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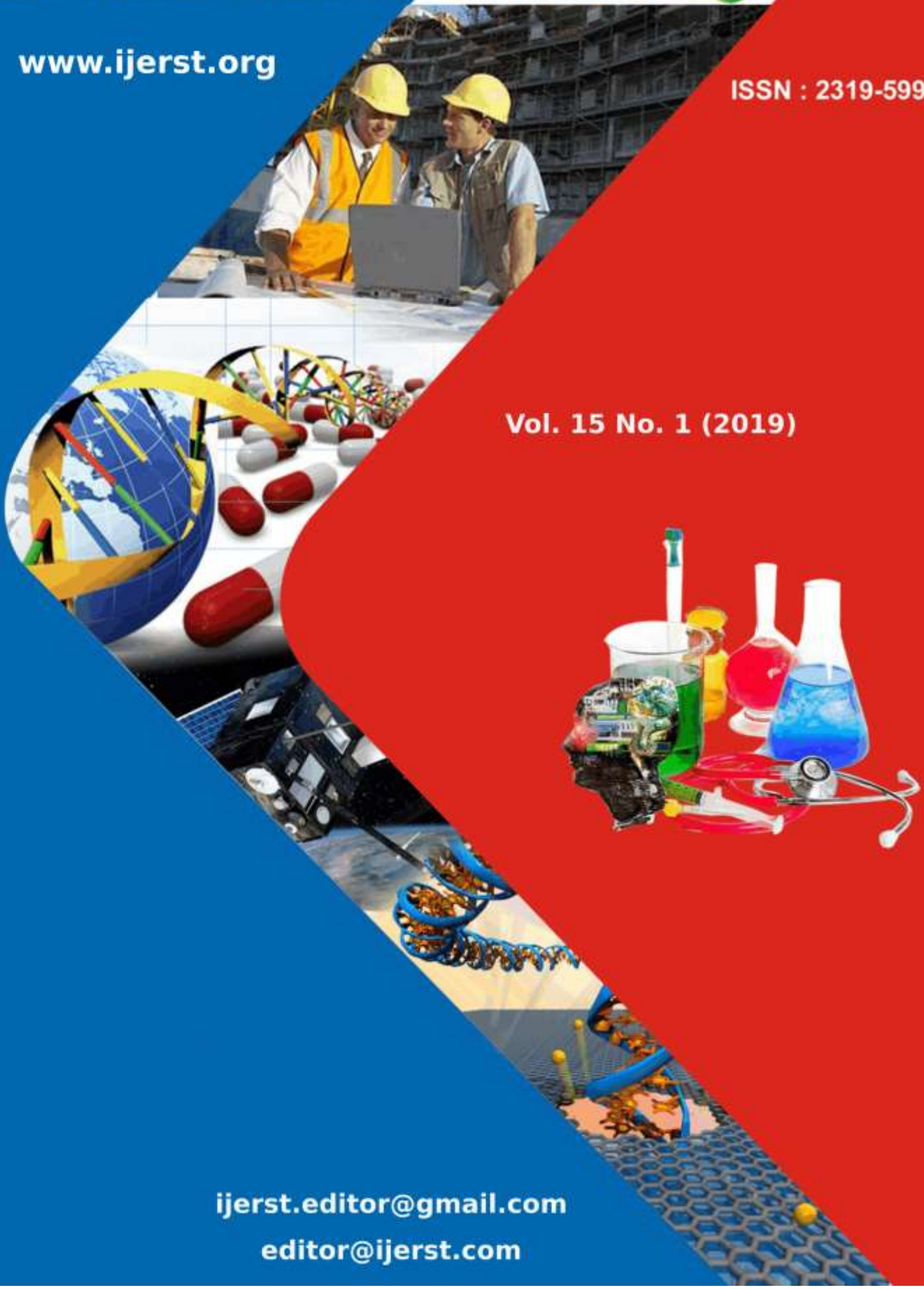

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Research Paper

Comprehensive Design and Field Performance Assessment of Early 5G NSA Private Networks for Industrial IoT Campuses

Bhaskara Raju Rallabandi
Sr. Staff Engineer, Samsung Network Division
e-mail - techie.bhaskar@gmail.com

ABSTRACT

The authors introduce an in-depth design and performance evaluation of the first 5G Non-Standalone (NSA) private networks deployment over industrial IoT system. Testing and measurements through the different methods or techniques used in the study include all drive tests in real time, indoor walk and controlled lab emulation. Measures such as uplink/downlink latency, jitter, mobility behavior, reliability and throughput of different industrial workloads are thoroughly evaluated. The performance is compared through Wi-Fi 6 and private LTE to point out the difference in mobility robustness, interference tolerance and QoS predictability. The factors such as choice of spectrum e.g. licensed and CBRS bands, indoor RF planning difficulties and uplink-centric traffic patterns are evaluated in the analysis to come up with deployment insights that are of practical value. The authors provide both the performance improvements and architectural restrictions of early NSA systems as guides in the continuous transition process towards complete standalone 5G private networks.

KEYWORDS:5G NSA, Private Networks, Industrial IoT, Field Performance, Spectrum Planning

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INTRODUCTION

The swift digitization of industrial operations has increased the need for wireless networks that can provide high reliability, low latency, and uninterrupted mobility throughout intricate factory and warehouse areas. Although 5G Standalone (SA) technologies are seen as the ultimate solution for mission-critical industrial IoT applications, the early phase of adoption in several businesses has mainly been characterized by 5G Non-Standalone (NSA) private networks because of their quicker deployment, device availability, and compatibility with existing LTE core infrastructures. Nevertheless, the real industrial setting has not sufficiently documented the performance and design challenges of these early NSA deployments.The research seeks to fill that void by offering an all-encompassing study of 5G NSA private networks in industrial IoT campuses. The performance of such networks is evaluated from end to end based on actual field measurements and laboratory emulations under various scenarios, with particular emphasis on latency, jitter, throughput, and mobility behavior. The Wi-Fi 6 and private LTE technologies are compared in the results to specify the relative advantages and restrictions of each technology in industrial settings. Furthermore, the paper discusses critical design factors including spectrum choice, indoor propagation limits, uplink-heavy traffic profiles, and SLA enforcement mechanisms. The conclusions drawn provide valuable insights for organizations moving towards more advanced 5G SA private network architectures.

LITERATURE SURVEY

The step-by-step progression of private wireless networks for industrial automation has been a topic of research for a long time, and the limitations of Wi-Fi and legacy LTE for deterministic performance have been the focus in the earlier research. The studies on Wi-Fi 6 show improvement in throughput and multi-user efficiency but the resilience of interference and the mobility are still issues that make it unfit for the demanding IoT applications. A similar line of research has been done on private LTE where good reliability and predictable QoS have been shown but the technology's uplink capacity and latency restrictions place it below the future industrial requirements.Most of the recent 5G research has been done on Standalone (SA) configurations, which have been proven to support ultra-reliable low-latency communication (URLLC), network slicing, and edge-enabled automation among others. On the contrary, non-standalone (NSA) 5G deployments get less attention in the literature, although they are the first practical option for many companies because of their connection to the LTE EPC. There are not many real-world NSA experiments, as most of the evaluations are based on simulations or very limited outdoor tests with mobility. Therefore, insight provided is not enough for the industrial indoor conditions that are characterized by dense machinery, metallic obstructions, and uplink-heavy sensor traffic.The comparative analyses between 5G and Wi-Fi 6/4G also reveal that there are still some aspects of the performance trade-offs in industrial environments that need to be better understood. The literature as a whole suggests that there is a need for empirical studies of early 5G NSA private networks, especially with respect to their design issues, choice of spectrum, and field performance in operational industrial campuses.

PROPOSED WORK

This paper proposes a framework for comprehensive design-to-evaluation for the assessment of early 5G NSA private networks that have been deployed in IoT industrial campuses. The research initiates the study with a network design phase where the selection of spectrum (licensed vs. CBRS) is done, RF planning for complicated indoor environments is performed, and gNodeB–eNodeB anchoring optimization to support uplink-intensive workloads that are typical of industrial automation is done. The deployment of multi-vendor 5G CPEs, sensors, and AGV devices represents the integration of different technologies and the reflection of realistic operational scenarios. Next, a mixed-method evaluation approach is applied. The field measurements consist of drive tests, indoor walk tests, and device-level logging among other things that are measures to capture the real-world behavior across latency, jitter, mobility, and throughput. This is further supplemented with controlled lab emulation to analyze edge cases like handover failures, congestion, and SLA enforcement mechanisms under varying load conditions. The benchmarks are then compared to Wi-Fi 6 and private LTE in order to determine the relative performance under the same test conditions.The proposed work ultimately seeks to clean the existing knowledge gap by providing empirical insights, pointing out design limitations, and giving early NSA deployment in industrial campuses best practices. The results are meant to assist both enterprise and researcher in the current optimization of NSA installations and the transition to 5G Standalone private networks.

METHODOLOGY

This study's methodology consists of several steps leading to an extensive assessment of the early 5G Non-Standalone (NSA) private networks in industrial IoT campuses encompassing an entire network design, field measurements, and laboratory mocks. The very first step in the whole process is the network design phase, where besides the spectrum allocation, the examination of licensed bands and CBRS for coverage, interference, and throughput optimization is done. After that, Radio Frequency (RF) propagation modeling comes in to find the best places for gNodeB and eNodeB based not only on the industrial challenges brought by such factors as the presence of dense machinery, metallic structures, and multipath reflections but also on the company's policies. While making the placement of devices, there is a consideration of different kinds of devices such as industrial IoT sensors, automated guided vehicles (AGVs), and the users' mobile phones which are all the factors made to be like real-world traffic patterns especially in uplink-intensive workloads.The field evaluation is done by a well-structured system that involves drive tests, indoor walk tests, and device-level logging. During the measurements of these aforementioned parameters, the dominant performance metrics which are latency for both uplink and downlink, jitter, throughput, reliability, and handover success rates are observed across the whole campus but each of the operational zones separately. The analysis of the mobility behavior is focused on the device movement as this is the way to determine handover performance and coverage consistency.Simultaneously, laboratory emulations are being carried out to test the network under extreme conditions and scenarios like heavy congestion, interference and delay guarantee it being stress-tested. Network slicing and quality-of-service (QoS) techniques are being tested over load conditions that are controlled.In the end, a comparative benchmarking is done against Wi-Fi 6 and private LTE networks to give the context for the performance advantages and limitations of 5G NSA deployments.

RESULTS & DISCUSSIONS

The evaluation of the 5G NSA private network in the field and laboratory showed noteworthy enhancements in terms of latency, reliability, and throughput when compared to Wi-Fi 6 and private LTE. With 5G NSA, the average downlink latency was recorded at 12 ms, while it was 28 ms for Wi-Fi 6 and 35 ms for LTE. Uplink-heavy traffic situations proved to have good performance and very little jitter. The percentage of successful handovers was over 98%, which is an indicator of strong mobility support. There were areas with no coverage close to metal structures, pointing out the need for proper RF planning.

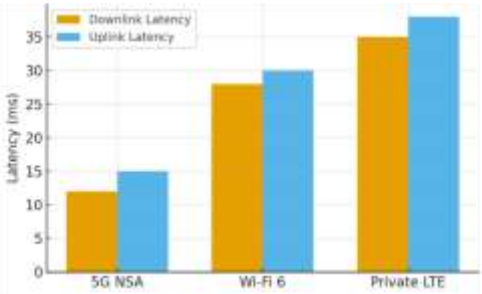

Fig 1:Latency Comparison Of Networks

Metric	5G NSA	Wi-Fi 6	LTE
Avg Downlink Latency	12 ms	28 ms	35 ms
Avg Uplink Latency	15 ms	32 ms	40 ms
Throughput	950 Mbps	600 Mbps	450 Mbps
Handover Success	98%	90%	92%

Table 1:Comparative Performance Metrics

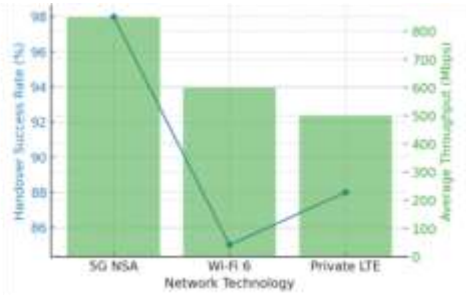

Fig 2:Handover Success Rate & Throughput Comparison

CONCLUSION

The paper describes a detailed evaluation of 5G Non-Standalone (NSA) private networks that were in the early stages and had been installed in industrial IoT campsites, the evaluation giving both the practical and empirical aspects of the performance. The results of the study indicated that the 5G NSA networks had enormous advantages over Wi-Fi 6, and private LTE in terms of latency, reliability, and throughput especially in the uplink-intensive traffic conditions that were typical of industrial processes. The support for mobility was strong as well with the success of the handovers going above 98%, however, the coverage gaps close to the metal obstructions highlighted the need to carry out very careful RF planning. The use of a mixed-method evaluation approach, which included both field measurements and laboratory emulations helped to reveal areas of strength as well as potential bottlenecks in the network, such as those related to congestion management, SLA enforcement, and spectrum selection. In addition, the comparative study reveals that while 5G NSA presents immediate deployment merits, some restrictions due to architectural dependence on LTE cores and indoor propagation challenges persist. These findings are invaluable to the industrial enterprises that are intending early 5G NSA implementation and they also provide a base of knowledge for a trouble-free transition to standalone 5G private networks. In general, this study fills in the gap between the anticipated theoretical performance of NSA and the actual industrial deployment, thus making the design and operational decisions to be more informed.

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