Sub-Meter Hybrid Positioning with Flying 5G Networks and Synchronization Corrections

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ABSTRACT

This work presents a synchronization correction mechanism of a dedicated flying fifth generation (5G) network enabling sub-meter positioning. Field results are shown thanks to a first-of-a-kind testbed for hybrid Global Navigation Satellite Systems (GNSS), 5G new radio (NR) and sensor positioning, called Hybrid Overlay Positioning with 5G and GNSS (HOP-5G) testbed. As shown in previous works, this dedicated 5G network achieves sub-meter ranging performance, by exploiting in real-time 5G NR positioning reference signal (PRS) transmissions of 80MHz. This paper presents the correction mechanism necessary to enable sub-meter hybrid positioning with these high-accuracy ranging measurements. To the best of authors' knowledge, this paper demonstrates for the first time the feasibility to apply such 5G network synchronization corrections to dedicated flying 5G base stations for positioning, achieving sub-meter hybrid positioning in a field deployment.

1 INTRODUCTION

Enabling the positioning capabilities of Fifth Generation (5G) technologies in complement to Global Navigation Satellite Systems (GNSS) is a promising concept to enhance the accuracy and reliability of existing GNSS stand-alone solutions. Nowadays, GNSS is the most widely-adopted and backbone technology for outdoor positioning applications. However, GNSS performance is severely degraded due to signal blockages (e.g. in urban environments) and interferences (e.g. intentional and unintentional). Thanks to the predominance of 5G modems in the user equipment (UE) and the native support of positioning services in the 5G standard (i.e., using dedicated positioning signals and protocols), 5G systems can thus be considered a suitable technology to complement GNSS under harsh environments. Nonetheless, the lack of tight network synchronization in conventional deployments prevent the exploitation of 5G precise positioning solutions, such as when using downlink time-difference of arrival (DL-TDoA) methods with large signal bandwidth. Therefore, the goal of this work is to demonstrate a mechanism to achieve sub-meter level positioning with 5G stand-alone and its hybridization with GNSS code-based methods in a field deployment.

The exploitation of 5G positioning in real demonstrations has been mainly performed with signals of opportunity (SoP) approaches by academia or with prototype deployments by 5G network vendors and chipset manufacturers. For instance, experimental 5G positioning results have been presented in predecessor testbeds, such as in Crapart et al. (2018); Mata et al. (2020), as well as with signals of opportunity approaches in Shamaei & Kassas (2021); Abdallah & Kassas (2021). However, there is a very limited literature on the positioning capabilities of dedicated 5G positioning networks, i.e., 5G NR networks tailored to support positioning services. Thus, a first-of-a-kind testbed has been developed under the Hybrid Overlay Positioning with 5G and GNSS (HOP-5G) project, in order to experiment with 5G new radio (NR) precise positioning capabilities in real-time. One of the key features of the testbed is the support of the positioning reference signal (PRS) in the 5G NR downlink transmissions both at the base station (BS) and UE, by using software-defined radio (SDR) and an upgrade of OpenAirInterface (OAI) software stack, using the baseline introduced in Kaltenberger et al. (2020). Indeed, thanks to the OAI PRS code developments in the HOP-5G project, a testbed with four OAI base stations or gNBs and the OAI user equipment is deployed in Palamà et al. (2024) to exploit the PRS transmissions for DL-TDoA positioning.

The HOP-5G testbed has demonstrated the sub-meter ranging performance, which is achievable either with a single flying base station as studied in del Peral-Rosado et al. (2023a) or in a dedicated flying and ground 5G network in del Peral-Rosado et al. (2023b). However, although each BS embeds a GPS disciplined oscillator (GPSDO), there are still clock misalignments and drifts over time between BSs. Thus, this paper describes a correction mechanism to resolve these network synchronization impairments, and demonstrates sub-meter 5G stand-alone and hybrid positioning with field measurements. The mechanism is based on a BS time offset estimation module that provides time offset and drift corrections (with respect to a reference BS) to the UE positioning engine. The HOP-5G testbed is deployed with flying and ground-fixed BSs, one UE and one positioning reference unit (PRU), which is a user equipment with known location that can be used for BS time offset correction generation. To the best of authors knowledge', these are the first field results that demonstrate the feasibility of this network synchronization mechanism using flying 5G base stations, enabling sub-meter 5G and hybrid positioning accuracy.

2 FLYING 5G NETWORK FOR USER POSITIONING

The HOP-5G testbed is a first-of-a-kind demonstrator on the exploitation of dedicated flying 5G networks for positioning. The design considerations of such networks are studied in del Peral-Rosado et al. (2022a), leading to significant advantages in terms of optimization of positioning geometry thanks to the on-demand 5G network deployment. Certainly, to enable high-accuracy positioning services, these dedicated deployments rely on the following considerations:

- precise knowledge of the base station antenna locations;
- line-of-sight (LoS) propagation conditions between 5G BSs and UE;
- high 5G signal bandwidths, and
- accurate correction mechanisms.

Indeed, the 5G network synchronization is a significant issue in TDoA-based positioning algorithms. The HOP-5G testbed proposes a hybrid 5G and GNSS positioning system that exploits the usage of a monitoring unit for a real-time estimation of the time offsets between the BSs. This monitoring unit is also identified as PRU within the 3GPP, as described in 3GPP TS 38.305 (2022), whose known position allows to estimate the time-varying delays between base stations with suitable models. The estimated time offsets are then used as corrections, either in real-time or post processing, by the hybrid positioning technique within the UE, to further improve the positioning solution, especially for TDoA-based localization approaches.

A high-level architecture of the HOP-5G testbed is shown in Figure 1. For simplicity, the figure does not highlight every data link among the nodes, i.e., based on MQTT messages exchanged through an ad-hoc Wi-Fi network. Note that the 5G PRU is a separate entity with respect to the UE, and both units are connected with the ad-hoc communication channel. A single monitoring unit is potentially capable of serving several UEs within a certain coverage area in LoS conditions. The main functionalities of this correction mechanism are:

- Estimate 5G ToA: This block has the responsibility of estimating the ToA of the visible BS signals, denoted as ToA_i, where i is the index of the BS. The ToA measurements are used both for the hybridization algorithm and for the estimation of the BS time offsets.
- Estimate BS time offset: This block is in charge of estimating the BS time offsets, which are subsequently sent to the hybrid solution algorithm. It exploits the following inputs:
    - Estimated ToA of the visible BS signals;
    - Precise BS positions, computed by the GNSS real-time kinematic (RTK) receivers of the BSs (including fusion with IMU and barometric data for the UAVs, if available);
    - Precise UE position, computed by the GNSS RTK receiver of the UE (including fusion with IMU data for dynamic scenarios and barometric data when the UE is an UAV).
- Hybrid solution: This block implements the hybrid 5G and GNSS location algorithm. It exploits the following inputs:
    - Estimated ToA of the visible BS signals;
    - Precise BS positions, computed by the RTK GNSS receivers of the BSs (including fusion with IMU and barometric data for the UAVs, if available);
    - UE position or GNSS observables, computed by the GNSS receiver of the UE (without using RTK corrections).

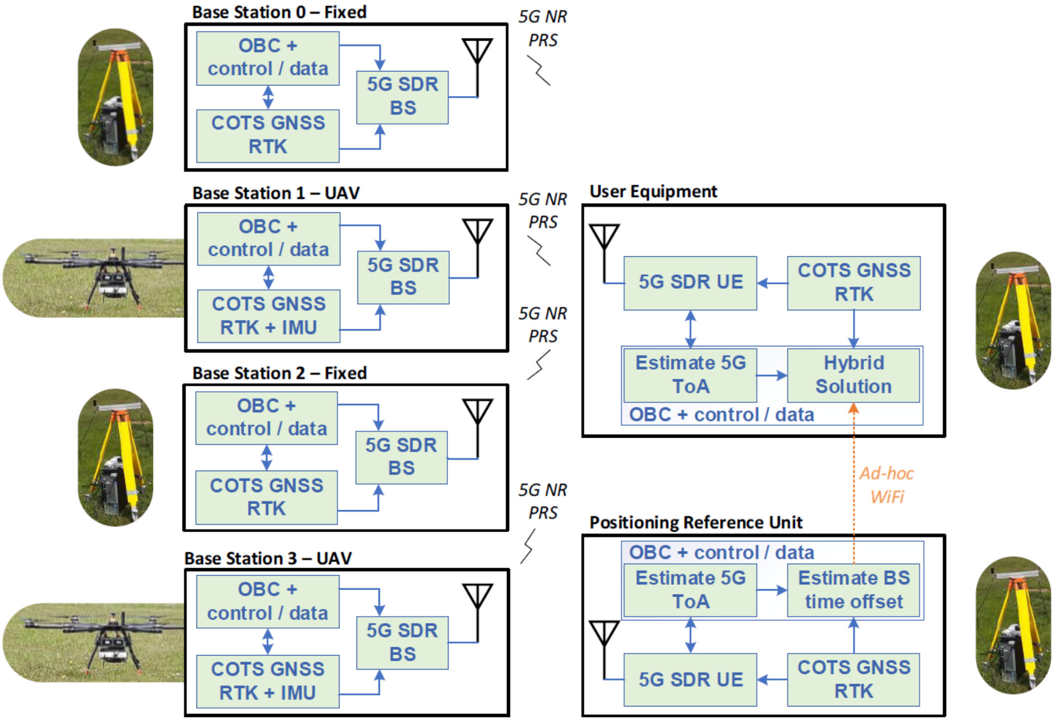

FIGURE 1 Flying 5G network for user positioning with synchronization corrections.

Note that the identified solution to enable the high-precision position and time estimation on-board of the BSs is based on a COTS GNSS receiver. Indeed, RTK is a GNSS augmentation technique based on the use of carrier measurements and the transmission of differential corrections from one multi-frequency GNSS receiver that has known location and that acts as RTK reference station. The corrections are received by other GNSS receivers acting as RTK rovers, whose locations are to be estimated with an error lower than 1 m. The role of the RTK reference station can either be played by the receiver attached to one fixed BS of the testbed, or by an external reference station in the surrounding area.

Besides the location of the BSs, GNSS is also exploited to synchronize spatially-distributed BSs in time. GNSS receivers, indeed, can combine the long-term stability of GNSS with the short-term stability of the internal oscillator. The simplest solution is based on the integration of one GPSDO in each BS, so that the transmissions are ensured to fall within 50 ns from Coordinated Universal Time (UTC). A GPSDO works by disciplining, or steering, an internal oscillator with small frequency adjustments, exploiting the long-term stability of the GPS-based pulse-per-second (PPS) signal, in order to generate a stable (in short- and long-term) 10-MHz clock and a PPS signal synchronized with UTC.

3 NETWORK SYNCHRONIZATION CORRECTIONS

Having a PPS signal well synchronized to UTC and a very stable 10 MHz clock is a necessary but not sufficient condition to achieve BS synchronization. Indeed, BS synchronization also depends on how the SDR equipment exploits these inputs. There may be some delays introduced by the SDR equipment that cannot be completely corrected, independently on how the SDR equipment is programmed or configured. This possibility is the reason why a monitoring station is necessary for the operation of the positioning system. This station is in charge of the real-time estimation of time offsets between BSs. Such offsets could either be used as corrections in a close loop, if they are timely returned to the BSs for some sort of delay compensation (the feasibility of this solution depends on the capabilities of the BSs, in particular, for the case of the current testbed, on the capabilities of the SDRs), or be used as corrections by the hybrid positioning technique within the UE. The latter option is adopted in the HOP-5G testbed, in order to cope with potential time offsets between the BSs.

For localization purposes, the estimated 5G ToA measurements are used to compute TDoA measurements among pairs of base stations, allowing the removal of the dependency of the measurement from the receiver clock. A TDoA measurement at time t can be written as:

$$\mathrm{TDoA}_{ij}(t) = \mathrm{ToA}_j(t) - \mathrm{ToA}_i(t). \tag{1}$$

It is important to remark that $\mathrm{ToA}_i(t)$ and $\mathrm{ToA}_j(t)$ must be extracted from signals that have been synchronously transmitted by the BSs i and j, with exception of the residual time offsets errors whose estimation is the goal of the monitoring functionality. They cannot refer to signals that have been transmitted by the BSs at different pulses of the PPS signal (e.g., because a signal arrived with significant delay due to multipath). To avoid this possibility, the "Estimate 5G ToA" shall associate to each ToA measurement a timestamp that can be extracted from the 5G signal message, more specifically from the System Frame Number (SFN) of the 5G signal, such that ToA associated to transmissions occurred at the same PPS pulse can be identified and differentiated to get the correct TDoA measurement.

The TDoA measurement model is here defined as:

$$\mathrm{TDoA}_{ij}(t) = \left(d_j(t) - d_i(t)\right)/c + \left(\epsilon_j^d(t) - \epsilon_i^d(t)\right)/c + \Delta T_{ij}(t) + \epsilon_j^{\mathrm{ToA}}(t) - \epsilon_i^{\mathrm{ToA}}(t), \tag{2}$$

where $d_i(t)$ and $d_j(t)$ are the estimated distances at time t among the BS i and the UE and among the BS j and the UE, respectively, $\epsilon_i^d(t)$ and $\epsilon_j^d(t)$ are the estimation errors of $d_i(t)$ and $d_j(t)$, respectively, due to positioning errors of the RTK GNSS receivers, c is the speed of light, $\Delta T_{ij}(t)$ is the time offset between the BS i and the BS j at time t, and $\epsilon_j^{\mathrm{ToA}}(t)$ and $\epsilon_i^{\mathrm{ToA}}(t)$ are the estimation errors of $\mathrm{ToA}_i(t)$ and $\mathrm{ToA}_j(t)$, respectively.

Assuming that all the estimation errors (i.e., ϵ_i^d, ϵ_j^d, $\epsilon_i^{\mathrm{ToA}}$, $\epsilon_j^{\mathrm{ToA}}$) have a bias equal to 0, it is straightforward to estimate the best possible value $\Delta T_{ij}(t)$ from an instantaneous TDoA measurements $\mathrm{TDoA}_{ij}(t)$:

$$\Delta T_{ij}(t) = \mathrm{TDoA}_{ij}(t) - \left(d_j(t) - d_i(t)\right)/c. \tag{3}$$

Unfortunately, the above equation has the problem that is affected by the noise of three position estimations (i.e., pair of BSs and UE) and two ToA estimations (i.e., $\mathrm{ToA}_i(t)$ and $\mathrm{ToA}_j(t)$). The combination of all these errors may lead to a significant and instable error (i.e., jumping from time to time) for the BS time offset. In order to cope with this problem, it is possible to exploit the time dimension, considering a dynamic model for the variation of the BS time offset, in order to filter multiple measurements and to converge to a more accurate and stable estimation of the BS time offset.

In the literature, it is common to consider a first-order model for the time offset of a clock, made by a bias component and a drift component. The BS time offset is a differentiation of the two individual clock offsets, with respect to UTC, of the two BS. As a consequence, a first-order model of the two individual clock offsets leads to a first-order model on the time offset between the BSs:

$$\Delta T_{ij}(t) = B_{ij}(t_0) + D_{ij}(t_0) \cdot (t - t_0), \tag{4}$$

where $B_{ij}(t_0)$ is the bias of the BS time offset at time t_0 and $D_{ij}(t_0)$ is the drift of the BS time offset at time t_0.

Exploiting the above dynamic model with the previously defined measurement model for the BS time offset $\Delta T_{ij}(t)$, a Kalman filter (KF) is proposed to sequentially estimate the parameters B_{ij} and D_{ij}, characterizing the dynamic behaviour of the time offset between BS i and BS j. The KF is an optimal estimation method assuming a normal (Gaussian) distribution of the estimation errors. In addition, the KF process noise allows taking into account small variations of some parameters, such as the drift, hence tracking the dynamic behavior of the BS time offset even if the first-order model is too simplified.

4 FIELD CAMPAIGN

4.1. DESCRIPTION OF THE FIELD TEST CAMPAIGN

The HOP-5G field test campaign demonstrates the high-accuracy positioning capabilities of a dedicated 5G network deployment with flying and ground base stations. The campaign is conducted on the 12th July 2023 at the heliport of Airbus premises in Ottobrunn (Germany). The 5G deployment is based on four ground units, i.e., UE, PRU, BS0 and BS2, and two flying base stations, i.e., BS1 in a UAV and BS3 in another UAV. This paper focuses on the first flight of the demonstration, which includes take-off, hovering of flying base stations and landing. The signal transmission of each BS is based on the 5G NR PRS over a bandwidth of 80MHz.

The HOP-5G test setup in the field is shown in the following figure, where BS1-UAV and BS3-UAV are hovering in the vicinity of UE and PRU, while BS0 and BS2 are located statically on ground.

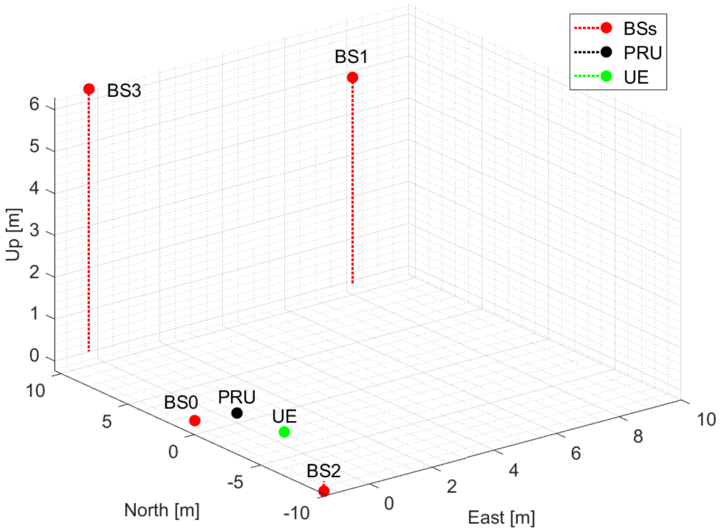

FIGURE 2 HOP-5G deployment during the field test campaign.

The NovAtel Inertial Explorer® software is used for post-processing of the recorded GNSS raw data in order to achieve the precise reference positions (of UE, PRU, BS0 and BS2) and reference trajectories (of BS1 and BS3) for each element of the HOP-5G testbed. Dual-frequency pseudo-range, carrier-phase and Doppler measurements are processed from multiple GNSS. Note that sensor data is not available for the post-processing of this field test campaign. Therefore, only reference position information is determined with the help of the post-processing software, but no reference attitude information. The GNSS reference station data from Oberpfaffenhofen (“OBE4”) is downloaded, in order to determine an accurate differential GNSS solution of each HOP-5G element with the commercial post-processing software.

4.2. REFERENCE POSITION ACCURACY OF HOVERING FLYING 5G BASE STATIONS

The reference position of the hovering flying 5G base stations is certainly a critical aspect to provide high-accuracy positioning in such dedicated deployments. In this section, the reference position of these flying 5G base stations is analysis over a period of two minutes, i.e., a time span from 11:30 to 11:32 UTC (or TOW from 300600s to 300750s). The quasi-static hovering period of the flying 5G base stations is then used to determine a single reference position applicable during this period. However, there is a reference position error resulting from the static assumption of the hovering periods for both UAV-BS1 and UAV-BS3, as it is shown in Figure 3. While the quasi-static hovering assumption matches quite well for UAV-BS1, it is fairly rough for UAV-BS3. The north-component of UAV-BS3 varies by more than ±1m over the “quasi-static” hovering period as per Figure 3 (plot in the middle on the right-hand side). The quasi-static hovering of UAV-BS1 and UAV-BS3 only lasted for 100 seconds. The resulting dilution of precision (DOP) for the quasi-static hovering period is 2.09 for HDOP, 5.44 for VDOP and 5.83 of PDOP. Neither HDOP nor VDOP should significantly exceed a threshold of 3 when considering the relatively small size of the 5G testbed, in order to allow for reasonable positioning accuracies. These DOP values already indicate that one should better limit to 2D positioning when working with 5G measurements from this hovering period, otherwise the flying base stations should be repositioned to improve the DOP.

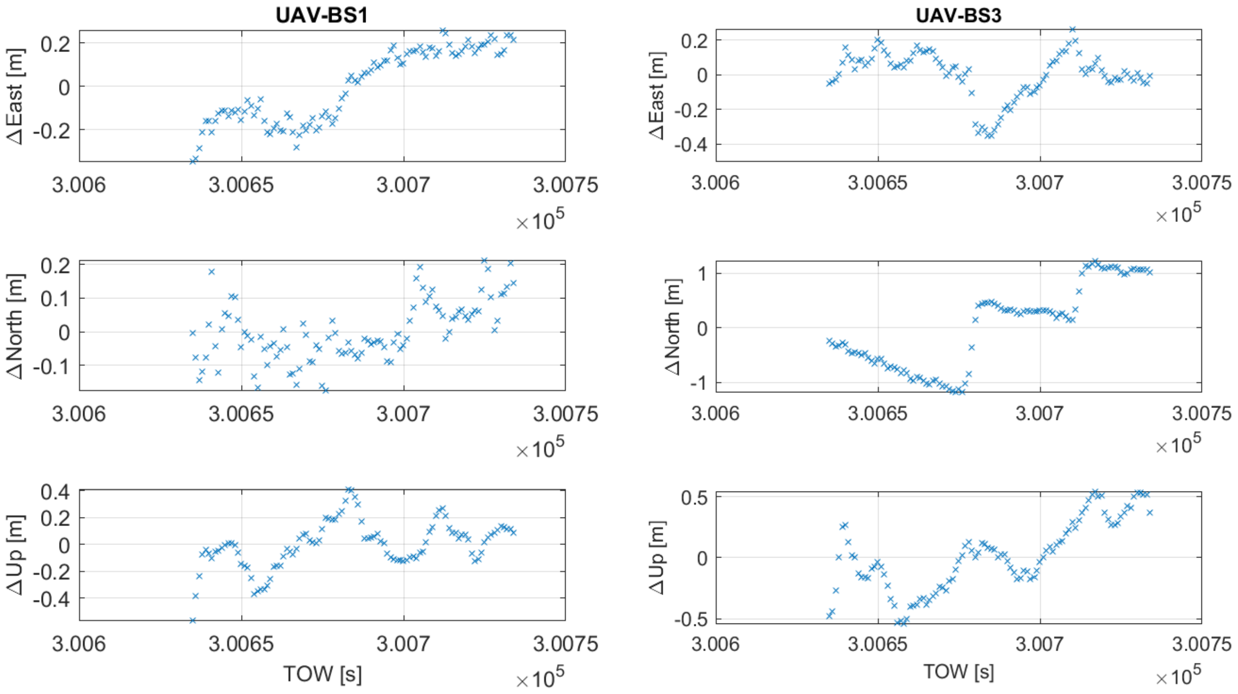

FIGURE 3 Deviations from the assumed quasi-static hovering position in-between $\text{TOW}_{\text{start}}$ = 300635s and TOW_{end} = 300734s: UAV-BS1 (left), UAV-BS3 (right).

4.3. FIELD RESULTS

The collected data during the field campaign is then post-processed based on the reference positions obtained in the previous section. Based on these reference inputs, the base station time offset estimation corrections are generated offline and injected in the measurement file. The initial position is obtained with GNSS and the GNSS signals are then cut-off, leaving only 5G measurements for positioning. Thanks to the BS network corrections, the resulting 5G stand-alone positioning is achieved with a high accuracy below 2 meters for each of the coordinates, as it is shown in Figure 4. Then, the GNSS code measurements are combined with the 5G measurements, enabling sub-meter positioning with the hybrid solution.

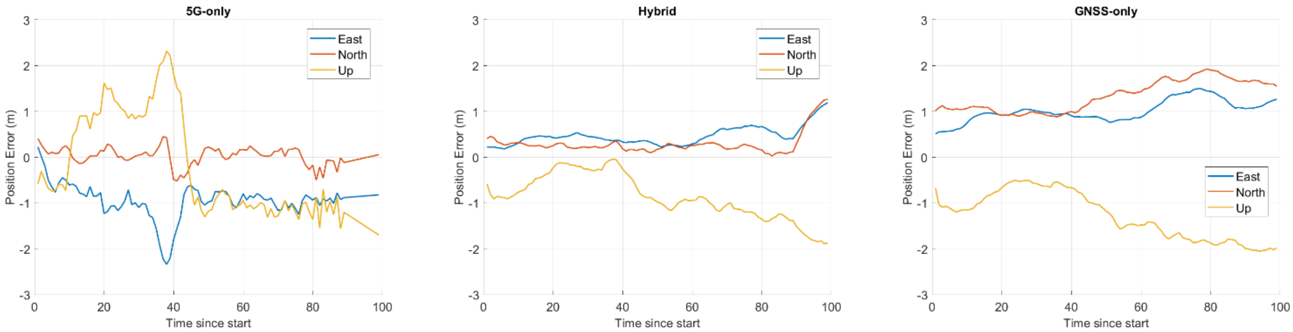

FIGURE 4 Performance accuracy of 5G-only (left), hybrid 5G and GNSS (middle) and GNSS-only (right) positioning solutions.

As it is shown in Figure 5 with the cumulative density function (CDF) of the position error for each positioning solution, the hybrid solution improves the 2D and 3D position accuracy with respect to GNSS-only and 5G-only. This is thanks to the enhanced performance provided by the inclusion of 5G measurements in presence of the network synchronization corrections. The resulting positioning accuracy is below 3 m in almost 100% of the cases.

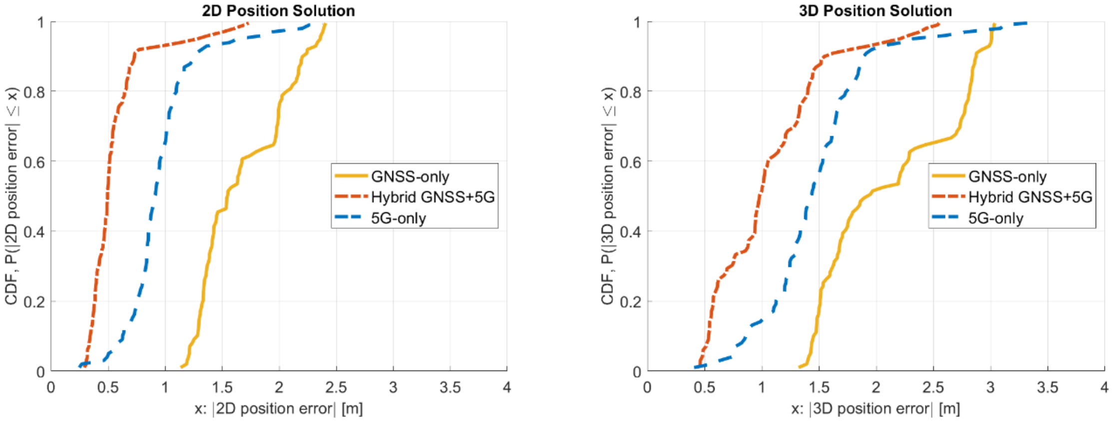

FIGURE 5 CDF of the positioning engine solutions (i.e., GNSS-only, 5G-only and hybrid GNSS and 5G).

5 CONCLUSIONS

This paper demonstrates the feasibility to deploy flying 5G networks dedicated for high-accuracy positioning purposes. The field results show the key design parameters of such deployment and their impact, especially requiring the precise knowledge of the BSs antenna locations, the line-of-sight (LoS) propagation conditions between 5G BSs and UE, high 5G signal bandwidths, and accurate correction mechanisms. This work focuses on the feasibility to enable sub-meter positioning with a flying 5G network and synchronization corrections. The hovering capability of these flying base stations is shown to result in quasi-static periods on the air, which can be exploited to obtain a single accurate reference position. This reference position is shown to be sufficient to achieve accurate synchronization corrections for two-dimensional (2D) sub-meter hybrid positioning above 90% of epochs. Thanks to the use of the HOP-5G testbed, a barrier has been surpassed on the real-time 5G experimentation, to prove the 5G timing correction assistance necessary to enable high-accuracy hybrid and 5G positioning with flying base stations. Future work is foreseen to further address the real-time positioning capabilities of flying 5G networks.

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DISCLAIMER

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