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MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL

Plan de Recuperación, Transformación y Resiliencia

ADV5G-TWINS- BOTTLENECKS

Resumen del Proyecto

Versión 1.0

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Detalles del proyecto

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Acrónimo	ADV5G-TWINS- BOTTLENECK
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Descripción

Este entregable público resume el trabajo hecho por Keysight Technologies en el proyecto. Más detalles se encuentran en los entregables privados.

Criterio de aceptación

N/A

Versiones y contribuciones

Versiones

#	Descripción	Contribuyentes
0.1	Versión inicial	
1.0	Versión Entregada	

Contribuyentes

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Revisores

Revisor	Partner

Abreviaturas

BS	Base Station
CIR	Channel Impulse Response
CSV	Comma-Separated Values
DT	Digital Twin
FR	Frequency Range
KPI	Key Performance Indicator
MAT	MATLAB file format
MS	Mobile Station
NDT	Network Digital Twin
NR	New Radio (5G standard)
OSM	OpenStreetMap
PCI	Physical Cell Identity
RSRP	Reference Signal Received Power
RTK	Real-Time Kinematic (GPS technology)
SS	Synchronization Signal
SS-RSRP	Synchronization Signal Reference Signal Received Power
TDD	Time Division Duplex
UPV	Universitat Politècnica de València
USD	Universal Scene Description (3D format)
UTM	Universal Transverse Mercator

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Resumen ejecutivo

This deliverable outlines the creation and validation of a Digital Twin (DT) platform for 5G networks, developed by Keysight Technologies under the ADV5G-TWINS-BOTTLENECK project. Using the private 5G network at UPV Vera Campus as a case study, the project demonstrates how DTs can enhance network planning and optimization.

Key steps included:

- **High-fidelity modeling** of the campus using drone-based 3D mapping.
- **Integration with Keysight's RaySim tool** for accurate RF propagation simulation.
- **Calibration and validation** through field measurements and automated parameter tuning.
- **Optimization use case**, showing how DTs can guide antenna downtilt decisions.

Results confirm that the calibrated DT closely matches real-world measurements, enabling data-driven network configuration. This work establishes a foundation for scalable DT solutions in 5G, supporting advanced optimization and real-time management.

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1. Introduction

The advent of **Digital Twin (DT)** technology has introduced a transformative paradigm in the design, operation, and optimization of complex systems, including **5G mobile communication networks** [1], [2]. A **network digital twin** is a high-fidelity virtual replica of a physical communication network that mirrors its structure, behavior, and dynamics in real time. This virtual model enables continuous monitoring, predictive analysis, and intelligent decision-making, thereby enhancing network performance, reliability, and adaptability.

In the context of **5G**, digital twins are particularly valuable due to the network's inherent complexity—characterized by ultra-dense deployments, heterogeneous access technologies, and stringent performance requirements such as low latency and high throughput. DTs can simulate and analyze network behavior under various conditions, support proactive fault detection, optimize resource allocation, and facilitate autonomous network management. Use cases include:

- **Network planning and optimization**: DTs can simulate traffic patterns and user mobility to optimize cell placement and spectrum usage.
- **Predictive maintenance**: By analyzing historical and real-time data, DTs can forecast equipment failures and schedule maintenance proactively.
- **Security and anomaly detection**: DTs can model normal network behavior and detect deviations indicative of cyber threats.
- **Training and testing of AI models**: DTs provide a safe and controlled environment for developing and validating machine learning algorithms for network control.

Despite promising developments, several challenges remain, including the need for standardized DT models, real-time data synchronization, and scalable simulation frameworks. Addressing these issues is critical for realizing the full potential of digital twins in 5G and beyond.

In this project, our goal is to demonstrate the creation, calibration and validation of a DT of a 5G network, as well as to illustrate its use to optimize certain radio parameters. As a case study, the private 5G network deployed at UPV Vera Campus will be used. A short description of the targeted network Is provided next. In order to accomplish this goal, we will mainly use Keysight's F9860500A Channel Studio RaySim Tool [3], henceforth referred to simply as RaySim. The tool is briefly introduced in Section 3.

2. The 5G Private Network at UPV Campus

ADV5G-TWN aims to research and address some of the open challenges in the application of DT platforms to 5G networks by, as a case study, building, calibrating, and validating a DT prototype of the private 5G network present at the Universitat Politècnica de València (UPV) Vera Campus. This private network, deployed in cooperation with Nokia Spain and Telefónica, is made of different nodes, combining spectrum in frequency range 1 (FR1) and FR2. A description of the network's architecture is provided in Figure 1.

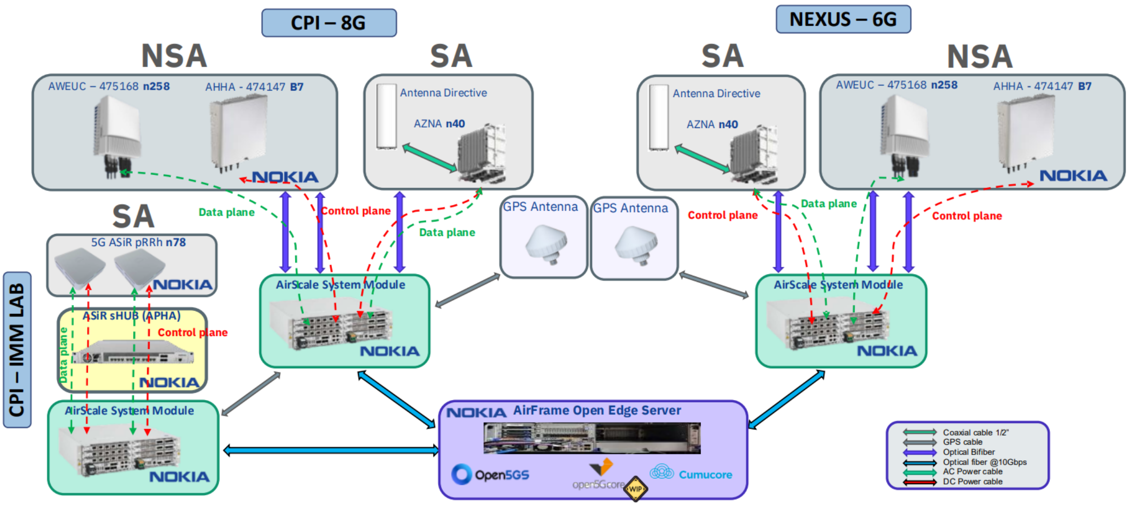

Figure 1: Architecture of UPV's 5G Private Network

As it can be seen, the 5G network is composed of 3 types of nodes. On the one hand, there are two outdoor stand-alone gNodeB's operating at band n40 (2300—2400 MHz), one at the CPI building and one at the Nexus building. Similarly, there are two mmWave gNodeB's, using a non-stand-alone configuration, at each of the two buildings. These gNodeBs operate at the n258 band (24.25 – 27.5 GHz). Finally, a stand-alone mmWave indoor node operating in band n78 (3300 - 3800 MHz), deployed inside the CPI building, at the Immersive Communications Lab. The RAN is powered by Nokia's AirScale System Modules, whereas multiple open-source and proprietary 5G cores can be configured to run at a local edge server.

Figure 2: Location of the outdoor nodes at Nexus and CPI buildings in the UPV Vera Campus

The location of the outdoor nodes in relation to the UPV Vera Campus is illustrated in Figure 2.

It was decided at an early stage of the project to limit the scope of the DT implementation to the n40 nodes at FR1, as data collection and implementation in RaySim of the gNB models was deemed more feasible as an initial step. Nonetheless, the methodology described in this report can be easily adapted to the generation and calibration of DTs in other frequency bands, such as FR2 and FR3.

3. Keysight's Radio Digital Twin Platform: RaySim

Keysight's Channel Studio RaySim [3] is a powerful simulation tool designed for high-fidelity modeling of radio frequency (RF) signal propagation in complex environments. It leverages advanced raytracing techniques to simulate interactions such as reflection, diffraction, and scattering, enabling accurate analysis of signal behavior in urban, indoor, and industrial scenarios.

RaySim offers a comprehensive suite of features that support advanced RF simulation workflows:

- High-fidelity environment modeling using 3D map data.
- Support for OpenStreetMap (OSM) and CityGML formats with automated RF parameterization.
- GPU-accelerated raytracing for real-time simulation.
- Interactive 3D visualization of propagation paths and channel characteristics.
- Integration with Software-in-the-Loop and Hardware-in-the-Loop systems.
- JSON-based scenario import/export for seamless interoperability.
- Extensive antenna library with customizable parameters.
- Export options including CSV, MAT, Parquet, and PROPSIM formats.

3.1. RaySim's GUI and functionalities

Many of the functionalities and capabilities of RaySim can be explored by inspecting RaySim's main interface. RaySim's graphical user interface (GUI) is shows in Figure 3, with the numbered panels corresponding to the following elements:

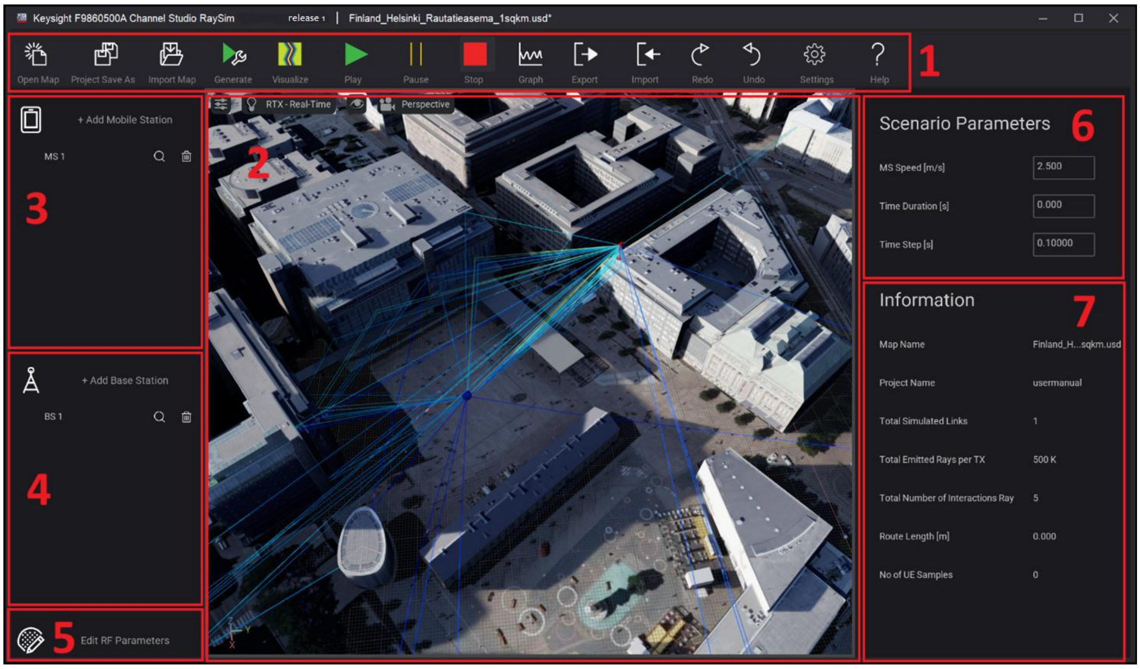

Figure 3: RaySim's GUI

1. **Toolbar:** provides quick access to various tools and functions essential for efficient navigation and operation within the RaySim software. It includes buttons for common tasks such as opening maps, saving projects, and running simulations.
2. **Viewport:** is the central visual component of the RaySim GUI, and it displays the 3D simulation environment, including terrain, buildings, the placement of Mobile Stations (MS) and Base Stations (BS), and the ray propagation paths visualization.
3. **MS panel:** provides a structured overview of all Mobile Stations (MS) currently defined in the simulation scenario, and allows managing them and their configuration settings.
4. **BS panel:** similar as the panel above, but detailing the Base Stations (BS) defined in the scenario.
5. **RF parameters editor:** this button opens the Radio Environment Editor in the Properties Panel. This tool allows users to modify the electromagnetic properties of map layers and materials, such as reflection coefficients and scattering models.
6. **Scenario parameters:** allows users to define key simulation settings that govern the behavior and resolution of the simulation, such as the speed of mobile users, the duration of the simulation, and the resolution of the computed channel responses. These parameters are especially important when configuring dynamic scenarios involving moving Mobile Stations (MS).
7. **Information:** this section provides a summary of the current simulation project and key statistics. This information is useful for verifying the setup and understanding the scope and complexity of the simulation. Most importantly, it hosts key settings of the ray-tracer, such as the maximum number of rays emitted per transmitter, and the maximum

number of electromagnetic interactions (reflections, diffractions, scattering, etc.) that each ray is allowed to undergo before reaching the receiver.

4.3D Map Construction and Processing

Next, we detail the phases that enabled the construction and configuration of the three-dimensional digital twin of the UPV campus, which served as the foundation for simulating and analyzing the iTEAM private 5G network in the N40 band. It describes the acquisition and processing of 3D models of the campus, and their subsequent integration into the virtual environment. Additionally, it explains the georeferencing process of the virtualized 3D elements and the assignment of materials, with the aim of establishing a digital scenario consistent with the real environment to serve as a basis for experimental validation and optimization of the UPV private 5G network.

4.1. Acquisition and processing of the 3D model

RaySim allows the automated importing of 3D maps from open-source cartographic repositories, such as OpenStreetMap (OSM) or CityGML. When this was attempted, however, it became obvious that the information present in freely-available sources was not of sufficient fidelity to produce accurate ray-tracing results. The available maps had overly simplified building and terrain designs, some of them even missing some key buildings.

As an alternative procedure to obtain a high-fidelity 3D model of the campus, an external company specializing in aerial surveying was contracted. This company carried out drone flights over the study area and generated a three-dimensional model of the campus using photogrammetry techniques. The drone used for this operation is depicted in Figure 4, standing on the ground of UPV's campus before taking off for the flight.

Figure 4: Drone used to survey the campus and create the 3D map

The resulting files obtained from the drone flight with photogrammetry were then subject to set of postprocessing methods to transform them to a format that can be directly imported into RaySim, as well as to correct some inaccuracies in the collected data.

Subsequently, a georeferencing process was applied to link the virtual scenario to the actual location of the campus, resulting in a 3D map that is georeferenced using Universal Transverse Mercator (UTM). The result was a model correctly aligned with the physical location of the campus, ensuring spatial consistency between the virtual environment and the real space.

Once this process was completed, the scenario could be integrated into the RaySim platform, yielding the results illustrated in Figure 5.

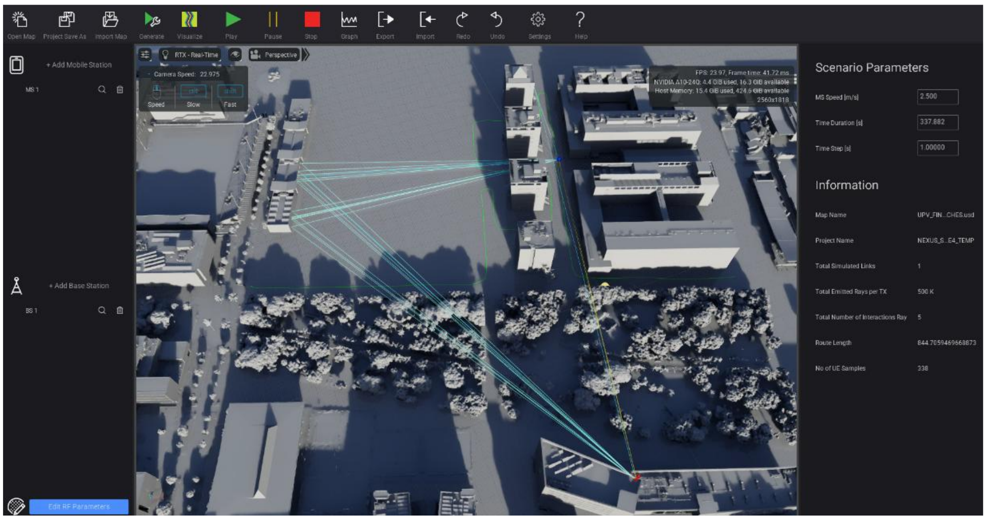

Figure 5: Final result of importing the post-processed 3D map into RaySim

4.2. Modeling of BSs, Antenna Arrays, and UEs

In addition to the modeling of the propagation environment, the radio elements of the network need to as well be modeled and included in the DT. In order to achieve the best possible accuracy, gathering as much information as possible from the nodes (especially the BS) to be modeled is particularly important. In particular, the two following aspects are critical:

1. The modeling of the directional radiation properties of the antenna arrays at the BS nodes.
2. The inclusion of other BS parameters, such as the transmission power, the array orientation, and the mechanical and electrical downtilt settings.

With regards to the antenna array radiation patterns, RaySim allows for the inclusion of custom antenna array radiation patterns. For this purpose, however, a full spherical characterization of the electrical field components as complex numbers, which is typically only available via electromagnetic computation. More often, what is available instead is the measured radiated power in vertical and horizontal cuts. This was the case for the antenna arrays at the two nodes in the UPV network, where the information described in Figure 6 was found from the certification report of the BS installation at the

Nexus building. The report also states that the horizontal cut has a 3dB beamwidth of 68 degrees, while the vertical cut has 5.2 degrees.

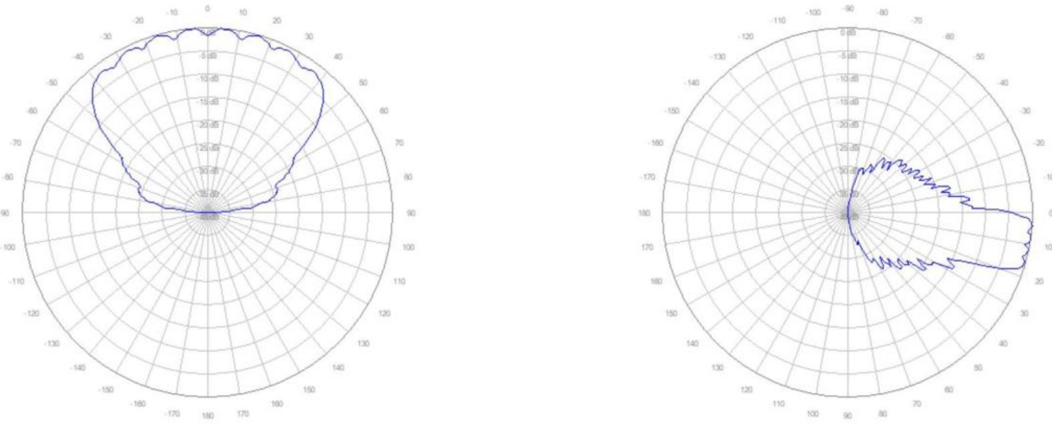

Figure 6: Measured horizontal and vertical cuts of the Nexus BS array radiation pattern

Given that this information was not sufficient to create a full, custom model of such radiation pattern in RaySim, we resorted to explore the available models in RaySim antenna array library in order to find the closest match. This was found with a model that displayed 8 degrees of vertical 3dB beamwidth, with the radiation pattern displayed in Figure 7 per antenna element. As it can be seen, the shape of the patterns are similar, except that the chosen model has significantly lower attenuation towards the back of the array in the horizontal dimension than the actual antenna. Nonetheless, this was the best match that could be found among the available models.

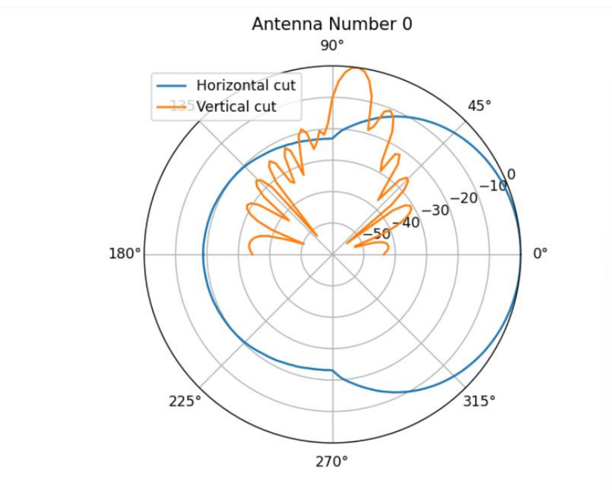

Figure 7: Horizontal and vertical radiation patterns of a single element of the modeled array.

For the MS modeling, since there was no target device in mind, we resorted to model a generic device consisting of a single omnidirectional antenna. This was assumed to be the best option since, in any case, radiation patters of terminals where not feasible to measure or obtain in the frame of the project. Even if they were obtained, aspects such as the user grip on hand-held terminals have a crucial and unpredictable effect on the terminal's antenna radiation pattern, making efforts to accurately model the receiver directional properties futile.

With regards to the rest of parameters used to model the base stations, those listed in Table 1 were initially used, as the information could be obtained from the actual physical network:

Table 1: Parameters of the two gNodeBs of interest.

Node	Azimuth orientation	Mechanical Downtilt	Electrical Downtilt	Transmit Power	PCI
Nexus	0°	10°	0°	26.5 dBm	61
CPI	290°	0°	0°	26.5 dBm	41

In addition, the coordinates of placement of both BS, as well as the height of their masts were also accurately replicated in the 3D environment.

4.3. Ray-Tracing Configuration

The processed scenario was integrated into RaySim, allowing visualization of buildings and terrain. The next step was to assign materials to the different structures. In this case, it was decided to retain brick for most of the buildings.

Finally, the initial parameters of the propagation engine were configured. A total of 500,000 rays emitted by the base station were set. This configuration balanced propagation simulation accuracy with computational cost, as a high number of rays improves the resolution of the results, but a maximum value would significantly increase processing time. Additionally, the maximum number of interactions per ray was set to 5, which was essential to more realistically represent propagation in an environment with multiple buildings and, at the same time, ensure greater accuracy in the model calibration phase.

5. Calibration and Validation of the DT

Once an initial scenario of the target network has been created in RaySim – including the 3D map of the propagation environment, the models of BS and MS in the network, and the configuration parameters of the ray-tracer—the network DT is ready to start producing the first radio propagation predictions. One or more users (or MS) can be deployed in the scenario by defining mobility tracks for them, along with the speed of the users. If this is done, RaySim will calculate channel impulse responses (CIRs) at the desired frequency range (in this case the n40 band) with a time-resolution –and, consequently, spatial-resolution as well—that can be set by the user.

Based on the computed CIRs, and using the available information about transmit power at the BSs and their 5G NR air interface configuration (subcarrier spacing, transmission bandwidth, SSB location, etc.), radio performance indicators such as the reference signal received power (RSRP) measured on the synchronization signal (SS), that is, the SS-RSRP. Based on the RaySim input, the calculated RSRP values were represented in a heatmap overlayed with the map of the campus (in addition to other representations).

The crucial question is, however: "***How close are the predictions delivered by the DT to the performance that is actually experienced in the field?***" In this section, we attempt to answer this question using SS-RSRP as our key performance indicator (KPI). In order to have a baseline for comparison, an extensive campaign of field measurements was carried out using the methodology described in Section 5.1. The comparison between the field measurements and RaySim prediction is then presented in Section 5.2. Subsequently, we describe the calibration process carried out to enhance the DTs accuracy.

5.1. Field Measurement Methodology

There are two fundamental tools that were used to collect field measurements. The first one is a commercial 5G terminal (in this case a Samsung S25) equipped with Keysight's Nemo Handy [4] software. The second one is an external GPS receiver, which is used to get better location tracking and accurate coordinates for the collected measurements. We briefly discuss these tools and their use in this project in the following.

5.1.1. Nemo Handy/Outdoor

Nemo Handy is an Android application that enables, among other functionalities, measuring wireless diagnostics information of the air interface of wireless networks. In this project, we use it to collect SS-RSRP measurements from the two targeted BSs by locking the terminal at the specific mobile standard (5G NR TDD) and band (n40) of interest. In addition to RSRP, some other potentially interesting metrics such as handover locations or experienced throughput (when generating 10 Mbps DL traffic via an iPerf server).

In addition to Nemo Handy, we also used its laptop-based version, Nemo Outdoor [5]. While Nemo Outdoor can be connected to a mobile terminal and be used as well to collect air-interface diagnosis information, in this case it was only used for convenient visualization and analysis of the Nemo Handy measurements, allowing for running sanity check of the obtained results and troubleshooting issues encountered. Furthermore, Nemo Outdoor was used to export the outcome of the field measurements as a time-series and encoded as CSV files for later postprocessing and analysis.

5.1.2. GPS coordinate tracking

The use of Nemo Handy was complemented by an external GPS receiver that provides cm-level accuracy on the tracking of the coordinates. This solution was adopted because, after trying to use the internal GPS of the S25 terminal, it was clear that its accuracy was not sufficient. Note that the obtainment of accurate GPS coordinates of the collected measurements is essential in this work, since the GPS coordinates recorded during the field measurements can be directly imported into RaySim in order to simulate an analogous trajectory in the DT. Hence, it will be used to recreate RaySim simulations with the MS traversing exactly the same (virtual) path as it was followed during the field measurements. This will enable a direct comparison of field measurements to DT predictions and, in a later stage, even the use of the field measurements to calibrate parameters of the DT.

The external GPS receiver used is an RTK Emlid Reach Rx [6], and is illustrated together with the Nemo Handy-equipped terminal in Figure 8.

Figure 8: The mobile terminal equipped with Nemo Handy and the external GPS receiver

Note that the positional difference between the GPS receiver and the Nemo Handy terminal has been removed through GPS calibration. The coordinates can be recorded by the GPS with custom time granularity, and synchronization of GPS and terminal clocks was checked. The GPS coordinates where recorded by the app Emlid Flow.

After completion of the measurements, the data collected by Nemo Handy and the GPS were postprocessed together. With this, high-precision localization of each of the RSRP measurement points was obtained.

5.2. Initial results

In this section, we document and discuss the initial results obtained through the field measurements campaign and its comparison to RaySim's predictions. While both the field measurement campaign and the simulations were planned and conducted for both of the gNodeBs of interest –the node in the CPI building and that in the Nexus building—there were severe challenges in achieving a meaningful comparison between measurements and predictions for the CPI building. This was due to certain inaccuracies in the rendering of the fine details of the CPI building –and, in particular, the rooftop where the gNodeB antenna is located—in the virtual 3D environment. The presence of a railing on the rooftop that blocks the line of sight to the antenna from positions closest to the front of the CPI building was not appropriately captured by the point cloud generated by the drone. This element is essential for radio propagation prediction in the area covered by the CPI node, as shadowing and diffraction mechanisms associated to it are likely to have indispensable contributions to the radiated electromagnetic fields.

While we tried to add similar elements manually designed via 3D modeling, no appropriate fix was found and, unfortunately, a repetition of the drone flight was not feasible due to the time required to hire the external company services, obtain the required flight permissions, etc. Since the comparison obtained with the CPI node under these suboptimal conditions was deemed meaningless in terms of the insights they can provide to the project, we opted to omit those results and focus instead on the description of results for the node at the Nexus building.

5.2.1. Path Definition and Initial Measurement Analysis

We began by defining a path that ensures full coverage of the cell, with particular attention to the beam direction. This makes it easier to calibrate the DT. The selected path is shown in Figure 9.

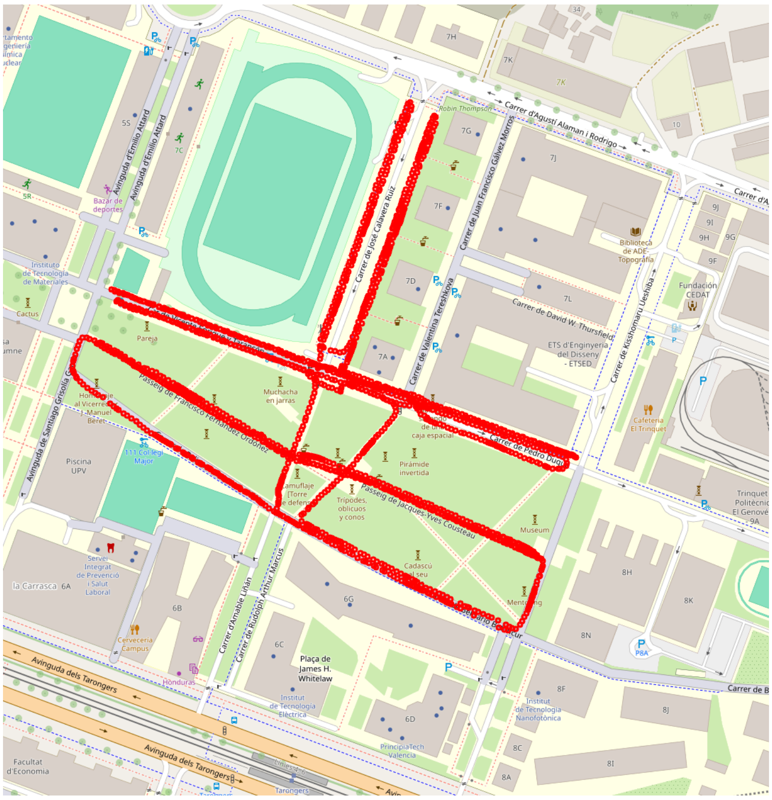

Figure 9 Path followed for PC61

After completing the route using Nemo Handy, we moved on to analyze the collected measurements. This analysis helps us understand the behavior of the cell.

Figure 10 shows the RSRP values recorded by Nemo Handy (blue points) as a function of the distance from the base station. The orange line represents the average of these values, giving a general idea of how signal strength varies with distance.

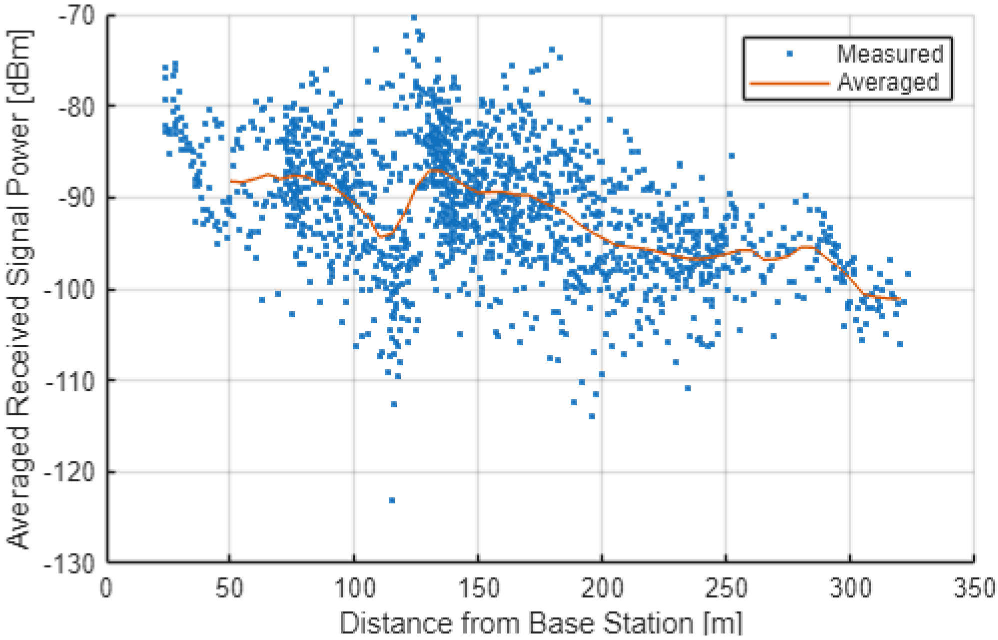

Figure 10 Nemo - RSRP vs Distrance from Base Station

However, averaging based solely on distance can mix different propagation conditions—such as LOS and NLOS—which may distort the results. To address this, Figure 11 presents a heatmap of the RSRP values. The base station is marked with a red cross to provide spatial reference.

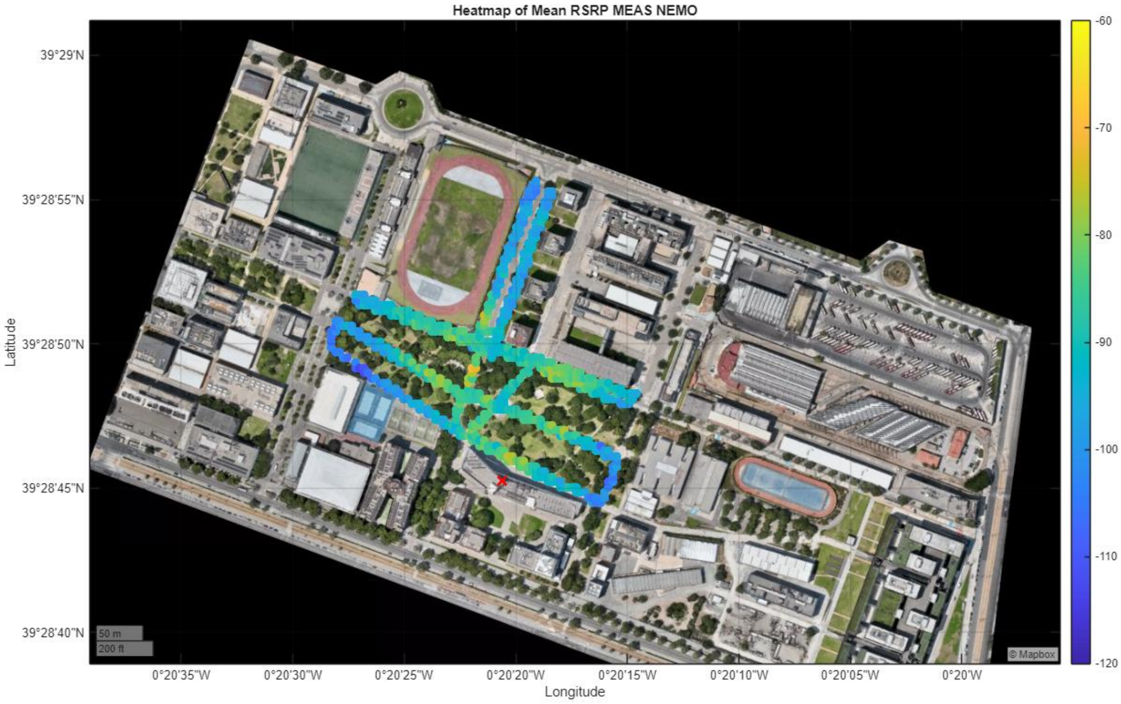

Figure 11. Heatmap of Nemo RSRP

5.2.2. Initial DT Results

With the measurements analyzed, we proceeded to simulate the environment using RaySim. These simulations were based on the drone-obtained 3D map described in Section 4. For the initial setup, we used an antenna orientation of 75° azimuth and 10° downtilt. It's important to note that in RaySim, 0° azimuth points along the X-axis, not north—so the mapping between real-world azimuth and RaySim azimuth is not direct.

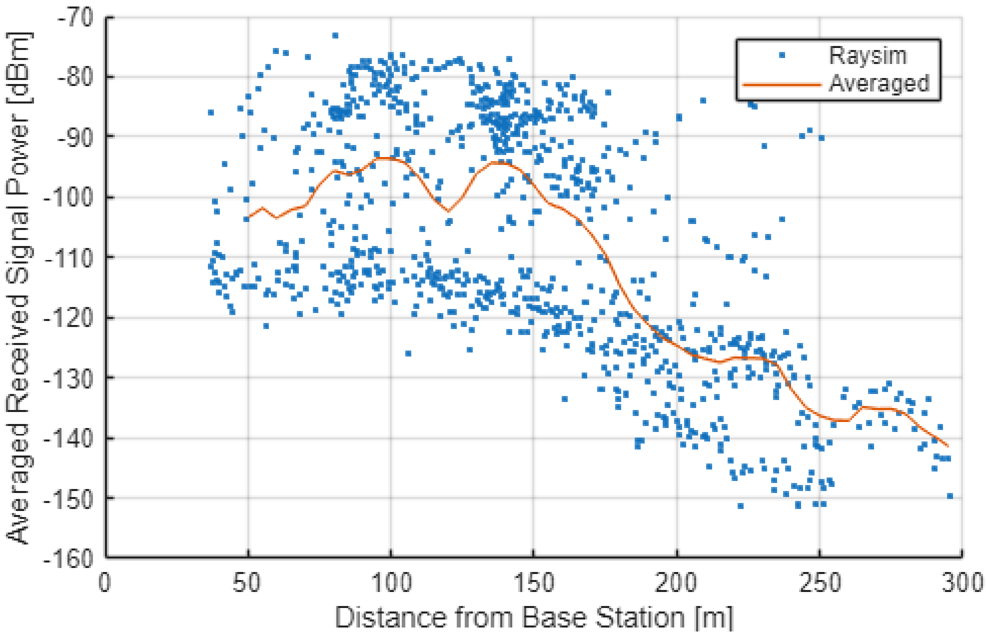

Figure 12: RaySim - RSRP vs Distrance from Base Station

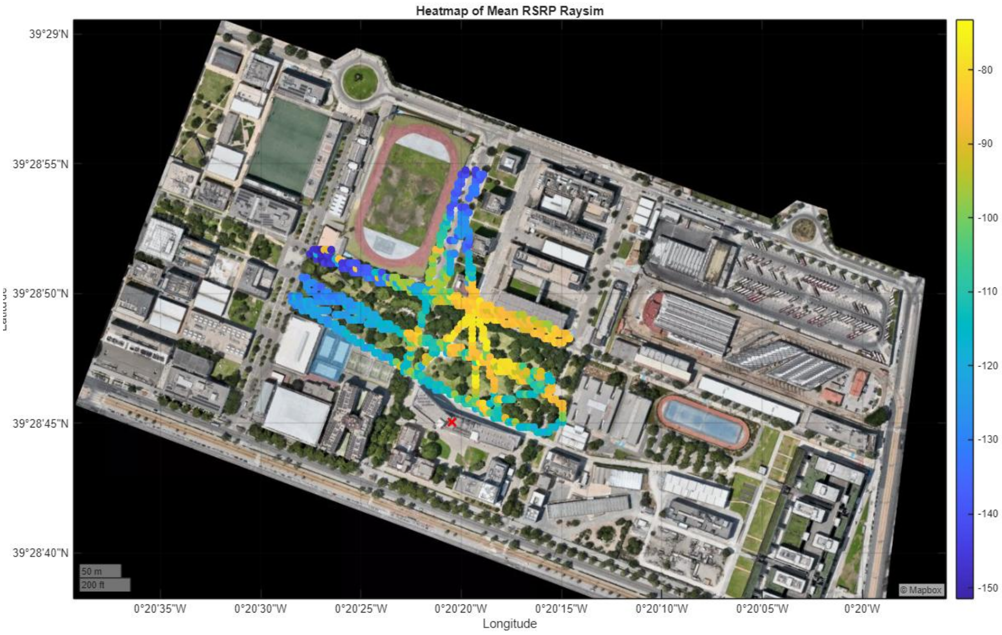

Figure 13: Heatmap of Nemo RSRP

Following the same approach as with the Nemo data, we analyzed the RaySim results individually. Figure 12 corresponds to Figure 10, and Figure 13 to Figure 11.

Comparing these figures helps identify discrepancies between the simulation and the real-world measurements, both in terms of signal distribution and path alignment.

5.2.3. Initial Comparison

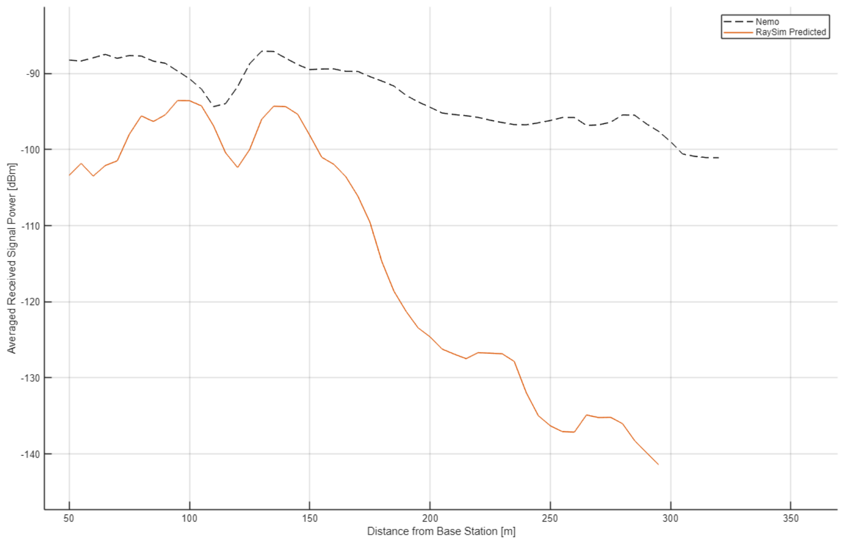

Figure 14: Comparison between average RSRP measured with Nemo and predicted by RaySim

Figure 14 compares the average RSRP values. The dashed black line represents the Nemo Handy measurements, while the solid black line shows the RaySim simulation. This figure format will be used consistently throughout the deliverable.

In Figure 14 RaySim closely follows the trend between 100 and 150 meters. Beyond that, however, the results diverge significantly. Around 300 meters, the difference reaches up to 50 dB, clearly indicating that the DT is not yet properly calibrated.

To complement the previous analysis, Figure 15 presents a heatmap showing the difference between the RSRP values measured by Nemo and those simulated by RaySim. This spatial representation helps us better understand where discrepancies occur. Such visualizations are particularly useful for identifying areas of interest, which will be useful to later calibrate the DT.

In Figure 16, we highlight in **red** the locations where RaySim underestimates the RSRP by more than 10 dB, and in **white** those where it overestimates by more than 10 dB. As shown, a significant portion of the area falls outside the acceptable error range, indicating that further calibration is required before the DT can yield accurate predictions.

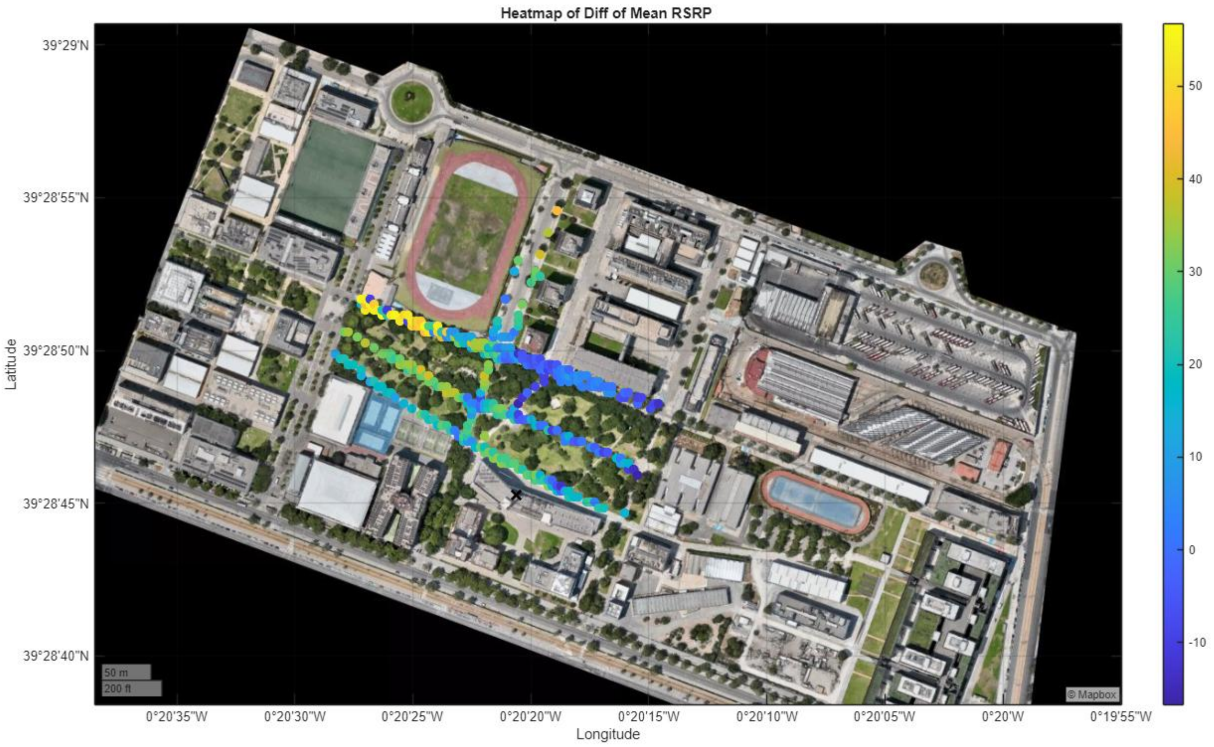

Figure 15: Heatmap difference between RSRP measured with Nemo and predicted by Raysim

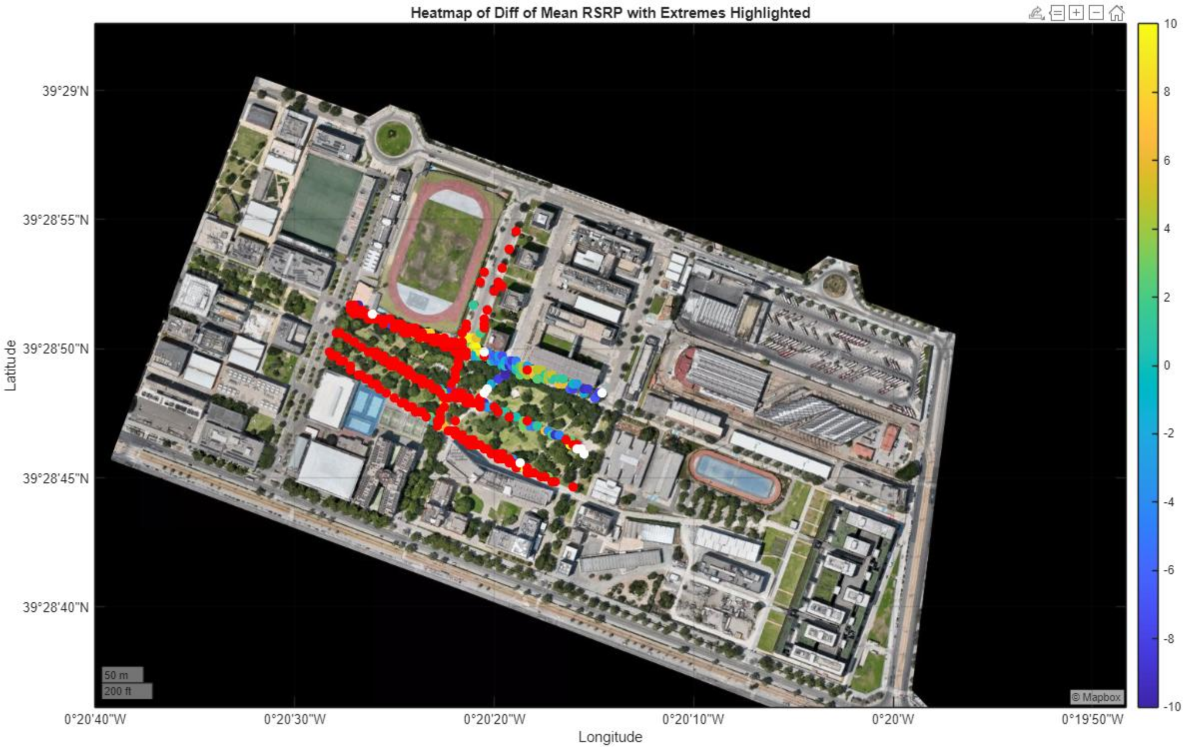

Figure 16: Highlighted view of RaySim underestimates (red) and overestimates (white) by more than 10 dB

5.3. Calibration of the DT model

The calibration process of the DT involved 3 main steps, namely:

1. Removal of invalid values
2. Region diagnosis
3. Automated parameter optimization

We shortly describe these steps next, and then present the results of the SS-RSRP comparison after applying all the calibration steps.

5.3.1. Removal of invalid values

From the initial results obtained, it was evident that the RSRP ranges differ significantly between Nemo and RaySim. Nemo Handy can measure RSRP values down to approximately -120 dBm, while RaySim is capable of simulating values as low as -150 dBm. This discrepancy stems from the nature of the input sources: Nemo is a real mobile device with hardware limitations that prevent it from maintaining a connection when the signal is too weak. In contrast, RaySim, as a ray-tracing simulator, does not have such constraints.

To ensure that predictions outside the sensitivity range of the device used for measurements do not impact the calibration process, we excluded RaySim data points below the Nemo measurement threshold.

5.3.2. Region Diagnosis

During RaySim execution and calibration, it is very important and helpful to provide diagnostic feedback. For instance, when the emulation area is divided into small grids and regions (groups of adjacent grids), if we observe that one region has consistently large discrepancies in RSRP between emulation and measurement values, this may indicate misconfigurations, such as misclassified objects around that location. However, this is not a trivial process in practice, as manually identifying these regions by examining various RaySim emulation results is both time-consuming and error-prone.

To address this challenge, a platform was developed that automatically highlights problematic regions on the map by generating bounding boxes, whose parameters for this diagnosis can be tuned in real time.

Using the described tool, we identified several buildings with imperfect segmentation, which negatively affected the accuracy of the simulation.

Another area highlighted by our tool was a parking area. At the time of the measurement there were some cars stationed there that caused reflections that affected the signal. As a solution, we added cars to that part of the map manually, increasing the fidelity.

Finally, the tool identified unusual results in front of the running track. These are caused by the complex structure of the area. The track is elevated, and the space underneath is used as a parking lot. Modeling these open areas accurately is particularly challenging, especially without detailed information about the vehicles present at the time of data collection. For now, no solution has been found to resolve this issue.

5.3.3. Automating parameter selection and calibration

After the first to steps, the final calibration process consisted in optimizing the antenna parameters. To automatically determine optimal parameters in RaySim, such as the tilt and azimuth angle of the gNBs, a Keysight-developed solution that leverages Optuna [7], which is an open-source framework for hyperparameter tuning, was utilized.

5.4. Validation of the calibrated DT

The figures below show the final results after selecting the optimal azimuth and tilt using the automated parameter tuning tool.

In Figure 17, the simulation aligns almost perfectly with the real measurements between 50 and 150 meters. From 150 to 300 meters, the model continues to follow the general trend, with most differences remaining under 10 dB—an acceptable margin for this type of analysis.

Figure 18 and Figure 19 display the updated heatmaps, which show significant improvement. Extreme errors are now concentrated in a single area—directly in front of the running track. This region had already been flagged by our region diagnosis tool due to the complex deployment of the track at the university. Outside of this zone, most values fall within the desired range.

It's important to keep in mind that real-world measurements always include some level of noise and uncertainty. However, maintaining differences within 10 dB ensures that the behavior observed in the calibrated digital twin closely reflects reality in most cases.

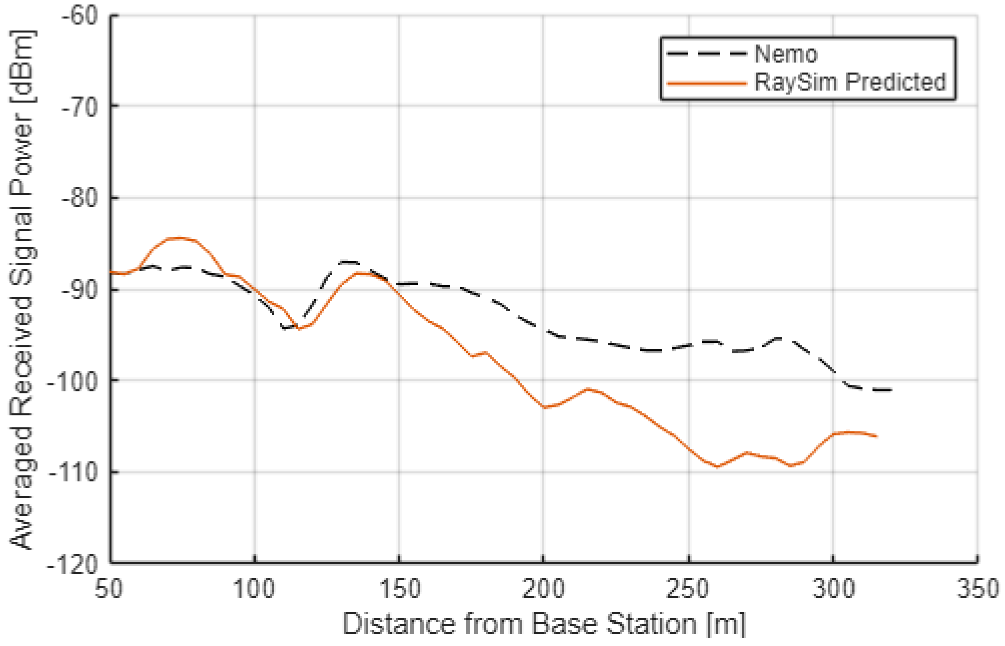

Figure 17: Comparison between measured RSRP and RaySim-predicted RSRP after automated antenna parameter calibration

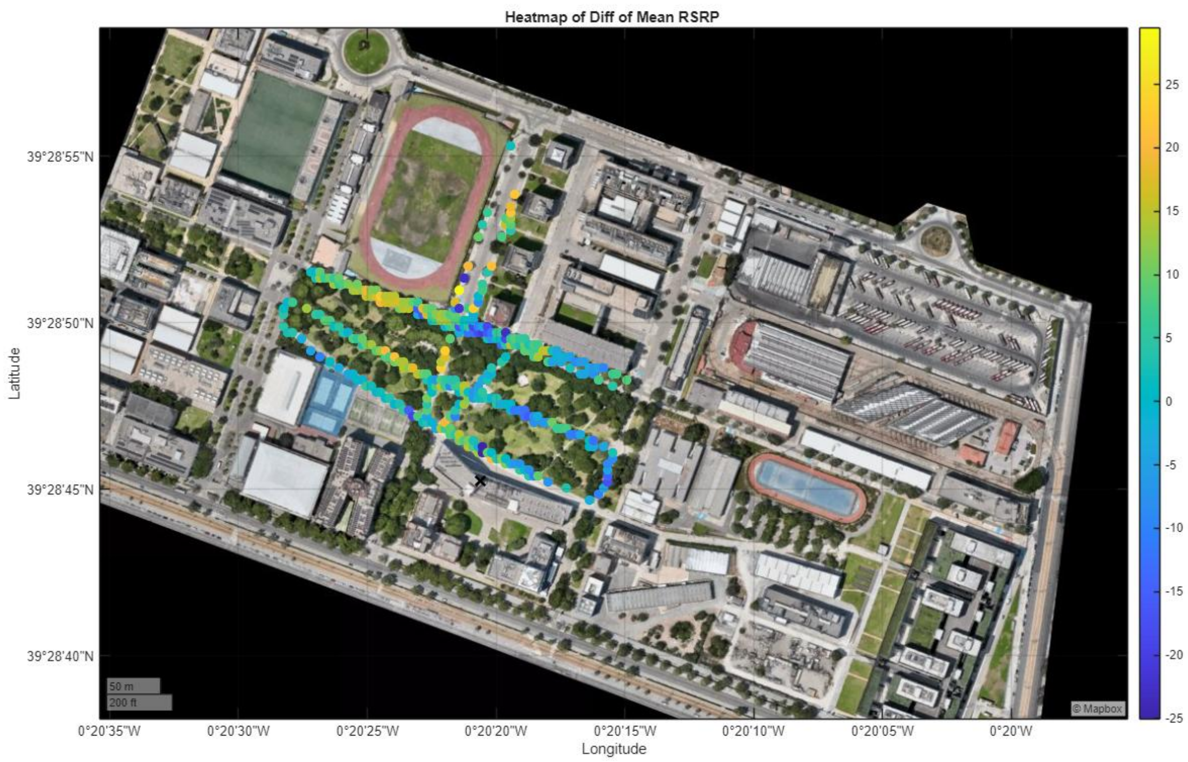

Figure 18: Heatmap difference between measured RSRP and RaySim-predicted RSRP after automated antenna parameter calibration

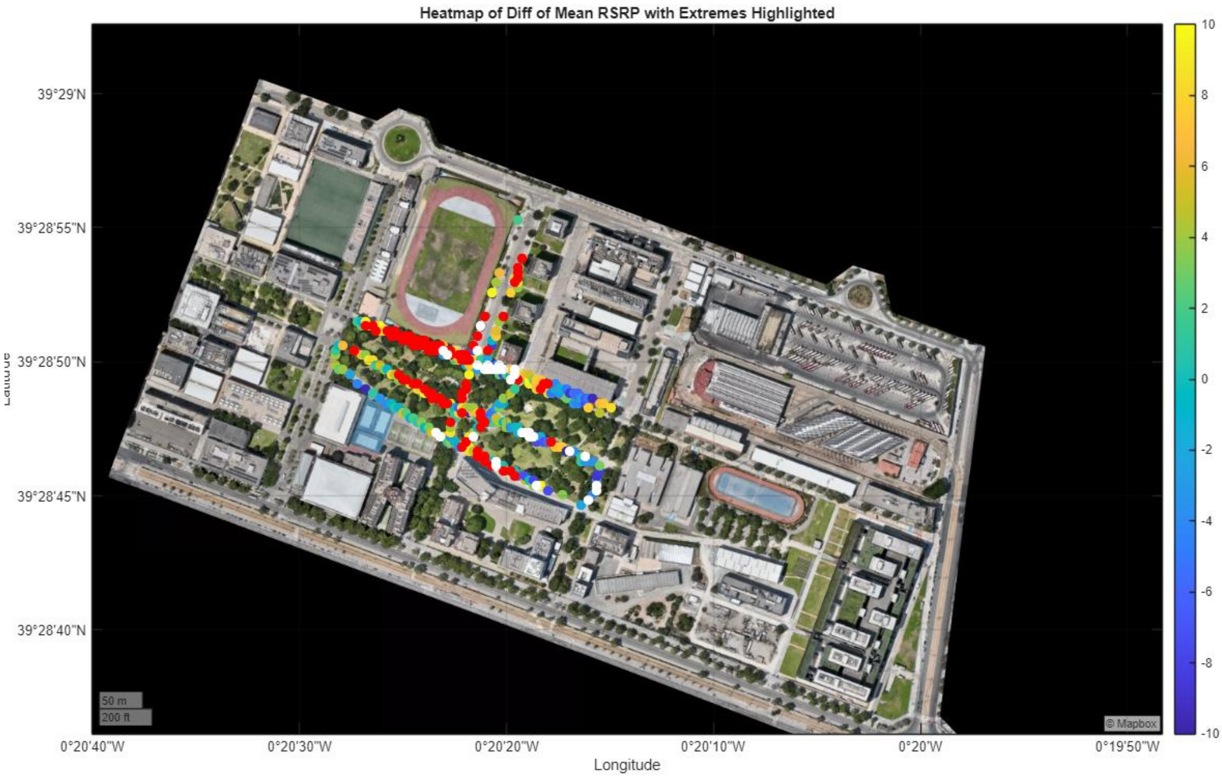

Figure 19: Heatmap difference between measured RSRP and RaySim-predicted RSRP after automated antenna parameter calibration. Differences larger than +10 dB and smaller than -10 dB are highlighted in red and white respectively.

6. Network optimization using the DT

Once the digital twin has been calibrated, our goal is to now showcase its usefulness as a network optimization tool. To that end, we target the analysis of a simple parameter for the air interface, namely the electrical downtilt to be applied to the gNodeB at the Nexus building. The empirical cumulative distribution function (ECDF) of the SS-RSRP is used as a metric to compare configurations and draw robust statistical conclusions.

The procedure followed for this optimization was to launch multiple simulations with the calibrated model following the same user trajectory that was used to calibrate the DT. Each of these simulations keeps identical parameters, except that the downtilt of the base station antenna was set to different values in each of them.

Using this procedure, multiple datasets –one for each downtilt setting—of RSRP values predicted by RaySim throughout all the relevant coverage area of the BS are obtained. In order to evaluate which of the evaluated downtilt configurations provides altogether a better RSRP, we first inspect the empirical cumulative distribution function (ECDF) of the predictions, depicted in Figure 20.

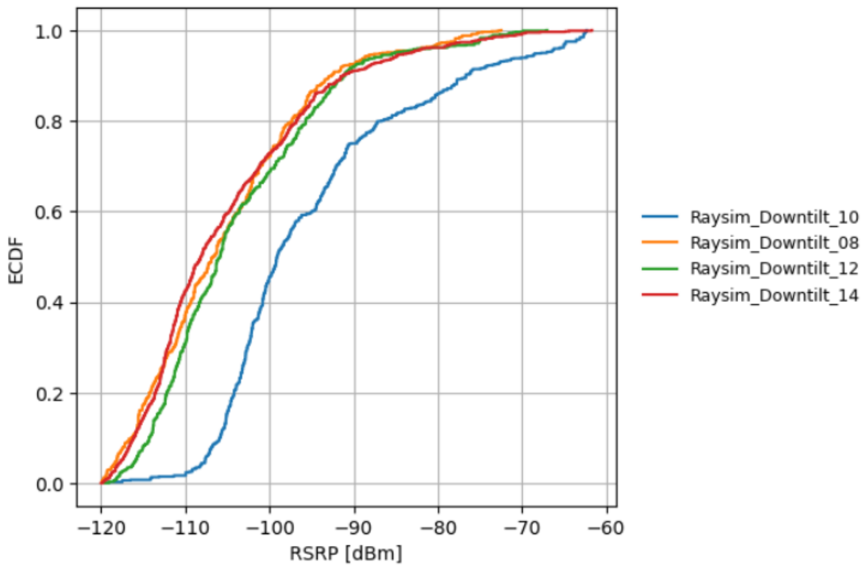

Figure 20: ECDF of the SS-RSRP predicted by RaySim with different downtilt configurations

The results shown in the ECDF are somewhat surprising, from the point of view that there is a very clear advantage of the downtilt setting at 10° as compared to higher and smaller downtilt. One may have expected that, for instance, a larger downtilt could have provided better RSRP values in areas close to the BS, whereas providing worse signal levels at further positions. This would have manifested in the ECDF by a less steep curve, providing higher RSRP values than other settings at the high percentiles, but lower ones at low percentiles. However, the ECDF results suggest that a downtilt of 10° is clearly the best option at all examined percentiles. To illustrate this, we display the ECDF values at different percentiles in Figure 20.

Table 2: Predicted statistics of the SS-RSRP with different BS downtilt settings

Downtilt (°)	Mean (dB)	St. Dev. (dB)	Median (dB)	10th percentile	95th percentile
8	-105.17	9.92	-106.68	-116.68	-86.63
10	-94.94	11.91	-99.1	-105.84	-67.8
12	-103.72	10.0	-105.86	-114.3	-85.15
14	-105.07	10.7	-108.16	-116.15	-83.57

While these results are surprising, they should also be considered in the right context. They are a deliberately oversimplified exercise with the goal of illustrating how the developed DT can be used to predict the effects of different network configuration settings and, therefore, be used as a tool for optimization. Should one desire to optimize the downtilt for a real application, such analysis should not be based on a single base station, but should be done for all base stations in the network at the same time. In addition, the study optimization should not just be based on a signal strength parameter such as RSRP, but requires the use of metrics that account for co-channel interference, such as signal-to-interference-and-noise ratio (SINR). Obviously, the number of simulations to be run would increase exponentially with the number of considered cells; here, the use of an automated parameter tuning procedure such as the one described in Section 5.3.3 would help minimizing human intervention, and the availability of strong cloud computing resources would alleviate the computational complexity burden.

7. Conclusions

This deliverable has presented the model creation, calibration, validation, and testing efforts carried out on the DT platform developed by Keysight for the ADV5G-TWINS-BOTTLENECK project. The work focused on building and refining the DT of the private 5G network deployed at the Vera Campus of UPV, with the goal of achieving a high-fidelity simulation environment capable of supporting network optimization tasks.

The calibration process, which included filtering invalid values, diagnosing problematic regions, and automating antenna parameter tuning, significantly improved the alignment between simulated and measured RSRP values. The use of tools such as Optuna for hyperparameter optimization and the development of a region diagnosis interface proved instrumental in accelerating the calibration workflow and enhancing accuracy.

Following calibration, the DT was successfully employed to evaluate the impact of different downtilt configurations on network performance. The results demonstrated that a 10° downtilt provided the most favorable SS-RSRP distribution across the coverage area, validating the DT's utility as a decision-support tool for network configuration.

While the optimization exercise was deliberately simplified to illustrate the DT's capabilities, it highlighted the potential of DTs in real-time network management and planning. Future work should extend this approach to multi-cell scenarios and incorporate interference-aware metrics such as SINR to enable more comprehensive optimization strategies.

In conclusion, the calibrated DT platform developed in this project represents a robust foundation for future research and deployment of digital twin technologies in 5G networks. Its integration with automated calibration and optimization tools paves the way for scalable, data-driven network design and operation.

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