Overview of Positioning in 5G New Radio

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Abstract— **Accurate and real time location knowledge is an important requirement for various new services like e.g. emergency services, vehicular related use cases and factories of the future. 3GPP Rel-16 will specify positioning support for 5G New Radio (NR). A study item was concluded in March 2019 to investigate positioning support for NR Rel-16 and a follow up work item is in progress to specify positioning support for Rel-16. Several positioning solutions will be supported in 5G NR. The operation in higher carrier frequencies and utilization of massive antenna arrays provides additional degrees of freedom to improve the positioning accuracy compared to LTE. Rel-16 positioning is targeting to < 3 meters positioning accuracy for some use cases. Next 3GPP Releases are expected to further specify methods for sub-meter accuracy and low latency. In this work an overview of the positioning work within 3GPP is given, highlighting both architectural and physical layer aspects.**

Keywords—3GPP New Radio, Rel-16, positioning methods

I. Introduction

Positioning of nodes in wireless networks continues to become more important for future applications and use cases like the Industrial Internet of Things (IIoT), emergency services and vehicular use cases. Research has been ongoing for decades in the positioning and localization areas [1-2]. Using measurements made by wireless devices on cellular radio signals it is possible to estimate the location or position of a device. In recent years an increased interest in positioning using cellular technology has occurred due to the higher accuracies expected which will enable new use cases. Positioning schemes typically rely on timing-based techniques, angle-based techniques, or hybrid techniques.

Timing-based techniques take advantage of the speed of RF signals to calculate the distance between a transmitter and receiver pair by estimating the time of arrival (TOA) or time difference of arrival (TDOA) of signals. Angle-based techniques take advantage of either transmit beamforming of signals and/or differences of phase across receive antenna elements to determine the angle between a transmitter and receiver pair. Hybrid techniques take advantage of a combination of timing-based and angle-based or some additional measurements. Additional measurements that have been studied for positioning are power based techniques (e.g., fingerprinting) [3] and carrier phase based positioning [4].

The Federal Communications Commission (FCC) in the United States has set E911 regulatory requirements for positioning support in cellular networks. These regulatory requirements have been one of the main motivators for positioning work within the Third Generation Partnership Project (3GPP). Recently new use cases have been identified which have caused increased interest in positioning support within 3GPP beyond the regulatory use case. A recent study item was conducted to identify the various use cases and their respective requirements [5].

It is envisioned that New Radio (NR) will eventually enable a wide range of positioning use cases. The location services in 5G NR are targeted for different categories of use cases. The commercial location services (LCS) are used with applications deployed for value-added location-aware services, such as local area advertisement. The internal LCS use the location information to assist the operations of a network, such as location aware handovers and augmenting the measurement information with a location. The emergency LCS are fulfilling the mandatory requirements for example assisting the state or regional authorities to locate the subscribers who place emergency calls. The lawful intercept LCS supports legally required or sanctioned services by providing the location information.

One of the major changes in NR compared with legacy cellular networks, like LTE, is the addition of the millimeter wave (mmWave) frequency band. In 3GPP the carrier frequencies below 6 GHz are referred to as Frequency Range 1 (FR1) and the mmWave frequency bands are referred to as Frequency Range 2 (FR2). There are additional changes to the physical design in NR like the variation of subcarrier spacing (SCS) which is not fixed for most deployments as it was in LTE. Another new feature of NR is the support for beam-based operations. Especially at FR2, massive antenna systems will support the ability to achieve more accurate positioning by exploiting spatial and angular domains of propagation channels in combination with time measurements.

A study item was concluded in March 2019 to investigate positioning support for NR Rel-16 [6]. A follow up work item is in progress to specify positioning support for Rel-16. As part of the specification work the following positioning solutions will be supported: Downlink Time Difference of Arrival (DL-TDOA), Uplink Time Difference of Arrival (UL-TDOA), Multi-Cell Round Trip Time (Multi-RTT), Downlink Angle of Departure (DL-AoD), Uplink Angle of Arrival (UL-AoA), and Enhanced Cell ID (E-CID) [7]. In addition to these RAT-dependent solutions there are another group of RAT-independent solutions, which include Global Navigation Satellite System (GNSS) and barometric pressure as well as other techniques.

This paper is structured as follows. Section II covers the accuracy and latency requirements for Rel-16 positioning. Section III presents the overall NG-RAN architecture, interfaces and the 5G base station architecture used for radio access and positioning. Section IV gives an overview of the six RAT-dependent positioning solutions agreed to be supported in NR Rel-16 while section V discusses about the various physical layer measurements as well as the downlink and uplink reference signals. Section VI gives a short overview of the 3GPP related simulations results with performance overview and the paper concludes with Section VII.

II. Requirements for Rel-16 Positioning and Beyond

NR Positioning requirements are discussed and evaluated in [6]. Regulatory requirements set the minimum performance targets for positioning, as listed below:

- Horizontal positioning error <= 50m for 80% of UEs
- Vertical positioning error < 5m for 80% of UEs
- End to end latency < 30 seconds

Additional targets are based on the needs from commercial use cases. 3GPP Study [6] has listed the following target performance for commercial use cases indoor and outdoor deployment scenarios, also noting that no single positioning technology has to meet all the targets for every scenario:

- Horizontal positioning error < 3m for 80% of UEs in indoor deployment scenarios
- Vertical positioning error < 3m for 80% of UEs in indoor deployment scenarios
- Horizontal positioning error < 10m for 80% of UEs in outdoor deployments scenarios
- Vertical positioning error < 3m for 80 % of UEs in outdoor deployment scenarios
- End to end latency < 1s

The use case family "higher accuracy positioning" for NR was defined in [14]. High positioning accuracy includes requirements that the location information is available with low latency and high reliability. A typical example of for these requirements is collision avoidance of vehicles. All vehicles must have their position known all the time as well as the positions of near-by vehicles and their expected paths. In addition to traffic roads, high accuracy positioning service for vehicles must be supported in tunnels and underground car-parks. Moreover, positioning needs to support high mobility, up to 200 km/h for cars. 3GPP Study proposed that next generation high accuracy positioning will require a level of accuracy less than 1 m in more than 95 % of service area, including indoor, outdoor and urban environments. Specifically, network-based positioning in three-dimensions should be supported with accuracy from 10 m to <1 m in 80% of situations, and better than 1 m for indoor deployments.

III. Positioning Architechture Aspects

Typical positioning architecture consists of the target UE, Radio Access Network (RAN) and Core Network (CN) with the positioning server and one or more location service clients. The location 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 computes and provides the position back to the client

Fig. 1 shows 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 UE, the network nodes and positioning server. In NR two protocols are used to exchange the location information. The extension of LTE Positioning Protocol (LPP, [15]) covers signaling between UE, the Location Management Function (LMF) and the location server, e.g. Evolved Serving Mobile Location Center (E-SMLC). The NR Positioning Protocol Annex (NRPPa, [16]) defines procedures to transfer positioning related information between NG-RAN nodes and LMF. Additionally, the Radio Resource Control (RRC, [17]) protocol transports the LPP messages over the NR-Uu interface to the target UE. In NG-RAN the gNB and ng-eNB are the network base stations that receive the positioning requests from LMF, provide positioning related measurement information to target UE, perform the uplink positioning measurements and handle the signaling between NR-RAN and LMF in CN.

The LMF manages and controls the location service request of target UEs and delivers the positioning related assistance information to UEs over the LPP. The signaling over NRPPa between LMF and gNB is used to control the positioning measurements. This includes the uplink measurements made by gNB and/or downlink measurements made by the UE. The LMF may interact with a target UE over LPP protocol to deliver positioning related assistance data. The LMF is responsible for selecting the positioning methods. The selection of positioning methods is based on the location client, the accuracy and latency according to required QoS, the UE and gNB positioning capabilities. When several positioning methods are used as a hybrid location service, the LMF may combine all the received results and provide a single location estimate. The LMF can have a signaling interface to the E-SMLC to support the NG-RAN positioning methods, for example E-UTRAN based OTDOA downlink PRS signal measurements by the target UE from supporting eNBs.

The Access and Mobility Function (AMF) may initiate the positioning request and select the positioning method to locate, for example, a device who has placed an emergency call, or AMF may receive a request coming from Gateway Mobile Location Center (GMLC) to start location services associated with a particular target UE. The AMF sends a location services request to the LMF which processes the request and defines the assistance data to be transferred to the target UE, including the positioning method and if the positioning methodology is UE-based and/or UE-assisted. LMF returns the location service response back to the AMF, which then returns the location service result back to the entity that requested the location.

Fig. 2 shows the NG-RAN gNB architecture where the logical gNB consists of one Centralized Unit (gNB-CU) and one or more Distributed units (gNB-DU) connected over the F1 interface [18]. A CU can control several gNB-DUs as transmission/reception points (TRP or TP/RP) with full NR protocol stack to support specified radio access capabilities, or as TP/RP mainly capable of transmitting and/or receiving the positioning reference symbols (PRS).

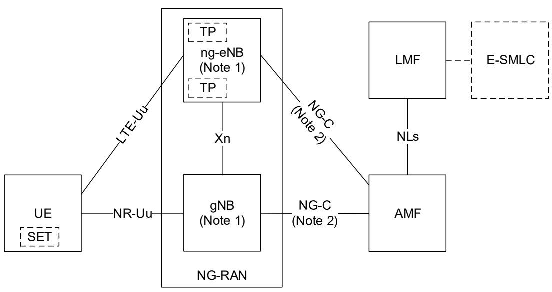

Figure 1. NG-RAN positioning architecture.

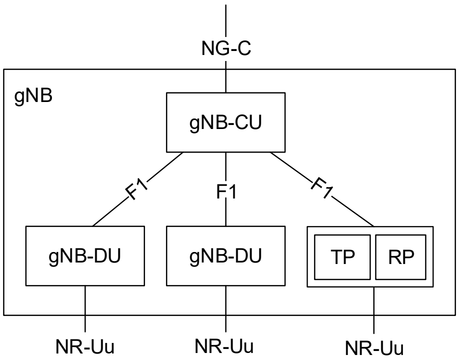

Figure 2. NG-RAN gNB architecture with CU/DU split and transmission measurement function.

IV. RAT-Depedent Positioning Solutions

In this section an overview of the six RAT-Dependent positioning solutions agreed to be supported in NR Rel-16 will be given. First, we will give a brief overview of the solutions which were previously standardized in LTE. For the solutions which were previously specified in LTE the differences in NR will be highlighted. Second, we will introduce the new positioning solutions for NR and how they are expected to look in Rel-16. E-CID using NR signals will be supported in Rel-16. While many details are still being worked on within 3GPP the method is likely to be similar to LTE where it was based on measurements done using the serving cell only. For brevity the details of E-CID will not be discussed further.

A. Downlink Time Difference of Arrival

DL-TODA was called Observed Time Difference of Arrival (OTDOA) in LTE and was one of the commonly deployed positioning solutions [8]. In LTE the DL signal used for OTDOA was the PRS. The UE measures the reference signal time difference (RSTD) using the PRS from different cells and reports the RSTD to the location server. The location server then uses the known positions of the base stations and the RSTD measurements to calculate the position of the UE.

In NR the DL-TDOA standardization work is ongoing and expected to be completed during Rel-16. As part of this work an NR PRS will be introduce and specified. The support of beam sweeping will be one of the major changes for the NR PRS design. Many other design options for the NR PRS are still open such as the comb structure and number of symbols.

B. Uplink Time Difference of Arrival

UL-TDOA, which was called UTDOA in LTE, was standardized in 3GPP Release 11 for LTE and is again being standardized in NR Rel-16. In UL-TDOA the UE sends a sounding reference signal (SRS) which is received at multiple locations. In NR the measurement function for uplink solutions may be called the transmission measurement function (TMF). At the TMFs the relative time of arrival (RTOA) is measured and reported to the location server. The location server then uses the RTOA measurements along with the known locations of the TMFs to estimate the UE position.

Various enhancements to the SRS for positioning purposes are under discussion in 3GPP. Enhancements to the power control, comb structure, symbol locations within a slot, and beam alignment considerations are being discussed. The main challenges associated with UL-TDOA are the limited number of base stations that are able to receive the SRS from the UE with sufficient power to make accurate RTOA measurements. Enhancements to the SRS will be discussed in Section V.C.

C. Multi-cell Round Trip Time

In NR Rel-16 multi-RTT will be standardized as a positioning solution. RTT methods have been studied in the literature and Wi-Fi, in IEEE 802.11-REVmc, uses similar ideas to do indoor positioning [9]. The general idea of the multi-cell RTT method is to estimate the RTT between a UE and multiple gNBs by transmitting and receiving signals between the necessary devices. The distances between the UE and the gNBs are then estimated using the RTT. Then, similar to other timing-based techniques (e.g., DL-TDOA) a trilateration estimation algorithm can be used to estimate the position of the UE. In DL-TDOA and UL-TDOA one source of timing estimation error comes from the synchronization errors between the gNBs. The advantage of using the RTT to estimate the distance between a UE and a gNB is that these synchronization errors are no longer a factor. However, the cost of multi-RTT is the increased resource overhead due to the use of both DL RS and UL RS.

As part of the work in 3GPP the UE Rx-Tx time difference and gNB Rx-Tx time difference measurements will be introduced. These measurements existed in LTE but were only for the serving cell while in NR they will also be defined for neighboring cells. Fig. 3 shows an overview of the expected structure for multi-RTT in Rel-16.

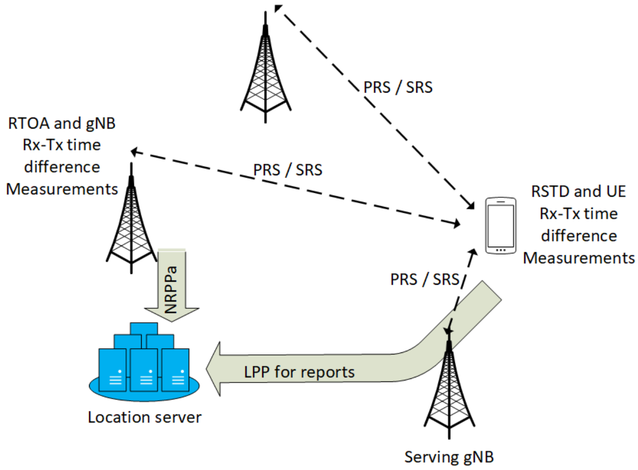

Figure 3. Expected structure of Multi-cell RTT for NR Rel-16.

D. Uplink Angle of Arrival

Another new positioning solution for NR will be the UL-AoA. The AoA at a gNB can be estimated using uplink signals. In LTE the AoA measurement was specified as part of E-CID and defined only for the serving cell. In NR a full positioning solution using only multiple AoAs will be specified. In order to do so the AoA measurement will be defined at both the serving and neighbor cells. Once multiple AoA measurements have been passed to the location server the UE position can be estimated using triangulation. To perform AoA estimation itself there are many known algorithms such as the DFT beam method and the Multiple Signal Classification (MUSIC) Method [10]. There are other methods for AoA estimation as well. The SRS will be used in NR Rel-16 as the reference signal to measure the AoA. Fig. 4 gives an overview for how UL-AoA may look in Rel-16.

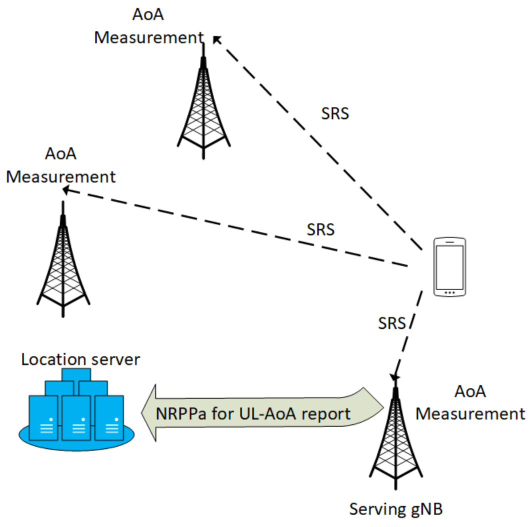

Figure 4. Expected structure of UL-AoA for NR Rel-16.

E. Downlink Angle of Departure

In addition to AoA on the UL there is the potential to estimate the AoD on the DL. In NR Rel-16 another angle based method, DL-AoD, will be introduced. One way to estimate the DL-AoD is using reference signal received power (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 fingerprinting like estimation to determine the AoD based on RSRP reports across multiple beams received from the same gNB at the UE [19].

The UE can use existing Rel-15 reference signals for the RSRP measurements such as CSI-RS. Another option for the UE is to use the NR PRS to make the RSRP measurements. In fact, a hybrid between DL-TDOA and DL-AoD may be possible using the same transmissions of PRS. Fig. 5 shows an overview of the DL-AoD solution for NR Rel-16. One of the major problems for both DL-AoD and UL-AoA are the non-line of sight (NLOS) conditions. NLOS is also an error source in timing based techniques but better models to mitigate the errors in timing based techniques exist [11].

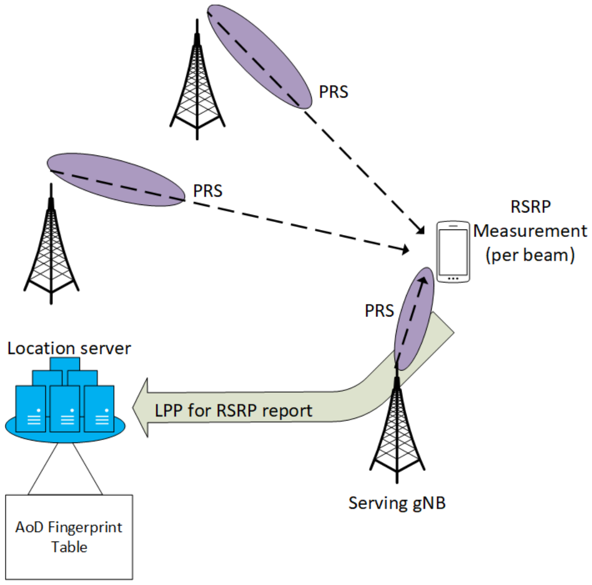

Figure 5. Expected structure of DL-AoD for NR Rel-16.

V. Physical Layer Aspects

In this section the physical layer aspects of the work within 3GPP on NR positioning will be discussed. The various physical layer measurements to enable NR positioning support are discussed as well as the reference signals needed in both downlink and uplink for those measurements.

A. Measurements

As described in the previous sections, measurements either at the network devices (e.g., gNBs) or UEs need to be made and reported for use in the positioning calculation. At least seven new NR measurements are on track to be specified in NR Rel-16 to facilitate positioning support [7].

On the UE side the RSTD measurement will be defined. RSTD was defined in LTE [12] and it may be used as a baseline for the definition in NR which is under discussion in RAN1. The beam based nature of the PRS is also being taken into consideration for the NR definition of RSTD. Another UE measurement is the PRS-RSRP which is being built off similar RSRP measurements from Rel-15 (e.g., SS-RSRP). The third UE measurement is the UE Rx-Tx time difference measurement which is necessary to enable multi-cell RTT. UE Rx-Tx time difference was defined in LTE but was only valid for the serving cell where in NR it will be defined for both serving and neighboring cells.

On the gNB side the RTOA measurement is being defined and it was previously specified in LTE. Again, the beam based operation of NR is being considered while RAN1 defines RTOA in NR. The AoA measurement (including azimuth and zenith angles) will be specified in Rel-16. In LTE the AoA measurement was only defined for the serving cell but in NR this definition will extend to the neighboring cells as well. The UL-RSRP will be defined in Rel-16 and will likely be built from prior RSRP definitions. The final new measurement is the gNB Rx-Tx time difference, which similar to the UE RX-Tx time difference, was defined in LTE but will be extended to be defined for both serving and neighboring cells in NR.

B. Downlink Reference Signals

As discussed in previous section, three different downlink positioning measurements, i.e. RSTD, PRS-RSRP, and UE Rx-Tx time difference, based on applicable downlink reference signal from a serving, reference and neighboring cells need to be specified in Rel-16. NR Rel-15 provides support for a large variety of different downlink reference signals, e.g. Channel State Information Reference Signal (CSI-RS) for beam management, CSI-RS for time-frequency tracking, CSI-RS for CSI acquisition, CSI-RS for mobility measurements, Phase Tracking Reference Signal (PTRS), Demodulation Reference Signal (DMRS). However, none of Rel-15 reference signals have not been specifically designed for positioning measurements.

To enable flexible and high accuracy positioning in various scenarios in Rel-16 and beyond, there is a need to enhance existing Rel-15 reference signal support for downlink positioning measurements for both FR1 and FR2. To reduce specification impact and costs of implementation, DL PRS design (i.e., NR PRS) will reuse technical components of reference signals in Rel-15, such as sequences are generated by Gold sequences and mapped to QPSK constellation points (similar to Rel-15 CSI-RS) and at least 4096 different sequence IDs supported. Furthermore, the resource element (RE) pattern of DL PRS will follow Rel-15 comb-structure (e.g. CSI-RS for beam management) with potentially a larger number of different densities, e.g. 1,2,3,4,6,12. per PRB. Rel-16 PRS supports single antenna port resources that can be configured as periodic or aperiodic. The bandwidth of PRS is configurable. Same cyclic prefix lengths and sub-carrier-spacings for DL PRS are support as in Rel-15. As in the LTE PRS design a staggered RE pattern over time and frequency will be used to achieve an effective comb-1 structure at the receiver (i.e., UE). This effective comb-1 allows for improved estimation properties for the reference signal for timing measurements like RSTD. Even though RAN1 has made a progress on DL PRS design, there are still many open technical issues to be discussed and agreed during Rel-16.

C. Uplink Reference Signals

So far in 3GPP only the sounding reference signal (SRS) has been agreed to be used in UL for positioning purposes. In Rel-15 the SRS was designed for reception at the serving cell only. As part of the Rel-16 work within 3GPP various enhancements of SRS for positioning purposes have been discussed and some already agreed. A staggered resource element mapping which allows for an effective full bandwidth signal to be received at the measurement point will be a major enhancement to SRS in Rel-16. In addition, multiple enhancements aimed at higher amounts of orthogonality between UEs will be introduced, including higher comb size and flexible symbol starting position within a slot. The ability to allow transmission power control that takes into account the fact that reception at a neighboring cell is desired will be included in Rel-16. The number of OFDM symbols that can be configured for SRS will also be increased for positioning purposes which is aimed at increasing the number of gNBs that can hear the SRS with sufficient power to make accurate RTOA measurements. Similar to the DL PRS design there are many open technical issues to be discussed and agreed about the SRS for positioning purposes during Rel-16 work.

VI. Performance Results

During the recent study item, [6], many simulations results were produced for a variety of the proposed NR positioning solutions. Three different evaluation scenarios were studied and are captured in Section 6.1 of [6]: Urban Macro (UMa), Urban Micro (UMi), and Indoor Office (InH). It was shown by all sources providing input to the TR 38.855 that DL-TDOA could meet the regulatory requirements in all scenarios. It was also shown that depending on the specific evaluation assumptions that some techniques can meet the commercial performance targets, as well, in some scenarios.

Our evaluation of DL-TDOA for a bandwidth of 5 MHz in all three evaluation scenarios is shown in Fig. 6 below. The figure shows the horizontal positioning error over 1000 random UE drops and position estimates. The detailed simulation assumptions used can be found in [13]. Some important assumptions from [13] are 0.5 thresholding for TOA estimation, carrier frequency of 4 GHz, perfect PRS muting assumption, and ideal network synchronization error. From the results we can see that for outdoor deployments the regulatory requirements can be met using DL-TDOA even with only a 5 MHz bandwidth signal and that for indoor deployments the results are even more promising. In addition, the performance is expected to be improved for wider bandwidth signals in NR.

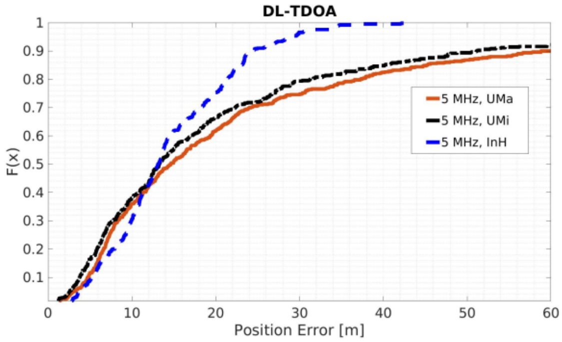

Figure 6. DL-TDOA horizontal positioning accuracy.

VII. Conclusion

NR has the potential to enable many new positioning services using cellular networks, as well as support legacy regulatory use cases like E911 calls. In this paper an overview of the 3GPP specification work to include positioning support has been given. In particular a focus on the RAT-dependent techniques being introduced for NR Rel-16 was made. The requirements of various use cases were provided, architecture aspects, and physical layer aspects were discussed. Simulation results in this paper, and presented during 3GPP's work, show the promising accuracies that NR positioning should bring to NR networks.

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