5G Positioning for Emergency Calls via Assisted GPS on Mobile Devices

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Abstract

Despite advancements in GNSS-based positioning, dense urban environments continue to pose challenges due to signal obstructions, which degrade positioning accuracy and compromise the effectiveness of emergency services. Given the urgency of locating User Equipment (UE) in emergency scenarios, this work investigates the use of Assisted GPS (A-GPS) in emergency calls over 5G networks, evaluating its impact on positioning accuracy and the time required to obtain the location during the call on mobile devices. The study was conducted using the Spirent GSS7000 simulator to emulate controlled environments with realistic characteristics. Both Mobile Station Assisted (MSA) and Mobile Station Based (MSB) positioning modes were implemented in the UE. The results showed that the MSB mode of A-GPS achieved the lowest response time (17.80 s) compared to the MSA mode (18.58 s), while maintaining equivalent positioning accuracy. Furthermore, the adoption of 5G significantly improved A-GPS performance, reducing the average assistance data acquisition time to 1.41 s, compared to 3.50 s in 4G, therefore a reduction of more than 50%. Location accuracy also improved, with the horizontal error reduced to 1.05 m in 5G, compared to 1.36 m in 4G. These experiments demonstrate that 5G offers a superior platform for A-GPS systems, providing greater efficiency and accuracy in critical scenarios such as emergency calls. Future work will include analyzing new 5G positioning capabilities, power consumption, and integrating multiple GNSS constellations to enhance robustness across different environments.

Keywords

Emergency Call, Location Services, 5G Positioning, Mobile Devices, GNSS, A-GPS

1. Introduction

In the context of emergency call services [1], accurately identifying the position of the UE is crucial for reducing response times and improving the efficiency of rescue teams [2]. However, a more precise location than that provided by the Cell ID enables more effective support in natural disasters and medical emergencies. A Global Navigation Satellite System (GNSS) such as the Global Positioning System (GPS) is highly effective in outdoor environments, offering high accuracy in determining the UE's position [3, 4]. However, their main limitation is the long time required to establish an initial connection with the satellites, known as Time to First Fix (TTFF), which can be a challenge in emergencies where rapid location acquisition is essential. To address this limitation on UE, A-GPS was developed to reduce the time needed to acquire a position, improving GPS performance in critical scenarios [5]. A-GPS accelerates satellite configuration on UE, enabling faster location acquisition.

Previous research shows that using A-GPS during emergency calls on 4G networks does not compromise communication quality [6]. An experimental evaluation using custom source code and laboratory testbeds demonstrated that A-GPS improves location identification, achieving an average horizontal error of $1.49\,\mathrm{m}$ and meeting the 20-second 3GPP standard for location reporting over 4G network. In related work, [7] used the Spirent GSS7000 simulator to assess GNSS accuracy under varying satellite power levels, highlighting the importance of clear sky visibility and the impact of signal interference. The experiments achieved an accuracy of $2.77\,\mathrm{m}$ with a response time of $19.15\,\mathrm{s}$, outperforming traditional GPS. These results support the development of adaptive algorithms to optimize GNSS parameters

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in real time, particularly for emergency calls using A-GPS.

With the advent of 5th Generation (5G) technology, known as New Radio (NR), significant improvements have been achieved not only in data transmission speeds and reduced latency but also in advanced positioning techniques that enhance the accuracy and reliability of UE location estimation [8, 9]. Furthermore, 3GPP Release 16 introduces broadcast positioning assistance data, including support for Global Navigation Satellite System Real-Time Kinematics (GNSS-RTK) [10]. Despite these advancements, GNSS-based positioning remains problematic in dense urban environments, where tall buildings create high-rise urban settings that obstruct or degrade satellite signal reception [11]. Nevertheless, these developments enable high-precision Location-Based Services (LBS) across diverse applications, supporting more robust and context-aware services even in challenging environments.

The work by [12] investigated the integration of 5G networks and GNSS for positioning, using experimental data and an Extended Kalman Filter (EKF) to process Time of Flight (TOF) data from Synchronization Signal Blocks (SSBs). The study showed that, in autonomous 5G positioning, tracking base station clock deviations was essential for reducing errors from over $100\,\mathrm{m}$ to approximately $5\,\mathrm{m}$ in static scenarios with an improvement of about $95\,\%$. Additionally, fusion with single-frequency GNSS (L1), using the Galileo and GPS constellations, increased the reliability of the position estimates. The results confirmed the feasibility of this integration and suggested that future enhancements in the 3GPP Release 16 standard may further improve accuracy. The study also highlighted challenges such as the limited availability of affordable commercial devices for time measurements in 5G and the need for improved network synchronization.

In the work by [13], the authors proposed a machine learning-based solution to improve localization accuracy in urban areas, where GNSS performance is degraded due to dense infrastructure. The approach involves data fusion [14] between GNSS data and Received Signal Strength Indicator (RSSI) fingerprints from 5G network beamforming. The experiments used synthesized GNSS data with realistic errors based on the smartLoc dataset [15]. Two Neural Network (NN) models were proposed. The first, using only 5G network data, achieved a mean localization error of $3.4\,\mathrm{m}$. The second combined 5G data with GNSS information, resulting in a $49\,\%$ reduction in mean localization error, reaching $1.75\,\mathrm{m}$. The authors noted that applying Convolutional Neural Networks (CNNs) to detect new patterns may further improve localization, as Non-Line-of-Sight (NLOS) conditions and multipath propagation continue to affect RSSI-based systems.

Although the localization methods discussed in previous works show promising results, accuracy can still be improved. Furthermore, these studies often rely on signal filtering techniques and machine learning, which increase resource consumption in embedded systems and primarily focus on accuracy rather than response time. To address this, we propose investigating the use of A-GPS, motivated by its established improvement in response time, combined with the higher data rates provided by 5G. This approach has not yet been explored in the available literature. This study examines the use of A-GPS in emergency calls over 5G, focusing on its impact on positioning accuracy and the time required to obtain the location during the call. The objective is to assess the benefits of this approach in the context of 5G and evaluate its applicability to emergency services. The results of this work may support the optimization of mobile location systems based on 5G, offering benefits to both operators and users in emergency scenarios.

The remainder of the paper is organized as follows: Section 2 provides a review of 5G technology, and presents the proposed A-GPS implementation on Android UE with 5G network support; Section 3 details the experimental methodology employed to evaluate and compare the performance metrics of 5G and 4G; Section 4 discusses the findings and the impacts of 5G network during emergency calls; and Section 5 concludes the paper with future research directions.

2. A-GPS on 5G Mobile Devices

This section presents 5G positioning concepts and the implementation of A-GPS on 5G mobile devices for emergency calls, emphasizing the benefits of 5G and the operation of MSA and MSB modes.

2.1. 5G Positioning

5G technology promises intrinsic features that significantly improve the positioning capabilities of mobile device networks, such as ultra-wideband signals, tight network synchronization, high base station density, and narrow beam transmission [16]. The 5G standard supports any positioning method available within the wireless mobile device. Figure 1 shows the most relevant components of the 5G positioning architecture.

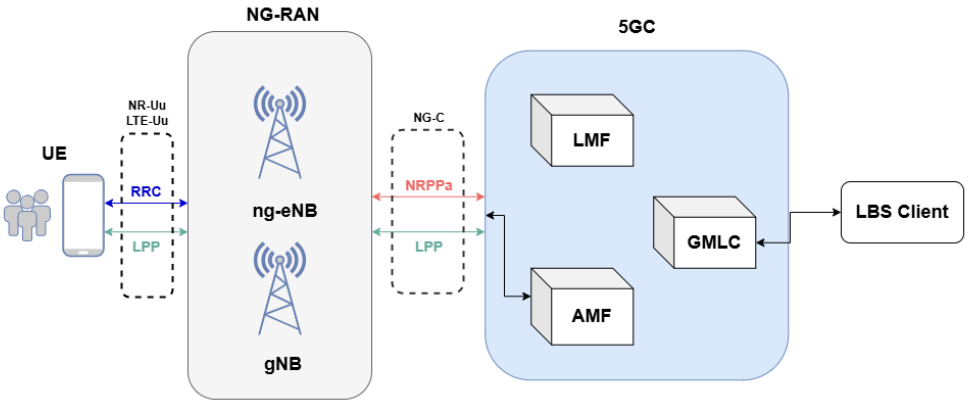

Figure 1: 5G architecture for positioning.

Concerning protocols, the LTE Positioning Protocol (LPP), originally introduced in LTE, remains the primary protocol for communication between the UE and the Location Management Function (LMF). For communication between NG-RAN nodes (gNB/ng-eNB) and the 5G Core Network (5GC), the NR Positioning Protocol A (NRPPa) was defined in Release 15 for the LMF. The NG-C and NL1 interfaces are used solely as transport links for NR positioning protocols and are transparent to UE positioning.

5G brings several improvements, including advancements in positioning techniques such as Observed Time Difference of Arrival (OTDOA) and Round Trip Time (RTT) [17]. Therefore, 5G can improve A-GPS performance in challenging environments such as dense urban areas and indoor spaces where satellite signals tend to be weak. In addition, the optimized 5G network architecture reduces communication latency, enabling faster delivery of A-GPS assistance data and reducing TTFF. Most recently, 3GPP Release 18 further expands these capabilities by defining new positioning capabilities such as Sidelink positioning and Reduced Capability (RedCap) positioning [18].

In industrial applications, combining high-precision GNSS with 5G connectivity enables advanced automation, real-time asset tracking, and greater operational efficiency. Use cases such as autonomous robots, smart logistics, and precision agriculture benefit from accurate, low-latency positioning, allowing systems to respond reliably in fast-changing environments [19]. This integration also plays a key role in autonomous vehicle navigation, where it supports collision avoidance, route planning, and adaptation to traffic conditions. The low latency and high reliability of 5G make real-time processing of location data possible, enabling quick and accurate decision-making. In emergency scenarios, precise location data is essential for the rapid dispatch of services such as connected ambulances and coordinated traffic control. The Location Retrieval Function (LRF) ensures accurate location access, improving emergency response and reducing delays during accidents or mechanical failures.

2.2. Proposed Method

The literature analysis reveals a lack of testing with A-GPS using currently deployed 5G cellular networks for positioning. In this context, and aiming to improve 5G positioning methods for wireless mobile devices as a UE, the A-GPS method was enabled and evaluated.

An overview of the event sequence for UE positioning during a 5G emergency call [1] is illustrated in Figure 2. Assuming the UE has already established a connection to a 5G network, when an emergency call is made (1), the serving Access and Mobility Management Function (AMF) element determines the need to locate the UE and initiates a location request (2). The request is then transferred to the LMF (3), which is responsible for managing various location services for the target UE, such as delivering assistance data and obtaining the location estimate. The LMF initiates all location procedures with the UE using the LPP protocol (4). Note that for the AMF and NG-RAN layers, these messages are carried as transparent Protocol Data Units (PDUs) using their respective protocols [20], functioning solely as transport layers. The response obtained by the LMF is returned to the AMF (5). The AMF then uses the location service response to support the service that triggered the request—in this case, providing a location estimate associated with an emergency call to a Gateway Mobile Location Center (GMLC) (6).

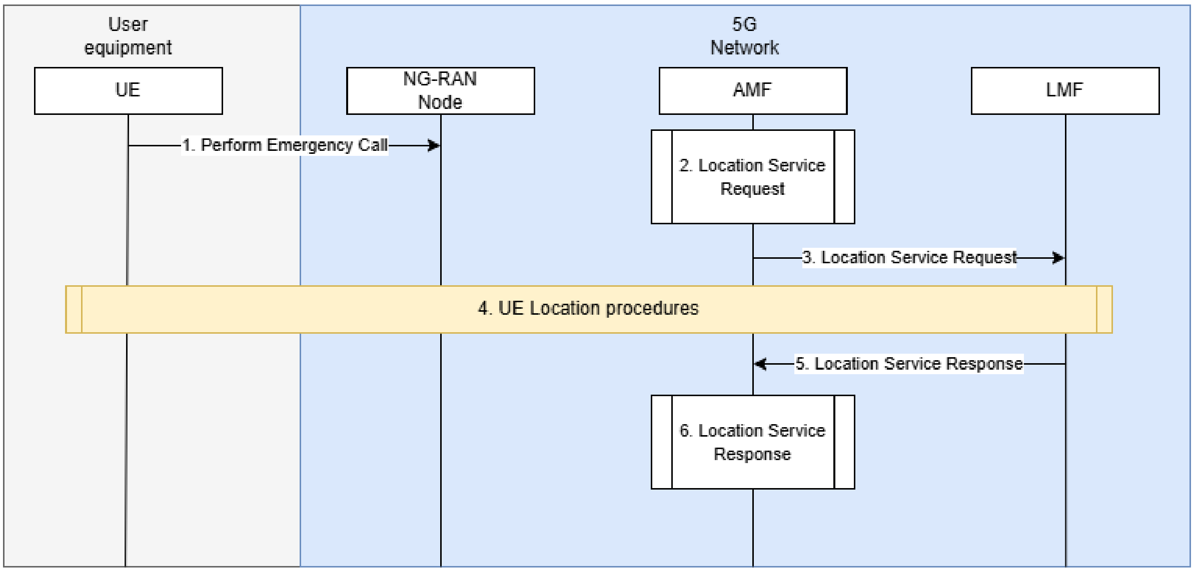

Figure 2: A-GPS UE operation over 5G network.

The A-GPS positioning methods adopted were MSA and MSB, allowing the device to calculate its position with network assistance. In the MSA mode, the network performs the position computation, while the device collects satellite signals and transmits the measurements. In contrast, in the MSB mode, the device itself calculates its position using the assistance data received from the network.

This key difference leads to variations in data requirements. In MSA, the device does not need to store or process satellite orbit data, such as almanac or ephemeris. Instead, the server maintains this information and provides acquisition assistance, including expected Doppler frequencies and code delays. These parameters help the device reduce the frequency and time search space, speeding up signal acquisition. In the MSB mode, the device performs these computations locally, requiring access to complete satellite data to determine its position independently.

The LPP protocol manages the exchange of messages between the network and the device during an A-GPS session. Figure 3 shows how this process works in the UE. In a network-induced session, the process begins with a *requestCapabilities* message sent by the network to determine the device's supported features. The device responds with a *provideCapabilities* message, which includes information such as supported GNSS systems, available A-GNSS modes (Standalone, MSA, or MSB), supported coordinate formats (e.g., *ellipsoidPoint*, *ellipsoidPointWithUncertaintyCircle*, *ellipsoidPointWithAltitude*), and other relevant capabilities. Depending on the A-GPS mode supported by the device and the network, the network sends a *provideAssistanceData* message, which varies depending on the selected mode. For MSB, the assistance data includes time, reference frequency, position, and satellite orbit data such as almanac and/or ephemeris. For MSA, the assistance data consists of reference time, reference frequency, and expected Doppler shifts and rates from visible satellites. The session concludes when the network sends a *requestLocationInformation* message, specifying parameters such as desired accuracy, response time, and permitted GNSS methods. The device then replies with a *provideLocationInformation* message, which contains the estimated position, effectively completing the A-GPS session.

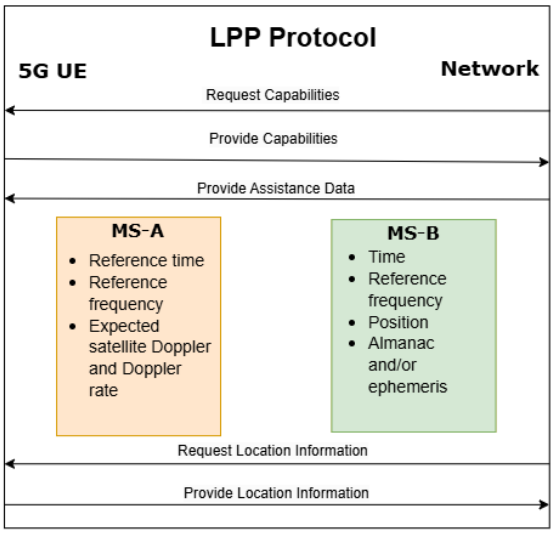

Figure 3: LPP protocol communication process between UE and network.

In the Android ecosystem, the implementation of A-GPS relies on a combination of hardware and software components working together on the device side, as illustrated in Figure 4. The Android operating system plays a central role in managing how location data is accessed and used by applications. A Network-Induced Location Request (NI-LR) is triggered by the serving AMF to determine the UE location. The LoCation Service (LCS) client sends a location request carrying Quality of Service (QoS) parameters to obtain data about the UE. This may occur for regulatory purposes, such as during an emergency call, or to verify the UE's location when accessing NR satellite services. The GNSS framework, which processes GPS sensor and radio data, is responsible for acquiring satellite signals and determining the user's position based on signals from multiple satellites. However, this process is affected by environmental factors such as signal obstructions, multipath interference, and satellite geometry, all of which can degrade accuracy and increase response time. To improve positioning efficiency, the Android device incorporates a radio module that enables communication with cellular networks. This supports a hybrid positioning approach, combining GNSS data with network-based location techniques. The interaction between the GPS and radio modules is managed by the Android system, allowing seamless switching between different positioning methods depending on signal availability and reliability.

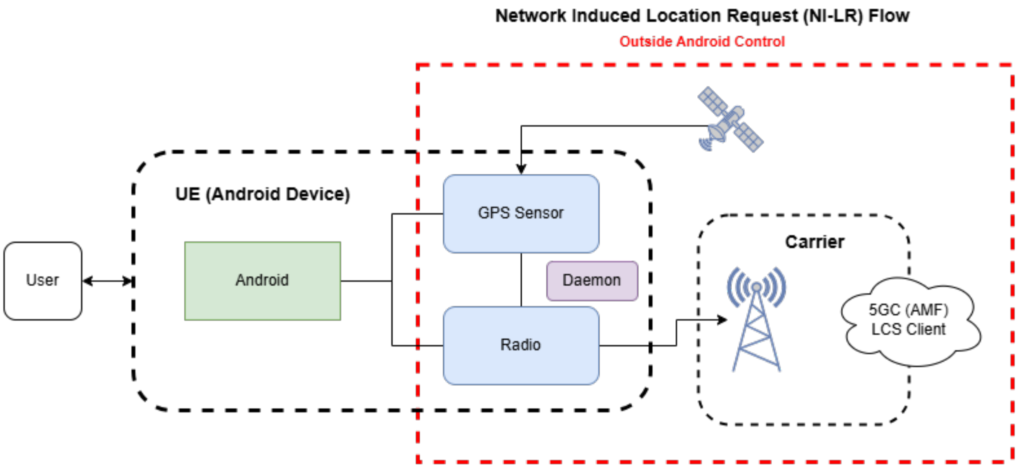

Figure 4: A-GPS implementation for Android UE.

3. Experimental Methodology

The experiment used the Spirent GSS7000 simulator, which emulates eight GPS satellites to create a controlled testing environment. The network simulation was based on 5G NR Non-Standalone (NSA) mode, operating on band 78 with a TDD duplex scheme. During the test, 30 location measurements were collected using the Control Plane as the transport layer via the LPP protocol. The positioning methods adopted were MSA and MSB, allowing the device to calculate its position with network assistance. According to 3GPP standards, the maximum response time was set to 20 s, with a required accuracy of 10 m. The GNSS scenario was configured to simulate an environment in Japan, including parameters such as the ionospheric model, navigation model, reference location, and reference time. On the device, the A-GPS session was enabled through the LPP protocol. Table 1 shows a summary of the parameters used in the experiment.

Table 1
UE and Network specification used during emergency call over 5G.

Parameter	Configuration
GNSS Simulator	Spirent GSS7000
GNSS Pos Technology	GPS
GNSS Number of Simulated Satellites	8
GNSS Scenario	Japan
LBS Transport Layer	Control Plane
LBS Method	MSA and MSB
Positioning Protocol	LPP
Response Time (s)	20
Measurement Accuracy (m)	10
NR Core	National Instrument PXIe-8880
NR Network Mode	5G Standalone
Number Of NR Cells	1
NR Duplex Schemes	TDD
NR Band	78
5G UE Model	Samsung S24 Ultra
5G UE GNSS Sensor	Qualcomm Gen 9
5G UE GNSS Band	L1 + L5
5G UE LBS Solution	GPS

Figure 5 illustrates the detailed architecture and operation of A-GPS in a 5G environment. The test scenario includes several components: a 5G UE, an A-GPS server, a GNSS simulator (Spirent GSS7000), a test controller, and the 5G network infrastructure. The 5G UE integrates an A-GPS-enabled GNSS/GPS receiver, which utilizes location-based services and communicates via LPP protocol. The LPP protocol manages the positioning data exchange, including capability negotiation, assistance data provisioning, and location reporting between the UE and the A-GPS server.

The Control Plane standard was used on the A-GPS Server, utilizing both Radio Resource Control (RRC) and LPP protocols to handle positioning requests and responses. Communication between the NG-RAN nodes (such as gNB and ng-eNB) and the 5GC is performed using the NRPPa, standardized by 3GPP. Within the 5GC, the National Instruments PXIe-8880 embedded controller implements essential functions: the AMF coordinates signaling and message routing; the LMF manages the initiation and processing of positioning sessions, computes UE positions, and delivers positioning assistance data; and the GMLC interacts with external entities requesting or providing positioning information. The GNSS Simulator (GSS7000) provides controlled testing conditions by simulating realistic GPS satellite constellations (GPS SV1 to GPS SV8), enabling precise and repeatable evaluations of GNSS-based positioning. The Test Controller contains the DNS Server and the Test Driver Application, which coordinate and automate the execution of test cases, manage measurements, and oversee the network interactions throughout the experiments.

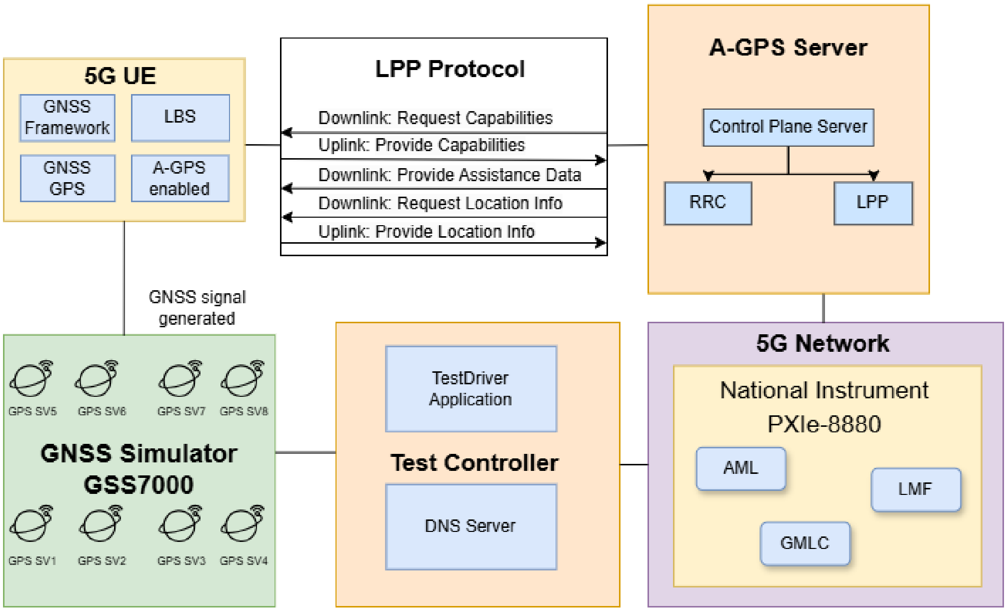

Figure 5: A-GPS in 5G experimental environment.

4. Results and Discussion

This section presents the results obtained from the comparison between 4G and 5G networks, as well as the performance of A-GPS in 5G networks, based on the test environment shown in Figure 5 and following the steps described in Section 3.

4.1. Assistance Data Acquisition Time: 4G and 5G

A preliminary test was initially conducted to illustrate and evaluate the improvement in assistance data acquisition provided by 5G compared to 4G. In this test, only the acquisition times for assistance data were measured. Figure 6 shows the distribution of 30 measurements.

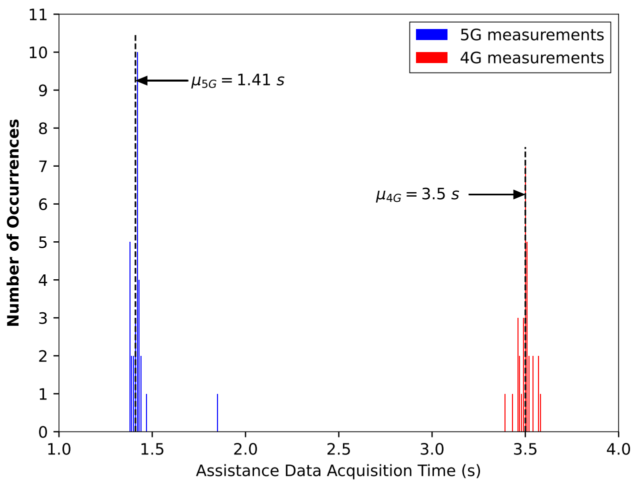

Figure 6: Assistance data acquisition time in 4G and 5G networks.

Considering the upper limit calculated by the interquartile range of the 5G data, two values are identified as outliers: 1.47 s and 1.85 s. These outliers impact the mean and standard deviation, distorting the statistics and compromising the representativeness of the data. They can be attributed to atypical environmental conditions during the simulation. A value is considered an outlier if it is outside the closed interval $[Q_{1/4} - 1.5 \times IQR,\ Q_{3/4} + 1.5 \times IQR]$, where $Q_{1/4}$ is the first quartile (value that delimits the 25% smallest observations), $Q_{3/4}$ is the third quartile (value that delimits the 25% largest observations) and IQR is the interquartile range, calculated by $IQR = Q_{3/4} - Q_{1/4}$. After removing the outliers, the mean assistance data acquisition time in 5G (μ_{5G}) was $1.41\,\mathrm{s}$, with a standard deviation (σ_{5G}) of $0.0188\,\mathrm{s}$. In 4G, the mean (μ_{4G}) was $3.50\,\mathrm{s}$, with a standard deviation (σ_{4G}) of $0.0387\,\mathrm{s}$. A Student's t-test was conducted to compare the mean acquisition times between the two networks. The resulting t-statistic was -253.92, with a p-value of 2.00×10^{-87}. As the p-value is far below the standard significance level of 0.05, we reject the null hypothesis that the means are equal. These results indicate a statistically significant difference between the acquisition times of the two networks, with 5G significantly outperforming 4G. The 5G network not only achieves much faster acquisition times but also exhibits lower variability, suggesting both superior and more stable performance. This reduction corresponds to over $50\,\%$ improvement in acquisition time. Beyond lower latency, this improvement can significantly benefit applications requiring rapid response, such as emergency calls.

4.2. Signal-to-Noise Ratio

Figure 7a shows that the Signal-to-Noise Ratio (SNR) values for the MSA and MSB modes using A-GPS over 5G are very close, at $47.39\,\mathrm{dB}$ and $47.08\,\mathrm{dB}$, respectively. This small difference suggests that both modes perform similarly in terms of SNR, indicating consistent signal reception conditions under 5G. The consistency of testing under 5G confirms that both modes were evaluated in the same environmental conditions, ensuring a fair comparison and isolating the effects of differences in assistance mechanisms.

However, experiments with the 4G network revealed a lower SNR in the MSB mode, at $35.68\,\mathrm{dB}$. The improvement observed with 5G is possibly due to better transmission conditions enabled by directional signal beams.

4.3. Horizontal Location Error

The horizontal error is defined as the horizontal difference between the ellipsoidal point calculated from the UE measurement report and the UE's actual simulated position during the experiment. For 5G MSA, errors ranged from a minimum of 0.32 m to a maximum of 1.93 m, while for 5G MSB, a minimum error of 0.32 m and a maximum error of 2.16 m was observed. For 4G MSB, errors ranged from a minimum of 0.28 m to a maximum of 2.95 m. During VoLTE emergency call testing using only 4G MSB mode, using the same methodology in [6], the mean error was 1.36 m, while in VoNR emergency calls in this work the average error was 1.11 m for MSA and 1.05 m for MSB, as shown in Figure 7c. The improvements seen in these metrics are in part due to the improved performance enabled by 5G technology.

Figure 8 presents the Cumulative Distribution Function (CDF) of horizontal localization errors for the 5G MSA, 5G MSB, and 4G MSB modes. The results show that the 5G MSA and 5G MSB modes had similar error distributions; however, 5G MSB outperformed in $98\,\%$ of the tests, despite reaching a maximum error of $2.2\,\mathrm{m}$. It was only outperformed by 5G MSA in cases where the error reached $2.0\,\mathrm{m}$. The 4G MSB mode, in turn, showed lower errors than 5G MSA in the range of $0.2\,\mathrm{m}$ to $0.6\,\mathrm{m}$, matching it at $0.7\,\mathrm{m}$. However, from $0.8\,\mathrm{m}$ onwards, 4G MSB became the worst among the three modes, reaching a maximum error of $3.0\,\mathrm{m}$. The horizontal error CDF curve for 4G MSB mode had a smoother slope, indicating greater data dispersion, which includes errors closer to 3.0 m. These results reinforce the superiority of 5G modes, especially MSB, for applications requiring higher localization accuracy.

4.4. Altitude Location Error

Altitude measurements are estimated based on atmospheric pressure readings, and keeping the error within predefined limits is essential, particularly for locating individuals in multi-story buildings. In the altitude estimation experiments, a mean error of $1.27\,\mathrm{m}$ was obtained for both the 5G MSA and 5G MSB modes, as shown in Figure 7d. However, the 5G MSB mode exhibited a lower standard

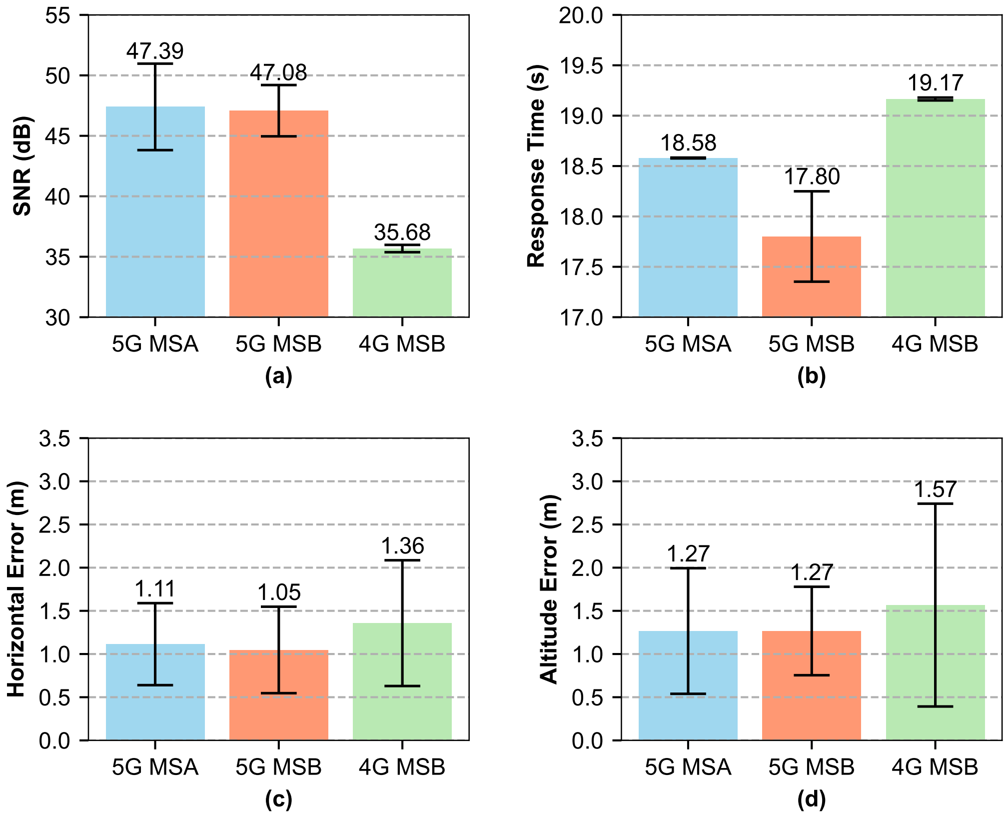

Figure 7: Metrics in MSA and MSB operation modes.

deviation, indicating greater consistency in the estimates. Compared to the results obtained using VoLTE technology, where the maximum error with the 4G MSB mode reached $4\,\mathrm{m}$, this work, using VoNR, achieved a maximum error of only $2\,\mathrm{m}$ for both 5G MSA and 5G MSB, as shown in Figure 9, representing a $50\,\%$ reduction.

The CDF of the altitude error in Figure 9 shows that, although 4G MSB had $23\,\%$ of the tests with zero error, 5G demonstrated more consistent performance, with no errors exceeding $2\,\mathrm{m}$. Additionally, 5G showed a higher proportion of tests with errors below $1\,\mathrm{m}$ and $2\,\mathrm{m}$, indicating a more concentrated error distribution within these limits. This suggests that 5G offers greater reliability by maintaining errors within a narrower range.

4.5. UE Location Response Time

In our tests conducted within a 5G architecture, we evaluated the response time metric, defined as the interval between the receipt of the last LPP Request Location Information message by the UE and the initiation of the transmission of the Report Location Information containing the estimated position obtained via A-GPS. This metric is critical, as it determines how quickly a device can transmit its location to the network, enabling time-sensitive applications such as emergency services and autonomous vehicles to operate with high precision and safety.

According to 3GPP standards, this transmission must occur within a maximum time window, typically around $20\,\mathrm{s}$, to ensure effective assisted positioning. In a 5G environment, reduced latency is a key advantage, enabling faster and more reliable communication between the device and the network.

Our experiments showed that the response time for the 5G MSB mode was $17.80\,\mathrm{s}$, while the 5G MSA mode recorded $18.58\,\mathrm{s}$, as shown in Figure 7b. Both values are within the expected limits. In contrast, tests conducted with the 4G network showed the worst performance, with an average response time of

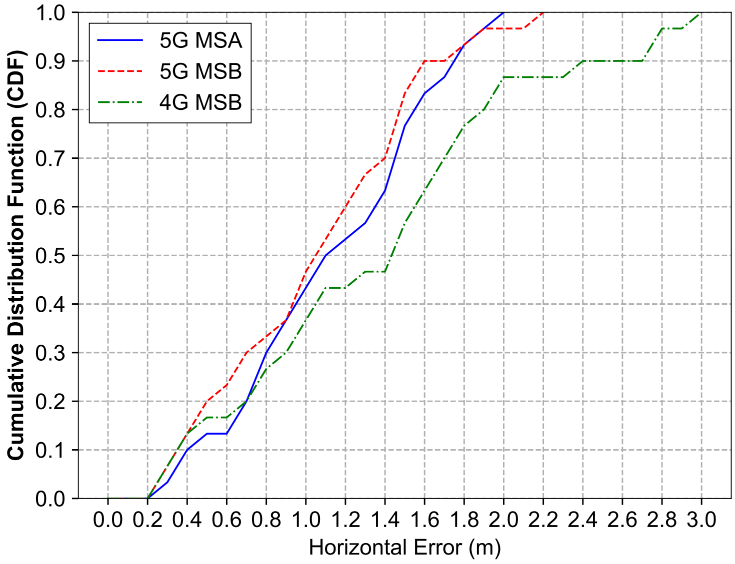

Figure 8: Cumulative distribution function of the horizontal error.

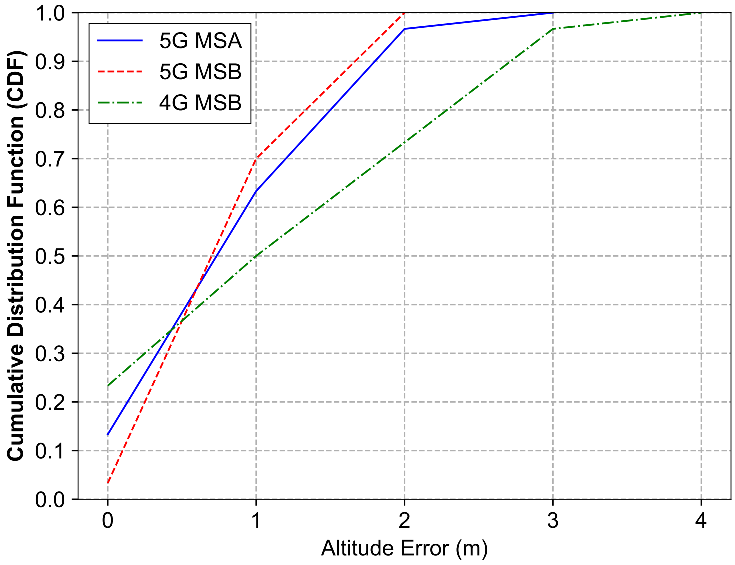

Figure 9: Cumulative distribution function of the altitude error.

19.17 s, highlighting the advantage of 5G in improving the performance of positioning systems.

5. Conclusion

This study investigated the performance of A-GPS for emergency calls using 5G networks. The evaluation compared MSA and MSB positioning modes, focusing on metrics such as Signal-to-Noise Ratio, horizontal and altitude location errors, and response time. The SNR values obtained in both modes were very similar, with 47.39 dB for MSA and 47.08 dB for MSB, indicating consistent and stable signal reception in the 5G environment. Regarding positioning accuracy, both horizontal and altitude location errors showed nearly equivalent performance. Specifically, the average horizontal errors for

MSA and MSB were $1.11\,\mathrm{m}$ and $1.05\,\mathrm{m}$, respectively, while the mean altitude error was $1.27\,\mathrm{m}$ for both modes. Despite these similarities, the MSB mode exhibited superior performance in terms of response time, averaging $17.80\,\mathrm{s}$, compared to $18.58\,\mathrm{s}$ for the MSA mode. Both response times were comfortably within the limits defined by 3GPP specifications, reinforcing MSB mode as the most efficient option for quickly obtaining UE location.

Additionally, the study highlighted the substantial performance advantages of 5G over 4G, particularly in the reduction of assistance data acquisition time. In 5G, the average assistance data acquisition time was only $1.41\,\mathrm{s}$, representing a significant improvement (over $50\,\%$) compared to $3.50\,\mathrm{s}$ in the 4G network. Moreover, positioning accuracy also improved noticeably. The maximum horizontal location error in 5G MSB was reduced to $2.16\,\mathrm{m}$, significantly lower than the $2.95\,\mathrm{m}$ observed with 4G MSB. Similarly, altitude accuracy improved, with the maximum error in 5G MSB limited to $2\,\mathrm{m}$, compared to a maximum of $4\,\mathrm{m}$ recorded in 4G MSB tests.

In conclusion, this research demonstrates that 5G significantly enhances the performance of A-GPS systems, ensuring higher accuracy, reduced latency, and greater reliability, particularly in critical applications such as emergency services. Future studies will explore advanced 5G positioning capabilities, power consumption analysis, and the fusion of multi-constellation GNSS data, aiming to further improve positioning accuracy and robustness across diverse operational scenarios for industrial applications.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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