Use Case Driven Feasibility Study on the Technical Capabilities of 5G Indoor Positioning in the Automotive Production

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Abstract

The digitalization and automation of processes are essential for successful industrial production systems. Real-time positioning data is crucial for intelligent, automated, and quality-assured production. However, the lack of standardization in current real-time locating systems leads to high costs, inoperability, and limited multi-vendor availability. On the other hand, 5G technology offers in theory opportunities for high-accuracy positioning beyond mobile communication. Local 5G networks in industrial settings could leverage existing infrastructure for positioning. Although previous research demonstrates the theoretical capabilities of 5G positioning, practical trials cannot be performed due to hardware still being in early research developmental stages. This research aims to close the gap between research and industrial use by assessing the technical feasibility of 5G indoor positioning in an automotive production environment. To achieve this, use cases from research and industry are categorized into different scenarios based on distinct requirements. Representative use cases are analyzed considering system requirements and their feasibility. For this, first the overall concept of 5G positioning is tested in a research lab, followed by simulations of 5G positioning in an industrial environment. This is performed to determine the technical capability and expected accuracy. The simulations show that sub-meter accuracies can be achieved when combining 5G positioning with line-of-sight filtering. This study highlights the promising role of 5G as a real-time locating system in industrial settings. However, further research is needed to evaluate its accuracy and reliability in complex practical scenarios. Real industrial piloting will contribute to the validation and optimization of 5G positioning systems, facilitating widespread adoption across industries.

Keywords
5G Positioning, Feasibility, Automotive Production

1. Introduction

The automotive industry is undergoing significant transformations, driven by factors such as global competition, evolving customer expectations, and a shift towards electrified vehicles from conventional combustion engines [1–3]. These changes necessitate a continuous pursuit of optimization, transparency, and innovation to ensure long-term competitiveness [4]. In this context, the concept of Industry 4.0 has emerged as a prominent topic in both business and academia, offering benefits such as enhanced flexibility, efficiency, effectiveness, and product safety and quality in manufacturing [5]. Location information plays a crucial role in achieving these qualities [6, 7]. Particularly in automotive production, where precise positioning (also known as localization) of vehicles, components, and tools is paramount. Real-time locating systems (RTLS) and the processing of positioning data not only facilitate transparency but also

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enable automatic process control, contributing to enhanced operational efficiency and quality assurance [8]. The emerging 5G cellular standard, renowned for its powerful communication features, has also been recognized as a potential solution for precise positioning. Leveraging global standardization, 5G offers high process reliability, making it an attractive choice for industrial applications. However, despite its promising potential, the practical testing of 5G positioning in industrial environments remains limited. Laboratory tests demonstrate the capability of decimeter-accurate positioning [9–13], but realistic testing in industrial settings, especially in automotive production characterized by constrained sites and challenging positioning conditions, is lacking. While numerous publications focus on the improvement of 5G positioning procedures and algorithms, the industrial feasibility of this technology for production usage remains uncertain.

To address this gap, this paper conducts a use case driven feasibility study for industrial positioning applications. Section 2 presents background information and the state of the art of 5G positioning based on a literature review and expert interviews. Use cases are then analyzed in order to determine the requirements for 5G positioning in industrial environments (Section 3). The concept of 5G positioning is then tested in a research setting (Section 4), followed by simulations in an industrial environment (Section 5).

2. State of the art of 5G positioning

In this Section the state of the art of 5G positioning is presented based on a literature review and empirical expert interviews.

5G holds considerable promise as a technology that offers robust communication capabilities and potential applications in positioning. It boasts high process reliability, a crucial prerequisite for industrial utilization, and benefits from global standardization [14]. Presently, 5G, particularly in terms of positioning, is still in the developmental phase. Standardization efforts by the 3rd Generation Partnership Project (3GPP) demonstrate that the precise positioning requirements were initially incorporated after the first release, referred to as 'release 15,' in late 2017. The 3GPP, a global collaboration of mobile communication standardization bodies, independently introduced the positioning requirements in the specifications of release 16 in mid-2020, aiming to achieve meter-level positioning accuracy [15]. Recognizing the immense interest from the industrial sector, future releases 17 and 18 dedicated focused attention and detailed advancements towards achieving low decimeter-level positioning capabilities [16].

However, despite the significant potential offered by this standardization, practical testing of the technology remains limited. One contributing factor is the time required for the development of commercial hardware aligned with the finalized standardization releases. Nonetheless, since tests in industrial settings do not employ commercial hardware, the maturity of the technology for industrial usage remains uncertain. [17]

In an empirical Study with 28 experts from both industry and research, they highlight the significance of RTLS as a critical tool for production in the automotive industry. Historically, real-time radio frequency positioning has primarily relied on Ultra-Wideband (UWB), Wi-Fi or RFID within the manufacturing sector. However, the emergence of 5G technology in the industrial domain brings forth immense potential as a positioning system. It is important to note that, as of 2023, 5G is not yet commercially available for precise industrial positioning applications. Experts concur that the development of 5G for positioning is still in its early stages, with standardized sub-meter level accuracies anticipated in future 5G releases. However, the corresponding hardware required to achieve such accuracies is projected to be available only after 2023. The industry has set demanding requirements for 5G positioning systems, including extended battery life, low latency, robustness, and high availability, in addition to precise position accuracy. These requirements are actively being integrated into the ongoing standardization efforts of 5G. Consequently, the specifications for industrial 5G positioning systems are currently in the developmental phase and predominantly exist in theory. Thus, the maturity of industrial 5G positioning has not yet been attained. However, comprehensive research is imperative to implement 5G positioning into realistic industrial test scenarios, particularly within the complex manufacturing and automotive sectors. [18]

3. Use Case Analysis

As discussed in the previous section, the capabilities of 5G as an RTLS in automotive production has already been described in theory. However, the transfer of theory into practice is missing for actual industrial use.

In order to take the step from theoretical capabilities to industrial use in a structured approach, a concept for the use of 5G as an RTLS in the industrial automotive production is developed in Figure 1. The technical feasibility strongly depends on the requirements of the use cases to be implemented in the future. Therefore, existing, and possible future use cases from research and industry are analyzed. Following, they are grouped into Reference Use Cases (RUCs) based on their requirements.

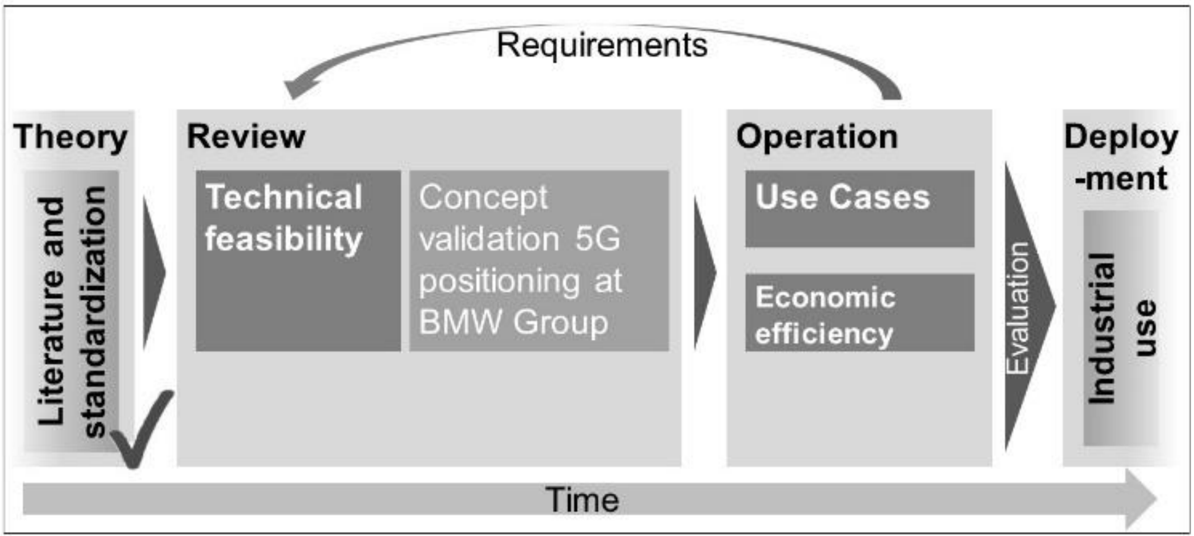

Figure 1: Conceptual framework for the use of 5G as RTLS in industrial automotive production

Industrial positioning use cases have already been identified in literature and industry – examples can be seen in [19, 20]. These include applications from the areas of asset management, vehicle tracking, parts and tool tracking, and process automation. Since each of these use cases has different requirements for possible location using 5G, the requirements are grouped into the RUCs (see Table 1).

Table 1:
Clustered reference use cases (RUCs).

RUC	Example Use Case	Characteristic
"Find my User Equipment (UE)"	• Intralogistics (sequence containers) • Goods tracking • Dolly tracking (outdoor)	• Coarse localization in the low meter range • clearer areas indoors and outdoors
Material flow	• Material feed to the assembly line • Flexible, modular assembly area • Augmented reality in smart factories • Monitoring of autonomous vehicles	• More accurate localization in the sub-meter range • Longer assembly aisles and corridors

Process automation	• Goods storage • Parts within assembly line • Tool assignment to cars/ parts	• Accurate localization in the low decimeter range • Tight environmental conditions in assembly line or storage area

The RUCs cover a wide range of possible applications. Whereas "Find my User Equipment (UE)" only requires accuracies (mostly horizontal) in the range of 1 - 5 m, the determination of material flow and process automation requires 0.5 to 1 m and < 0.3 m, respectively. The required latency also differs. It ranges from several seconds of tolerable delay to required real-time in the millisecond range. In addition, the requirements for update rate, device density and battery life (as well as their constructional limitations) determined in the literature are examined. The update rate ranges from under 1 Hz up to more than 4 Hz. The battery life is in the range of several months and the structural limitation of this is irrelevant for the first use case "Find my UE", but in the range < 30 cm3 for the second and third use case (material flow and process automation) – see Figure 2.

	Accuracy horizontal	Accuracy vertical	Latency	Update rate	Battery life	Construction limitation (of the battery size)
Finde my UE	1-5 m	irrelevant	1-5 s	> 1 Hz	> 6 m	irrelevant
Material flow	< 1 m	< 3 m	< 100 ms	1-4 Hz	6-12 m	< 30 cm^3
Process automation	< 30 cm	< 1 m	< 25 ms	> 4 Hz	> 12 m	< 20 cm^3

Figure 2: Requirements of the reference use cases (RUCs)

4. Analysis of technical feasibility

The technical feasibility of the use cases is investigated in two steps. 5G positioning hardware is not yet available at the time of these tests, which is why a research setup for 5G positioning is being used in cooperation with the Fraunhofer Institute for Integrated Circuits (Fraunhofer IIS) in Nuremberg, Germany. In their test- and application center L.I.N.K. localization over 5G can be tested in a controlled research environment. In a second step, the tests will be transferred to real environmental conditions of automotive production. Due to the lack of available hardware, the tool of simulation is used. For this purpose, a virtual 3D model is generated from an automotive production, which represents all three RUC environmental conditions. This 3D model is then used to perform a ray tracing analysis. From the results of this analysis, conclusions can be drawn about a possible achievable accuracy and improvements in network planning.

The Fraunhofer IIS test- and application center L.I.N.K. has set up a 5G test field for Industry 4.0. The goal is to provide a 5G standalone non-public network for the investigation of industrial use cases. It provides a standalone 5G system with features according to 3GPP compliant specifications. The frequency range is the same as the German industry-assigned 3.7 - 3.8 GHz range, and the system has precise time synchronization, enabling localization and low-latency transmission. There are 8 panel antennas installed in the 45 x 31 x 9 m hall (see Figure 3).

Figure 3: L.I.N.K. Hall of Fraunhofer IIS

This hall is used to test 5G localization by means of emulation. A 5G-capable device is driven through the test site on a wagon (see Figure 4, top left) in the form of a loop (see Figure 4, top right). The X and Y positions (Figure 4 below) are recorded in real time [21]. When evaluating the measurement, a theoretical accuracy of 0.2 m can be achieved with downlink time difference of arrival (DL-TDOA) for this application. This is done in combination with machine learning [22]. It should be noted that the environmental conditions for the location are optimal and only one object is located in the test. However, positioning using 5G shows potential for real-world use cases if the network is installed with positioning requirements in mind. To evaluate the environmental impact, the RUCs are next simulated in real environmental conditions in the following section.

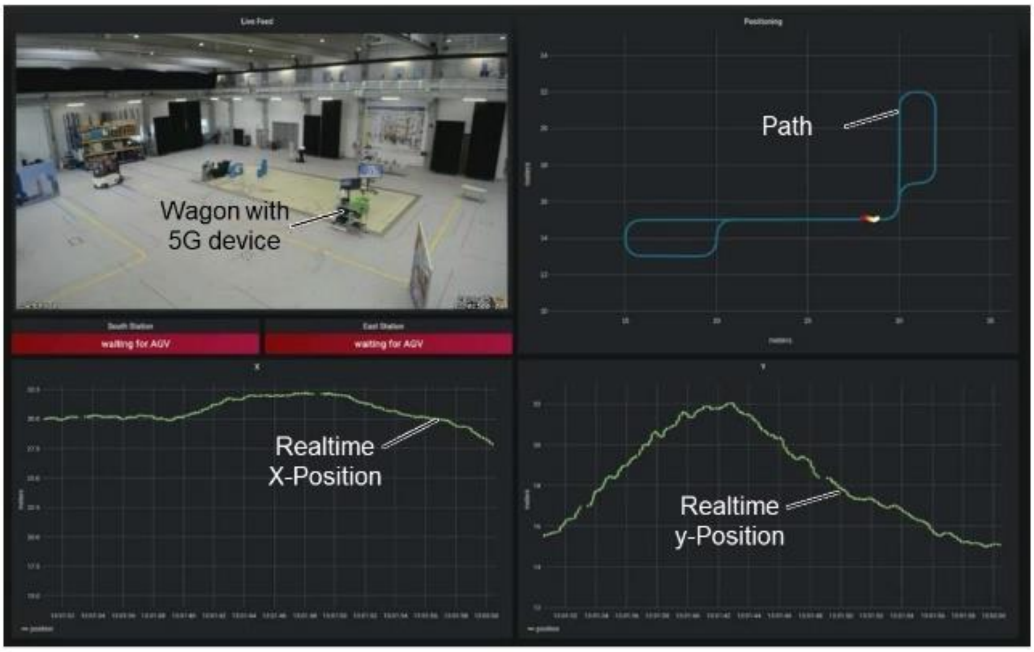

Figure 4: Implementation of the locating test in the research setup [21]

5. Simulation of 5G positioning in an industrial environment

In this section the implementation of 5G positioning in a real industrial environment is simulated and the results presented.

5.1. Implementation of the 5G positioning simulation in real environmental conditions

In order to simulate 5G localization with environmental conditions that are as real as possible, a test field is created from real CAD data of an industrial automotive production. This includes all three environmental conditions of the RUCs in a virtual assembly hall of approx. 80 m x 100 m in size. For this purpose, models of the machines and conveyors including the vehicles are first assembled (see Figure 5). At the top left and bottom right are free areas as they would appear in the "Find my UE" use case. Between the assembly lines there are corridors and transport routes for the material flow to the assembly line. In the assembly line itself, process automation can be simulated e.g., by locating vehicles and tools.

The used simulation models the propagation of 5G signals in constrained environments, taking shadowing and multipath effects into account. In addition, material properties can be specified as they directly affect the signal behavior. Limitations of the simulation are given in missing parameters like the synchronization of the positioning network. For real networks the radio units with the antennas must be well synchronized, otherwise the time differences cause significant errors in the position calculation. For the simulation, the commercial SE-NAV simulator with ray tracing for GNSS (GPS, Galileo) was used. This was extended for the 4G "Position Reference Signal" (PRS), the 5G PRS and the 5G "Sounding Reference Signal" (SRS) [23].

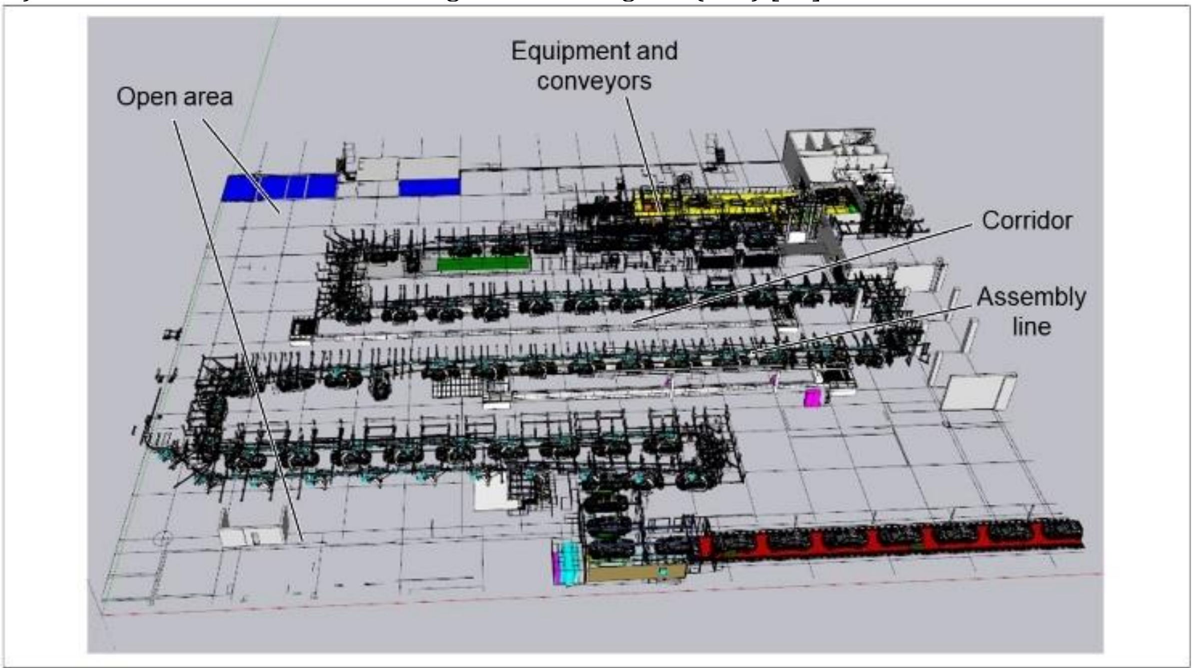

Figure 5: 3D model of the reference environment

In the next step, the vehicle contours are optimized for the simulation. In addition, the ceiling, floor, and walls are added (see Figure 6). These are relevant for the later beam propagation and reflections.

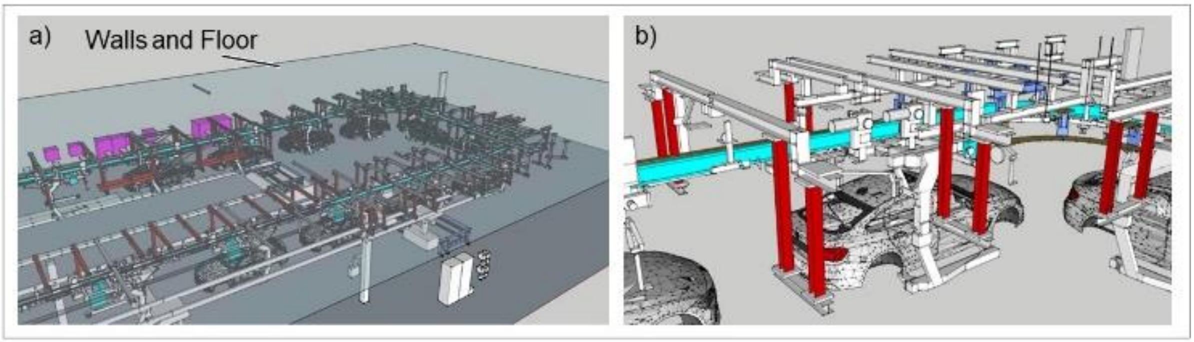

Figure 6: Simulation room and vehicle optimization

This model can be used to simulate different 5G antenna configurations. For this purpose, a virtual path (shown in yellow) is placed through the test areas of the different RUCs and analyzed by means of ray tracing. A visualization of the calculation can be seen in Figure 7 as an example of this simulation. The green dots represent the antenna configuration. The white rays are primary rays, which are emitted by the antennas. Blue and red rays show diffractions and reflections at the edges and nodes of the 3D model.

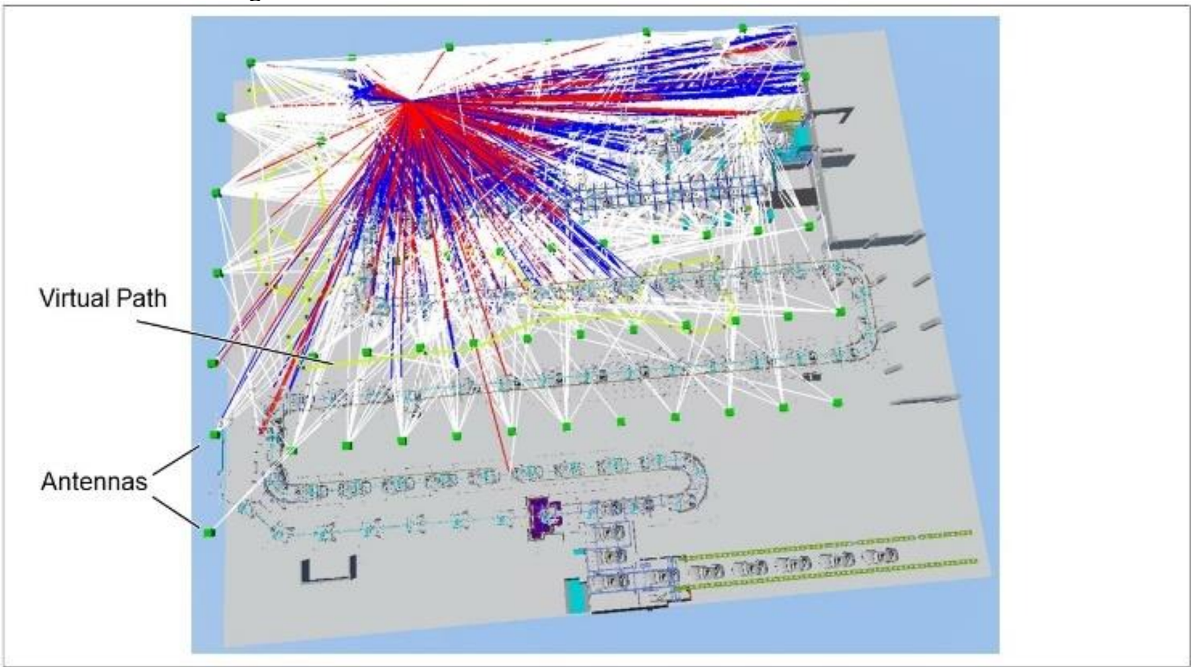

Figure 7: Visualization of the ray tracing simulation

These simulations are performed iteratively and evaluated in intermediate evaluations. Based on the results of this evaluation, parameters such as the path or the antenna distribution/number are adjusted. Besides their position, the signal carrier frequency, the transmit power and the antenna pattern are the main settings that determine the beam characteristics and the received signal power. The transmit antenna model is defined as an antenna with an aperture angle of 120 degrees, a carrier frequency of 4 GHz, and a bandwidth of 100 MHz. The results of these iterations are described in the following sub-section 5.2. A maximum of two reflections and two diffractions are considered.

5.2. Technical feasibility results

The simulations for reference use case 1 (find my UE) and 2 (material flow) are performed in a joint simulation. The virtual path is placed through the free areas in the assembly hall as well as in the supply aisles between the assembly lines. The position calculation is performed using the TDOA method. To get an understanding of the efficiency regarding the number of antennas, the results are shown for 17 and 37 distributed antennas. The antennas are placed in such a way that they have optimized radiation angles with respect to the environment. For 17 antennas, the simulated location accuracy is less than 1 m for most of the path (see blue portion in Figure 8). In some areas, however, the accuracy deviates up to several meters. These can be seen in the color gradient orange to red (for example on the path on the far right of Figure 8). This is due to a lack of antenna density or too many multipath effects.

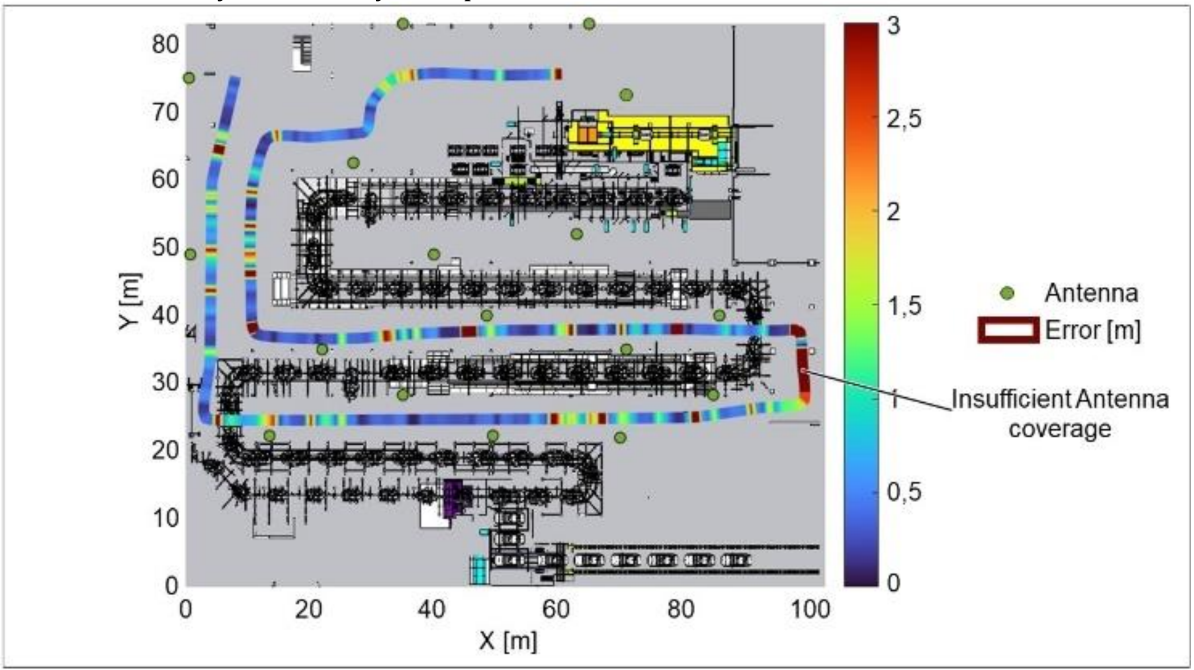

Figure 8: Simulation results use case 1+2 with 17 antennas

The results for 37 distributed antennas are presented in Figure 9). There is no significant improvement for the achieved location accuracy. Many signals are still only evaluated via multipath paths and reflections. This leads to an error in the distance calculation, which affects the positioning accuracy.

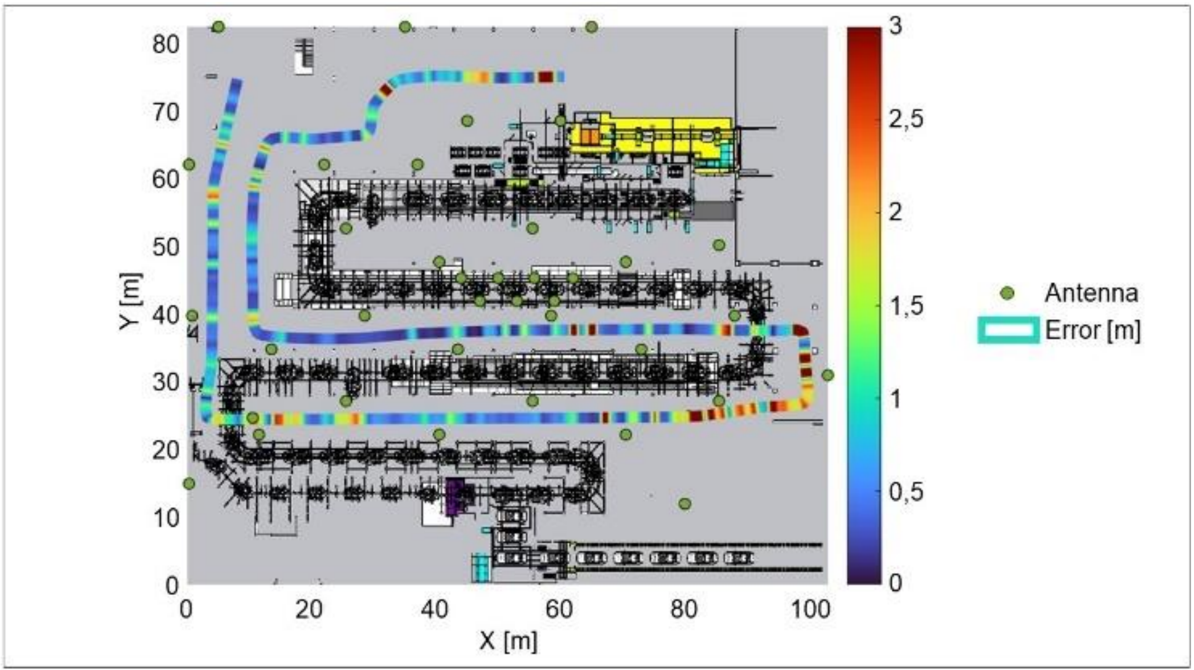

Figure 9: Simulation results use case 1+2 with 37 antennas

The effect of multipath propagation can be tested by using only the LOS signals for the position calculation in the simulation. Here, a significant improvement of the positioning accuracy results (see Figure 10). The errors are in the sub-meter range. The disadvantage of this evaluation method is that in some areas, where not enough LOS signals of the antennas are available, no positions can be determined.

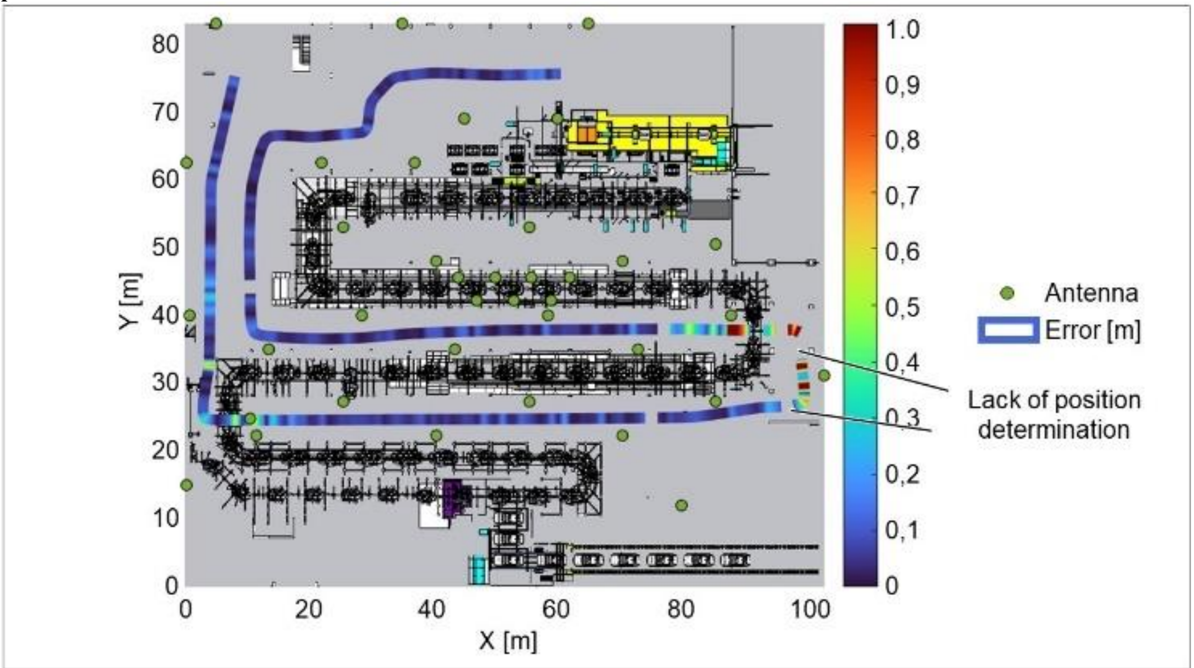

Figure 10: Simulation results use case 1+2 with 37 antennas (LOS only)

For comparison, the same evaluation method (pure consideration of LOS signals) is also carried out for the antenna distribution with 17 antennas (see Figure 11). Here it is shown that even with fewer antennas a high accuracy of mostly less than 1 m can be achieved. The disadvantage here is that even more often than in the previous test, no position determination is possible in some areas (as it can be seen from the missing path on the right in the figure).

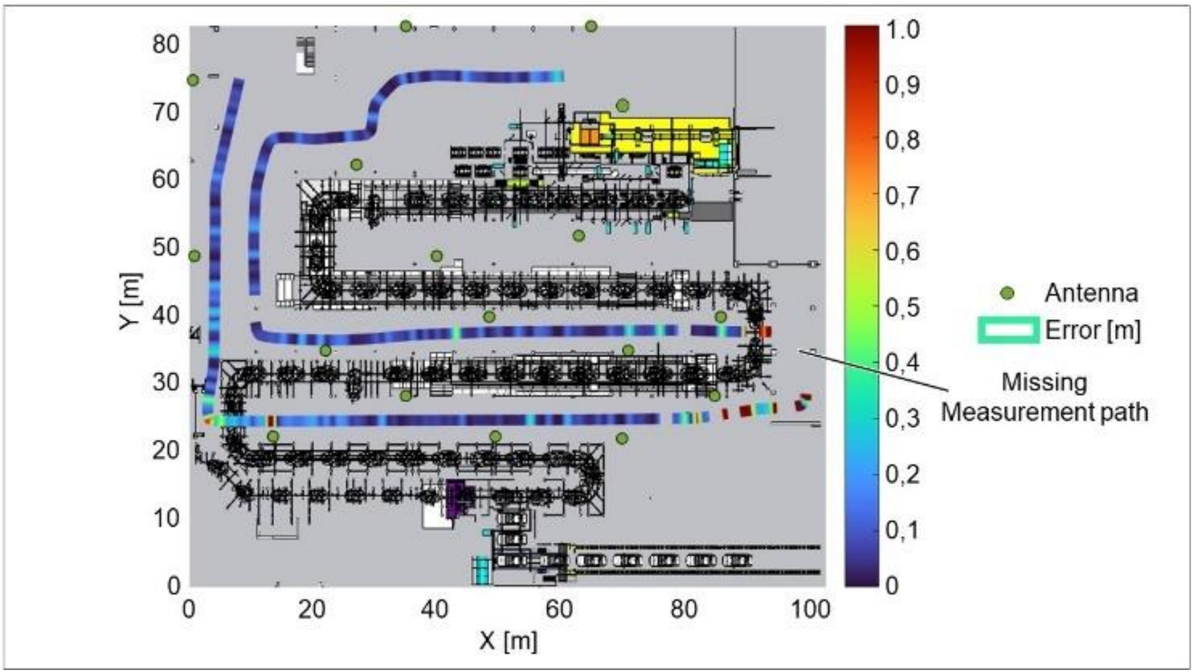

Figure 11: Simulation results use case 1+2 with 17 antennas (LOS only)

The achieved accuracy can be described by the Cumulative Distribution Function (CDF). This provides the achieved positioning accuracy as a function of the probability with which this accuracy is achieved. The difference of the LOS evaluation compared to the NLOS evaluation for both 17 and 37 antennas is clearly presented in Figure 12. The NLOS evaluation for a probability of 90 % has an accuracy of 2 – 3 m. If only LOS signals are used, this probability is achieved with an accuracy of up to 0.3 m. It can also be seen that especially for the 17 antennas LOS evaluation the 100 % cannot be reached, because there are points on the path for which the position cannot be calculated due to missing signals.

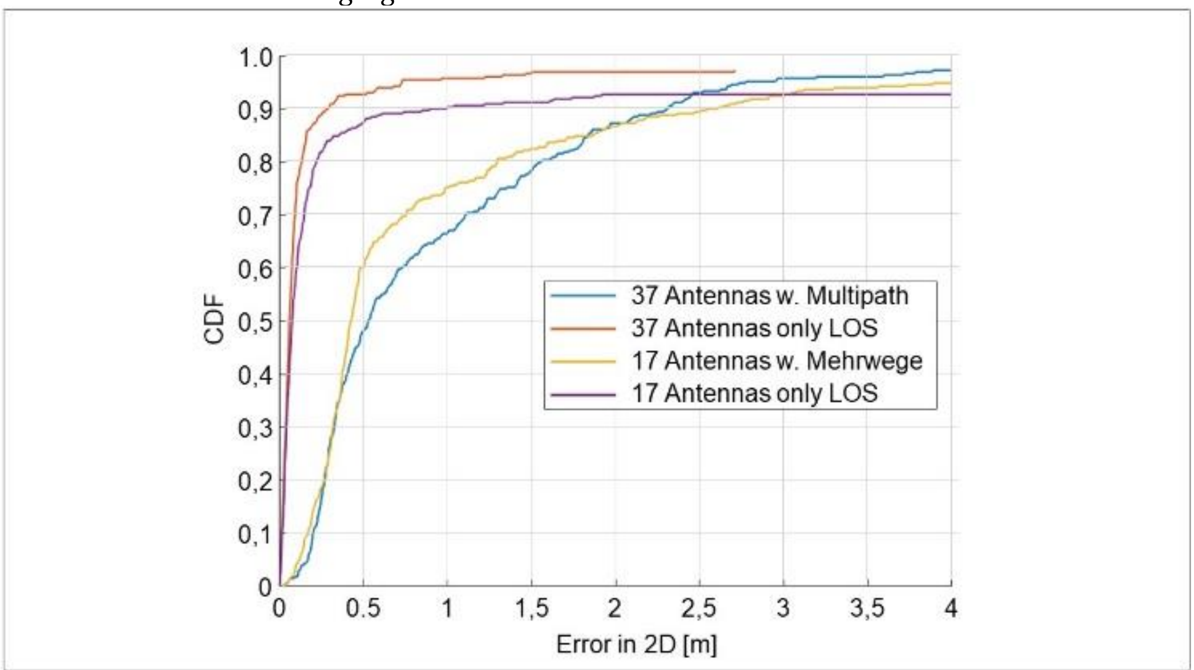

Figure 12: CDF of use cases 1+2 with LOS/NLOS evaluation

For the third use case (process automation), the evaluation is also performed for two different numbers of antennas. Due to the high number of reflections, only the LOS signals are taken into account. Comparing Figure 13 and Figure 14, it can be seen that very good localization accuracies are achieved for both simulations. They are in the range of less than 0.2 m. However, this scenario is not meaningful because the optimizations of the simulation affect too many parameters that would have a large impact on the accuracy in a real environment. The decisive factor here is the increased number of objects (boxes, movable walls, components, and tools) that are not represented in the simulation. They create shadowing and multipath effects. The multipath effects can be analyzed using machine learning [24], but they cannot be filtered out in reality as well as it is the case in the simulation. Thus, for a real implementation of this scenario, a significantly worse positioning accuracy is to be expected. For accurate positioning in such industrial environments, solutions need to be developed that can deal with multipath propagation or even make use of it like current approaches from research based on machine learning [25, 26].

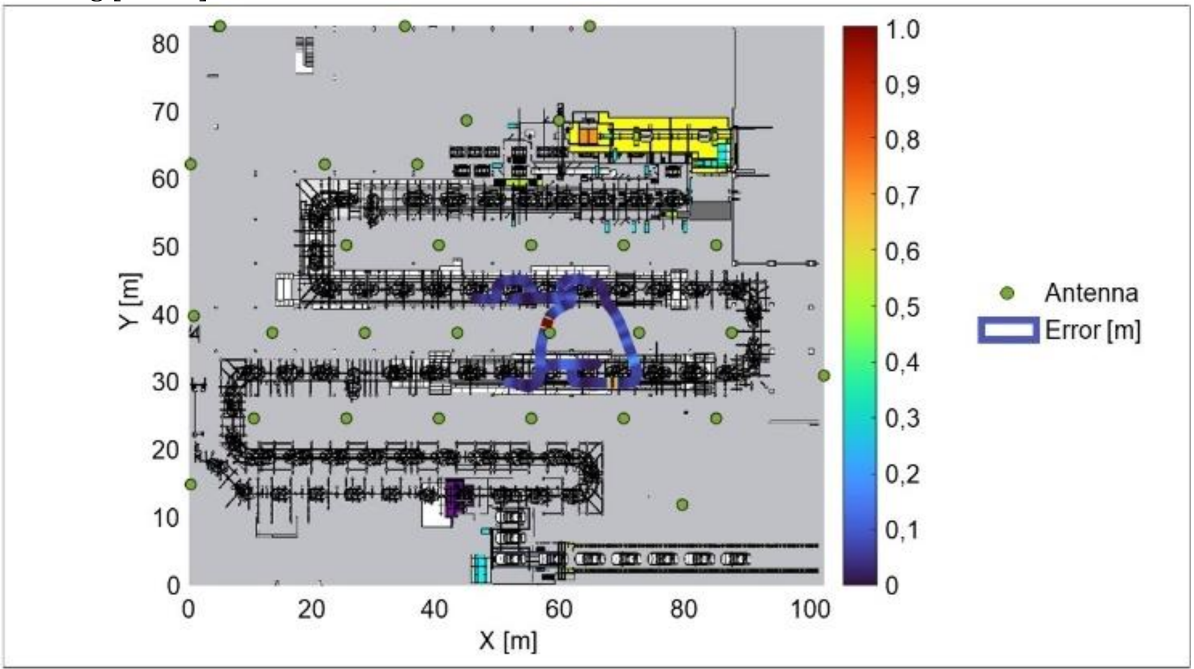

Figure 13: Simulation results Application case 3 with 29 antennas (LOS only)

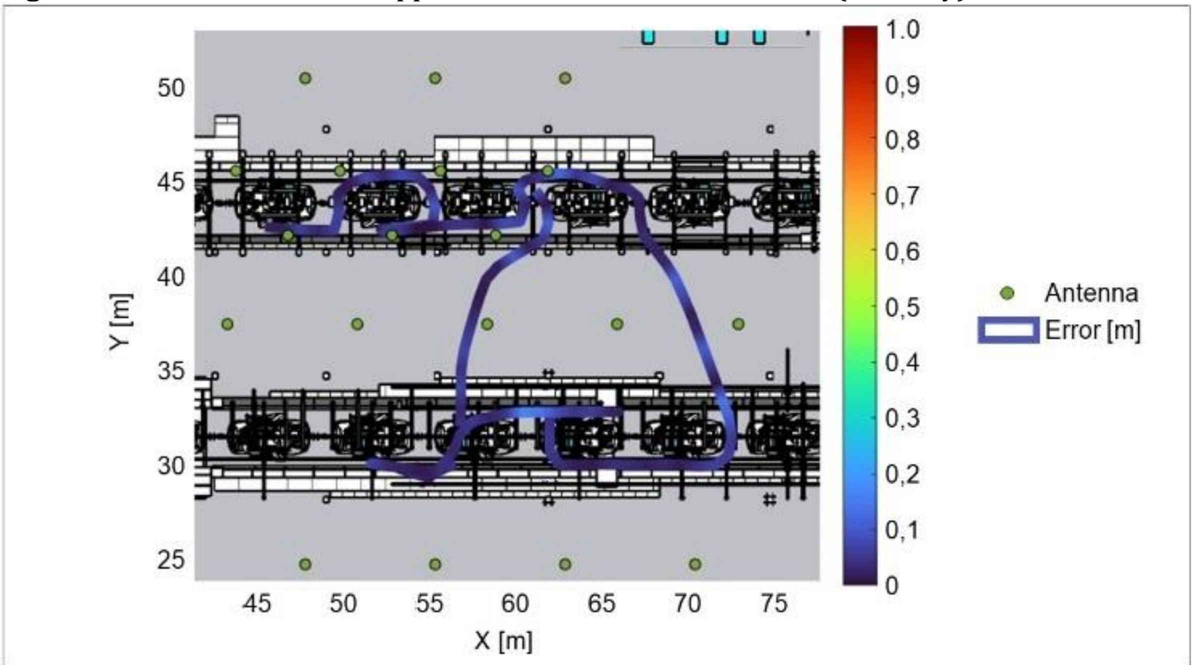

Figure 14: Simulation results Application case 3 with 36 antennas (LOS only)

6. Conclusion

In conclusion, the feasibility of utilizing 5G technology for localization purposes has been demonstrated through practical concept tests conducted in research areas and simulations under real environmental conditions. The study has yielded valuable insights into antenna distribution, network planning, and evaluation algorithms, all of which play crucial roles in achieving accurate positioning. In the research test setup requirements such as accuracy (< 0.3 m), update rate (100 Hz) and latencies of less than 1s were achieved. In the following simulations in industrial environments accuracies of < 1 m for 95% of the positions was achieved and the importance of LOS detection for position calculation is proven. With this, the feasibility of the technical capabilities for 5G positioning in an industrial environment is provided for two of the three reference use cases. The requirements for "find my UE" and "material flow" are met in terms of accuracy, update rate and latency. The requirement of battery lifetime and its size will need to be tested with industrial hardware. For the third RUC, the impact of multipath and shadowing are not sufficiently represented in the simulation.

Therefore, practical implementation in the form of pilot tests are necessary to validate these results in real environments. Challenges such as antenna synchronization, scattering effects of unrepresented objects, and the dynamic nature of production operations present additional hurdles for an effective positioning system. Furthermore, the identification of line-of-sight (LOS) signals is vital for accurate evaluation and position calculation, with ongoing research focusing on machine learning solutions to detect these signals [21]. Furthermore, robust and accurate positioning systems should make use of the information in the radio signals related to multipath propagation [24]. Based on these findings, a piloting of 5G as a real-time location system (RTLS) in an industrial automotive production is recommended, aiming to validate the simulated findings through practical implementation.

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