Among the key differentiators of 6G compared to 5G will be the increased emphasis on radio-based positioning and sensing. These will be utilized not only for conventional location-aware services and for enhancing communication performance but also to support new use case families with extreme performance requirements. This article presents a unified vision from stakeholders across the value chain in terms of both opportunities and challenges for 6G positioning and sensing as well as use cases, performance requirements, and gap analysis. Combined, this motivates the technical advances in 6G and guides system design.

**Introduction and Motivation**

Large bandwidth and massive arrays employed in the emerging wireless communication networks along with network densification enable additional services, such as radio-based positioning and sensing, which are beyond data transmission, with minimal cost by using the same infrastructure and spectrum. The positioning of active communication devices has become an integral part of the recent and ongoing standards, such as in the 3rd Generation Partnership Project (3GPP) and IEEE [1]. Position accuracy requirements have also been increasing from tens of meters, as mandated by regulatory agencies, to the decimeter level for future use cases, such as indoor factories, unmanned aerial vehicles (UAVs), vehicle-to-everything applications, and so on [2].
On the other hand, the positioning of passive targets, i.e., the sensing of objects that do not transmit (only reflect/scatter) radio signals, has not yet been included in 3GPP standards. Radio-based sensing covers a broad class of applications, such as radar-like range and Doppler estimation, radio imaging, environmental monitoring, and material identification. Hence, there is no single performance indicator and requirement that can be defined for a sensing service. As discussed in this article, different use case families have different and new key performance indicators (KPIs) and require varying levels of sensing accuracy.

In addition to supporting new use cases, another important motivation of integrated positioning and sensing in a mobile communication network is that information about the environment can also be used to improve the communication performance. As an example, a digital twin of the environment that is created by sensing can be used to aid communication functions, such as radio resource management, beamforming, mobility management, minimization of driving tests, and so on.

In a recent 6G localization and sensing study conducted by the authors for the European Union Hexa-X project [2], the potential of sensing with radio waves to enable new use cases and applications as well as improve communication aspects of 6G systems was investigated. In this article, we highlight the key findings from that study, providing a detailed gap analysis for positioning and sensing use cases in 6G as well as envisioned 6G radio enablers and challenges, which serve to motivate continued research in this area.

**Mobile Radio Positioning and Sensing**

In this section, we provide an overview of the fundamentals of mobile radio positioning and sensing.

**Positioning and Sensing Fundamentals**

Positioning is the process of estimating the location (and, in some cases, the orientation and velocity) of a device from radio measurements, such as the received signal power, time of flight between the transmitter and receiver, direction of the signal, and any combination of those, as illustrated in Figure 1. The position estimate performance depends on the resolution and accuracy of the underlying measurements, number of base stations (BSs) involved, and relative positions of the BSs with respect to user equipment (UE). The cellular positioning reference signals (PRSs) employed in 5G include the downlink (DL) PRS and uplink (UL) sounding reference signal (SRS). Among the time and angle positioning methods, the UL/DL time difference of arrival (TDoA) uses SRSs/PRSs, respectively; the UL angle of arrival uses SRSs; and the DL angle of departure uses the beam index, whereas the multicell round-trip time (multi-RTT) relies on both PRSs and SRSs [3].

In a typical 5G network, signaling information that is intrinsic to the network, such as the serving cell, serving beam, timing advance, and reference signal received power, can be exploited to estimate location information. Methods using such information are called enhanced cell ID methods. The reference signals, such as the DL-PRS and UL-SRS, can be employed to compute the TDoA between a pair of reference nodes (e.g., BSs), which can, in turn, yield a locus of points along a hyperbola in which UE may be present. Thus, TDoA measurements from multiple pairs of reference nodes can triangulate to a precise UE location. These are broadly termed TDoA-based trilateration methods. In addition, 5G millimeter-wave (mm-wave) operation enables large-dimension multiple-input, multiple-output (MIMO), which can provide high angular resolution, thereby enabling precise angle information between the reference node and UE. The angle measurements between the UE and multiple reference nodes can be exploited to arrive at the position of the UE. These are usually termed angle-based positioning methods. To avoid the need for tight synchronization in the TDoA, RTT-based methods from multiple BSs have also been introduced [1].

Sensing is the process of detecting and tracking targets, such as vehicles, obstacles, humans, and so on, and estimating their relative range, velocity, size, shape, orientation, and material properties. Depending on where the transmitter(s) and receiver(s) are placed,

![Figure 1](image-url) The (at left) positioning of user equipment (UE) with several base stations (BSs) and (at right) sensing of an object. Positioning using the time difference of arrival (TDoA) from three BSs is shown in red dashed lines, constraining the UE to lie at the intersection of two hyperbolae in 2D. Alternatively, the downlink (DL) angle of departure (AoD) (or uplink (UL) angle of arrival) form lines that intersect at the UE location. Combinations of the TDoA and AoD are also possible. Monostatic sensing by the BS (in the DL) and the UE (in the UL) is shown in black, while bistatic sensing is shown in green.
the sensing process can be classified as mono- or bi/multistatic sensing, as depicted in Figure 1. The 5G standard does not explicitly specify methods, signaling, and protocols for sensing; however, there have been some attempts in research to exploit 5G signals for sensing [4]. Considered use cases in these works include activity detection, presence detection, and so on. It is envisaged that 6G may support new signaling, protocols, and methods similar to positioning to support emerging new use cases for sensing.

**Use Cases and Requirements**

Potential use cases for the future wireless generation can be categorized into five use case families. An overview of these use case families together with the main positioning and sensing KPIs is presented in Figure 2 and elaborated in the following. Further details of the use cases together with some of the most commonly used metrics for sensing and positioning are available in [2] and the references therein. The use cases are not fully orthogonal across the use case families.

**Sustainable Development**

This use case family encompasses 6G use cases that address the sustainable development of society and, at the same time, reduce the environmental impact of different industries. One such use case is providing health care for all, regardless of geographical location. Remote health care is one such enabler, which requires a rather fine location accuracy (e.g., drone deployment for medical sample collection). The required latency, in this case, is rather relaxed, and a moderate availability is enough for a service guarantee. Other example use cases are the remote sensing and monitoring of weather conditions, keeping track of biodiversity around the globe, and asset tracking, all of which have rather relaxed accuracy (meter-level) and latency (second-level) requirements.

**Immersive Telepresence**

Sensing and positioning can improve immersive telepresence for enhanced interactions. This family of use cases includes gesture recognition for human–machine interactions and augmented reality (AR). Gesture recognition requires rather fine range and angular accuracy. Depending on the specific use case, AR may have different requirements. For example, while AR for providing context-aware services, such as a shopping mall experience, requires moderate location and angular accuracy, AR for placing an object in the real world requires centimeter-level location and tight orientation accuracies.

**Local Trust Zones for Humans and Machines**

Another use case family that can utilize sensing and positioning is information security and providing local trust zones for humans and machines. One part of this family includes use cases with very tight location and orientation, availability, and latency requirements, such as telesurgery, localizing microrobots within the human body, and placing medical equipment on the body. Another part of the family includes patient tracking and monitoring, a sensor infrastructure web to support devices without sensing capability, cooperative positioning to support devices with little or no network coverage, and providing temporary local coverage when coverage from planned network infrastructure is not available, which can operate with more relaxed location accuracy.

**Massive Twinning**

Providing an efficient digital twin of objects and events in the digital domain can open up a host of new possibilities. One possible use case is in manufacturing, where configuring and using industrial tools can be done remotely. This type of use case requires location and range resolution on the order of centimeters. Also, this use case requires a good velocity resolution on the order of a fraction of a meter per second for moving objects. Another area where twinning can provide value is immersive smart cities, where, in one scenario, obtaining a real-time digital twin of the city can help optimize utilities. Another scenario in this area is traffic monitoring. The smart city use case requires meter-level to submeter-level location accuracy and rather relaxed latency and availability requirements. On the other hand, the digital twin of a smart building, where the location of each power switch, lamp, heater, and so on is important for effective interaction, requires more precise positioning while tolerating longer delays and less
availability. The most stringent requirement is the high scalability requirement.

**Robots to Collaborative Robots**

This final use case family includes solutions that can enable collaborative robots (cobots), such as cobot positioning, obtaining maps of cobots’ environment, cobot sensing of objects, and the fine positioning of vehicles around cobots. Some positioning use cases in this family, such as localizing cobots, require very accurate positions, down to the centimeter level, and also low latency requirements. Sensing applications, such as the environmental mapping of robots, have tight sensing location accuracy requirements as well as velocity resolution and angular resolution.

Figure 3 summarizes the requirements for accuracy, maximum latency, and availability for different use cases. The color-coding of the use cases represents their availability requirements. These requirements have been derived based on the available literature (the full list is available in [2] and [5]) and data provided by industry organizations. Table 1 shows the requirements for location accuracy, range resolution, and velocity resolution for sensing use cases.

**Gap Analysis**

**Positioning Gap Analysis**

To identify the gap between the requirements for the envisioned 6G use cases in the “Use Cases and Requirements” section and the capabilities of existing technologies, we need to establish the achievable performance of state-of-the-art technologies in localization and sensing. For

| Use Case                        | Location Accuracy (m) | Range Resolution (m) | Velocity Resolution (m/s) |
|---------------------------------|-----------------------|----------------------|----------------------------|
| Gesture recognition for human–machine interface | 0.01                  | 0.01                 | 0.3                        |
| Digital twins for manufacturing | 0.01                  | 0.01                 | 0.5                        |
| Traffic monitoring              | 0.5                   | 0.5                  | 0.5                        |
| Robots-to-cobots environment mapping | 0.01                  | 0.01                 | 0.5                        |
| Robots-to-cobots object sensing | <0.01                 | <0.01                | 0.1                        |
localization, we use 3GPP Release 16 as the baseline, and for sensing, we consider the performance of commercially available radar and lidar sensors.

Position Accuracy
The positioning accuracy of different positioning methods, namely, multi-RTT, UL-TDOA, and DL-TDOA in 5G New Radio frequency ranges (FRs) 1 and 2, is shown in Table 2. Simulations are done for 3D urban macro (UMa), 3D urban micro (UMi), and indoor open office (IOO) environments, with a 50-ns synchronization error. It is seen that the achievable accuracy for 90% of the users with the best method can be around 1 m for FR1 and 10 cm for FR2 in an IOO, and 3–4 m with FR1 in UMi and UMa areas.

5G capabilities for positioning accuracy are drawn as vertical lines in Figure 3. As evident from the figure, the required accuracy for the majority of use cases cannot be met for the corresponding deployment scenario. For example, the positioning accuracy that is required for remote health care, which is supposed to be available for both indoor and outdoor scenarios, can be met only by the 5G indoor positioning capability. Use cases demanding moderate accuracy (0.1–1 m) can be supported by 5G positioning methods, mainly in IOO-like scenarios. Finally, the stringent positioning accuracy (<0.1 m) requirements cannot be met in the considered scenarios.

Latency
End-to-end positioning latency in 5G depends on the signaling delays among participating nodes and the positioning method employed. Latency evaluations for the DL-TDOA, UL-TDOA, and multi-RTT are presented in [2], which shows latencies on the order of 150–300 ms depending on the positioning method. Considering the most stringent latency for the 6G use cases, which is around 10 ms, there is at least a one-order-of-magnitude gap between the state-of-the-art methods and envisioned 6G use cases. 5G capabilities for positioning latency are presented as diagonal lines in Figure 3 for different device speeds.

### Table 2: The achievable 5G positioning accuracies (in meters) for different methods and deployment environments [1].

| Method      | UMa   | UMi   | IOO   |
|-------------|-------|-------|-------|
| DL-TDoA     | FR1   | 4.37 m| 3.48 m| 2.10 m|
|             | FR2   | N/A   | 1.11 m| 0.17 m|
| UL-TDoA     | FR1   | 35.14 m| 3.88 m| 2.19 m|
|             | FR2   | N/A   | N/A   | 0.18 m|
| Multi-RTT   | FR1   | 30.29 m| 2.99 m| 1.11 m|
|             | FR2   | N/A   | N/A   | 0.07 m|

UMa: urban macro; UMi: urban micro; IOO: indoor open office. Cases with coverage limitation are shown as N/A.

Scalability
5G positioning methods that are based on broadcast signals (e.g., PRSs) can be used by multiple UEs and transmission and reception points for positioning measurements, given that the nodes performing the measurements are in the coverage of the broadcast signals. Hence, those methods are scalable and can be practically used to support the scalability requirements of the previously elaborated use cases. There is, however, an important limitation that will still be present in 5G. Accurate positioning requires radio resources (e.g., PRSs), which would thus occupy communication resources while locating. The higher the accuracy required, the larger the bandwidth of the channel that will be unavailable for communication. 6G must solve this well-known problem by enabling simultaneous communication and positioning.

Availability
Future generations of cellular networks need to be designed to obtain seamless and pervasive connectivity in a variety of different contexts, matching stringent quality-of-service requirements in outdoor and indoor scenarios through a cost-aware and resilient infrastructure [6]. The availability of the positioning system indicates that the position error is less than a threshold. High path loss is one of the major issues affecting availability, which can be mitigated with the implementation of directional antennas and massive MIMO. Nevertheless, the angular coverage of antenna arrays (compared with omnidirectional antennas) will unavoidably be sacrificed. We expect that new techniques, such as reconfigurable intelligent surfaces (RISs), distributed MIMO, and scene-aware localization and sensing, can meet the availability requirements.

Considering the rather limited availability of 5G, there is a significant gap between 5G capabilities and the required availability for 6G use cases, as shown by the color mapping in Figure 3, based on reported values in the technical literature (e.g., [2] and [5]), when available. We observe three groups of requirements: use cases with not very stringent requirements, involving asset and people tracking and context-aware services; use cases involving robots and vehicles, with strict availability requirements; and, finally, new medical use cases requiring extreme availability. Considering that the achievable availability of 5G is 90% [1], the availability for most of the use cases needs to be improved.

Orientation Accuracy
The development of radio access technology-based positioning has been done considering regulatory and Industrial Internet of Things use cases, where UE orientation estimation is not a primary objective. For example, in regulatory use cases, such as the positioning of emergency-call-originating UE, knowing the UE heading is not
Identified Gaps
The position accuracy, latency, and availability gaps between 5G and 6G systems are summarized in Figure 3. To support the identified positioning use cases, future radio access networks must meet the requirements for the preceding fundamental KPIs. The required positioning and orientation accuracy can be achieved only when the localization service is available, which is subject to coverage (indoor and outdoor), network deployment (the geometric dilution of precision is one of the limiting factors), and synchronization among the network nodes. As a result, the next-generation positioning methods must, in principle, be able to address these issues and should offer more accurate position and orientation estimations by exploiting potential wide bandwidth and array sizes.

To achieve high scalability supporting many more devices in future networks, it is of utmost importance to utilize the time (PRS allocation), frequency (bandwidth distribution), and spatial (beamforming and codebook optimization) resources with the highest efficiency. Latency budget evaluations show that the latency of 5G positioning methods depends on the employed method and can support many of the identified use cases. Nonetheless, the newly emerged use cases (e.g., enhanced remote health care, telesurgery, and cobots) demand quasi-real-time positioning and mandate new technologies to obtain a much lower latency than what can be achieved by 5G systems.

Sensing Gap Analysis
In 5G, there is, so far, no support for radio-based sensing. To have a baseline against which to compare the expected performance requirements in 6G, we use radar and lidar.

Legacy Solutions
What can be achieved with radar and lidar technologies differs depending on the application and environment. To have some numbers for comparison with the forseen use cases in 6G, we have chosen the Arbe radar, which can achieve a location accuracy and range resolution of around 0.5 m at a range of 300 m and a velocity resolution of 0.1 m/s, with a latency of 33 ms [2]. The example we have chosen for lidar is the Hesai Pandar64, which can reach a position accuracy of 0.02 m at distances in the range 0.5–200 m, with a latency of 50 ms and a surface with reflectivity of at least 10% [2]. It does not provide any velocity estimate, though. When comparing these values with the requirements for the different sensing use cases listed in Table 1, a few things can be noted.

The lidar is good at positioning and is close to satisfying the location accuracy and range resolution demands of all the listed use cases except for the object sensing in robots to cobots. Worth noticing, though, is that the gesture recognition and object sensing are performed at short ranges, which decreases the accuracy of the lidar. There is also a possible safety risk of having lasers pointing at a user from a very short distance, as would be the case in gesture recognition. Another problem for the lidar is the lack of velocity measurements, meaning that it cannot fulfill the velocity resolution requirements for any of the use cases.

The radar is much better than the lidar in terms of velocity resolution and does actually fulfill the requirements for all the use cases. On the other hand, it lacks the precision in location accuracy and range resolution and fulfills the requirements only for the traffic monitoring use case. An advantage of the radar compared to the lidar is that it is not as sensitive to the reflectivity of different materials in the surroundings. Possible health risks for users are also lower compared to the lidar.

Identified Gaps
It is possible to satisfy most of the requirements in Table 1 by using legacy radar and lidar. However, there is only one use case where it is possible to satisfy all the requirements with only one technique, and that is road traffic monitoring. As mentioned earlier, there exists a wide range of different radars and lidars, and in this case, we have used only two different examples for comparison. There are radars that perform better at positioning and lidars that give velocity information, but that is, then, at the cost of other performance metrics. The bottom line of this gap analysis is that there is no technique available today that satisfies all the requirements of the use cases. To provide a fair evaluation of the gap between 6G requirements and the capabilities of legacy solutions, we consider radar as the baseline solution. Figure 4 describes the gap between the most stringent requirements for 6G use cases and the corresponding capabilities of legacy radar mentioned earlier.

Opportunities and Challenges for Positioning and Sensing in 6G

Radio Enablers
To close the gap between 5G capabilities and 6G requirements, various technical enablers, including high-frequency signals with large bandwidths and massive arrays, intelligent surfaces, and the joint design of multifunctional hardware/waveforms, have been considered. In the following, these are discussed in detail.
High-Resolution Sensing With Large Bandwidths and Large Arrays

The resolvability of multipath components in angle, range, and Doppler domains plays a crucial role in positioning and sensing. Higher carrier frequencies can accommodate larger bandwidths, resulting in superior range resolution. In addition, smaller wavelengths can bring significant antenna miniaturization, thus enabling the deployment of massive antenna arrays and leading to high angular resolution [7]. This enables high-resolution sensing and mapping applications without being affected by ambient light and weather conditions, as opposed to visible light- and infrared-based technologies [8].

RISs

As one of the key enablers in 6G, a RIS can reflect an incoming electromagnetic wave toward a desired direction via programmable passive reflecting unit cells and a controller, which implies lower deployment and operational costs than a BS or a relay [9]. Under line-of-sight (LoS) blockage conditions, RISs can create controllable non-LoS links to improve coverage and communication quality. In positioning and sensing applications, RISs with known locations can boost accuracy by providing additional geometric measurements [10]. Through a tailor-made design of RIS phase shifts (i.e., passive beamforming), positioning and sensing performance can be enhanced significantly when there is a priori knowledge of UE/target locations.

Joint Hardware and Waveform Design

Future positioning and sensing services will rely on a ubiquitously available communication network and its hardware, thus avoiding the deployment of costly parallel infrastructure. Regarding joint waveform design, multicarrier communication waveforms, such as orthogonal frequency-division multiplexing (OFDM), are attractive for positioning and sensing, thanks to wide availability and efficient implementation [11]. On the other hand, single-carrier waveforms can offer a better solution in terms of hardware efficiency, due to a low peak-to-average power ratio, but may lead to higher side lobe levels than OFDM. To investigate their resolution, accuracy, and clutter rejection characteristics, waveforms (single- and multicarrier) can be evaluated through the range–Doppler ambiguity function. Due to inherent tradeoffs, the joint waveform optimization for positioning, communications, and sensing requires careful consideration of conflicting requirements, such as the data rate, accuracy, and main lobe width and side lobe levels of the ambiguity function [12]. Moreover, joint communications–sensing waveforms should be robust to hardware imperfections at high frequencies, necessitating the simultaneous design of multifunctional transceiver hardware and waveforms.

Algorithmic Developments

With the high delay/angular resolution in 6G, two promising research threads for positioning/sensing algorithms arise in a complementary manner. Model-based algorithms can exploit geometric optics in conjunction with optimization theory and statistical signal processing [13], while model-free techniques rely on data-driven machine learning [14]. Through their rigorous mathematical foundations and explainability, model-based methods seem attractive. Under severe hardware impairments and/or intractable mapping from measurements to position, data-driven approaches can become highly effective. In 6G scenarios, algorithms that can harness both data and domain knowledge will be key to achieving extreme positioning/sensing performance.

Challenges

To fully harness the radio enablers for extreme performance (Figure 5), two fundamental challenges have been identified: hardware impairments and harsh channel conditions. In addition to those radio challenges, integrating highly accurate and low-latency positioning and introducing the totally new feature of integrated sensing pose further challenges and requirements, for example, to the architecture and service offering concepts.

Figure 4 The sensing gap between legacy radar (in blue) and 6G (in red).
Hardware Limitations and Impairments

Hardware impairments have more severe effects on positioning and sensing than on communication. Ranging accuracy degrades mainly due to timing errors, whereas angle estimation accuracy is degraded by antenna imperfections. Examples of hardware imperfections include phase noise, mutual coupling, nonlinear distortion, and frequency-selective impairments [15]. While some of the hardware impairments can be compensated through calibration (antenna mutual coupling and linear distortions), others, such as phase noise, must be compensated dynamically during operation. To meet the low-latency demands, a large bandwidth is required, but that is subject to hardware limitations. In addition, a large volume of data requires more storage and computational resources that can, in turn, limit the performance improved by these features.

Harsh Propagation Channels

Depending on the relation between the wavelength and the size of objects, the radio channel can exhibit varying characteristics. At sub-6 GHz, the channel has a very complex relationship to the environment, and small movements lead to large power fluctuations due to small-scale fading. At mm-wave bands, obstacle penetration is reduced, and reflection and scattering become more important phenomena. A sparser channel allows for higher multipath resolvability (characterized by fewer propagation clusters), and larger bandwidths and large antenna arrays enable accurate positioning. At 100 GHz and above, mainly, multipath due to metallic objects will be visible, either in the form of moving incidence points and virtual anchors or (groups of) smaller objects (e.g., pillars) behaving as static points. Additionally, the Doppler shift will greatly increase at the upper mm-wave FR. At such frequencies, the channel state changes faster, requiring more frequent updates, which demands better spatial consistency of the developed channel models so that consecutive channel impulse response samples are accumulated over time. The characterization of the angular, delay, and Doppler spreads due to extended objects, molecular absorption, link gains, and behavior under mobility are important challenges to be addressed, e.g., through measured evidence and channel models.

Outlook for Positioning and Sensing in 6G

In contrast to 5G, 6G will consider positioning and sensing an integrated part of the system, with joint waveforms and hardware as well as important cross-functional benefits. One of the important foreseen uses of 6G radio will be to support a wide variety of extremely challenging use cases, not only in terms of communication requirements but also for positioning and sensing. The goal of this article has been to list a selection of these 6G use cases, determine their positioning and sensing requirements, and perform a gap analysis against the state of the art. In terms of positioning, we revealed that in three key KPIs (accuracy, latency, and availability), there is a significant gap between the 5G capability and the 6G requirements. In terms of sensing, we similarly found gaps in certain KPIs (accuracy and resolution) between state-of-the-art sensors and 6G sensing requirements. To bridge this gap, this article also presented a practical view of positioning for 6G radio, considering foreseen enablers (large bandwidths and arrays, RISs, and algorithmic developments) and challenges (channel model mismatch and hardware impairments).

Next-generation mobile networks will feature improved positioning performance and enable sensing the environment. Through this, new services will arise to use such information, which will have other implications. For instance, certain services will require intermediate information with uncertainty and integrity guarantees, while other services will have security concerns that need to be carefully addressed, such as access rights to different location services, location jamming, location falsification, and issues related to privacy and secrecy. Overcoming the challenges while harnessing the enablers in support of 6G use cases will constitute a major research endeavor for the coming years.

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![Figure 5](image-url) The 6G radio enablers that can help close the gaps in support of 6G use cases. Closing the gaps requires addressing two important challenges.
Localisation and sensing use cases and gap

The promise of radio analytics: A future paradigm of wireless positioning, tracking, and sensing.

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