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EXECUTIVE SUMMARY OF THE THESIS

5G Positioning: A Feasibility Study with Real Data

LAUREA MAGISTRALE IN TELECOMMUNICATION ENGINEERING - INGEGNERIA DELLE TELECOMUNICAZIONI

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1. Abstract

This thesis is about positioning with fifth-generation (5G) cellular networks. The presented work examines sets of real 5G measurements collected from the public network in urban and rural areas in Milan. The analysis of data allows us to infer coverage analysis, received signal quality, Time-of-Arrival (ToA), and range analysis as well as the issues of strong outliers due to multipath and obstructed visibility. Thus, we analyze filtering techniques operating over the raw ToA measurements to mitigate such undesired effects. We also compare different positioning and tracking algorithms. Our findings suggest that, at present, synchronization errors are highly limiting 5G performance, and enhanced algorithms are required as the use of standalone raw measurements allows to reach an accuracy of only 40 to 150 m.

2. Introduction

Wireless network positioning has recently gained higher attention as new use cases are introduced in daily life, industrial, and emergency applications. Global Navigation Satellite System (GNSS) has been the dominant positioning system used in today's applications [1]. However, GNSS also suffers from major limitations like extremely weak signals in certain environments, e.g., indoors and urban canyons [2]. On the other hand, cellular positioning has been the less popular positioning system, due to poor signal quality and less availability. However, the poor performance of cellular positioning systems is expected to change with the development of 5G, the new-generation cellular communication network.

5G introduces enhanced positioning capabilities thanks to the introduction of dedicated positioning signals, the availability of large bandwidths especially at millimeter-wave [3], advanced beamforming techniques enabled by mimo, and dense deployments [4]. Such features should bring cellular positioning to the next level, making it suitable for augmenting or even replacing current popular GNSS-based solutions, targeting to reach the sub-meter level of accuracy.

3. Objectives

The ultimate goal of this thesis is to investigate the positioning performance of real-world network deployments using standalone 5G NR. Moreover, this thesis aims to investigate different data processing and positioning methods in urban and rural environments. Data processing techniques and positioning algorithms are compared to assess their impact on handling severely perturbed and noisy Time of Arrival (ToA) observations.

In order to investigate the positioning performance we use data collected from two campaigns, one collected in an urban and another collected in a rural site. Both campaigns contain data from one static receiver (i.e., User Equipment (UE)) and the rural campaign also contains data from a mobile UE.

The first step of the thesis work is to determine a preprocessing method that reduces the effects of noise and interference on data. This thesis uses and evaluates the performance of two types of preprocessing methods: Savitzky-Golay filtering with a joint outlier removal process and a Kalman filter that tracks the received TOA from the Sync Sign Block (SSB) measurements of each base station.

Furthermore, ToA and Time Difference of Arrival (TDoA) measurements are used in two positioning algorithms, nonlinear least squares (NLS) and Kalman filter (KF).

The objectives and original contributions of this thesis can be summarized as:

- Collection and analysis of 5G data, evaluating range errors of base stations and mappings of the coverage areas.
- Design of preprocessing tools that reduce the noise and interference effects using Savitzky-Golay and Kalman filters. Evaluation of these filters on single point range errors collected from base stations.
- Design of weighted nonlinear squares (WNLS) and Kalman filter positioning algorithms considering the 5G physical layer properties.
- Evaluation of these algorithms using data from rural and urban environments. Assessment of the performance of these positioning methods in different environments.
- Assessment of the positioning performance of the current 5G networks and comparison with performances of the simulations presented in the literature.

4. 5G NR Positioning

The positioning capability of 5G cellular networks has been strongly pushed by the standardization group of 3GPP, which aims to release a joint communication and positioning standard that targets to fulfill the requirements of most advanced applications, ranging from industrial services to intelligent transportation systems. This is done thanks to the design of a flexible frame structure that opens possibilities of personalization and the design of custom signals for the desired services.

4.1. State of the Art

The utilization and performance of 5G signals under ideal conditions need to be studied in order to understand the true potential of the 5G positioning.

In one of the studies, different channel conditions and their effects on 5G positioning are investigated. Using the 3GPP channel models: urban macro (UMa), urban micro (UMi), and indoor open office (IOO) [3]. For UMa and UMi environments downlink-TDOA (DL-TDOA), and for IOO uplink-AOA (UL-AOA) is used as the positioning algorithm. The carrier frequency for FR1 is chosen as 2 GHz, and for FR2 it is 28 GHz. Subcarrier spacing is 30 kHz and 128 kHz respectively. Receiver noise is assumed to be 9 dB and UE speed is assumed 60 km/h for UMa, 3km/h for UMi, and IOO. For UMa and UMi, frequency band FR1 is used while for IOO, FR1 and FR2 are used collaboratively [5]. The results of this study indicate that outdoor scenarios 5G can reach a couple of meter errors, while indoor scenarios, especially for the higher frequency FR2, can reach submeter error distances.

Another study demonstrates the effects of network density, and how it affects the performance of the 5G positioning system. In this simulation, the performance of an ultra-dense network (UDN) is simulated to observe the capabilities of 5G UDN with the TDOA positioning technique [6]. The results demonstrate that the errors can be down to the submeter in LOS conditions in a UDN. It can also go down to the submeter for NLOS conditions depending on the position and network density and geometry around the area, nonetheless, it can go up to 50m error in NLOS conditions.

These studies are conducted using simulations and software-defined radios (SDR) considering ideal channel conditions modeled by 3GPP. However, the performance of real network deployments differs from these simulations as the current technologies used in base stations do not meet the requirements in these studies. Hence, in this thesis, we analyze the performance of real data collected from current network deployment and investigate whether the performance of real data validates the results of these studies.

4.2. 5G NR Physical Layer

For localization and synchronization applications in 5G NR, the synchronization block (SS/PBCH) plays a critical role. SSB also denotes this block.
The SSB structure is the same for all numerologies in a 5G NR network. However, for a half frame, the number and first symbol indexes for candidate SSBs are different and determined according to the corresponding subcarrier spacing defined by 3GPP [7]. The subcarrier spacing for case C is indicated in the table 1.

SCS	Starting OFDM Symbol	$3 < f_c < 6$ GHz
Case C: 30 kHz	{2,8} + 14n	n = 0,1,2,3 (8 SSBs)

Table 1: Subcarrier spacing table [7]

Node base station (gNB) uses beam sweeping to transmit SS bursts periodically that are formed by multiple SSB signals, each SSB representing a beam formed by the gNB. As shown in figure 1, each beam has a specified interval and direction. These SSBs are indexed in ascending order from 0 to L-1, L being the number of SSBs.

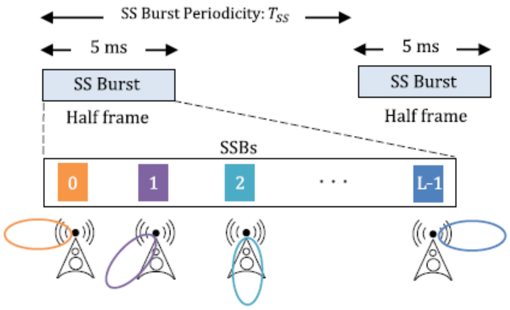

Figure 1: SSB transmission [8]

In this thesis, the data collected from the base stations use case C as their subcarrier spacing scheme. Subcarrier is 30 kHz with the carrier frequency being 3.7 GHz. The number of SSBs, L is 8. For each SSB, the corresponding ToA measurement is recorded and used in the positioning algorithm.

4.3. Measurement of 5G Signals

The measurement of 5G signals is done through instruments that are compatible with the available installation/gNBs. In this thesis, R&S® ROMES4 v21.1 Drive Test Software and driver are used to measure the 5G NR radio signals with a TSMA 6 scanner [9].
During the measurements with R&S® ROMES4 v21.1 Drive Test Software, data can be viewed without storing (measurement mode), data can be viewed and stored (recording mode) or past data can be loaded and viewed (replay mode). As the data processing is part of this thesis and done through MATLAB®, this software is used to record the data.

5. Data Preprocessing

In this thesis, data preprocessing is used to both utilize the side information and verify the analysis we performed, as well as reduce the noise and interference effects on the measurement signals.

5.1. Site Mapping

Using the physical layer properties of 5G beams mentioned in section 4.2 and matching them with the positions and azimuth angles of the base station antennas, we can have a rough estimate of the SSB coverage maps. Hence, we can have prior information on the line-of-sight (LOS) SSB.
In figure 2 we have the SSB mapping of the urban base station 4 (UBS4), and in figure 3 we have the SSB mapping of the rural base station 13 (RBS13). We can conclude that for UBS4, data collected from SSB4 and SSB5 will be better than other SSBs, and for RBS13, data collected from SSB0 will be better than the other SSBs. We can notice the differences between the urban and rural areas, the density of the buildings, and the density of the network.
In order to validate the LOS SSBs obtained from the mappings, SINR values are used. An example of boxplot visualization of SINR values collected from UBS7 is shown in figure 4.

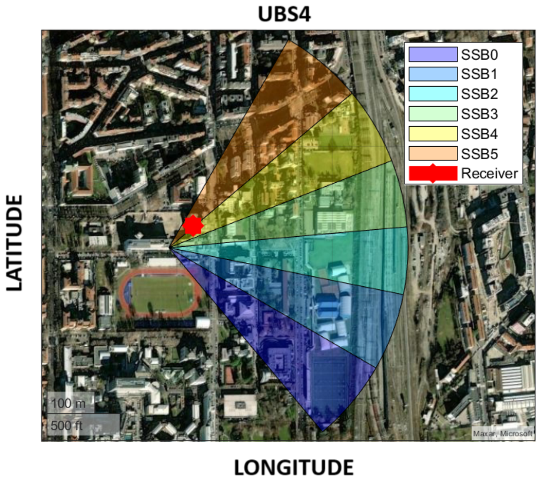

Figure 2: SSB mapping of UBS4

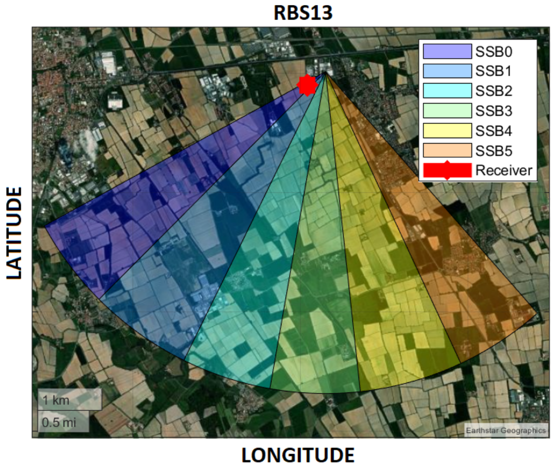

Figure 3: SSB mapping of RBS13

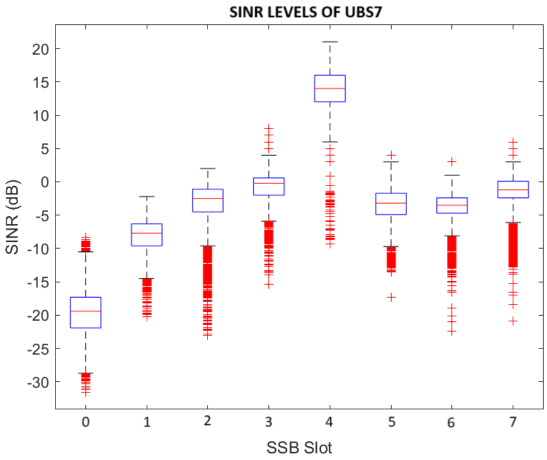

Figure 4: Boxplot of SINR values recorded from UBS7

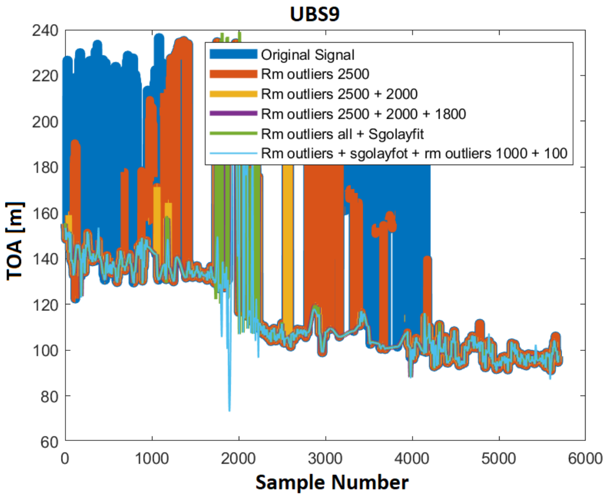

Figure 5: Savitzky-Golay filtering of ToA collected from UBS9

5.2. Filtering TOA Measurements

In this thesis, two types of digital filters are used in order to reduce the effects of noise and interference: Savitzky-Golay filter and Kalman filter. Savitzky-Golay filter is used with a joint outlier removal and interpolation process working on different window sizes, in order to detect the different sizes of interference blocks and reduce their effects. However, these window sizes also introduce a delay to the processing, which is a drawback for real-time operations. Figure 5 demonstrates each step of Savitzky-Golay filtering and how the signal changes after each step. Kalman filter is another preprocessing method used in the thesis and it can work in real-time without introducing a delay to the processing. Considering timing is a critical factor for real-time operations Kalman filter is recommended for reducing noise and interference. Figure 6 demonstrates the signal after Kalman filtering.

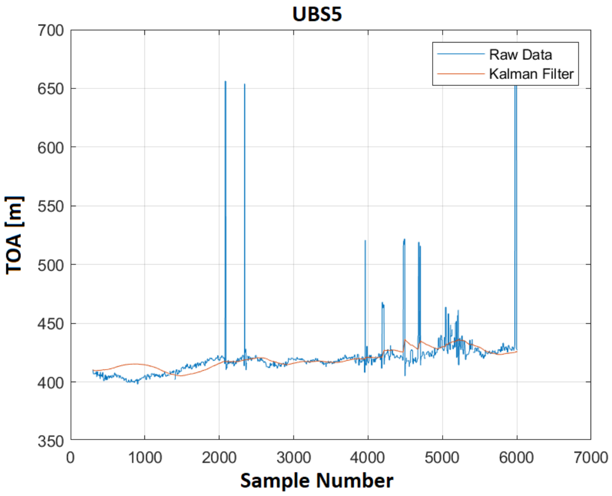

Figure 6: Kalman filtering of ToA collected from UBS5

6. Positioning Methodology

This thesis analyzes data from two types of users: static and dynamic. The data from the urban environment only contains a static user while the data from the rural environment contains a static and a dynamic user.

For the positioning of the static user, the iterative weighted nonlinear squares algorithm (WNLS) is used using ToA and TDoA measurements.

For the ToA-WNLS algorithm, ToA measurements coming from individual base stations are used to estimate the position of the target. Weights are identified according to the signal variance of the base station. The variance of the base station is calculated after removing the clock drift of the base station.

For the TDoA-WNLS algorithm, TDoA measurements are identified based on the ToA measurements. The reference station is chosen with three different methods: a base station with the overall best SNR values, a base station with the best real-time SNR value, and a random base station to observe if it compensates for the randomness of the error.

For the dynamic user, ToA-WNLS and a Kalman tracking method are used to estimate the position. The dynamic tracking method allows us to build a path for the dynamic user accounting for the motion model of the target, using Bayesian estimation techniques.

7. Results

The table 2 summarizes the overall results from all methods used during the analysis of the collected data. Column "Env" stands for environment type and U denotes the urban environment while R denotes the rural environment. In the column "User", S stands for the static user and D stands for the dynamic user. In the positioning method, TDoA-WNLS1 is the TDoA with the reference station that has the highest overall SNR, TDOA-WNLS2 corresponds to the reference station with the highest SNR real-time, and TDOA-WNLS3 corresponds to the random reference station selection. Moreover, in the preprocessing column, SG stands for Savitzky-Golay preprocessing, KF stands for Kalman filter preprocessing.

Env	Pos. Method	Preproc.	Avg. Error
Static			
U	ToA-WNLS	SG	58.2 m
U	ToA-WNLS	KF	51.4 m
U	TDoA-WNLS1	SG	48.9 m
U	TDoA-WNLS2	SG	49.6 m
U	TDoA-WNLS3	SG	48.7 m
U	TDoA-WNLS1	KF	43.6 m
U	TDoA-WNLS2	KF	47.2 m
U	TDoA-WNLS3	KF	48.6 m
R	ToA-WNLS	KF	51.4 m
R	TDoA-WNLS2	KF	125.3 m
Dynamic			
R	ToA-WNLS	KF	553.0 m
R	KFTrack	KF	126.5 m

Table 2: Results of positioning algorithms

8. Conclusions

This thesis addressed the problem of 5G positioning in urban and rural environments using data collected from current network deployments. The objective was to analyze the experimental data, develop methods to reduce noise and interference, propose positioning algorithms using the 5G data, and evaluate the 5G positioning performance of the current network deployments using different methods in different environments. The analyses we conducted showed that as a preprocessing method, using a 1-D Kalman Filter is a better technique than the Savitzky-Golay filter assuming that the positioning method is the same. In the urban environment, TDoA methods dominate the perfor-

mance of the ToA methods while in the rural environment, TDoA performs particularly worse than ToA. This indicates that the geometry of base stations needs to be considered when using ToA and TDoA methods due to the different properties of the circle and hyperbola. Also, performance differences between rural and urban environments indicate a synchronization issue between base stations. Well-synchronized base stations improve the positioning performance, while clock errors between the base stations can reduce the performance of the positioning algorithm significantly. These results also indicate that tracking the synchronization of the base stations is an important aspect of positioning performance. In the case of the dynamic target, the ToA method performs worse than the static case, indicating that ToA cannot compensate for the introduction of dynamic noise. However, using dynamic Kalman tracking as the positioning method compensates for this noise and performs better than the WNLS method compensating for the dynamic noise accounting for the motion model.
Overall, using these results we have demonstrated that the simulations performed in ideal conditions should be always complemented with data collected from the real environment. The reasoning can be explained as the key factors to achieve the true potential of 5G positioning, including the utilization of higher frequency bands and high-density networks, are not used in current network deployments. Considering these factors, we have demonstrated that current network deployments cannot reach the true potential of 5G positioning.

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