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PRS for positioning, navigation and timing (PNT) services

White paper

Positioning, navigation and timing (PNT) is used for a wide range of services including emergency services, critical infrastructure, defence, and commercial applications such as autonomous systems and agriculture. While GPS has often been employed to support PNT services, there are several challenges including weak signals, vulnerability to jamming, and limitations in precision. The 3rd Generation Partnership Project (3GPP) has standardized a new signal, the Positioning Reference Signal (PRS), to enable higher availability and precision. In this white paper, we introduce PRS, describe the 3GPP-defined architectural enhancements for PNT, explore different positioning techniques that use PRS, and outline the key use cases that benefit from PRS.

Contents

Executive summary

Positioning, navigation and timing (PNT) services using the Positioning Reference Signal (PRS) in the downlink are part of the 3GPP 5G-NR standards. In 3GPP Rel-15, where initial features of 5G-NR were proposed, positioning was specified as an overlay solution using 4G position reference signals. Starting from Rel-16, dedicated signaling for positioning specific to 5G-NR has been proposed. Further advancements to support positioning have been proposed in Rel-17 and Rel-18.

In this paper, we study the technical aspects of PRS and its integration into the 5G-NR signaling framework from Rel-16 to Rel-18, and we assess the technological feasibility and suitability of a 5G PRS-based PNT solution across multiple critical applications. PRS signals, specifically when transmitted at lower frequencies, have wide coverage, very good indoor penetration, and reliable signal quality. Thus, PRS-based positioning is versatile and is applicable to both indoor and outdoor positioning.

We describe the 5G-NR architecture as it pertains to the introduction of PNT solutions such as the introduction of the Location Management Function (LMF) and the new interfaces within the network required to support LMF. A key feature that has been introduced and used in 5G positioning is the transmission of PRS from the base stations to the UEs. We first provide a short description of the PRS signal structure. The PRS signal elements can be very flexibly configured within the time-frequency resources, allowing extensive access due to the wide coverage provided by 5G cellular networks and minimal infrastructure cost due to the wide-spread deployment of radio towers, which could be used for PRS transmissions.

Following this, we identify various positioning solutions supported within 3GPP and focus on those that use PRS. These solutions use either UE-based measurements of the PRS or network-based measurements of other parameters that additionally use the PRS to assist the LMF to accurately calculate the UE position. We delve deep into two of these PRS signals-based solutions: one uses time-difference of arrival (DL-TDoA), the other, an angle of departure (DL-AoD). Additionally, we look at a carrier phase measurement-based enhancement that applies to both solutions.

A continuous positioning solution can enable navigation of a user from one location to another. Different parameters may be exchanged between the UE and LMF to enable positioning. As part of the description of the DL-TDoA and DL-AoD solutions, we discuss these parameters and their role in positioning.

Finally, we consider the effect of various radio parameters on positioning accuracy, the ecosystem support that is needed for 5G positioning, and the use-cases in different industry verticals that are enabled by 5G positioning. Numerous use cases, including critical emergency response and disaster recovery, can benefit from the high accuracy positioning and timing accuracy provided by 5G-based positioning solutions.

Introduction to 3GPP positioning and the PRS

In 3GPP, the Position Reference Signal (PRS) was introduced to support PNT applications with the use of cellular infrastructure, which is widely available. Compared to techniques that use GPS signals that have indoor coverage limitations or signal reception issues in dense urban areas (due to tall buildings that may cause an "urban canyon" effect), PRS signals, particularly at lower frequencies (such as in the 900 MHz band) offer wide coverage, very good indoor penetration, and reliable signal quality. As a result, PRS-based positioning can be used effectively for both indoor and outdoor PNT applications.

PRS was originally proposed in 3GPP Rel-9 to provide positioning capability in LTE. This was designed to perform Observed Time Difference of Arrival (OTDOA)-based positioning where the PRS from multiple cells (radios) are observed and differences in arrival time at the UE are used. As specific subframes were dedicated to send the signals and can be transmitted with higher power, PRS from multiple cells interfered with each other and weakened the signal received at the UE, thus leading to what is referred to as the hearability problem. The density of PRS signals within an LTE frame in Rel-9 was also quite limited, which led to less frequent PRS measurements, weakening the correlation properties among the PRS received from different cells and reducing the positioning accuracy. The smaller bandwidth in LTE also affected positioning accuracy due to the reduced precision in timing measurements. In Rel-10, carrier aggregation was introduced, which led to the use of larger bandwidths, somewhat improving the timing measurement precision.

Because of the limitations outlined above, LTE PRS-based positioning gained little traction. PRS as specified in these earlier releases was mostly designed to be used by OTDOA-based algorithms; however, because of the hearability problem, it was not very reliable or accurate. The accuracy of TDoA-based algorithms was substantially improved starting from Rel-16 through proposed modifications to PRS transmissions.

In Rel-16, as part of standardizing 5G positioning mechanisms, the PRS specification was significantly improved to enable more accurate and reliable cellular-based positioning. The key enhancements included the following [1]:

1. Unlike in LTE where existing signals were repurposed, dedicated PRS signals with higher resource element density were proposed; this enabled higher positioning accuracy due to more frequent reception of PRS signals at the UE and higher correlation that can be achieved among PRSs from different cells
2. Specific PRS transmissions were defined to enable different cells to transmit non-interfering PRS patterns; this technique, which is referred to as "muting", eliminated PRS signal interference at the UE and the hearability problem that was present in LTE PRS
3. A few other positioning techniques using PRS were introduced including downlink time-difference-of-arrival (DL-TDoA), downlink angle-of-departure (DL-AoD), and the use of multicell round-trip-time (RTT) as measured between the UE and the different cells that transmit PRS
4. 3D positioning was also introduced in Rel-16 by using PRS measurements on intersecting 3D beams transmitted by different cells.

Figure 1. Evolution of positioning features in 3GPP

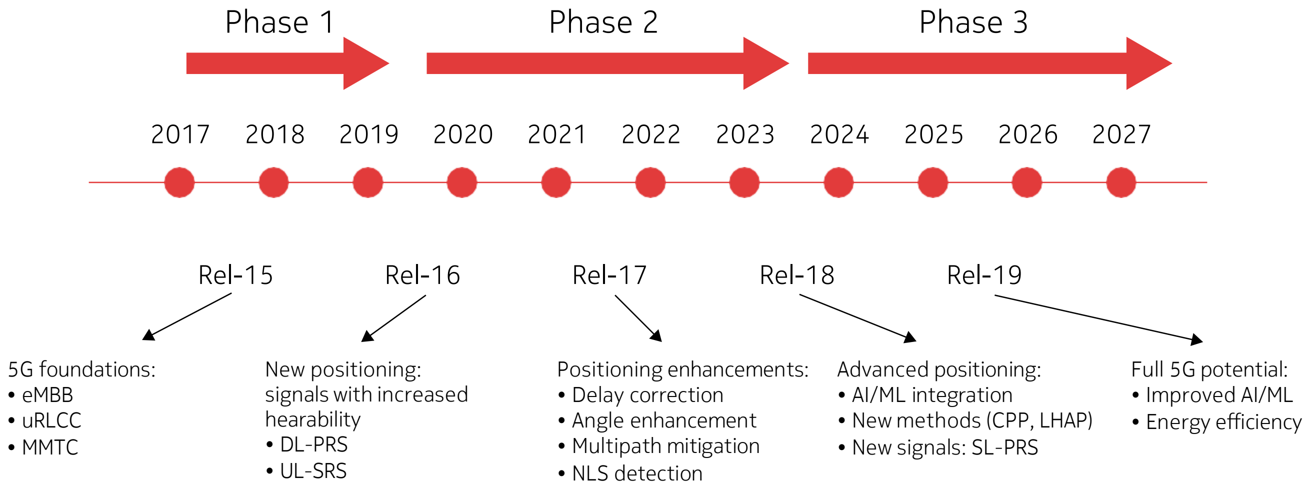


Figure 1 illustrates the evolution of 5G positioning features within the 3GPP standards at a high level. In 3GPP Rel-15, key components of the 5G standards with performance enhancements for data transport were introduced. However, this release applied only to the 5G NSA (non-standalone) mode of operation. Although a UE is connected to both a 5G radio and a 4G radio in the NSA architecture, the control signals from the UE were still sent over the 4G radio to a 4G core network. Because of this, no new positioning features were introduced that could provide more precise positioning than what LTE positioning techniques could provide.

Rel-16 specifications brought to bear the full capabilities of 5G through the introduction of the 5G-SA (standalone) architecture, which did not require a 4G anchor radio (as in 5G-NSA) to aid 5G connectivity and defined the requirements for a 5G-NR (New Radio) architecture. As part of Rel-16, a new PRS was defined that could be used by multiple positioning techniques, as described above.

Further advancements have been made in Rel-17 to make positioning even more precise. Although PRS signaling, as specified in Rel-16, has not been modified, additional mechanisms have been put in place that include advanced network and device-based positioning techniques. In Rel-16, direct device-to-device communication, referred to as 5G sidelink communication, was introduced to enable UEs to connect to a network under partial coverage or enable the formation of an ad-hoc network among the UEs [2]. Enhancement of 5G sidelink in Rel-17 included additional features to support UE positioning using PRS. This is an important addition to 5G sidelink as positioning is critical in ad-hoc network-type applications where network availability is limited. Both TDoA and received power levels are used in combination to measure the distance and direction between two devices. Although 5G sidelink positioning by itself can support only the determination of relative position between two devices, it could be augmented with absolute position information of a known anchor UE. A single anchor UE's absolute position is sufficient to determine the absolute position of each of the devices in the ad-hoc network. Rel-17 has additional latency reduction enhancements, including support for positioning in time-critical use cases.

Multiple enhancements have been made to 5G positioning in Rel-18. These include:

- Positioning for RedCap (reduced capability) devices, which allows for PRS reception on a wider band than what the device can support through frequency hopping
- Further enhancements to 5G sidelink positioning with PRS
- Accurate positioning for low-power systems through PRS reception in idle mode
- Bandwidth aggregation across multiple frequency layers to transmit PRS over a wider band
- Carrier phase positioning (CPP) using PRS.

From the perspective of PRS-based positioning, carrier phase positioning is a new enhancement that can be combined with any PRS-based positioning solution. In this enhancement, the distance between the base station and the UE is computed as a function of the carrier phase of the received PRS signal, which is then used within the positioning algorithm. Measurements on the received signal carrier phase (RSCP) and the received signal carrier phase difference (RSCPD) are used for this purpose.

In addition, Rel-18 positioning has been considered from the perspective of very specific uses cases. These include improving the distance ranging performance as part of 5G sidelink communication with improved accuracy, integrity and power efficiency, and IoT device positioning using RedCap IoT terminals. PRS-based 5G sidelink positioning could become an important component for the automobile industry to continuously monitor the distance between vehicles on a road, specifically in cases where GNSS may not be available, for example, in tunnels, urban canyons, underground parking, etc. In these cases, to convert relative positions of vehicles to absolute positions, Roadside Units (RSUs) whose absolute position is known a priori, could be used. Going forward, we expect the introduction of AI/ML techniques and continuous enhancement to improve the accuracy of 5G positioning methods.

With 3GPP initiating the development of 6G standards starting from Rel-20, it is highly likely that 6G would provide PRS signals for positioning like in 5G/5G-Advanced, however, the standards have not been developed yet [3, 4]. These signals are expected to be used for positioning using techniques like those used in 5G such as DL-TDoA, DL-AoD and CPP.

3GPP architectural enhancements to support PNT services

There has always been interest from the cellular technology community in providing localization methods to identify the position of a user device. Much headway has been made over the years, and the goal has always been to reach the best positioning accuracy possible— within the constraints of the positioning mechanism used, the morphology of the terrain for outdoor positioning, and the challenges posed for indoor positioning by clutter. The previous section provided a detailed background on the introduction of specifications, techniques and features that have been incorporated into different versions of the standard cellular technology. Especially when deployed in low bands, this technology can provide a comprehensive level of positioning due to its wide reach, both indoors and outdoors, including areas not covered by GPS or with very weak GPS signal reception. In fact, PRS-based positioning techniques are designed to provide better positioning accuracy than standalone GNSS solutions in indoor environments where GPS signals could be weak or unavailable and in outdoor dense urban areas where the GPS signals could be reflected, refracted or even completely blocked. In such situations, 5G base stations can overcome signal obstruction to provide high-quality PRS signals for positioning.

In the rest of the section, we consider the overall positioning architecture that includes the 5G RAN and the core network. The 5G-NR core network is based on a service-based architecture (SBA) that consists of multiple network functions (NFs) that can communicate over the SBA bus. It became convenient to add a location management function (LMF) as an NF to handle measurements received from the UE and the NG-RAN (next-generation RAN) to compute the position of a UE. A new protocol called NG-RAN Positioning Protocol A (NRPPa) has been introduced in 5G to carry information from the LMF to the NG-RAN and from the NG-RAN to the LMF [5]. The LTE positioning protocol (LPP) is used to send configuration information for signal measurement from the LMF to the UE. The architectural modifications, the additional NFs involved in enabling the communication to/from the LMF, and the new interfaces that have been put in place to support this communication, are detailed in 3GPP TS 38.305, Version 18.6.0 [6].

Figure 2. NG-RAN core components specific to positioning

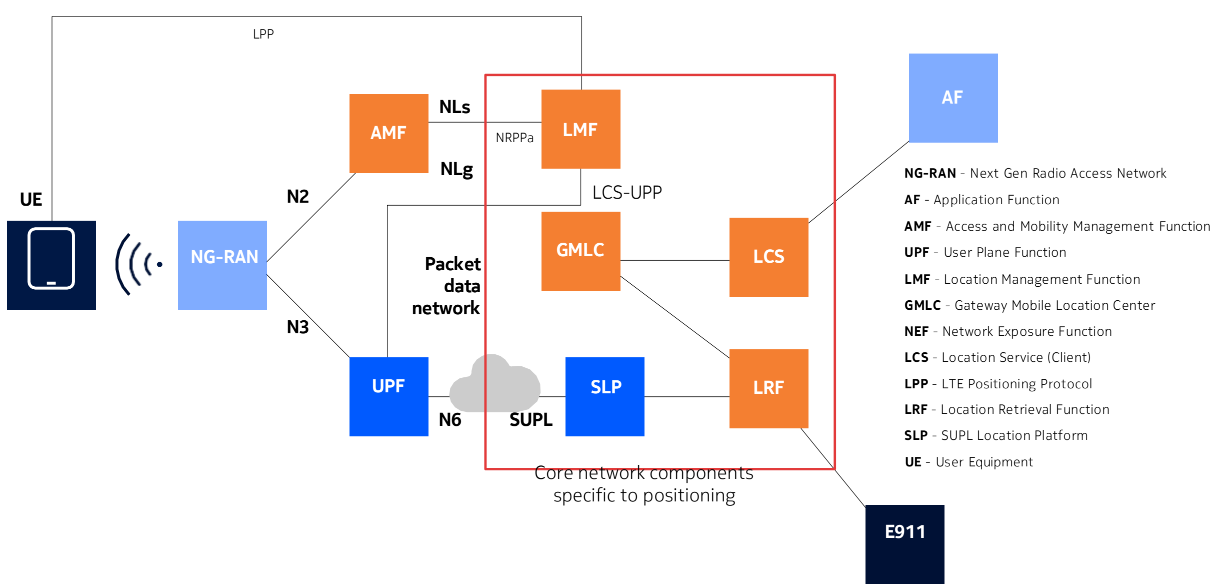


Figure 2 shows only the essential elements of the NG-RAN and the core network that enable the positioning features. As we will see in a later section, the location management function (LMF) is a key component. It communicates with the UE connected to the RAN to provide assistance information that helps the UE perform measurements on the PRS signal and collect the appropriate data required for positioning. This collected information is used by the UE to perform positioning locally (in case of UE-based positioning) or sent to the LMF (in case of UE-assisted positioning) to further process the data and execute the positioning algorithms. When an application (AF) requires the position of a UE, it communicates with the Location Service (LCS) within the core network, which then contacts a location gateway referred to as the Gateway Mobile Location Center (GMLC). The GMLC, through the AMF, retrieves the position of the UE and returns it back to the application.

When the position of a UE is required in an emergency, the data plane could be activated using the Secure User Plane Location (SUPL) protocol through the SUPL Location Platform (SLP) to communicate with the UE to make a request for its position. In the United States, SUPL-based positioning is primarily used during an emergency call (such as a 911 call) to locate a user. Different control plane-based positioning methods could be used as well during an emergency, however, SUPL protocol serves as a timely and flexible mechanism for positioning requests to be sent to the UE. The UE then follows the usual process for exchanging the position information. It either sends its locally computed position (in case of UE-based positioning) or sends the data required for the LMF to compute the position-based on radio measurements of the PRS signals (in case of UE-assisted positioning). The LMF sends the position information through the AMF to the GMLC, which in turn provides this to the location retrieval function (LRF), which serves as the client interface between the emergency application and the positioning platform.

The goal of this section is only to provide a high-level view of the positioning architecture in 3GPP. Call flows and related information can be found in 3GPP TS 38.305, Version 18.6.0.

Advantages of using PRS for 5G-NR positioning

The use of PRS in 5G positioning provides several advantages as listed below:

- The PRS signal elements can be very flexibly configured within the time-frequency resources in what is known as a comb pattern. Because different patterns lead to different positioning accuracy, when data traffic is low, PRS patterns can be made denser to make positioning more accurate. Further, different comb patterns could be used by the different base stations that transmit PRS to a UE (where each base station multiplexes the PRS on different symbols and subcarriers), thereby avoiding interference among them. As PRS transmissions can modify their periodicity depending on the environment and use case, 5G positioning using PRS is very versatile.
- PRS can adjust its bandwidth usage to achieve the target accuracy and can even use the full bandwidth of 5G-NR if needed. Additionally, as PRS signals are transmitted over multiple symbols and can be aggregated together, the received power can be improved thus improving coverage and quality by suppressing interference of any transmission by other base stations on the same symbol.
- PRS can be beamformed by a base station to improve its signal quality.
- Because PRS is a dedicated signal with flexible time-frequency configuration and potentially wide bandwidths, it also enables more accurate time measurements.

Within a 5G-NR physical resource block (PRB), PRS is sent over different sub-carriers in a pre-specified (i.e., comb) pattern. When a multi-transmit-receive point (TRP) configuration is used, these patterns are chosen so that the PRBs that carry PRS from different base stations do not interfere with each other at the UE. The number of sub-carriers allocated to a PRS is configurable, and some of the transmissions can be muted to further reduce interference. The PRS comb pattern and muting features improve the hearability of PRS and enable a multi-TRP configuration based on existing 5G deployment grids without requiring positioning specific densification. In this section, we provide an overview of PRS patterns and their integration into 5G-NR frames [7].

Figure 3. PRS comb patterns within a 5G-NR physical resource block

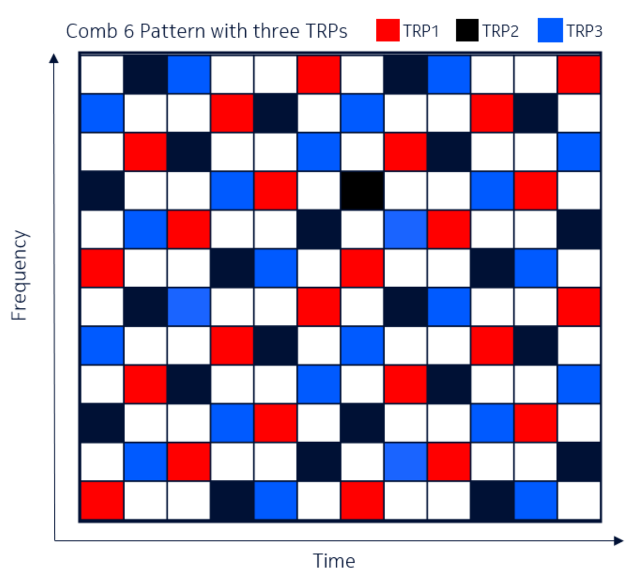


Figure 3 shows a 5G-NR physical resource block in time and frequency that are sent synchronously from three different TRPs. Some of the time-frequency slots are used to send the PRS signals. The PRS transmissions are in the form of a comb-like frequency structure as seen in the figure which means every Nth subcarrier is utilized to send out the PRS from each TRP. The length of the PRS within one slot is a multiple of M symbols (a column in figure 3) and the position of the first symbol within a slot is flexible. The comb value (N) could be 2, 4, 6 or 12. The figure shows a transmission where the comb value is 6, where each TRP sends the PRS signals every six subcarriers. In the figure, within each slot, we see twelve PRS symbols being transmitted and the transmissions from the different TRPs are staggered appropriately (by keeping the PRS transmission pattern separate for each TRP) so they do not interfere with each other. The UE is provided assistance information by the LMF to be able to parse a PRB and be able to separate and extract the PRS signals from each of the TRPs.

One question that may arise is why have separate PRB signals for positioning while there are other synchronization signals that are already being sent in the downlink from a gNB (TRP) to a UE? There are synchronization signal blocks (SSBs) that are used in 5G-NR to synchronize a TRP with a UE. The reason is that the SSBs are not optimized for positioning use. SSBs have limited bandwidth, cannot be configured to create patterns as in PRS transmissions, and have a fixed transmission structure. A summary of comparison between SSB and PRS is provided in table 1.

Table 1. Comparing SSB with PRS in 5G-NR

Comparative parameter	SSB	PRS
Primary purpose	Timing synchronization	Downlink positioning (DL-TDoA, DL-AoD)
Resource allocation	Limited (could be staggered among TRPs, however cannot be changed)	Highly flexible (fully configurable across both time and frequency to limit interference)
Available bandwidth	Narrow (limited to 20 resource blocks)	Can use wide bandwidth
Transmission timing	Fixed transmission	Configurable timing
Flexibility in adjusting periodicity	Limited	Highly flexible
Multipath robustness	Low	Highly robust (multi-layer PRS)
Beamforming support	Limited	Flexible availability

This is the reason that 3GPP decided to propose a new signal (PRS) with the required flexibility and robustness to handle very accurate positioning requirements and, so far, PRS is living up to its promise. In the next section, we list the various 5G positioning techniques and then provide a detailed discussion of two key examples that use PRS, namely DL-TDoA and DL-AoD.

Techniques for 3GPP-based positioning using PRS

A multitude of positioning techniques have been specified in the 3GPP standards and described in 3GPP TS 38.305, Version 18.6.0. Some of the ones specific to 5G-NR positioning include Downlink Time Difference of Arrival (DL-TDoA), Downlink Angle of Departure (DL-AoD), Multi-cell Round Trip Time (RTT)-based positioning, Enhanced Cell ID (E-CID)-based positioning, Uplink Time Difference of Arrival (UL-TDoA) and Uplink Angle of Arrival (UL-AoA). Of these, the DL-TDoA and the DL-AoD mechanisms could be either UE-based or UE-assisted and use specific measurements only on PRS signals; we provide focused discussion on these techniques later in this section.

Before we consider 5G positioning that uses only PRS, let us consider the various positioning mechanisms shown in table 2 to get a nuanced understanding of the mechanisms used. Positioning techniques that are classified as UE-based are those where the UE performs local measurements and can compute its position by itself. The techniques that are classified as UE-assisted/LMF-based are those where the UE measures parameters and sends them to the LMF, however, the UE does not compute the position itself and lets the LMF compute the UE position [8]. As seen in the table, some of the techniques could be both UE-based and UE-assisted in that, depending on the UE capabilities, the UE can compute the position on its own or may only be able to assist the LMF in determining the position, where the computation is performed at the LMF only. Within these two categories, there are two further sub-categories. One is where the positioning method requires only UE measured features (shown within the red box denoted as “UE specific features”), and the other where measurement information from both the UE and the gNBs are needed (shown within the blue box denoted as “UE-related features”). The positioning techniques that need measurement information from the gNB are listed under the category of NG-RAN-assisted technique.

Table 2. 5G positioning mechanisms

Method	UE-based	UE-assisted LMF-based	NG-RAN Assisted
DL-TDoA	Yes	Yes	No
DL-AoD	Yes	Yes	No
Multi-RTT	No	Yes	Yes
NR E-CID	No	Yes	Yes
UL-AoA	No	No	Yes
UL-TDoA	No	No	Yes

UE-specific features (red box)   UE-related features (blue box)

As the focus of this paper is on the use of PRS for positioning, in the rest of the section, we will focus on the two positioning techniques that require only UE-specific features, both of which use measurements based on only the PRS signal received from the gNB [9].

DL-TDoA-based positioning

Downlink Time Difference of Arrival (or DL-TDoA) uses the time difference in arrival of a PRS signal sent by multiple base stations (also referred to as transmission/reception points or TRPs) and whose geographic coordinates are known. This is a positioning scheme specified in Rel-16 of the 3GPP standards.

The received PRS signals from the different TRPs are used by the UE to perform what is referred to as downlink reference signal time difference (DL RSTD) measurements. Either these measurements or the time stamps required to perform these measurements are then sent by the UE through the uplink to the location management function (LMF). Additionally, the times at which the PRS signals are measured at the UE are also sent to form a frame of reference, in case the clock at the LMF is not precisely synchronized with that at the UE. Optionally, the reference signal received power (RSRP) of the PRS signal from each TRP, referred to as DL-PRS-RSRP, can also be measured and sent to the LMF. The DL RSTD and the DL-PRS-RSRP measurements, together with the known geographical coordinates of the TRPs, are used by the LMF to determine the position of the UE. For the UE to measure the relevant parameters, the LMF indicates the identification of the TRP whose PRS signals should be measured and information about what measurements to take.

In the following, we further investigate some of the information that may be transferred from the LMF to the UE as part of the LMF assistance provided to the UE for measurement purposes and the measurement results that may be sent from the UE back to the LMF for position calculations.

Information sent from LMF to UE for DL-TDoA

As mentioned earlier, DL-TDoA-based positioning computation can either be performed at the UE (UE-based) or at the LMF (UE-assisted) where the UE sends the appropriate information to the LMF to perform the computation. The Yes and No indicators in table 3 show a subset of the information specific to positioning that is being exchanged for DL-TDoA. The table also shows whether specific assistance information is needed at the UE or not depending on whether it is performing the calculation or only assisting the LMF in performing the calculation.

Table 3. Assistance information sent from LMF to UE for DL-TDoA-based positioning

Information	UE-assisted	UE-based
Physical cell IDs (PCI), Global cell IDs (GCI) ARFCN, PRS IDs of candidate TRPs to be used for measurement	Yes	Yes
Time at other TRPs (candidate TRPs) relative to the serving TRP	Yes	Yes
DL-PRS configuration of the candidate TRPs used by the UE for measurement	Yes	Yes
Time-frequency occupaion of the SSBs (synchronization signal blocks) at the candidate TRPs	Yes	Yes
Spatial direction of the DL-PRS resources from the candidate TRPs	No	Yes
Geographic location of the TRPs (which includes reference location of the transmitting antenna of the reference TRP, which is mostly the serving TRP, as well as the other TRPs)	No	Yes
PRS-only TP (Transmission point) indication	Yes	Yes

Let us now consider in more detail the assistance information that is listed in table 3 and its utility.

Physical cell ID (PCI), Global Cell ID (GCI), ARFCN, PRS ID

The PCI and ARFCN (Absolute Radio Frequency Channel Number) for each TRP indicates the physical cell and frequency on which the PRS is sent. The PRS-ID specifies the sequence in which the PRS signals are sent, and this needs to be known to the UE to identify the location of the PRS signals when they are sent by the TRPs. The GCI provides global identifiers of the candidate TRPs, which are used to identify the TRP geographical coordinates and to ultimately carry out triangulation for positioning estimates.

Time at candidate TRPs relative to the serving TRPs

As the PRS signal from the serving TRP is normally used as the reference TRP, the relative time at the other candidate TRPs is required to be sent to the UE to compensate for any clock drifts at the candidate TRPs and make DL RSTD measurements as accurate as possible. Time differences in the clocks between the serving TRP and the other candidate TRPs could lead to not-insignificant errors in position calculations.

DL-PRS configuration of the candidate TRPs

This information is needed in addition to the PRS-ID. The DL-PRS configuration provides information associated with a specific PRS-ID. This includes information such as the bandwidth, periodicity of the PRS signal, and how the resources are allocated, so that the location of the PRS within the radio frame can be identified by the UE.

Time frequency occupation of the SSBs

In addition to PRS ID and DL-PRS configuration parameters, synchronization signal block (SSB) information is needed at the UE to be able to synchronize with the candidate TRPs to get the timing and frequency reference of these candidate TRPs. Without this information, the UE will not be able to sync up with the candidate TRP, align correctly with the PRS signals when received from these TRPs, and measure them correctly.

Spatial direction of the DL-PRS resources from the candidate TRPs

This information is used predominantly in positioning techniques-based on Downlink Angle of Departure (DL-AoD)-based techniques, however, it can be used in hybrid solutions that have been designed to use a combination of DL-AoD and DL-TDoA techniques. Normally, such hybrid schemes are not used in UE-based positioning methods, thus they are limited to UE-assisted positioning at the LMF.

Geographic location of the TRPs

This information is included in the assistance data if the positioning is UE-based. In general, the position of the UE using DL-TDoA is eventually carried out by estimating the range of the UE from each of the TRPs. This range could be specified as a point on a curve on which the UE is estimated to lie. This estimate is computed using the DL RSTD values that are computed. A triangulation or multilateration technique is then used to determine the position of the UE-based on the geographic location of the TRPs and the estimated range of the UE from the TRPs. In the case of UE-assisted/LMF-based positioning, only DL RSTD information is needed from the UE as the LMF can calculate the ranges and, together with its knowledge of the coordinates of the TRPs, can determine the position of the UE.

PRS-only transmission point indication

There could be TRPs deployed to only send PRS signals. These are termed as PRS-only TRPs. Although such deployments may be very rare, and indication as to whether a TRP is meant only for this purpose could also be sent to the UE as assistance information by the LMF. From the UE perspective, an advantage of receiving this indication is that now it can prioritize these TRPs from the candidate set to synchronize, receive and process PRS signals without spending time and energy on other TRPs in the set.

Using the assistance information provided by the LMF, the UE measures a set of radio parameters required to perform positioning at the UE. In cases where assistance information is not available to the UE (such as the geographical location of the TRPs), the UE cannot calculate its position by itself and thus depends on the LMF to perform that function; the positioning method becomes UE-assisted and measurements at the UE need to be sent to the LMF.

Information sent from UE to LMF for DL-TDoA

In table 4, we list the data that is measured and sent back for the DL-TDoA-based solution, as required if the positioning computation is UE-assisted or UE-based followed by a description of these measured data and their utility.

Table 4: Measurement information sent from UE to LMF for DL-TDoA positioning

Information	UE-assisted	UE-based
Latitude, longitude, altitude and uncertainty shape	No	Yes
PCI, GCI, ARFCN, PRS resource ID set ID and PRD ID for each measurement	Yes	No
DL RSTD measurement	Yes	No
DL-PRS-RSRP measurement	Yes	No
Time stamp of the measurements	Yes	No
Time stamp of location estimate	No	Yes
Quality of measurement for each measurement data sent	Yes	No

Latitude, longitude, altitude and uncertainty shape

This is applicable only with UE-based positioning where the position of the UE has been determined locally and sent to the LMF. Besides the X and Y coordinates denoted by the latitude and longitude, the altitude information is also calculated and sent. The calculation of the altitude is not possible simply through the DL-TDoA method. Thus, when the DL-TDoA method is used on its own for position calculation, barometric sensors can be used to measure the pressure differential between sea-level and the pressure at the UE, which is used to calibrate and estimate the altitude. Regarding the uncertainly shape, in some cases, the UE could create an uncertainty area within which the real position might lie. This uncertainty area can be significantly reduced by comparing and adjusting the barometric pressure data against reference stations. This shape could be computed using an error radius-based on confidence intervals for the position measurement.

DL RSTD and DL-PRS-RSRP

These measurements using the PRS are sent back to the LMF if the positioning is UE Assisted.

Time stamps of the measurements

The time stamps of the measurements are sent only if the positioning is UE-assisted. These time stamps are needed at the LMF to compute the DL RSTD.

Time stamp of location estimate

If the positioning is UE-assisted, the time stamp at which the position is determined at the UE is sent back to the LMF for record keeping.

Quality of measurement

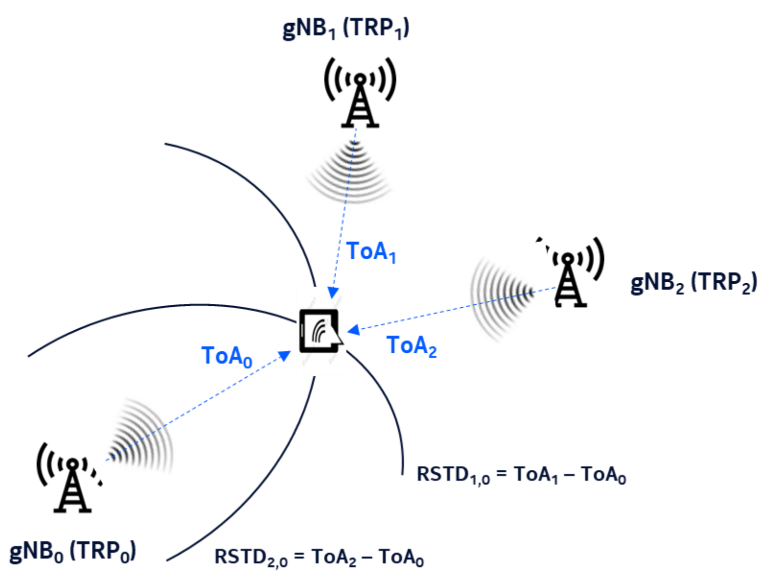
To indicate the level of confidence that the UE has in its measurements, when the DL-TDoA technique is used to compute the position at the LMF (UE-assisted), the UE sends an indication on a prespecified scale regarding the timing measurement quality. If the LMF is not satisfied with the quality of data, it can wait for the next round of DL-PRS-based measurements to be collected at the UE. This is useful in cases where a UE is being continuously tracked and instantaneous position information is not always required.

It should be noted that the 3GPP standards only specify the positioning architecture, the entities involved in positioning, and the information exchanged between these entities that is needed to execute the positioning algorithms. However, the details of how positioning techniques (including those that use DL-TDoA or DL-AoD) are implemented are left open, enabling different vendors to develop their own algorithms and differentiate themselves through the positioning accuracy they provide [10].

Computing UE position using DL-TDoA, an example

The example in figure 4 shows the computation of position using a TDoA method based on reference signal time difference (RSTD) at the UE between multiple PRS signals received from different TRPs. The RSTD is used to perform multilateration or trilateration on a set of hyperbolas that are created using the RSTD estimates. To avoid a synchronization error in RSTD measurements, the base stations (TRPs) transmit the PRS in a synchronous fashion.

Figure 4. DL-TDoA-based positioning, an example



The RSTD value obtained for a pair of TRPs corresponds to a hyperbola equation on which the UE is assumed to be located, with foci located at these TRPs. A set of hyperbola equations are deduced from a set of RSTD values, and the equations are solved to estimate the UE position. This process is called hyperbolic multilateration. The multilateration process involving one reference TRP and two neighboring TRPs is called trilateration, which is the minimum requirement for UE positioning in two dimensions. The hyperbolas are computed using the RSTD values so that they make up a set of points that mimic the constant delay difference between TRPs and are plotted relative to known TRP positions. The intersection of these hyperbolas is computed to estimate the position of the UE. It is possible there could be ambiguity due to the hyperbolas meeting at multiple points. However, adding more TRPs reduces this probability for the time difference of arrival (TDoA) problem. This example focuses on the 2-D positioning estimate of a UE by assuming that all TRPs are synchronized.

Figure 4 shows the positioning scenario with one reference TRP, which functions as the serving TRP, and two neighboring TRPs. The UE receives the PRS signals transmitted by all the TRPs at different timing instances (TOA0, TOA1, and TOA2) based on the geographic distance and channel environment between the UE and TRPs. From this network of three TRPs, the system obtains two RSTD values from the time of arrival (TOA) values. Each RSTD value corresponds to a hyperbola equation, on which the UE is assumed to be located. One can solve these two hyperbola equations to get UE position in 2-D.

DL-AoD-based positioning

Downlink Angle-of-Departure is another positioning technique that was specified in 3GPP Rel-16 standards. In this technique, PRS signals are received from multiple TRPs (as in the DL-TDoA) method, however, each TRP now sends the PRS over multiple beams towards the UE. The UE determines, for each TRP, the beam on which it received the PRS with the highest RSRP. The angle of the strongest beams of each TRP combined with the knowledge of TRP locations determine the estimated position of the UE. Note that if timing information is known, the time of flight (and the associated pairwise distances) between the UE and the strongest TRP beams can be used as supplementary information to improve positioning accuracy.

The assistance information sent from the UE to the LMF to compute the UE position using the DL-AoD method is shown in table 5. It is largely similar to that used for the DL-TDoA technique as shown in table 4 with the primary difference being that DL RSTD is not required.

Table 5. A subset of measurement information sent from UE to LMF for DL-AoD-based positioning

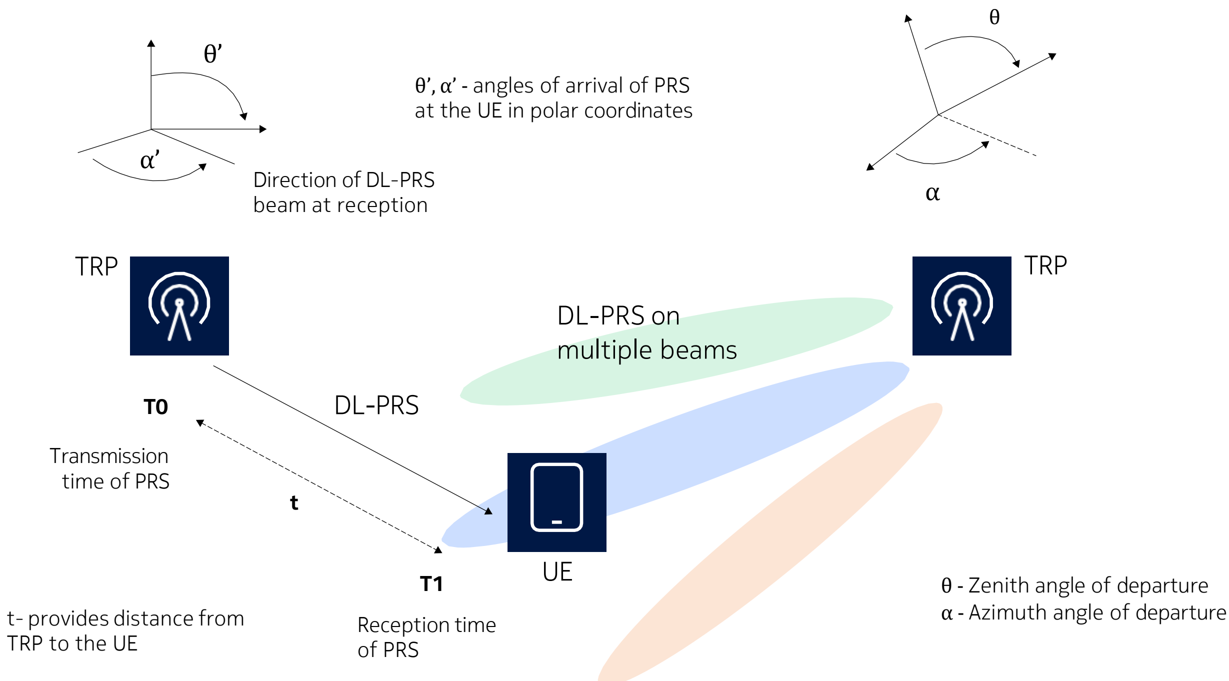
Information	UE-assisted	UE-based
Latitude, longitude, altitude and uncertainty shape	No	Yes
PCI, GCI, ARFCN, PRS resource ID set ID and PRD ID for each measurement	Yes	No
DL RSRP measurement	Yes	No
Time stamp of the measurements	No	No
Time stamp of location estimate	No	No
DL-PRS receive beam index	Yes	No

All the parameters in the above table, except DL-PRS receive-beam index, have been described earlier. The beam index is provided to determine the angle between each respective TRP and the UE.

Computing UE position using DL-AoD, an example

Figure 5 shows an example of DL-AoD positioning. Two TRPs are shown that send PRS signals using different beams. The beams are characterized by their azimuth and zenith angles. For illustrative purposes, only the beams sent by one of the TRPs is shown. The UE measures the beams on which the PRS signal is received from each of the TRPs. The beam indices of the received beams together and their respective RSRPs are sent back to the LMF, which then uses this information to compute the position of the UE. For triangulation purposes, at least PRS signals from three TRPs must be received on different beams and the required measurements made on them. It is also possible for DL-AoD to be UE-based, and the computation performed locally. This would require the UE to know the location of all the TRPs. Note that it is also possible to use timing information, if available, to estimate the time of flight (and ultimately the distance between the UE and TRPs) to enhance the accuracy of AoD positioning.

Figure 5. DL-AoD-based positioning, an example



Carrier Phase Positioning (CPP)

In Rel-18, a new 5G positioning enhancement technique has been introduced that is referred to as Carrier Phase Positioning (CPP). Based on the PRS received at the UE, it either uses the following information to help compute the position locally or sends this information to the LMF for it to compute the position of the UE. This enhancement is expected to be used in conjunction with other PRS-based positioning techniques:

- The reference signal carrier phase (RSCP) of the PRS signal when received at the UE and the time difference between the Tx time of the PRS at the TRP and the Rx time of this signal at the UE (UE Rx-Tx).
- The reference signal carrier phase difference (RSCPD) of the PRS signal when received at the UE and the time difference between the Tx time of the PRS at the TRP and the Rx time of this signal at the UE (UE Rx-Tx).

The RSCP provides the estimate of the phase of the carrier when PRS is received by the UE, however, it provides an estimate of the distance from the TRP to the UE based only on that cycle. Thus, there is an integer ambiguity, which is the total number of cycles before this specific cycle that have elapsed before the PRS signal was received at the UE. Thus, carrier phase measurement by itself cannot be used to compute the UE position. Thus, a UE needs to report carrier phase measurement and add other measurements such as RSTD or UE Rx-Tx measurements. These measurements can then be used to resolve the integer ambiguity and determine the distance between the TRP and the UE. These measurements from three or more TRPs can then be used to perform multilateration to compute the position of the UE. Although RSCP, together with either RSTD or UE Rx-Tx, is sufficient for positioning at the UE, RSCPD can be used to enhance the positioning accuracy by reducing what is the known as the receive phase bias at the UE.

5G-NR parameters that influence positioning using PRS

Multiple techniques discussed in the previous section depend on time delay, angle estimates and smaller variation in angle of departure of the received PRS signal from the transmission points (TRPs). There are five key points to note: carrier frequency, number of antennas, density of PRS symbols and subcarrier spacing (SCS), time synchronization, and bandwidth [11].

Carrier frequency

At lower frequencies, 5G positioning is more reliable especially in indoor environments where the penetration loss of the signals transmitted by base stations is low. For indoor positioning that requires positioning only in the order of a few meters, it would be preferable to use PRS transmitted in the lower band such as 700 MHz and 900 MHz.

Number of antennas

Large antennas arrays at the TRP would enable PRS signals to be sent over finer beams, leading to a large number of beams over which the PRS signal could be sent. This would increase the accuracy of measurement of the angle of departure of PRS signals (from the TRPs) as measured at the UE, which in turn would lead to more accurate DL-AoD-based positioning.

Density of PRS symbols and subcarrier spacing (SCS)

If more PRS symbols are sent, the real-time accuracy of positioning an object would improve. However, this would come with increased overhead. This trade-off needs to be considered carefully. Larger SCS leads to better time resolution making time measurements more accurate, which in turn makes positioning accuracy higher. However, this also comes with reduced signal robustness.

Time synchronization

5G-NR provides techniques for very fine time synchronization among the TRPs and between the serving TRP and the UE for methods such as DL-TDoA.

Bandwidth

The time delay error variance of a signal decreases in the order of the square of the bandwidth as the bandwidth increases. Because of this, 5G-NR provides much better time delay measurement of PRS signals, improving DL-TDoA-based positioning technique.

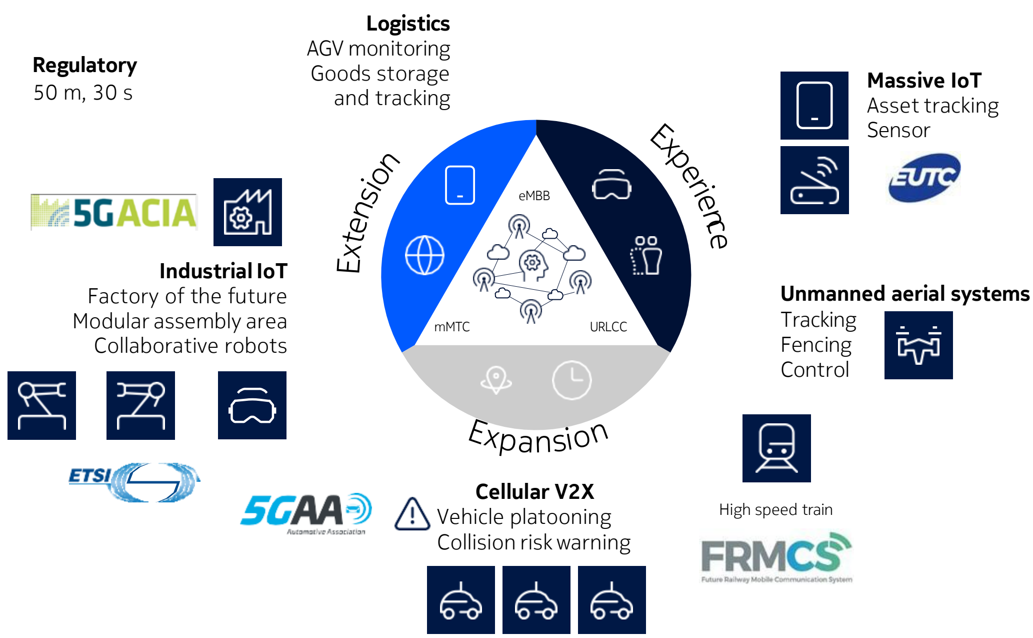
Key use cases that benefit from PRS-based positioning

The success of a new technology such as PRS is borne out by the use cases that leverage the advantages and the ecosystem that forms as a result.

Regarding ecosystems, the ecosystem needed to support and sustain PNT solutions using 3GPP-based solutions would need to involve multiple parties. These include chip manufacturers, designers of sensors that may complement PRS-based solutions, manufacturers of communication modules and other components, device vendors that cover UE, base stations, and network elements, mobile operators, PNT solution vendors, vendors that use PNT information to create value-add applications and services, integrators of these services into field environments, and many others.

Numerous use cases can benefit from the high accuracy positioning and timing accuracy provided by 5G-based positioning solutions as shown in figure 6. These run the gamut of application areas that include industrial automation and logistics, V2X, collision risk warning, emergency response and disaster recovery, drone tracking, and smart city applications. Specific applications include positioning solutions for industrial automation, robots, drones, and other types of autonomous vehicles, navigation solutions for emergency services and route planning, fleet and supply chain management and time synchronization required for low latency closed-loop control applications across wide areas such as those in the utility sector.

Figure 6. 5G positioning use cases [12]



A key list of very important and sometimes life-saving applications that we believe could only be supported by 5G positioning is provided below. These include both indoor and outdoor applications [13, 14].

Emergency response

5G positioning can provide much more accurate positioning with precise horizontal and vertical location information of an individual, vehicle or key asset. Complemented with route planning of the emergency vehicles, 5G positioning can provide end-to-end service for responders to quickly reach an individual in distress and need of help.

Disaster recovery

In disaster recovery situations such as earthquakes and hurricanes wide availability of 5G coverage allows for personal devices of people to be used to accurately locate their whereabouts during rescue operations.

Virtual perimeter (geo-fencing)

Virtual perimeter, also known as geo-fencing, is an important 5G positioning application where children could be tracked to determine if they are within safe areas. Similarly, in factories and work locations, workers could be tracked so they can be notified if they are close to a danger zone within their work area.

Robust drone tracking beyond visual line of sight (BVLOS)

The FCC has now allowed for drones to carry packages and be controlled without visual line-of-sight (NVLoS). This is a key component for using drones to detect people during floods and similar situations where people are marooned and need to be evacuated.

Tracking vehicles

Fleet vehicles can be tracked continuously and accurately from source to destination to secure their journey.

Tracking assets including robots

Tracking of automated guided vehicles (AGV) and autonomous mobile robots (AMR) on the factory floor are key applications that can be accurately supported by 5G positioning.

Utility sector

Accurate, continuous and real-time grid monitoring is essential to keeping the electricity grid highly available. Utility providers deploy distributed automation (DA) devices that require monitoring, control and timing synchronization such as phasor measurement units (PMUs). In this context, precise timing measurements at these devices become very important for grid stability. Currently, GPS is used for synchronizing grid elements. With the deployment of microgrids that may have indoor components, there would be GPS denied environments. In such cases, PRS should be able to provide timing services.

Conclusion

In this paper, we have provided an overview of 5G positioning technologies focusing on the PRS signal as a key enabler for implementing the positioning algorithms. We provided a description of the evolution of the positioning features through various releases of the 3GPP standards from Rel-16 onwards followed by a discussion of the 5G core network architectural elements that have been added to support positioning. We then focused on the transmission aspects of PRS within a PHY frame and described how PRS signals from different TRPs are integrated into 5G physical layer blocks (PRB) in such a way that PRS signals from different TRPs do not interfere with each other. We followed that with a detailed description of the key techniques for positioning that use PRS signals, namely DL-TDoA and DL-AoD. This was followed by a discussion of the various radio parameters that influence the accuracy of 5G positioning. We concluded the paper by briefly looking at the ecosystem around PRS and its availability in practical deployments and the use cases enabled by PRS-based positioning.

In summary, 5G positioning is considered versatile and could be applied in multiple environments and scenarios for the following reasons:

- Versatility in supporting positioning across various geographical environments, both outdoors and indoors
- Extensive access due to the wide coverage provided by 5G cellular networks
- Minimal infrastructure cost due to the wide-spread deployment of radio towers that could be used for PRS transmissions
- Robustness due to PRS design features and being transmitted over licensed spectrum
- Emergency positioning is better served by 5G-positioning solutions than any other technology; as we saw in an earlier section, 5G networks have specifically incorporated additional support within the network by including data plane-based communication (using the SUPL protocol) to provide faster access to the UE by an emergency application to identify its position as quickly as possible.

Abbreviations

3GPP	Third-generation partnership project
5G	Fifth generation
5G-SA	Fifth generation standalone
5G-NR	Fifth generation new radio
5G-NSA	Fifth generation non-standalone
AF	Application function
AGV	Automated guided vehicles
AMF	Access and mobility management function
AMR	Autonomous mobile robots
ARFCN	Absolute Radio Frequency Channel Number
BVLOS	Beyond visual line of sight
CPP	Carrier Phase Positioning
DA	Distributed automation
DL-TDoA	Downlink time-difference-of-arrival
DL-AoD	Downlink angle of departure
DL-PRS	Downlink PRS
DL RSTD	Downlink reference signal time difference
E-CID	Enhanced Cell ID
IoT	Internet of things
GCI	Global cell ID
GMLC	Gateway mobile location center
gNB	Next-generation node B
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LCS	Location service
LMF	Location management function
LTE	Long-term evolution
LPP	LTE Positioning Protocol
LRF	Location retrieval function
NEF	Network exposure function
NF	Network function
NG-RAN	Next-generation RAN
NRPPa	NG-RAN Positioning Protocol A
NVLoS	Non-visual line of sight
OTDOA	Observed time difference of arrival
PCI	Physical cell ID
PMU	Phaser measurement units
PNT	Positioning, navigation and timing
PRB	Physical resource block
PRS	Positioning reference signal
PRS-ID	PRS identity
RAN	Radio access network
RedCap	Reduced capability
RSCP	Reference signal carrier phase
RSCPD	Reference signal carrier phase difference
RSU	Roadside units
RSRP	Reference signal received power
RTT	Round-trip time
SBA	Service-based architecture
SCS	Sub-carrier spacing
SLP	SUPL location platform
SSB	Synchronization signal blocks
SUPL	Secure User Plane Location (protocol)
TDOA	Time difference of arrival
TOA	Time of arrival
TRP	Transmit-receive point
UE	User equipment
UL-TDoA	Uplink time difference of arrival
UL-AoA	Uplink angle of arrival
UPF	User plane function
V2X	Vehicle to everything

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Nokia OYJ
Karakaari 7
02610 Espoo
Finland
Tel. +358 (0) 10 44 88 000

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