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Experimental Evaluation of 5G NR TDoA Indoor Localisation Accuracy on a Private Standalone Network

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Abstract

An experimental evaluation of a 5G New Radio (NR) Time Difference of Arrival (TDoA) indoor localisation system was conducted on a private 5G Standalone network. A structured 50-point measurement grid, with 50 measurements per location, produced 2,500 position estimates for analysis of radial error, root mean square error (RMSE), and 95% confidence intervals. The uncalibrated RMSE of 17.1 cm improved to 14.7 cm after global bias calibration, a reduction of 14.2%. Central grid regions achieved 7-11 cm accuracy, while boundary regions showed 15-25 cm errors consistent with geometric dilution of precision. The results demonstrate decimetre-level indoor positioning accuracy and provide a spatial experimental reference for 5G NR TDoA localisation.

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1. Introduction

Accurate indoor localisation is essential for emerging 5G and 6G applications in logistics, robotics, industrial automation, digital twins, and extended reality. 5G New Radio (NR) introduces advanced positioning capabilities, including wideband reference signals, multi-RU synchronisation, and Time Difference of Arrival (TDoA) based multilateration. Nonetheless, the efficacy in practical implementations is significantly influenced by the propagation of signals, the configuration of the antennas, and the precision of the calibration. Indoor environments exhibit

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significant multipath effects, obstructions, and suboptimal anchor placement, all of which can substantially diminish positioning accuracy if inadequately characterised. Although the propagation characteristics differ from outdoor environments, geometry and synchronisation effects remain important in both scenarios.

Measurement based evaluation remains essential for a comprehensive understanding of these consequences. Multiple studies demonstrate that 5G positioning can attain decimetre-level accuracy under ideal radio geometry and bandwidth conditions; nevertheless, precision may decline at boundaries or in non-line-of-sight (NLOS) scenarios. Nonetheless, most published research rely on either limited measurement grids, simulation-based on Geometric Dilution of Precision (GDOP) analysis, or constrained single-point jitter evaluation. Therefore, there is a requirement for regulated, high-density empirical datasets that record the consistent variation in 5G localisation accuracy within a controlled indoor environment.

This study addresses this deficiency by detailing a comprehensive 50-point measurement campaign conducted on a private 5G SA network utilising a commercial Telit FN990A28 user equipment module and a RunEL positioning enabled Radio Unit. A total of 50 position estimations were obtained for each of the 50 grid points, resulting in a cumulative collection of 2,500 samples. We computed statistical metrics such as radial error, RMSE, accuracy, and 95% confidence intervals prior to and subsequent to calibrating for global bias. The resulting dataset is analysed using statistical localisation metrics including radial error, RMSE, precision, and 95% confidence intervals to characterise positioning behaviour across the measurement area. The analysis enables detailed examination of spatial error variation, calibration effects, and geometry dependent localisation performance within a controlled private 5G Standalone deployment.

This manuscript presents four main contributions to the experimental evaluation of 5G NR indoor positioning performance.

1. A high-resolution spatial characterisation of Time Difference of Arrival (TDoA) localisation accuracy across a structured indoor grid, enabling systematic observation of accuracy variation between central and boundary regions.
2. An empirical validation of geometric dilution of precision (GDOP) effects in a controlled private 5G Standalone deployment using commercial positioning-enabled radio hardware.
3. A quantitative evaluation of the impact of global bias calibration on localisation accuracy, demonstrating measurable RMSE reduction and improved spatial consistency across the measurement area.
4. A comprehensive statistical characterisation of localisation accuracy, precision, and confidence intervals using a dense indoor measurement dataset.

Unlike many previously published studies that rely on sparse measurement grids, simulation based evaluation, or limited temporal stability testing, this work provides a dense spatial localisation dataset consisting of 50 calibrated reference locations and 2,500 measured position estimates collected within a private 5G Standalone deployment. This enables detailed analysis of spatial error behaviour, confidence intervals, and geometry dependent localisation performance across the entire measurement area.

Together, these contributions provide a detailed experimental reference for practical 5G NR indoor localisation behaviour and support future comparative evaluation of positioning systems and localisation techniques in beyond 5G environments.

2. Related work

In recent years, there has been a lot of research on indoor localisation using 5G NR, especially when Release 16 added positional features. Numerous studies demonstrate that multilateration employing Time Difference of Arrival (TDoA), Angle of Arrival (AoA), and wideband reference signals can attain decimetre-level precision under optimal radio conditions [8][9][10].

Recent 3GPP standardisation efforts have further expanded positioning support within New Radio systems through positioning reference signals, enhanced timing measurements, and multi anchor localisation frameworks. These developments have accelerated research into high accuracy positioning services for industrial, private network, and beyond-5G applications.

Liu et al. [1] examined the positioning effectiveness of 5G NR utilising multi-cell TDoA and determined that an accuracy of less than 0.5 m may be attained with adequate bandwidth and optimal anchor configurations. Sun et al.

[2] investigated NR-based CSIRS placement, proving its effectiveness in indoor settings with multiple anchors, characterised by good repeatability and little error variance.

Further investigations assess GDOP and geometric influences. Wang et al. [3] conducted a thorough examination of localisation error related to anchor configuration, demonstrating that boundary regions often have heightened radial error, a pattern that aligns with our measurement results. Temiz et al. [4] utilised a 5G millimeter-wave testbed for practical installations and discovered that near-linear anchor configurations led to considerable precision erosion, necessitating calibration or filtering to enhance accuracy.

In indoor spaces, multipath effects are still a big problem. Hybrid AoA/TDoA positioning approaches have been shown to improve localisation robustness in multipath environments. Filtering-based approaches have been widely shown to improve temporal stability and reduce localisation jitter in multipath environments [5].

Recent efforts have shown how important private networks are for controlled indoor positioning testbeds. Standardisation efforts such as 3GPP Release-16 positioning support studies define the framework for high-accuracy NR positioning using multilateration, reference signals, and synchronised anchor deployments [4].

In contrast to the existing literature, this work offers several distinct contributions. First, we present one of the densest grid based indoor localisation datasets reported to date for a 5G NR positioning system, enabling a level of spatial granularity that is rarely achievable in practical deployments. Second, the study provides an empirical examination of how localisation accuracy varies across the physical layout, differentiating clearly between the high localisation accuracy observed in central regions and the systematic degradation that occurs near boundaries due to GDOP and multipath effects. Third, the paper contributes a comprehensive statistical characterisation of localisation performance through analysis of RMSE, radial error distributions, precision metrics, and 95% confidence intervals across all 50 grid points. Finally, the dense spatial dataset enables detailed observation of geometry-dependent localisation behaviour within a controlled private 5G Standalone deployment, providing valuable empirical insight into practical indoor positioning performance. Together, these contributions extend the understanding of practical 5G indoor localisation behaviour and provide a rigorous foundation for future localisation research and comparative evaluation of positioning systems.

3. 5G network architecture

The localisation experiments were conducted on a fully operational private 5G network based on RunEL's distributed "Network-in-a-Box" (NIB) architecture. The system integrates a hybrid O-RAN compliant design consisting of a Smart Radio Unit (SRU), a virtualised Distributed Unit (O-DU), and a virtualised Central Unit (OCU), all connected through a high-capacity Ethernet fronthaul fabric. This architecture allows sub-millisecond latency, deterministic synchronisation, and high precision Time Difference of Arrival (TDoA) extraction of key properties required for high precision indoor localisation.

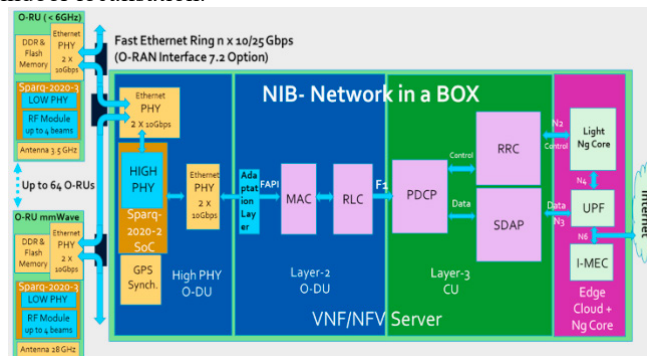


Fig. 1. 5G Network-in-a-Box architecture.

As shown in the architecture diagram in Fig. 1, the system uses a 10/25 Gbps X-Haul ring to interconnect up to 64 SRUs in a star or ring topology, providing high bandwidth and low latency for both localisation and broadband services. Key capabilities drawn from the Sparq-2025-SRU datasheet include:

- 3GPP Rel-15/16 compliance.
- PHY split with O-RAN Option 7.2 fronthaul.
- 3.3-3.8 GHz operation (Band n78) with beamforming phased arrays.
- FPGA-accelerated low-PHY enabling <0.5 ms latency and Sparq Mini slots for URLLC.
- Embedded ToA measurement engine designed for high accuracy localisation applications.
- Support for CSI-RS, DMRS, PTRS for advanced positioning.
- IEEE-1588 and GPS synchronisation for accurate timing alignment.

4. Testbed setup

4.1. Measurement Geometry

The indoor localisation experiments were carried out in a controlled laboratory testbed designed to replicate realistic 5G positioning conditions in factories while maintaining full control over antenna geometry and measurement repeatability. Fig. 2 illustrates the complete setup used for the 50-point grid evaluation. The testbed consists of a rigid aluminium frame on which four 5G antennas were mounted at the corners to provide full coverage of the measurement area. These antennas were connected to a RunEL Radio Unit (RU), while the user equipment (UE) under test was Telit FN990A28 5G module operating in Standalone (SA) mode.

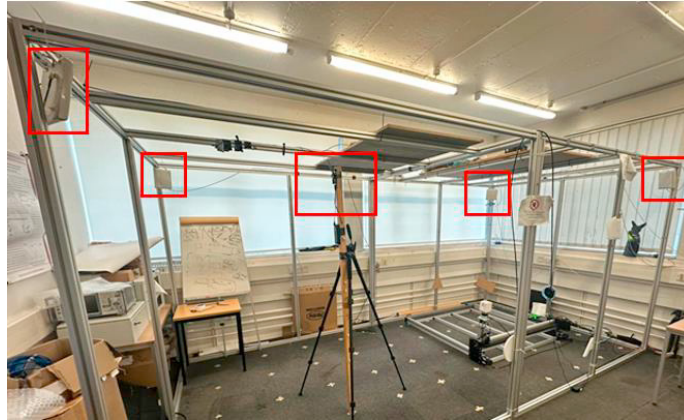


Fig. 2. Indoor testbed used for the 50-point measurement campaign.

The antennas were positioned to form an Length=5 m × Width=2.5 m x Height=2.2 m rectangular area, matching the dimensions of the localisation grid. Their fixed and elevated placement ensured largely unobstructed line of sight across the whole testbed, allowing for clean Time Difference of Arrival (TDoA) measurements. The physical arrangement of the antenna frame, grid layout, and coordinate reference alignment used during the measurement campaign is illustrated in Fig. 2.

4.2. Grid Configuration

A total of 50 reference points were marked on the floor inside the antenna rectangle, spaced at 50 cm intervals along the x-axis and 25 cm along the y-axis. This layout allowed systematic sampling of localisation accuracy across central, intermediate, and boundary regions. The controlled laboratory conditions, including minimal human movement, stable RF propagation, and absence of external interference, ensured that all variations in accuracy could be attributed directly to system geometry, multipath effects, or calibration state, rather than environmental randomness. This configuration makes the indoor testbed particularly suitable for evaluating systematic accuracy trends, GDOP behaviour, and the effects of global bias calibration.

4.3. TDoA positioning model

The localisation system used in this study is based on Time Difference of Arrival (TDoA) multilateration, in which the position of the user equipment (UE) is estimated from relative propagation time differences measured between multiple synchronised radio anchors.

For a pair of anchors i and j , the measured time difference of arrival corresponds to a difference in propagation distance given by

$$\Delta d_{ij} = c \cdot \Delta t_{ij}$$

where c is the speed of light. Each time difference measurement defines a hyperbolic locus of possible UE positions. By combining measurements from multiple anchors, the UE position can be estimated through hyperbolic multilateration.

With four anchors deployed at fixed and known coordinates, the UE position (x, y) is obtained by solving a system of nonlinear equations of the form for multiple anchor pairs.

$$\sqrt{(x - x_i)^2 + (y - y_i)^2} - \sqrt{(x - x_j)^2 + (y - y_j)^2} = c \cdot \Delta t_{ij}$$

Theoretical bounds on localisation accuracy for wideband timing based positioning systems have been extensively studied by Shen and Win [7], demonstrating the strong relationship between timing estimation precision, anchor geometry, and achievable localisation accuracy.

In practical implementations, the solution is typically obtained using nonlinear least-squares estimation to minimise residual timing errors across all anchor pairs. While the internal implementation of the positioning engine used in this work is vendor-specific, it follows this standard multilateration framework.

Global bias calibration was applied after position estimation to compensate for systematic timing offsets introduced by hardware synchronisation and propagation asymmetries, improving absolute localisation accuracy without affecting measurement precision.

5. Results

5.1. Overall positioning accuracy

Across the full 50 point grid, the uncalibrated data produced an overall RMSE of 17.1 cm, as computed from the full 2500 sample dataset. After subtracting the estimated global bias $(\Delta x, \Delta y)$, the RMSE reduced to 14.7 cm, representing a 14.2% reduction in error.

This corresponds to typical positioning errors within approximately 15 cm across most measurement locations. A performance level consistent with mid-precision indoor positioning in multipath rich 5G environments.

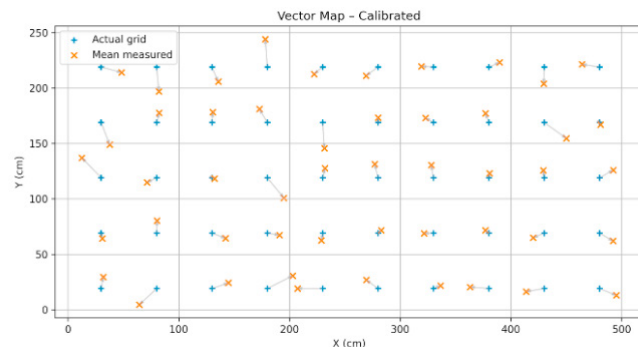


Fig. 3. Reference grid and calibrated mean positions, with error vectors.

The spatial distribution of localisation error vectors across the measurement grid is shown in Fig. 3, where each arrow represents the displacement between the estimated position and the corresponding reference point. Most arrows are short and consistently aligned, confirming that calibration successfully removed the global shift present in the uncalibrated results. Accuracy is highest at the centre of the grid, with mean radial errors typically below 10 cm. Larger errors appear at the edges and corners, driven primarily by GDOP and increased multipath intensity near walls and metallic structures. Overall, the vector field indicates a stable and uniform localisation field, with predictable degradation only near boundaries.

5.2. Distribution of errors

The statistical distribution of calibrated mean radial localisation errors across all grid points is illustrated in Fig. 4. The histogram shows that the majority of grid points cluster tightly within the 8–15 cm range, indicating that the system achieves consistent mid-level accuracy throughout most of the measurement area. A smaller secondary grouping is visible around 18–22 cm, corresponding predominantly to locations near the grid boundaries where anchor geometry and multipath effects degrade accuracy.

Importantly, the calibrated results do not exhibit any extreme outliers; no point exceeds approximately 26 cm. This indicates that the calibration procedure effectively removed large systematic offsets and compressed the error distribution into a much narrower, more predictable range. Overall, the histogram confirms that the calibrated system behaves in a stable and controlled manner, with most localisation errors falling into lower accuracy bands and very limited spread across the grid.

5.3. Errors heat map

The spatial variation of localisation accuracy across the grid is visualised using the heatmap shown in Fig. 5. Central grid cells consistently show high localisation accuracy (7–11 cm), while outer rows and corner points exhibit increased positioning error.

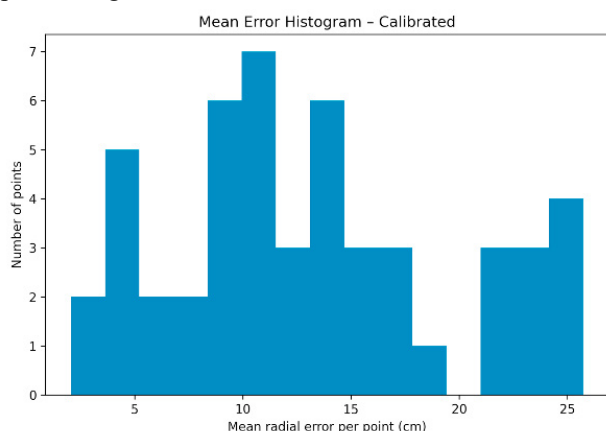


Figure 4: Histogram of calibrated mean radial errors

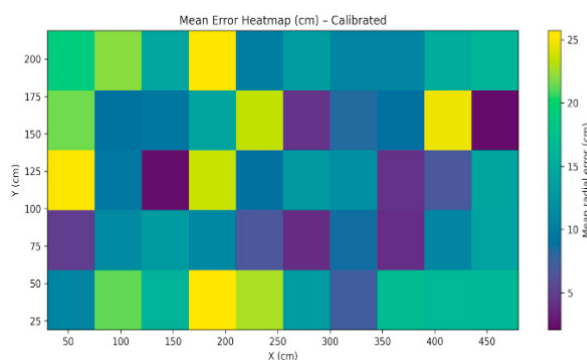


Fig. 5. Spatial heatmap of calibrated mean radial error.

This pattern closely follows classical GDOP behaviour, where localisation accuracy degrades as the target moves outside the convex hull formed by the radio anchors. The heatmap therefore reinforces the earlier vector analysis and confirms that anchor geometry, rather than random noise, is the dominant contributor to error variation.

5.4. Precision analysis and confidence intervals

Precision was evaluated by analysing the standard deviation of the 50 samples collected at each grid point. Across the entire grid, the system demonstrated consistent repeatability, with typical standard deviations ranging between 4–

7 cm, improving to 2-4 cm in the central region where anchor geometry is most favourable. As expected, precision degraded slightly near the boundaries, where standard deviation values increased to 8-12 cm due to GDOP and multipath effects. To further quantify reliability, 95% confidence intervals were computed for the mean estimated coordinates at each point. In the centre of the grid, confidence interval widths were typically within ± 1.2 -2.8 cm, while boundary points exhibited wider intervals of approximately ± 4 -5 cm. Overall, these results indicate that the system maintains high statistical stability, with tight confidence bounds even in areas where geometric conditions reduce absolute accuracy.

5.5. Comparison of uncalibrated and calibrated performance

A direct comparison of uncalibrated and calibrated performance confirms the benefits of systematic correction. Calibration reduces the overall RMSE by 14.2%, eliminates global positional offsets, and produces a more uniform distribution of errors across the grid. The maximum mean error decreases from roughly 32 cm to 26 cm, and the spread of radial error values becomes narrower and more consistent. Calibration does not alter precision (standard deviation), but it significantly enhances accuracy and interpretability by aligning the measurement field more closely with the reference coordinates.

6. Discussion and limitations

The spatial error field indicates that anchor geometry and systematic bias are the main drivers of performance. Central grid locations achieved mean radial errors of 7-11 cm, whereas edge and corner locations typically reached 15-25 cm, consistent with reduced angular diversity and stronger reflected paths. Global bias calibration reduced the overall RMSE from 17.1 cm to 14.7 cm (14.2%) without changing measurement repeatability, confirming that a material component of the observed error was systematic.

The confidence-interval analysis complements the accuracy results: central locations showed 95% confidence intervals of approximately ± 1.2 to ± 2.8 cm, while boundary locations were typically within ± 4 to ± 5 cm. The system therefore remained repeatable even where absolute accuracy degraded, indicating that improved anchor placement, calibration, or multi-stage correction should address the boundary performance.

The campaign was limited to static UE measurements in a compact, largely line-of-sight laboratory deployment and uses a vendor-specific positioning engine; it does not characterise motion, handover, dynamic obstruction, or algorithm-level reproducibility. The platform was supplied by RunEL Ltd., whose employees are co-authors. The analysis reports experimentally observed radial error, RMSE, precision, and confidence intervals rather than validating proprietary algorithms.

7. Conclusion

The 50-point grid evaluation provides a comprehensive assessment of the positioning system's accuracy and reliability. Following global bias calibration, the system achieved an RMSE of 14.7 cm, with most grid points within approximately 15 cm and central locations near 10 cm. The error distributions, precision metrics, and confidence intervals demonstrate consistent and predictable behaviour across the controlled testbed. These findings establish an experimental reference for geometry-aware 5G NR TDoA indoor positioning and provide the RF baseline for future hybrid RF-optical localisation research.

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