the estimated contribution of the predictor variable (*Throughput* in this case).



**Figure 6** PDPs for Throughput showing the effect of the network features on the predicted network throughput, based on GAM analysis. In the Direction plot the value of 1 denotes Sent, a value of 0 Received.

From Figure 6, we can find some interesting relationships. For example, as RSRQ approaches -12.5 dB the *Throughput* exhibits a decay. A positive impact value indicates that the specific value of the predictor variable contributes to a higher predicted value of the target variable *Throughput*. A negative impact value indicates that the specific value of the predictor value contributes to a lower predicted value of *Throughput*. The steepness of the curve represents the sensitivity or magnitude of the effect at that point. The zero line is added to each plot to simplify the interpretation. The value is above, it improves the *Throughput*, below, it reduces it.

## 5 Perspectives

Further extension of the work can address the deeper analysis of the data through the extensive utilization of GAM modeling for the different KPIs versus input factors. Additionally, more PDPs should be used to show the correlations of more target variables. The current results can serve as a foundation to design more advance measurement campaigns focused on specific aspects of the 5G network, for example to analyse the effect of buildings and trees in the surroundings.

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