# 5G Automotive Association XWI Evaluation of Radio-Based Positioning Enhancements for Automotive Use Cases

5GAA Automotive Association
Technical Report

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|---|---|
| VERSION: | V1.0 |
| DATE OF PUBLICATION: | |
| DOCUMENT TYPE: | Technical Report |
| EXTERNAL PUBLICATION: | Yes |
| DATE OF APPROVAL BY 5GAA BOARD: | 25 September 2023 |

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# Foreword

This Technical Report has been produced by 5GAA.

The contents of the present document are subject to continuing work within the Working Groups (WG) and may change following formal WG approval. Should the WG modify the contents of the present document, it will be re-released by the WG with an identifying change of the consistent numbering that all WG meeting documents and files should follow (according to 5GAA Rules of Procedure):

x-nnzzzz

(1) This numbering system has six logical elements:
    (a) x: a single letter corresponding to the working group:
        where x =
        T (Use cases and Technical Requirements)
        A (System Architecture and Solution Development)
        P (Evaluation, Testbed and Pilots)
        S (Standards and Spectrum)
        B (Business Models and Go-To-Market Strategies)

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(2) No provision is made for the use of revision numbers. Documents which are a revision of a previous version should indicate the document number of that previous version

(3) The file name of documents shall be the document number. For example, document S-160357 will be contained in file S-160357.doc

# 2 References

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies.

[1] 3GPP TS 36.355 “Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP)”

[2] 3GPP TS 37.355: “LTE Positioning Protocol (LPP)”

[3] 3GPP TS 37.331: “NR; Radio Resource Control (RRC); Protocol specification”

[4] 3GPP TS 38.455 “NG-RAN; NR Positioning Protocol A (NRPPa)”

[5] 3GPP TR 38.855 “Study on NR Positioning Support”

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# 3 Definitions and abbreviations

## 3.1 Definitions

For the purposes of the present document, the following definitions apply:

| | |
|---|---|
| **Ranging accuracy:** | Expressed as the difference (error) between the calculated distance/direction and the actual distance/direction in relation to another node |
| **Relative pos. accuracy:** | Expressed as the difference (error) between the calculated horizontal/vertical position and the actual horizontal/vertical position relative to another node |
| **Absolute pos. accuracy** | Expressed as the difference (error) between the calculated horizontal/vertical position and the actual horizontal/vertical position |
| **HD Map:** | High-definition map |
| **GNSS:** | Global Navigation Satellite System |
| **GLONASS:** | Russian Global Navigation Satellite System |
| **Galileo:** | European Union Global Navigation Satellite System |
| **GPS:** | US Global Positioning System |
| **Direction:** | Direction of travel in degrees from true north |
| **Orientation:** | Direction the vehicle is pointed (can be relative or absolute) |
| **Bounding Box:** | Box outlining the guaranteed position (vehicle size + position inaccuracy) |

## 3.2 Abbreviations

For the purposes of the present document, the following symbols apply:

| | |
|---|---|
| AGV | Automated Guided Vehicle |
| AoA | Angle of Arrival |
| AMF | Application Management Function |
| BLE | Bluetooth Low Energy |
| CCC | Car Connectivity Consortium |
| CIR | Channel Impulse Response |
| C-ITS | Connected Intelligent Transport System |
| CN | Core Network |
| DL-PRS | Downlink Positioning Reference Signal |
| DS-TWR | Double-sided Two-way Ranging |
| E-CID | Enhanced Cell IDentifier |

| | |
|---|---|
| E-SMLC | Evolved Serving Mobile Location Centre (the 4G equivalent of GMLC) |
| E-UTRA | Evolved Universal Terrestrial Radio Access |
| FCC | Federal Communications Commission(US) |
| GMLC | Gateway Mobile Location Centre |
| GNSS | Global Navigation Satellite System |
| gNodeB | (gNB) 5G radio base station |
| GNSS | Global Positioning System |
| IIoT | Industrial Internet of Things |
| KPI | Key Performance Indicator |
| LCS | Location Services |
| LMF | Location Management Function |
| LPP | LTE Positioning Protocol |
| NEF | Network Exposure Function |
| NRA | National Road Authorities |
| MUSIC | Multiple Signal Classification |
| NG-RAN | NG-Radio Access Network |
| NRPPa | NR Positioning Protocol A |
| OTDOA | Observed Time Difference Of Arrival |
| PAPR | Peak-to-average Power Ratio TDoA (Time Difference of Arrival) |
| PDU | Protocol Data Unit |
| PLMN | Public Land Mobile Network |
| PRB | Physical Resource Block |
| PRU | Positioning Reference Unit |
| RAT | Radio Access Technology |
| RRC | Radio Resource Control |
| RSSI | Received Signal Strength Indicator |
| RSTD | Received Signal Time Difference |
| RSU | Road Side Unit |
| SIB | System Information Block |
| SLR | Service-Level Requirement |
| STS | Scrambled Time Stamp |
| UC | Use Case |
| UDM | Unified Data Manager |
| UE | User Equipment |
| UL-SRS | Uplink Sounding Reference Signal |
| UWB | Ultrawideband |
| V2I | Vehicle-to-Infrastructure |
| V2V | Vehicle-to-Vehicle |
| V2P | Vehicle-to-Pedestrian |
| V2V | Vehicle-to-Vehicle |
| V2X | Vehicle-to-Everything |
| VRU | Vulnerable Road User |

## 3.3 Assumptions

### 3.3.1 Road configuration

Parameters regarding the road configuration for urban grids and highways are given in the following table:

*Table 1: Road configuration for urban grid and highway from [24]*

| Parameter | Urban case | Highway case |
|---|---|---|
| Number of lanes | 2 in each direction (4 lanes in total in each street) | 3 in each direction (6 lanes in total in the highway) |
| Lane width | 3.5m | 4m |
| Note: 3m is reserved for sidewalk per direction (i.e., no vehicle or building in this reserved space). | | |

Unless otherwise stated, the following assumptions are used in the analysis.

### 3.3.2 Antenna model

Parameters regarding antenna height are given in the following table:

*Table 2: Antenna height from [24]*

| Parameters | Urban grid for eV2X | Highway for eV2X |
|---|---|---|
| BS antenna height | Macro BS: 25m<br>Micro BS: 5m | Macro BS:<br>35m for ISD 1732m<br>25m for ISD 500m<br>Micro BS: 5m |
| UE antenna height | Vehicle UE: As defined in Subclause 6.1.2<br>Pedestrian UE, cellular UE: 1.5m<br>UE-type-RSU: 5m | Vehicle UE: As defined in Subclause 6.1.2<br>Pedestrian UE, cellular UE: 1.5m<br>UE-type-RSU: 5m |

Note: The values for UE antenna may be revised after discussions on antenna placement, etc., if any.

### 3.3.3 UE drop and mobility modelling

Three vehicle types are defined as follows:

*Table 3: Vehicle types [24]:*

| | Length | Width | Height | Antenna height |
|---|---|---|---|---|
| Type 1 (passenger vehicle with lower antenna position) | 5m | 2m | 1.6m | 0.75m |
| Type 2 (passenger vehicle with higher antenna position) | 5m | 2m | 1.6m | 1.6m |
| Type 3 (truck/bus) | 13m | 2.6m | 3m | 3m |

The following UE dropping options are supported for the highway scenario according to [24]:

- Option A
    i. Vehicle type distribution: 100% vehicle type 2.
    ii. Clustered dropping is not used.
    iii. Vehicle speed is 140km/h in all the lanes as baseline and 70km/h in all the lanes optionally.
- Option B
    i. Vehicle type distribution: 20% vehicle type 1, 60% vehicle type 2, 20% vehicle type 3.
    ii. Clustered dropping is not used.
    iii. Vehicle speed in each lane is as follows:
    iv. Speed in Lane 1: 80km/h
    v. Speed in Lane 2: 100km/h
    vi. Speed in Lane 3: 140km/h
    vii. Speed in Lane 4: 40km/h
    viii. Speed in Lane 5: 30km/h
    ix. Speed in Lane 6: 20km/h
- Option C
    i. Vehicle type distribution: 0% vehicle type 1, 67% vehicle type 2, 33% vehicle type 3.
    ii. Clustered dropping is used. Each cluster consists of 6 Type 3 vehicles with a gap of 2 meters.
    iii. Vehicle speed is 140 km/h in all the lanes.

The following UE dropping options are supported for the urban grid scenario:

- Option A
  - i. Vehicle type distribution: 100% vehicle type 2.
  - ii. Clustered dropping is not used.
  - iii. Vehicle speed is 60 km/h in all the lanes.
  - iv. In the intersection, a UE goes straight, turns left, turns right with the probability of 0.5, 0.25, 0.25, respectively.
- Option B
  - i. Vehicle type distribution: 20% vehicle type 1, 60% vehicle type 2, 20% vehicles type 3.
  - ii. Clustered dropping is not used.
  - iii. Vehicle speed in each lane is as follows:
  - iv. In the East-West direction:
    1. Speed in lane 1: 60km/h
    2. Speed in lane 2: 50km/h
    3. Speed in lane 3: 25km/h
    4. Speed in lane 4: 15km/h
  - v. In the north-south direction:
    1. 0km/h in all the lanes.
  - vi. No vehicles are dropped at the intersections in the north-south direction. Vehicles do not change their direction at the intersection.

Pedestrian UE speed is 3km/h.

A bike UE speed is 15km/h.

# 4 Radio-based positioning enhancements for automotive use cases

## 4.1 Overview and background

The landscape of existing positioning techniques is constantly evolving to promote safe driving. In particular, automotive use cases can be very diverse. New features introduced in wireless standards or new technologies are not necessarily always focused on automotive use cases and would require specific evaluation scenarios. Moreover, the positioning performance depends on various factor, e.g.:

- environmental conditions such as urban canyons, tunnels, highways, weather conditions, etc.
- deployment of supporting infrastructure (e.g., 5G-base stations, RSU, UWB beacons, GNSS augmentation services etc.)
- regional regulatory requirements, e.g., frequency spectrum, etc.

This work item aims to identify and evaluate a selection of evolving and emerging technologies for positioning in line with the 5GAA roadmap for automotive use cases.

## 4.2 Motivation

Radio-based positioning provides a unique capability that has many benefits that may not be obvious. Radio-based technology provides the ability to measure the distance between two points using the antennas on each of the radio frequency (RF) devices – as such, it is also sometimes referred to as “ranging”.) The technique allows various methods of measurement including double-sided ranging, where both ends know the distance between the two points after the ranging is completed. Two antennas can provide additional information about the angle of arrival (AoA) factoring in not only the distance but also the direction towards the other end of the link.

If one of the ends of the system is fixed to a known location on the earth, then the other end of the link could extrapolate its actual location. If three or more fixed points are available, then only distance is needed to triangulate the location. If a vehicle is moving and collecting multiple samples from a single fixed point with a known location, it could also determine its location with only a single antenna. For example, a vehicle travelling under a toll collection station where the station has a radio-based positioning system pointing down at the vehicle. As the vehicle passes under the toll transmitter and the vehicle is continually collecting distance samples, the samples can then be analysed to determine the shortest measurement, and then the vehicle would know at it was directly under the toll booth transmitter at that exact moment.

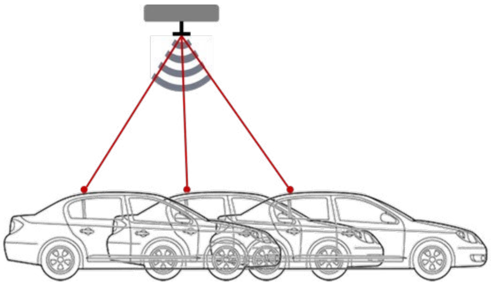


*Figure 1: Vehicle passing under a toll station*

If both ends of the system are mobile, such as on two vehicles, then the measurements can provide the distance between the vehicles. If both vehicles have two antennas (such as with AoA), then the relative position of the vehicles can also be established. If the two antennas are separated by some distance, the relative orientation of each vehicle can also be established with greater accuracy. This could allow two vehicles in a platoon to track each other very precisely.

Vehicle-to-everything (V2X) solutions provide a unique method to exploit such a radio-based system. V2X broadcasts positional information based on GNSS signals. With this information, a vehicle can know who or what is in its vicinity and then start direct communications between the two vehicles. This provides the basis for initiating the radio-based distance measurement.

One V2X requirement is to establish trust between two vehicles, ensuring that the positional information being transmitted is accurate. By using radio-based measurements, the location of both vehicles can be validated. In addition, if there is a systematic error in the measurement, the radio-based positioning could be used to establish an offset in order to correct this information, thus providing additional accuracy. Radio-based positioning is a great way to establish trust between two entities before starting a critical and potentially dangerous manoeuvre.

In addition to well-established positioning technologies, 3GPP spends considerable effort on the standardisation of precise positioning solutions within the 5G framework. In earlier releases of 5G, i.e., Rel-15 until Rel-17, the focus was on positioning using dedicated 5G positioning waveforms involving the network. In the recent release, i.e., Rel-18, 3GPP started a standardisation effort for sidelink positioning, i.e., positioning between UEs without network involvement.

In this technical report, we will investigate the potential role of this novel radio-based positioning technology to support or enable automotive use cases with demanding positioning accuracy constraints.

# 5 Use cases, positioning requirements and frequency considerations

## 5.1 A review of relevant use cases based on the V2XHAP work item and 5GAA roadmap considerations

In its recent roadmap whitepaper, the 5GAA categorises use cases according to their degree of cooperation and the respective level of automation. This is illustrated in Figure 2. Starting from this roadmap consideration within the EPos work item, a representative use case was selected. In the roadmap paper, the integral importance of precise positioning is highlighted. Especially in use cases demanding the highest level of cooperation, i.e., connected cooperative driving, extremely accurate positioning is essential. As a result, in this work item we selected those use cases requiring the highest level of cooperation but with different levels of automation. In turn, cooperative manoeuvres and vulnerable road user (VNR) protection involving complex interactions became the lead use cases for this work item.

In addition, the service level requirements (SLR) for various use cases were derived in [29]. Matching the targeted use case classes, i.e., cooperative manoeuvres and VNR protection, the use case description for *Interactive VRU Crossing* and *Cooperate Lane Merge* serve as starting point.

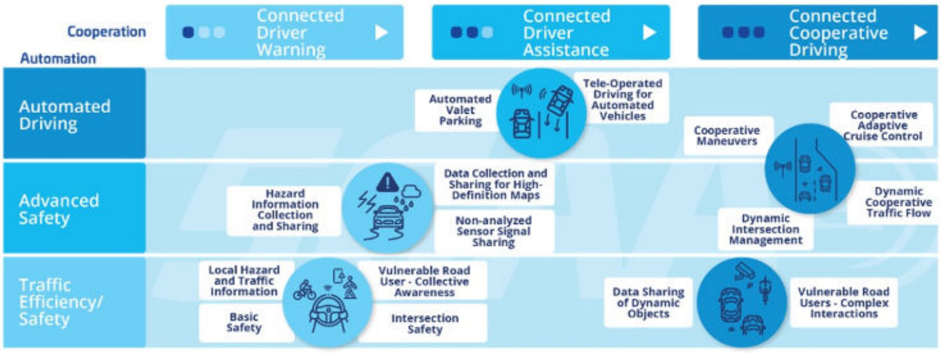


*Figure 2: Evolution of 5G-V2X use cases towards connected cooperative driving [Ref 30]*

In addition, the 5GAA work item on Trustable Position Metrics for V2X Applications (TPM4V2X) investigates to what extend trust in exchanged positions can be ensured. In this work item, we will solely focus on the positioning accuracy requirements and leave latency and trust considerations for further work or would refer readers to the TPM4V2X documents.

## 5.2 Definition of user stories considered in EPos

### 5.2.1 Interactive VRU crossing

The whitepaper [20] defines the use case “interactive VRU crossing” as “a vulnerable road user (VRU), such as a pedestrian or cyclist, signals his or her intention to cross a road and interacts with vehicles approaching the area in order to improve safety for VRUs and awareness for vehicles”.

Furthermore, the following SLRs for interactive VRU crossing are derived in [29] (see table below).

*Table 4: Service level requirements for interactive VRU crossing from [29]*

| | Positioning accuracy (m) | | | Velocity in km/h | Vehicle density (units/km2) |
|---|---|---|---|---|---|
| Urban | 0.2 | 3σ | 99.73% | 70 | 12,000 |
| Rural | 0.2 | 3σ | 99.73% | 120 | 9,000 |

In this work item we agreed to exclude the highway scenario originally considered for interactive VRU crossing from the investigations. In turn, we end up with two scenarios depicted in the figures below.

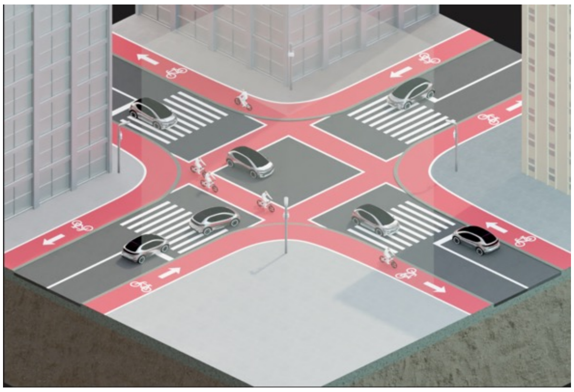


*Figure 3: VRU crossing – urban*

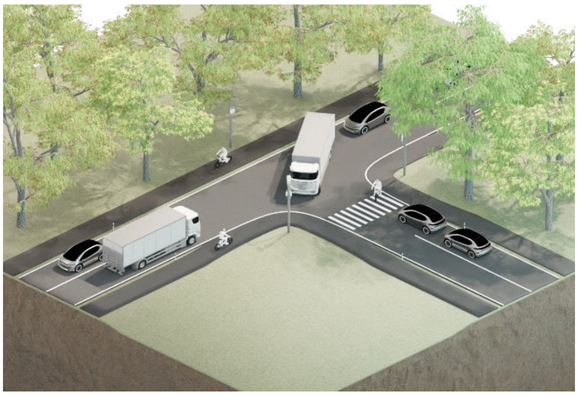


*Figure 4: VRU crossing – rural*

As in this work item, we are mainly investigating 3GPP radio-based positioning techniques, we also review the 3GPP positioning accuracy requirements from [21]:

- Set 1: 10-50m with 68-95 % confidence level. This includes Group 1 in [5] and Service level 1 in [3].
- Set 2: 1-3m with 95-99 % confidence level. This includes Group 2 in [5], Service level 2, 3, 4 in [3].
- Set 3: 0.1-0.5m with 95-99 % confidence level. This includes Group 3 in [5],

Service level 5, 6, 7 in [3], the requirements in [4].

In turn, we observe that interactive VRU crossing corresponds to requirement Set 3 from a 3GPP perspective. In addition, we observe that in [24], 3GPP assumes a maximum speed of 60km/h for vehicles in an urban scenario.

For ease of further investigations, we consider the VRU to be a bike and, according to [24], assume a speed of 15km/h. Thus, matching the SLR from 5GAA and the requirements from 3GPP we end up with the following parameters for the VRU use case in EPos:

*Table 5: Service level requirements for interactive VRU crossing for EPos*

| | Positioning accuracy (m) | Confidence level | Velocity (km/h) |
|---|---|---|---|
| Urban | 0.5 | 95% | Cars: 60<br>VRU: 15 |
| Rural | 0.5 | 95% | Cars: 60<br>VRU: 15 |

User story – Car-to-bicyclist detection:

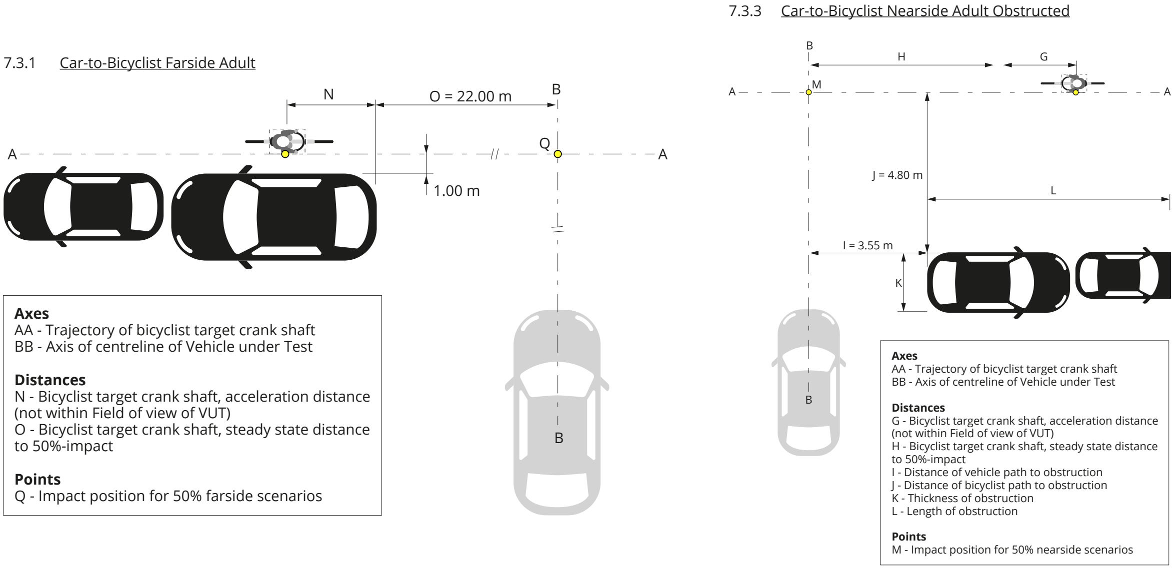


*Figure 5: Illustration of two common sources of accidents currently also under investigation in EuroNCAP*

In the first user story, we would like to address a traffic scenario that is known to cause a statistically significant high number of accidents [Ref GIDAS]. In both cases, the line of sight is at least partially obstructed. In these cases, the (automated) vehicle might not detect the bicyclist with its classical onboard sensors. Therefore, V2X communication messages were proposed to share the positions of the road participants. In this work item, we will investigate if the 5G positioning solutions, in combination with other radio-based positioning solutions, could be used to determine the absolute position or at least relative distance between the road users in this specific intersection scenario.

### 5.2.2 Cooperative lane merge

The whitepaper [20] defines the use case "cooperative lane merge" as a host vehicle accommodating a remote vehicle that is merging into the HV's traffic lane.

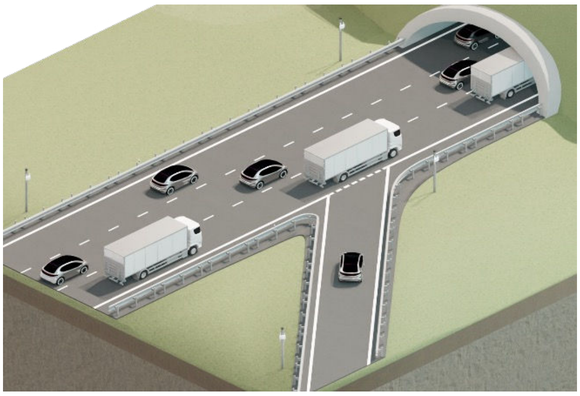


Figure 6: Cooperative lane merge – highway

Table 6: Service level requirements for cooperative lane merge [29]

| | Positioning accuracy (m) | Confidence level | Velocity in km/h |
|---|---|---|---|
| Highway | 1.5 | 99.73% | 250 |

In this work item we agreed to exclude the rural scenario originally considered for cooperative lane merge from the investigations. In turn, we end up with the scenario depicted in the figure below:

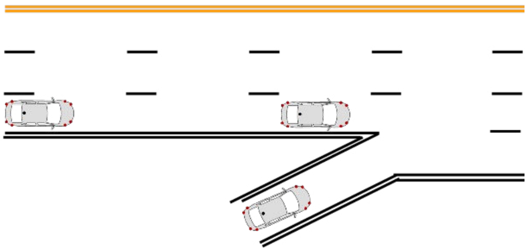


Figure 7: User story – lane merge on a highway

Table 7: Service level requirements for cooperative lane merge for EPos

| | Positioning accuracy (m) | Confidence level | Velocity in km/h |
|---|---|---|---|
| Rural | 1.5 | 95% | 140 |

In the second user story, we would like to address a cooperative traffic scenario. Here, one vehicle aims to enter the highway and determines its relative distance to neighbouring vehicles using 5G positioning solutions.

## 5.3 Frequency bands for positioning and regional considerations

### 5.3.1 Europe

From a spectrum regulation perspective, which frequency bands in Europe could be used by 5G-V2X technologies for automotive positioning applications?

We address the following bands:

1) Bands authorised for use by mobile/fixed communication networks (MFCNs) – Uu/PC5
2) Bands authorised for use by intelligent transport systems (ITS) – PC5

We tentatively conclude that the examined bands can be used for purposes of automotive positioning so long as

a) the radio equipment transmissions and receptions comply with the conditions (technical or otherwise) as set out in the authorisation regulations (in the licences or licence exemption rules); and

b) the positioning is performed in addition to or as part of (but not as a substitute for) the application for which the use of the band is authorised.

The use of 5875-5925MHz in Europe is authorised through licence exemption by national regulatory authorities (NRAs). The conditions for exemption are harmonised through ECC Decision (08)01 (Europe) and EC Decision (EU) 2020/1426. An inspection of the ECC and EC decisions, as well as licence exemption regulations issued by NRAs reveals the following:

a) While the licence exemption regulations are technology agnostic, they are not service agnostic. Specifically, 5875-5925 MHz is authorised for use by safety related ITS applications.

b) The regulations do not explicitly prohibit the use of the band for the purpose of positioning.

On the basis of (a) and (b), one may conclude that the 5875-5925MHz band could be used for the purpose of positioning of radio equipment, as long as 1) the transmitted signals comply with the technical conditions specified in the licence exemption regulations, and 2) where the positioning itself is an operation that is part of a safety-related ITS application. That said, confirmation with national road authorities (NRA) is advised.

Requirement (b) arises because, while European spectrum regulations are technology agnostic, they are not service agnostic. So, radio equipment is strictly authorised to operate and deliver a specific application. As long as the transmitted signals comply with the conditions of authorisation, the user of the equipment ought to be able to use the same signals for purposes of positioning. This of course assumes that other relevant regulations (e.g., privacy) are not contravened.

### 5.3.2 US

Similar to Europe, one may conclude that the now-reduced 5895-5925MHz band could be used for positioning radio equipment, so long as 1) the transmitted signals comply with the technical conditions specified in the licence exemption regulations, and 2) where the positioning itself is an operation that is part of a safety-related ITS application.

### 5.3.3 Korea

In the scope of this work item, we identified that 5G positioning service can be used in the respective bands of the regulated ITS spectrum in Korea as well.

# 6 5G network-based positioning (3GPP Rel-16 and Rel-17 Uu-positioning solutions)

## 6.1 Overview of 5G network-based positioning solutions

With the advent of 5G, a new 5G-based positioning framework has been introduced in Rel-16. The whitepaper [14] provides an overview of the main features and typical accuracy requirements and illustrates the enhancements of positioning in 5G networks over various 3GPP releases. Figure 8 below presents an overview of the subsequent feature extensions of 5G positioning and the increased accuracy that comes with each new 3GPP release.

In 3GPP, a work item was concluded in March 2019 to investigate positioning support for NR Rel-16 and a follow-up work item *FS_NR_pos* was set up to specify network-based (so-called RAT dependent) positioning support for Rel-16. Several positioning solutions will be supported in 5G NR. The operation in higher carrier frequencies and utilisation of massive antenna arrays provides additional degrees of freedom to improve the positioning accuracy compared to LTE.

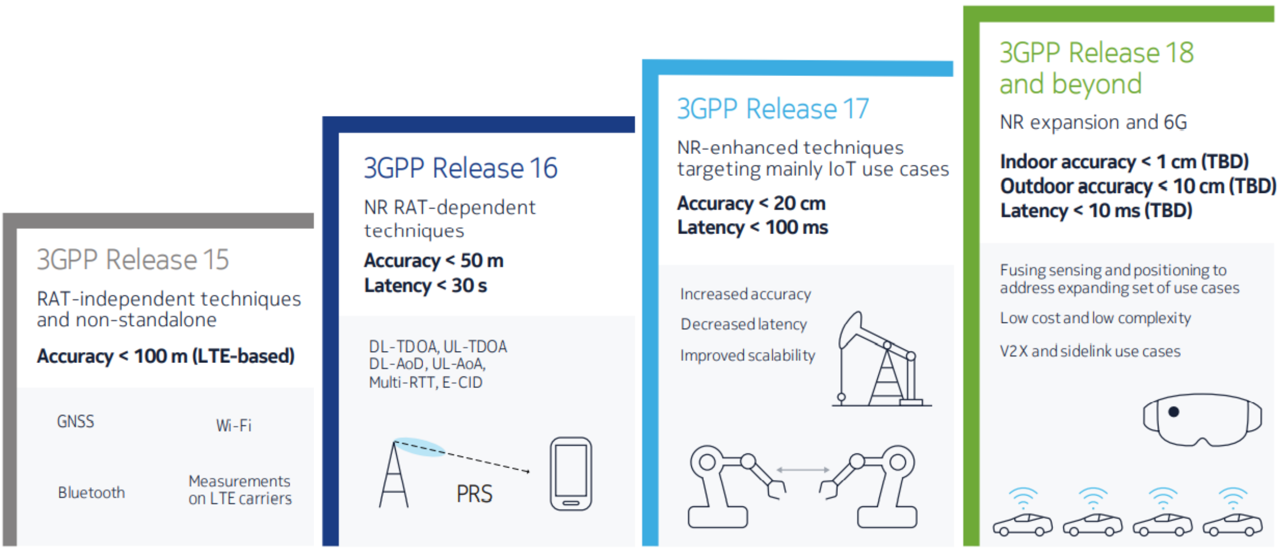


*Figure 8: Overview of 5G-based positioning over 3GPP releases [14]*

Table 8: Overview of 3GPP releases 16, 17 and 18

| 3GPP release | Rel-16 | Rel-17 | Rel-18 |
|---|---|---|---|
| WI acronym | FS_NR_pos | FS_NR_pos_enh | FS_NR_pos_enh2 |
| 3GPP specification | TR 38.855 Study on NR positioning support [5] | TR 38.857 Study on NR positioning enhancements [6] | TR 38.859 Study on expanded and improved NR positioning [7] |
| Main features | New 5G system architecture supporting positioning in 5G networks<br>New logical function in 5GC:<br>LMF TS29.572 (CT4)<br>GMLC<br>System architecture TS23.273 [9] (SA2)<br>New protocols:<br>NRPPa TS 38.455<br>LPP TS 36.355<br>New 5G positioning reference signals/ sequences (DL-PRS, UL SRS)<br>Six different RAT dependent methods defined in TS38.215<br>E-CID, DL-TDoA, UL-TdoA, DL-AoD, UL-AoD, multi-RTT | UE in RRC_INACTIVE<br>Indoor positioning | Carrier-phase based positioning<br>Sidelink positioning<br>Positioning in unlicenced spectrum<br>Low-lost and low-complexity positioning |

### 6.1.1 3GPP-based positioning architecture

The typical 3GPP positioning architecture consists of target UE (i.e., the UE to be positioned or the UE requested to be localised), Radio Access Network (NG-RAN) and 5G Core Network (CN) with positioning server and location service client. The position information may be requested by and reported to a client (e.g., an application) associated with the UE, or by a client within or attached to the core network. The client entity requests the location information of the target device and based on the measured location-related information the positioning server computers and provides the position back to the client. In TS23.273 [9], various types of location request have been specified:

Network Induced Location Request (NI-LR): The serving AMF for a UE initiates localisation of the UE for a regulatory service (e.g., an emergency call from the UE) or for verification of a UE location (country or international area) for NR satellite access.

Mobile Terminated Location Request (MT-LR): An LCS client or AF external to or internal to a serving PLMN sends a location request to the PLMN (which may be the HPLMN or VPLMN) for the location of a target UE.

Mobile Originated Location Request (MO-LR): A UE sends a request to a serving PLMN for location-related information.

Immediate Location Request: A LCS client or AF sends or instigates a location request for a target UE (or group of target UEs) and expects to receive a response containing location information for the target UE (or group of target Ues).

Deferred Location Request (so far only for MT-LR): An LCS client or AF sends a location request to a PLMN for a target UE (or group of target Ues) and expects to receive a response containing the indication of event occurrence and location information if requested for the target UE (or group of target Ues) at some future time (or times), which may be associated with specific events associated with the target UE (or group of target Ues).

Figure 9 and Figure 10 below show the NG-RAN positioning architecture. 3GPP has specified the control plane-based solution where the control channels are used to exchange the location information between Ues, the network nodes and positioning server. Under NR, two protocols are used to exchange the location information. The extension of LTE positioning protocol (LPP) covers signalling between Ues, the location management function (LMF) and the location server.

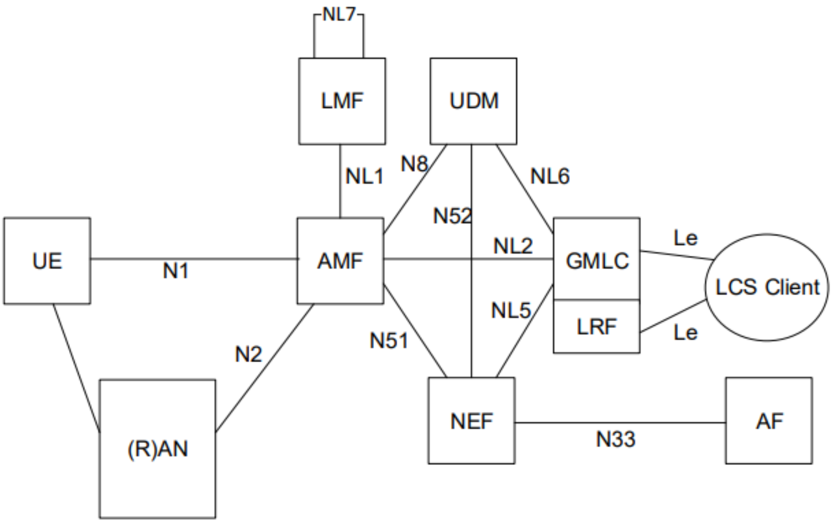


*Figure 9: Non-roaming reference architecture for 5G network-based positioning in TS23.273 [9] (reference point representation)*

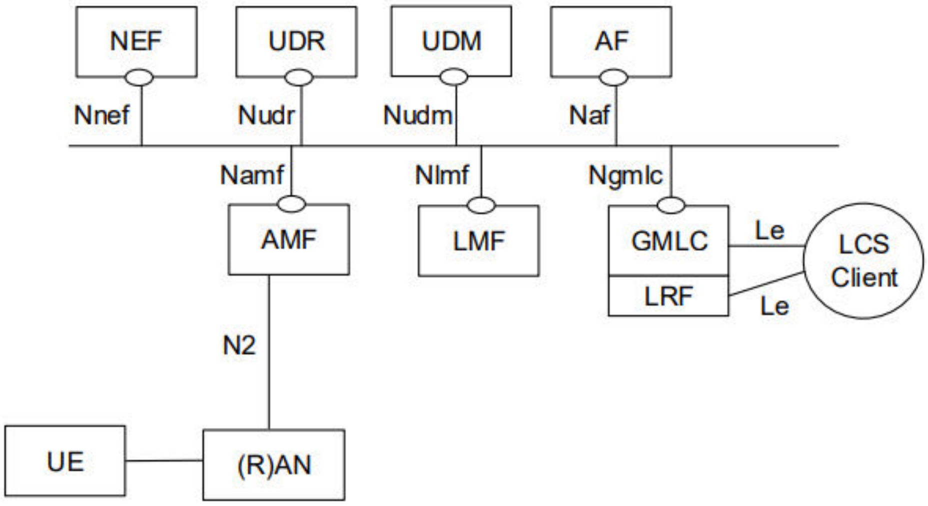


*Figure 10: Non-roaming reference architecture for 5G network-based positioning in TS23.273 [9] (SBI representation)*

### 6.1.1.1 Location management function

The location management function is a new network entity that has been introduced in Rel-16 in the 5G core network (5GCN). The LMF manages the overall coordination and scheduling of resources required for the location of a UE registered with or accessing 5GCN. It also calculates or verifies a final location and velocity estimates as a basis for accuracy checking. The LMF receives location requests for a target UE from the serving AMF using the Nlmf interface. The LMF interacts with the UE in order to exchange location information applicable to UE-assisted and UE-based position methods. In short, the LMF is supporting the following functionality:

- Determines location for a UE with geographical or local coordinates as defined in TS 23.032 [8].
- Configures downlink resources for transmission of DL PRS from the NG RAN.
- Obtains downlink location measurements or a location estimate from the UE.
- Obtains uplink location measurements from the NG RAN.
- Obtains non-UE associated assistance data from the NG RAN.
- Provides broadcast assistance data to Ues and forwards associated ciphers/keys to an AMF.
- Terminates the NRPPa Protocol (TS 38.455) [4] towards NG-RAN.
- Terminates the LPP Protocol (TS 36.355) [1] towards UE.
- Offers to other network functions the following services:
    - Nlmf_Location
    - Nlmf_Broadcast

#### 6.1.1.2 Gateway mobile location centre

The gateway mobile location centre (GMLC) is a network function in the 5GC that contains functionality required to support LCS. The GMLC is the 5G equivalent of the E-SMLC in EPC (LTE networks). In a PLMN, there may be more than one GMLC. A GMLC is the first node an external LCS client accesses in a PLMN (i.e., the Le reference point is supported by the GMLC). Afs and NFs may access GMLC directly or via NEF. The GMLC may request routing information and/or target UE privacy information from the UDM via the Nudm interface. After performing authorisation of an external LCS client or AF and verifying target UE privacy, a GMLC forwards a location request to either a serving AMF using Namf interface or to a GMLC in another PLMN using the Ngmlc interface in the case of a roaming UE.

#### 6.1.1.3 NR positioning protocol A

The NR positioning protocol A (NRPPa) [4] carries information between the NG-RAN node and the LMF. It is used to support the following positioning functions:

- E-CID for E-UTRA where measurements are transferred from the ng-eNB to the LMF.
- Data collection from ng-eNBs and gNBs supporting OTDOA positioning for E-UTRA.
- Cell-ID and cell portion ID retrieval from gNB’s for support of NR Cell-ID positioning method.
- Exchange of information between LMF and NG-RAN node to assist data broadcasting.
- NR E-CID where measurements are transferred from the gNB to the LMF.
- NR Multi-RTT where measurements are transferred from the gNB to the LMF.
- NR UL-AoA where measurements are transferred from the gNB to the LMF.
- NR UL-TDOA where measurements are transferred from the gNB to the LMF.
- Data collection from gNBs for support of DL-TDOA, DL-AoD, Multi-RTT, UL-TDOA, UL-AoA.

The NRPPa protocol is transparent to the AMF. The AMF routes the NRPPa PDUs based on a routing ID corresponding to the involved LMF over NG-C interface without knowledge of the involved NRPPa transaction. It carries the NRPPa PDUs over NG-C interface either in UE associated mode or non-UE associated mode.

In case of a split gNB architecture, the NRPPa protocol is terminated at the gNB-CU as shown below.

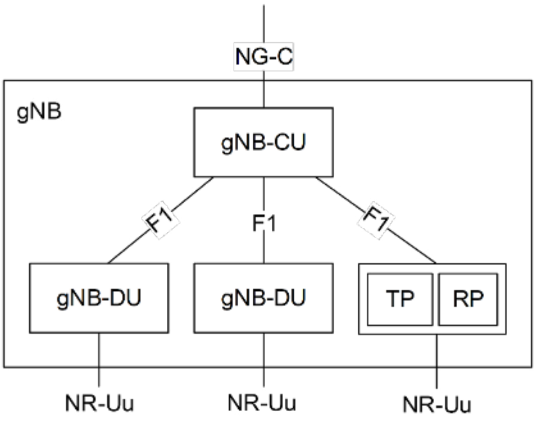


*Figure 11: CU/DU split architecture*

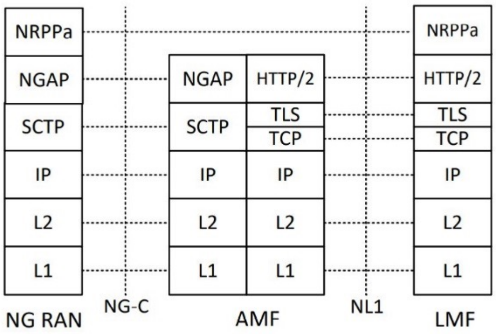


*Figure 12: NRPPa layering for LMF – gNB signalling*

### 6.1.1.4 LTE positioning protocol

The LTE positioning protocol (LPP TS 36.355 [1]) is terminated between a target device and the LMF. LPP messages are carried as transparent PDUs across intermediate network interfaces (so LPP is a NAS protocol) using the appropriate protocols (e.g., NGAP over the NG-C interface, NAS/RRC over the LTE-Uu and NR-Uu interfaces). The LPP protocol is intended to enable positioning for NR and LTE using various position methods, while isolating the details of any particular positioning method and the specifics of the underlying transport from one another. The protocol operates on a transaction basis between a target device and the LMF, with each transaction taking place as an independent procedure. More than one such procedure may be in progress at any given moment. An LPP procedure may involve a request/response for message pairing or one or more "unsolicited" messages. Each procedure has a single objective (e.g., transfer of assistance data, exchange of LPP related capabilities, or positioning of a target device according to some QoS and use of one or more positioning methods). Multiple procedures, in series and/or in parallel, can be used to achieve more complex objectives (e.g., positioning of a target device in association with transfer of assistance data and exchange of LPP-related capabilities). Multiple procedures also enable more than one positioning attempt to be ongoing at the same time (e.g., to obtain a coarse location estimate with low delay while a more accurate location estimate is being obtained with higher delay). An LPP session is defined between a positioning server (LMF) and the target device. LPP-defined data structures for assistance information are reused to support RRC broadcasting of assistance data embedded in positioning system information blocks (SIBs). This enables broadcast assistance data using the same structures as those found in point-to-point location.

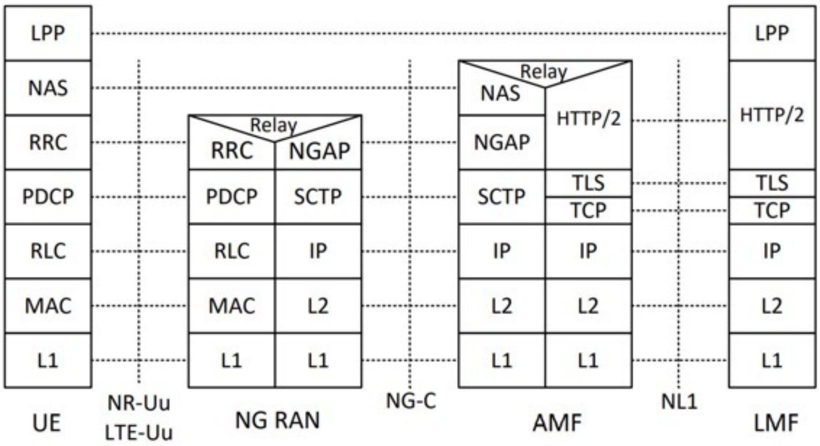


*Figure 13: LPP layering for LMF-UE Signalling*

## 6.1.2 5G positioning reference signals

### 6.1.2.1 DL-PRS

Rel-16 has introduced new downlink positioning reference signals/sequences (DL-PRS) for RAT-dependent positioning methods. A NR DL-PRS can be configured at two levels, within a slot and at multi-slot level. Within a slot, the starting resource element can be configured in terms of time and frequency from a TRP. Across multiple slots, gaps between PRS slots as well as their periodicity and density within a period can be configured.

Maximum Bandwidth: The PRS footprint on the time frequency grid is configurable with a starting physical resource block (PRB) and a PRS bandwidth. The PRS may start at any PRB in the system bandwidth and can be configured ranging from 24 to 276 PRBs in steps of 4 PRBs. This amounts to a maximum bandwidth of about 100MHz for 30kHz subcarrier spacing and to about 400MHz for 120kHz subcarrier spacing. The flexible bandwidth configuration allows the network to configure the PRS while keeping out of band emissions to an acceptable level.

Resources and resource sets: The PRS can be transmitted in beams. A PRS beam is referred to as a PRS resource while the full set of PRS beams transmitted from a TRP on the same frequency is referred to as a PRS resource set. The different beams can be time-multiplexed across symbols or slots. To assist UE RX beamforming, the DL PRS can be configured to be quasi-co-located (QCL) Type D with a DL reference signal from a serving or neighbouring cell, signalling that the same RX beam used by the UE to receive said reference signal can be used to receive the configured PRS. The beam structure of the PRS improves coverage especially for mm-wave deployments and also allows for AoD estimation, e.g. the UE may measure DL PRS received signal time difference (RSTD) per beam and report the measured RSTD including DL PRS Resource id (beam id) to the LMF.

Repetition and periodicity: In order to improve positioning accuracy, more measurements can be collected. Measurements are collected per resource. Hence, repeated transmissions of PRS resources helps to collect more measurements. The repetition of resources can be done in two ways, repeat before sweep and sweep before repeat. The amount and type of repetition can be configured with parameters for the gaps between resources and the number of resource repetitions within a period or resource set. The DL PRS resources can be repeated up to 32 times within a resource set period, either in consecutive slots or with a configurable gap between repetitions. The resource set period in frequency range 1 (FR1) ranges from 4 to 10,240ms.

Interference suppression: The DL PRS is designed to allow the UE to perform accurate time of arrival (TOA) measurements even in presence of interfering DL PRSs from nearby TRPs. Each symbol of the DL PRS has a comb-structure in frequency, i.e., the PRS utilises every Nth subcarrier. The comb value N can be configured to be 2, 4, 6 or 12. The length of the PRS within one slot is a multiple of N symbols and the position of the first symbol within a slot is flexible as long as the slot consists of at least N PRS symbols. It allows the accumulation of contiguous subcarriers across a slot which improves correlation properties for ToA estimation. The resource element pattern can be shifted in frequency with offsets of 0 to N-1 subcarriers thus allowing N orthogonal DL PRSs utilising the same symbols. All configurable patterns cover every subcarrier in the configured bandwidth over the pattern duration, which gives a maximum measurement range for the ToA measurement in scenarios with large delay spreads. The DL-PRS is QPSK modulated by a standardised 31-bit Gold code sequence initialised based on a DL-PRS sequence ID taking values from 0 to 4,095.

Hierarchical structure: There can be at most four frequency layers and each one has at most 64 TRPs. Each TRP per frequency layer can have two DL-PRS resource sets, thus resulting in a total of eight resource sets per TRP and each resource set can have up to 64 resources. Each resource corresponds to a beam. Having two different resource sets per frequency layer per TRP allows gNB to configure one set of wide beams and another set of narrow beams for each frequency layer.

The RRC (TS38.331) defines for Rel-16 the IE *LocationMeasurementInfo* sent by the UE to the network to assist with the configuration of measurement gaps for location-related measurements.

For Rel-17 the IE *NR-DL-PRS-PDC-Info* defines downlink PRS configuration for propagation delay compensation.

To illustrate the configuration of DL-PRS, we refer to the example in [25], where the DL-PRS resembles a N=6 comb-6 pattern for three TRPs (left figure) and the UL-SRS sent from a UE has a comb-4 pattern.

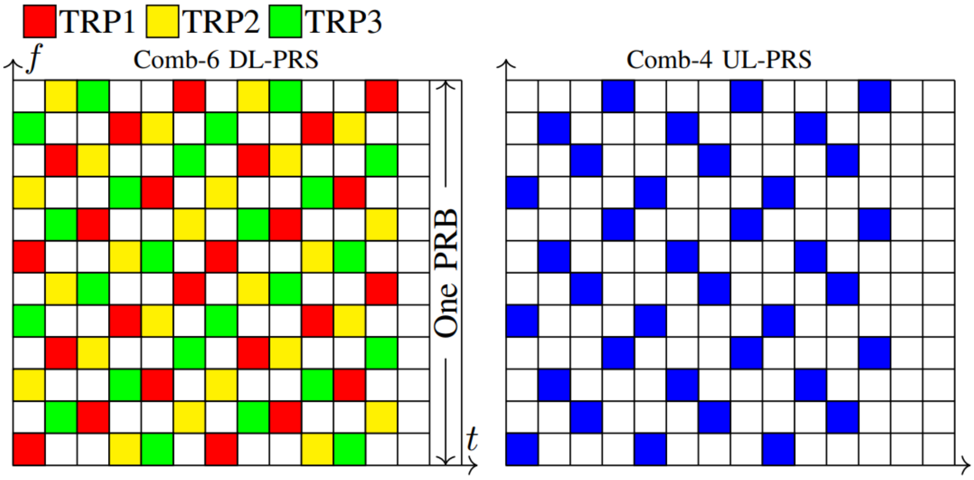


*Figure 14: Configuration of DL-PRS with comb-6 pattern for 3 TRPs (left figure) and UL-SRS with comb-4 (right figure) – taken from Fig. 2 in [25]*

#### 6.1.2.2 UL-SRS uplink sounding reference signal

The SRS for positioning is a reference signal based on the SRS for communication. Although the signals have a lot in common, SRS for positioning and for communication are configured separately and with different properties specific to their usage.

Resources and resource sets: The SRS for positioning is configured in a resource, which in turn can be part of a resource set. An SRS resource corresponds to an SRS beam, and SRS resource sets correspond in turn to a collection of SRS resources (i.e., beams) aimed at a given TRP.

Coverage features: The SRS resource is defined as a collection of symbols transmitted on the time-frequency grid. Like the DL-PRS, the UL-SRS resources for positioning are transmitted on a single antenna port and can be placed to begin on any symbol in the NR uplink slot. In the time domain, the SRS resources for positioning can span 1, 2, 4, 8, or 12 consecutive OFDM symbols, which provide enough coverage to reach all TRPs involved in the positioning procedures. Contrary to the SRS for communication, repetition is not supported in an SRS for positioning resource. Similar to SRS for communication, the SRS for positioning is using Zadoff-Chu sequences as a base signal, to ensure low-PAPR transmission from the UE. The particular sequence used to generate an SRS symbol depends on configuration parameters and sequence hopping is supported as in the SRS for communication.

Interference-free UE multiplexing: Since 3GPP Rel-15, NR has used a comb structure for the SRS, so that only a fraction of the OFDM subcarriers are occupied by a given SRS resource. For SRS communication, the comb size is either 2 or 4, meaning that the SRS occupies 1 subcarrier out of 2 or 4, respectively. In Rel-16, several enhancements were added in the specification of the SRS for positioning. The comb size for the SRS for positioning is 2, 4, or 8, and new comb-patterns were specified in order for all the subcarriers to be sounded in one resource. Different resource element offset patterns can be configured as a function of the comb size and the number of symbols in the resource. For UE multiplexing, SRS for positioning can be configured with an initial comb offset and a specific cyclic shift.

### 6.1.3 5G positioning methods

#### 6.1.3.1 RAT-dependent positioning methods

#### 6.1.3.1.1 (NR) Enhanced cell ID

In the Cell ID (CID) positioning method, the position of a UE is estimated with the knowledge of its serving ng-eNB, gNB and cell. The information about the serving ng-eNB, gNB and cell may be obtained by paging, registration, or other methods. Enhanced Cell ID (E-CID) based on LTE positioning signals refers to techniques which use additional UE measurements and/or NG-RAN radio resource and other measurements to improve the UE location estimate. In the case of a serving ng-eNB, uplink E-CID may be supported based on NR, GERAN, UTRA, or WLAN signals.

NR Enhanced Cell ID (NR E-CID) positioning refers to techniques which use additional UE measurements and/or gNB measurements to improve the UE location estimate. Although NR E-CID positioning may utilise some of the same measurements as the measurement control system in the RRC protocol, the UE generally is not expected to make additional measurements for the sole purpose of positioning; i.e., the positioning procedures do not supply a measurement configuration or measurement control message, and the UE reports the measurements that it has available rather than being required to take additional measurement actions.

#### 6.1.3.1.2 Downlink time difference of arrival

Downlink time difference of arrival (DL-TDoA) positioning makes use of the DL RSTD (and optionally DL-PRS-RSRP and/or DL-PRS-RSRPP) of downlink signals received at the UE from multiple TPs. The UE measures the DL RSTD (and optionally DL-PRS-RSRP and/or DL-PRS-RSRPP) of the received signals using assistance data received from the positioning server, and the resulting measurements are used along with other configuration information to locate the UE in relation to the neighbouring TPs. DL-TDoA requires tight synchronisation between the gNBs/TPs as the method is based on the absolute timing differences.

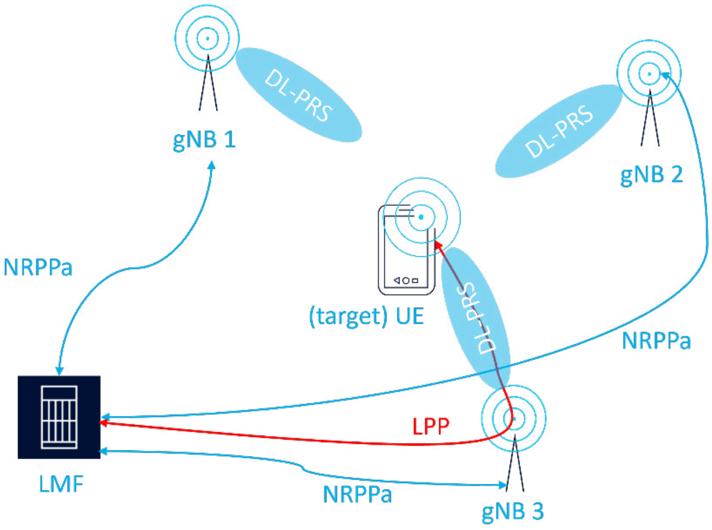


Figure 15: DL-TdoA

#### 6.1.3.1.3 Uplink time difference of arrival

Uplink time different of arrival (UL-TDOA) positioning makes use of the UL-RTOA (and optionally UL-SRS-RSRP and/or UL-SRS-RSRPP) at multiple RPs of uplink signals transmitted from a UE. The RPs measure the UL-RTOA (and optionally UL-SRS-RSRP and/or UL-SRS-RSRPP) of the received signals using assistance data received from the positioning server, and the resulting measurements are used along with other configuration information to estimate the location of the UE.

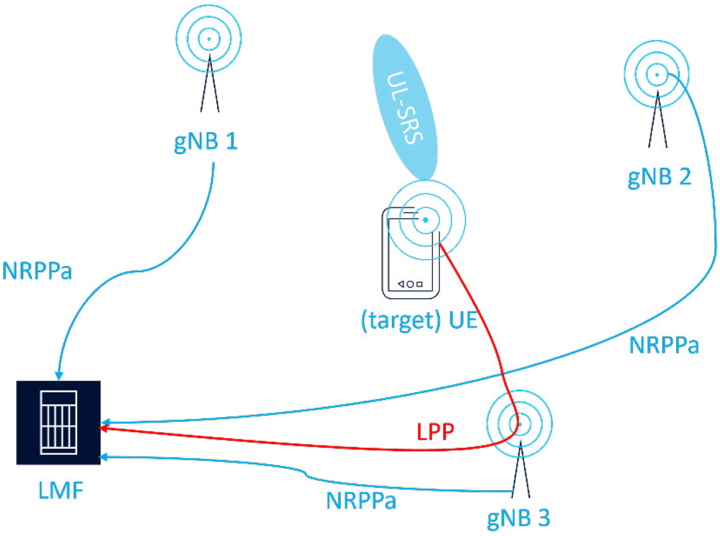


*Figure 16: UL-TdoA*

#### 6.1.3.1.4 Downlink angle of departure

Downlink angle of departure (DL-AoD) positioning is an angular estimation method that makes use of the measured DL-PRS-RSRP (and optionally DL-PRS-RSRPP) of downlink signals received at the UE from multiple gNBs. One way to estimate the DL-AoD is using RSRP reports from the UE to estimate the AoD from multiple transmission points and therefore triangulate the UE using the AoDs. Once the RSRP has been reported from the UE there are multiple methods to estimate the AoD. One possibility is to use a fingerprint-like estimation to determine the AoD based on RSRP reports across multiple beams received from the same gNB at the UE.

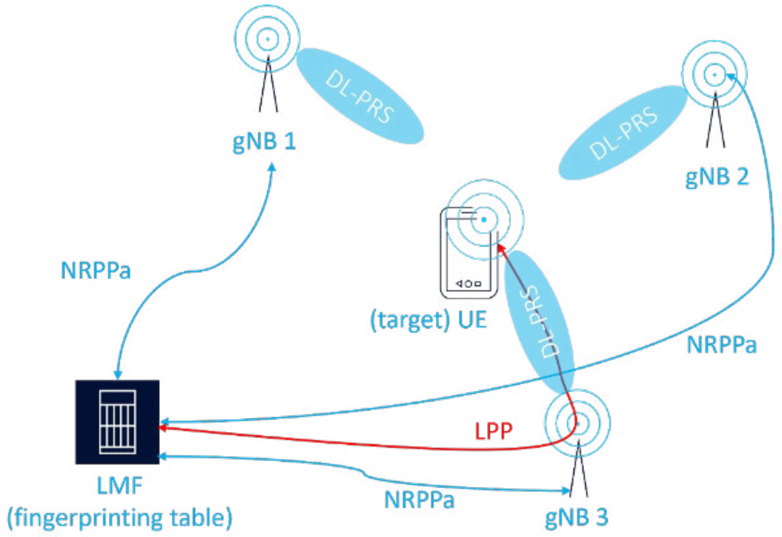


*Figure 17: DL-AoD*

#### 6.1.3.1.5 Uplink angle of arrival

Uplink angle of arrival (UL-AoA) positioning makes use of the measured azimuth angle of arrival (A-AoA) and zenith angle of arrival (Z-AoA) at multiple RPs of uplink signals transmitted from the UE. The RPs measure the A-AoA and Z-AoA (and optionally UL-SRS-RSRPP) of the received signals using assistance data received from the positioning server, and the resulting measurements are used along with other configuration information to estimate the location of the UE. To perform AoA estimation itself there are many known algorithms such as the DFT beam method and the Multiple Signal Classification (MUSIC) method, among others.

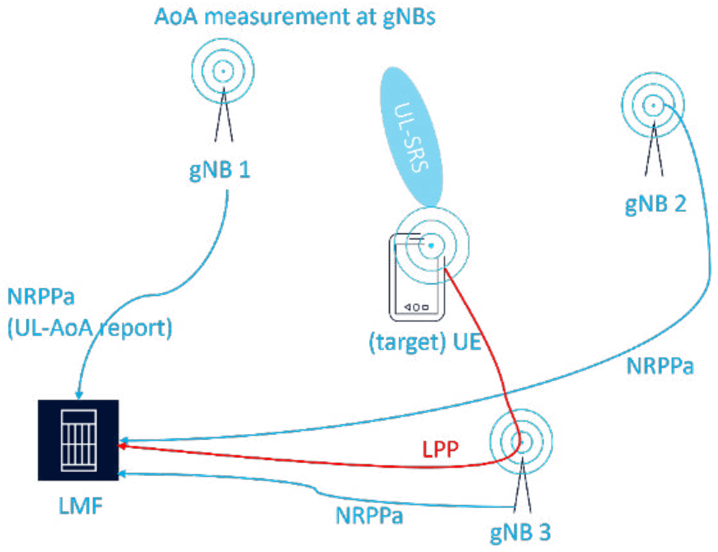


*Figure 18: UL-AoA*

#### 6.1.3.1.6 Multi-cell RTT

Multi-cell RTT positioning makes use of the UE Rx-Tx time difference measurements (and optionally DL-PRS RSRP and/or DL-PRS-RSRPP) of downlink signals received from multiple TRPs, taken from the UE and the gNB Rx-Tx time difference measurements (and optionally UL-SRS-RSRP and/or UL-SRS-RSRPP) at multiple TRPs of uplink signals transmitted from UE. The UE measures the UE Rx-Tx time difference measurements (and optionally DL-PRS-RSRP and/or DL-PRS-RSRPP of the received signals) using assistance data received from the positioning server, and the TRPs measure the gNB Rx-Tx time difference measurements (and optionally UL-SRS-RSRP and/or UL-SRS-RSRPP of the received signals) using assistance data received from the positioning server. The measurements are used to determine the RTT at the positioning server which are then used to estimate the location of the UE.

While for DL-TDOA and UL-TDOA one source of timing estimation error comes from the synchronisation errors between different gNBs, the advantage of using the RTT to estimate the distance between a UE and a gNB, is that synchronisation errors are no longer a factor. However, a downside of Multi-cell RTT method is the increased resource overhead/cost due to the use of both DL-PRS and UL-SRS.

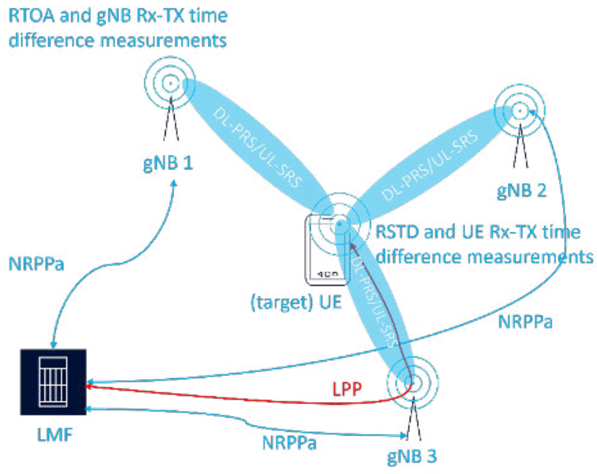


Figure 19: Multi-cell RTT

### 6.1.4 3GPP location service procedures

Section 6 of the 3GPP LCS specification (TS23.273 [9]) lists several procedure types (signalling flow diagrams) for the different location requests. For brevity, we just list the categories here and for the detailed flow charts refer readers to TS23.273 [9]

- 5GC-MT-LR procedure (for the regulatory location service/for the commercial location service)
- 5GC-MO-LR procedure
- Deferred 5GC-MT-LR procedure for periodic, triggered and UE available location events

- LMF change procedure
- Unified location service exposure procedure
- NG-RAN location service exposure procedure
- Low power periodic and triggered 5GC-MT-LR procedure
- Bulk operation of LCS service request targeting to multiple UEs
- Procedures to support non-3GPP access
- Procedures dedicated to support regulatory services
- Common sub-procedures
- UE location privacy setting procedure
- Procedures with interaction between 5GC and EPC
- Procedures for broadcast assistance data

## 6.2 Network-based positioning demos

### 6.2.1 Network-based positioning in a factory

The 5G network-based positioning setup used in this demo has been installed inside the ARENA2036 (Active Research Environment for the Next generation of Automobiles), which is an innovation and research campus in Stuttgart, Germany to test new technologies for future manufacturing processes in the automotive industry. The positioning setup consists of an area on a shop floor of 20m x 10m. Several 5G Positioning Reference Units (PRU) have been deployed in two columns at 7m in height with three PRUs per column. The six PRUs have perfectly known position and have been tightly synchronised. Each PRU has 2D planar antenna array which also allows for angular-based methods to be investigated. A 5G private/campus network licence at 3.7GHz carrier frequency with 100MHz bandwidth has been used.

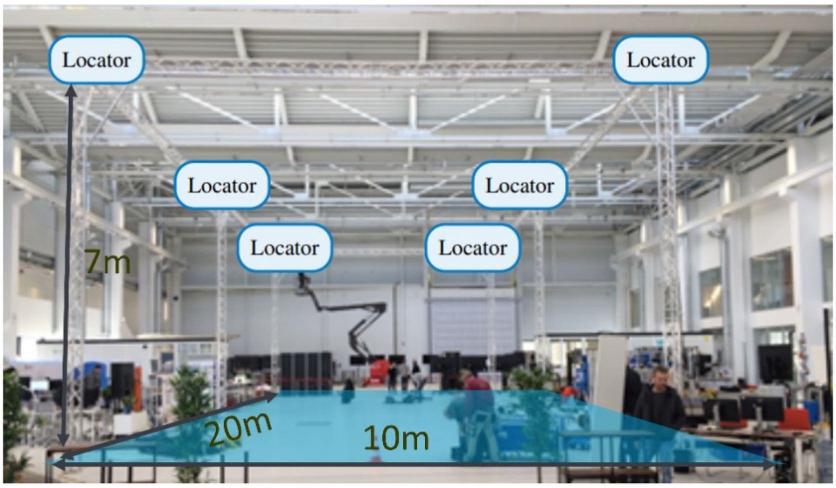


*Figure 20: Indoor positioning setup at ARENA2036*

The 5G UE was placed on a movable platform (AGV) and moved to 28 individual ground truth points, represented by the small green squares in Figure 21. At each of the reference positions the UE was transmitting UL-SRS, received by the six PRUs.

*Figure 21: Ground truth position of the UE on the shop floor [26]*

Various positioning methods (AoA, UL-TdoA) and post-processing methods (outlier detection) have been applied to the measured uplink signals. Figure 22 shows the measurement setup, where the minimisation of the position error is achieved by examining the maximum likelihood of the AoA and the TdoA. The achieved positioning accuracy for AoA-only, UL-TdoA and combined AoA+TdoA is shown in the CDFs in Figure 23 for various additional post-processing methods. The outlier rejection algorithm as well as the robust initialisation routine are described in detail in [26].

The best achievable accuracy in this demo setup is 0.51m for the 95% tile (joint AoA+TDoA) for TDoA-only the 95% tile is 0.96m.

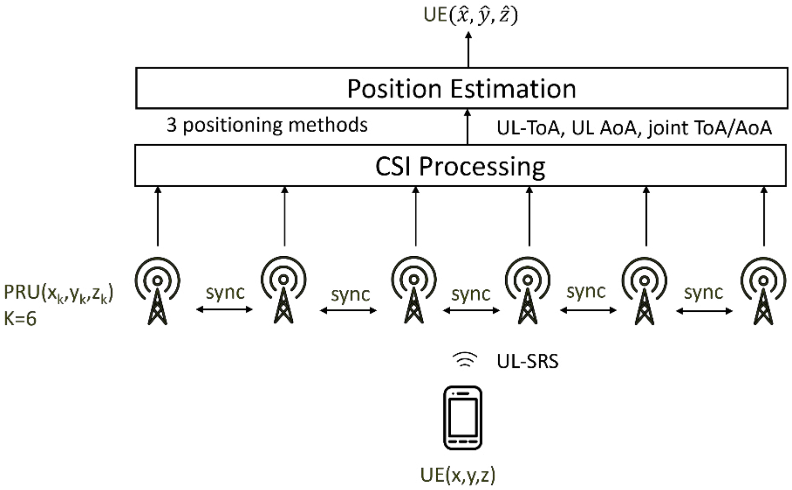


*Figure 22: Schematic measurement setup [26]*

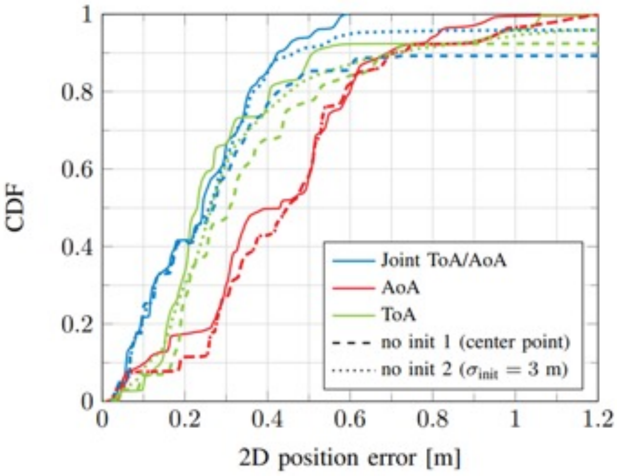


*Figure 23: Achievable positioning accuracy shown as CDF [26]*

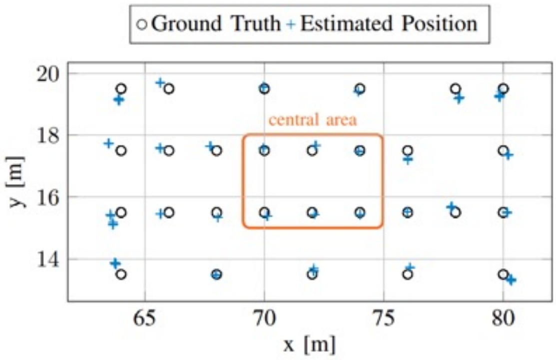


*Figure 24: Ground truth positions (circles) and estimated positions (crosses) of the UE [26]*

### 6.2.2 Network-based positioning in an outdoor automotive test track

The second demo setup for network-based positioning that has been investigated within the EPos work item was an outdoor testbed at the *autodrome de Linas-Montlhéry* (France). The demo was based on the EU-funded project 5GCAR – 5G Communication Automotive Research and Innovation and showcased VRU protection through 5G network-based positioning. The demo showed 5G radio-based positioning enriched with road user trajectory estimation for a collision warning system. The use case was to apply positioning to the prediction of an imminent collision and automatic messages which alert the car driver to prevent the collision with a VRU dummy.

The setup consisted of two UEs; one representing a car, and the other a VRU. Both UEs move along predefined trajectories shown in Figure 25. The VRU dummy is arranged to cross an intersection that is approached by the car with the potential risk of a collision. Both UE types are transmitting 5G UL-SRS at 3.6GHz carrier frequency.

Six receiver antenna arrays are connected to four tightly synchronised receiver units (AP7, AP8, AP17, AP18), as shown in Figure 25. In that setup, two scenarios have been studied: the critical scenario, where a second/unrelated car is obscuring the view (preventing the first car from "seeing" the VRU). In the non-critical scenario, there was no obstruction.

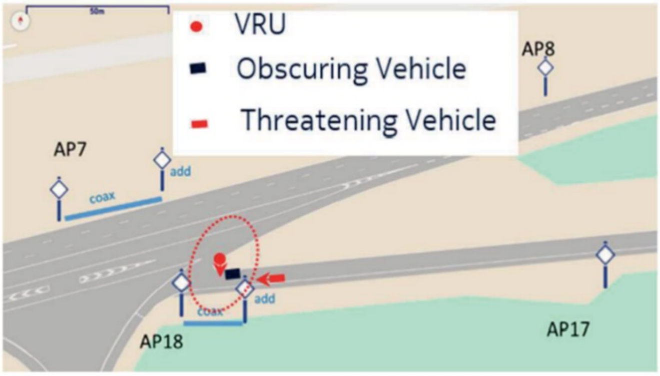


*Figure 25: 5GCAR outdoor demo setup at test track in France [27]*

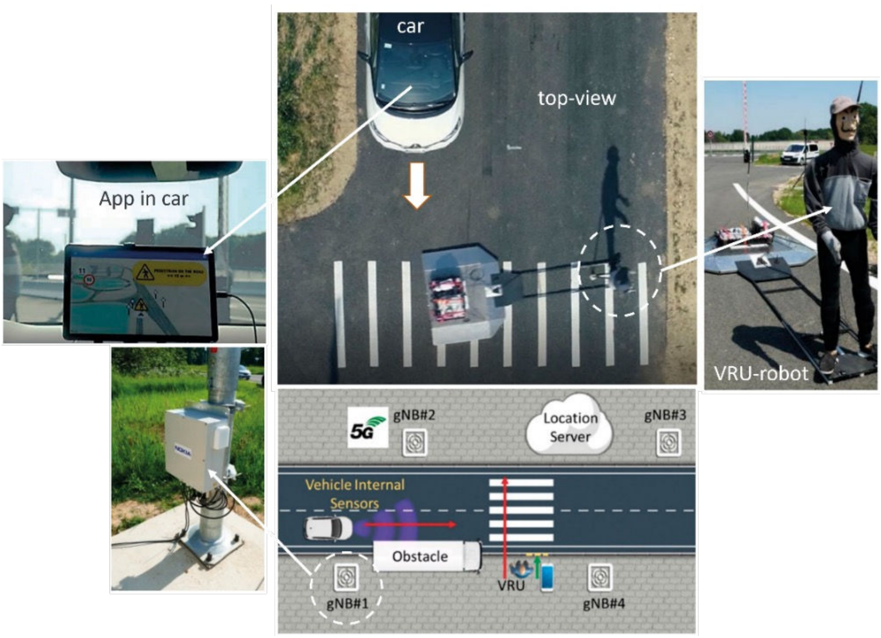


*Figure 26: Overview of the components used in the demo setup*

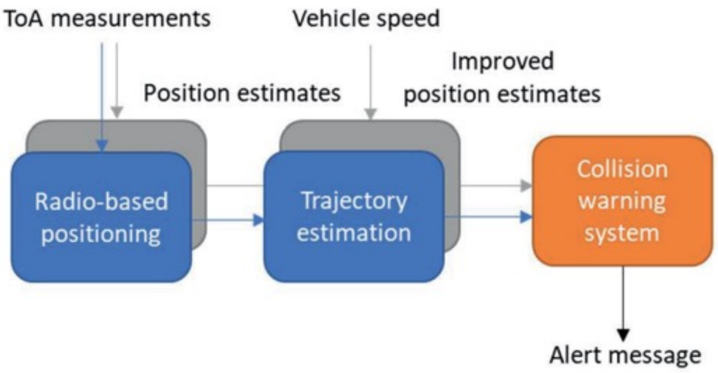


*Figure 27: Signal flow for network-based positioning and trajectory estimation [27]*

As illustrated in Figure 26 the 5G network-based positioning has been enhanced by tracking methods (estimating the trajectories of the moving car and the VRU) applied to improve the positioning estimates by Unscented Kalman Filter (UKF) and Particle Filter (PF). The network-based positioning is based on UL-TDoA. The initial position estimates are then further fed into to the trajectory estimation module, which carries out Bayesian tracking of the position and the speed of the road users. Further details on the applied algorithms for the trajectory estimation can be found in [27].

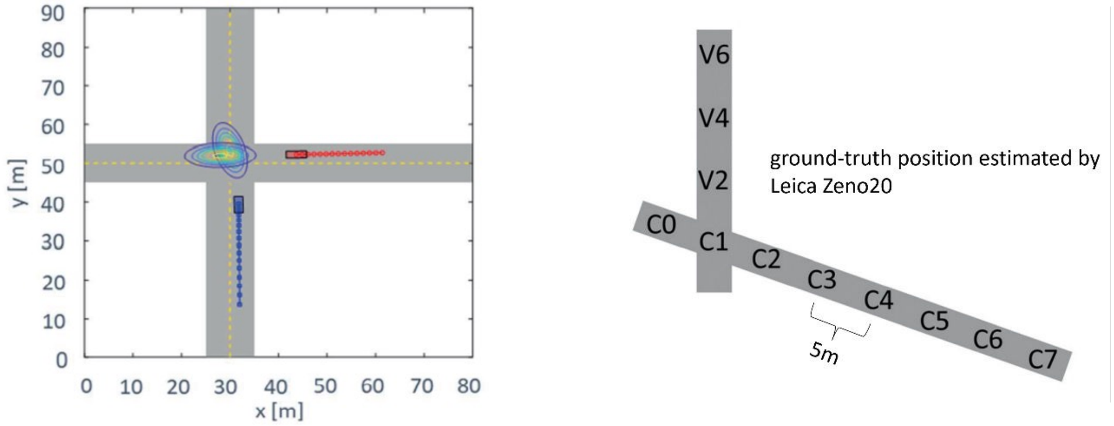


*Figure 28: Probability of collision based on estimated trajectories [27]*

Figure 28 shows the computed probability of a collision based on the estimated future trajectories derived from the positioning estimates. That algorithm has been applied to the experimental setup, where the 11 ground truth reference positions have been defined with 5m distance (C points for the car trajectory and V points for the VRU trajectory).

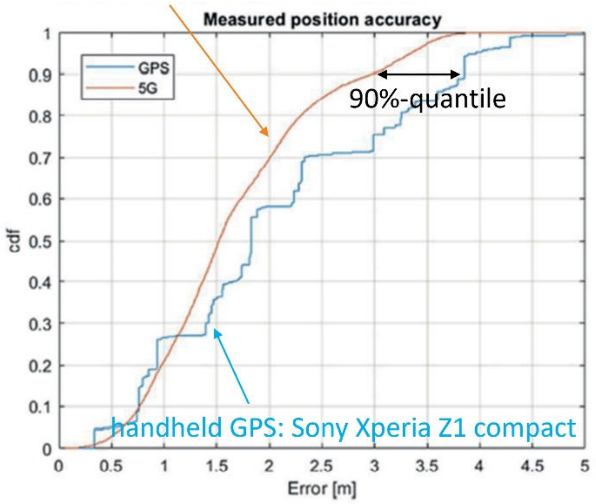


*Figure 29: 5G network-based positioning (without any post-processing) [27]*

Figure 29 shows the cumulative density function of the position error calculated by measuring the above-mentioned reference points with the 5G-based demonstrator setup at the test track, without any PF post-processing or sensor fusion. The baseline is the GNSS position estimate (blue curve) obtained with a handheld device (Sony Xperia Z1 Compact). As can be seen from the CDF by the step-wise behaviour of the blue curve, the handheld device did some filtering of the raw measurements. However, the 5G positioning system still provides better performance in the considered scenario (90%-quantile of 3.0m vs. 3.8m).

### 6.2.3 Network-based positioning deployment assumptions in 3GPP

While the positioning demos in sections 6.2.1 and 6.2.2 have been based in real-life deployments of RAN nodes, 3GPP has discussed within the scope of Rel-18 the deployment options for roadside units (RSU) in the context of using the RSU for positioning (either network- or sidelink-based positioning). The generic deployment options are based on the typical 3GPP outdoor Uma & Umi hexagonal grid with inter-site distances from 500m (case 1) up to 1,732m (case 3).

RAN1 (agenda item 9.5.1.2 Eval of NR SL Positioning) considers *symmetric* and *staggered* RSU deployments with a RSU distance of 200m. The two figures below illustrate assumed deployments for RSU.

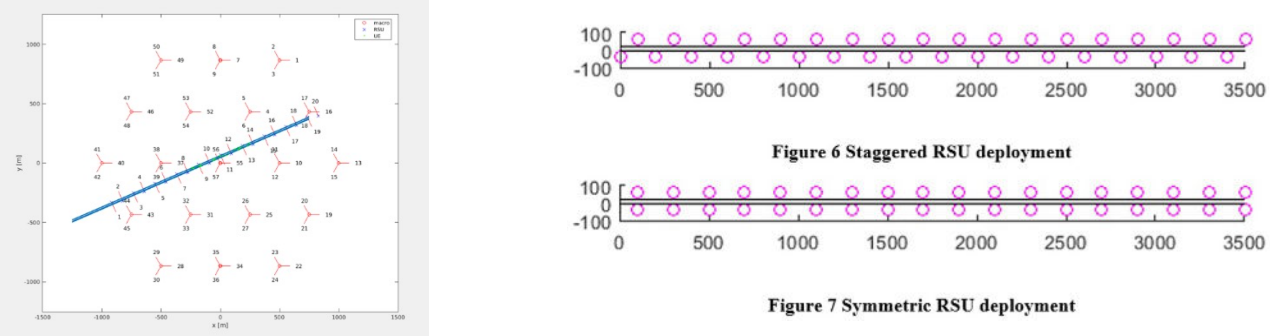


**Figure 6 Staggered RSU deployment**

**Figure 7 Symmetric RSU deployment**

Figure 30: Assumed RSU deployment [left: R1-2207619, right: R1-225854]

## 6.3 5G-V2X network simulator: Positioning in 5G Bavaria automotive testbed

Fraunhofer IIS has developed a 5G C-V2X (i.e. a 5G-V2X) network simulator to analyse V2N/I and V2V use cases for remote driving and sidelink communication. The versatile tool is accessible via a web-GUI at iis.fraunhofer.de/c-v2xsim.

The scenario used in the EPos work item to evaluate network-based positioning methods is based on the real-life deployment of the *5G Bavaria* automotive testbed in Rosenheim, Germany. This is a 5G test environment, in operation since May 2022, consisting of an independent 5G network with three sites (real traffic) in Rosenheim. Handover and roaming scenarios in the 5G testbed and to public networks can be analysed for various road types. In the context of EPos, this network simulator was used to create a virtual drive-test, whose heatmap resembles the RSSI at or on the UE/vehicle. The underlying question is: How many base stations are above a certain threshold for reception (e.g., RSSI above -90 dBm) in order to fulfil the requirement to perform triangulation?

*Table 9: Main parameter of 5G-V2X network simulator*

| Parameter | Possible values |
|---|---|
| Custom scenarios | Simulation area + vehicle density + BS placement |
| Scheduler policy | Choice of Proportional Fair, Max CI, Round Robin, QoS-based Scheduler |
| Frequency band | Currently availableN1 (2.1GHz), N7 (2.6GHz), N3 (1.8GHz), N78 (3.5GHz) |
| Bandwidth | Configurable between 20MHz, 50MHz, 90MHz |
| Building height | Configurable average building height |
| RSSI threshold | Determines how the heatmap for EPOS is visualised |
| Used channel model | Choice of various channel models from TS 38.901<br>Different fading models (JAKES, Rayleigh, Nakagami)<br>Configuration of BS/UE Noise Figures<br>Enable/Disable Shadowing |
| Node Tx power | Configurable BS + UE TX power<br>Default values are 23 dbm for UE and 43 dbm for gNB |
| Antenna parameters | Configurable antenna gain + height<br>(Default: 0dBi/ 1.5m for UE and 8dBi/25m for gNB)<br>SISO model, Omni-directional antenna patterns |
| Numerology | 5G Numerologies (μ = 0,1,2,3,4) |
| Noise parameterisations | Cable Loss, Noise figures for terminals, and Thermal Noise PSD<br>Default values: (CL:2dB, NF_UE: 7dB, NF_gNB:5dB, TN_PSD: -174 dBm/Hz) |

The simulation is built to estimate the coverage of a give network scenario. In order to generate the heatmaps, the simulation area is divided into equidistant data points with a user-defined granularity. Whenever a vehicle/UE performs a measurement, its position is mapped into the closest data point and its calculation statistics are updated. Finally, all collected data is processed after the simulation run and transformed into the shown heatmap.

The calculation of the RSSI is done within a user-defined period at all UE terminals and from all candidate gNBs in the simulation. The channel model used to calculate the RSSI is compliant with the 3D model described in (3GPP – TR 36.873) for the calculation of the 'pathloss' component. In addition to the stochastic models to determine LOS/NLOS existence, we implement a deterministic model to establish whether a building lies as an obstacle between UE and gNB based on the simulation geometry, terminal positions and configured building heights. The RSSI is calculated as follows:

$RSSI = P_{Tx} + G_{Tx} + G_{Rx} + N - PL$

Where $P_{Tx}$ is the gNB power and the $G_{Tx}$, $G_{Rx}$ are the gains of the gNB and UE respectively, N is the total noise power (thermal + Receiver NF), and PL is calculated according to the specifications in (3GPP – TR 36.873) given the type of scenario and the existence of LOS and NLOS components. For example, in the case of urban macro-cell and LOS components the PL will be calculated as follows:

$PL = 40\log_{10}(d_{3D})+28.0+20\log_{10}(f_c) - 9\log_{10}((d'_{BP})^2+(h_{BS}-h_{UT})^2)$

Where the $h_{BS}$, $h_{UT}$ are the user configured heights of the base station and UE terminal and the $d_{3D}$ is the 3D distance between the terminals visualised in the figure below.

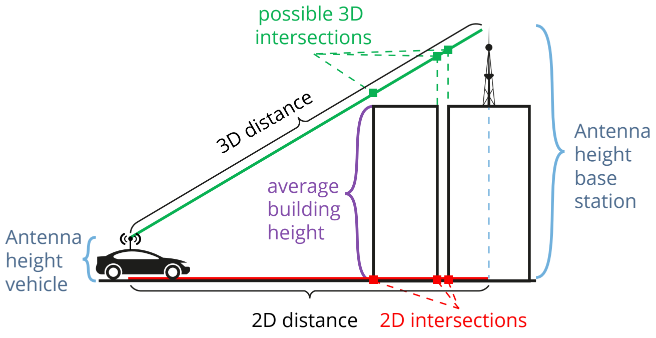


*Figure 31: Calculation of 3D distance*

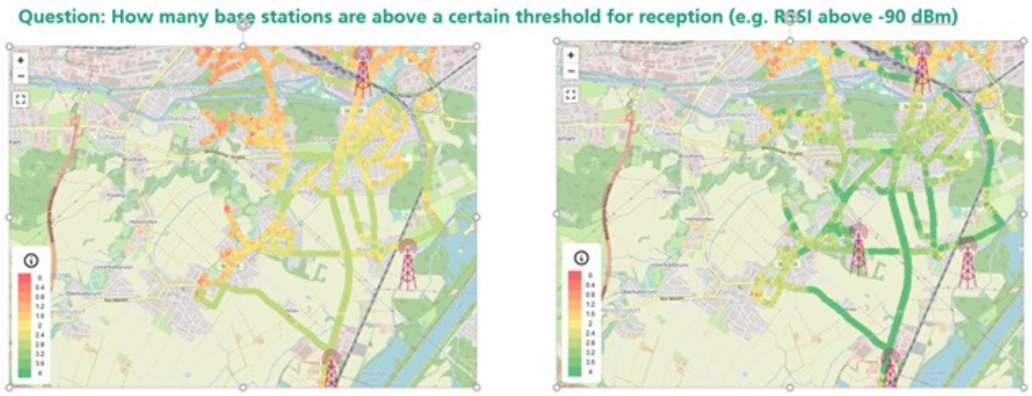


*Figure 32: Example simulations with three and four GnodeBs*

## 6.4 Conclusions on 5G-based positioning in Rel-16/17

With the introduction of 5G as of Rel-15, a versatile framework for positioning has been started. This framework includes new core-network functionalities as well as powerful positioning solutions, such as TDoA, AoA and AoD/UL-TDoA, etc. In subsequent releases, 3GPP paved the way for continuous enhancement of 5G positioning. As positioning became a native service in the 3GPP ecosysem, it can be seen as add-on to the existing communication services in 5G networks. Without the need to deploy additional dedicated positioning infrastructure, 5G positioning solutions can be used with standardised modules.

We observed that the network-based positioning investigations to date have mainly focused on indoor use cases. In the previous subsection we tried to relate or apply the findings to outdoor use cases. The first real-world demonstration and simulation using the testbed in Germany revealed that the achievable positioning accuracy is highly dependent on the deployment of the positioning infrastructure. In the analysis of the simulator in Section 6.3. we have investigated various 'deployments', viewed in terms of coverage optimal vs. position optimal, or a point along the time scale between the two.

It should be noted that 3GPP is currently working to enrich the positioning framework by introducing new aspects – such as carrier-phase positioning and positioning integrity – into current and future releases.

# 7 5G sidelink-based positioning (3GPP Rel-18 positioning solutions)

## 7.1 Sidelink-based positioning

In Rel-17, the study on “Scenarios and requirements of in-coverage, partial coverage, and out-of-coverage NR positioning use cases”, which focused on V2X and public safety use cases, has been captured in [21]. Additionally, SA1 has developed requirements for so-called “ranging-based services” in [22] and positioning accuracy requirements for IIoT use cases in TS [23] in out-of-coverage scenarios. To support the use cases, scenarios and requirements identified by the above activities, 3GPP has decided to study and develop sidelink (or SL) positioning solutions in Rel-18.

The scope of Rel-18 sidelink positioning is defined in [7] as follows:

- Scenario/requirements/use cases/spectrum for SL positioning
- Identify specific target performance requirements for the evaluation based on existing 3GPP work and inputs from companies
- Define evaluation methodology to evaluate the use cases and coverage scenarios of SL positioning, reusing existing methodologies of sidelink communication and positioning wherever possible
- Study and evaluate the feasibility and performance of potential solutions for SL positioning, considering relative positioning, ranging, and absolute positioning
- Evaluate bandwidth needed to meet the identified accuracy requirements (FR1: up to 100MHz, FR2: up to 400MHz)
- Design positioning methods (e.g., SL-TDOA, SL-RTT, SL-AOA/D, etc) including SL-only-based positioning, combining Uu- and SL-based positioning
- Design physical layer perspective schemes for sidelink positioning purposes, including SL positioning reference signal design, resource allocation, measurements and reporting, and associated physical layer procedures
- Design positioning architecture and signalling procedures to enable sidelink positioning covering both UE-based and network-based positioning.

In parallel to this work item, 3GPP conducted the respective study. In this chapter, we will review the outcome of the study and derive implications on the respective use cases and user stories. Please note that at this point the normative phase of SL positioning is not finalised. The performance and capabilities of Rel-18 sidelink positioning might therefore slightly differ from the study outcome.

### 7.1.1 Study outcome Rel-18

The agenda under Rel-18 specifies solutions for support of sidelink positioning (including ranging) in NR systems, and included the objectives summarised in the table below.

*Table 10: Objectives during Rel-18 sidelink positioning study*

| | | |
|---|---|---|
| 1 | Specify SL PRS for support of sidelink positioning such that the SL PRS uses a comb-based (full RE mapping pattern is not precluded) frequency domain structure and a pseudorandom-based sequence where the existing sequence of DL-PRS is used as a starting point:<br>- Support for SL PRS bandwidths of up to 100 MHz in FR1 spectrum.<br>- SL PRS transmission in FR2 is not precluded but no FR2 specific aspects will be specified. | RAN1 |
| 2 | Specify measurements to support RTT-type solutions using SL, SL-AoA, and SL-TDOA. | RAN1<br>RAN2 |
| 3 | Specify support of resource allocation for SL PRS; including resource allocation Scheme 1 and Scheme 2, where Scheme 1 corresponds to a network-centric SL PRS resource allocation and Scheme 2 corresponds to UE autonomous SL PRS resource allocation. | RAN1 |
| 4 | Specify support of resource allocation for SL PRS: Support resource allocation for shared resource pool with Rel-16/17/18 sidelink communication and dedicated resource pool for SL PRS. | RAN1 |
| 5 | Specify procedures for transmit power control for SL PRS transmissions at least based on open loop power control (OLPC). | RAN1 |
| 6 | Specify signalling and associated UE behaviour for support of unicast, groupcast (not including many-to-one) and broadcast of SL PRS transmissions. | RAN1<br>RAN2 |
| 7 | Specify reporting signals and procedures to facilitate support of SL positioning in all coverage scenarios and for PC5-only and joint PC5-Uu scenarios:<br>- Protocols and procedures for SL positioning between UEs (i.e. protocol for sidelink positioning procedures, or SLPP).<br>- Protocols and procedures for SL positioning between UEs and LMF. | RAN2<br>RAN3 |
| 8 | Specify signalling to NG-RAN for sidelink positioning and ranging service authorisations as needed. | RAN3<br>RAN2 |
| 9 | Specify corresponding new core requirements, as well as identifying and specifying the impact on the existing RAN4 specification, including RRM measurements and procedures. | RAN4 |

In Rel-18, some agreements were made on the following topics summarised in the table below.

*Table 11: Selection of agreements during sidelink positioning study*

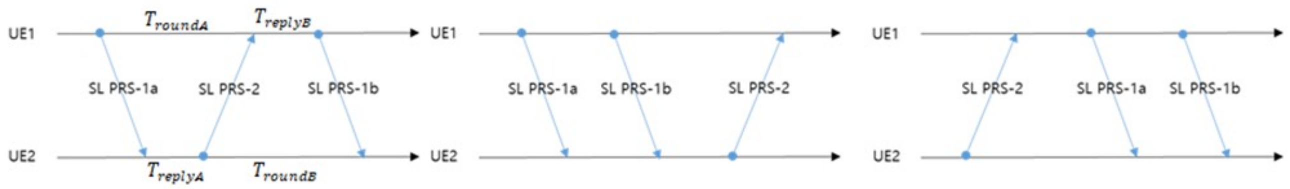
| | |
|---|---|
| SL positioning reference signal | - Gold sequence used in DL PRS<br>- DL PRS comb-patterns are reused as much as possible<br>- Comb-based and TDM-based multiplexing of SL PRS resources within a slot |
| Measurement and reporting for SL positioning | - SL-PRS based RSTD measurement<br>- SL-PRS based RTOA measurement<br>- SL-PRS based Azimuth of arrival (AoA) and SL zenith of arrival (ZoA) measurement<br>- SL-PRS based RSRP measurement<br>- SL-PRS based RSRPP measurement |
| Resource allocation for SL positioning reference signal | - Network-scheduled (Scheme 1) and UE autonomous selection (Scheme 2)<br>- Slot structure for SL PRS transmission in a dedicated/shared resource pool<br>- Coexistence of SL PRS and SL communication data transmission in a shared resource pool |

In Release 18, synchronisation error-handling for SL TDoA and the reliability of SL PRS reception were discussed.

Synchronisation error is a source of positioning error in many techniques explored. In particular, TDoA is sensitive to synchronisation error between anchors. Typically, UEs have not synchronised with each other in sidelink communication.

RAN1 identified possible options to mitigate the impact of synchronisation error in SL TDoA, including UE implementation, reporting sync-timing error, restricting anchor UEs to minimise error, and other mitigation mechanisms.

RTT is a more robust way of handling synchronisation errors, but they can still appear if the clock frequencies of one two UEs don't match. Double-sided RTT can solve such 'clock frequency' errors, and details including the flexibility of the transmission order are being discussed.



Another discussion topic is reliability. SL transmission, especially in Scheme 2, may have a reliability issue due to the imperfection of the scheduling. Repeated SL PRS transmission is being considered as a potential solution to enhance the reliability.

In turn, 3GPP investigated the sidelink positioning accuracy for V2X in two different environments, i.e., an urban grid and the highway.

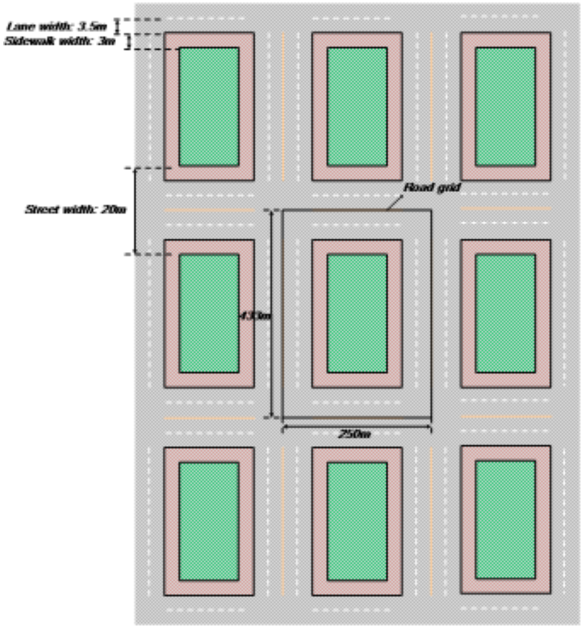


Figure 33: Urban grid from [24]

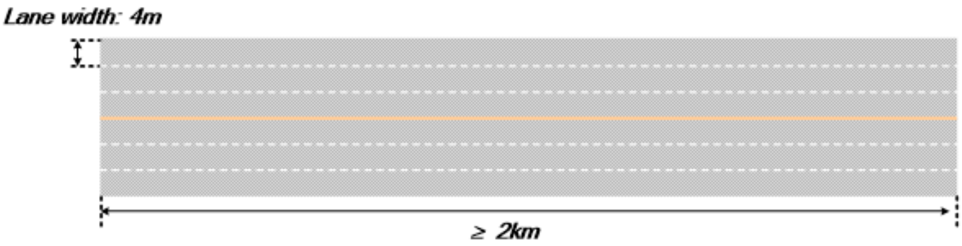


*Figure 34: Highway from [24]*

In a first step, we will compare the positioning requirements defined in the Rel-18 study with the requirements from the selected use cases in this work item.

*Table 12: 3GPP Rel-18 sidelink positioning requirements from [7]*

| SL positioning KPIs | V2X | Public Safety | IIoT | Commercial |
|---|---|---|---|---|
| Horizontal positioning accuracy | Set A: 1.5m for 90% of UEs (absolute or relative) | 1m for 90% of UEs; (absolute and relative) | Set A: 1m (absolute or relative) for 90% of UEs | 1m (absolute or relative) for 90% of UEs |
| | Set B: 0.5m for 90% of UEs (absolute or relative) | | Set B: 0.2m (absolute or relative) for 90% of UEs | |
| Vertical positioning accuracy | Set A: 3m for 90% of UEs (absolute or relative) | 2m (absolute or relative between 2 UEs) for 90% of UEs | Set A: 1m (absolute or relative) for 90% of UEs | 2m (absolute or relative) for 90% of UEs |
| | Set B: 2m for 90% of UEs (absolute or relative) | 0.3m (relative positioning change for 1 UE) for 90% of UEs | Set B: 0.2m (absolute or relative) for 90% of UEs | |
| Angle accuracy | Set A: Y = ±15° for 90% of the UEs | | | |
| | Set B: Y = ±8° for 90% of the UEs | | | |
| Note 1: For evaluated SL positioning methods, companies are expected to report: (1) whether each of the two requirements are satisfied, and (2) %-ile of UEs satisfying the target positioning accuracy for a requirement that may not be satisfied with 90%.<br>Note 2: Target positioning requirements may not necessarily be reached for all scenarios and deployments.<br>Note 3: All positioning techniques may not achieve all positioning requirements in all scenarios. | | | | |

It can be observed that 3GPP has down-selected the three requirement sets submitted from 5GAA to two sets, i.e., Set A and Set B. If we recall the requirements for the selected use cases from Section 5.2, we identify that the VRU protection use case would match Set B, and the lane merge use case can be enabled if the requirements from Set A are satisfied.

In addition to the positioning solutions – i.e., RTT type solutions, SL-TDoA and SL-AoA – 3GPP also studied resource allocation. Similar to sidelink communication, SL positioning studies two resource allocation schemes, i.e., resource-allocation assisted by the network (Scheme 1) and a self-organised version (Scheme 2). Please note that in NR sidelink communication, the resource allocation is termed mode 1 and mode 2. Furthermore, two types of resource pools, i.e., a dedicated and shared resource pool, were studied.

The following tables summarise briefly the results of the study, for more details, we refer readers to [7].

Highway scenario:

*Table 13: Overview of number of sources from [7] achieving a respective absolute horizontal accuracy for the highway scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | 3 | 4 | 7 | 3 |
| 0.5m@90% (Set B) | - | 1 | 5 | 1 |

*Table 14: Overview of number of sources from [7] achieving a respective relative horizontal accuracy (no RSU deployment) for the highway scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | - | 2 | 5 | 5 |
| 0.5m@90% (Set B) | - | - | 2 | 5 |

*Table 15: Overview of number of sources from [7] achieving a respective distance accuracy of ranging for the highway scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | 5 | 1 | 4 | - |
| 0.5m@90% (Set B) | - | 3 | 4 | 3 |

Urban Grid Scenario:

*Table 16: Overview of number of sources from [7] achieving a respective absolute horizontal accuracy for the urban grid scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | 2 | - | 1 | 7 |
| 0.5m@90% (Set B) | - | - | 1 | 9 |

*Table 17: Overview of number of sources from [7] achieving a respective relative horizontal accuracy (no RSU deployment) for the urban grid scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | - | 2 | 5 | 3 |
| 0.5m@90% (Set B) | - | - | 1 | 6 |

*Table 18: Overview of number of sources from [7] achieving a respective distance accuracy of ranging for the urban grid scenario considering different transmission bandwidth*

| | 20MHz | 40MHz | 100MHz | Not achieved |
|---|---|---|---|---|
| 1.5m@90% (Set A) | 4 | 2 | 4 | 3 |
| 0.5m@90% (Set B) | 1 | 4 | 4 | 7 |

Following the study outcome from [7] and considering the available spectrum we conclude that the requirements for Set B are very difficult to achieve, especially in the VRU protection use cases. At the same time, there is a quite broad range in the achieved accuracy among the companies contributing to the 3GPP study. This is caused by the different assumptions regarding deployment of RSUs and the maximum distances between the UEs. As the maximum distance mainly impacts the probability of NLOS conditions, the observed accuracy can vary significantly. Furthermore, it should be noted that the study only takes single snapshots, i.e., no tracking. As we observed in the previous chapter, introducing Kalman filtering and other such techniques might improve the performance.

Therefore, in the next subsections we try to adjust the rather generic 3GPP simulation assumptions to our specific use cases.

## 7.2 Real-world deployments overview

As 3GPP has not finalised the normative work, no real-world demonstrations or deployments for sidelink positioning considering V2X use case are available. Nevertheless, in this section we will discuss simulation results for SL positioning considering the use cases considered in this work.

## 7.3 Findings related to the use cases

As discussed above, real-world implementations are difficult to realise at this stage. Nevertheless, in literature, multiple publications address sidelink positioning and also hybrid positioning approaches including the coexistence with SL communication [18, 19].

In the scope of this work item, we identified that paper [19] adequately addresses the VRU use case and evaluates the achievable performance using ray tracing simulations.

*Figure 35: VRU Use Cases Description from [19]*

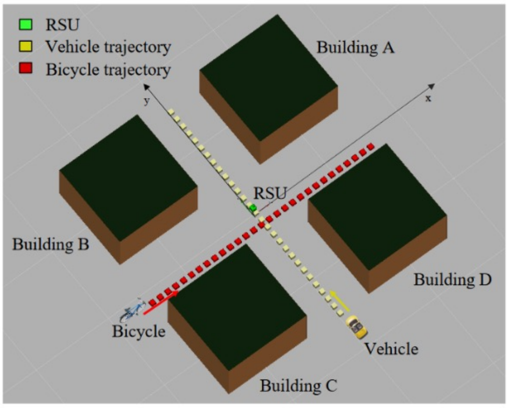


*Figure 36: VRU trajectories from [19]*

In [19], the authors performed a realistic evaluation of sidelink V2X round-trip-time (RTT) positioning towards 3GPP Release 18 using ray-tracing data, and focusing on operations outside the network coverage. In addition, novel performance bounds were proposed to predict positioning in extreme multipath situations – by accounting for inter-path interference.

In the paper, both the positioning performance with support by the RSU and without RSU support, is evaluated.

Table 19: Simulation assumptions in [19]

| Parameter | Settings |
|---|---|
| Transmitter | Single omnidirectional antenna |
| Receiver | Single omnidirectional antenna |
| Carrier frequency | 5.9GHz |
| Bandwidth | 20MHz in total, 167 subcarriers, 120kHz subcarrier spacing |
| Pilot signal | OFDM, 12 symbols with a constant amplitude |
| Transmitter power | 10dBm |
| Noise spectral density | −174dBm/Hz |
| Receiver noise figure | 8dB |
| Number of RSU | 1 |
| Number of users | 1 vehicle, 1 bicycle |
| RSU location | [0 0 10] metre |
| Landmarks | 4 buildings |
| Sampling time | 100ms |
| Speed | Vehicle: 4m/s, bicycle: 1.4m/s |

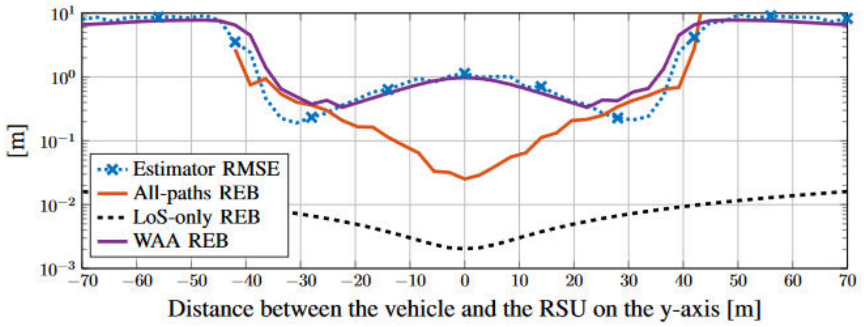


Figure 37: Sidelink ranging performance for the VRU use cases with RSU deployment

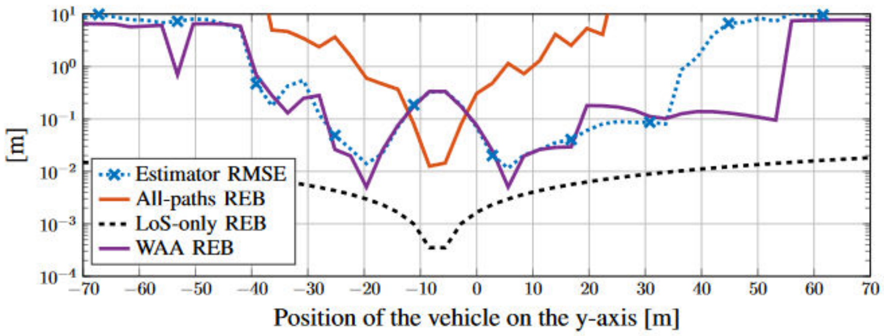


Figure 38: Sidelink ranging performance between vehicle and VRU from [19]

Figure 37 shows the RMSE performance of the ranging to the vehicle and bicycle. Figure 38 shows the RMSE for the Scenario without RSU. With respect to the positioning requirements, we note that for the scenario with RSU support, within about 40m from the RSU, the moderate accuracy (1-3m) requirement can be exceeded. For the second scenario, moderate accuracy is also attainable when vehicle and bicycle are sufficiently close to each other. The sudden decreases/increases in ranging accuracy are caused by the disappearance of strong NLOS paths caused by the buildings, which in turn alleviate the inter-path interference.

## 7.4 Conclusions on 5G sidelink-based positioning

In this section we investigate the potential role of sidelink positioning to achieve the required positioning accuracy and enable the use cases selected in this work item.

As sidelink positioning is a new technique added in Rel-18, only the outcome of the study phase (not the normative phase) can be reviewed. We observe that 3GPP will enhance the already quite powerful 5G-positoning framework with a large set of new SL positioning-related features, including RTT, TDoA, AoA positioning solutions, but also aspects of resource allocation and resource pool configurations.

Considering the generic 3GPP simulation framework, the strict VRU positioning requirements could not be satisfied with the bandwidth available in the ITS spectrum. However, as the 3GPP investigations did not model the exact user story defined in 5GAA, we performed ray-tracing simulations for simplified urban environment, which revealed that it seems possible to achieve the required accuracy under very specific conditions.

Therefore, we conclude that **sidelink positioning could emerge as an important enabler for precise positioning** considering the availability of sufficient spectrum. Furthermore, real-world tests for the actual user stories are required as the achievable accuracy is highly dependent on the channel conditions, transmission environment and user placement.

# 8 Non-3GPP radio-based positioning complementing/supporting 5G-V2X

## 8.1 UWB-based positioning

One challenge for 5G radio-based positioning is limited bandwidth availability. The accuracy of the distance measurement is related to the bandwidth of the signal. To increase accuracy, there needs to be an increase in the bandwidth.

In 2002, the Federal Communications Commission (FCC) allowed ultra-wide band (UWB) to be used in unlicenced bands, establishing the power, bandwidth, and frequency of the UWB pulses. FCC regulations thus require the bandwidth to be greater than 500MHz with a maximum output power of -41.3dBm/MHz in several bands (most popular from 6GHz to 8.5GHz). For many years, IEEE_802.15.4 worked on standardising UWB for precise positioning and finalised the IEEE_802.15.4z specification in 2020.

A step that catapulted UWB to the commercial forefront was its integration into Apple's iPhone 11 in late 2019. Samsung followed suit with the Galaxy Note 20. Additionally, the Car Connectivity Consortium (CCC) – a cross-industry organisation advancing global technologies for smartphone-to-car connectivity – announced in its release of the Digital Key specification V3.0, the inclusion of UWB as a key part of the security protocol. This allows people to unlock their cars using their cell phone without even needing to take the devices out of their pockets. The base of UWB devices in vehicles will grow as adoption of Digital Key grows.

Digital Key relies on the UWB device in the cell phone communicating with the UWB devices on or in the vehicle. In addition, Bluetooth Low Energy (BLE) is used as the high layer protocol which first connects the phone to the vehicle. Once the BLE connection is established, the UWB then starts its ranging sessions to provide real-time distance measurement. The UWB ranging is point-to-multipoint where there can be several sensors on the vehicle.

In a similar way, 3GPP could be used to implement the higher layer protocol required to establish a trigger-before-talk UWB system enabling distance measurements between any two UWB nodes.

Bluetooth is also referenced in 3GPP 37.355 as an adjunct technology that can be used to establish location. Bluetooth can provide accuracy < 10m. The 3GPP specification provides an interface to Bluetooth devices and beacons to provide positioning measurements. A similar interface could be developed by 3GPP with UWB allowing for exchanges of capabilities, operating parameters, and initialisation and operation.

UWB technology can provide very accurate point-to-point distance measurements. There are many differences between UWB and other RF technologies, mainly in that UWB has been developed specifically to provide high accuracy. A major key to this accuracy is operating with a wide bandwidth of 500MHz. This is significantly larger than most 5G carriers and wider than Bluetooth or WiFi. UWB transmits narrow 2ns impulses and operates below the noise floor at -41.3 dBm/MHz. By measuring the exact time an impulse stream was transmitted and the exact time it is received, the distance can be calculated based on the speed of light.

In order to determine the exact time of reception, a known sequence is transmitted. A very unique, uncorrelated Ipatov sequence [28] is transmitted many times to improve signal to noise ratios. An autocorrelation filter is used to create a histogram which represents the channel impulse response, or CIR. During analysis of the CIR histogram, the first response peak is extracted to determine the line-of-sight distance. This ensures that strong reflections are not misinterpreted as the correct distance. By properly analysing the CIR and extracting the precise timing of the peak, ranging accuracy at the decimetre level is possible.

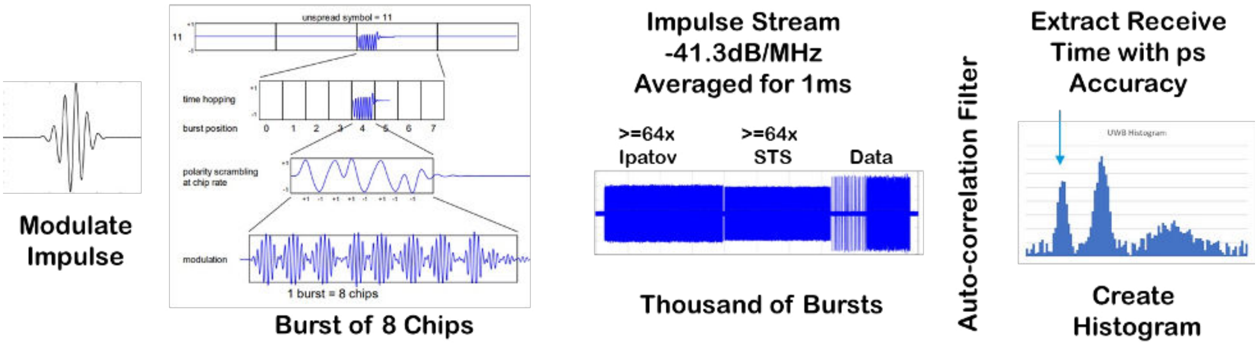


Figure 39: UWB characteristics

The next sequence transmitted is the scrambled time stamp, or STS. The seed for the STS is one of the key pieces of information which would be securely transmitted over the V2X link in setting up the distance measurement connection. Cybersecurity methods are used to generate the seed and then communicate that between endpoints. This ensures that no one can inject a signal aimed at generating a fake or incorrect distance. The STS is a key advantage of UWB to provide security in its distance measurements, thus preventing these “spoofing” attempts.

Establishing trust is a very strong benefit of UWB ranging. While there are many strong cybersecurity methods to ensure secure V2X sessions, there is no way to ensure that the data being communicated can be trusted. As a secure distance measurement system UWB can be used to validate the position of a V2V source transmission, thereby enabling a higher level of trust between the vehicles. In addition, this could also be used to identify misbehaviour, providing a method to further enforce security and trust within the V2V network.

Once both ends of the link have the STS, they can start exchanging distance measurement datagrams and extracting times of arrival. During these exchanges, they also transmit the exact time the signal was transmitted. After several exchanges, known as double-sided, two-way ranging (DS-TWR), both ends can calculate the distance between the two points. One benefit of double-sided ranging is that it allows for the removal of “clock skew” (asynchronous clocks) between the two systems.

Some other key aspects of UWB are beneficial. The exchange of datagrams happens very fast; in under 1ms. This means that many points can be collected at a very high repetition rate. This is much faster than radar, lidar or other radio-based distance measurement systems. Another key aspect of UWB is its simplicity. The full system can be implemented in a single CMOS device with minimum external components. This leads to a very small footprint and less complex software development as well as lower cost. Fast operation coupled with the distance accuracy means UWB can be a very effective method of point-to-point distance measurement.

3GPP incorporating UWB as a non-RAT positioning system would enable V2X to establish and manage UWB links. This would then allow for distance measurement between any two V2X nodes if they are both equipped with UWB transceivers.

### 8.1.1 UWB CCC and FiRa standards

The FiRa (Fine Ranging) Consortium develops requirements for UWB systems. These are extensions of the IEEE 802.15.4z PHY and MAC specifications. The goal is to provide specifications to ensure end-to-end, interoperable UWB systems. The FiRa Consortium has published a UWB MAC and PHY Technical Requirements documents as well as UWB MAC and PHY Conformance Test Specifications. These outline the details for operating UWB devices. They support many modes of operation including double-sided, two-way ranging and angle of arrival (AOA) techniques.

FiRa Consortium UWB PHY Technical Requirements states: “The FC-PHY shall have a ranging accuracy of ±10cm with ≥ 95% success rate at 1-to-10-meter separation in a Line of Sight (LoS) environment.” It also states: “If the FC-PHY supports Angle of Arrival (AOA), the FC-PHY shall have an AOA accuracy of ±5° with ≥ 95% success rate at 0.1 to 2 meter separation and AOA coverage of (-60°) to (+60°) in LOS environment.”

For accuracy, CCC relies on the 802.15.4z specification which provides for confidence levels and confidence interval fields. This provides accuracies from 100ps to 3ns (plus a 0.5 to 4x scaling factor) with confidence from 99% to 20%. 100ps would imply a 3cm accuracy. CCC also states that for the vehicle, clk_ref tolerance should be regulated within ±15ppm over operation conditions.

A great deal of information about the confidence can be extracted from the CIR. If the CIR has a low noise floor and a single clear peak, it can provide greater confidence that the distance is correct. If there is a high noise floor and multiple peaks, the confidence would be lower.

The above accuracies are stated for FiRa and CCC use cases. With the utilisation of UWB in an automobile for distance measurements between vehicles as a new use case, new data must be gathered to determine the accuracy as a function of the use case. Other use cases for a vehicle to infrastructure distance measurement, UWB would likewise need to be quantified.

### 8.1.2 UWB for vehicle-to-vehicle

Using DS-TWR and two UWB transceivers on each surface of a vehicle enables both the distance and orientation between the vehicles to be measured. Two sensors also provide redundancy to help meet automotive safety integrity level (ASIL) requirements. Having sensors on all four surfaces provides 360 degrees of coverage.

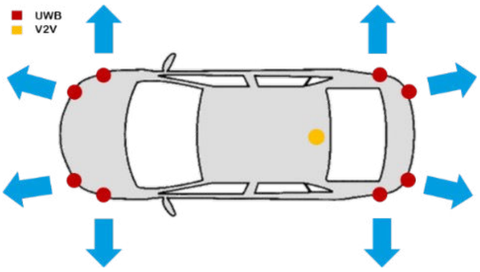


*Figure 40: Exemplary antenna placement*

UWB is limited to line-of-sight distance measurements. However, the use cases needing the most accuracy are when two vehicles are close to each other and in direct line of sight. For example, two vehicles following each other can accurately measure the distance between them since it is a direct line-of-sight measurement. The antennas are directly facing each other and there is nothing between the two vehicles (except possibly rain or snow).

### 8.1.3 UWB for vehicle-to-infrastructure

With vehicle to infrastructure positioning, one end of the distance measurement is fixed at a known point which could be conveyed using an HD map. Given the known location, the exact position of the vehicle could be determined. Knowing the vehicle is in motion and collecting distance measurements to the fixed object along the path and knowing the distance travelled between each point (via "dead reckoning") the exact location of the vehicle can be determined. A V2X + UWB sensor mounted in a RSU, such as a streetlight or a traffic light, could be used to determine the exact location. This could provide periodic updates to the dead-reckoning system in the vehicle in situations where GNSS is inaccurate or unavailable (such as a tunnel). It could also help to detect C-ITS stations which are misbehaving.

### 8.1.4 UWB and interactive VRU crossing

One of the key factors that can improve VRU safety is that most people carry cell phones. At the same time, UWB is becoming common in many of these cell phones as well as in many vehicles. If RSUs were to adopt UWB as well, then it could become a ubiquitous method of measuring distance between two V2X-enabled systems.

The following shows a possible configuration where a vehicle and a vulnerable road user are connected with two UWB links enabling the vehicle to determine the exact position of the VRU. They can establish a UWB link and continually measure the distance between them, to ensure they maintain a safe separation.

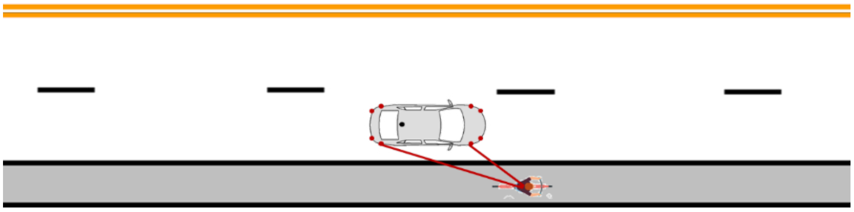


*Figure 41: UWB Point-to-Point Connections in a Lateral Overtaking*

### 8.1.5 UWB and cooperative lane merge

In the cases involving merging traffic, the vehicles involved can use V2X to form a group and then start a three-way UWB connection enabling them to continuously monitor their separation. This would allow for all vehicles in a group to know the relative distance between them.

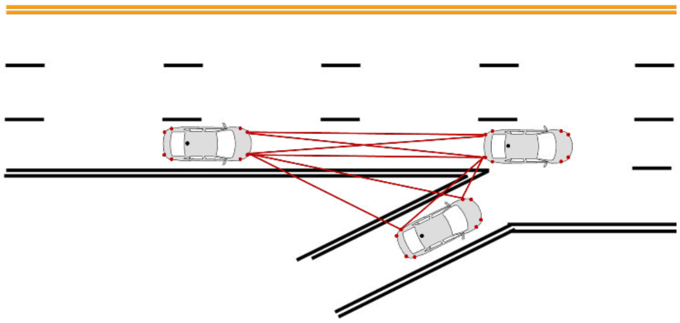


*Figure 42: UWB Point-to-Point Connections in a Lane Merge*

## 8.2 Sound-wave-based positioning

A smartphone based VRU protection service is being proposed to protect VRUs such as children and pedestrians. The service utilises messages (i.e., PSM, VAM) containing VRU status information, thus making precise positioning and the technology that delivers it an essential feature.

However, the performance of the GNSS module installed in the smartphone is not suitable for precisely locating the VRU. For example, it is difficult to distinguish whether the location of the VRU is a pedestrian street or a vehicle road. Therefore, additional local positioning technology is required in areas where GNSS positioning performance is low or in certain dangerous areas (i.e., school zone, parking lot, crossroad). Sound-wave positioning can obtain high-precision positioning results on a smartphone using an existing microphone without an additional device.

### 8.2.1 Sound-wave positioning overview

For sound-wave positioning, four anchors in fixed positions are basically required. Synchronised anchors simultaneously transmit acoustic signals on different frequency bands. Local servers generating sound-wave signals can be centralised or decentralised, as shown in the figure below. Positioning parameters such as frequency band and location information of each anchor are transmitted to the smartphone in advance through the SP server. Then, the smartphone receives the sound-wave signal through the built-in microphone and establishes the VRU's position through a process shown and explained below.

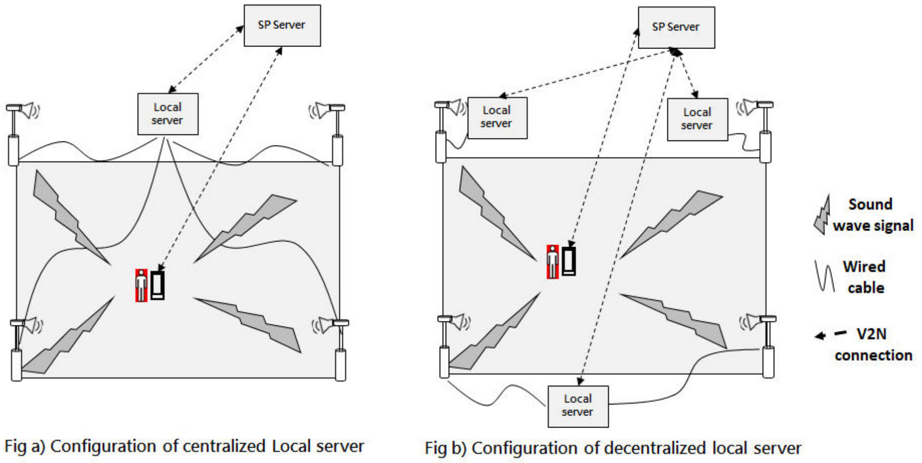


Fig a) Configuration of centralized Local server

Fig b) Configuration of decentralized local server

*Figure 43: Overview of the sound-wave positioning system*

In the case of a sound wave, people can generally hear it as an audible frequency up to 18kHz, and a sound-wave signal of 18kHz or higher is classified as an inaudible frequency. Smartphones can receive sound waves up to 22kHz, which exceeds the audible frequency. The positioning device transmits the status (speed, microphone specification, noise) of the device in advance and selects the anchor multiplexing method and parameter based on this information. The sound- wave positioning system utilises these inaudible frequencies to calculate the coordinates of each device. The positioning system transmits sound waves through multiplexing methods such as FDM (Frequency-Division Multiplexing), TDM (Time-Division Multiplexing), and CDM (Code-Division Multiplexing). The positioning device receives anchor parameters (anchor location, multiplexing method, etc.) in advance.

The figure below shows the frequency band of acoustic positioning technology using FDM.

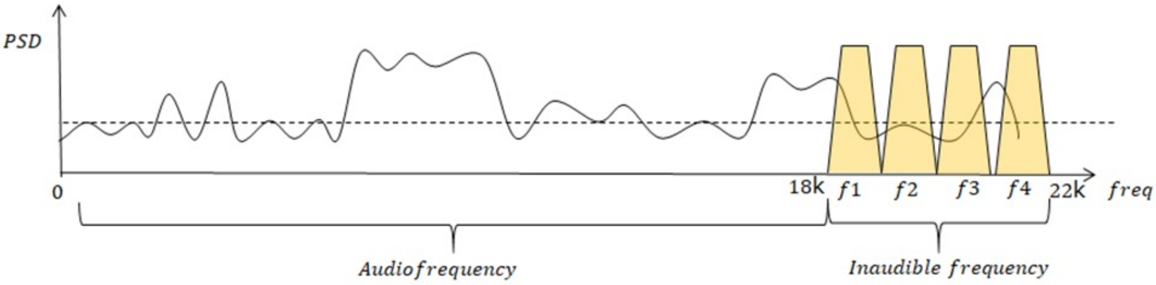


*Figure 44: Sound-wave spectrum and frequency band*

The system configuration for performance evaluation of sound-wave positioning is shown in the table below.

An anchor system is configured as a synchronisation tool for TDoA calculation: four such anchors use inaudible bands in the range of 18~20kHz) with each frequency measuring 1kHz (i.e., 17.5~18.5kHz, 18.5~19.5kHz, 19.5~20.5kHz, 20.5~21.5kHz).

So-called “chirp signals” are used as sound-wave signals because of their ability to handle multipath effects. Each chirp signal is transmitted for 10msec, and each signal is transmitted periodically through a period of 340msec. The transmit power of sound waves is transmitted at 106dB SPL.

*Table 20: Simulation parameters*

| | Parameter |
|---|---|
| Anchor system | Synchronous system |
| Positioning algorithm | TDoA |
| Channels frequencies | 18kHz, 19kHz, 20kHz, 21kHz |
| Channel width | 1kHz (17.5~18.kHz, 18.5~19.5kHz, 19.5~20.5kHz, 20.5~21.5kHz) |
| Sound-wave signal | Chirp signal |
| Pulse time | 10ms |
| Time duration | 340ms |
| Signal power | 106dB SPL |

The figure below shows the reception result after analysing the received signal in the time- and frequency domains for various environments (handheld, pocket, backpack).

Figure a) is the result measured 1m from the speaker with the smartphone in hand. It can be seen that the received signal is good and the influence of multipath is small. Figure b) is the result of measurement at a distance of 40m with a smartphone in the hand. Although the signal is attenuated due to path loss, it is possible to extract the first signal. Figure c) is the result of measuring the received signal at a distance of 5m from the speaker carrying a smartphone in a jacket pocket. Figure d) is the result of measuring the received signal at a distance of 5m from the speaker carrying the smartphone in a backpack.

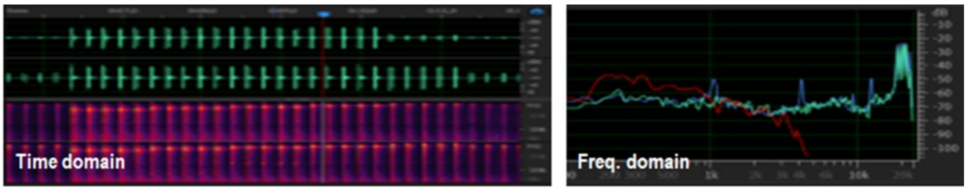


fig a) 1m from the Speaker

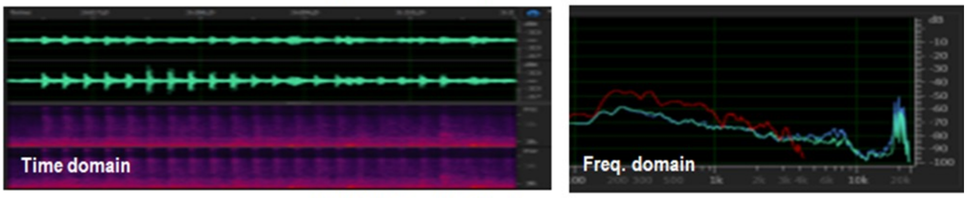


fig b) 40m from the Speaker

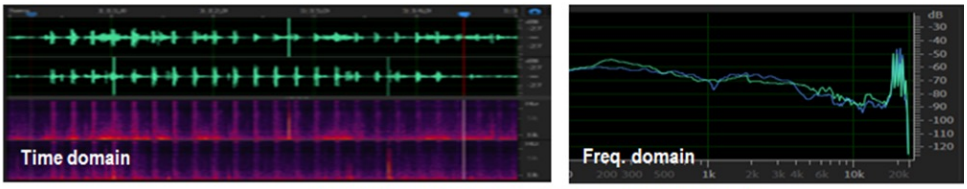


fig c) 5m from the Speaker in the pocket of the jacket

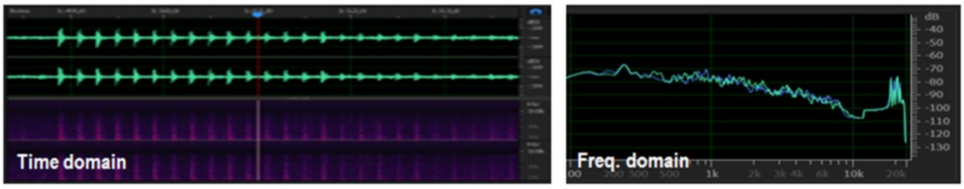


fig d) 5m from the Speaker in the backpack

*Figure 45: Sound-wave signal reception characteristics*

The receiver of sound-wave positioning system is configured as shown in the figure below. It can use multiple smartphone microphone sources to perform a merged signal used for sound-wave positioning or to take an optimal signal using a "MIC Selector" function – the signals are separated by frequency band through a filtering process. Next, the reception time of each separated signal is calculated through a noise-cancelling and matched-filtering process. This then helps to calculate the user (U1) position with reference to anchor positions and the different arrival times of ultrasonic signals from these anchors (TDoA). Finally, the calculated position value is corrected using the vector correction field of each anchor node.

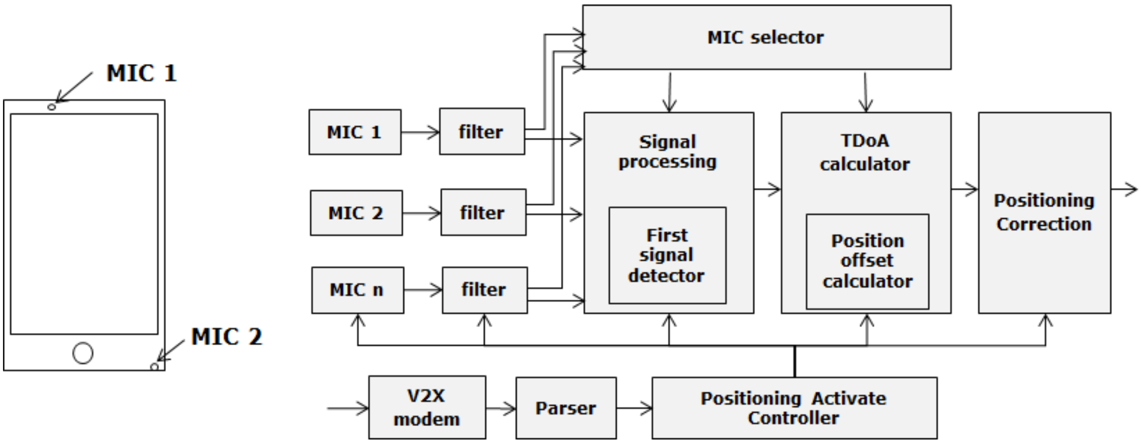
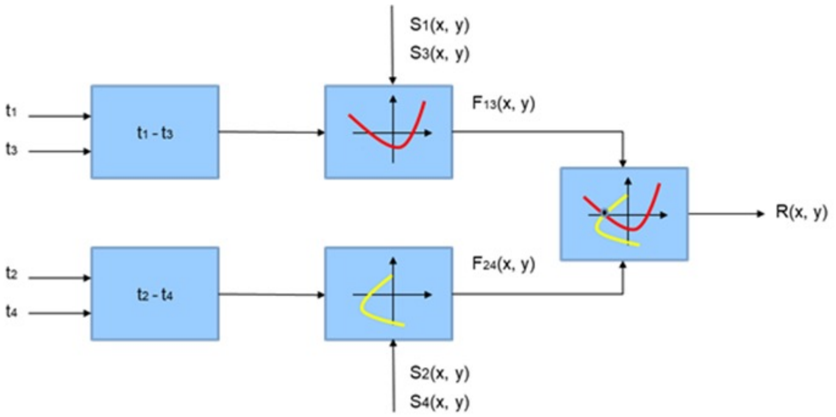


Figure 46: Positioning system architecture

If objects are moving within a limited area, a reference field (electromagnetic or acoustic) can be generated around the area and the object coordinates relative to this field can be identified. The reference field is generated by sound sources installed around the area, the number of sources depends on the method of navigation and required accuracy.

In the case under consideration, there are four sound sources (sufficient minimum is three, the fourth source is used to increase reliability and measurement accuracy). The sound source-receiver synchronisation is not used or impossible. The source signals are strongly synchronised with each other and separated in terms of spectrum for ease of identification at the receiver end.

The difference in arrival time of the pulses from two sound sources defines the difference in the distance between the sound sources and the receiver. This, in turn, defines the surface where the receiver can be located in space. In this case, it is a hyperboloid rotation with the pair of sound sources in its foci. Another pair of sound sources (one of which can also be included in the previous pair) allows the tracing of a second hyperboloid.



| # | Description |
|---|---|
| $S_i$ | Source signals |
| $S_i(x,y)$ | Source signals coordinates |
| R | Receiver |
| R(x,y) | Receivers position |
| $F_{ij}$ | Positioning algorithm function |
| $t_i$ | Signals propagation time |

Figure 47: Positioning processing technology (TDoA) at the receiving device

The intersection of the two hyperboloids gives a line along which the receiver is located. The point at which this line and the hyperboloid intersect, forming a third pair of sound sources, defines the receiver position. What is more, if there are two such points a third hyperboloid is built based on the next pair to identify a correct coordinate. This method helps solve the 3D problem but requires a large number of calculations.

Moving along a plane is a 2D problem and the hyperboloids are replaced by planar lines – hyperbolas. When the receiver and the sources are of different height, but the receiver is moving above a planar surface without changing the height. This is also a 2D problem, but it requires coordinate correction because the slant range distance from the source to the receiver differs from its projection onto a horizontal plane.

The area layout (sound source positions) and the Uniformly Divided Field are merged into a single input source. That data is used to calculate four variants of Vector Correction Field (V1, V2, V3, V4), which are saved by the algorithm. The operation runs once before the start of the navigation calculation. The actual positioning starts when the time delay data (t1, t2, t3, t4) is fed to another input. The data is used to select the best variant and calculate 2D coordinates. The selected variant and coordinates are used to calculate the corrected coordinates.

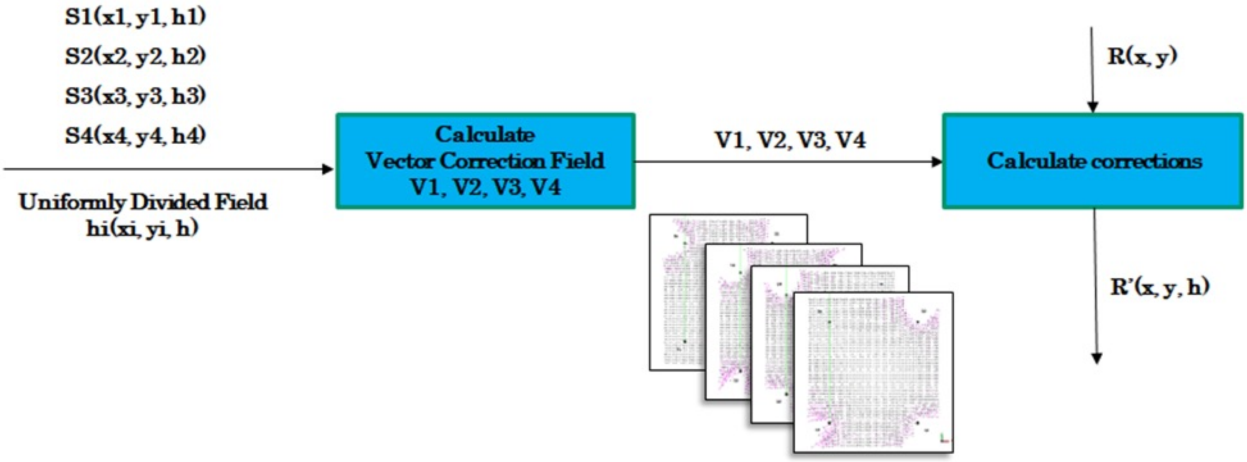
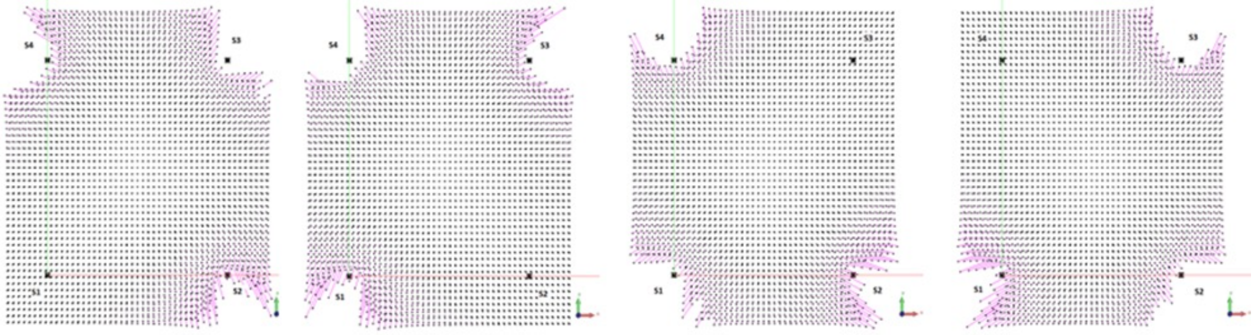


*Figure 48: Positioning correction method using vector correction field*

The correction field is saved and then used to fix the coordinates calculated with the hyperbolic navigation algorithm. The calculated coordinates are used to find the nearest points in the selected correction field, and the linear interpolation is applied to calculate coordinate corrections. A variant of the correction field is selected by excluding a source with the worst signal for the current measurement.



S1 is excluded S2 is excluded S3 is excluded S4 is excluded

*Figure 49: Vector correction field*

A downside of sound-wave positioning technology is its high battery consumption because the smartphone app is continuously in use.  To prevent this, the sound-wave positioning functions are controlled in the phone's Positioning Activate Controller block. The activation methods are as follows. First, the server activates the system by comparing the location of the devices. Second, the device directly compares the position with the local positioning area and activates it. The last method is to activate the positioning system based on the anchor signal.

### 8.2.2 Sound-wave positioning performance

The proposed coordinate correction method improves the accuracy of positioning. The effect is especially visible near the sound sources (anchors).  In the centre, the difference is hardly noticeable. The difference in the height of the sound sources and the receiver is 2m.

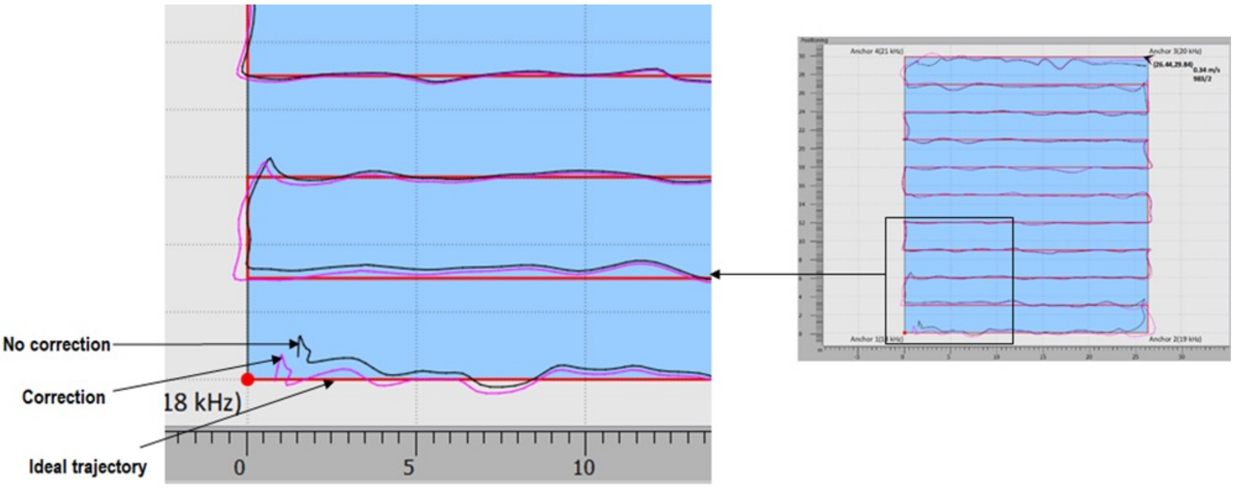


*Figure 50: Positioning correction result*

A test was conducted to verify the performance of sound-wave positioning. Anchor nodes were located at the corners of the 26.4x30m test area (a playground). A 2m corridor along the perimeter of the test area was the critical area to determine the coordinates. In the figure, the red line represents ground truth, and the width of the pink line is 0.8m, indicating a +/-0.4m error.

Measurements were taken while walking along the ground truth path with a smartphone (Samsung S21; Android version) in hand. The total number of test points was measured to be 718. Six samples with an error of more than 1m were measured. The measurement inside the anchor had an error of 0.26m, while outside the anchor recorded 0.38m.

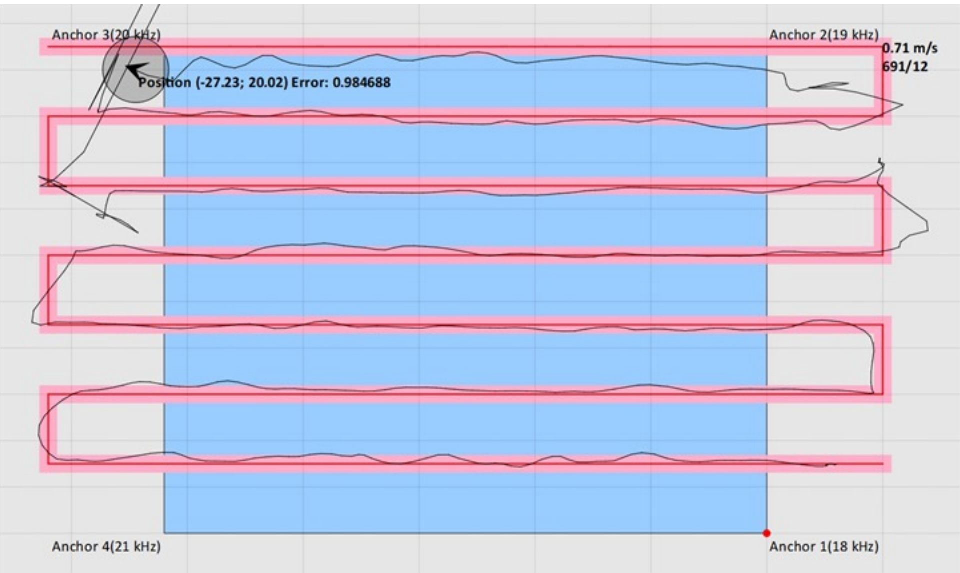


*Figure 51: Sound-wave positioning result*

### 8.2.3 Local positioning service

Using sound-wave positioning can deliver precise results in environments such as underground parking lots where GPS signals are not available, or in areas such as school zones or crossings that require very accurate positioning. Speakers for voice guidance are already installed in school zones and crossings, so it is possible to easily mount a sound-wave positioning system.

### 8.2.4 VRU cross walk service

At crossings and in environments where VRUs need to cross through traffic, accurate positioning is possible through sound-wave positioning. With precise positioning, a VRU in a safe location can avoid false alarms/warnings (pedestrians on the road) due to GNSS offset. It also helps to counter the opposite problem occurring in a dangerous area or crossing for VRUs, where no warning message is sent due to a GNSS error.

## 8.3 Conclusions on non-3GPP radio-based positioning

In this section, we investigated different radio-positioning approaches not relying on the 5G waveform. We discussed the possible interplay between non-3GPP positioning techniques and 5G-V2X. It was observed that using spectrum in the unlicenced regime or in the acoustic domain could also be used to perform fairly precise positioning. In contrast to the positioning approaches studied in the previous chapters, the techniques in this chapter might be especially helpful if the relative distance is small (i.e., less than 20m) and transmission power is restricted.

# 9 Overall conclusion

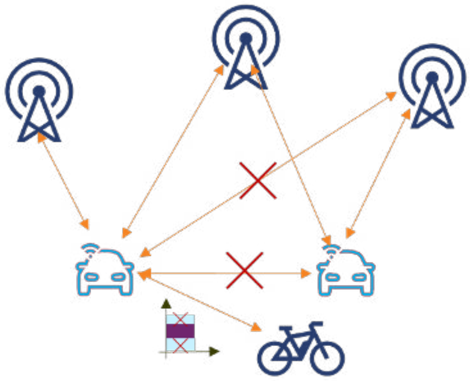


Figure 52: Positioning accuracy depends on available deployment, bandwidth, device capability

This Technical Report has provided an in-depth exploration of the ever-evolving landscape of positioning techniques for safe driving, with a particular focus on automotive use cases. As new wireless standards and technologies continue to emerge, it becomes imperative to evaluate their applicability in specific scenarios, especially in the automotive domain. The performance of positioning systems is influenced by a multitude of factors, including environmental conditions, infrastructure deployment, and regional regulatory requirements.

Through our study in network-based positioning, sidelink positioning, and non-3GPP technologies, we have made several important observations. Advanced positioning capabilities are now integrated into recent 3GPP releases, offering promising potential for improved accuracy. However, the achievable accuracy relies heavily on the available deployment and bandwidth. In scenarios where high-precision positioning is essential, the existing bandwidth in the ITS band may not be sufficient to support stand-alone, highly accurate 5G positioning for demanding vulnerable road user (VRU)use cases.

The automotive industry is undergoing a transformative phase with the emergence of electric, connected and automated vehicles. The realisation of fully automated driving hinges on highly accurate and reliable positioning systems. These systems enable vehicles to perceive their surroundings, make informed decisions, and navigate complex environments without human intervention. As such, the importance of advancing positioning technologies cannot be overstated, and this TR sheds light on the challenges and opportunities that lie ahead in this domain.

One of the key takeaways from our investigation is the recognition that the pursuit of precise positioning should be tailored to specific prerequisites. There is no one-size-fits-all solution, as different use cases and scenarios demand varying levels of accuracy and reliability. For instance, safety-critical applications, such as VRU protection at an intersection require extremely high accuracy to prevent accidents and protect road users. On the other hand, less critical applications, such as infotainment systems, may have more relaxed positioning requirements.

To address the diverse needs of automotive use cases, it is crucial to encourage real-world testing and validation. Simulation-based evaluations and controlled laboratory tests can provide valuable insights, but they may not fully capture the complexities and uncertainties present in real-world environments. Therefore, collaborative efforts are needed to conduct large-scale field trials and data-collection exercises.

Real-world testing can also shed light on the impact of various environmental conditions on positioning performance. Urban canyons, tunnels, and adverse weather conditions can significantly challenge traditional positioning technologies, such as Global Navigation Satellite Systems (GNSS). However, the integration of multiple complementary positioning techniques, such as sensor fusion and cooperative positioning, can help mitigate the effects of these challenging environments.

Moreover, the deployment of supporting infrastructure plays a pivotal role in enhancing positioning accuracy. 5G base stations, roadside units, ultra-wideband beacons, and GNSS augmentation services contribute to the creation of a robust positioning ecosystem. Well-designed infrastructure can provide additional reference points and enhance the overall positioning accuracy.

As we move forward, it is essential to address the regulatory aspects that impact positioning technologies. Regional variations in frequency spectrum allocation and regulatory frameworks can affect the deployment and performance of positioning systems. Collaboration with regulatory bodies is vital to advocate for appropriate spectrum allocation, reduce interference, and harmonise standards to enable seamless positioning across borders.

Furthermore, this TR highlights the potential of sidelink positioning as a promising technology to complement existing positioning techniques. By utilising the licenced-exempt bands, sidelink positioning could provide additional spectrum resources, which can be particularly beneficial for the urban VRU use cases that require more bandwidth to resolve challenging multipath conditions.

In conclusion, the pursuit of precise positioning for automotive use cases is a multi-faceted problem that requires a holistic approach. It demands a deep understanding of the specific challenges faced by different use cases. By leveraging the insights presented in this report, stakeholders in the automotive industry can work together to develop further cutting-edge positioning solutions that enhance safety, efficiency, and user experiences.

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