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5G-Based Localization in Industrial Environments

A survey on challenges of localization via 5G in industrial scenarios

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Abstract: This paper focuses on challenges occurring when using the 5G NR standard as a real-world application for precise localization in industrial environments. The different aspects of a mobile network based localization approach are discussed. First an overview on mobile network setup is given. Based on a mobile network emulation a first localization is conducted in an indoor laboratory. Afterwards the influence of indoor channel properties and the arising problems are discussed. With the results from this discussion, a new system model is introduced to improve the localization accuracy down to one meter.

Keywords: 5G, Survey, Localization, Indoor, Rising Edge

1 Introduction

The use of autonomous industrial vehicles in companies not only offers opportunities for increasing productivity, but also the risk of accidents. For this reason, strict regulations are in place, e.g. by specifying low speeds or special right-of-way rules. For an increased productivity and safety, all internal road users must be able to be informed of the current position of other participants in order to adjust their trajectory and thus avoid accidents.

Goal of the 5G SAIFE project is to establish a 5G based real time positioning solution for factory traffic participants. At the same time, the capabilities of the 5G standard shall be used for a low latency, high precision positioning. Key enhancements for a more precise positioning are defined in 3GPP 5G standard release 16 and further enhanced in release 18, whereas practical guidelines and implementation as missing at the current point in time.

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The roadmap of 5G provided by the 3GPP states that release 18 will be finished by end of 2023 respective start of 2024 [3G23].

This paper mainly presents evaluation and research gathered during the 5G SAIFE project.

Availability of feasible hardware solutions for test and measurement showed up as a key challenge. For FR2, with higher bandwidths, there does not exist "off the shelf" hardware for campus networks. In FR1 some proprietary hardware exists. The proprietary hardware only supports software releases up to release 15. As localization is introduced in release 16, the existing equipment does not support localization. In this paper a solution to emulate 5G localization is presented. Afterwards, localization measurements are conduced and evaluated. These results are refined by theoretical considerations based on a new system model.

The following section gives a brief overview on related work.

2 Related Work

Wireless localization is a widespread topic of discussion. [Tr16] shows the different approaches of wireless positioning in mobile communications. These approaches are classified in [Ga20] into signal strength based, time based and angular based procedures.

The release 16 standard introduces improved localization to 5G NR mobile communication networks. In this release, the positioning reference signal (PRS) is introduced for usage of the three classes of localization approaches [Dw21].

As shown in [Hu22], bandwidth is the most important factor for high accuracy localization. The 5G standard defines bandwidths of up to 100 MHz in frequency range 1 (FR1) and 2 GHz in frequency range 2 (FR2), enabling improved localization compared to previous mobile communication standards. With increased bandwidths, time based localization approaches have advantages, compared to power based approaches which do not depend on the bandwidth but suffer from low accuracy due to randomness of small-scale fading.

[Tr21] shows angular based approaches for FR2. A lack of available hardware does not allow for an implementation in practice. Resulting from the lack of hardware for angular based approaches and insufficient localization from power based approaches, time based approaches are the most used and promising techniques for 5G indoor localization [Pa22].

For time based approaches there are three main techniques: Round-Trip-Time (RTT), Time of Arrival (ToA) and Time Difference of Arrival (TDoA).

Localization accuracies vary depending on the used algorithms and scenarios. In [Ha23] the authors simulate a 5G FR2 scenario where an accuracy of 50 cm for 90 % of all cases is achieved. A more than generous bandwidth of 1200 MHz was used. At time of writing and to the author's knowledge, no systems for use in industrial environments exist that make use of FR2 of 5G NR.

Measurements with equipment for FR1 localization has been discussed in literature. The authors of [Pa23] use a TDOA approach. To increase the accuracy of the measurements the results are oversampled with a factor of 16 resulting in an accuracy of 4 m without averaging and calibration. Taking averaging into account and by properly calibrating the devices, 90 % of all measurements give an accuracy of better than 3 m. The main source of errors is a lack of synchronization.

In [Ru22a] a power based approach was used to determine the accuracy of localization in FR1. To increase precision, a neural network was used. This method uses a technique called fingerprinting where the receiver stores channel state information (CSI) and received signal strength indicators (RSSI) before the active localization in a database. During active localization the so called iPos-5G algorithm uses an AI to compare actual CSI and RSSI information to the database. The resulting accuracy dependents on the scenario. In an office environment the authors achieve an accuracy of 2.39 m, and 3.26 m in a corridor. This technique requires extensive measurements before active localization. It is questionable, how long the fingerprinting will stay valid in a non-static environment. In a follow-up publication, the authors improved the accuracy to 2.35 m in 90 % of all cases [Ru22b]. Combining fingerprinting and angular based approaches in a neural network is shown in [Zh21] with a mean accuracy of 50 cm in simulations. A sensor fusion approach combining LIDAR data and signal strength data in a simulation by [Mu21] results in a high error of 6.55 m.

In [Ga17] the authors present an excellent discussion on using super-resolution algorithms like MUSIC or ESPRIT for TOA and TDOA localization. While these approaches are more tolerant regarding noise, the increased needs for computational power makes these algorithms undesirable compared to the approach shown later in this paper.

Our previous work evaluated channel impulse responses (CIR) in industrial environments [Kn22] with respect to ToA measurement. The paper shows that the CIR does not consist of a single line-of-sight (LOS) impulse but rather of a LOS impulse and multiple echoes which arrive shortly after the initial LOS component. Echoes result from multiple reflections in indoor propagation scenarios. Using high bandwidth systems, it is possible to identify each echo and remove it afterwards. For low bandwidth systems the superimposed echoes deform the LOS path impulse. For a 5G system this will be discussed in section 5 and following sections.

The following section covers the lack of available commercial equipment or software for setting up a 5G NR localization network and test environment.

3 Getting Started

The first approach to 5G localization in industrial environments is to use already existing networks from public mobile communication providers. In 5G exists the option that parts of a network can be dedicated to a special service. This method is called slicing. However, current mobile operators do not offer network slicing. Moreover, mobile operators do not offer localization even as a service on their own. Thus a campus network needs to be could be implemented at industrial sites, though still lacking any location service.

As mentioned in section 1, there is no hardware available to conduct localization in self operated campus networks. Based on software defined radios (SDR), Open Source software solutions such as O-RAN and SRS-RAN offer an alternative to proprietary hardware. While it is possible to set up a running 5G base station (gNB) using SRS-RAN, the software is also lacking the location management function (LMF), which is needed for localization.

Since off the shelf solutions do not exist, gNBs and UE have to be emulated to be able to conduct experimental research. The emulation has to match the requirements provided by the standard. Therefore, vector signal generators (VSG) are used as gNBs. Each VSG is fitted with an individual 5G test signal. Table 1 shows parameters for the 5G test signals.

Parameter	**Value**
Transmission Frequency	3.75 GHz
Bandwidth	100 MHz
Subcarrier Spacing	30 kHz
Number of Subcarriers	3276
Frame Length	10 ms
Number of Slots	20 Slots
OFDM Symbols per Slot	14 Symbols per Slot

Tab. 1: Parameters of the 5G test signal

A 10 ms frame consisting of 20 slots is used for transmissions. In the first transmitted slot the synchronization signal block (SSB) is transmitted to synchronize UE with gNBs. On the four following slots, each of the four different gNBs transmit their channel state informations (CSI) and PRS. The first OFDM symbol is used for the CSI, the second is left out and the remaining 12 symbols are used for the PRS. Each gNB has its own distinctive PRS signal depending on the assigned cell ID. After the five initial slots, the whole process gets repeated three times to match the frame length of 20 ms.

Meanwhile the UE is modeled by a portable handheld spectrum analyzer. The UE samples the whole received signal which is later post processed in MATLAB.

As a localization technique, a time based approach is used. The chosen methods are ToA and TDoA to determine 2D coordinates. With this approach, only three gNBs are needed for localization. However, using more gNBs gives the opportunity to use different base station combinations for the case that one measurement is off due to interference. For every gNB the time of flight needs to be determined. This is conducted by correlating the PRS which is unique for each gNB, to the received overall signal. From the obtained time delays, the slot offset needs to be subtracted to normalize all results.

In the following section the results and challenges of the experiment are discussed.

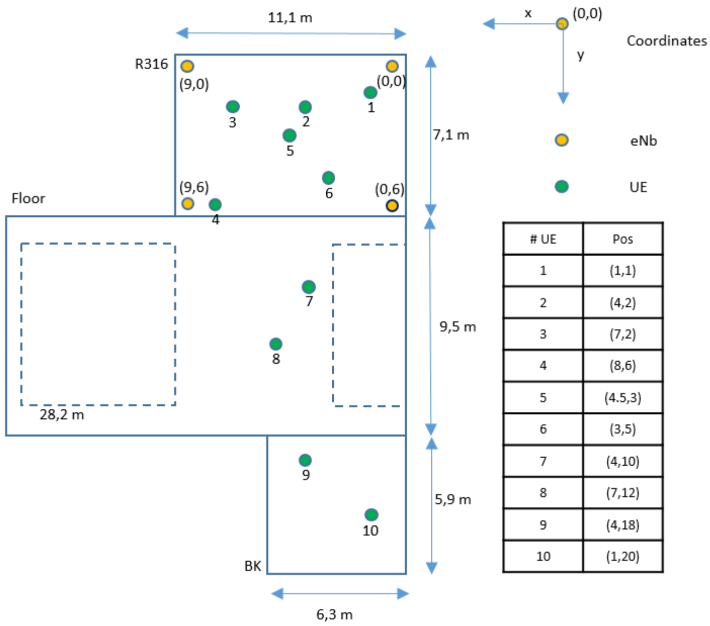
4 Emulation of 5G Localization using 5G Test Signals

For the emulation of 5G localization, four base stations are used. The site consists of the main room, in which the gNBs are placed and two adjacent rooms, to emulate shadowed LOS scenarios. The UE is moved across the site to the positions 1-10. Locations of the gNBs and the UE can be taken from fig 2.

As shown in section 2, the synchronization is the most important source of errors. To reduce the impact of synchronization errors, the VSGs are manually synchronized.

The measurement starts by an impulse issued by a signal generator, which also starts the transmission by the gNBs. Furthermore, to evaluate drift of the generators, position 5 is placed at the exact center of the four gNBs. Every occurring synchronization mismatch can be corrected during the post processing by correcting the time of flights, as these have to be equal.

The post processing in MATLAB correlates the received signal with each of the original PRS signals. To improve accuracy, the literature shown in section 2 recommends to use oversampling. In this experiment, an oversampling factor of 10 is used. Then the maximum of the oversampled correlation result is selected and converted into a time of flight value.



# UE	Pos
1	(1,1)
2	(4,2)
3	(7,2)
4	(8,6)
5	(4.5,3)
6	(3,5)
7	(4,10)
8	(7,12)
9	(4,18)
10	(1,20)

Fig 1: Layout of the scenario with marked positions of base stations and UE

Figure 3 shows the exemplarily correlation result for position 6.

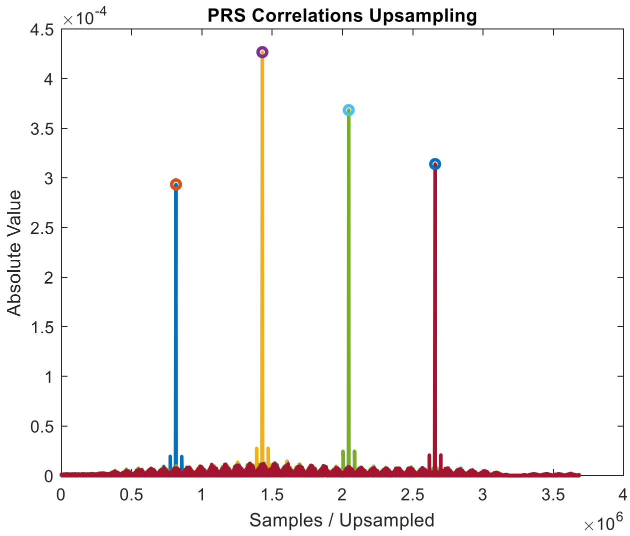


Fig 2: Correlation result of position 6

When looking at the peaks of the correlation, the influence of echoes can be examined. For individual UE and gNB position combinations, there are multiple peaks as shown in fig 4. A maximum search would lock onto the higher peak, even if it logically does not make sense. The LOS component of the signal will always arrive first at the receiver. Therefore, the first peak with a significant amplitude can be interpreted as the time of flight.

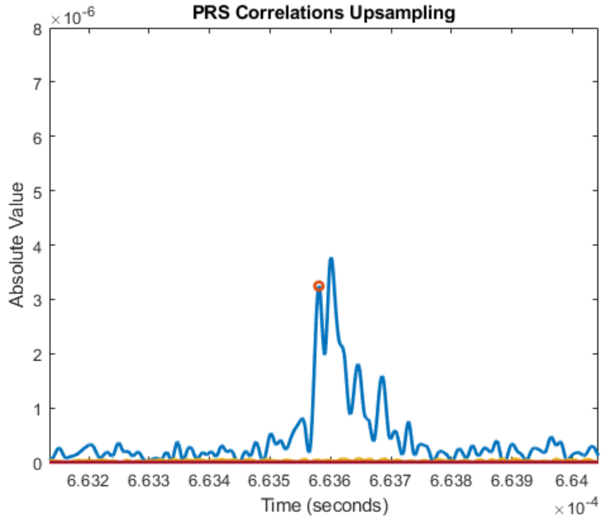


Fig 3: The improved maximum algorithm locks onto the first significant maximum and not on the global maximum

The derived positions for all nine positions, including time of flight correction and improved peak detection, are depicted in table 2

Real Position (X,Y)	**Calculated Position (X,Y)**	**Deviation In m**
POS1 (1,1)	(1.4, -1.65)	0.76 m
POS2 (4,2)	(4.37,1.44)	0.67 m
POS3 (7,2)	(6.98, 0.76)	1.24 m
POS4 (8,6)	(15.78, 14.43)	11.47 m
POS5 (4.5,3)	(4.5,3)	0 m
POS6 (3,5)	(1.46, 4.83)	1.55 m
POS7 (4,10)	(2.49, 5.65)	4.60 m
POS8 (7,12)	(4.87, 5.21)	7.11 m
POS9 (4,18)	Not measured	Not measured
POS10 (2,20)	(0.96, 4.97)	15.07 m

Tab. 2: Calculated positions and the deviation to the real positions

Despite the made corrections, an exact localization is not possible for every combination of gNBs. When observing the correlation results, the influence of echoes on the main LOS peak is obvious. The following section focuses on modeling the influence caused by echoes.

5 System Model for a new Approach

An industrial environment suffers from multiple echoes which arrive close to the LOS path. To model the LOS and echoes mathematically, dirac impulses are used. Through the band limitations, impulses get deformed into SINC impulses. Understanding the influence bandlimited impulses have on each other is key in improving the accuracy of localization in wireless communication networks.

In a first investigation, one SINC impulse with an amplitude of 1 is superimposed with a second SINC impulse of same amplitude. When there is no time difference between these two SINC impulses, the sum results in one SINC impulse with doubled amplitude. Now, a time offset is applied to the second impulse. For small time offsets the resulting signal corresponds to a slightly time shifted SINC impulse with an amplitude greater than1. The original SINC impulse could not be extracted from the superimposed signal. For large time offsets, the superimposed signal has two distinctive peaks at exact the positions of the peaks of the single SINC impulses. The scenario shows that for sufficient big time delays a maximum peak detection can detect the correct time of flight of the LOS. If the time difference between LOS and one echo is smaller, the maximum of the signal is shifted to a later point of time. Thus, distorting the calculated time of flight.

The model, consisting of a LOS path and one echo, is extended to fit a more real scenario by adding multiple echoes. The channel impulse response becomes:

$$h_d(t) = \sum_{k=0}^{E} a_k SINC\big(B(t - E_k T)\big)$$

Where $a_k$is a complex scaling factor, B is the bandwidth of the signal, $T$is the sampling Time and $E_k$is the time delay for an echo k. In the following section, an improved localization approach is presented based on this system model.

6 Approach to improve 5G Localization Accuracy

The system model presented in section 5 consists only of scaled SINC impulses. As already shown, the peak of the LOS path is deformed by following echo impulses. The signal is now divided into a main peak area, rising edge area and a pre-oscillation area. If the following echo impulses are close to the LOS impulse, the maximum of the function (the main peak) is shifted to a later point of time. For a real system, the maximum cannot be shifted to an earlier point of time. However, for some LOS-echo combinations, the maximum shows up before the time of the LOS impulse peak. These special cases are based on seldom phase combinations of LOS and echo paths.

The question arrives which area of the superimposed signal should be evaluated to have the best match to the LOS path only?

Observing the pre-oscillation area makes no sense as this area is mostly influenced by noise due to very low amplitude of the SINC impulse in that area. The rising edge is left as an interesting area to observe. The rising edge of the whole signal is dominated by the first received impulse. As stated before, the first received impulse in a LOS scenario is always the LOS impulse. Only the maximum is shifted by subsequent impulses.

7 Simulation of Approach

When simulating a channel model with different numbers of echoes, it gets clear that the resulting superimposed signal will either have a distinct maximum, when the echoes arrive significantly later than the LOS path, or a distorted maximum due to short time offsets between echoes and LOS. As seen in previous work and section 4, the latter case is mostly present in industrial environments. This scenario is now simulated by using the system model provided in section 5. In 200 different realizations, 25 superposed impulses are used to create channel impulse responses. The LOS impulse has a normalized amplitude of one. Fig. 5 presents a selection of 10 out of the 200 realizations.

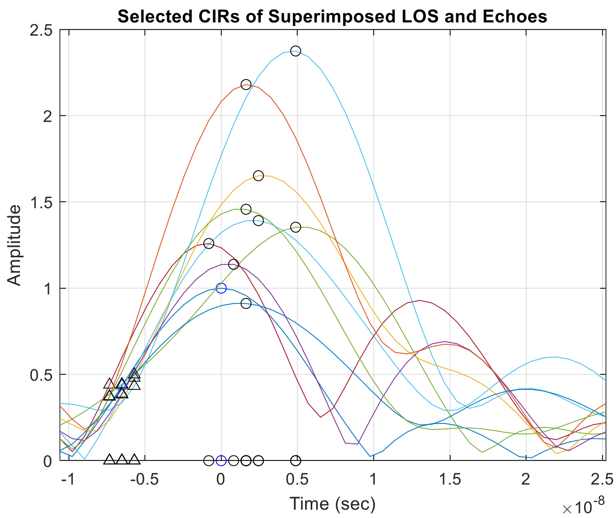


Fig 4: Multiple CIR of different realizations. The spread of the rising edge is significantly smaller than the spread of the maxima.

The figure shows that a pure maximum detection algorithm has a wider spread compared to an algorithm which locks onto the rising edge. A smaller spread of time values reduces the resulting error of a ToA or TDoA algorithm. Of course, the underlying time offset has to be compensated.

The following section makes use in practical measurements with the improved simulation approach.

8 Emulation of 5G Localization using VNA

The newly introduced approach is now applied to a new set of measurements. As the approach focuses on reducing the time error of one link, the experiment will consist of emulating only one base station UE combination. A whole TDoA or ToA procedure is not needed. When the accuracy of one distance measurement is increased, the resulting localization accuracy is also increased.

The measurements are conducted in a 7 m by 7 m room. From a Vector Network Analyzer (VNA) one port is used as a receiver (UE) and one port is used as a transmitter (base station). The UE is placed at 25 different positions in the room. To detect unpredicted changes in the channel, a third antenna is placed at a reference position. For every position the measurement is conducted with greater bandwidth (7.5 GHz) and a restricted bandwidth of 100 MHz. The restricted bandwidth is used as a substitute for a 5G FR1 signal while the full bandwidth allows a better understanding of the channel.

The received CIRs are post processed with the proposed rising edge algorithm and the conservative maximum approach. For the full bandwidth, the two approaches determine the distance between transmitter and receiver correctly. The biggest deviation is about 10 cm. When using the limited bandwidth, the errors naturally increase. Here, the rising edge algorithm allows for a better distance measurement accuracy with a variance of 0.252 m and a standard derivation of 0.502 m compared to the maximum peak algorithm which has a variance of 1.403 m and standard deviation of 1.184 m. Obviously wrong detections are excluded. The measured distances for a 100 MHz system with both approaches are depicted in Fig. 6.

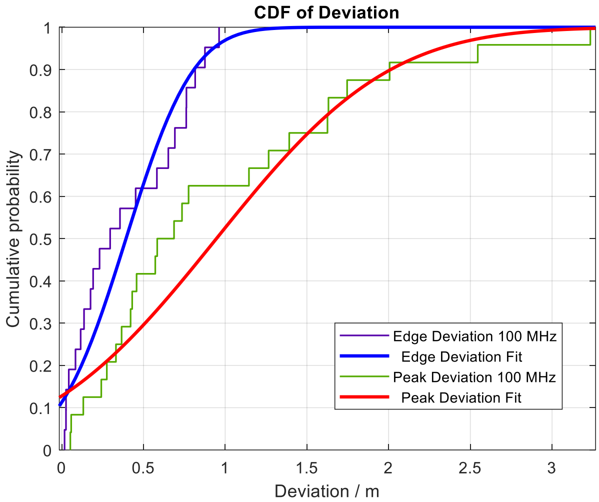


Fig 5: Comparison of deviations of rising edge and maximum approach

As shown, the usage of a rising edge detection algorithm allows an increase in accuracy. The standard derivation of the accuracy error can be halved by using the rising edge detection, compared to a maximum search detection.

9 Conclusion and Future Work

This paper shows the practical use case of 5G localization in industrial environments and the challenges occurring during measurement implementation. Existing 5G public communication networks do not provide the service of localization. The alternative is a campus network which depends on availability of off the shelf components. As localization using signal generators, transmitting 5G test signals, suffers from critical synchronization, a VNA based approach helps to overcome discussed issues. This paper discussed a different methodology to identify the LOS path. A basic maximum search is proposed and afterwards improved by using the rising edge of the CIR. With this approach, an accuracy of sub 1 m is possible for indoor scenarios with 5G NR FR1 bandwidth limitations.

Future work investigates trajectories of moving targets in close indoor environments to further improve localization accuracy.

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