Delft University of Technology
Faculty of Architecture

P2 - GRADUATION PLAN

MSc GEOMATICS

5G POSITIONING

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Contents

Abbreviations

3GPP	3rd Generation Partnership Project
5G	Fifth-Generation
AOD	Angle of Departure
AOA	Angle of Arrival
AP	Access Point
AT	Attention
CID	Cell-Identity
DL	Downlink
DL-AoD	Downlink Angle of Departure
DL-TDOA	Dowlink Time Difference of Arrival
DOP	Dilution of precision
eMBB	Enhanced Mobile Broadband
FSPL	Free Space Path Loss
FR	Frequency Range
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IoT	Internet of Things
IT	Information Technology
LTE	Long Term Evolution
LOS	Line-of-Sight
mmWave	millimeter-Wave
MC RTT	Multi-Cell Round Trip Time
MC-RTT	multi-cell round trip time
MIMO	multiple-input multiple-ouput
mMTC	massive machine-type communication
NTRIP	Networked Transport of Real Time Configuration Management (RTCM) via Internet Protocol
NR	New Radio
NSA	non-standalone
OSR	Observation Space representation
PDOP	Position Dilution of Precision
RP	Reference Point
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RSRP	Reference Received Signal Power
RTK	Real-Time Kinematic
RTT	Round Trip Time
RTCM	Real Time Configuration Management
SA	standalone
SRS	Sounding Reference Signal
SSR	State Space representation
TDoA	Time Difference of Arrival
TMF	Transmission Measurement Function
ToA	Time of Arrival
UE	User Equipment
UL	Uplink
UL-AOA	Uplink Angle of Arrival
UL-TDOA	Uplink Time Difference of Arrival
UP-AoA	Uplink Angle of Arrival

1 Introduction

The development of Fifth-Generation (5G) communication technology plays a significant role in connectivity, offering enhanced speed, low latency, and revolutionary applications in a variety of fields. Global Navigation Satellite System (GNSS)s have been the primary technology for positioning lately, and simple devices such as our smartphones integrate GNSS data with insights from other sensors to enhance their position estimation accuracy. The deployment of 5G technology promises new possibilities in positioning, beyond its crucial role in the communication field. First of all, GNSS corrections can be broadcasted by 5G networks, but this is out of the scope of this project. Secondly, additional range measurements can be provided especially in environments where there is limited visibility to satellites in order to augment GNSS.

This study addresses the core question of the current accuracy of 5G positioning in different scenarios based on the Received Signal Strength Indicator (RSSI) and includes the evaluation of 5G positioning with GNSS-Real-Time Kinematic (RTK).

The project takes place in collaboration with CGI[1], a global Information Technology (IT) and business consulting services firm. The external supervisor is Robert Voûte and the university supervisors are Edward Verbree (1st supervisor) and Martijn Meijers (2nd supervisor). They all provide valuable guidance throughout. Additionally, Ericsson[2], a 5G hardware vendor, is also playing crucial role by providing the necessary equipment for testing various cases as well as expertise and resources due to previous similar projects (see Section 6).

However, it is crucial to note that the equipment necessary for the project was delivered in the second week of 2024. Consequently, no preliminary results have been obtained at this stage. Testing and analysis that lead to meaningful insights into 5G positioning accuracy and its integration with GNSS-RTK will take place in the upcoming weeks.

[1]https://www.cgi.com/en
[2]https://www.ericsson.com/en

2 Related Work

2.1 5G and possibilities

The precise determination of location information facilitated by 5G cellular networks provides a great potential for various commercial applications in fields like transportation, public safety, retail and healthcare. In comparison to previous mobile generations like Long Term Evolution (LTE), 5G technology introduces New Radio (NR) access technology, offering advantages for precise positioning. 3rd Generation Partnership Project (3GPP), a global collaboration defining mobile communication standards for interoperability and compatibility, introduced 5G NR in release 16, stating that it meets diverse metrics for Enhanced Mobile Broadband (eMBB), low-latency communication, and massive machine-type communication (mMTC) (Pileggi et al., 2023 & Cardoso et al., 2020).

The 5G positioning methods include a variety of measurements that are associated with the user equipment. These measurements can refer to either the angles or the distances of the received signals. Angular measurements encompass the Uplink Angle of Arrival (UP-AoA) or the Downlink Angle of Departure (DL-AoD). Distance-based measurements include Time of Arrival (ToA), Downlink (DL) and Uplink (UL) Time Difference of Arrival (TDoA), Round Trip Time (RTT) and multi-cell round trip time (MC-RTT). These are implemented in several modes: User Equipment (UE)-assisted, UE-based, stand-alone and network based (Alghisi and Biagi, 2023 & Elshaer et al., 2014 & Pileggi et al., 2023).

Frequency Range (FR) 1 is a high-frequency range that is used for 5G deployment. It ranges from 24.3 GHz to 52.6 GHz in addition to FR 2, which covers frequencies below 7 GHz. Thanks to these bands, is used to overcome the challenge of limited spectrum availability in wireless communication, enabling high data rates, capacity, and bandwidth with minimal latency. It also ensures superior positioning accuracy. Radio signals within this frequency range experience penetration and diffraction losses, resulting in a predominant Line-of-Sight (LOS) element and reduced multipath effects . Although millimeter-wave wireless signals have advantages, they also present challenges such as high path loss. However, these challenges can be addressed through the adoption of specialized compensation techniques like beamforming and highly directional antennas (Alimi et al., 2020 & Pileggi et al., 2023).

NR provides a crucial improvement in comparison to LTE, by providing up to 100 MHz in FR1 and 400 MHz in FR 2, at the same time that LTE supports a maximum of 20MHz. The variability in delay estimation is inversely related to signal bandwidth. This means that as signal bandwidth increases, the uncertainty in delay estimation decreases due to the narrowing of the main lobe in the correlation function. A narrower lobe makes it easier for the receiver to discriminate, leading to improved differentiation between direct and reflected paths (Pileggi et al., 2023 & Alimi et al., 2020).

Massive multiple-input multiple-ouput (MIMO) refers to the utilization of base stations with numerous antennas leading to potential interference challenges. These interference issues can be effectively addressed by employing beamforming. Beamforming is a strategic process that shapes the radiated beam patterns of antennas by consolidating processed signals towards intended terminals while nullifying interfering signal beams. The use of beamforming optimizes the energy consumption of the system, enhances the overall data transmission capacity and contributes to increased system security by mitigating interference. Moreover, beamforming proves to be well-suited for millimeter-Wave (mmWave) bands, demonstrating its versatility across different frequency ranges (Ali et al., 2017).

2.2 Positioning Methods

2.2.1 Cell-Identity-Based

Cell-Identity (CID) method, also known as proximity-based method is used in order to determine whether an object is located in a specific radio coverage area. To estimate this location, essentially the service base station's location should be known as well as the area of the serving cell that is utilised. For more effective results, a considerable amount of base stations needs to be deployed (Liu et al., 2017 & Mogyorósi et al., 2022).

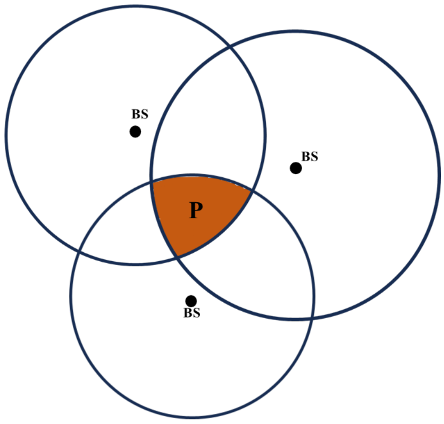

Figure 1: Cell-Identity-Based Positioning

2.2.2 Angle-Based

Angle-based positioning is a technique used to determine the position of a target in a given space by leveraging angle measurements of the received radio signals. In this method, the angles between the target and known reference points are measured. By triangulating these angle measurements, the system can calculate the target's location (Liu et al., 2017 & Mogyorósi et al., 2022).

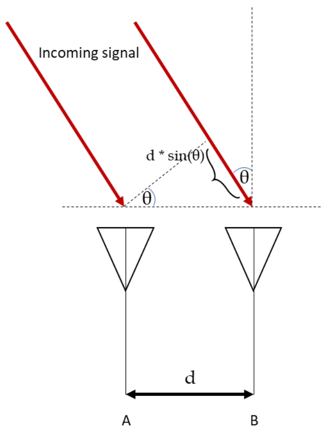

Figure 2: Angle-of-arrival

2.2.3 Trilateration

Trilateration depends on the distance between the transmitters and a receiver or the other way around, aim to determine the unknown location of the user equipment. These measurements involve the extraction of information such as the Received Signal Strength (RSS), the ToA, and the TDoA. The ToA method refers to measurements of the speed of wavelength and the time taken by radio signals to travel between an anchor node and a node with unknown position, enabling the estimation of this node's coordinates. (Liu et al., 2017 & Mogyorósi et al., 2022).

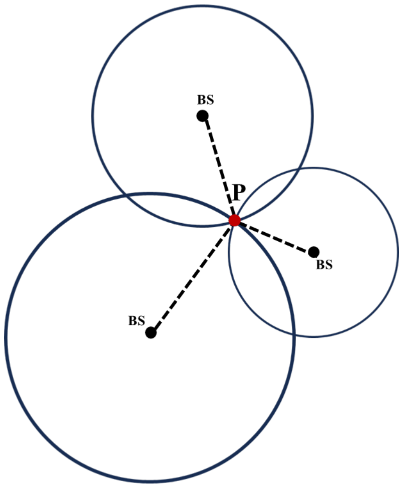

Figure 3: Trilateration

2.2.4 Fingerprinting

Fingerprinting refers to the measurements of the signal strength of different Access Point (AP)s at known Reference Point (RP)s to determine the user's location. The first phase of the method is the offline, where the fingerprint database is created according to the collection of signal strength data at various RPs. The online phase utilizes real-time signal strength measurements from the mobile device, employing at the same time specific matching algorithms to identify the closest fingerprint match in the database. The location information associated with the matched fingerprint reveal the user's location. (Xia et al., 2017 & Liu et al., 2017 & Mogyorósi et al., 2022).

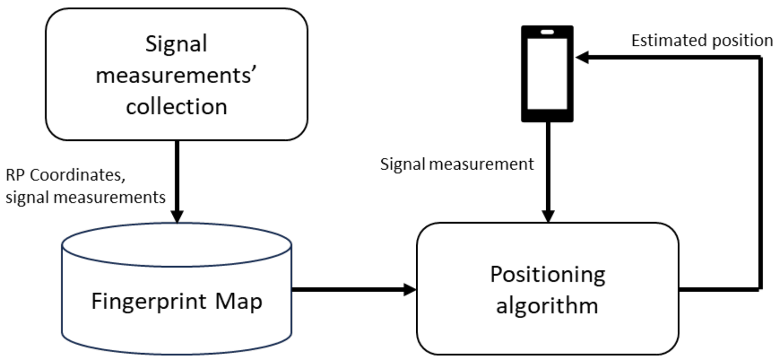

Figure 4: Fingerprinting

2.3 5G Positioning methods

Many of the positioning methods mentioned in 2.2 , can be implemented with 5G technology. Its observations can be transmitted either from the user to the base stations (uplinked) or from the base stations to the user (downlinked). These methods are summarized in figure 5 (Alghisi and Biagi, 2023 & Keating et al., 2019).

The 5G positioning methods:

- Dowlink Time Difference of Arrival (DL-TDOA):
  DL-TDOA is a positioning technique where the receiver measures the difference in arrival times of DL signals from multiple base stations. This is typically achieved by comparing the timing of reference signals, from these base stations. Then, the receiver reports these reference signal time differences to the network's location server. Using known positions of the base stations and the reference signal time differences' measurements, the location server calculates the position of the receiver.

- DL-AoD:
  The DL-AoD is utilizes the Reference Received Signal Power (RSRP) reports from the receiver to determine

the Angle of Departure (AOD) from multiple base stations, enabling triangulation of the receiver based on the AOD. More specifically, it refers to the angle at which signals are transmitted from the base station to the user device, departing from the base station antennas.

- Uplink Time Difference of Arrival (UL-TDOA):
  In this case, the receiver transmits a Sounding Reference Signal (SRS) that is received by multiple base stations. Using the NR measurement function that was introduced in Release 16 called Transmission Measurement Function (TMF), the measurement of the relative ToA is computed and tranmsmitted to the location server. The receiver's position is then calculated based on the relative ToA measurements of the signals of all the base stations.

- Uplink Angle of Arrival (UL-AOA):
  The SRS is utilized as the reference signal for measuring AoA. The receiver transmits SRS signals to the base station periodically. By analyzing the received SRS signals at the base station, the network can estimate the Angle of Arrival (AOA) of the incoming signals. This involves processing the signal to determine its phase and amplitude characteristics relative to the antenna array, enabling the calculation of the angle of arrival.

- Multi-Cell Round Trip Time (MC RTT):
  MC RTT method is similar to the other time-related techniques. However, the main difference of this method is that it utilizes both the DL and UL received signal in order to perform the trilateration and estimate the receiver's position. The increased the total cost should be considered as a big disadvantage, but using MC RTT the synchronization errors are avoided.

Method	Description
DL-TDOA: Downlink Time Difference of Arrival	Based on Time of Arrival (TOA) measurements of DL signals received from multiple base stations (BSs) to user equipment (User). Computed quantities: - OTDOA: Observed TDOA - RTD: Real time difference - GTD: Geometric time difference
DL-AOD: Downlink Angle of Departure	Based on reference signal received power (RSRP) measurements performed by user. User requires assistance data from the network: a list of candidate BSs, BSs' geographical locations and beam information.
UL-TDOA: Uplink Time Difference of Arrival	User's signal is received by multiple BSs, which compute the TOA. Measurements have a common time scale and are called UL-Relative TOA (UL-RTOA). Then, they are sent to the location management function (LMF), which computes the TDOA.
UL-AOA: Uplink Angle of Arrival	The received signal from the user is transformed by gNodeB (gNB) in azimuth and elevation, and directional antennas are required, implying the network-based mode.
RTT: Round Trip Time	Uses two-way TOA measurements and requires no BS synchronization.
MC RTT: Multi-Cell Round Trip Time	Estimate RTT between multiple gNBs, requires both UL and DL. No synchronization errors.

Figure 5: 5G Positioning Methods (Alghisi and Biagi, 2023)

2.4 Free Space Path Loss

During the transmission of radio or electromagnetic waves in open space, wireless communication can be affected by many loss mechanisms such as attenuation, reflections and refractions. One of them is Free Space Path Loss (FSPL) which is the reduction of the signal strength along a direct LOS path through open space. This type of loss is proportional to the square of the distance separating the transmitter and the receiver, as well as the square of the frequency of the radio signal. The equation that describes this expression mathematically is shown below (Ahmad et al., 2019 & Islam and Haider, 2010):

$$\begin{aligned}\text{FSPL(dB)} &= 10\log_{10}\left(\left(\frac{4\pi df}{c}\right)^2\right)\\ &= 20\log_{10}\left(\frac{4\pi df}{c}\right)\\ &= 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)\\ &= 20\log_{10}(d) + 20\log_{10}(f) - 147.55.\end{aligned} \tag{1}$$

where f is the frequency, d is the distance between the transmitter and the receiver, and c is the speed of light. Utilizing SI units, d is measured in meters, f in hertz (s^{-1}), and c in meters per second ($\frac{\text{m}}{\text{s}}$). In a vacuum, the speed of light (c) is $299,792,458\,\text{m/s}$.

For typical radio applications, it is common to find d measured in kilometers and f in gigahertz, in which case the FSPL equation becomes:

$$\text{FSPL(dB)} = \text{RSSI(dB)} \tag{2}$$

$$\text{RSSI(dB)} = 20\log_{10}(d_{\text{km}}) + 20\log_{10}(f_{\text{GHz}}) + 92.45, \tag{3}$$

$$\text{RSSI(dB)} = 20\log_{10}(d_{\text{km}}) + 20\log_{10}(f_{\text{GHz}}) + 92.45 \implies$$

$$\text{RSSI(dB)} = 20\log_{10}(1000 * d_{\text{m}}) + 20\log_{10}(f_{\text{GHz}}) + 92.45 \implies$$

$$\text{RSSI(dB)} = 20\log_{10}(d_{\text{m}}) + 20 * 3 + 20\log_{10}(f_{\text{GHz}}) + 92.45 \implies$$

$$\text{RSSI(dB)} = 20\log_{10}(d_{\text{m}}) + n1 + n2 + n3 \tag{4}$$

where:

$$n_1 = 20 * \log_{10}(1000) \rightarrow n_1 = m * 3 \tag{5}$$

$$n_2 = 20 * \log_{10}(f) \tag{6}$$

$$n_3 = 92.45 \tag{7}$$

So, by putting together all additive constant parts in "n", the final equation for finding RSSI is:

$$\text{RSSI(dB)} = 20 * \log_{10}(d_{\text{m}}) + n \tag{8}$$

However, the idea of multiplying the $\log_{10}(d_{\text{m}})$ with 20 (10×2) is only valid for omnidirectional free-space propagation. The 5G antennas are not omnidirectional, so in this case, it will be a different value than 2. In any case, m and n are both constant values as the frequency is always the same, regardless of the distance. So, the final equation is:

$$\text{RSSI(dB)} = m * \log_{10}(d_{\text{m}}) + n \tag{9}$$

2.5 Real-Time Kinematic (RTK)

RTK is a technique used to improve the accuracy of a standalone GNSS receiver. RTK is an advanced positioning method surpassing standard Global Positioning System (GPS) accuracy, which is two to four meters. Unlike conventional GPS, which relies on pseudorandom codes, RTK utilizes carrier waves for more precise measurements (Hexagon, 2023).

Two GNSS receivers are utilised in RTK, a base station and the user's GNSS receiver, also known as the rover. In this method, a GNSS base station is positioned at a fixed location, and both the base station and the user's GNSS receiver simultaneously gather GNSS observations. The base station then transmits its observations, including pseudo-range and carrier-phase data, along with its accurate position, to the user through a suitable communication link (Feng and Wang, 2008). The user's GNSS receiver uses this correction data to improve its own computed position from the GNSS and then it is able to achieve centimeter precision.

By incorporating GNSS carrier-phase observations and ambiguity resolution, RTK positioning achieves centimeter-level accuracy in open-sky scenarios. However, its performance faces challenges in deep urban environments where the accuracy requirements for dynamic systems are not consistently met. In such settings, buildings can obstruct, weaken, reflect, and diffract GNSS signals, leading to insufficient visible satellites and observations affected by severe multipath effects. This limits RTK's effectiveness in delivering high-precision positioning in urban landscapes (Feng and Wang, 2008).

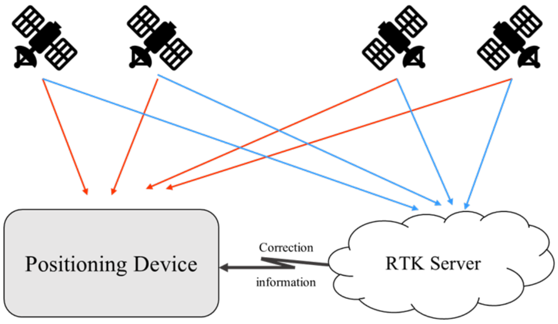

Figure 6: GNSS - RTK

2.6 RTK Errors

Pseudo range, is derived from the observed travel time of a signal transmitted from a satellite to a receiver, multiplied by the speed of light. This measurement, however, is susceptible to various sources of error such as satellite orbit and clock discrepancies, biases in satellite and receiver hardware, and atmospheric effects like ionospheric and tropospheric influences. Providers of GNSS augmentation services generate corrections in real-time by constantly monitoring signals received from reference stations (Geo++, 2023).

GNSS positioning accuracy is based on several types of errors(Groves, 2013):

- Ionospheric errors: as the signal "travels" through the ionosphere, the conditions of it and its density of electrons can play a significant role in the signal propagation.
- Tropospheric errors: GNSS signals are delayed while passing throughout the troposphere depending on the differente heights of earth's surface. That is why, very high height difference between the base stations and the rover is not ideal.
- Signal obstructions: the number of visible satellites is reduced when an obstacle exists leading to reduced GNSS performance. Also, different types of materials and surfaces such as glass, can reflect the signal and affect travel time of it.
- Geometric configuration of satellites: GNSS design is based on autonomous code observation with world-wide coverage, ensuring the visibility of at least four satellites positioned above 5°all time. A deficient satellite arrangement (distribution as perceived by the observer) results in elevated Dilution of precision (DOP). Moreover, for 3D positioning, having at least four observable satellites is essential when relying on phase observations. So, when brief interruptions exist, then Real-Time Kinematic (RTK) measurements become impracticable with a single GNSS system.
- Other errors: satellites transmit to the GNSS receivers information for their clock offsets and orbits.

For these corrections there are two types of representations that provide different qualities, the Observation Space representation (OSR) and the State Space representation (SSR) (Chen et al., 2023 & Verbree, 2023).

More specifically, the objective of OSR is the creation of virtual GNSS reference stations by interpolating observations of multiple GNSS reference stations (Geo++, 2023). The total GNSS error for the carrier phase observations is an aggregate of distance-dependent errors. In RTK-networking, an inherent uncertainty exists, referred to as the representation error, influenced by the irregular physical conditions between the real reference stations. This error persists unless the distance between the stations is reduced and cannot be mitigated (Chen et al., 2023 & Wübbena et al., 2005).

On the other hand, in SSR all the the individual GNSS error components are estimated as state parameters. These real-time parameters are sent to the rover, allowing the user to refine their observations from a singular GNSS receiver. By using the SSR corrections that are specific to their individual position, RTK positioning is conducted based on the adjusted observations (Chen et al., 2023 & Wübbena et al., 2005).

The utilization of high-speed cellular networks such as LTE or 5G leads to the share of data in order to improve the accuracy of location information of single devices. The integration of GNSS correction data with other capabilities of the cellular network to enhance location-related services can take place in order to regularly update a server with information about where a device is located, to use the cellular network to independently confirm and validate the accuracy of the location information provided by GNSS and most importantly, to determine a device's location using methods that rely on the characteristics of the specific radio access network, such as 5G, for improved precision (Gunnarsson and Shreevastav, 2022).

3 Research Objectives

3.1 Research Questions

The main research question is "To what extent can the trilateration method for positioning utilizing only the RSSI of the 5G network serve as an alternative to current positioning solutions?".

The subquestions to be addressed in this research are:

1. What is the potential accuracy of standalone 5G positioning with trilateration method in comparison to the 'ground truth' given by GNSS-RTK solution?

2. What is the impact of topographic factors (e.g., buildings, urban canyons) on the accuracy of 5G positioning?

3. What is the latency performance of standalone 5G positioning?

4. How is Position Dilution of Precision (PDOP) affected by the distribution of the 5G network?

3.2 Scope

The project's scope is about finding the position of a device using the 5G network. Practical aspects of the project refer to attaching 5G antennas to a device (see Section 6) to assess signal reception as well as get precise positioning with a GNSS-RTK device (see Section 6) . This equipment allows real-world assessment of how well the system performs in the cellular network in terms of signal strength and stability. The positioning algorithm that will be implemented is based on trilateration method of positioning using the RSSI. The position measurements are validated with regards to the given "ground truth" through GNSS-RTK.

The study's practical implementation and validation against ground truth enhance the reliability and applicability of the proposed 5G positioning methodology (see Section 4). The research advances the understanding of positioning technologies, crucial for optimizing location-based applications in the 5G era.

3.3 CGI Scope

The reliance on GNSS faces many challenges such as availability in obstructed environments, accuracy issues and vulnerability to spoofing. CGI is interested in this thesis project, because 5G positioning promises an alternative solution, offers broader coverage, and potential enhanced reliability and resistance to spoofing. The integration of 5G positioning alongside GNSS addresses the limitations of traditional positioning systems, ensuring reliable and accurate location data for CGI's applications and clients.

3.4 Potential Use Cases

This study aims to have practical applications across various domains. The high accuracy positioning using RSSI promises precise personnel tracking for enhanced safety and operational efficiency. The integration with storage databases facilitates improved asset management in industrial environment. Its versality extends to outdoor and indoor positioning, optimizing logistics and navigation. In healthcare, it enables effective patient monitoring and staff coordination (Traboulsi, 2022).

3.5 Out of Scope

Out of the scope of the project is the fingerprinting method for positioning. Although fingerprinting can be effective in certain scenarios, it introduces complexities and requirements, such as the need for an extensive database and ongoing maintenance to account for changes in the environment. For accurate positioning, cell-id based method is not preferred since its main purpose is to identify the general proximity of a device to particular 5G cell. Furthermore, positioning methods that involve time or angle of arrival or departure of signals rely on the capabilities of the provided equipment and pose challenges in terms of signal processing and mathematical modelling. So, the most suitable positioning method is trilateration based on RSSI which offers a more streamlined and manageable implementation, ensuring that resources are directed towards achieving the project's primary goal of assessing the performance of the positioning system.

4 Methodology

The methodology is divided in five steps as is shown in figure 7.

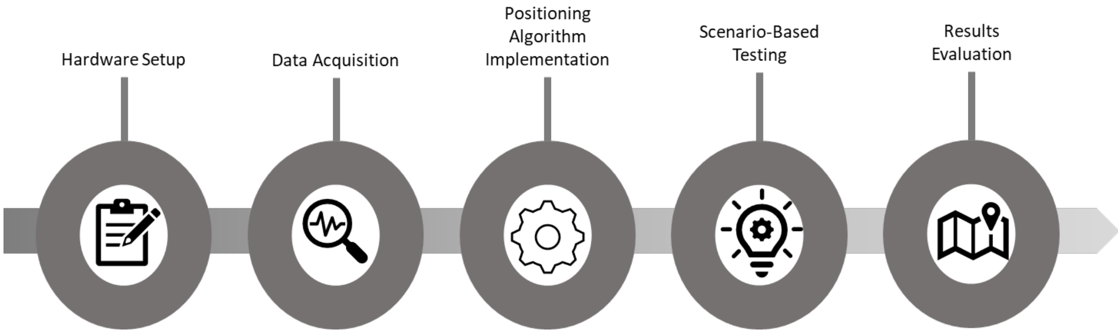

Figure 7: Methodology Steps

- Hardware Setup

  Since the equipment has just been delivered, it is necessary to ensure proper configuration and functionality of both devices that are going to be utilized for the scope of this study, the Ublox C099-F9P (see Section 6) and Quectel RM520N-GL (M.2. device) (see Section 6). So far, the GNSS-RTK seems to operate properly by delivering real time coordinates. Regarding, the 5G modem, this has also been installed and configured in the Linux environment. However, it needs to be ensured that it is successfully attached to the right network, and get the location information of the surrounding cell towers.

- Data Acquisition

  The next step is to collect the relevant data from the devices. The Quectel RM520N-GL designed for network communication, will provide network information such as the signal strength and the cell id, the identification of the current cell in the cellular network. These two types of data as well as the Location Area Code will play a crucial role in the positioning methods.

  To obtain this information, the use of Attention (AT) commands over a serial interface will be utilized. The module responds with information in text format.

  The idea of the preliminary testing is to record the RSSI from a specific cell tower with a known position for different distances i along the direction towards which the antenna transmits signals and then use the equation 9 to calculate the $\log_{10} d_i(\text{m})$ for all d_i. Then, a linear regression will be performed to determine m and n best fitting the linear relation between the $RSSI_i$ and $\log_{10} d_i(\text{m})$. The distances i from the 5G antenna will be validated by the GNSS-RTK device.

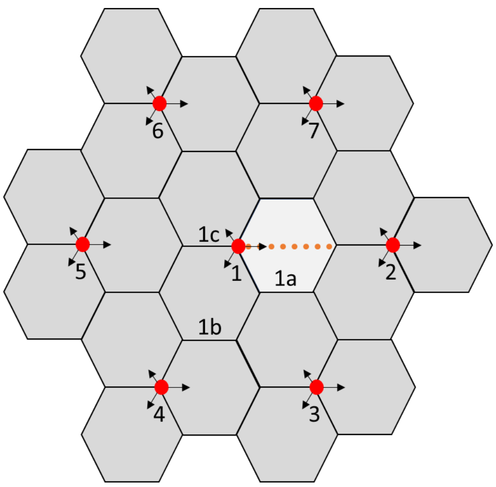

Figure 8: Preliminary testing along the direction towards which the 5G antenna transmits signals

After achieving having some first results, the potential error will be determined. The next step, is to complete some measurements for the same cell tower, but this time along an angular direction as shown in figure 9 so as the distribution of the RSSI is evaluated.

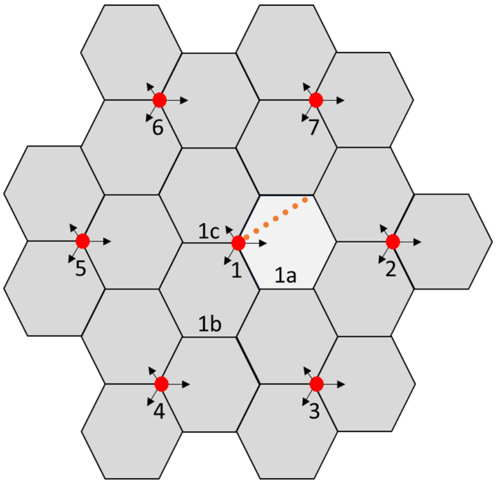

Figure 9: Preliminary testing along an angular direction in regards with the one which the 5G antenna transmits signals

On the other hand, U-blox C099-F9P is a high-precision GNSS positioning module. So, information will be gathered about latitude, longitude, altitude and the current time as provided by the GPS satellite sytem. The signal strength and the number of visible satellites will be obtained too. The estimated errors for both horizontal and vertical positions will be stated, and when there is connection to the Networked Transport of RTCM via Internet Protocol (NTRIP) module, corrections will be received to improve the accuracy of the position. This information will be used just to validate the error of the 5G positioning algorithm.

- Positioning Algorithm Implementation

  The positioning algorithm that will be implemented is based on the positioning method of trilateration. All the neighboring 5G cell towers will be utilized for the computation of it. Knowing the RSSI of at least 3 cell towers, it will be possible to calculate the distance from the receiver to each one of them. Then, the position of the receiver can be determined as described in Section 2.2.3. The error of the computed position will be evaluated according to the known coordinates that will be provided from the GNSS-RTK device. During the experiments, the latency of both 5G RSSI and GNSS-RTK data will be measured to precisely quantify the time delay in data transmission. In this way, the respective performance characteristics will be analyzed aiming to find an answer for the research sub-question 3.

- Scenario-Based testing

  In addressing the research sub-question 2, the system's accuracy will be evaluated in a stationary environment to establish a baseline, and monitor how the signal stability is handled and maintains accuracy over time. Then, the system will be tested in optimal conditions, which are an open outdoor environment with a clear line of sight to satellites and minimal signal obstructions. As soon as the process of the first scenario is finished, the system's performance will be assessed through simulations with movement and its adoption to changes in position and whether it can provide accurate and timely updates will be investigated. It needs to be mentioned that all the tests are going to take place in the city of Delft, as well as in Prins Alexander area in Rotterdam where the CGI offices are. In figures 10 and 11 the 5G cell towers' distribution provided by Vodafone[3] are shown. These locations offer diverse urban environments suitable for assessing the performance of the 5G positioning system in different scenarios, such as urban canyons, open spaces, and areas with various signal obstructions. The estimation precision parameter PDOP will also be evaluated so as an answer to 4 is given, after evaluating the error in regards to the distribution and ranges of the 5G cell towers.

[3]https://antennekaart.nl/

Figure 10: 5G network Delft (provided by Vodafone)

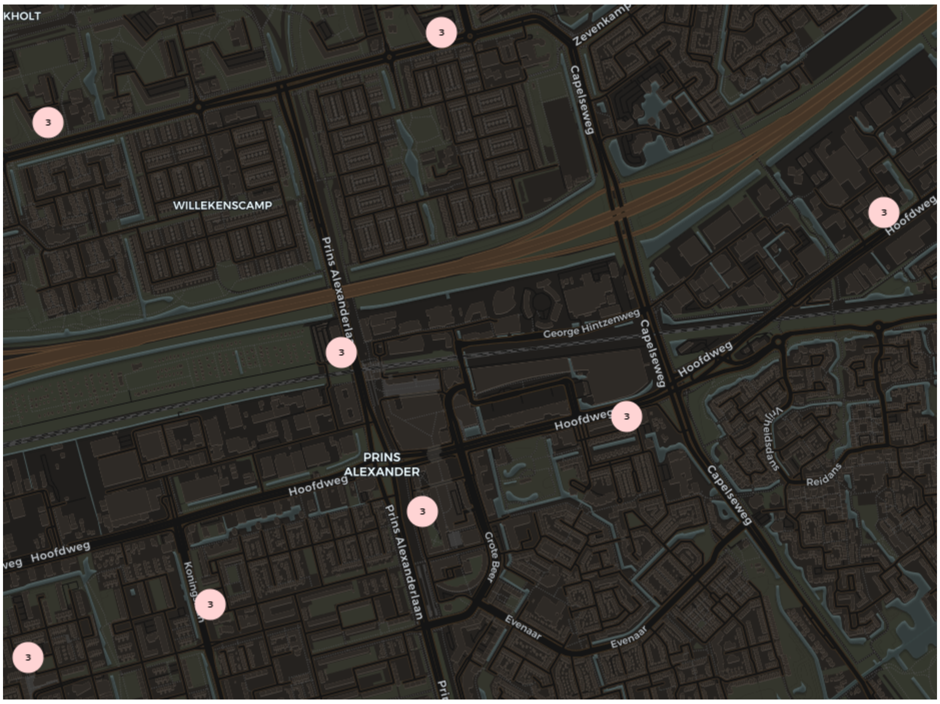

Figure 11: 5G network Prins Alexander area, Rotterdam (provided by Vodafone)

- Results Evaluation

  In the last step, the system's accuracy will be measured by comparing the calculated positions with the ground truth data so as the research sub-question 1 is answered. Moreover, the analysis of the impact of topographic factors (e.g. buildings, terrain) on the accuracy will take place (sub-question 2). Results will be visualized through maps, graphs, and charts to illustrate the analysis of the 5G positioning system in different scenarios and environments.

5 Time Planning

The Gantt chart outlines the comphrehensive sets of activities that need to be implemented in order to meet the research objectives of this thesis. The initial phase involved establishment of the theoretical foundation and conduction of research around similar use cases. The equipment was delivered lately, in the second week of the year. After the P2, the hardware setup is the main focus followed by initial testing and data acquisition. Before the P3 meeting, data preprocessing scripts will be implemented so as the positioning algorithm is developed. The experiments will undergo refinement and the results will be evaluated before P4. The period between P4 and P5 will be dedicated to code refinement, generating visually illustrative materials, and finalisation of the documentation. These will contribute to the enhancement of the overall quality of the final research report.

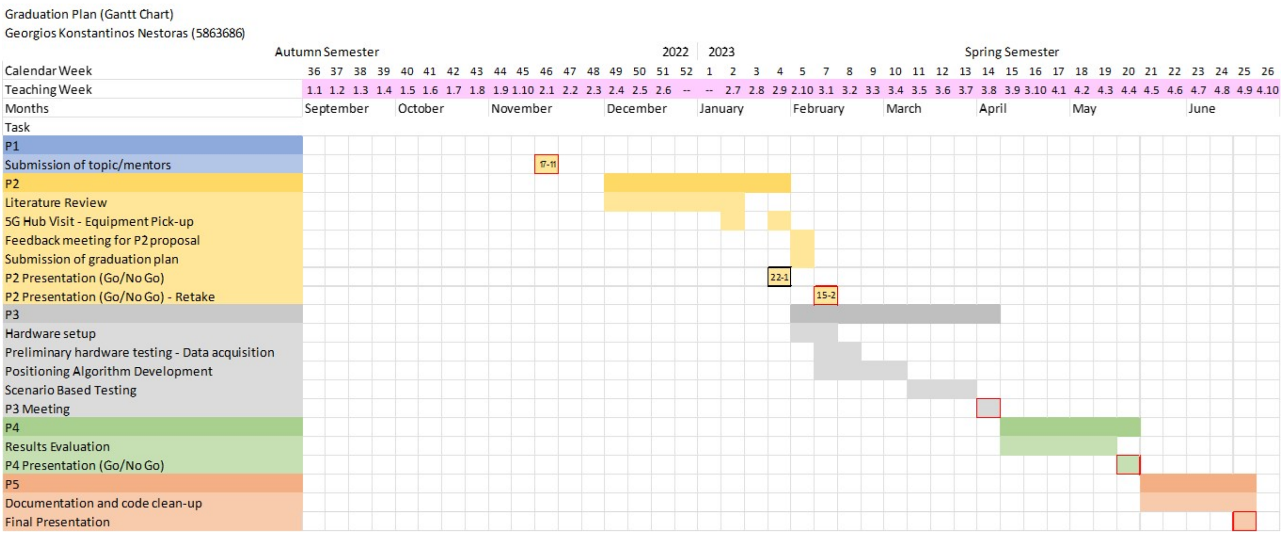

Figure 12: Time planning - Gantt Chart

6 Tools and Datasets

- **Ublox C099-F9P**[4] **(RTK device)**
  The C099-F9P application board facilitates the effective assessment of the ZED-F9P, u-blox's high-precision positioning module. The ZED-F9P module offers multi-band GNSS positioning and incorporates built-in RTK technology, delivering centimeter-level accuracy. The application board, C099-F9P, integrates the ZED-F9P module and includes an ODIN-W2 short-range module for connectivity options. Designed to support ZED-F9P module evaluation, the ODIN-W2 module adds wireless connectivity.

  The u-center software is the platform for assessing u-blox GNSS receivers.Through u-center, data can be both logged and visualized in real-time. Additionally, the u-center software features an NTRIP server/-client, enabling the management of the RTCM correction stream to and from a C099-F9P application board.

  The kit includes:

  - Application board with ZED-F9P
  - Active multi-band GNSS antenna
  - Bluetooth / Wi-Fi antenna
  - USB cable

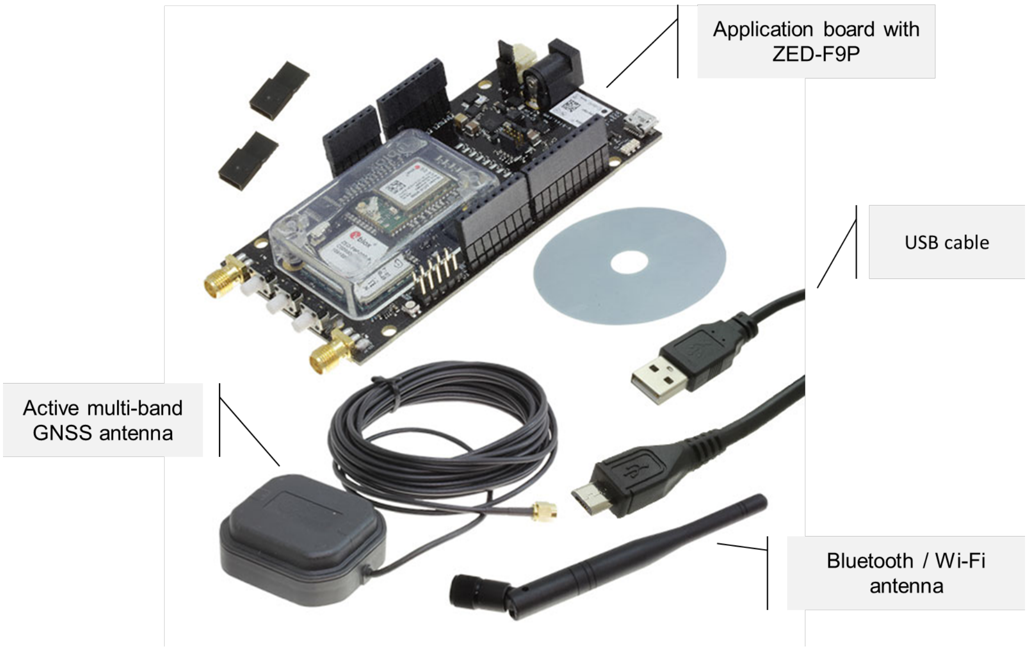

Figure 13: Ublox C099-F9P components

- **Quectel RM520N-GL**[5] **(M.2 device)**[6]
  RM520N-GL is an Internet of Things (IoT) and eMBB module specifically crafted for 5G sub-6GHz applications. It incorporates 3GPP[7] Release 16 technology, enabling support for both 5G non-standalone (NSA) and standalone (SA) modes.

  The USB TO M.2 B KEY is as a module driver board designed to interface with M.2 modules for 5G connectivity.

[4]https://www.u-blox.com/en/product/c099-f9p-application-board
[5]https://www.waveshare.com/wiki/RM520N-GL
[6]https://www.waveshare.com/wiki/USB_TO_M.2_B_KEY
[7]https://www.3gpp.org/

(a) RM520N-GL

(b) USB TO M.2 B KEY

Figure 14: Quectel RM520N-GL (M.2 device)

The equipment suggested and provided by Ericsson[8] was delivered in week 2 of 2024. As of now, no preliminary results are available.

[8]https://www.ericsson.com/en

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