From Concept to Reality: 5G Positioning with UL-TDoA in OpenAirInterface

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***Abstract*—This paper presents, for the first time, an open-source implementation of the 3GPP uplink time difference of arrival (UL-TDoA) positioning method using the OpenAirInterface (OAI) framework. UL-TDoA is a critical positioning technique in 5G networks, leveraging the time differences of signal arrival at multiple base stations to determine the precise location of user equipment (UE). This implementation aims to democratize access to advanced positioning technology by integrating UL-TDoA capabilities into both the radio access network (RAN) and core network (CN) components of OAI, providing a comprehensive and 3GPP-compliant solution. The development includes the incorporation of essential protocol procedures, message flows, and interfaces as defined by 3GPP standards. Validation is conducted using two distinct methods: an OAI-RF simulator-based setup for controlled testing and an O-RAN-based localization testbed at EURECOM in real-world conditions. The results demonstrate the viability of this open-source UL-TDoA implementation, enabling precise positioning in various environments. By making this implementation publicly available, the study paves the way for widespread research, development, and innovation in the field of 6G positioning technologies, fostering collaboration and accelerating the advancement of cellular network positioning.**

***Index Terms*—5G Positioning, TDoA, OpenAirInterface, NRPPA, LMF.**

I. Introduction

5G new radio (NR) represents a major leap in wireless communications, significantly improving speed, connectivity, and latency. Beyond enhancing mobile broadband (eMBB), 5G NR enables ultra-reliable low-latency communication (URLLC) and massive machine-type communications (mMTC). A key innovation is precise positioning, which can impact industries such as automotive, healthcare, logistics, and smart cities. Traditional positioning methods like GPS, Wi-Fi, and BLE beacons have limitations in accuracy, latency, and reliability, especially in urban or indoor environments. 5G positioning technologies, leveraging advanced techniques like *time difference of arrival* (TDoA) and *angle of arrival* (AoA), offer superior accuracy and low latency. These are enhanced by 5G's high-frequency bands, massive MIMO, and beamforming, enabling reliable positioning even in challenging environments.

This paper focuses on 3GPP-compliant UL-TDoA positioning procedure [2], a method that calculates the UE location by measuring the time differences of uplink signals at multiple base stations. While promising, UL-TDoA poses challenges, including synchronization between base stations and addressing non-line-of-sight conditions. 3GPP-compliant proprietary solutions are often costly and rigid, limiting customization. Open-source software, particularly OpenAirInterface (OAI) [3], addresses these challenges by providing a flexible, 3GPP-compliant platform for LTE and 5G RAN and CN development. Several projects, such as E-CID positioning [4] and the HOP-5G project [5], [6], have utilized OAI to develop and test positioning techniques. This paper presents an open-source implementation of UL-TDoA in OAI, enabling precise UE positioning in 5G networks. Key contributions of our work include:

- UL-TDoA Integration in OAI: UL-TDoA procedure is integrated into the RAN and CN components of OAI, supporting accurate positioning.
- Design Insights: Insights into the architecture, protocols, and 3GPP standards compliance are provided.
- Implementation Validation: Validation is done via the OAI-RF simulator and EURECOM's localization testbed, showing functionality in both simulated and real environments.
- Documentation and Tutorials: Comprehensive documentation and tutorials support the implementation of UL-TDoA within OAI.

This open-source implementation aims to encourage research and innovation in cellular network positioning technologies. The following sections will cover the UL-TDoA framework, OAI capabilities, implementation details, validation, and future research directions. A live demonstration of this work was first presented at the OAI workshop 2025 [7] and a video is available on YouTube [8]. A longer version of this paper is also available on Arxiv [1].

II. 3GPP's Framework for UL-TDoA Based Positioning

The 3GPP framework for positioning in 5G networks involves a combination of network components, interfaces, and positioning methods to provide accurate and reliable location information for UE. The 3GPP standards supporting UL-TDoA positioning are detailed in technical specification TS 38.305 [2], which outline the technical requirements for all location services, including UL-TDoA. The framework defined by 3GPP for UL-TDoA-based positioning of a target UE, as well as the delivery of location assistance data to a UE with NG-RAN access in 5G systems, is illustrated in Figure 1.

The work included in this paper has been supported by the "France 2030" investment program through the projects 5G-OPERA and GEO-5G. The full version of this paper can be found at [1].

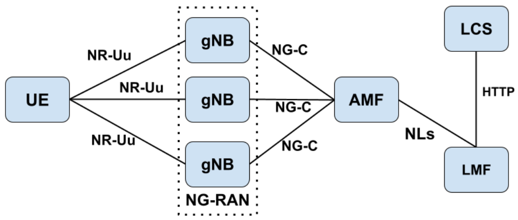

Fig. 1. UE Positioning Architecture [2, Section 5.1]

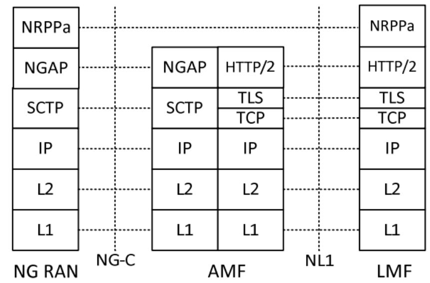

Fig. 2. Protocol Layering for LMF to NG-RAN Signalling [2, Section 6.5]

The key network components involved in positioning are:

- User Equipment (UE): A mobile device enabled with 5G services whose location is being determined.
- Next generation radio access network (NG-RAN): Comprising gNB(s) and Transmission Reception Points (TRPs), responsible for the radio connection between the UE and the 5G core.
- Access and Mobility Management Function (AMF): Manages access and mobility functions, ensuring seamless UE registration and mobility across cells.
- Location Management Function (LMF): Central entity overseeing location services and coordinating TDoA measurements to calculate the UE's final position.
- LCS entity: Manages location-based services by processing requests and coordinating with network elements to determine the UE's location.

The following interfaces facilitate communication among these components:

- NR-Uu: Connects the UE to the gNB, enabling data transmission, signaling, and radio resource management.
- NG-C: Connects the gNB to the AMF, handling control plane tasks and serving as a transport link for positioning protocols.
- NLs: Connects the LMF and AMF, serving as a transport link for the LTE Positioning Protocol (LPP) and NR Positioning Protocol (NRPPa).

A. Protocol Required for UL-TDoA Positioning Method in OAI

In the UL-TDoA positioning method [2, Section 8], the UE location is estimated based on UL-RToA measurements gathered at various gNBs/TRPs for uplink signals from the UE, along with other configuration details. To perform these uplink measurements, participating gNBs/TRPs need to be informed about the characteristics of the *sounding reference signal* (SRS) signal transmitted by the UE for the required measurement period. These characteristics must remain consistent across the periodic SRS transmissions. The LMF directs the serving gNB to instruct the UE to transmit SRS signals for positioning. The serving gNB then decides on the necessary resources and communicates the SRS configuration to the LMF, which in turn relays this information to the neighboring gNBs/TRPs participating in the UE positioning procedure.

Figure 3 illustrates the UL-TDoA procedure, highlighting the role of the NRPPa protocol in facilitating communication between the LMF and gNB. NRPPa PDUs exchange positioning-related data, such as configuration settings and measurement results, enabling gNBs to measure the TDoA of uplink signals, which the LMF uses to calculate the UE's location. Notably, NRPPa messages must pass through the AMF, as there is no direct link between the gNB and LMF. Figure 2 outlines the protocol layering required for NRPPa message transfer. In the next section, we describe in detail our implementation of UL-TDoA in OAI framework, along with the messages exchanged during the NRPPa PDU Transfer process.

III. Implementation of UL-TDoA Procedure in OAI

In this section, we first outline the essential components of the UL-TDoA positioning procedure and how they were implemented in OAI's 5G RAN and 5G CN. In the next subsection we will focus on the implementation of the ToA estimator in the gNB. Due to the page limit in this paper, we present a summary of the implementation of these messages in the OAI framework. We encourage the reader to refer to the full version of this paper for complete details [1].

A. Implementation of the NRPPa protocol

As outlined in the previous section and also depicted in Figure 3 the NRPPa procedure for UL-TDoA positioning involves the LMF, AMF and gNBs. We will examine each message exchange in the procedure and highlight the specific developments we contributed to the OAI framework.

Initiation of Location Request: The UL-TDoA positioning process starts when an external API sends a location request for a target UE to the LMF. The request is made via the *determine-location* API of the LMF, containing an *InputData* [9, Section 6.1.6.2.2] type data structure. To enable the exchange of this message, we first developed the 3GPP-compliant LMF framework and integrated it into OAI's CN framework [10]. Then within that LMF framework, we develop the determine-location API [9, Section 6] to handle the positioning request following the 3GPP standard. The 3GPP specifies several identification methods for UE positioning. In our implementation, we use the *subscription permanent identifier* (SUPI), represented by the *international mobile subscriber identity* (IMSI), to identify the UE. The key information

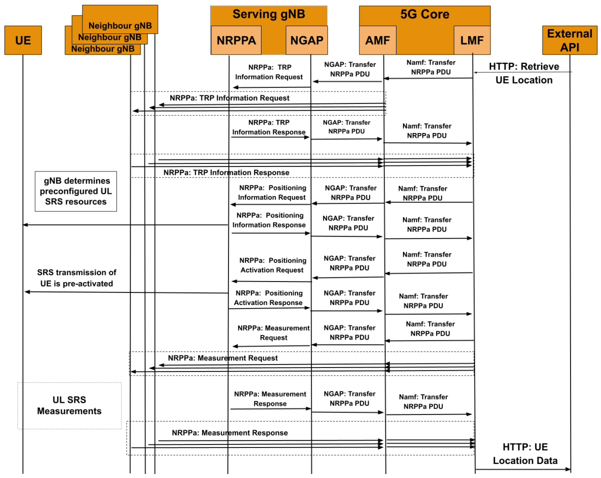

Fig. 3. End-to-End Implementation of 3GPP-compliant UL-TDoA Positioning Procedure [2, 8.13.3.4] in OAI.

elements in the InputData structure for our implementation include:

- SUPI
- NR Cell Global Identifier (NCGI)
- Periodic Event Info

Upon receiving the request, the LMF initiates the UL-TDoA positioning procedure, exchanging NRPPA messages between the LMF and gNB(s) to gather the necessary information for positioning. To enable the UL-TDoA positioning procedure within OAI's 5G framework, we have added support for these messages across LMF, AMF, gNB-NGAP, gNB-NRPPA, gNB-RRC, gNB-MAC, and gNB-PHY components.

TRP Information Request: The LMF initiates the UL-TDoA positioning by sending a TRP information request [11, Section 9.1.1.14] to gather necessary TRP data for UE positioning, as specified by 3GPP. The key information elements in our implementation of this message include:

- Message Type
- NRPPa Transection ID

This request is part of the non-UE-associated NRPPa procedures. In our implementation, the AMF forwards the request to all connected gNBs, where it is processed by the MAC handler.

TRP Information Response: All gNBs participating in the positioning procedure prepare a TRP information response and send it to the LMF, providing essential data such as configuration and location, which are crucial for accurate UE positioning. The TRP information response message terminates at the LMF. The key information elements in our implementation of this message include:

- TRP ID
- NG-RAN CGI
- Geographical Coordinates

Positioning Information Request: After receiving TRP Information Responses from all gNBs, the LMF retrieves SRS configuration details for the target UE by sending a positioning information request [11, Section 9.1.1.10] to the serving gNB. The serving gNB then allocates resources for SRS and configures the UE with the appropriate SRS resource sets. The key information elements in our implementation of this message include:

- Requested SRS Transmission Characteristics

As part of the UE-associated NRPPa procedures, the AMF forwards this message only to the serving gNB. The message is processed in the MAC handler of the gNB.

Positioning Information Response: After processing the positioning information request, the serving gNB sends a positioning information response [11, Section 9.1.1.11] with the SRS configuration for the target UE. In the current OAI RAN framework, the SRS configuration is predefined in the gNB settings and does not support dynamic adjustments for individual UEs. Therefore, the gNB returns the existing SRS configuration already applied to the target UE, regardless of the specific request from the LMF. The response message terminates at the LMF. The key information elements in our implementation of this message include:

- SRS Configuration

Positioning Activation Request: Once the LMF receives the SRS configuration for the target UE, it initiates UE SRS transmission by sending a positioning activation request [11, Section 9.1.1.12] to the serving gNB. As part of the UE-associated NRPPa procedures, the AMF forwards this message only to the gNB serving the UE. The request terminates in the MAC handler of the gNB. The key information elements in our implementation of this message include:

- SRS Resource Set ID
- SRS Resource Trigger

Positioning Activation Response: In the current OAI RAN framework, UE SRS transmission is preactivated, and real-time modifications are not supported. When the gNB receives the request, it generates a positioning activation response [11, Section 9.1.1.18] and sends it to the LMF, confirming that the UE is transmitting the SRS. The key information elements in our implementation of this message include:

- System Frame Number
- Slot Number

The positioning activation response message terminates at the LMF. Although UE SRS transmission is preactivated, allowing the positioning activation request to be handled entirely at the gNB-NRPPa with a response generated there, we have included the processing of this message in both the gNB-RRC and gNB-MAC for completeness. This approach ensures future compatibility with potential OAI code developments that may support on-the-fly SRS activation.

Measurement Request: Once the LMF receives the positioning activation response, it retrieves ToA measurements from all participating gNBs/TRPs by sending a measurement request [11, Section 9.1.4.1] to each one. This request includes the SRS configuration from the positioning information response for the target UE. The gNBs use this configuration to perform ToA measurements and return the results to the LMF. The key information elements in our implementation of this message include:

- TRP ID
- SRS Configuration

As part of the non-UE-associated NRPPa procedures, the AMF forwards the request to all connected gNBs. The message terminates in the PHY handler of the gNB.

Measurement Response: All gNBs involved in the positioning procedure generate a measurement response and send it to the LMF, providing crucial ToA measurements for accurate UE positioning. Precision in these measurements is vital, as any errors can significantly affect positioning accuracy. To improve measurement precision, we have integrated an advanced channel and ToA estimation procedure into the gNB (detailed in Section III-B). The key information elements in our implementation of this message include:

- TRP ID
- UL RToA Measurement
- gNB Rx-Tx Time Difference

Message 10 Location Response: The LMF receives ToA measurements from each gNB/TRP along with their relative Cartesian coordinates (x, y, z). Before using these ToA measurements, the LMF maps them to actual values using UL RToA report mapping tables from [12]. The LMF then converts the ToA values into TDoA values, referencing the TRP with the strongest *Reference Signal Received Power* (RSRP). Using known TRP locations, the LMF's localization algorithm—employing linear and nonlinear least squares solutions—calculates the user's position and returns it via the determine-location API. The localization function accepts TDoA values and TRP positions, allowing for integration of any compatible algorithm. After determining the UE's position, the LMF sends a response [9, Section 6.1.6.2.3] to the external API that initiated the request, including the following key elements:

- Geographical coordinates
- Relative Cartesian Location

The next subsection covers our state-of-the-art ToA estimation procedure integrated into OAI's gNB.

B. Enabling ToA estimation in OAI's gNB

1) gNB-PHY: The PHY layer involves two primary processes: channel estimation and subsequent ToA estimation based on the pilot symbols of the SRS. The SRS is a wideband reference signal transmitted by the UE in the uplink. The SRS for positioning is generated using the Zadoff-Chu sequence [13], similar to the SRS for communication, although they can be configured differently. During the SRS channel estimation, essential parameters such as the OFDM symbol size N_{OFDM}, subcarrier offset k, number of received antennas N_{RX}, and transmitter antenna port size N_{TX} are extracted from the gNB structure. For each receive antenna $n \in \{1, \dots, N_{\text{RX}}\}$ and antenna port $m \in \{1, \dots, N_{\text{TX}}\}$, Least Squares (LS) estimation is performed by correlating the received SRS signal $\mathbf{Y}_{SRS_{n,m}}$ with the generated signal $\mathbf{X}_{SRS_{n,m}}$ to estimate the channel $\hat{\mathbf{H}}_{n,m,l}$:

$$\hat{\mathbf{H}}_{n,m,l}[k] = \frac{\mathbf{Y}_{SRS_{n,m,l}}[k]}{\mathbf{X}_{SRS_{n,m,l}}[k]} \quad (1)$$

Since the SRS can be mapped to multiple consecutive OFDM symbols $l \in \{1, \dots, N_{symb}^{SRS}\}$, during the channel estimation process, the SRS channel is estimated over all the symbols. The channel estimate is then interpolated and oversampled before converted to the time domain denoted by $\hat{\mathbf{h}}_{n,m,l}^{\text{oversamp}}(t)$. We refer readers to our full paper [1] for details on signal processing. The sample delay is estimated by identifying the index τ_n^{peak} corresponding to the maximum of the magnitude squared of the channel impulse response averaged over all the SRS OFDM symbols:

$$\tau_n^{\text{peak}} = \arg\max_t \{ \frac{1}{N_{\text{symb}}^{\text{SRS}}} \sum_{l=1}^{N_{symb}^{SRS}} \sum_{m=1}^{N_{TX}} \left| \hat{\mathbf{h}}_{n,m,l}^{\text{oversamp}}(t) \right|^2 \} \quad (2)$$

This delay in samples can be translated to ToA in seconds by dividing the sampling rate.

a) FAPI interface: The FAPI interface, standardized by the small cell forum [14], facilitates communication between the PHY and MAC layers. SRS measurements are sent from PHY to MAC via the *SRS.indication* message, which includes a "*Timing advance offset in nanoseconds*" field for UL-TDoA positioning. However, the standard does not account for multiple measurements from multiple TRPs connected to the same DU. To address this, we added a new SRS type (5) and a new report type ("Localization") to the SRS indication message. These additions remain compatible with implementations that do not support this report type. The timing advance offsets from multiple TRPs are sent as an array in the Report TLV, with each value using 16 bits.

2) gNB-MAC: The MAC handles SRS scheduling and processes SRS indication messages from the PHY. For serving cell measurements, SRS scheduling is already activated during the PDU session establishment. Upon receiving an F1 positioning measurement request, the MAC retrieves the latest ToA measurement from the PHY and generates the F1 positioning measurement response. For neighbor cell measurements, the MAC must first activate the SRS measurements. Since the FAPI interface does not support this usage, we introduced a special RNTI for this purpose. The RNTI is used in both the SRS PDU (UL_TTI request) from MAC to PHY and in the SRS indication from PHY to MAC, allowing us to link the measurement to the request.

IV. Validation of our Open-Source UL-TDoA Positioning

In this section, we validate our open-source UL-TDoA positioning implementation within the OAI framework. All the code for this project is available on the OAI gitlab repository [15] on the branch *NRPPA_Procedures*[1].

[1]If the NRPPA_Procedures branch no longer exists, use the *develop* branch instead.

We validated end-to-end protocol testing and message exchange using the OAI RF simulator and the GEO5G testbed at EURECOM. The OAI RF simulator enables controlled testing, while the GEO5G testbed provides real-world validation. Due to space constraints, we present only the GEO5G testbed setup and results. A detailed OAI RF simulator setup tutorial is available in [16].

A. GEO5G Localization Testbed at EURECOM

The GEO5G localization testbed is part of the broader Open5G testbed at EURECOM. This testbed includes computing and switching infrastructure connected via high-speed fiber to various radios (e.g., USRP or commercial O-RAN units), enabling virtualized 5G network deployment. A key feature is its integration with OpenAirInterface, which provides the virtualized network functions necessary to run the 5G network. A detailed tutorial on building an O-RAN-based setup is available here [17]. A live demo of UE tracking based on this work, using this testbed, was presented at the OAI Workshop 2024 [7]. The video demo can be found here [8].

1) Deployment: To evaluate the localization features, we deployed 3 additional outdoor ORAN RUs from Firecell (see the full paper [1] for details). Figure 5 shows an aerial view of the EURECOM building, which has two symmetric wings on different levels. Two antenna sites are located on the roof of each wing, part of the EURECOM 5G testbed. These sites, connected via fiber to EURECOM's server room, house Firecell RUs, each driving two external antennas mounted on roof railings with 10m low-loss cables (7 dB attenuation included in the link budget). These antennas overlook the lower roof, where the northeast wing serves as an experimentation area, while the southwest wing, off-limits to people, hosts the third RU with four antennas mounted on tripods 10m apart and 2m high.

2) Logical Architecture: The logical architecture of the localization testbed is depicted in Figure 4. It follows a basic O-RAN architecture with sync option LLS-C3, i.e., the synchronization is provided by Qulsar Qg 2 Telecom Grandmaster (T-GM) whose Primary Reference Time Clock (PRTC) is derived from a Global Navigation Satellite System (GNSS) receiver. The timing signals are distributed from the PRTC/T-GM to the O-RU and the O-DU via the fronthaul network through the O-RAN S-plane. The CU and DU run on a server "colibri" with a Intel(R) Xeon(R) Gold 6354 CPU @ 3.00GHz CPUs with 18 cores each and an Intel X710 4x10Gbps NIC. Two of the four ports are used to connect to the backhaul network (via a CISCO C9364C-GX switch) and the two other ports are connected to the fronthaul network (via a Cisco 93180-YC-FX3 switch). The CN runs on the server "alambix" in a docker environment.

3) Ground truth measurements: In this work, 16 ground truth positions (A-P) were selected in a Cartesian coordinate system on the GEO5G testbed at EURECOM. The distances from each point to all antennas were measured using a BOSCH laser distance meter. The reference antenna on RU3 was set at (x=0, y=0, z=2.2), and other antenna positions were recorded

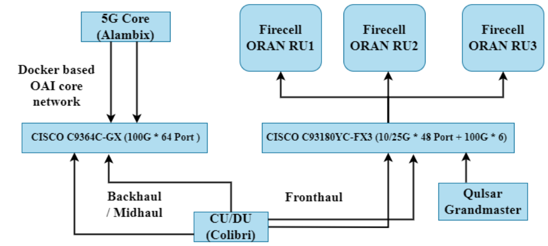

Fig. 4. Logical architecture of the localization testbed.

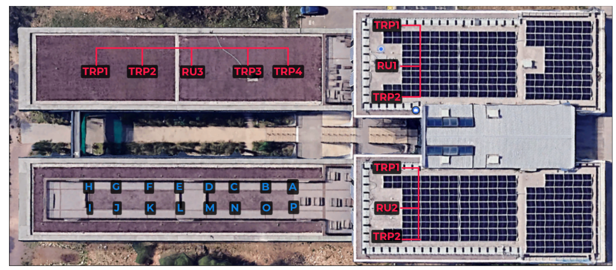

Fig. 5. TRPs and test points of GEO5G testbed at EURECOM

relative to it. The distances were used in nonlinear Euclidean distance equations to calculate the coordinates for each ground truth point. In MATLAB, the `fsolve` function was employed to iteratively find the coordinates $P_i = \{x_i, y_i\}$ by minimizing the discrepancy between measured and calculated distances.

B. Preprocessing and Position Estimation

In a multi-RU positioning setup, precise RU synchronization is crucial for accurate TDoA measurements, as just a 1-nanosecond error can cause a 0.3-meter positioning inaccuracy. While in some setups this accuracy can be achieved, in our GEO5G testbed we have observed timing errors of up to 40ns. Using a common reference TRP across all RUs will therefore result in inaccurate TDoA measurements and degraded positioning estimates.

To mitigate this, a per-RU reference approach is adopted, where within each RU, one TRP is designated as the local reference for TDoA calculations, ensuring that all measurements within the RU remain internally consistent and unaffected by synchronization drifts in other RUs.

Next, to ensure robust TDoA estimation while mitigating synchronization errors, a two-stage filtering mechanism is employed. Firstly, by averaging over the N most recent TDoAs from each RU, we avoid small-scale fluctuations in the measurements. Secondly, for compensating larger spikes in the TDoAs, another filter is used that exploits the geographical information of the testing area. Knowing the minimum and maximum possible TDoA values based on known TRP positions, we define a filter that discards any invalid TDoA measurement and retains only those within a predefined bound, along with their corresponding TRP coordinates. This filtering approach effectively mitigates the impact of noisy measurements caused

Point	1 RU MAE (m)	2 RUs MAE (m)	Point	1 RU MAE (m)	2 RUs MAE (m)
A	4.77	1.88	I	3.02	0.60
B	4.69	1.13	J	2.32	0.83
C	0.81	0.82	K	3.38	0.82
D	1.30	0.83	L	3.23	1.20
E	2.37	0.95	M	3.34	0.64
F	2.00	0.55	N	4.85	0.68
G	2.27	0.92	O	5.41	0.97
H	3.31	0.56	P	4.12	1.98

TABLE I
MAE FOR SINGLE RU (RU3) AND MULTI-RU (RU2+RU3) SETUPS AT POINTS A-P

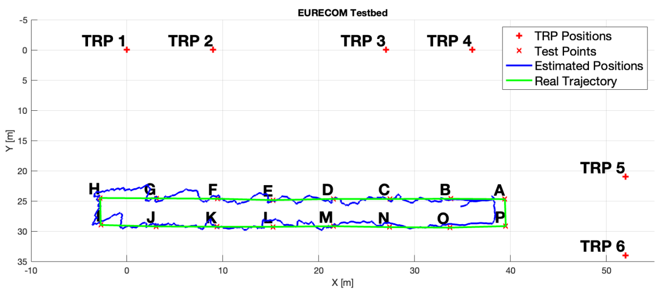

Fig. 6. UE tracking in a mobile scenario

by multipath, Non-Line-of-Sight (NLoS) conditions, and hardware impairments.

C. Results

This section validates the performance of our deployed 5G network by registering a UE and triggering the location determination API. The TRP coordinates and UL-RToA values from each TRP are used in a stochastic optimization method for position estimation from our previous work [18]. The positioning error was evaluated for two setups: a single RU (RU3) and a multi-RU (RU2 and RU3). The results show that multiple RUs improve accuracy by increasing TRP diversity in both the x and y axes. In the single RU setup, the TRPs are arranged linearly, causing higher uncertainty in the y-axis, which is reduced with the multi-RU setup. Points A, B, O, and P on the edge of the testing area show degraded accuracy due to NLoS, multipath and diffraction conditions to the buildings around them. Table I, is summarizing the Mean Absolute Error (MAE) for both setups. Also, Figure 6 shows a mobile scenario where a person holds the UE and takes a trajectory covering all testing points in the multi-RU setup.

In future developments, a multi-gNB setup with additional RUs and increased TRPs is expected to enhance accuracy by enabling techniques such as multipath and NLoS mitigation.

V. Conclusions

This paper provided the first open-source implementation of the 3GPP UL-TDoA positioning method within the OAI framework, successfully integrating UL-TDoA into both the RAN and CN components. By adhering to 3GPP standards, this implementation enabled precise and real-time positioning of UE in 5G networks, offering a flexible alternative to proprietary solutions. The approach was validated through both simulation and real-world testing, demonstrating its reliability and accuracy. This work not only enhanced the capabilities of OAI for 5G positioning but also contributed to the broader research community by providing a valuable tool for further innovation and collaboration in the field of cellular network positioning technologies.

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