SA-TDoA: A Spatially Aware TDoA-based Localization in 5GNR Networks

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ABSTRACT

Localization is a vital aspect of many autonomous mobile robots. Accurate tracking especially indoors is key for the next generation of smart factories, automated workflows, and efficient supply chains. The integration of 5G networks within industrial settings offers the promise of high connectivity, yet challenges persist in achieving higher accuracy. This paper introduces the Spatially Aware Time Difference of Arrival (SA-TDoA) approach, designed to harness the dense network topology of 5G New Radio (NR) for advanced indoor localization. Departing from conventional TDoA methods that predominantly rely on Line-of-Sight (LoS) measurements, SA-TDoA incorporates an intelligent anchor selection mechanism. This mechanism evaluates both LoS and Non-Line-of-Sight (NLoS) signal paths, considering the relative spatial positioning of user equipment (UE) as the robot to determine the most precise location estimations. Our simulation results, conducted in a representative industrial setting, demonstrate a 33% reduction in error and a 24% increase in robustness for estimation error in 90% and 95% of UE positions respectively compared to conventional LoS methods.

1. RESEARCH OBJECTIVE

In ultra-dense 5G and beyond cellular networks, particularly in indoor environments, the deployment of multiple low-power small-cell gNBs is a strategic choice driven by the need to enhance capacity and coverage. Higher frequencies are used to provide the extra bandwidth that these UE-dense networks require. Choosing mmWave/ THz bands shrinks each cell's coverage while boosting its ability to serve a dense population of mobile and stationary Internet of Things (IoT) devices, such as robots and sensors. This scenario typically results in a high density of gNBs, providing different anchor sets for UE localization. Using this as a leverage, in this paper, we focus on selecting the most effective anchor set from the existing, uniformly installed gNBs within the UE’s reception range. Our methodology revolves around determining the best anchor set for localization by analysing the distribution of different anchor set errors. According to the TDoA Cramér-Rao Lower Bound (CRLB) calculations presented in [1], the factors affecting the error variance of a TDoA estimator include the variance of measurement errors and the relative positions of UE with respect to each base station (gNB) in the anchor set. As a result, both Non-Line-of-Sight (NLoS) measurements and the geometric configuration of UE and gNB can significantly influence the estimation error. This study introduces a mechanism to ascertain whether NLoS conditions or relative positioning contributes more significantly to the error. This approach recognizes that relying solely on LoS measurements might not always yield the most accurate localization results. There are specific instances where the spatial configuration of the anchor set relative to the UE’s position can lead to situations where NLoS measurements, or a combination of LoS and NLoS measurements, could result in lower localization error. Therefore, our strategy involves a nuanced selection process where the anchor set is chosen based on a comprehensive assessment of measurement error distribution, influenced by the UE’s location and the spatial arrangement of the gNBs. By adopting this methodology, we aim to enhance the accuracy and reliability of UE localization in dense gNB environments, particularly in indoor settings where traditional approaches may fall short.

2. METHODOLOGY

The anchor selection algorithm presented in this study aims to refine TDoA estimation accuracy by introducing a dynamic selection process. Utilizing an offline analysis, the method aims to determine the adequacy of the LoS anchor-set based on the geometric configuration of UE and gNBs within this set. If the analysis indicates a potential for high estimation error, an alternative anchor set may be recommended to enhance accuracy. This algorithm procedure is as follows:

1) *Offline Mode*: Adequate UE measurement data across various positions is collated. This data is paired with the optimal anchor set identified through an exhaustive search and then used to train an LSTM deep-learning network. The network’s objective is to associate each measurement set with a defined ’proximity zone’ within the indoor area, segmented into 10m × 10m zones for a close approximation of the UE’s actual position. A ’success table’ is maintained to record the frequency of each anchor set being the best choice for specific zones.

2) *Online Mode:* Utilizing the LSTM model trained in the offline mode, live UE measurements are assigned to a proximity zone. LoS measurements are discerned by their significantly lower variance compared to NLoS measurements. The algorithm selects the LoS anchor set based on the ’success table’ data for that zone and its adjacent areas. If the LoS set is deemed suboptimal (i.e. no success rate was recorded for this anchor-set), the

algorithm explores neighbouring anchor sets, potentially incorporating a mix of LoS/NLoS anchors, to enhance positioning. Should these alternatives also prove unsatisfactory, the set with the highest success rate, regardless of LoS status, is chosen for the final estimation.

3. RESULTS

Our simulation environment, detailed in MATLAB, constructs a 5G network with seven uniformly placed gNBs within an indoor setting (InF) explained in detail in [2]. For each simulation iteration, the UE's position is randomly generated. During these runs, Positioning Reference Signals (PRS) and dummy Physical Downlink Shared Channel (PDSCH) data are created and allocated to the resource grid. The UE then receives these signals, which have been modified by the channel characteristics. Subsequently, sample delays are deduced, and the Relative Standard Time Differences (RSTDs) are measured. These RSTDs are then conveyed to the Location Management Function (LMF) to facilitate the position estimation process. In the offline phase of the SA- TDoA algorithm, the indoor space—measuring 120m × 50m meters as determined by [2]—is segmented into 60 zones. An LSTM network is trained to categorize UE measurements into these zones, identifying the optimal anchor set through exhaustive search, and compiling a success table for each anchor set across all zones. The online mode operates as previously described. Figure1 provides a comparative analysis of localization errors derived from three distinct anchor selection strategies. Among these, the 'Best' anchor-set serves as a benchmark, identified through exhaustive search among all possible anchor sets estimation error and therefore impractical. The figure contrasts the combined LoS/NLoS scenario with outcomes from the 'LoS' and 'SA-TDoA' strategies. Notably, the SA-TDoA method demonstrates superior performance, maintaining localization error below 5.17 meters for 90% of User Equipment (UE) locations, in stark contrast to the LoS strategy's less effective 7.8 meters threshold. This 33% reduction in error underlines the critical advantage of accounting for the relative positions of anchor sets and UEs. The analysis underscores SA-TDoA's potential to significantly enhance localization accuracy, offering valuable insights for the development of more reliable positioning systems.

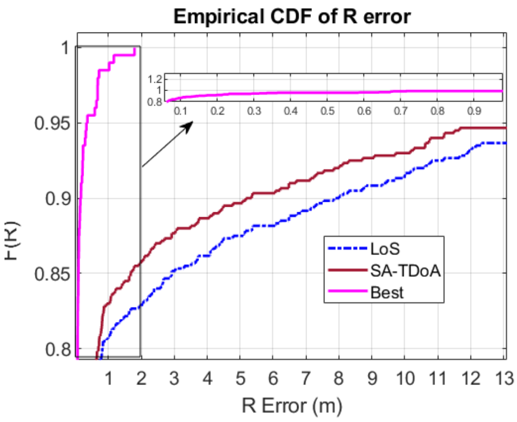

Figure1. demonstrates the CDF of localization error based on three different anchor selection strategies. The "Best" anchor-set which is determined through an exhaustive search among all possible anchor-sets and is only mentioned as a benchmark. The "LoS" anchor-set and the so-called "SA-TDoA" anchor-set.

4. CONTRIBUTIONS

This study emphasizes the interplay between network topology and channel effects in indoor positioning. The contributions are manifold:

- We introduce a novel spatially aware TDoA-based localization algorithm by examining the geographical configuration of the network, pinpointing scenarios where Line-of-Sight (LoS) anchor sets are inadequate.
- We conduct a detailed, zone-wise examination of the indoor area to determine the most suitable anchor sets for each specific zone.

Integrating these aspects, the spatially aware-time Difference of Arrival (SA-TDoA) algorithm is developed. This algorithm detects when LoS anchor sets fall short and suggests alternative anchor sets that ensure more precise localization.

5. REFERENCES

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