Design Considerations of Dedicated and Aerial 5G Networks for Enhanced Positioning Services

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***Abstract*—Dedicated and aerial fifth generation (5G) networks, here called 5G overlay networks, are envisaged to enhance existing positioning services, when combined with global navigation satellite systems (GNSS) and other sensors. There is a need for accurate and timely positioning in safety-critical automotive and aerial applications, such as advanced warning systems or in urban air mobility (UAM). Today, these high-accuracy demands can partially be satisfied by GNSS, though not in dense urban conditions or under GNSS threats (e.g. interference, jamming or spoofing). Temporary and on-demand 5G network deployments using ground and flying base stations (BSs) are indeed a novel solution to exploit hybrid GNSS, 5G and sensor algorithms for the provision of accurate three-dimensional (3D) position and motion information, especially for challenging urban and suburban scenarios. Thus, this paper first analyzes the positioning technologies available, including signals, positioning methods, algorithms and architectures. Then, design considerations of 5G overlay networks are discussed, by including simulation results on the 5G signal bandwidth, antenna array and network deployment.**

***Keywords*—5G, GNSS, UAV, Hybrid Positioning**

I. INTRODUCTION

Safety-critical automotive, aerial applications and industrial verticals demand high-level of accuracy, availability and reliability in terms of positioning, navigation and timing (PNT) systems. These applications can be found in innovative areas, such as smart cities, autonomous vehicles and urban air mobility (UAM). Most of current PNT solutions are based on the hybridization of global navigation satellite systems (GNSS) with sensors (i.e., inertial sensors, cameras, lidars or radars). But, there is a growing interest on the exploitation of cellular networks for positioning [1], especially thanks to the key positioning features of the fifth generation (5G) networks.

The 3rd Generation Partnership Project (3GPP) 5G new radio (NR) technology is uniquely positioned to provide added value in terms of enhanced location capabilities to fulfill the requirements motivated by commercial use cases. The operation in low and high frequency bands (i.e., below 6 GHz and above 24 GHz), and utilization of massive antenna arrays, i.e., massive multiple-input multiple-output (MIMO), provides additional degrees of freedom to substantially improve the positioning accuracy. The possibility to use wide signal bandwidth in low and especially in high bands brings new performance bounds for user location from well-known positioning techniques, such as downlink and uplink time-difference of arrival (DL/UL-TDoA), round-trip time (RTT) or enhanced cell ID, using known base station (BS) positions and ranging and angular measurements for user equipment (UE) positioning.

A novel approach on the exploitation of 5G positioning enablers is the deployment of 5G overlay networks as a complimentary or stand-alone technology to GNSS for the provision of enhanced positioning services. As it is shown in Fig. 1, the 5G overlay network is an on-demand dedicated deployment of 5G BSs over a local area to enhance the existing positioning solutions. This approach is in line with the 3GPP vision of 5G enhanced positioning service area [2], where additional infrastructure is deployed to enable positioning solutions not fully available with the existing 5G network or user equipment. Indeed, the overlay concept proposed in this paper goes beyond a static or fixed deployment with ground BSs, such as in high-density or private networks, as it also covers a temporary and dynamic deployment based on flying BSs, e.g. by exploiting unmanned aerial vehicles (UAVs). This innovative approach offers new opportunities to provide enhanced positioning services in a timely and reduced cost manner, with a flexible, scalable and versatile approach.

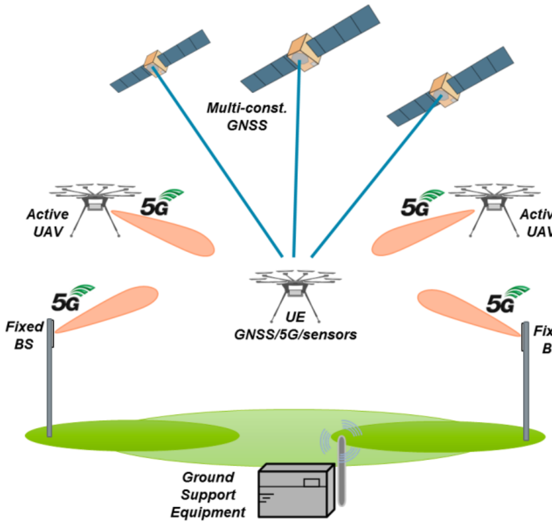


Fig. 1. Example of dedicated and aerial 5G network or 5G overlay network based on two ground-fixed BSs and two aerial BSs.

This paper focuses on the provision of design considerations for the deployment of 5G networks in combination with GNSS and sensors for enhanced positioning services, especially considering dedicated and aerial deployments. This approach exploits the complementary improvements achieved by fusing different technologies. For instance, GNSS provides absolute, global and precise positioning in open-sky conditions, and it is very well complemented by 5G networks and/or sensors with accurate local and temporary positioning-related measurements in urban environments, where GNSS performance is typically degraded due the lack of satellite visibility and multipath.

This paper is structured as follows. The positioning targets are first introduced in Sec. II, following the 3GPP standardization. Then, the trade-off of the positioning technologies is performed in Sec. III. The design factors of 5G overlay networks are discussed in Sec. IV with simulation results. Finally, conclusions are drawn in Sec. V.

II. POSITIONING TARGETS

A. *Positioning Service Levels*

One of the most expected advantages of the new 5G radio access networks, technically specified under the term 5G NR, is the capability to provide high-performance positioning services. In earlier generations, such as 4G Long Term Evolution (LTE), the positioning functionality was first introduced to fulfill the regulatory positioning requirements for emergency calls, and was enhanced over time to address a wider set of use cases. The 5G system requirements includes high performance positioning and therefore, the 5G NR specifications define that positioning should be enabled with state-of-the-art positioning technologies [3] and position information to become a central entity to digitalization [4].

The 5G positioning is expected to be an important enabler on top of the already available positioning technologies, such as GNSS, by increasing the positioning accuracy as well as coverage and availability. In order to provide positioning services to different types of use cases from commercial user navigation to mission-critical applications, there are various positioning service levels with specific performance criteria defined in the specifications [3]. Besides positioning accuracy, availability, latency and coverage (among others) have their own specific performance requirements. A summary of essential positioning performance requirements for different positioning service levels is given in Tab. I.

TABLE I. 3GPP POSITIONING SERVICE LEVEL REQUIREMENTS [3].

Service level	**Accuracy (95%)**		**Availability**	**Latency**
	Hor.	***Ver.***		
1	10 m	3 m	95 %	1 s
2	3 m	3 m	99 %	1 s
3	1 m	2 m	99 %	1 s
4	1 m	2 m	99.9 %	15 ms
5	0.3 m	2 m	99 %	1 s
6	0.3 m	2 m	99.9 %	10 ms
7	0.2 m	0.2 m	99 %	1 s

An important observation regarding the positioning requirement specifications in [3] is that these are the positioning requirements defined by different 5G use-cases in system architecture discussions. 3GPP radio access network (RAN) groups takes these requirements and positioning service levels as input to the 5G positioning standardization work in different releases starting from Release 16 in NR and continued in Releases 17 and 18 with gradual enhancements. In addition to the Radio Access Technology (RAT)-dependent positioning methods, there are also RAT-independent positioning methods, such as GNSS, inertial sensors, etc., that can be adopted in a hybrid fashion.

B. *Positioning Accuracy, Availability and Latency*

Positioning accuracy and availability are some of the key metrics traditionally adopted by cellular standards to assess the positioning method performance, while latency has been recently added. Each 3GPP release targets certain metric requirements, and positioning methods and enhancements are studied and evaluated in an agreed set of deployment scenarios in consideration of the requirements. The technical reports [5] for 3GPP Rel. 16 and [6] for 3GPP Rel. 17 summarizes the accuracy, availability and latency evaluations of the positioning methods studied in these releases.

C. *Positioning Integrity and Reliability*

Most of the 3GPP standardization efforts on 5G positioning technologies have been focused on fulfilling the target positioning accuracy, availability and latency of commercial services, as well as industrial IoT use cases. From a use case perspective, there is also a need for positioning uncertainty assessments and an ability to assess trust in the uncertainty in real-time. Examples include automotive, railway, maritime and airborne applications. In the 3GPP Rel-17, NR positioning is enhanced with an integrity concept for GNSS. It is based on defined feared events and associated error statistics and flags that can be provided to devices together with alert limits and key performance indicators to enable the device to assess the trust of the accuracy of the position-related data and to provide timely warnings. The integrity concept is expected to be extended to also RAT-dependent positioning methods, such as DL/UL TDoA and RTT [6]. This means that positioning integrity for 3GPP hybrid positioning systems is still to be completed.

III. TRADE-OFF OF THE POSITIONING TECHNOLOGIES

The design of 5G overlay networks for enhanced positioning services requires a trade-off analysis of the positioning technologies to be implemented. This trade-off analysis highlights the strengths and weaknesses of the envisaged technologies considering the following aspects:

- the exploitation of 5G innovative technologies for positioning purposes;
- the use of new and existing 5G signals to obtain positioning measurements;
- the stand-alone and hybrid positioning solutions;
- the positioning algorithms to compute the user position;
- the network- and receiver-based positioning architectures;
- the deployment of the envisaged 5G technologies.

This trade-off analysis is performed focusing on the fulfillment of 5G NR positioning requirements.

A. *5G Technologies for Positioning*

The 5G landscape offers innovative technologies that can substantially improve the user positioning performance. Let us start this trade-off with the frequency range 1 (FR1) or cmWave transmission (i.e., below 6 GHz), which is well consolidated and with known limitations due to the long evolution of previous cellular generations:

- *Advantages*: The 5G NR transmission in FR1 has many similarities to 4G LTE transmissions: both are based on OFDM radio interfaces below 6 GHz bands. This translates in terms of maturity of the hardware technology, where even the existence of consolidated software defined radio (SDR) equipment can be considered as viable solution for 5G FR1 transceivers. This significantly helps to extend to 5G NR developments of open-source software tools (e.g. OpenAirInterface or srsRAN) or proprietary software tools (e.g. MATLAB). Furthermore, a large literature can be found on field experimentation in FR1 that helps to assess the expected performance of positioning measurements.
- *Disadvantages*: Due to the large use of FR1 for many wireless applications, there is a very limited spectrum that prevents large contiguous bandwidth allocations, which are enablers for high-accuracy ranging measurements. Furthermore, antenna arrays are expected to have a reduced number of elements, due to the relatively large wavelengths, limiting the resolution and accuracy of angular measurements.

The frequency range 2 (FR2) or mmWave transmission (i.e., above 24 GHz) is one of the disruptive features of 5G, which encompasses highly innovative aspects with a limited maturity of the technology:

- *Advantages*: The 5G NR transmission in FR2 offers great advantages with respect to FR1 in terms of positioning enablers. The large available spectrum offers the possibility to transmit with large bandwidth (i.e., up to 400 MHz) that enables high-accuracy ranging, and the high carrier frequency enables massive antenna arrays or massive MIMO to achieve accurate angle measurements. Furthermore, dense deployment in FR2 provides a high line-of-sight (LoS) probability, which ensures accurate measurements. The introduction of analogue beamformers also significantly eases the angle estimations.
- *Disadvantages*: Besides these positioning benefits, FR2 introduce challenges, in terms of real-time baseband processing (due to the high sampling rate) and angle-based positioning (due to beam misalignment and potentially unknown orientation of moving BSs or UEs). The reduced coverage of FR2 limits its deployment to local hotspots. Furthermore, despite the first commercial mmWave equipment and reliable laboratory setups, equipment in FR2 is expected to be more expensive than in FR1.

The higher network density is another key feature of 5G, which can enable high-accuracy positioning. Indeed, dedicated 5G network deployments (including ground- and UAV-based BSs) have many benefits, in terms of flexibility, increased coverage, flexible location of BSs for better geometric dilution of precision (GDOP) and higher positioning accuracy, with respect to conventional network deployments. However, these dedicated deployments are expected to be temporal and to introduce additional infrastructure costs. This may eventually be affordable given the potential revenue of positioning services for the envisaged critical applications.

The exploitation of carrier aggregation and full-duplex communications for positioning is still an open area with minimum research conducted in the positioning domain. The positioning application of these features poses significant challenges, such as the synchronization offsets between multiple carrier bands or the self-interference, and their benefits in positioning still need to be unveiled.

B. *5G Signals for Positioning*

Understanding the resource allocation of reference signals in the 5G NR specifications is crucial for their exploitation in positioning services. Indeed, the 5G NR specifications propose a large set of reference signals for both DL and UL that can be exploited for positioning [7].

The baseline reference signals for positioning are the positioning reference signal (PRS) in the DL and the sounding reference signals (SRS) in the UL. While the SRS is available since 3GPP Rel. 15, the PRS is specified in 3GPP Rel. 16 and offers several configuration features to improve the measurement accuracy and rate. Regarding the available reference signals, it is important to understand the pilot resource allocation and potential limitations for their positioning use. For example, certain signals are repeatedly broadcasted by each cell, such as Synchronization Signal Block (SSB), whereas other signals are only available when there is active communication between the UE and the network, such as the Demodulation Reference Signal (DMRS) and Phase Tracking Reference Signal (PTRS), or scheduled, such as Channel-State Information Reference Signal (CSI-RS), PRS and SRS. Moreover, certain signals are bandwidth-limited according to UE-specific band allocation, given by the network scheduling decisions (e.g. DMRS and PTRS), whereas other signals use the full system bandwidth regardless of the specific resource allocations per UE (e.g. PRS, CSI-RS and SRS). A summary of the considered 5G NR reference signals are found in Tab. II.

TABLE II. SUMMARY OF CONSIDERED 5G NR REFERENCE SIGNALS FOR POSITIONING.

Reference Signal	**Transmission Direction**	**Bandwidth**	**Availability**
PRS	Downlink	Full band	Scheduled
SSB	Downlink	Fixed to 240 subcarriers	Broadcasted repeatedly, also available in idle
CSI-RS	Downlink	Full band	Scheduled
DMRS	Downlink / Uplink	Limited to the resource allocation	Available in user data and control data transmissions
PTRS	Downlink / Uplink	Limited to the resource allocation	Available in user data and control data transmissions
SRS	Uplink	Full band	Scheduled

C. *Stand-alone and Hybrid Positioning Methods*

Given a set of measurements from diverse positioning signals and sensors, the task of a stand-alone or hybrid positioning algorithm (depending if these measurements come from one or multiple technologies) is to combine the measurements into the estimation of the position, velocity, and other states of interest, which could include clock biases of the various system elements, UE attitude, inertial measurement unit (IMU) biases, environmental parameters relating to the propagation channel, local air pressure, etc. The number of unknown states to be solved will thus be somewhere between few and some dozens. Considering GNSS, 5G and sensors, it is expected that on each epoch there are at least some tens and probably less than a hundred different measurements. For instance, the measurements for the hybrid solution could include a few different types of measurements between the UE and each of the 5G BSs, a few measurements from external sensors, such as barometer, and GNSS measurements from at least 15 satellites on two frequencies.

1) GNSS Stand-alone Methods: Stand-alone GNSS receivers (including multi-frequency and multi-constellation) are expected to provide accurate positions at meter-level, and to enhance this positioning accuracy down to the centimeter-level with Real-Time Kinematic (RTK)-solutions or to the decimeter-level with Precise Point Positioning (PPP)-based solutions. As stand-alone GNSS is already a mature technology, commercial off-the-shelf (COTS) receivers can be primarily considered for GNSS-only solutions:

- **Stand-alone COTS GNSS** can achieve meter-level position solutions with open sky.
- **COTS RTK GNSS** requires transmitting Radio Technical Commission for Maritime Services (RTCM) stream from a reference station to the GNSS receiver. The reference station could either belong to the dedicated network deployment, or be a nearby commercial or publicly operated reference station connected to public internet. This produces real-time centimeter-accurate position within some seconds under open sky, but is not expected to produce solutions in degraded GNSS environments.
- **COTS PPP GNSS** requires transmitting the State Space Representation (SSR) PPP corrections to the GNSS receiver in a supported format. There are several public and proprietary formats. This produces meter to decimeter level accuracy under open sky.

2) 5G Stand-alone Methods: The 5G stand-alone positioning methods defined in 3GPP [8] are considered as baseline for implementation in the dedicated 5G networks, while 5G-based complementary measurements (e.g. carrier phase or Doppler frequency measurements) could also be considered in non-standard solutions. The following list includes possible standard options for implementation in both DL and UL positioning:

- **Received Signal Strength (RSS)-**based positioning can use RSS measurements either from the UE using DL reference symbols, such as SSB or CSI-RS, or from the BS using UL reference symbols, such as SRS. Since this method is expected to have a low positioning accuracy, RSS measurements can be used as supplementary function to assist the hybrid positioning, such as by weighting the measurements.
- **TDoA**-based positioning can achieve high-accuracy positioning (i.e., meter-level accuracy) thanks to a high bandwidth and a high expected LoS probability in FR1 and FR2 overlay deployments. The main drawback of this method is the need for tight synchronization of the BSs. This method can be based on DL PRS or UL SRS. Both PRS and SRS can provide similar positioning accuracy when the UL coverage is not an issue, and the main differences are in terms of measurement and positioning implementation. For instance, UL SRS-based positioning or UL-TDoA has the advantage that Rel. 15 COTS terminals can be used with existing software tools (e.g. OpenAirInterface); instead, at the date of writing, Rel. 16 PRS is not supported by any COTS terminal, hence requiring solutions with SDR-based processing functions or proprietary hardware for early deployments.
- **RTT**-based positioning (including multi-RTT) overcomes the need for synchronization in TDoA-based positioning, because it exploits two-way ranging. The RTT is measured by transmitting and receiving signals between the BS and the UE. However, this comes at the expense of a higher number of signaling between BS and UE, a limited number of UEs serviced simultaneously, and additional ranging errors, due to the intrinsic receiver-transmitter synchronization error within the BS equipment and within the UE equipment, which can be limited with calibration. Still, the hybridization of this method with GNSS is especially interesting with very reduced number of measurements [9], because the RTT is directly a distance between BS and UE (i.e., there is no need to estimate 5G receiver clock bias with respect to a timing reference system), which can be combined with GNSS observables.
- **Angle of arrival (AoA)** and **angle of departure (AoD)**-based positioning can be performed with antenna array or beamformers, whose configuration, number of antenna elements and distance to the UE determine the positioning accuracy. In the case of FR1, the reduced antenna arrays (in the order of 4 to 8 elements) limit the resolution of the angle, which can be compensated with a reduced distance between BS and UE under LoS conditions. In the case of FR2 when beamforming is used, it is also possible to simply measure the AoA and AoD based on the currently used beam at reception and at transmission, respectively. The current beam of the serving cell is determined by the initial beam selection procedure or the beam refinement procedure, which relies on DL SSB and CSI-RS. In addition, the best beam of the neighboring cells can also be measured with CSI-RS or SSB signals. These measurements are available at both the UE and the network side. Note that the unknown (and dynamically changing) UE orientation makes angle measurements at the UE challenging from the 5G stand-alone positioning perspective. Nonetheless, this can be resolved with sensors in a hybrid method if the UE has fully integrated IMU.

Note that the 5G positioning capabilities could potentially enable single-BS positioning thanks to the combination of 5G RTT and AoD/AoA measurements.

3) Hybrid Methods: Hybrid positioning is based on the exploitation of multiple technologies. Several benefits are envisaged on the hybridization of GNSS, 5G and sensors:

- **Improved accuracy**: While precise GNSS methods in nominal conditions are expected to reach a very high accuracy, hybrid methods are expected to improve the stand-alone GNSS performance, as well as the GNSS performance in degraded conditions.
- **Improved availability and continuity**: The use of multiple positioning technologies is expected to improve the availability and continuity with respect to only GNSS (i.e., this is valid for all GNSS positioning techniques), especially when operating in a challenging environment (e.g. urban or indoors).
- **Improved security and integrity**: Hybrid methods are expected to improve the security and the level of integrity of the final position estimation, since GNSS signals may be affected by unintentional or intentional interferences, such as jamming and spoofing. This is valid for all GNSS positioning techniques, in particular for stand-alone GNSS, since it is easier to detect spoofing jumps in PPP and RTK.

The hybridization strategy between measurements is here defined at different levels:

- Position-level: The position is estimated as a combination of independent position estimates from GNSS, 5G or sensors (i.e., loose integration).
- Mixed-level: The position is estimated as combination of position estimates and measurements from different systems, e.g. GNSS position, velocity and time (PVT), 5G measurements and sensors (i.e., loose integration).
- Measurement-level: The position is estimated as combination of measurements from different systems, e.g. GNSS raw measurements, 5G measurements and sensors (i.e., tight integration).
- Carrier-level: The position is estimated as combination of measurements from different systems including carrier-phase measurements either from GNSS and/or 5G.

Note that although GNSS carrier-phase techniques are well studied, the exploitation of 5G carrier-phase measurements is at its conception with few research studies. Thus, it would be a matter of research to determine if an RTK solution would be possible from a set of mixed GNSS and 5G carrier-phase measurements.

4) Trade-off of Positioning Methods: The selection of a preferred positioning technology depends on the use cases or operational conditions. The trade-off analysis is summarized in Tab. III, considering the achievable positioning accuracy (i.e., being high at meter-level) for a given measurement availability in outdoor urban conditions with dedicated 5G networks, while assuming low (receiver) complexity to be similar to using single-antenna ranging measurements with broadcast corrections (as in GNSS).

TABLE III. TRADE-OFF ANALYSIS OF MAIN POSITIONING METHODS IN OUTDOOR URBAN CONDITIONS.

Positioning methods	**Accuracy**	**Availability**	**Complexity**
GNSS	High	Moderate	Low
Precise GNSS	Very high	Low	Low
5G TDoA	High	High	Moderate
5G multi-RTT	High	Moderate	High
5G angle-based	High	Low	High
Hybrid (position-level)	High	High	Moderate
Hybrid (mixed-level)	High	High	Moderate
Hybrid (measurement-level)	High	Very high	High
Hybrid (carrier-level)	Very high	Moderate	Very high

The following aspects are considered in this selection:

- **GNSS as backbone technology**: In nominal conditions, GNSS provides a high accuracy and availability with low implementation complexity, thanks to maturity of methods and COTS receivers.
- **Precise GNSS methods**: In nominal conditions, precise GNSS methods can be exploited to achieve high-accuracy positioning. However, the sensitivity of these techniques to environment variations limit their availability.
- **5G ranging-based methods**: The dedicated 5G overlay deployment results in a high availability of 5G TDoA methods, in which positioning accuracy is limited by bandwidth and propagation conditions. The complexity of this ranging method is mainly driven at network level, due to the need to tightly synchronize BSs within the 5G network. The 5G RTT method circumvents this synchronization issue by considering both DL and UL ranging measurements. This introduces an extra complexity, due to the precise time-stamps required and calibrated equipment, while availability is limited to two-way links established with the reference BS and the neighbor BSs.
- **5G angle-based methods**: 5G angle-based methods exploit the antenna array configurations at BS and/or UE, in contrast to GNSS and 5G ranging-based methods that can operate with a single antenna. This increases the complexity in terms of implementation due to the need to install the antenna array, while antenna orientation need to be considered. The antenna array and its orientation certainly limit the accuracy and availability of this positioning method. For instance, in 5G cmWave (FR1), the number of antenna elements is expected to be small, limiting the achievable angle accuracy, while in 5G mmWave (FR2), the high number of antennas allows beamforming of narrow beams increasing the angle accuracy, at the expense of an increased complexity (e.g. due to beam tracking needs).
- **Inertial measurement-based methods**: Inertial measurements can be used with gravity model for positioning without any availability issues. However, the usage of the solely inertial measurements limit the

length of the accurate positioning period, since the inertial solution drifts in time when the inertial system operates in coasting mode (i.e., without integrating information from other positioning technologies). Also all the initial values, needed at the beginning of the positioning period, are not known without external information and/or measurements.

- **Hybrid methods**: The fusion of GNSS, 5G and sensors is expected to achieve an enhanced positioning performance. In nominal GNSS conditions, the enhancement from 5G can be limited to bootstrapping of the GNSS solution, while in degraded GNSS conditions the hybridization certainly improves accuracy and availability at the expense of an additional complexity. Both technologies are fully complementary and multiple fusion configurations can be considered. The hybrid method at position-level merge both positioning solutions, resulting in an increase of the availability and a slight increase of complexity. The hybrid method at measurement level merges measurements from both solutions increasing accuracy and availability, but also complexity. The hybrid method at carrier level merges carrier-phase measurements from GNSS and 5G, and it is expected to increase the accuracy and complexity, while the availability is reduced due to sensitivity to the environment. As commented before, the exploitation of 5G carrier-phase measurements is an area of research in itself.

D. Positioning Algorithms

This section provides a trade-off analysis of common solution methods used for positioning problems:

1) Weighted Least Squares: Weighted Least Squares (WLS) is a widely-adopted solution method that involves forming a measurement model function that computes expected measurements given a position or state candidate, and finding iteratively the position or state estimate that minimizes the difference between the actual and expected measurements. For some specific types of measurements, the solution achieving this goal can be computed in closed form, but as pointed out in [10], the WLS has numerous advantages over proposed closed-form solutions, the most important in this context being that it can flexibly accept any combination of various types of measurements, so the closed-form approach is not considered further. The advantages and disadvantages of the WLS are:

- Advantages: WLS is comparatively simple to implement, it can accept a diverse range and number of different types of measurements, it can weight diverse measurements based on their relative accuracies, deal with correlated measurements, and as it does not have an internal state, each estimate is independent of the previous ones so that one outlier estimate does not contaminate subsequent estimates.

- Disadvantages: All included measurements need to be expressed by derivable measurement equations so that, for example, sector limits cannot readily be included. Also, the expected measurement errors need to be unimodal and not, for example, have two likely values. Additionally, if some of the measurements have strong nonlinearities, as range measurements close-by base stations, WLS may have troubles converging, or the convergence may depend on the choice of the initial guess.

The WLS could be used to form the initial estimates of the solution, to be then handed over to EKF described in the following subsection. WLS can be used both for standalone GNSS or standalone 5G positioning, as well as hybrid solutions. Note that IMU measurements are not considered in the WLS solution, as they relate to the motion of the receiver between time instants and not on the absolute position, indeed IMU measurements are typically exploited through Kalman filter techniques.

2) Extended Kalman Filter: The Extended Kalman Filter (EKF) can be seen as an extension of WLS method, which combines information from the measurements to model the time dynamics of the unknown states. The advantages and disadvantages of EKF are:

- Advantages: An important property of Kalman filter is that also a model of the dynamics of the unknown states and their relationships to each other is exploited in the state information. In addition to the UE position and velocity, the unknown states could include clock biases of other network elements of interest, propagation path parameters, local air pressure, etc., even if they are not directly measurable. EKF is also comparatively straightforward to implement and in practice the CPU and memory requirements are comparable to that of WLS.

- Disadvantages: EKF works by linearizing the state transfer and measurement models around the estimated state, and can diverge if either is strongly non-linear, or if the process noise is poorly modelled. Thus, it requires a good enough initial state and some effort in tuning the model parameters for each practical use case.

Integrating IMU measurements with GNSS using EKF can be based on standard approaches [11], [12], that could be generalized to cover the 5G integration as well. The GNSS and 5G measurements help in IMU attitude initialization, especially if the UE has multiple antennas that can be used to measure its attitude with respect to the base stations.

3) Particle Filter: Particle Filter (PF), also known as Sequential Monte Carlo (SMC), is another type of nonlinear filter. Instead of propagating a single solution estimate like EKF, the PF considers a cloud of solution candidates, usually numbering from thousands to millions, and propagates them with the dynamics and measurement models. The advantages and disadvantages of PF are:

- Advantages: The PF has a more general approach than EKF to model the measurements and state dynamics. These can be given as probability distributions instead of just measurement equations. This allows including for example maximum range or sector limits, strongly non-Gaussian measurement errors, or integer-valued states. Also, the measurement error distributions do not have to be Gaussian-shaped, but any error distribution can be modelled, allowing for example modelling of measurement truncation and heavy-tailed or unsymmetrical errors.

- Disadvantages: The number of particles required for stable solution grows exponentially with state dimension, which can lead to excessive computational load. Implementation also involves more tuning and tailoring the approach for the problem at hand than EKF.

While the computational load makes PF unsuitable for intended real-time implementation, it might be a useful tool in design and development stages to provide an offline reference solution to benchmark against EKF positioning solutions.

IMU measurements can be integrated into PF, for example, as a control signal in the dynamics model [13]. Note also that the biases for the IMU were found to be modelled better by the PF than EKF. PF can be used both for stand-alone GNSS or stand-alone 5G positioning, as well as hybrid solutions.

4) Filter Bank: Filter-bank approaches are originally meant for integrity monitoring, however, together with their Fault Detection and Exclusion (FDE) capabilities, they also provide robust positioning (i.e., their use may impact position solution and accuracy also in fault-free scenarios). The main idea underlying a filter bank approach [14], [15] is that a pool of similar filters (e.g. EKF) run in parallel by taking as input a different subset of the available measurements (e.g. GNSS, 5G and sensor). A specific sub-filter can then be associated to each subset, creating a parallel filter bank with filtering elements. The output of all the sub-filters is then merged with proper methodologies, which depend on the specific implementation. The advantages and disadvantages of the filter-bank approach are:

- Advantages: First, the overall navigation algorithm is augmented with an intrinsic FDE capability, which is beyond the standard Mahalanobis distance for finding multivariate outliers. The intrinsic FDE capability is capable of strongly reducing the impact of input outliers on the final output. Therefore, no significant time correlated error should be observed on the estimates. Second, under a proper assumption on the number of input samples, there is the guarantee that at least one of the sub-filters is fault-free at each epoch. With a proper merging strategy, the output of that sub-filter will be trusted much more than the others, yielding to an accurate estimation.
- Disadvantage: The computation complexity increases proportionally with the number of observation subsets with respect to that of a single filter.

The key aspects of a filter bank design are represented by the way the sub-filters interact each other, and the way the partial outputs are merged together to produce the final estimate. It should be noted that both items have a clear impact on the way that integrity is monitored and provided.

E. Network- and Receiver-based Positioning Architectures

Network-based positioning solutions are based on the collection of GNSS, 5G and sensors raw measurements at the UE, as well as 5G positioning measurements at the BS from UE UL signals, and on the transfer of all these measurements to a network location server that computes the UE position. The advantages and disadvantages of network-based positioning solutions are:

- Advantages: The network can exploit more advanced and complex positioning algorithms that may require a high computational burden. For instance, transferring processing load from the receiver to the cloud or network, significantly alleviates the computational burden at the UE. In addition, since the network server is independent from BS and UE, the network server can be updated with new algorithms without affecting the rest of network elements. Furthermore, since the network is expected to be connected to the Internet, as well as to other resources (e.g. internal network databases), complementary assistance data (e.g. corrections) can be exploited without the need to establish additional data links. Finally, the collection of multiple measurements from close-by UEs allows the exploitation of crowd-sourcing or collaborative positioning methods.
- Disadvantages: There is a higher latency on the provision of its location estimate to the UE, due to the inherent data transfer delays between the network and the UE.

Receiver-based positioning solutions are based on the exploitation of GNSS, 5G and sensor positioning measurements at UE for its position computation. The advantages and disadvantages of receiver-based positioning solutions are:

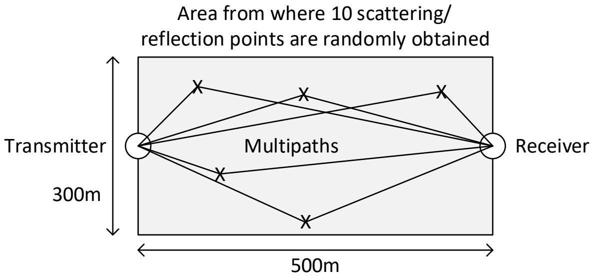
- Advantages: The receiver-based positioning solution allows a tight-coupling on the hybridization of GNSS, 5G and sensor measurements within the receiver architecture, which can enhance its performance. This solution allows the lowest latency to retrieve the UE position solution.
- Disadvantages: The complexity of the positioning algorithms is limited by the computational capacity of the UE on-board computer or processing unit. The assistance data needs to be retrieved with additional data links. Updates of the positioning algorithm typically require firmware updates for COTS equipment, while only software updates may be required for application-level positioning algorithms.

IV. Design Factors of 5G Overlay Networks

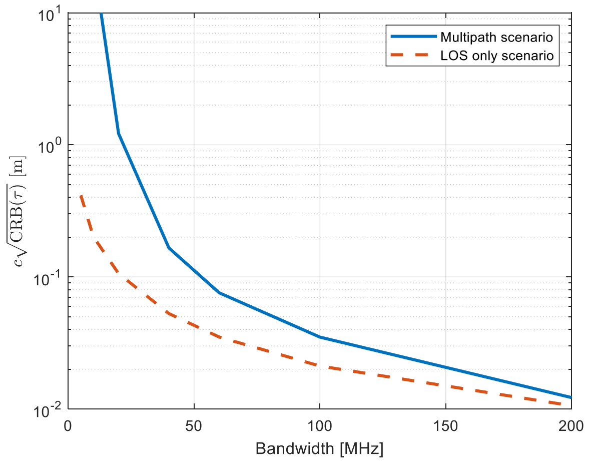
A. 5G Signal Bandwidth

The 5G signal bandwidth has a key impact on the achievable ranging accuracy within the positioning system. As starting point, considering AWGN propagation conditions, this achievable ranging accuracy is theoretically defined by the Cramér-Rao Lower Bound (CRLB) for the ranging estimation, which depends on the signal bandwidth and the signal power level. As it is shown in [16], sub-meter accuracy is expected to be achieved for any 5G bandwidth in AWGN propagation conditions, thanks to dedicated deployments (in this example for road applications) resulting in a high signal level. Nonetheless, this ranging accuracy is not expected to be achieved for a bandwidth below 100 MHz in multipath scenarios. As it is shown in [16], considering ranging-based positioning simulations with harsh and mild multipath channel models over a road scenario, a signal bandwidth higher than 20MHz is expected to achieve positioning accuracies below 10m on the 80% of cases.

Besides improving the ranging time resolution, increasing bandwidth can help to reduce negative effects of multipath propagation or even to allow the exploitation of the multipath components for positioning. Indeed, even when a LoS path is available, multipath propagation can cause significant degradation to the range estimate, especially with low signal-to-noise ratio (SNR) scenarios. This is because each path contributes to the overall detected channel response at the receiver, thus detection of a single path is interfered by the others. In order to mitigate the multipath interference to the ranging estimate, larger bandwidths can be used to increase the time resolution, and thus, to have an improved separation between different paths in time. The magnitude of ranging errors due to multipath propagation depends greatly on the underlying multipath scenario, that is, the exact propagation delays and channel coefficients (including the path loss and interactions with objects in the channel) of each path. In addition, by utilizing directional antennas in the transmitter and/or receiver it is possible to spatially filter the non-LoS (NLoS) components. However, the most critical multipath components are often the ones with small delay difference compared to the LoS path, and therefore the propagation paths of these NLoS components are not much deviated from the path of the LoS component. This means that these critical NLoS components and the LoS path often share similar angular characteristics, which is difficult to spatially filter with practical antenna array sizes.



(a) Illustration of the considered multipath scenario



(b) Ranging accuracy of multipath and LoS-only scenarios as a function of bandwidth

Fig. 2. Example of the effect of multipath propagation on the ranging accuracy. For the multipath scenario, in addition to the LoS path, there are 10 multipath components randomly obtained based on single reflection/scattering objects located in the area between the transmitter and receiver as shown in sub-figure (a). The ranging accuracies in (b) are defined as a median over 200 simulation trials.

Nevertheless, assuming time of arrival (ToA) estimation bounds derived for a multipath channel in [17], an example of the effect of multipath propagation on the ranging accuracy is shown in Fig. 2 for different bandwidths, including the bound for a LoS-only scenario as a reference. The results of the multipath scenario are obtained by considering a LoS path and 10 multipath components, which are randomly obtained based on single reflection/scattering objects located in the area between the transmitter and receiver as shown in Fig. 2(a). Then, the ranging accuracies in Fig. 2(b) are defined as a median (i.e., 50% percentile) from 200 simulation trials. It can be clearly observed that with a smaller bandwidth, the ranging accuracy considerably suffers from the multipath propagation. However, the difference between the multipath scenario and the LoS-only scenario decreases when employing larger bandwidths.

B. 5G Antenna Array and Elements

Antenna arrays enable beamforming, which is defined as the power of a transmitted or received radio signal directed towards certain points of interest. Depending on the configuration of the antenna array and the related RF transmission chains, antenna arrays can also be used for spatial multiplexing and/or spatial diversity. Beamforming can be implemented based on digital beamforming, analog beamforming, or hybrid beamforming [18]. In the literature, numerous different antenna arrays have been introduced. The most traditional ones include linear arrays (with elements on the same line in xy-plane), planar arrays (with elements on grid-like rectangular shape in xy-plane), circular arrays (with elements on a circle in xy-plane), or conformal arrays (with elements on a 3D surface, e.g., cylindrical or spherical structures). In general, with all arrays, the spatial selectivity and beamforming accuracy can be improved by increasing the number of array elements. However, different array types offer different type of spatial coverage, e.g., regarding the azimuth and elevation domain as well as the range of unambiguous angles.

When considering 3D beamforming, the 1D linear array is not able to provide spatial selectivity in both azimuth and elevation directions, but can perform well in 2D scenarios, such as with high-speed train positioning [19]. However, since many 5G NR uses cases consider 3D scenarios, probably one of the most popular array type is the planar array, more specifically the uniform rectangular array (URA), which is also depicted in the 5G NR specifications by the 3GPP in [20]. It is remarked that in the same document different coordinate systems, angular rotations and antenna orientation aspects are defined in the context of 5G NR antenna arrays. The URA, used for example in [21], consists of antenna elements organized in a planar array. By selecting the number of antenna elements in the rows and columns, it is possible to tune the spatial selectivity in elevation and azimuth directions, respectively. The beam pattern for a URA array (with half-wavelength element separation) as a function of azimuth angle is illustrated in Fig. 3 by considering three different array sizes assuming the same number of row and column elements. The beam pattern is defined based on the boresight beam angle (i.e., an angle directly in front of the array), where the angular resolution is maximized. Moreover, considering the same number of row and column elements in the array (i.e., the square shape), the corresponding vertical pattern is identical with the azimuth pattern. In practice, the beam pattern based on array processing is also affected by the used antenna element type, as described in [20]. In order to better illustrate the 3D aspect of beamforming, the beam pattern of an 8x8 URA is illustrated jointly over the azimuth and elevation angles in Fig. 4. It is noted that with a square shaped URA (i.e., having the same number of row and column elements), the beam pattern in elevation domain is identical with the azimuth domain pattern.

One important aspect when using antenna arrays for positioning is the array orientation and the suitable angular coverage, which determines the maximum possible angle offset compared to the boresight angle, where the array is still able to maintain a desired angular resolution. Furthermore, for many array structures, due to symmetry, there is only a certain range of angles wherein the angles can be unambiguously defined. For example, with URA, the 0-degree angle results in the same array response as the 180-degree angle. However, by introducing directive antenna elements, such as the ones considered in [20], the element-wise gain can be used to mitigate the unambiguity issue. In Fig. 5, the beam pattern of an 8x8 URA is illustrated for three different beams pointing in azimuth at 0 degree, 30 degrees and -60 degrees, being 0 degree angle the boresight, while assuming a boresight elevation angle. In the figure, it can be clearly observed that the beamwidth increases, and thus the angular resolution decreases, when the offset from the boresight angle increases. To overcome the beam resolution issue as well as the angle unambiguity with URAs, it is possible to exploit circular arrays, at the expense of a poor vertical angular resolution. Using conformal arrays, such as cylindrical arrays, the vertical resolution can be improved, making the array suitable for 3D positioning [21].

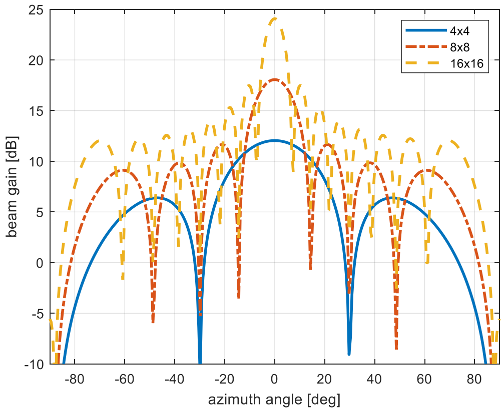


Fig. 3. Beam pattern in azimuth direction for different size URAs assuming a boresight elevation angle.

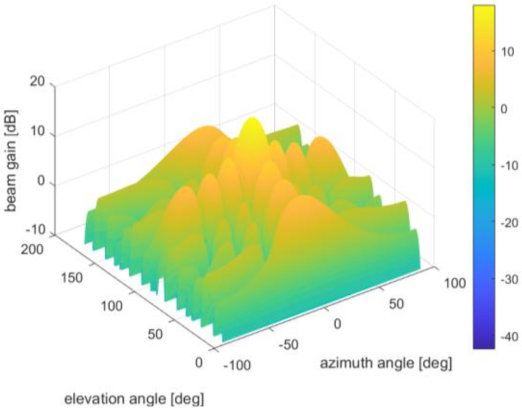


Fig. 4. Beam pattern of a 8x8 URA over the azimuth and elevation angles (similar as in [20], the boresight elevation angle is defined as 90 degrees).

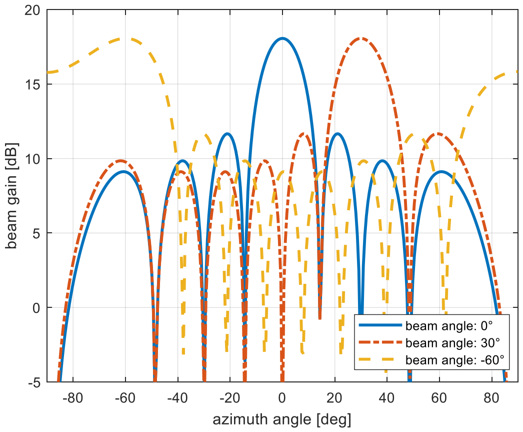


Fig. 5. Beam pattern of 8x8 URA for three beam angles in azimuth.

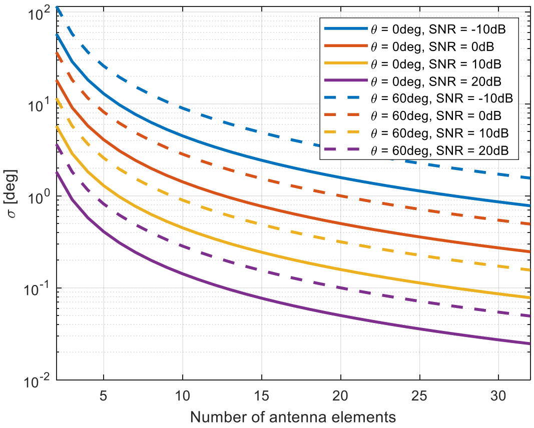


Fig. 6. Standard deviation of the AoA estimation error (based on CRLB) with a ULA as a function of the number of antenna array elements. The curves are shown for different AoA and SNR values.

In mobile networks, BS deployment is traditionally designed in such a way that a single cell covers one specific sector at a given BS site. This type of setup is favorable to URA-based antenna design at BSs, since URAs are able to provide a good selectivity in both azimuth and elevation domain within a limited sector. At the UE side, the most suitable array type can vary according to the considered scenario. For instance, when equipped with drones, the UE orientation is rather well-controlled, which enables efficient array implementations.

Regarding positioning aspects, antenna arrays play an important role in obtaining angular estimates, i.e., AoD or AoA estimation. Overall, the angle estimation accuracy is dependent on the number of antenna elements in the array. In order to study the effect of array dimensions on the positioning accuracy without considering any specific implementations detail, it is convenient to formulate a CRLB for the angle estimation, as in [22] for AoA and linear arrays. Regardless of the considered estimation algorithm, the CRLB indicates the smallest possible angle estimation error variance under specified circumstances. In Fig. 6, the standard deviation of the AoA estimation error with a uniform linear array (ULA) is shown as a function of the number of antenna array elements. Results are shown for three different SNR values as well as for two different AoA values. It is remarked that, besides the array dimensions and SNR, the estimation accuracy depends also on the estimated angle itself, because the angle resolution changes as a function of the angle offsets from array boresight.

Furthermore, the knowledge of the antenna orientation is very important for angle-based positioning. For instance, the antenna orientation is unknown in many receiver implementations, such as in handhelds or smartphones, resulting in another estimation parameter within the positioning problem. Nonetheless, this constraint is avoided in UAV setups thanks to fixed mounts within its payload.

When angle estimation is used for position estimation, the usability of the angle information is affected by the underlying system geometry. Thus, in order to study the effect of angle estimation on the positioning accuracy, the angular measurements need to be transformed to the position domain. A simplified approach is to consider a BS with an ideal range estimate and an erroneous angle estimate. Based on geometrical derivations, the bias on the positioning estimate due to angle estimation error can be approximated based on a chord of a circle as $b = 2 \cdot r \cdot sin(\theta/2)$, where r is the ideal range estimate (radius of a circle) and θ is the angle estimation error (in radians). For example, an angle estimation error of $\theta = 0.05°$ results in a position bias of 0.87 m at a distance of 1 km. Another approach to study the effect of angle estimation error on the positioning accuracy is via the definition of a Positioning Error Bound (PEB). It essentially presents a CRLB for positioning error (considering jointly the error over x, y and z coordinates) by transforming the CRLBs of positioning measurements, such as the AoA, into the positioning error domain [22].

The impact of angular estimation accuracy on the positioning accuracy, in terms of PEB, is depicted in Fig. 7, as a function of the UE distance, assuming a single BS with a varying array size. In this example, the BS obtains both ToA and AoA measurements, without BS synchronization offsets. Here the included CRLB for ToA is defined based on a 200 MHz bandwidth, which is sufficiently large to make the considered AoA as the dominating positioning error source (i.e., essentially the angle estimation accuracy defines the position estimation accuracy). Moreover, in the given setup, the SNR is assumed to be fixed at 10 dB regardless of the actual radio propagation distance. From the figure it is evident that, when considering AoA measurements, positioning error increases as a function of UE distance to the BS due to the system geometry. It is noted that by including path losses in the setup, the dependency of the positioning accuracy on the UE distance increases further.

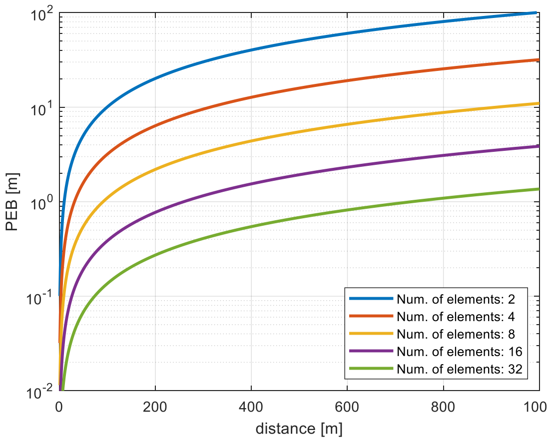


Fig. 7. Effect of angle estimation accuracy via different array sizes on the positioning error, based on PEB, as a function of UE to BS distance.

C. 5G BS Deployment

This section exploits the PEB with ToA and AoA (i.e., representing ranging- and angle-based methods) to assess the deployment of 5G BSs for positioning over a certain area, rather than to assess the absolute achievable positioning results. In terms of PEB [22], the theoretical positioning accuracy is illustrated in Fig. 8 for two separate BS deployments based on AoA measurements obtained from a 32-element ULA. The PEB is obtained by considering a CRLB-level angle estimation accuracy from each BS while taking into account the free-space path loss, which affects the experienced SNR at each location. The PEB is then obtained for each location by transforming the AoA CRLB into a position CRB and combining the information from all BSs. One important observation of the PEB in the figure is that the PEB increases heavily when the angular offset with respect to the array boresight is close to 90 degrees. Therefore, when using angular estimates for positioning (with linear or planar arrays), it is important to design the BS deployment so that the targets are always operating in a sector close to the antenna boresight. In the figure the BS antenna boresights are shown with a specific pointing vector at its location.

In Fig. 9, the corresponding PEB results for the two BS deployments are shown by using ToA measurements with 200MHz bandwidth, and without BS synchronization offsets. It should be noted that the PEB scale includes significantly smaller PEB values than with the AoA measurements before. In order to reach comparable accuracy with AoA, there would need to be hundreds of antenna elements at each BS antenna. Nonetheless, with the collinear deployment (top figure) the PEB with ToA has similar challenges as the AoA when the target is located between the BSs. This is due to errors in the y-coordinate, as the ranging circles obtained with ToA do not have a clear and unambigious intersection.

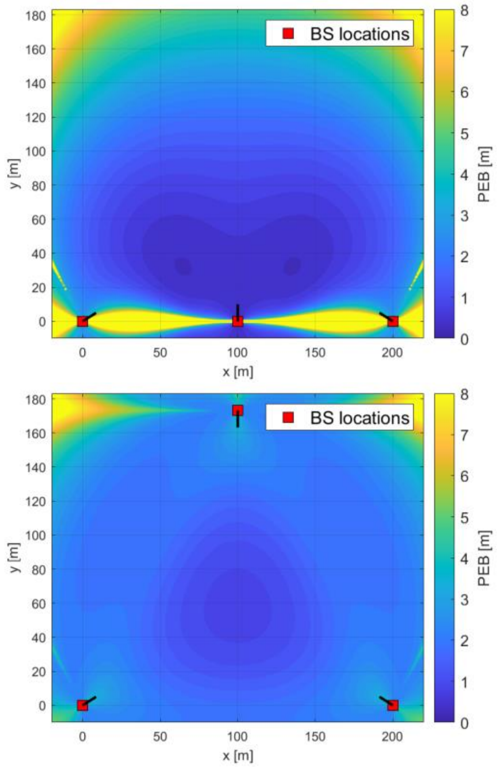


Fig. 8. Theoretical PEBs for two separate BS deployments considering AoA measurements and 32-element ULA. The BS antenna orientations are shown with a specific pointing vector at each BS. All PEB values larger than 8m are shown with a bright yellow color for a clear illustration.

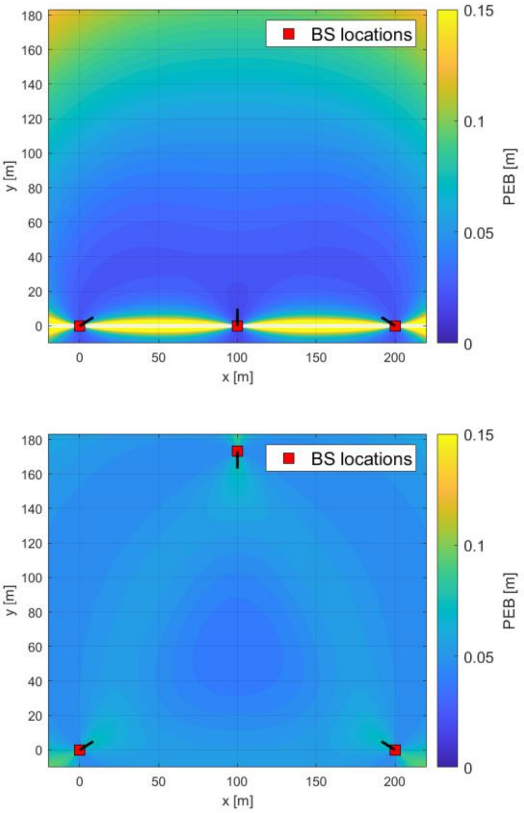


Fig. 9. Theoretical PEBs for two separate BS deployments considering ToA measurements with 200MHz bandwidth. All PEB values larger than 0.15m are shown with a bright yellow color for a clear illustration.

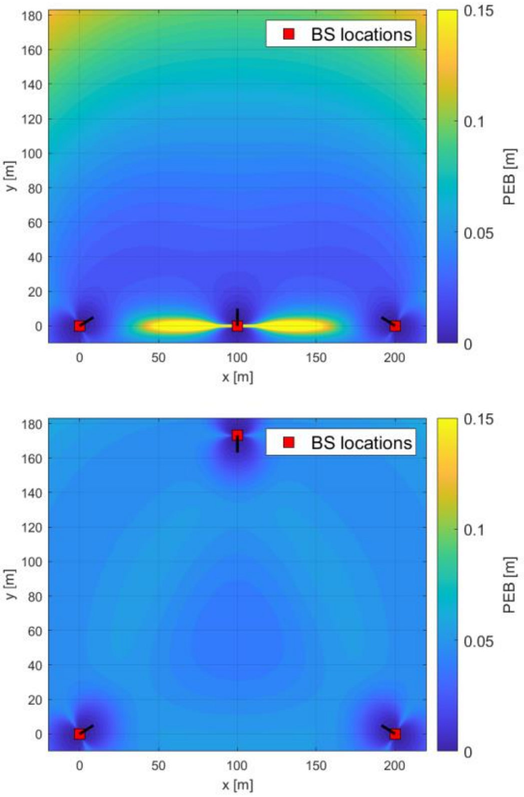


Fig. 10. Theoretical PEBs for two separate BS deployments considering ToA and AoA measurements with 200MHz and BS array size of 32-element ULA. The BS antenna orientations are shown with a specific pointing vector at each BS. All PEB values larger than 0.15m are shown with a bright yellow color for a clear illustration.

When introducing both ToA and AoA measurements for the positioning system, the positioning performance can be further increased. In Fig. 10, the PEB is illustrated for the two BS deployments based on using both ToA (with 200MHz bandwidth and no BS synchronization offsets) and AoA (with 32-element ULA) measurements. Compared to the scenario with ToA-only measurements, there is a clear improvement especially when the target is close to any of the BSs. Moreover, with the triangle deployment (in the bottom figure), the positioning performance is rather consistent throughout the whole area.

D. 5G BS Location and Synchronization

Certainly, position and time estimates are mutually correlated when it comes to positioning systems that rely on measuring signal time of flight, such as GNSS, 5G ToA/TDoA or 5G RTT. In fact, it is well known in the literature that the accuracy of location estimates based on ranging are very sensitive to errors in the knowledge of BS locations [23], while the time offset between the BSs only affects ToA- or TDoA-based methods [24]. Therefore, the performance of the whole 5G positioning system highly depends on such target accuracies.

The 3D accuracy of the BS locations directly impacts the UE positioning accuracy, as it is discussed in [25]. Concerning the time synchronization accuracy, and considering the case of a UE that is surrounded by BSs, a synchronization error of 50 ns contributes to a positioning error below 15 m. To limit the synchronization impact on the 5G-based positioning error, a synchronization requirement close to 10 ns [26] can enable a positioning service with location accuracies below 3 m on the 80% of the cases.

This synchronization requirement poses a significant implementation challenge. Typically, very tight network synchronization has been achieved with wired solutions, such as in the White Rabbit project [27] or the SuperGPS project [28]. Still, GNSS-based timing solutions are widely adopted in wireless networks, and the 50-ns synchronization can even be achieved with GNSS mass-market receivers [29]. Therefore, the very tight network synchronization is a topic that still deserves further research and development.

E. Deployment Considerations

Spectrum (e.g. transmission) and UAV flight regulations (e.g. beyond LoS flight conditions) are expected to limit the coverage area of the dedicated 5G networks. This section introduces certain regulatory aspects to be considered within the design of 5G overlay networks, with some examples of European regulations:

1) Spectrum: Dedicated and aerial deployments can be based on the use of licensed or unlicensed spectrum. The main advantage of the licensed spectrum is the low interference levels expected with respect to unlicensed spectrum, at the expense of an extra cost and access request procedure. Furthermore, the 5G NR unlicensed (NR-U) transmission requires the adoption of RF signal conditioning, in order to fulfil the regulatory requirements (e.g. in terms of power back-off, filtering and out-of-band emissions, among others) in the unlicensed band. In Europe, there are common 5G licensed bands, i.e., 3.4-3.8 GHz band for FR1 and 24.25-27.5 GHz for FR2, that eases the commercial launch of 5G networks across countries.

2) UAV: Deployments based on the use of UAVs require the adoption of regulations in terms of UAV flight, UAV payload and operator license, among others. In Europe, the European Union Aviation Safety Agency (EASA) defines the rules, exceptions and conditions on drone operations. The national aviation authorities implement these rules and issue the operating licenses, e.g in [30] for Germany. One common restriction that applies to UAVs across national regulations is the maximum weight, which is limited up to 25 kg with certain EASA operational restrictions. Another limiting factor is the flight envelope, which is recommended to be with minimum and maximum altitude of 1.5 m and 100 m, respectively, and the avoidance of beyond LoS operations due to regulatory restrictions.

3) Experimentation: Open-source 5G physical-layer solutions, such as OpenAirInterface [31] or srsRAN [32], can be considered on the deployment of standard and non-standard 5G networks for experimental purposes.

V. CONCLUSIONS

This paper discusses design considerations of a dedicated and aerial 5G network deployment for enhanced positioning services. The 5G overlay network is a novel approach to exploit the 5G positioning enablers, by deploying on-demand base stations (BSs) integrated on unmanned aerial vehicles (UAV), as well as at ground locations, for positioning purposes. The trade-off of positioning technologies among GNSS, 5G and sensor solutions allows to determine the best hybrid positioning approach within a defined dedicated network for a certain application. The assessment provides an overview of the 5G positioning features, in terms of advantages and disadvantages, and it indicates a high-degree of complementary between GNSS, 5G and sensor technologies. Design considerations of these 5G overlay networks are then discussed in terms of signal bandwidth, antenna array and BS deployment. While increased bandwidth and antenna elements clearly improve the positioning performance, the dynamic deployment of 5G overlay networks to ensure line-of-sight (LoS) propagation with the user equipment is expected to be one of the main benefits of this approach for enhanced positioning services.

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DISCLAIMER

The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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