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Value Beyond Communication: Indoor Positioning with Private Sub-6 GHz Cellular Networks

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***Abstract*—Accurate positioning services will be crucial for future autonomous factories, but remain a key challenge for mobile devices. Satellite-based systems are ineffective in indoor factory (InF) environments, and deploying dedicated infrastructure is often undesirable. Thus, this study investigates the potential of private cellular networks to provide position estimates as an integrated value-added service alongside their communication capabilities, wherein our proposed extension of the *STING* system allows for systematic spatiotemporal performance monitoring of critical joint communication and sensing (JCAS) services. A measurement campaign conducted with a 5G network employing time difference of arrival (TDOA)-based positioning in an indoor hall environment demonstrates sub-meter accuracy in 95 % of cases under optimized conditions, thereby exceeding the requirements of service level (SL) 2-grade commercial positioning use cases. The results further highlight that radio unit (RU) placement and environmental factors, e.g., metallic clutter, can critically impair device positioning performance. The *STING* companion for future industrial 6G JCAS networks thus recommends mitigation by using further standardized positioning methods or improving RU placements through positioning-oriented network planning.**

***Index Terms*—Positioning, cellular system, JCAS monitoring.**

I. Introduction

Accurate user positioning has been identified as a key capability of modern mobile radio networks, enabling location services (LCS) for vertical applications, such as the transportation of goods and automation of machines. The integration of improved positioning capabilities into the 5G standard promises greater accuracy and availability than previous generations. It lays the foundation for joint communication and sensing (JCAS) services in future 6G networks, which will extensively leverage wireless channels as sensors, enabling perceptive networks via pervasive data processing at the network edge [1, 2].

In private industrial networks, positioning features are of particularly high relevance, cf. top of Fig. 1. On the one hand, this is because conventional methods, e.g., based on global navigation satellite system (GNSS), are not applicable due to major parts of the value chain being within buildings. On the other hand, due to the increasing digitization of indoor factory (InF) environments, wireless networks are used to connect machines, robots, and automated guided vehicles (AGVs), such that the integration of localization services is beneficial to the operator because this avoids the deployment of a costly dedicated positioning system, e.g., ultra-wideband (UWB) [3, 4].

Although the 3GPP standards family specifies high-accuracy positioning features, their practical realization, particularly in indoor environments, remains insufficiently explored. LCS in public networks still exhibits limited accuracy, as they are primarily optimized for coverage and capacity rather than

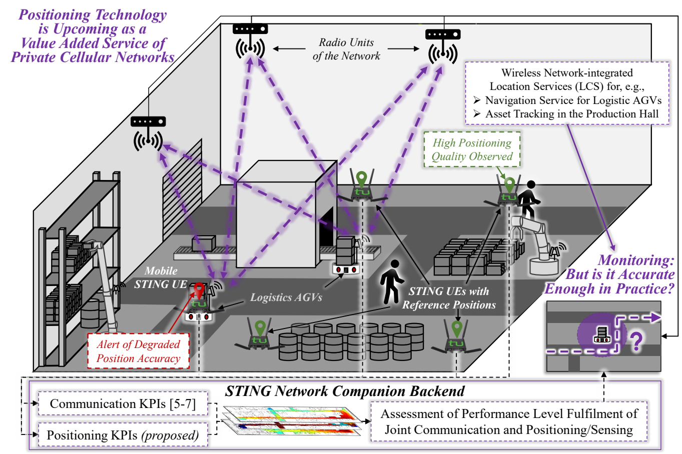

Fig. 1. Joint communication and positioning for critical industrial applications: Private wireless network infrastructure deployments offer a dual benefit, but service compliance must be validated by rigorous performance monitoring.

user positioning. At the same time, private cellular networks equipped with dedicated positioning capabilities remain uncommon, resulting in limited empirical evidence on achievable performance under realistic conditions. This is partly due to ongoing efforts to evaluate their communications-centric potential and operational feasibility [5]. To address this gap between standardized positioning capabilities and practical implementation, we conduct measurements in a scaled indoor scenario to characterize the current potential of this technology.

In this context, we further propose an extension of the Spatially Distributed Traffic and Interference Generation (STING) [5, 6] concept from the communications domain to a 6G JCAS services monitoring system. The cellular-based position information complements the internal positioning reference of our mobile STINGs collecting communication performance data through distributed orchestrated stress tests. So far, these data enabled the identification of regions with insufficient connectivity for the critical InF use cases, triggering mitigation strategies [7]. Similarly, we envision that spatio-temporal comparisons of the actual STING positions and the network-based estimates also allow for assessing positioning/sensing service compliance, cf. bottom of Fig. 1, as demonstrated in this work.

The remainder of the paper is structured as follows. We first provide a brief overview of standardized cellular positioning techniques and service levels in Sec. II. Sec. III presents our experimental setup featuring a commercial private network in an indoor hall environment. The evaluation of the attained measurement results is conducted in Sec. IV. Last, Sec. V closes with a summary of our findings and a brief outlook.

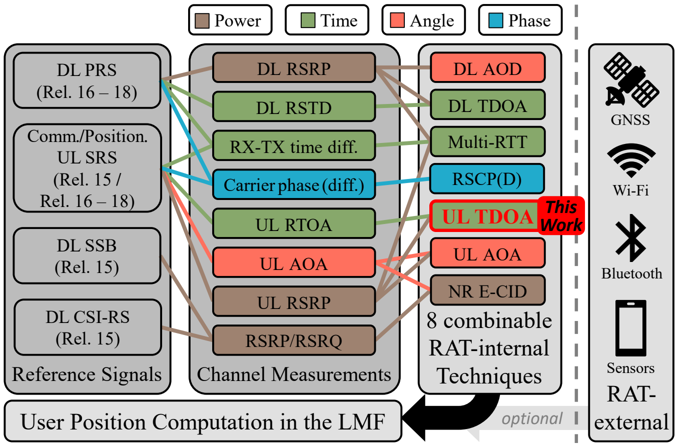

Fig. 2. Overview of the positioning options standardized in 5G [8].

II. Cellular Positioning in a Nutshell

Recent 3rd Generation Partnership Project (3GPP) releases enhanced cellular positioning capabilities by introducing new reference signals (RS) – positioning RS (PRS) in the downlink (DL) and extended sounding RS (SRS) in the uplink (UL) – while also leveraging legacy signals such as SSB and CSI-RS within the radio access network (RAN), cf. Fig. 2: They enable channel measurements in time, power, angular, and phase domains, e.g., the time difference of arrival (TDOA) metric between multiple radio units (RUs) and the user equipment (UE). The Location Management Function (LMF) in the core network (CN) collects these metrics to compute UE position estimates using, for example, multi-lateration or -angulation algorithms. Moreover, hybrid methods may also use radio access technology (RAT)-external measurements of, e.g., GNSS or inertial sensor sources [1, 8].

The 3GPP defines service levels (SLs) 1 to 6 for positioning, each with thresholds on horizontal accuracy and availability, which can be mapped to use cases from industry [9, Tab. 7.3.2.2-1]: To illustrate, SL 1 demands $\leq 10\,\mathrm{m}$ horizontal accuracy at $\geq 90\,\%$ availability, while SL 2 targets $\leq 3\,\mathrm{m}$ accuracy at $\geq 95\,\%$ availability. The positioning SLs 3 to 6 aim for 1.0 m to 0.3 m accuracy, and require availability of at least 99.0 % or 99.9 %. We note that achieving these higher SLs hinges not just on the utilized reference signals and positioning techniques, but also on the number and position of RUs, the ambient radio environment, and signaling bandwidths [8].

Expectations from non-cellular technologies, such as Wi-Fi, Bluetooth, and UWB, indicate that SL 2 and higher could be met in practice [10]. For cellular positioning, one expects the highest positioning accuracy when operating in the millimeter-wave (mmWave) spectrum due to favorable propagation conditions for positioning, broad bandwidths, and better antenna technology. As shown in an experimental setup, angle-based positioning methods with mmWave antenna arrays can result in cm-level accuracy [11]. At the same time, hostile conditions for communications have also led to a low adoption rate of private mmWave networks compared to sub-6 GHz (frequency range 1 (FR1)) networks. Private FR1 networks have become broadly available from different infrastructure vendors, but typically do not support positioning services. In contrast, the Open RAN (O-RAN) initiative has already implemented these features, but performance testing has not yet been conducted outside of the lab [12]. Using software-defined radios (SDRs) with cellular-like physical layer implementation, experimental studies have identified promising positioning performance under more realistic indoor conditions, e.g., using a fingerprinting approach [4]. TDOA-based positioning, as used in this work, and at a carrier frequency similar to the one used in this work, was found to provide SL 1 to 2 performance in [13]. Against this background, we contribute to the identified experimental gap on what positioning accuracy can be achieved with a sub-6 GHz private network.

III. Private Indoor Network Deployment

This section first introduces the utilized positioning-capable private network setup in Sec. III-A. This is followed by a description of the measurement campaign in Sec. III-B.

A. Private Network Environment with Positioning Capabilities

Our experimental trial of the upcoming 5G positioning services for private network operators deploys a 5G FR1 network along with a commercial UE in a laboratory hall at TU Dortmund University, as shown in Fig. 3 and details being provided in Tab. I. The utilized communication system represents a state-of-the-art cellular system that is employed in real-world shop floors [5]. The one considered in this work further integrates a sample implementation of an UL-based TDOA positioning solution (in beta development stage, [14, Sec. 2.4]) and is evaluated using a 100 MHz system bandwidth, which is the German maximum bandwidth for FR1 private networks.

Four RU antennas, connected to the central GNSS-synced baseband unit of the network, were installed for the intended purpose at heights of 2.49 m to 2.81 m, making it suitable for

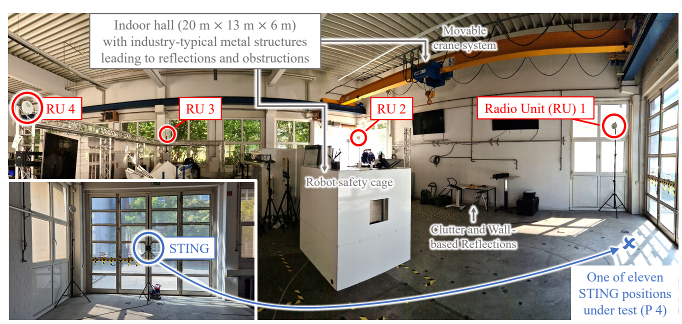

Fig. 3. Cluttered laboratory hall environment for positioning measurement campaign with private cellular sub-6 GHz (FR1) network.

TABLE I. Details on Utilized Private Network Equipment.

	Parameter	Description/Value
Network	Comm. & Pos. System	Ericsson Private 5G (EP5G)
	Radio Units	4× Radio Dot 4479 B78L
	Baseband Unit	RAN Processor 6651, GNSS-synchronized
	Frequency Band	5G band n78 (sub-6 GHz/FR1)
	Carrier, Bandwidth	3.75 GHz using 100 MHz
	Transmit Power	Max. 30 dBm / 1.0 W
	Capabilities	Release 15+, NR standalone
STING	UE Device Model	Quectel RM520N-GL
	Power Class	Class 2 (max. 26 dBm / 0.4 W)
	Capabilities	Release 16, NR standalone
Position	Technique	UL-TDOA (beta)
	Measurement Rate	API Requests at 1 Hz
	2D Position Estimate	Longitude and Latitude [°]
	Number of Samples	≥100 for all 11 UE positions

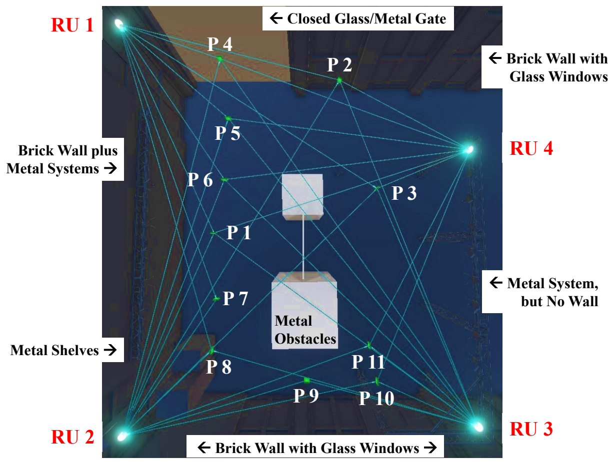

Fig. 4. Digital twin of the hall environment with eleven reference positions (green points), central metallic obstacles, and LOS RU-to-STING paths.

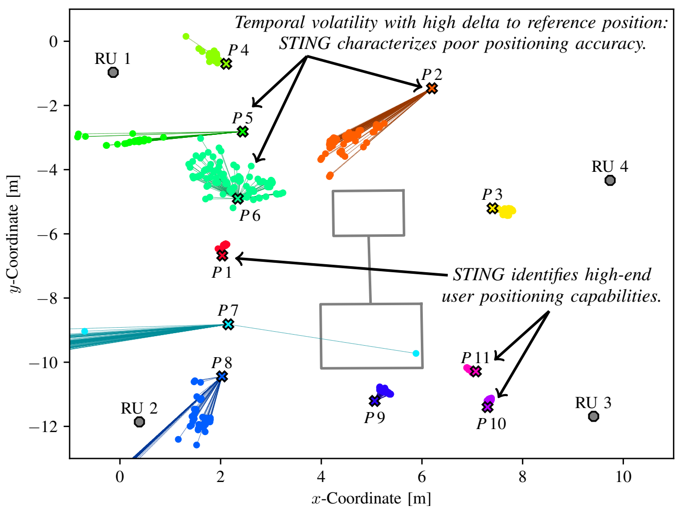

Fig. 5. Reference positions *P 1* to *P 11* (cross marker) and raw associated position estimates (colored points) depicted in top view. Metal clutter in the middle and RU positions in the corners of the indoor hall depicted for context.

2D positioning. To attain maximum coverage, corner positions within the hall were selected to enable a comprehensive and uniform radio coverage throughout the hall. They span an area of approximately $9.87\,\mathrm{m} \times 7.53\,\mathrm{m}$ wherein a static, pole-mounted UE is served at the mean height of $1.65\,\mathrm{m}$. We note that both the positions and number of employed RUs have a high impact on the achievable positioning accuracy of the network [8, 13]. Considering they are few and at communications-centric positions, this study is reporting on the expected lower-end positioning accuracy for future industry deployments.

B. STING-based Monitoring of JCAS SL Compliance

Eleven STING UE positions were selected in the hall. We subsequently refer to them shortly by *P 1*, *P 2*, …, *P 11*. Like the four RU positions, they were carefully measured with a *Leica 3D Disto* laser system, providing high-accuracy reference data for the position estimates of the radio network. For each UE position, at least 100 position estimates were retrieved from the network. Similar to GNSS-based positioning solutions, the present implementation for the private network provided 2D position estimates in a geodetic coordinate system (in degree). To evaluate positioning accuracy, the data were thus converted to a local Cartesian coordinate system (in meter).

The positions were chosen to create both potentially challenging environmental conditions due to reflections and shadowing (e.g., non-LOS (NLOS)) and good conditions (i.e., LOS) between UE and RU antennas, as well as due to distance to the RUs. This is in order to cover a broad spectrum and evaluate the performance of the cellular system and the proposed positioning/sensing-extended STING system in different InF-typical situations.

Fig. 4 shows a digital twin of the hall environment with the 11 reference positions and their line-indicated LOS connections to the RU antennas. The figure also shows the central obstacles, i.e., two cages and a partition wall, and annotates other ambient influences on the radio propagation in the facility.

IV. Evaluation of Positioning Performance

The four positions of the RUs are shown in Fig. 5 together with the recorded position estimates and their assignment to the eleven reference positions, analogous to the visualization with the digital twin in Fig. 4. It can be seen that some STING UE positions are serviced well, i.e., the raw samples are all close to the reference position marker, particularly *P 1* on the left side, *P 3* on the right side, and *P 9*–*P 11* at the bottom-right of the figure. For *P 9*, this high accuracy is interesting as there is only LOS to three of the four RUs; the NLOS path to the fourth RU, however, may be negligibly longer than the LOS path owing to diffraction at the nearby obstacle. On the contrary, we also observe that some positions are served with systematic error, such as *P 2*, *P 5*, *P 7*, and *P 8*, which can be attributed to the weakness of the employed TDOA technique, which may perform poorly if the UE is close to one of the RUs. It seems likely that the degraded positioning performance on the left and top sides was emphasized by metal clutter or wall reflections, leading to multipath-based measurement errors, which are weaker on the right side of the indoor hall environment.

A statistical evaluation is supplied based on Figs. 6 to 7, which depict the empirical distributions of incurred 2D positioning error: Fig. 6 shows the UE position-specific distribution with a violin plot, whereas Fig. 7 shows the empirical cumulative distribution functions (ECDFs) for UE groups:

- At two of the eleven positions, i.e., *P 7*–*P 8*, the position estimates may miss the true positions by more than $10\,\mathrm{m}$, as shown in Fig. 6. The STING network companion may thus suggest the use of other or extra positioning techniques to improve the accuracy at these positions. Nonetheless, the observed performance mostly matches the 3GPP's threshold for commercial positioning services in terms of positioning accuracy specifically for the lower-end SL 1 category. Considering the performance over all eleven positions, Fig. 7 shows that this performance level is attained in more than 90 % of the recorded samples, as mandated for SL 1 compliance. Thus, our case study finds that the employed private network can provide this service level throughout the entire considered indoor hall environment.
- It can further be extracted from Fig. 6 that only four positions are challenging for the employed mobile network's positioning

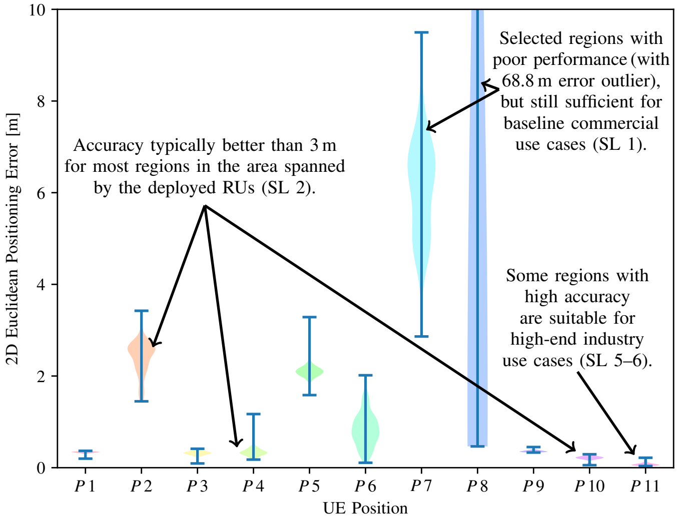

Fig. 6. Distribution of positioning error per position under test underscores that sub-meter accuracy can be provided reliably for UEs firmly in the spanned area of the RUs ($P\,\{1, 3, 9-11\}$). Performance outside the area ($P\,\{2, 4\}$) and close to the RUs ($P\,5$ – $P\,8$) deteriorates.

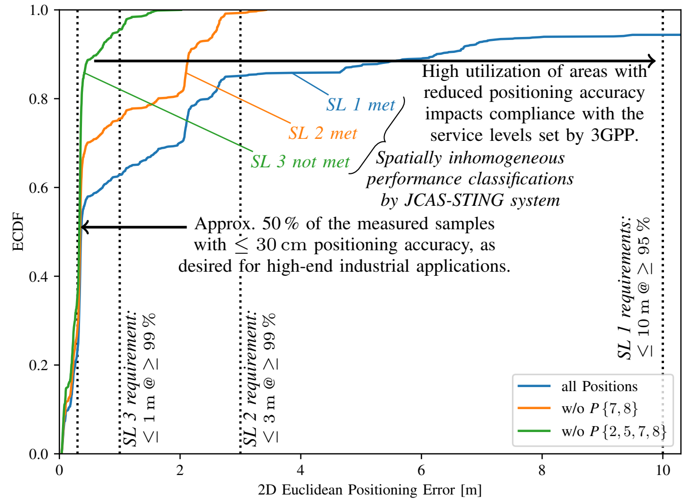

Fig. 7. Empirical distribution of 2D positioning error, taking into account all measurement positions or those with high accuracy. Comparison with accuracy requirements of positioning service levels of the 5G standard (vertical dashed lines) show that commercial-grade SLs $(1, 2)$ are achievable.

setup to service with high accuracy. For example, users at the positions $P\,2$ and $P\,4$ incur an error firmly in the meter range. Whereas the tail of the distribution exceeds 3 m, the mean error is still below 3 m, respectively. Considering these two together with the other seven well-performing positions, we find in Fig. 7 that sub-3 m accuracy is provided in more than 95 % of all samples. This shows that the setup is SL 2 compliant in large sections of the hall, even if some challenging positions are contained.

- Fig. 6 shows that sub-1 m accuracy is attained at seven of the eleven considered positions, with sub-30 cm accuracy being attained in more than half of the recorded positioning estimate samples. This underlines that high-end location services (i.e., SLs 3–6) aiming for such accuracy levels are feasible with UL TDOA. However, the ECDF over these seven positions in Fig. 7 shows that the availability of sub-30 cm and sub-1 m quality estimates is below the required 99 % threshold. While the SL 3 requirements are not met, we can conclude that SL 2 performance is not only achieved but clearly exceeded, particularly in the right-hand area with fewer reflecting objects. This is a strong result considering the low number of employed RUs at communications-centric mounting positions, the use of only a single positioning technique, and that only non-positioning-specific reference signals were employed.

V. Conclusions

Satellite-based navigation is well established outdoors, but indoor positioning demands alternative technologies. For instance, private cellular networks can support both mobile communication and positioning services for industry. This work thus extends the STING concept such that it assesses not just communication but also sensing, i.e., JCAS service compliance. The measurements show that the geometry between the radio units, the mobile connected device, and obstacles is decisive for cellular positioning accuracy. In a large part of the deployment setup, promising sub-1 m accuracy was observed with a relative frequency exceeding 95 %. This underlines readiness for use in SL 1–2 category mobile applications, even when utilizing just parts of the standardized positioning features. Our work has thus validated an initial component of future 6G JCAS capabilities, while achieving comparable accuracy through radar-like positioning of (unconnected) people and assets remains a key benchmark for upcoming 6G systems.

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