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NEXT-GENERATION POSITIONING WITHIN 6G

A Fraunhofer 6G white paper

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Executive Summary

The focus of 6G will be on immersive applications like eXtreme Reality (XR) and digital twins. The ambition is to close the gap between the physical and the digital world. In that sense, 6G can be considered the communication standard for the metaverse. As the perception of the physical world requires our senses, sensing and localization are among the hot topics in 6G. While positioning in 5G requires the active participation of a 5G-enabled device, passive sensing of the environment will be one of the disruptive features in 6G. For the envisioned use cases, 6G will also need to enhance the localization accuracy to below one centimeter.

In 5G, a variety of localization technologies are employed in addition to the communication features to enable accurate positioning. These include methods to measure the time differences of the arrival of signals (TDOA), multi-cell round trip time measurements (RTT), angle of departure (AoD) and angle of arrival (AoA) determination, leveraging of wide signal bandwidth and massive MIMO antennas for more accuracy, as well as using the sidelink for relative UE-to-UE positioning. Even though the required signaling is already part of the 5G waveform, the 5G location services framework is still a separate entity with its own mechanisms.

In 6G, however, it will not be sufficient anymore to handle communication and positioning as separate services. Tackling the challenges of the metaverse requires a tight integration of communication and positioning to achieve highest data rates and lowest latencies along with best positioning results and descriptive information about objects and the environment.

Extending mere location information to detailed data about the environment requires the extension of active positioning to passive sensing. Position and other relevant information about objects within the environment can be estimated without the necessity of active participation of the objects to the sensing process. This is a fundamental paradigm shift enabling new 6G use cases based on immersive experience.

Key enablers for ultra-precise and tightly integrated positioning in 6G will be:

- THz spectrum and ultra-wide bandwidths for extreme precision
- Pencil beams for accurate angular positioning
- Coverage extensions and leveraging of multipath by using intelligent reflecting surfaces (IRS)
- Immediate coarse positioning with dense cell-free network architectures and low-complexity radio units
- AI/ML algorithms for higher positioning accuracy in challenging non-line-of-sight scenarios
- Communications-enhanced positioning and positioning-enhanced communications by integrated sensing and communications (ISAC)

To meet the ambitious goals for positioning and sensing, 6G offers a wide variety of critical technology elements. Fraunhofer provides early practical hands-on experience in all these elements within the lighthouse project 6G SENTINEL [1]. This collaborative activity involving five Fraunhofer institutes has been initiated in 2021, well ahead of the expected start of 6G standardization in 2025 to provide detailed and well-founded data about the advantages and limitations of the different technology elements. In addition to positioning, energy efficiency, flexible 3D networks and THz frequencies, data privacy, security, and trust are important topics in the on-going discussions to shape the next generation of mobile communications.

New 6G Use Cases: Precise Location Awareness as Foundation of New Applications

Use Cases and the Importance of Positioning

Use cases involving location information have already been emerging during previous generations of mobile networks and gained importance. For 6G, it is foreseen and discussed that there is another leap with respect to importance, availability, complexity, and quality of location information.

Is there a crucial new feature of 6G use cases involving positioning?

For example, the aspect of "immersive participation" in remote, augmented, or virtual realities requires that the 6G system perceives the overall environment (new aspect emerging for 6G) and has accurate, highly available and non-delayed position knowledge (low latency) of key objects including their orientation, physical expansion, and path (mobility).

The radio interface of 6G gains information of the environments in its spatial dimensions and over time without the need of cooperative active participation of objects to be located, i.e., the objects may be passive. Please note that positioning in 4G and 5G was active, i.e., the object, in all cases the User Equipment (UE), had to participate in an active manner using its radio interface, e.g., for receiving or transmitting positioning reference signals. Positioning used to be named "UE Positioning." For 6G, however, it is anticipated that the generation of location information depends on both: active emitter positioning as well as passive sensing of (parts of) the environment.

Apart from the user-related use cases, the 6G network fine-granular features such as the radio connectivity decisions, handovers and even service continuity at very high frequencies as well as the ability to optimize the network performance, mobility robustness, load balancing and energy consumption can be exceptionally optimized with a precise knowledge of the momentary location of the connected devices. It represents a cornerstone in understanding the momentary wireless environment and how to adapt to it.

Examples of new 6G location-relevant use cases:

- Interacting/cooperating robots
    - Robots in industrial and home or care applications
- Vehicular communication and autonomous driving
    - Incl. (sub-)THz device-to-device links for cooperative perception
- Extended/eXtreme, virtual or augmented Reality (XR, VR, AR)
    - Augmented workspace
    - Telemedicine
    - Immersive smart city
    - Immersive sport and cultural events
- Digital twins
    - Industrial applications and industrial Internet-of-Things (IIoT)
- Sustainable development
    - Location information as enabler for energy savings

Why can't positioning use cases be seen as separate from data-centric ones?

In most or nearly all cases, the usage scenarios include positioning or location information while also demanding high data rates. In addition, also other challenging performance indicators may have to be met, like high lowest latency or highest availability. Looking at the example of XR, all these requirements come together: linking virtually displayed objects to true objects and the environment in the real world requires very precise location information, while providing the images for the virtual impression demand for very high data rate at low latency in order to be able to interact.

Outstanding Performance Targets

In our previous Fraunhofer white paper [2], we identified the convergence of the physical and the human world with the digital domain as an important trend with frequently discussed use cases for 6G like XR, tele-presence, tele-operation and autonomous driving, and digital twins. To enable these use cases, a significant increase of 10 times or more in the traditional Key Performance Indicators (KPIs) like peak data rate (up to Tbps), reliability (seven nines), latency (10s to 100s of µs), connection density (up to 10 per m2), and localization accuracy (below 1 cm) is required compared to existing 5G technologies.

On the technological side, the key enablers introduced and discussed in this white paper are crucial to achieve the required improvement in the KPIs.

Positioning in Mobile Networks from 4G, via 5G, towards 6G

How did locations services of mobile networks start in 4G?

First driven by the need from regulations to locate mobile devices during emergency calls in 4G (expected accuracy 50 m), over the years and from 4G to 5G, 3GPP's positioning framework has been expanded to support an ever-increasing number of use cases with higher performance targets.

The standardized positioning methods that were already supported by LTE include:

- Enhanced-Cell ID (E-CID): a user equipment (UE)-assisted but network-based positioning method, E-CID simply uses different existing measurements to lead to location estimates, e.g., cell IDs, the signal power from multiple cells, timing advance (i.e., coarse ranging)
- Assisted GNSS (A-GNSS): a UE-based or optionally UE-assisted method, A-GNSS uses positioning satellite signals, such as those of GLONAS, GALILEO, GPS, etc. to obtain the position of the mobile device.
- (Downlink) Observed Time Difference of Arrival (OTDOA): using a special reference signal, the so-called positioning reference signal (PRS), the serving base station (or cell) and neighboring cells transmit the PRS to the mobile device. Then, the mobile device determines the reference signal time difference (RSTD) between the arriving signals of the different cells, which is used to estimate the position of the mobile device.
- Uplink Time Difference of Arrival (UTDOA): first defined in Release 11, UTDOA is an alternative to OTDOA, but using uplink signals. In contrast to OTDOA, a different reference signal, the sounding reference signal (SRS) is transmitted by the mobile device.

A framework with procedures, signals, measurements, and protocols came into existence, that supported own cellular measurements and integrated external sensors like GNSS or barometers and inertial sensors. So, hybrid schemes combining different positioning schemes are possible through implementation.

Why was there momentum to enhance UE positioning in 5G?

For the fifth generation (5G), new application scenarios from vertical domains like industry (support of indoor factories and campus networks) and automotive (solutions for "vehicle-to-everything V2X"), as well as from public safety and commercial use cases, demanded for better positioning solutions in terms of achieved accuracy (down to the meter and partly decimeter range), higher availability, lower latency, and better scalability. Still, all usage scenarios dealt only with positioning of UEs and not yet of additional passive objects.

What kind of additional solutions was 5G coming up with?

5G built upon the positioning architecture of 4G, but an extensive expansion and modification was adopted. The signals and procedures for positioning in 5G are defined in Release 16 for 5G New Radio (NR). New positioning concepts, in addition to the ones from previous generations such as TDOA either in downlink or in uplink, were devised, for example multi-cell round trip time "multi-RTT" measurements and angular readings based on the use of beamforming at the base-station, downlink angle of departure (DL-AoD) determination for outgoing signals and uplink angle of arrival (UL-AoA) estimates for incoming ones. For better time resolution, timing-based methods make use of the wider signal bandwidths of NR increasing to 100 MHz in the sub-6GHz-range. The new mm-Wave bands even allowed to go to up to 400 MHz for a single carrier. Massive MIMO antennas provide perfect angular resolution. At smaller wavelengths, especially in the FR2 spectrum, very large arrays of antenna elements can be implemented to form one massive MIMO antenna. Further enhancements to the standard, introduced in Release 17 and currently being expanded upon in Release 18, target higher positioning accuracy, lower latency and UE power consumption. For example, carrier aggregation and the usage of carrier phase information are considered for positioning. Furthermore, positioning becomes possible for UEs in the idle state and for UEs with reduced capabilities. As the largest new objective for 3GPP's current Release 18, a sidelink UE-to-UE positioning solution is being developed providing new architecture variants including UE positioning in out-of-network coverage scenarios. Products implementing all the features have to follow suit and are still to bring the features to use.

Will 6G allow to bring all aspects related to positioning to the next level?

Looking forward to the future, the sixth generation (6G) of mobile communications offers a great opportunity to bring positioning methods and services to the next level. Of all new proposed technology enablers for the next generation of mobile communications, for example the terahertz (THz) frequency spectrum or cell-free massive MIMO systems, have gained attention in the academic and applied-research communities. Positioning-related approaches like "sensing" of passive objects or the whole environment are on everyone's lips. Envisaged use cases like positioning for extended reality or safety critical applications (e.g., in industry and in public safety scenarios) demand for improved key performance indicators (requirements) not just in terms of location accuracy but also for availability, reliability and latency [13]. Positioning and communications ("data rate") are no longer considered as separate services or features for separate use, but increasingly tightly integrated within the usage scenarios. For example, "extended reality" needs both the highest data rate and best quality positioning.

New Technology Elements: Performance Enablers for 6G Positioning

(Sub-)THz Mobile Spectrum and Systems

For 6G systems, a shift to frequencies even higher than what was adopted for 5G NR, i.e., FR2, is envisioned. This time, the focus is on the THz spectrum, where a very large bandwidth is available. This presents a new opportunity for not only increasing the achievable data rate, but in the case of positioning, to achieve very precise time resolution. However, there are challenges to be conquered.

What antenna-array designs should be used?

To counteract the high path loss of the THz band, high-gain antennas or antenna arrays must be employed. With the small wavelength of terahertz signals, however, a very large number of antenna elements can be packed in an ultra-massive MIMO array. Designing these arrays is of great importance.

If we consider the primary candidates for the THz carrier frequencies, i.e., 150 GHz and 300 GHz, the individual antenna elements have a resonant length ($\lambda/2$) assuming air dielectric of 1 mm and 0.5 mm, respectively. Moving to higher frequencies results in even smaller lengths. Realizing elements of such small dimensions quickly becomes particularly challenging using traditional metallic materials. Instead, primary research has shown that metamaterial-based and graphene-based realizations present many advantages [4].

What about beamforming?

Due to the very large bandwidth available in these THz frequency bands, typical DFT-based beamforming approaches lead to beam squinting, i.e., beams pointing in different angular directions throughout the signal bandwidth. These beamformers are designed for narrow and not-so-wide bandwidth signals. In fact, this problem may also occur in wideband mm-wave signals but is much less prominent there than in the THz band. To solve this issue, other beamforming designs are required. Moreover, designs should be also (partly) implementable in the analog domain, as a fully digital implementation might not be feasible. One such design is based on the delay Vandermonde matrices (DVM) [5], which unlike DFT (Discrete Fourier Transformation) beamformers, have frequency-independent beam angles. Additionally, such beamformers can be implemented in both the digital and the analog domain.

Having pinpoint accurate beams that properly point in the required spatial direction is key for THz-based positioning. This enables the usage of the very large bandwidth signals in the THz frequency range, leading to a very fine time resolution. Additionally, the angle of departure and angle of arrival information at the ultra-massive MIMO antenna array provides an opportunity to either obtain position information using one anchor, or to supplement a traditional multi-anchor positioning approach with side information to increase the positioning accuracy of the system.

Where could we envision THz-based positioning?

A prominent physical effect seen in the THz frequency regime is the high susceptibility to signal blockage due to organic, e.g., people, and inorganic materials, e.g., walls and other obstacles in the propagation environment. While signals at low frequencies, such as those commonly used for mobile applications, can penetrate most common materials (with some power loss), the power loss at THz frequencies becomes so high that objects can be considered virtually impenetrable. In addition, due to the very small wavelength, the ability of THz waves to diffract around obstacles or reflect off (non-ideally smooth) surfaces is greatly reduced. In fact, measurement campaigns, such as in e.g., [6], have shown that only a small number of multipath components contribute to the total power of the channel. This means that line-of-sight links must be established for a THz-based positioning system.

The Location Management Function (LMF) is a central entity in the 5G positioning architecture. It computes the position of a UE from collected measurement data. One of the envisioned use cases for THz-based positioning is indoor scenarios, where it would be possible to have an LMF close to the base stations. This means that low-latency multi-TRP measurement aggregation is possible. Additionally, the local LMF would support both "classical" position-estimation algorithms and ML-based solutions. Moreover, conventional algorithms must be adapted to take advantage of the sparsity of the THz channel – due to the high absorption and lower reflection coefficients of most materials, there are fewer multipath components when considering higher frequency signals, as mentioned above.

The THz frequency spectrum

- presents new opportunities for high precision-positioning solutions,
- needs clever antenna and beamforming designs,
- provides an opportunity: instead of thinking of the very short range as a hindrance, being closer to the measurement points enables (very) low-latency positioning solutions.

Intelligent Reflecting Surfaces

Development of intelligent radio environments is a new concept in which intelligent reflecting surfaces (IRS) are deployed to influence the propagation characteristics of the wireless channel. IRSs are seen as one of the key enabling technologies for future six generation (6G) wireless communications systems that scale up beyond massive MIMO.

What is an IRS (Intelligent Reflecting Surface)?

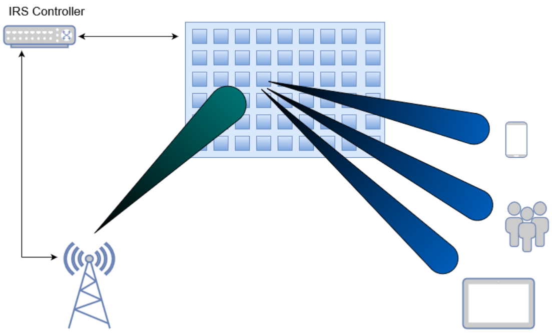

Fig. 1: IRS-assisted communication system

The IRS is generally a planar surface containing many passive reflecting elements that are capable of independently altering incident signal amplitude and phase. In wireless networks, IRSs can be deployed and smartly coordinated to reconfigure the channel between transmitters and receivers. Several attractive functions can be achieved using an IRS in wireless channels, such as establishing a virtual line-of-sight (LoS) link to bypass obstacles, creating additional signal paths towards desired directions, etc. Additionally, IRSs possess several practical advantages that could make them an attractive implementation candidate, for instance, an IRS is capable of lowering hardware and energy costs compared to traditional active antenna arrays as it uses only passive components without requiring transmit radio frequency (RF) chains. Another advantage is that IRSs can be operated in full-duplex (FD) mode without antenna noise amplification and self-interference [10].

How can IRS help radio localization?

With an increased bandwidth and large antenna arrays, 5G radio at millimeter-wave (mm-wave) and beyond-5G frequencies at THz can exploit angle and delay measurements for localization, but there are obstacles that limit the ability to use these measurements. Through passively reflecting radio waves in preferred directions and actively sensing this environment in receive and transmit modes, IRSs can control the physical propagation environment in which they are embedded and viewed as a transformative technology. Despite their primary purpose as communication devices, such IRSs can provide substantial performance, energy consumption, and costs benefits to localization efforts.

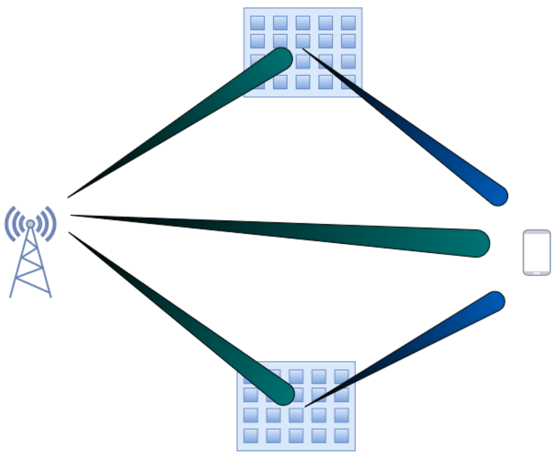

Fig. 2: IRS-assisted positioning system

Objects blocking the line-of-sight (LOS) path between the transmitter and receiver cause obstructions to high carrier frequencies. However, reliance on the LOS path can be reduced through multipath-aided localization. It is still not possible to control the electromagnetic (EM) interactions resulting from the physical environment, even when using the multipath channel as a constructive source of information in a localization problem geometry. As a result, the localization process is generally suboptimal.

A significant benefit of IRSs is that they provide coverage regardless of the LOS being blocked, improving communication by actively modulating the impinging EM waves. The IRS, thus, can be used as a transmitter, receiver, and anomalous reflector, allowing it to steer the direction of the reflected wave instead of following natural reflection laws.

It is possible to apply the IRS concept at a variety of wavelengths, including low sub-6GHz bands where the technology is well understood and commercial systems are available, and 28-GHz mm-wave bands, where IRSs can offer significant coverage benefits. As a result of considering the limitations and challenges of the THz regime, it is possible to extend the IRS concept to it.

As well as these properties, IRSs exhibit a good relationship with the environment's geometry, because they can easily be mounted on environment objects due to their low profile, lightweight, and conformal geometry. Providing great flexibility and compatibility, they are ideal for localization and positioning [11].

Integrated Sensing and Communications

Over the years, radio-wave-based systems for communications and sensing applications have been developed independently. In fact, looking back at the many advances made in each field, we can see that solutions initially developed for a problem in one field can be applied to the other, and moreover, a similar, or even the same system design (hardware, signals, and processing) is often seen in both domains, e.g., as in the case of OFDM radar. Thus, a tight integration of positioning, sensing, and communications will be one of the key features of 6G.

What’s the difference between positioning and sensing?

Positioning, as we define it here, is one special facet of sensing. In this case, the “target”, i.e., the UE, of which information is being acquired also plays an active role in the process. In literature, one often sees the term active sensing. This typically only refers to the transmitter side. To avoid confusion, when we talk about positioning, we always imply that the UE is playing an active role, either by transmitting the measurement sequence, or by assisting in the processing of a received sequence and feeding back information to the source, i.e., the base station.

Are the advantages in integrating positioning, sensing and communications into a joint system?

A tight integration of all aforementioned systems opens up new avenues where contextual information of one system can improve the performance of the other. This brings forward the concepts of positioning- or sensing-aware communications and communications-aware positioning or sensing. For the former, knowing where the communications endpoint (be that a UE or the base station) is, tasks such beamforming, base station handover, power management and radio resource management (and interference mitigation), to name a few, can be solved via more efficient and better performing algorithms. By sensing the geometry of the environment, akin to radar, we can more efficiently resolve spatial problems by filtering out areas where solutions do not exist, e.g., a beam should not be pointed to a certain area because it is completely blocked by some object, or by identifying spatial areas that can be used advantageously, e.g., knowing where a good reflecting surface is, we can use it to circumvent certain blockers that are in the way between the base station and the UEs. Moreover, this sensing knowledge can be also informative for positioning: knowing the geometry can help better resolve multipath components when obtaining spatial information for positioning.

For the latter, we can extract information from communications that can aid in positioning or sensing. Identifying the presence of (and estimating) a Doppler shift when estimating the channel can be used as additional information in positioning algorithms; we have knowledge about mobility. New modulation schemes, such as Orthogonal Time Frequency Space (OTFS), can be potentially exploited for radar sensing. OTFS is a 2-dimensional modulation scheme where data is transformed from the delay-Doppler domain to the time-frequency domain before transmission.

In addition, many new applications may only be implemented with such a system. This is especially true in the case of mobile robotics; in the future, a very large number or swarms of robots cooperating in a smaller area is foreseen. In this case, separate systems for positioning, sensing and communication might not be feasible due to the physical dimensions of the robots, and the available radio frequency spectrum will be at a premium. In order to achieve certain target KPIs, an efficient joint solution would be the only viable solution.

Cell-Free Massive MIMO Networks

By combining three technology enablers together, namely distributed massive MIMO, coordinated multipoint (CoMP) transmission, reception with joint processing (JP) and ultra-dense network deployments, a new paradigm for mobile communication emerges: the user-centric cell-free massive MIMO [7].

What makes cell-free networks special?

Unlike traditional cell topologies, instead of cells and handover mechanics, a dynamic clustering of the access points (AP) in the vicinity of the user is applied. Given the current radio environment, different users are jointly served by different subsets of the APs of the network. As the mobile device changes location, the clusters are dynamically adjusted. From the user's perspective, there are no more cells or cell edges.

Why are cell-free networks interesting for positioning?

In order to keep things as general as possible, we refer to the network-side connection point as access point (AP), e.g., a base station or a remote radio unit connected to a base station. Inherently, some positioning information is at hand, e.g., given the subset of APs that the user device is being currently served by, coarse localization is at hand. Moreover, cell-free massive MIMO networks are not tied to a specific radio band; for example, ultra-dense indoor networks for industrial applications operating in the THz regime are a prime candidate for a cell-free network.

As a steppingstone, one can always employ current positioning solutions in this new network paradigm: after a dynamic cluster has been established, one can treat this cluster in a similar fashion to the non-dynamic network. This on-top approach, although at first glance seems promising, may lead to a large increase in front and backhaul overhead, and/or an increase in the number of LMF nodes, as each time a change in the current dynamic clusters occur, the data paths of the measurements involved in the estimation of the UE's position also changes. Instead, new solutions where the computation is done in a dynamic distributed fashion are more interesting, leading to part-of-positioning approaches.

How would a distributed solution look like?

In recent years, closed-form algorithmic and machine-learning-based solutions for solving collaborative problems in a distributed fashion have gained attention. In particular, collaborative multi-agent methods that employ message passing approaches, such as payoff propagation [9], could provide a good starting point. Here, instead of aggregating all measurement data at one point, e.g., a non-dynamically located LMF, to calculate a position estimate, the data or functions thereof are passed as messages between the collaborating nodes only when needed, reducing overhead and allowing for a dynamic availability of the estimate.

Device-to-Device (Sidelink) Positioning

Why THz for direct communication (sidelink) between devices?

Device-to-device (D2D) communication or Sidelink is a key technology for vehicle-to-everything (V2X) communication. The motivation to use mmW and (sub)-THz for 6G sidelink/D2D communication is driven by the requirements for high data rates and low latency for the envisioned use cases, which can only be met by the bandwidths available in higher frequency bands. For instance, autonomous driving benefits from cooperative perception, where vehicles or devices share their sensing/imaging information with other devices directly without requiring a network. It is therefore expected that V2X communications will build a fundamental element for connected autonomous vehicles in future 6G systems.

Which problems need to be solved for the THz sidelink?

The transmission channel for frequencies in the THz range beyond 100 GHz, especially for sidelink communication between vehicles in the presence of high mobility, incurs a huge Doppler spread which in turn may lead to increased inter-carrier interference at high speeds. Another problem occurring at THz frequencies is the high path loss and blockage by obstacles, e.g., vehicles and buildings. Consequently, THz communication may be used efficiently only when using directional beam forming and / or over short distances under line-of-sight conditions.

Why is THz sidelink an attractive enabler for instant high-accuracy positioning?

When using sidelink between connected autonomous vehicles, especially for safety-related use cases, a cm-level accuracy ranging result coming in immediately is required for both absolute and relative positioning. This entails very high bandwidth requirements which can only be met using THz frequency bands. Furthermore, when directional beam forming is used to overcome the problem of high path loss and blockage by obstacles in the THz frequency range, the required beam management procedures (e.g., beam pairing, beam tracking, beam recovery) can be supported more efficiently by high-accuracy positioning of devices.

AI/ML for Enhanced Positioning

How can AI/ML support Positioning in 6G?

In the last few years, AI/ML-based systems have disrupted several industries in a wide variety of applications, ranging from autonomous driving to interactive, conversational web-search. Starting from Release 18, 3GPP standardization is actively exploring the integration of AI/ML models in air-interface-related use cases like beam management, direct and assisted positioning and Channel State Information (CSI) compression.

The envisioned benefits are two-fold. First, AI/ML-enabled positioning solutions achieve systematically higher positioning accuracy in challenging non-Line of Sight (NLOS) environments, both for direct positioning, where the model predicts the 3D location of a UE, as well as for assisted positioning, where the AI/ML model is used to extract useful information that would be used from a classical positioning algorithm (e.g., extracting the LOS path from CSI measurements).

To add to this, AI/ML models can address the complexity of beam management for positioning [8]. As envisioned 6G deployment scenarios are characterized by massive MIMO setups with large codebooks and dense deployments, the complexity of selecting the most suitable beams for positioning, from at least three APs for a high density of UEs in the area, becomes exponentially hard for classical methods.

What are the challenges?

The power that AI/ML models bring comes at a cost. A strong pre-requisite for their successful training is the availability of sufficient high-quality, labeled (meaning the real position is measured and is part of the dataset) data that are representative of the target area. This implies that organizations with the monetary budget, the knowledge and infrastructure already in place to collect substantial portions of labeled data, would have a huge advantage here. Novel approaches to reduce this dependency, such as channel charting [14], are now key topics in the research communities.

How can AI/ML be applied efficiently for Positioning in 6G?

One of the most prominent ways to democratize the adoption of AI/ML methods for positioning is the utilization of a simulator for pre-training several AI/ML models. Here, the models can be trained on a plethora of varying antenna configurations and topologies entirely with simulation data. When the models are deployed, they require only a small number of real-world data to adapt to the specific radio conditions of the application area. In fact, with techniques like active learning and transfer learning, targeted requests (e.g., per sub-region) for data collection and labeling can significantly relax the requirements on data availability.

Another important aspect that simulation-based pre-training implicitly addresses is the fragile generalization capabilities that AI/ML models often exhibit. Since such models are trained with data from target locations only, they learn to solve the local problem with high accuracy but are unable to provide acceptable performance in other areas, where the data vary. When the AI/ML models are trained on several different scenarios in simulation, they are robust enough to changes in the radio environment.

In addition, as with any other application that utilizes real-world deployed AI/ML models, the availability of an AI/ML model management component that monitors the performance of the model and can provide functionalities like switching between models depending on the radio environment conditions, deactivating the model once the radio environment has permanently changed making the model obsolete or even triggering data collection requests for model fine-tuning, is a cornerstone for the successful adoption of such models for positioning.

AI/ML will be a native functional element of 6G networks. In the special context of 6G positioning it actually provides huge benefits: the performance gain (in terms of positioning accuracy) AI/ML can bring in harsh NLOS environments with increased multi path propagation significantly outweighs the overhead cost of AI/ML model training and deployment. Also, considering the complex interplay of network components in dense 6G deployments, the integration of AI/ML is key to optimize the large number of parameters involved in enabling seamless coordination at network level.

Flexible Networks

What are key elements of 6G network flexibility?

As the world gears up for the next iteration, 6G, the network is poised to take another leap forward, expanding from local to global networks. With 6G, users can expect greater flexibility, as the underlying software technologies will allow for a more adaptive and scalable network infrastructure that can better accommodate the demands of the ever-growing number of connected devices [2], [3]. This does not only apply to the network itself, but also to the services offered by the network; a flexible and now vertical network must also include adapted positioning services that take advantage of this new paradigm.

Moving Radio Access Network (RAN) network infrastructure components as well as the support for non-GEO Non-Terrestrial Networks with their inherent mobility, means that the topology of the network itself is becoming highly dynamic. In these situations, to be able to understand the wireless environment and to be able to schedule the UEs appropriately to the different available RAN resources as well as to steer the RAN resources themselves requires dynamic and at the same time granular location mechanisms.
With this additional network flexibility, the location service in the network will be extended to support the following additional features:

- Self-positioning of mobile RAN components itself within the environment, especially in indoor environments where GNSS as external location sensor is not available. This positioning may only be relative to the other RAN elements within the environment.
- Additional positioning mechanisms to determine the location of the UEs, relative to flexible, even moving, RAN references.

How does a dynamic and flexible 6G network look like?

The dynamic network is an integration of space (satellite) network, air network, and ground (terrestrial) network, which features a high dynamicity (dynamic topology) due to the high mobility of the different segments of the network. The space network, which consists of multi-orbital satellites, e.g., GEO (Geostationary Earth Orbit), MEO (Medium Earth Orbit), and LEO (Low Earth Orbit) ensures a coverage and capacity enhancement at the expense of a higher latency and signal attenuation (low SNR). On the other hand, the ground network has a limited coverage, and it is difficult to be implemented in many places due to many restrictions. The air network, which mainly consists of airships, balloons, and UAVs operating at different heights, fills the gap between the space and the ground network and offers a high flexibility in providing services under different scenarios and requirements. As a result, the integrated space-air-ground network helps achieve the desired ubiquitous network accessibility as well as ultra-reliable and low-latency communications [12].

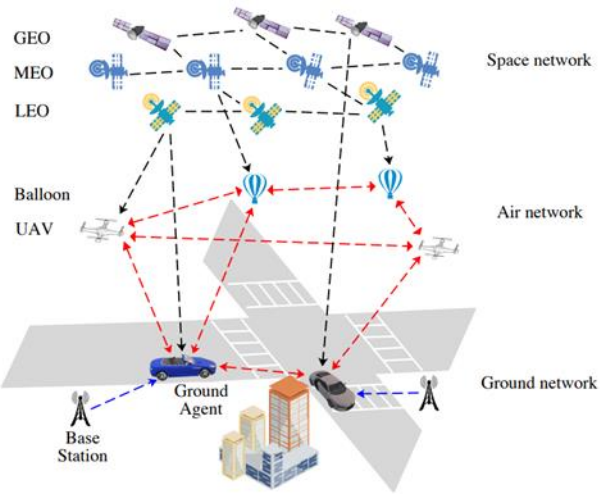

Fig 3. Example of a dynamic and flexible network that spans different vertical network topologies and enables positioning measurements via the mobile RAN components of the air and space networks

The dynamic nature of the integrated space-air-ground network is one of the challenges facing the integrated network when it comes to mobility management and traffic routing, as both the satellites and the flying objects in the space segment and the air segment respectively have a high mobility. Thus, determining the position of the satellites within the space network, as well as the UAVs, and other aircraft within the air network is important to ensure an optimal traffic routing between satellites on the ISLs (inter satellite links) and between the different segments of the network (space-ground, space-air, and air-ground, air-air) depending on the Quality of Service (QoS) requirements and the use cases. While the position of the satellites can be predicted based on different parameters such as the altitude and the velocity of the satellite (ephemeris data), the position of the flying vehicles in the air network needs to be determined by either having GNSS capabilities or by relying on the 6G space network or terrestrial deployment to take own positioning measurements.

The multi-level heterogeneous network consists of different network segments with different heights, which is beneficial when it comes to UE positioning applications on the ground, where a device can receive signals from multiple sources. This multi-source information can be used to determine the position of a device on the ground by measuring distances or directions (angles) from multiple reference points not only in 2-dimensions but in 3-dimentions (3D localization) [12]. As a major advantage, flexible networks potentially provide wider positioning coverage compared to terrestrial-only deployments through the naturally bigger signal illumination from aerial or space-based platforms.

Flexible Location Service Functionality

How does softwarization facilitate a Flexible Location Service Functionality?

The softwarization of the network functions brought a new level of flexibility which can be achieved in the placement of the network functions and their configuration towards the edges of the network.

With the adoption of near-real-time RAN management mechanisms such as the O-RAN Radio Interface Controller (RIC), many of the management functions which were typically located at the center of the network are pushed towards the edge in order to provide a localized fast response to environment changes. As many of these services are dependent on location services, such as coverage and network availability or interference management are reliant on the relative location of the base stations, or mobility management and subscriber QoS allocation have dependency on the relative location of the UEs, a new sort of localized location service needs to be included.

How can a Flexible Location Service be implemented?

This is possible through the immediate distribution of the current location service. However, it requires that many of the core network functions will also be placed at the edge of the network, especially the Access and Mobility Function (AMF) which leads to a highly distributed architecture and results in the deployment of a massive number of same network functions across the environment. To circumvent this, a new interface should be considered for the location services from the RAN itself, separated from the control plane interfaces.

Customized Services based on User Mobility Path

Starting with 5G, the network is not anymore able to handle all the users in a uniform and ubiquitous manner, especially due to the fragmentation brought by the highly divergent use case and deployment requirements. As such, dedicated networks either in the form of operator slices or as specially deployed campus networks are considered suitable complements or alternatives to a single macro-operator network.

What is required to create Customized Services?

To be able to further optimize the network beyond the uniform handling of the UEs, a better understanding of their network usage profiles is required. Specifically, in mobile networks, this includes next to the radio resources requested for the communication – the session and QoS profile – a mobility profile. However, as hinted in the previous section, the RAN is supposed to become highly dynamic through the mobility of the base stations as well as through antenna tilt, beam forming, and dynamic transmission power control. In these situations, the connectivity (i.e., to which radio head the device is connected) does not reflect anymore the position in the network as it may as well connect to another RAN in the same position at another moment in time.

To be able to still have a usable mobility profile, mobility paths should be determined including the prediction of immediate future locations as well as the likelihood that a device will follow a similar trajectory as in the past. With this, the network can prepare itself for the specific subscribers by scheduling appropriately the radio resources. This is especially beneficial in small-size networks such as factory shop floors where some devices may require extensive resources and may cause a denial-of-service for their neighboring devices, which could potentially be critical sensors not to be missed. All of that could happen due to automatic handovers of units such as virtual reality devices or complex digital twins based on multiple video cameras. A mobility path-based solution could proactively hand over critical devices to other alternative network slices or radio networks before taking care of the scheduling of the intensely consuming device. In general, understanding trajectory and speed can significantly influence and optimize the robustness of the network in mobility scenarios, as a better understanding of the user speed and direction can make target base station selection more appropriate.

How can Customized Services based on User Mobility Paths be implemented?

To reach this, historical positioning data of the devices may be stored in the positioning service and used to compute the mobility paths. The mobility paths would be then exposed to the access, mobility, and QoS management in the network to enable them to make more appropriate decisions as well as in an aggregate form to the RAN management functionality to adapt the network topology towards a better performance and lower energy consumption as well as to ensure more robustness.

Way Forward to Bring 6G Positioning to the End User

Further research is still required in various areas to bring 6G positioning to the end user. This includes developing new channel models that are spatially consistent to account for the unique challenges posed by the new physical layer technologies as well as the operational frequencies and bandwidths proposed for 6G. There is also a need for the definition of new network architectures that can support the high-speed and low-latency requirements of 6G positioning, which are expected to have much more flexibility compared to previous generations. Additionally, a review and update of existing procedures and protocols is required to ensure that a seamless integration of location services for 6G is possible. Finally, the development of new network functions, such as enhanced positioning algorithms and innovative data processing techniques, will be crucial in delivering accurate and reliable 6G positioning services to the end user.

Moreover, by linking the research to pre-product rollout activities, the development of 6G positioning technology can be optimized to meet the needs of the market and ensure its successful deployment and adoption. This includes further developing proof-of-concept demonstrations to validate the technology's performance and viability. This strategy applies to each of the key enabling technologies individually as well as using them jointly. The assessment is that only applying them in combination (all or substantial subsets) makes it possible to meet the outstanding expectations towards function and performance. The exchange between the research community and various industries is also important to make sure that 6G positioning meets the needs of the market. Additionally, conducting market studies and engaging with end customers, including different verticals, is crucial in understanding their needs and ensuring that 6G positioning meets their requirements. Consequently, not just technology validation is important but also early demonstration is vital within the envisaged 6G usage scenarios.

The standardization process in 3GPP guided by the recommendations of the International Telecommunications Union (ITU) on “IMT for 2030 and beyond” is expected to start around 2025. By this time, results of basic and applied research on 6G technologies will have reached a more mature and consolidated status required for assessment and selection during standardization. Already now, there are ongoing discussions about consideration of Integrated Sensing and Communications and Intelligent Reflecting Surfaces for 5G Advanced. If these technologies would become part of the later releases of 5G, the step from the fifth to the sixth generation of mobile communications may be even smoother as implied before.

In addition to the research and pre-product rollout activities, there are several other important aspects to consider in bringing 6G positioning to the end user. Regulatory aspects must be carefully evaluated. Ensuring data privacy and protection of location information is also crucial, as this information is extremely sensitive and must be kept secure. The development of 6G positioning technologies must also consider the principle of “access for all,” ensuring that the technology is available and accessible to everyone, regardless of their location or resources. Domain-suitable individual product life cycles, such as consumer-focused vs. industry-focused products, are also important to accomplish that the technology is optimized for the specific needs of each target market. Furthermore, ensuring energy efficiency and sustainability is one of the most urgent goals of our time for reducing the environmental impact of 6G. For sure, the availability of ubiquitous location information helps efficiently coordinate the network such that 6G positioning becomes key enabler for achieving sustainability.

Further reading

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