A Unified Hybrid Terminal for Augmented Positioning

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***Abstract*—Emerging positioning sources, such as 5G Terrestrial Networks (TN), Non-Terrestrial Networks (NTN), are becoming increasingly accessible. Combined with existing systems such as GNSS and Low Earth Orbit (LEO) technologies, they promise enhanced navigation performance, robustness, and reliability while providing communication capabilities. This convergence enables continuous and ubiquitous navigation and unlocks new applications and services. This paper presents the specification and design activities of a hybrid terminal that integrates these positioning technologies, highlighting preliminary results obtained with its 5G TN link.**

I. Introduction

The convergence of emerging Positioning, Navigation, Timing (PNT) sources, such as 5G TN, NTN, and LEO-PNT, with existing systems such as GNSS and LEO-Signal of Opportunity (SOP) introduces a transformative leap in navigation, significantly improving accuracy, robustness, and continuous and ubiquitous service. Integrating GNSS, 5G TN and NTN signals, and LEO sources across multiple satellite constellations will deliver precise, reliable, and robust navigation in harsh environments, while improving PNT performance and adding communication capabilities for maritime, rail, road, UAV, and Location Based Services (LBS) applications. This paper explores the development of a hybrid receiver that combines all these PNT sources, the Unified Hybrid User Terminal (UHUT), and focuses on the tests carried out to develop its 5G TN module. This work introduces a general description of the UHUT in Section II, delving into the characteristics of GNSS, LEO-PNT, and 5G TN & NTN. Section III will describe the complete hardware, software and processing used to perform the preliminary tests related to the UHUT 5G NR pipeline, as well as the preliminary results obtained.

II. Hybrid Terminal Specifications

The UHUT integrates multiple technologies for positioning and signal processing, including GNSS, LEO-PNT, LEO-SOP, and 5G (both TN and NTN). While each subsystem addresses different frequency bands, signal structures, and processing approaches, the overall architecture is designed to maximize modularity, signal diversity, and hybridization capability. Target performance figures have been defined to ensure positioning continuity and accuracy across diverse scenarios. When all systems are available and operating under open-sky conditions, the hybrid navigation module is expected to achieve a positioning accuracy below 2m [95%]. In urban environments with high multipath and degraded satellite visibility, the system is expected to maintain accuracy below 3m [95%], leveraging non-GNSS sources. In GNSS-denied scenarios, but with available 5G, LEO-PNT, and LEO-SOP signals, the terminal shall still provide positioning accuracy below 5m [95%] under open-sky conditions. These targets reflect demanding initial objectives which will be validated and refined through experimentation. A detailed description of the UHUT architecture and its interfaces with the different technologies is provided by Dominguez et al. [1], and it is beyond the scope of this paper. This study focuses instead on the overall system design and provides a deeper analysis of the 5G component.

A. GNSS and LEO-PNT

This section presents the unified receiver module responsible for processing both GNSS and LEO-PNT signals within the hybrid terminal. Although both systems share the same hardware platform, their signal processing pipelines operate independently, without joint tracking or data fusion. A single multi-band active antenna collects both GNSS and LEO-PNT signals; its broadband characteristics enable simultaneous reception across multiple frequency bands, simplifying the RF front-end design.

The GNSS chain follows a two-stage structure comprising acquisition and tracking, optimized for signals such as GPS L1 C/A and Galileo E1C. Once acquisition is complete, tracking is maintained through dedicated loops that ensure carrier and code synchronization. The LEO-PNT chain, while independent, follows similar processing principles, assuming GNSS-like waveforms for acquisition and tracking. From each tracked satellite, the receiver extracts key observables (Doppler, carrier phase, and pseudorange) which are subsequently used for position estimation once a sufficient number of LEO-PNT satellites are visible.

B. 5G TN and NTN

The proposed 5G architecture of the UHUT is designed to operate seamlessly across both TN and NTN 5G networks, in accordance with 3GPP Release 17 specifications. Its goal is to ensure interoperability with existing infrastructure while enabling advanced signal processing for positioning. The terminal integrates a reconfigurable RF front-end, a high-performance processing platform, and open-source software,

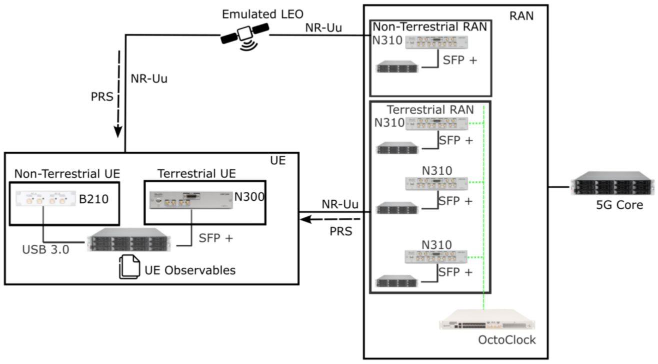

Fig. 1. 5G TN & NTN Setup for PNT.

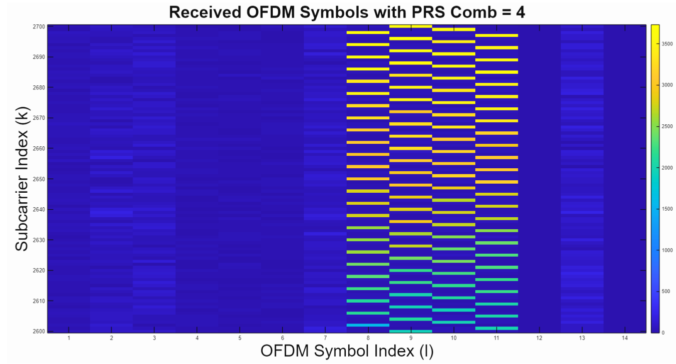

Fig. 2. PRS OFDM pilots, used for channel state information CSI extraction and subsequent TOA estimation.

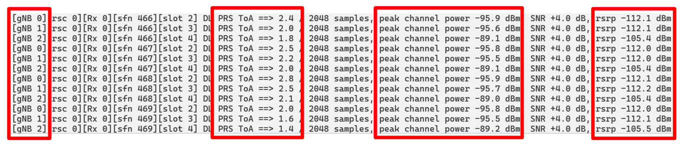

Fig. 3. OpenairInterface 5G logs, including PRS-computed ToA samples at 100 MHz of bandwidth.

supporting the full 5G New Radio (NR) protocol stack (gNB, UE, and Core Network), allow access to I/Q samples, and the integration with various RF front-ends, including those for NTN operation. For positioning, the UE must transmit and receive 5G NR signals compliant with Release 17. A key enabler is the Positioning Reference Signal (PRS), a standardized downlink signal used for 5G positioning.

III. 5G Processing and Testbed

This section describes the hardware, software, and the signal processing components that constitute the 5G NR pipeline of the UHUT, as well as the corresponding testbed used for preliminary validation. Figure 1 illustrates the complete experimental setup, including the UHUT, the Radio Access Network (RAN), and the 5G Core.

A. Hardware

The UHUT Radio Frequency (RF) front-end must operate across multiple 5G frequency bands, primarily within FR1, covering both 5G TN & NTN use cases. For this reason, the NR UHUT side consists of two Ettus Universal Software Radio Peripherals (USRP™): an N300 for the TN link and a B210 for the NTN link. A high-performance server is connected to the USRPs via SFP+ interface to handle baseband processing, enabling real-time operation with up to 100 MHz bandwidth for 5G TN signals and up to 30 MHz bandwidth for 5G NTN signals. To test the UHUT capabilities, we deploy multiple pairs of Ettus N310 USRPs and server units on the network side, where each pair operates as an independent 5G gNB instance. The network side is synchronized through a common timing reference, often provided by a timing distributor such as the Ettus OctoClock, to ensure precise alignment across all nodes. The complete 5G NR stack is implemented using the open-source OpenAirInterface (OAI) platform, which provides a reference implementation compliant with 3GPP Release 17 of the entire 5G system, including the gNB, UE and core network. OAI meets the required software specifications and is widely adopted in the research community for 5G innovation.

B. Signal processing

The signal processing is performed by a combination of OAI, the Ettus N300 and B210 SDR as the front-end and the high-performance workstation. For processing, the following UE observables are measured: Time of Arrival (TOA), Signal-to-Noise Ratio (SNR), Channel State Information (CSI), Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and Timing Advance (TA). Such observables help both redefine and adjust the raw measured data for finer processing. In addition to the observables measured over TN, the NTN segment of the UE shall also measure the Doppler shift.

The selected signal for positioning used in this context is represented by the PRS, a downlink Reference Signal (RS) standardized for 5G positioning techniques. This signal is a pseudo-random Gold Sequence, which uses Quadrature Phase Shift Keying (QPSK) modulation and leverages properties that minimize inter-UE interference within the same Orthogonal Frequency Division Multiplexing (OFDM) slot. The PRS configuration fully determines how the pilot signals are mapped onto the time–frequency grid. In frequency, the *comb size* controls the spacing between PRS subcarriers, and therefore the density of pilots available for channel estimation. The PRS occupies a specific bandwidth defined by the number of *resource blocks* and their starting position, while an additional *RE offset* within the comb can be used to shift the PRS pattern across subcarriers. In time, the *symbol start* parameter identifies the first OFDM symbol within the slot that carries PRS, and the *symbol length* gives the number of consecutive OFDM symbols used for PRS transmission. Together, these parameters precisely define the PRS time–frequency allocation, which directly impacts both the resolution and robustness of the resulting channel and positioning estimates. The configuration displayed in Figure 2, which corresponds to the one used in our tests, uses a *comb size* of 4, with PRS pilots starting at the seventh OFDM symbol and occupying four consecutive symbols (from symbol 7 to symbol 10).

The TOA is obtained from the lag n that maximizes the cross-correlation between the known (transmitted) PRS and the received PRS. Let $X[k]$ and $Y[k]$ denote the transmitted and received PRS in the frequency domain at subcarrier k. We first compute the frequency-domain cross-correlation:

$$R_{XY}[k] = X[k] \cdot Y^*[k], \tag{1}$$

and obtain the time-domain cross-correlation sequence via

$$r_{xy}[n] = \text{IDFT}\{R_{XY}[k]\}, \tag{2}$$

where $\text{IDFT}\{\cdot\}$ is the Inverse Discrete Fourier Transform. Then, the TOA estimate for the i-th observation is given by

$$\widehat{\text{TOA}}_i = \frac{1}{f_s} \arg\max_n \left| r_{xy}[n] \right|, \tag{3}$$

where f_s is the sampling rate, and $\arg\max_n$ returns the sample index n at which $|r_{xy}[n]|$ reaches its maximum.

Figure 3 showcases the computed ToA values on OAI, and other UE observables, for each connected gNB of a preliminary test ran at 100 MHz of signal bandwidth. To apply triangulation or multilateration algorithms, it is necessary to compute the Time Difference of Arrival (TDOA) [2] between two PRSs transmitted by different gNBs i and j:

$$\widehat{\text{TDOA}}_{i,j} = \widehat{\text{TOA}}_i - \widehat{\text{TOA}}_j \tag{4}$$

These raw TDOA measurements can be refined using techniques such as moving averaging, which improves the reliability and robustness of 5G localization by mitigating the impact of outlier ranging measurements, and oversampling, which enhances TOA/TDOA accuracy by increasing the number of collected samples. After computing all pairwise TDOAs between gNBs, the DL-TDOA technique can employ different algorithms for final position estimation, including Closed-Form Solution, Brute-Force Search, and Non-Linear Least Squares (NLLS).

C. Preliminary Results

Figure 4 displays the processing of the TOA samples of Figure 3 to estimate the position of the UHUT in a preliminary indoor test. The PRS signals coming from TN links with three gNBs are received by the UHUT every 10 ms in a 60 s acquisition window and the corresponding TOA samples are computed via Equation 3. From Equation 4, the TDOA values are derived. The Brute-Force algorithm is implemented for every sample, and the point on the 2D grid with the highest likelihood to the computed TDOA is selected as the position estimate, resulting in an error $\epsilon = 1.04$ m with respect to the true UHUT 2D coordinates. Results are aligned with the 5G localization study proposed by Palamà et. al. [3], and shows

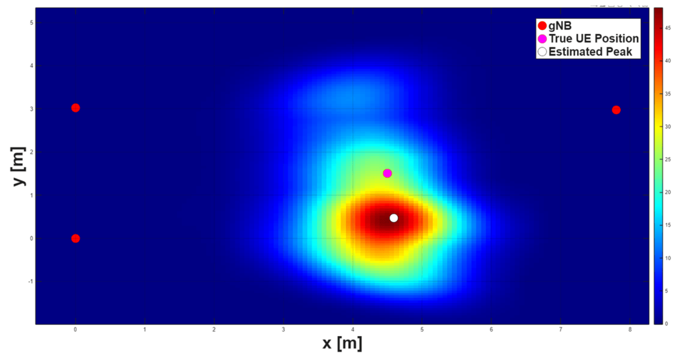

Fig. 4. 2D Histogram of TN TDOA positioning at 100 MHz of bandwidth.

the feasibility to perform 5G positioning even in GNSS-denied and multipath-rich environments.

The final implementation will employ Extended or Unscented Kalman Filters to fuse estimates from TN, NTN, GNSS, and LEO-PNT sources.

IV. Conclusion

In this paper, the development of a Unified Hybrid Terminal including the processing of GNSS, LEO-PNT, LEO-SOP and 5G signals for PNT has been presented. First, the hybrid terminal's added value was assessed to identify key PNT domains and applications. In particular, processing multiple signals can improve the accuracy and availability of the PNT solution, enhance robustness against threats such as jamming and spoofing, and support deployment in civilian, commercial, and safety-critical applications.

The high-level design of the hybrid terminal is described, focusing first, on the GNSS and LEO-PNT branch, and then on its 5G TN & NTN ones. Processing of the 5G PRS signal has been described, together with a presentation of preliminary tests for the UHUT localization estimation.

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