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Performance Evaluation of 5G-NR Positioning Accuracy Using Time Difference of Arrival Method

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Abstract— **In this paper we evaluate the performance of fifth generation new radio (5G NR) based positioning under realistic conditions model for cooperative connected automated mobility (CCAM) scenarios. We benchmark the performance using 3GPP release 16 proposed new positioning reference signal (PRS), of positioning in 5G NR mobile networks. Time difference of arrival (TDoA) positioning methods is one of the widely used method which is used for localization. Simulation results are showing that under line-of-sight (LOS) conditions, the desired positioning accuracy is achievable for various CCAM use-cases. In best case scenarios precision is less than 1m in 80% of cases. In more realistic cases, when there is no line of sight (NLOS) between user terminal (UT) and network nodes, then accuracy decreases significantly. Methods of automatic classification of LOS/NLOS channels are thus needed. TDoA positioning method suffers degradation of performance, when different network nodes are out of sync with each other. Thus, other methods, less sensitive to synchronization error, such as round-trip time (RTT) or angle-based measurements might be worth considering.**

Keywords—Positioning Reference Signal, 5G New Radio, Radio signal-based positioning.

I. INTRODUCTION

As 5G roll-out is on-going around the world and connectivity paradigm is evolving with the research efforts being intensified towards 6G, cooperative connected and automated mobility (CCAM) services are going to be widely available, reliable, safe and secure as well as affordable. Accurate positioning is one of the CCAM services that will enable a number of use-cases related to smart mobility i.e., cooperative driving, cooperative sensing, smart logistics and multimodality. In this context, 5G-NR has introduced new positioning reference signals (PRS) primarily designed for 5G-based positioning services.

Flexibility of 5G NR signal configuration allows to generate position reference signals (PRS), that are much more suitable for positioning than predecessors. Possibility to monetize positioning-based services and reduced performance of satellite navigation systems in dense city environment have contributed in rise of interest in 5G based mobile positioning.

There are number of available radiolocation technologies, each having their own advantages and respective drawbacks. Those techniques can be divided into four categories: angle-, timing-, carrier phase- and received signal power-based. In practice, timing-based methods are most commonly used. Most straightforward would to measure signals time of flight from three or more anchor nodes to UT which position we are trying to estimate. In case of mobile positioning those anchor nodes would be mobile base stations (5G NR gNodeB). Such measurements are relying on precise synchronization between base stations and UT. When only anchor nodes are synchronized to each other then UT can measure time difference between arrival of signals from different base stations. Positioning method based on measured time differences of arrival (TDoA) is known as multilateration.

As for related work, 5G positioning and localization has been studied to a great extent in the literature. Positioning research started at the same time with the overall research done on 5G NR in general. In [1] authors studied dense cellular environment in the presence of device to device communication to study cooperative 5G positioning scenario. Paper [2] gives a broad overview of the of 5G positioning starting by the main use cases and KPIs, including technologies of cellular positioning starting from 1G until 4G and positioning updates introduced in 5G. A recent work [3] is the study of positioning for 5G and beyond systems using deep learning and radio fingerprinting in system level simulator based on 5G NR.

PRS has been introduced since 3GPP release 9 for LTE positioning. Several works about studying and using PRS in

LTE and 4G systems has been carried out since. Modifications to the PRS for 5G NR positioning purposes have been made in the new release 16 3GPP TS 38.211 [4]. Before this standard has been frozen; some works based either on anticipated standard, existing LTE PRS or proposals for 5G's PRS are done. Authors in [5] evaluate the impact to accuracy of positioning with different PRS allocations (comb 1, comb 4 and comb 12) in a slot, as [6] discusses PRS configuration to support OTDoA (Observed Time Difference of Arrival) positioning method. More recent works have been done based on the Rel. 16 PRS for position estimation, however, they haven't studied the PRS itself. Some works [7], [8] and [9], are about 5G NR based indoor positioning and one is about urban canyon environment [10]. Different scenarios as indoor office and factory and also different positioning methods as TDoA, RTT and angle of arrival (AoA) are analysed. Information of selection and generation of PRS itself is very limited in all those works.

The main document for the NR positioning is 3GPP TR 38.855 [11] containing the main scenarios, parameters, technologies, and requirements for 5G NR positioning. Performance evaluation results for NR positioning from different vendors and research institutions can also be found in this document. More details about the results presented in TR 38.855 can be found in proposals of contributors, such as [12] where NR positioning was evaluated for uplink, downlink, and uplink-downlink positioning techniques.

Channel model used in these studies is the 3GPP 5G channel model TR 39.901 [13]. As this model is not designed for positioning purposes then some modifications to it suggested in [14] and [15] are used in our simulations. The actual structure of positioning reference signal as specified in [16] is used in our simulations. As there are no known work about the use of 5G NR Rel 16 PRS signal, then in current paper it is explained, how to generate and simulate this signal. The purpose of this paper is to simulate PRS in realistic conditions and investigate the impact of LOS/NLOS and synchronization of base stations to accuracy of positioning. Simulation results, are presented in current paper.

Only few similar works are done previously and in those very little attention is paid to the actual details of PRS and simulation in general. Second section of paper is dedicated to quite detailed description of 5G NR PRS. In addition to information covered in 3GPP technical reports some additional details about mapping PRS into resource grid are given. Third section is divided into two parts. First of them describes simulation setup and second presents and analyses simulation results. Final section concludes the paper and gives some possible directions for future work.

II. 5G NEW RADIO POSITIONING REFERENCE SIGNALS

3GPP technical specification TS 38.211 [16] defines special positioning reference signals PRS (7.4.1.7 at page 111) for 5G NR release 16. Those signals are meant for positioning purposes in downlink direction. As user terminals have limited transmission capacity compared to base stations, then for uplink positioning a different positioning signal, known as a sounding reference signal SRS, is used instead when necessary. Focus of current paper stays in downlink positioning and thus structure of PRS will be inspected closely below.

Specification defines QPSK modulated downlink positioning reference signal sequence $r(m)$ as

$$r(m) = \frac{1}{\sqrt{2}}[1 - 2c(2m)] + j\frac{1}{\sqrt{2}}[1 - 2c(2m+1)]. \qquad (1)$$

Generic pseudo-random sequences are defined by a length-31 Gold sequence. Sequence $c(n)$ of length M_{PN}, where n = 0, 1, 2, …, $M_{PN}-1$, is defined by (1)

$$\begin{gathered} c(n) = [x_1(n+N_C) + x_2(n+N_C)] \bmod 2, \\ x_1(n+31) = [x_1(n+3) + x_1(n)] \bmod 2, \\ x_2(n+31) = [x_2(n+3) + x_2(n+2) + x_2(n+1) + \\ + x_2(n)] \bmod 2, \end{gathered} \qquad (2)$$

where N_C = 1600 and the first m-sequence $x_1(n)$ shall be initialized with $x_1(0) = 1$, $x_1(n) = 0$, n = 1, 2, …, 30.

Initialization of the second m-sequence $x_2(n)$ depends on application of the sequence. Same Gold-sequence generator is used for generation of many different sequences for different purposes, indeed the same generator was also used in LTE. Sequence used for PRS is obtained when the pseudo-random sequence generator is initialized with value

$$\begin{aligned} c_{init} = \Bigg[& 2^{22}\left\lfloor\frac{n_{ID,seq}^{PRS}}{1024}\right\rfloor + 2^{10}\left(N_{symb}^{slot} n_{s,f}^{\mu} + l + 1\right) \cdot \\ & \cdot \left[2\left(n_{ID,seq}^{PRS} \bmod 1024\right) + 1\right] + \\ & + \left(n_{ID,seq}^{PRS} \bmod 1024\right)\Bigg] \bmod 2^{31}. \end{aligned} \qquad (3)$$

Downlink PRS sequence ID $n_{ID,seq}^{PRS} \in \{0, 1, \ldots, 4095\}$ value is given by the higher layer, $n_{s,f}^{\mu}$ is the slot number in frame and l is the OFDM symbol within the slot to which the sequence is mapped. Slot number in frame can have value between 0 and $N_{slot}^{frame,\mu} - 1$, where number of slots in frame depends on used numerology μ as $N_{slot}^{frame,\mu} = 10 \cdot 2^{\mu}$. Index of OFDM symbol in slot has value between 0 and $N_{symb}^{slot} - 1$, where number of symbols in slot N_{symb}^{slot} is 14 for normal- and 12 for extended cyclic prefix.

Seed value c_{init} of used Gold code depends on both slot number in frame $n_{s,f}^{\mu}$ and symbol number l in slot. Thus, it means that each OFDM symbol uses different Gold sequence mapped into its subcarriers. As up to twelve symbols in slot can be allocated for PRS signal then also up to twelve Gold codes must be generated to create single positioning reference signal.

Different cells, based on PRS sequence ID $n_{ID,seq}^{PRS}$, are also using different pseudorandom sequences to generate PRS in order to minimize inter-cell interference. Comb-like structure of PRS allows also decrease inter-cell interference as PRS signals can be simultaneously transmitted from many gNodeB's, each of them using separate and non-overlapping resource elements of resource grid.

The size of the downlink PRS resource in the time domain L_{PRS} has either value of 2, 4, 6 or 12. Which one of them is used is given by the higher-layer, as it also the number of the first symbol l_{start}^{PRS} used by PRS. Time domain indict l thus takes values

$$l = l_{start}^{PRS}, l_{start}^{PRS} + 1, \ldots, l_{start}^{PRS} + L_{PRS} - 1 \, . \qquad (4)$$

For each value of indict l corresponds separate initial seed value c_{init} and with that also separate Gold code. For each downlink PRS resource configured, the UT shall assume the sequence $r(m)$ is multiplied with a power scaling factor β_{PRS} and mapped to resource elements according to

$$\begin{gathered} a_{k,l}^{(p,\mu)} = \beta_{PRS} \cdot r(m) \\ m = 0, 1, \ldots \end{gathered} \qquad (5)$$

Maximal value of indict m is limited by condition that every resource element $(k,l)_{p,\mu}$ of PRS signal must be within resource blocks occupied by the downlink PRS resource. In other words, frequency domain indict k cannot have larger value than $N_{grid}^{size,\mu} N_{sc}^{RB}$ -1. Minimal grid size $N_{grid}^{size,\mu}$ is 20 RBs for all numerologies and maximal grid size is 275 for numerologies up to 3 with only exception being 138 for highest numerology $\mu = 4$. Based on previously stated, the value of m should not exceed 1649. Maximal used length of each Gold code $c(n)$ is then 3300 elements.

Frequency domain indict k of used resource elements is given by

$$k = mK_{comb}^{PRS} + \left(k_{offset}^{PRS} + k'\right) \bmod K_{comb}^{PRS}. \qquad (6)$$

The PRS comb size $K_{comb}^{PRS} \in \{2, 4, 6, 12\}$ is also given by the higher-layer. Comb size shows spacing between resource elements of same PRS signal in frequency domain. For example, comb size four means that every fourth subcarrier in symbol is used for PRS signal while three others are left unused and are available for other purposes. To minimize mutual interference between signals sent from different base stations or different sectors of same base station, frequency offset can be introduced to PRS. The resource-element offset $k_{offset}^{PRS} \in \{0, 1, \ldots, K_{comb}^{PRS} - 1\}$ allows up to K_{comb}^{PRS} different positioning reference signals to share same downlink PRS recourse. Additional frequency offset k' makes different symbols to use different subcarriers. Its values for different comb sizes and time domain offsets are given in table 7.4.1.7.3-1 in page 112 of 3GPP technical specification TS 38.211 [16].

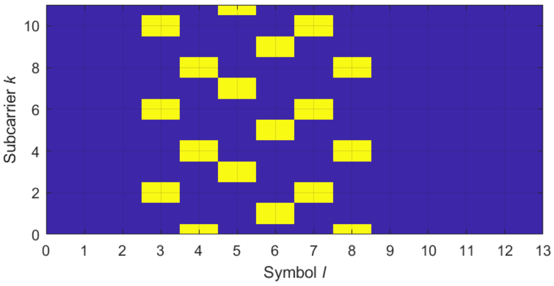

Figure 1 Example of resource grid of 5G NR PRS

Figure 1 shows an example of PRS resource grid. In order to bring out detail only single resource block is displayed on this figure. PRS signal sequence $r(m)$ is mapped in resource elements marked with yellow, blue area is unused by positioning reference signal. Number of first symbol is $l_{start}^{PRS} = 3$ and resource element offset is $k_{offset}^{PRS} = 2$. Figure 1 confirms that leftmost lowest resource element used for PRS is indeed element $(2,3)_{p,\mu}$. The size of the downlink PRS resource in the time domain is $L_{PRS} = 6$ so six consecutive symbols, from $l = 3$ to 8 are used. As the comb size is four, then every fourth resource element of each of the six symbols are used to map PRS signal sequence.

Bandwidth of positioning reference signal is determined by total number of resource blocks allocated for positioning purposes. Maximal available bandwidth in FR1 is 100 MHz and in FR2 400 MHz accordingly.

III. PERFORMANCE EVALUATION

A. Simulation setup

5G NR channel model, described in 3GPP TR 38.901 [13], is stochastic geometry-based (statistical ray-tracing) model, known as clustered delay line (CDL) model. Model takes also into account the locations of scatterers not just only time delay produced by different multipath components. This allows to simulate influence of environment to MIMO channel and take antenna radiation patterns into account. As model is stochastic, then locations of scattering objects, as trees or rough walls of buildings, are not based on exact actual geometry of any environment but are generated randomly.

TDOA based positioning does not depend on use of MIMO and PRS signal should be radiated in all directions. In such a case CDL model can be simplified into tapped delay line (TDL) model via spatial filtering procedure. Generated PRS $x(t)$ is then passed through TDL channel model with impulse response $h(t)$. Noise $n(t)$, which power is calculated based on simulation geometry and other parameters, is then added to the output signal $y(t) = x(t)*h(t)$ of TDL channel. Cross correlation $R_{xr}(\tau)$ between received signal realization $r(t) = y(t) + n(t) = x(t)*h(t) + n(t)$ and expected PRS $x(t)$ is calculated after that. Simplest estimate of signal's time of flight (TOF) is the location of maximum of obtained cross-correlation function $R_{xr}(\tau)$

$$TOF = \operatorname{argmax}[R_{xr}(\tau)]. \qquad (7)$$

Alternative approach would to measure the delay of the first received peak instead of highest peak. When there is direct line of sight (LOS) between transmitter and receiver then the first peak, corresponding to the LOS path, is also usually the highest. When direct path passes some medium that partially attenuates signal coming over shortest path, then reflected signal can have larger amplitude. This is the scenario that justifies described method. There are few different methods of obtaining this estimate, simplest of them are threshold based. One of the setbacks of such approach is possibility to erroneously take sidelobe of actual correlation peak as reflection.

When LOS component is not present at all (NLOS channel) then correct estimation of distance is not possible with either method. This is due to fact that length on NLOS path is not uniquely tied to the exact distance but it is dependent of actual environment thus practically random.

Used channel model 3GPP TR 38.901 [13] is designed with communication, not positioning, simulations in mind. Time delays in model are normalized so that first delay corresponding to shortest path is equal to zero. This means that model only describes delay spread and ignores propagation delay caused by finite speed of signal. As position estimation demands information about distances and thus actual propagation delays, then this issue must be addressed separately.

If we want to simulate the fact that UT is at the distance d from base station, then we can calculate LOS time delay easily as

$$\tau_{LOS} = d/c \tag{8}$$

and add obtained value to all delays τ_n of model. Even simpler solution is to add this LOS delay τ_{LOS} to the estimated delay obtained from output signal of channel model. It can be shown that when distance d between base station and UT is larger than distance from direct path to scatterers, then such simplification does not cause significant deviation from model.

During simulations we know actual location of UT and thus also distances between it and all anchor nodes. This means that we are actually only interested in time delay measurement errors $\Delta\tau$ and not in actual delay itself. Everything said about absolute values of delays so far is correct under assumption that there is indeed unobscured direct path between transmitter and receiver. If this condition is not fulfilled and we are dealing with NLOS channel, then the length of first path is always larger than direct one. This issue is again not addressed in channel model 3GPP TR 38.901 [13].

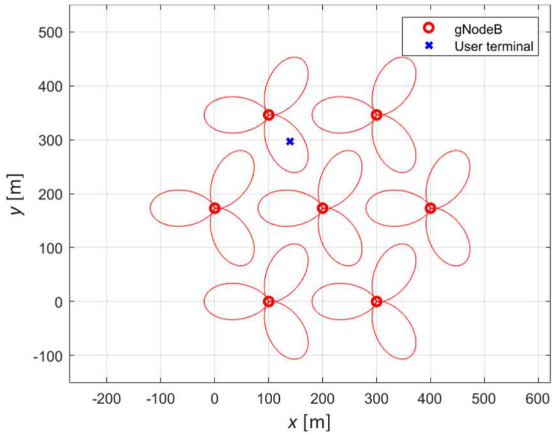

Figure 2 General layout of used simulation geometry

One possible solution is described in [15] where it is recommended, in case of TDOA measurements, to add an offset $\delta = (\alpha_1 \cdot d_2 - \alpha_2 \cdot d_1)/c$ to the generated cluster delays of the neighbour cell. Variable d_1 is the LOS distance between the UT and the reference cell, d_2 is the LOS distance between the UT and the neighbour cell, c is the speed of light and α_i depends on LOS/NLOS condition. In case of LOS channel, the value of α_i is simply one. When there is no line of sight, the parameter α_i is random variable with uniform distribution between 1 and 1.37 [15]. This approach assumes that length on NLOS path can be up to 37% longer than LOS distance. We name the above described model as NLOS model 1.

When cluster delays τ_n are generated from channel model then their values are randomly generated. Then the minimal delay is subtracted from all others resulting normalized delays with minimal value of zero. As an alternative solution in [17] it is recommended that, in order to introduce a NLOS bias this normalization of the spread delays τ_n should be omitted. Second approach will be named as NLOS model 2.

Used two-dimensional positioning geometry is illustrated in figure 2. Seven base stations, all 200 m apart from one another, are marked with red circles. Each base station has three sectors, radiation pattern of each sector antenna is shown with thin red line. UT is dropped on random location based on two-dimensional uniform random distribution, location of it is shown in figure with blue x.

There are very large set of possible configurations of positioning parameters. To narrow down number of necessary simulations three simulation cases were selected. First two of them are using carrier frequency $f_c = 2$ GHz and subcarrier spacing $\Delta f = 15$ kHz (numerology $\mu = 0$). Only difference between first two is in PRS signal bandwidth being 5 (case 1) and 50 MHz (case 2) respectively. Third case uses carrier frequency $f_c = 4$ GHz and subcarrier spacing $\Delta f = 30$ kHz (numerology $\mu = 1$) paired with bandwidth $B = 100$ MHz. Sampling interval for all simulations is equal to 5G time unit $T_C \approx 0.508$ ns. PRS signal used for all simulations has duration of 6 symbols and comb – 6 structure. Synchronization between anchor nodes are either assumed to be perfect or to follow truncated Gaussian distribution with standard deviation of 50 ns and a range of timing errors between -100 to 100 ns. The comparison of simulation results for both models in all 3 cases is presented in figure 3.

For each simulation location of UT is chosen randomly. Each distance measurement is done only once. If user is stationary or moves slowly then there is possible to measure distances multiple times and use average for more accurate estimation of position. Duration of PRS is short enough that users can be considered stationary during each distance measurement instance.

Euclidean norm of difference between estimated and actual position of UT, named as error vector magnitude EVM, is used as figure of merit.

B. Simulation results

We start the presentation of our simulation results with the channel model where both LOS and NLOS links are present. In the section about simulation setup, two possible modifications of the channel model were described, they were referred as NLOS model 1 and NLOS model 2, respectively.

Figure 3 represents the simulated cumulative distribution function (CDF) of the positioning EVM for both models in case there are no synchronization errors present. Results for NLOS model 1 are given with solid- and for NLOS model 2 with dashed lines. Percentiles of the depicted distributions are given in first two sections of table 1.

The results for different cases of either model are quite close to each other, although wider bandwidth gives a small decrease in distance error value for second model. In case of high-resolution peaks with large delays can be separated and sometimes erroneously, due to their large value, taken as ones corresponding to LOS path. This creates large errors. In case of low-resolution such peaks only shift location of maximum of cross-correlation towards them and thus created error of distance estimate is smaller.

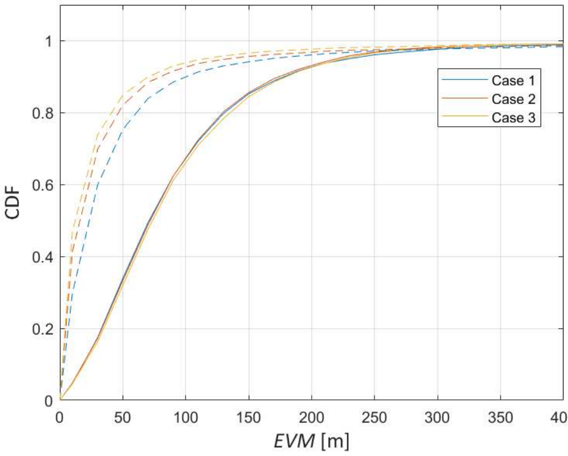

Figure 3 CDF in case of no sync error (model 1 – solid, model 2 – dashed line)

Simulation results for models are very different, although all other conditions were identical. This sugests that at least one of them must be incorrect. Neither model seems to be based on good arguments or experimental data, so such result was actually expected. NLOS scenarios are very hard to be modelled for positioning purposes and thus either LOS only channels are assumed for simulations or some method is derived in order to exclude measurements made under NLOS conditions.

In 3GPP TR 38.855 [11] it is stated that for release 16 the horizontal positioning error must be less or equal than 50 m for 80% of UTs. Comparing this to results given in table 1 we can see that this requirement is clearly not satisfied. Main reason behind this is in unpredictable nature and long delays of NLOS channel. It is worth mentioning that 5G mobile networks will be much denser than in case of previous standards. This is done in order to improve communication capacity but it will also helps to improve positioning capacity by offering more available LOS links. Inherently base stations are denser in street canyons than in open areas.

Simulation results, for assumption of perfect synchronization and LOS-only channels, are depicted for all three cases in figure 4. Percentiles in numerical format are given in third section of table 1. In case of LOS-only channel our obtained accuracy is well inside the limits of horizontal positioning error for release 16 even if we consider that according to 3GPP TR 38.855 [11] starting point for commercial use cases the horizontal positioning error should be less than 10 m for 80% of UTs in outdoor deployments scenarios.

Table 1 Simulation results, distances given in meters

Scenario	**Percentile**	**50%**	**67%**	**80%**	**90%**
NLOS model 1	**Case 1**	80.9	108.4	140.5	187.3
	Case 2	81.6	108.9	139.3	183.9
	Case 3	83.1	111.8	145.2	188.5
NLOS model 2	**Case 1**	32.3	47.6	69.1	107.7
	Case 2	24.6	37.2	55.8	88.8
	Case 3	21.5	33.2	48.9	80.1
LOS only, no sync err	**Case 1**	0.59	1.00	1.55	2.52
	Case 2	0.32	0.59	1.10	1.63
	Case 3	0.32	0.57	1.00	1.61
LOS only, 50 ns rms	**Case 1**	7.2	11.9	18.3	27.6
	Case 2	7.1	11.7	18.2	27.5
	Case 3	7.1	11.7	18.1	27.5

Case 1 has worst accuracy, while other two are showing almost identical results. As now the LOS component has strongest amplitude then having better resolution due to higher bandwidth has distinct advantage over narrowband signal.

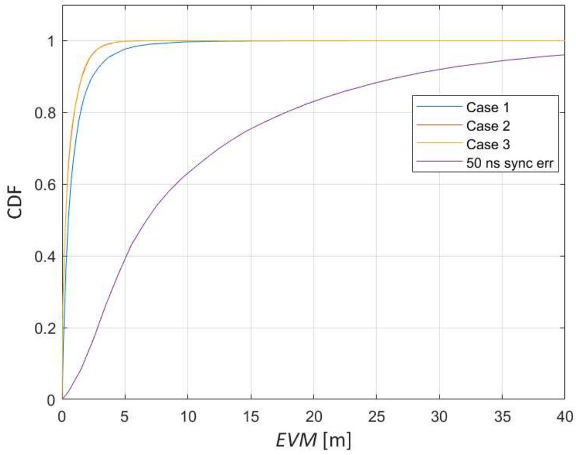

Figure 4 CDF in case of LOS only channels

Influence of synchronization errors are addressed next. CDF for LOS-only channel and 50 ns rms synchronization error is shown with the purple line in figure 4, and percentiles for all cases are given in last section of table 1. It is clear that even such a modest sync error causes large degradation of positioning accuracy in order of ten or more times. Less loose, 50 m accuracy condition for 80% of UTs, is still fulfilled, but stricter condition of 10 m one is not achievable anymore. As positioning error is now mainly caused by synchronization error, and other influences are small compared to it, then CDFs for all three cases are practically identical. Using PRS with larger bandwidths does not give any advantage in location accuracy anymore. When synchronization errors of given magnitude or larger are expected then there is no reason to commit large bandwidth resources to positioning reference signals. Distance measurement error, caused by synchronization mismatch, is under NLOS conditions much smaller than one caused by multipath propagation. Due that there is no noticeable difference in simulation results when synchronization errors are introduced to NLOS situations.

IV. CONCLUSIONS

The positioning accuracy in LOS conditions and without synchronization error in used base stations satisfies both the regulatory requirement (<50 m) and commercial requirement (<10 m outdoor and <3 m indoor) requirements stated in TR 38.855 [11]. If commonly used sync error of 50 ns is added to the simulations then the positioning accuracy was decreased to satisfy only the regulatory requirement. However, values of synchronization errors used for current simulations are estimated to be too optimistic for real life systems actual degrading effect can be much larger.

To simulate NLOS conditions, two NLOS models were used and as results show both failed to satisfy even the regulatory requirement of accuracy. Lack of direct line of sight between UT and base station causes large errors in distance estimates. Distance estimates with large errors in turn are causing large errors in position estimates. It must be emphasized that used channel model 3GPP TR 38.901 [13] is not meant for positioning simulations even if it was improved with recommendations from [14] and [15]. Used approximations for absolute time delay values in NLOS cases might not be consistent with reality as the delay of signal is practically unpredictable.

Synchronization errors are causing significant degradation in location accuracy but accuracy decreases more under NLOS condition. In either case for precise positioning only LOS measurements must be used. From there arises need for LOS/NLOS classification of received waveform. If satisfactory synchronization between base stations is not economically feasible for service providers, then TDOA based positioning methods cannot obtain necessary precision. In such case some other solutions could be implemented for positioning. RTT demands only good short-term stability of devices clocks. As distance between UT and anchor nodes are measured one by one then this method is more time consuming than TDOA. Angle based measurements are not very sensitive to timing, but their accuracy tends to be poorer than obtainable by time-based methods. For example, angle-based method from report [10] has simulated vertical accuracy than 2 m for 80% of UTs while best reported accuracy for TDOA method is 0.33 m under same conditions. Worst simulated accuracies form same report were 75.9 m for TDOA and 124.5 m for angle-based methods. Thus confirming that results presented in current paper are within expected limits.

V. ACKNOWLEDGMENT

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