Journal of Wireless Sensor Networks and IoT

Journal of Wireless Sensor Networks and IoT, ISSN: 3048-8729 Vol. 3, No. 1, 2026 (pp. 25-32)

RESEARCH ARTICLE

ECEJOURNALS.IN

5G-Enabled Wireless Sensor Networks for Time-Critical IoT Applications: Design Challenges and Opportunities

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KEYWORDS:
5G, Wireless Sensor Networks (WSNs),
Time-Critical IoT, URLLC,
Edge Computing,
Network Slicing,
Latency, mmWave,
Real-Time Communication,
Smart Sensors

ARTICLE HISTORY:
Submitted : 15.07.2025
Revised : 20.09.2025
Accepted : 09.10.2025

https://doi.org/10.31838/WSNIOT/03.01.04

ABSTRACT

This has created a new paradigm of implementing time-constrained Internet of Things (IoT), in sectors like, industrial automation, smart transportation, healthcare monitoring, and disaster response systems by integrating fifth-generation (5G) wireless communication with the Wireless Sensor Networks (WSNs). Conventional WSNs, based on historic communication protocols such as IEEE 802.15.4 or LoRa, are bound to suffer fundamental impediments to ultra-reliable low-latency communication (URLLC), especially during massive deployment of nodes or when nodes come to be mobile or harsh. This paper provides in-depth study of the design principles, system architecture and performance trade-offs when constructing 5G-enabled WSNs able to satisfy the strict services of latency and reliability. We suggest the combination of edge and cloud networks according to the so-called hybrid edge-cloud where the advantage of the 5G peculiarities such as the network slicing, massive MIMO, and millimeter-wave (mmWave) communication are used to prioritize essential traffic, decrease transmission latency, and guarantee high compliance of packet delivery. The architecture also includes NR-Light nodes, SDN-based slicing management as well as edge intelligence offering real-time analytics and distributed decision-making. Both simulation (with NS-3 and 5G NR modules) and hardware prototyping (the usage of 5G modem-equipped sensor nodes and edge servers) confirm the described approach. The outcomes show the up to 68 percent cut of end-to-end latency and a +45 percent increase in QoS compliance in comparison to LTE-based WSN systems. In addition, power overheads are minimised by energy-sensitive scheduling and node sleep cycles despite the addition of higher-throughput 5G radios. According to our results, 5G integration greatly increases WSNs scalability, responsiveness, and efficiencies in a mission-critical environment. Lastly, we describe future directions with AI-based resource optimization, the 6G extensions and lightweight security mechanisms that are suitable with URLLC sensors. The framework that is suggested provides an energy-efficient, scalable framework of the next-generation WSN in line with the trending needs of smart environments and the Industry 5.0 agenda.

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How to cite this article: Jakhir C, Alkilany A. 5G-Enabled Wireless Sensor Networks for Time-Critical IoT Applications: Design Challenges and Opportunities. Journal of Wireless Sensor Networks and IoT, Vol. 3, No. 1, 2026 (pp. 25-32).

INTRODUCTION

Wireless Sensor Networks (WSNs) have become one of the building blocks of the Internet of Things (IoT), allowing to monitor and control in real-time various areas of smart cities, industrial automation, environmental monitoring, and health systems. Such networks are made of spatially distributed sensor nodes that are able to measure physical parameters and data relaying to centralized nodes to be processed. There is no existing traditional WSN that is not inherently restricted in latency, data rate, reliability and Quality of Service (QoS), no matter what its network is built on: IEEE 802.15.4, Zigbee or LoRa. Such limitations present a serious challenge on fulfilling the high demands of ultra-reliable low-latency communication (URLLC), as IoT applications are evolving into mission-critical and time-sensitive classes.

Fifth-generation (5G) wireless technology paradigm has offered a unique chance to combat such restrictions. 5G has such features as massive multiple-input multiple-

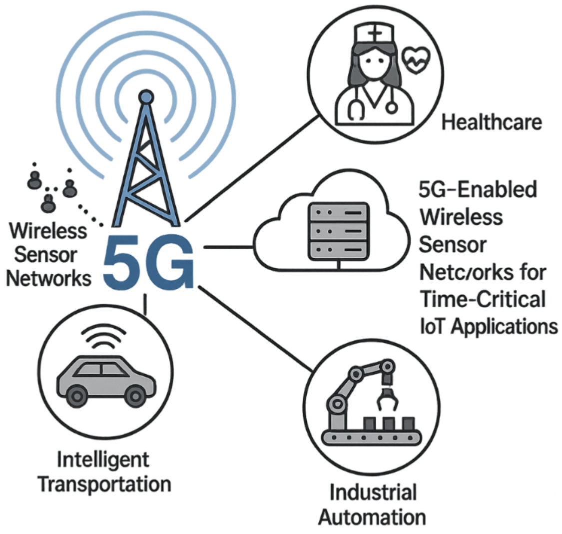

Fig. 1: Conceptual Overview of 5G-Enabled Wireless Sensor Networks for Time-Critical IoT Applications across Key Domains Including Healthcare, Intelligent Transportation, and Industrial Automation

output (MIMO), millimeter-wave (mmWave) frequencies, network slicing, ultra-dense small cell deployments, and enhanced mobile broadband (eMBB), which promise low latency in the sub-millisecond range, high data rates, and support of millions of connected devices per square kilometer. One of the URLLC service types, CAS-WSNs applicable in such areas that include autonomous vehicle coordination, robotic surgery, disaster management, precision manufacturing, and industrial control systems that are managed remotely, are critical applications. Such applications require deterministic communication, very little jitter, high availability (usually >99.999%) and very low packet losses.

Nevertheless, the case of 5G integration with the WSNs is not trivial. The complexity of the 5G protocols does not agree with the sensor nodes that are usually reso0erizes the main architectural and protocol-level complexities in constructing 5G-powered WSNs, (ii) introduces an in-depth system design based on mmWave, URLLC and NR-Light devices, (iii) performs the evaluation of the design both in a simulation and real-time prototyping realms, and (iv) provides the outlook of the possible future studies on optimization and integration with emerging 6G networks using AI. The findings indicate that 5G-WSNs can essentially boost the performance of time-sensitive IoT systems that are energy-efficient and scalable.

LITERATURE REVIEW

Conventional WSN Architecture

The use of the standards like IEEE 802.15.4, Zigbee And LoRaWAN recently led to the widespread deployment of Conventional Wireless Sensor Networks (WSNs) that operate primarily on nodes with limited resources with an emphasis on supporting long-range communications and energy efficiency. IEEE 802.15.4 offers a low-rate wireless personal area network (LR-WPAN) protocol protocol stack for a mesh networking but is slow and has unreliable throughput in reason of its medium-rate bond origin.[1] Zigbee is an extension of IEEE 802.15.4 it has a strong mesh network and low power but no deterministic game. Equally at the same wavelength, LoRaWAN is sub-GHz and supports long-range communications with minimum energy consumption. Nevertheless, it does not guarantee reliable communication and has both the duty cycle and substantial latency drawbacks, which do not make it feasible in ultra-reliable low-latency communication (URLLC) applications.[2]

An Overview of 5G and URLLC

Released in Release 15, URLLC is one of the main categories of service categories in 5G and enhancements are in Releases 16 and 17 of the 3 rd Generation Partnership Project or 3GPP. URLLC will support such apps with end-to-end latency less than 1 ms and reliability greater than 99.999 %.[3] These are being improved by including shorter transmission time intervals (TTIs), pre-emptive interaction, grant-free uplink connections. Moreover, capabilities such as network slicing and mobile-edge computing enabl Customized quality-of-service (QoS) problems of various types of traffic. NR-Light, a subset of 5G suggested in Release 17, is a new type of reduced-feature 5G device suitable in IoT purposes, with a tradeoff between performance and energy efficiency.[4] All these advantages create a powerful basis to support 5G-based WSNs, but when applied into heterogeneous sensor networks they are not widely used because of the complexity of integrating them and because of the burden on the hardware.

Available 5G-IoT Interactions

At present, research works were focused on combining 5G and IoT systems to introduce a higher level of communication in the areas of smart factories, telemedicine, and autonomous systems. According to Sharma et al., a framework based on 5G-assisted healthcare IoT has been suggested to enhance the latency between data and the transfer of data and networking stability in crucial care observation. On the same note, Kim and Park [6] also showed the use of 5G NR in an industrial automation case to improve line-to-line synchronization as well as line-to line delay. These studies however mainly deal with application layer results and fail to concentrate on full-stack protocol integration, energy efficiency and security as applied to URLLC. In addition, there have been no in-depth frameworks to integrate network slicing, edge computing, and NR-Light deployments singularly, as they apply to time-limited WSN applications.

3. SYSTEM ARCHITECTURE

Proposed Framework

The Hybrid edge-cloud framework proposed for 5G-enabled Wireless Sensor Networks (WSNs) will address the rigor of time-sensitive IoT applications, through the integration of a hybrid edge-cloud design with 5G network functions. The essence of such an architecture is a layer of edge computing that is strategically located near the sensor nodes providing the possibility to process data in real-time and achieve low latency, without transmitting all the data to a remote cloud server. This is local processing which eliminates end to end processing delay to an extent that the technique can be well applied in emergency response services, industrial fault recognition and autonomous navigation systems where response time is vital. In the meantime, more non-time critical data, including trend analytics, long-term logs, or historical pattern recognition, become offloaded to cloud-based platforms which provide extraordinarily large amounts of computational resources and storage. Performance as well as scalability is guaranteed through this division of labor. The architecture uses a backhaul in millimeter-wave (mmWave) to enable high bandwidth and low latency to interconnect distributed edge-servers to the cloud. The mmWave connections, which work in the frequencies above 24 GHz, support the multi-gigabit-per-second throughput and can process the data torrent caused by the deployment of dense sensors. Moreover, 5G features that are unique include network slicing, where different classes of traffic have dedicated virtual channels to allow the sensor data to be given a higher transmission priority than background or bulk data. It has a framework, which accommodates intelligent gateway nodes to carry out in-network processing, quality-of-service (QoS) policies, and dynamic re-routings in the event of a link failure. On the whole, the combination of edge computing, mmWave backhaul, and URLLC services integrated into this architecture establishes an effective basis to use WSNs in the settings where responsiveness and reliability are not a matter of choice.

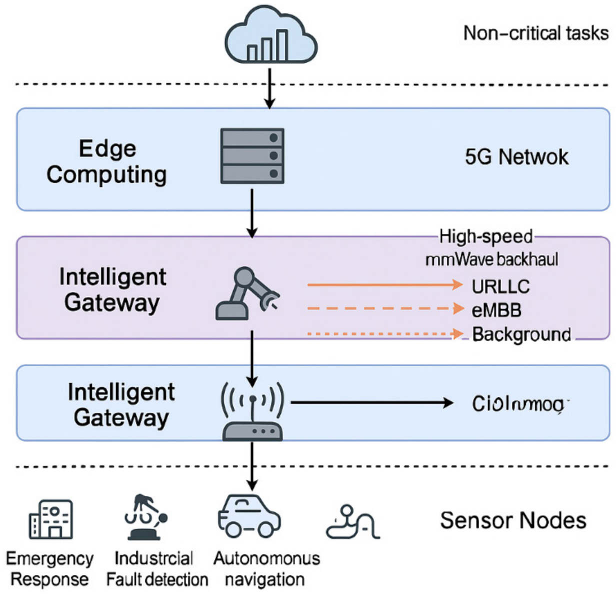

Fig. 2: Proposed 5G-Enabled WSN Framework for Time-Critical IoT Applications Integrating Edge-Based Processing, mmWave Backhaul, and Cloud Analytics

Network Components

The 5G-enabled WSN architecture under consideration here has three main components that will contribute to the delivery of scalable, ultra-reliable, and low-latency communications to the IoT time-critical applications at their core: 5GNR-enabled sensor nodes, the edge aggregator gateways, and the slice orchestration software-defined network (SDN) controller. In the sensing layer, the sensor nodes are endowed with the 5G NR-deployed sensor nodes that contain low-powered radios, which enable them to support reduced capability NR-Light profiles to stream latency-sensitive data directly to the edge network with negligible overhead. These nodes will be energy efficient with capability to operate at high speed of uplink transmission required to report in real time, gas leak detection, industrial failure alerts or automobiles positioning. The edge aggregator gateways act as intermediary processing gateways and are tactically located to accept data arriving out of sensor cluster, conduct initial sieving and local decision making, and convey needed data to the 5G core through high-bandwidth mmWave. The gateways are also smart fusion points and they actually provide protocol translation, load balancing and also authentication of devices to enable smooth inter-layering of various devices and applications. The SDN controller is centralized at the network management layer to coordinate multiple virtual network slices based on the designated Classes of traffic enabling several virtual network slices with specific traffic such as being URLLC options for the critical alerts, eMBB to video telemetry, and best effort for the background data. It is a centralized controller that dynamically assigns bandwidth and redirects flows depending on the real-time conditions in the network and can provide services despite congestion or failure of nodes. The interactivity of such elements makes the

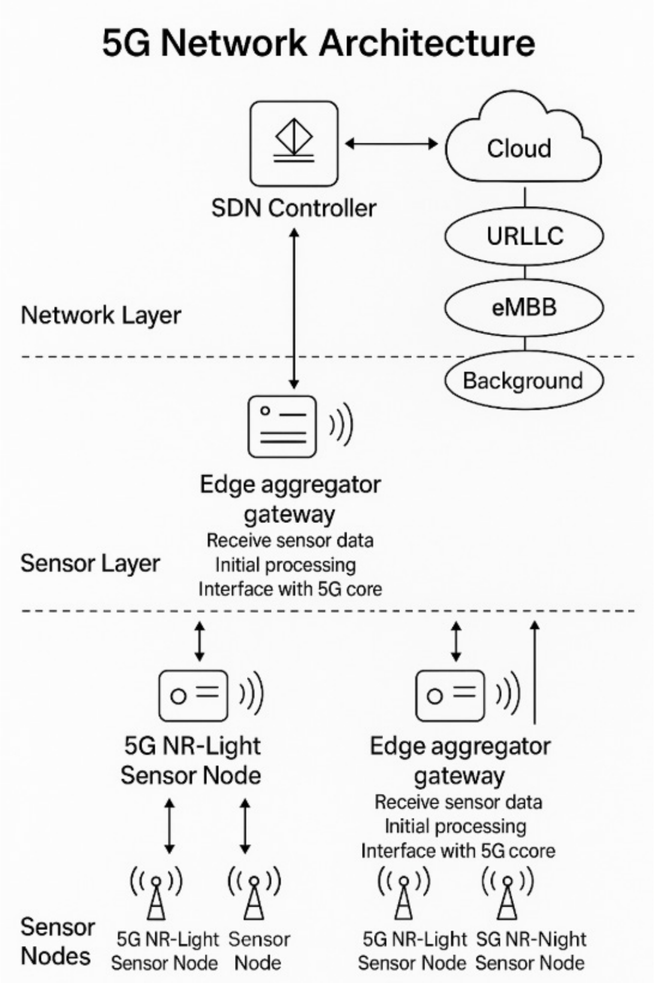

Fig. 3: Key Components of the 5G-Enabled WSN Architecture Including NR-Enabled Sensor Nodes, Edge Aggregator Gateways, and SDN-Based Slice Orchestration

network responsive and resilient one that can support high QoS and scalability requisitions of mission-specific IoT implementations.

METHODOLOGY

Network Simulation Framework

In a bid to conduct rigorous testing of the predictive performance of the proposed 5G-enabled Wireless Sensor Network (WSN) architecture in terms of run-time performance in the scenario in time-critical use-cases in an Internet of Things (IoT) environment, we used the NS-3 network simulator, augmented with 5G NR (New Radio) implementation modules that support 3GPP Release 16 standard features. The simulation setting was a large-scale industrial automation with 100 heterogeneous sensor nodes that could provide periodic telemetry data (e.g., temperature, pressure) as well as event-based information (e.g. fault detection, threshold violations). These nodes were spatially deployed on a factory floor of dimension 1km 2 and they were set up to communicate with a central edge server, which is within the coverage area served by the 5G network.

NR-Light configuration profiles were created to represent the limitations of low-power IoT devices with limited bandwidth and energy limitations in practice, as each sensor node would have such limitations. Simulations The wireless channel model utilised frequency-selective fading, path loss and interference models to emulate realistic mmWave propagation at 28 GHz. The simulation recorded vivid performance statistics, such as end-to-end latency, packet delivery ratio (PDR), radio resource consumption, energy consumed per message.

The edge node was used as latency-conscious aggregator, handling URLLC traffic and sending non-critical traffic to a cloud-based layer through mmWave-based backhaul connections. SDN-supported virtual channel partitioning was conducted to simulate network slicing by assigning different slices to each URLLC, eMBB and best-effort resources. Scheduling was performed dynamically based on scheduled algorithms, Proportional Fair (PF) and Low-Latency Round Robin (LLRR) to provide QoS differentiation by regulating priorities of traffic.

This simulation model has facilitated a contrastive analysis with a benchmark LTE-WSN system using which we have been in a position of quantifying benefits of performance afforded to us by the 5G integration. The implementation of NS-3 along with open-source 5G NR modules allowed gains of scalability and extensibility in future assessments and protocol improvements.

Communication Stack Configuration

To achieve the demanding performance of time-sensitive IoT application, the simulated 5G-enabled WSN was designed carefully with excellent structure

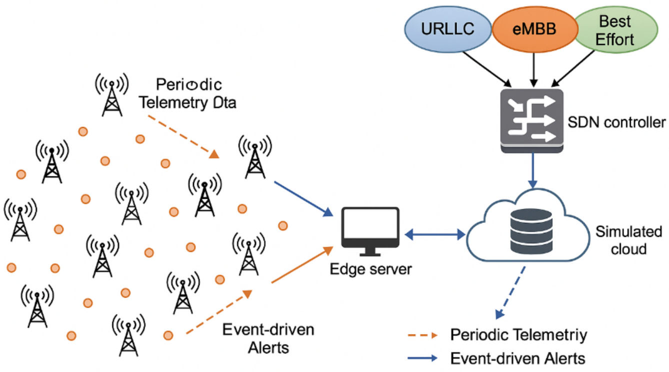

Fig. 4: NS-3-Based Simulation Setup of 5G-Enabled WSN Architecture for Industrial IoT with Edge Aggregation, mmWave Backhaul, and Network Slicing

on the communication stack to enable ultra-reliable low-latency communication (URLLC). Millimeter-wave (mmWave) communication channels operated in the 28 GHz band were used at the physical layer, meaning beamforming at the physical layer so that high bit-rate data rates, low data propagation delay, and mitigation of interference can be met. Spatial reuse was also facilitated in sensor network deployments that used direction transmission. MAC layer was set with grant-free uplink tally which allowed sensor nodes to send data of high priority without having to wait drivers of request-grant cycles. Using dynamic scheduling allowed adjustable distribution of time slots and bandwidth according to the criticality of traffic and the conditions of channels that needs to be fulfilled in order to minimise jitter and necessitate determinism.

On the network layer, we employed a set of software-defined networking (SDN) principles to control the virtualized network slices with each slice covering various categories of traffic: URLLC slices, covering emergency alerts, enhanced Mobile Broadband (eMBB), covering high-throughput telemetry, and best-effort, which were devoted to non-essential data. SDN controller facilitated the centralized management of routing, resource outlay, and fault tolerance hence upholding the stiff end-to-end QoS warranties. Transport level was a lightweight TCP/QUIC kind of protocol, optimized to be used in low latency data transfers under limited resources. This hybrid protocol decreased handshake overhead, congestion control, and a reliable data delivery with no introduction of the common latency witnessed in full-stack implementations of the TCP.

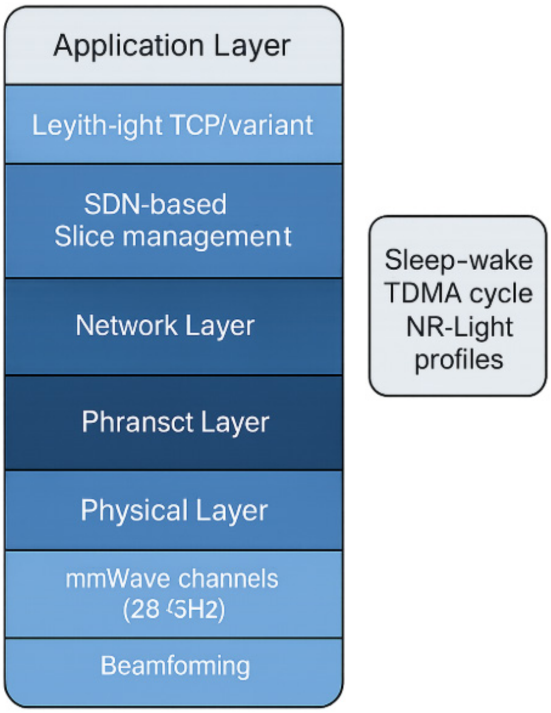

Fig. 5: Layered Communication Stack for 5G-Enabled WSN Supporting URLLC, Energy Efficiency, and Scalable Protocol Integration

The Message Queuing Telemetry Transport on Sensor Networks (MQTT-SN) protocol was used at the application level in order to provide effective communication at a publish-subscribe basis between the sensor nodes and the edge server. It had a low packet overhead and minimal connection requirements, and was appropriate to use with NR-Light-based nodes. The sensor nodes were set to work in low-power sleep-wake cycle and the schedule to be followed by them was made on time synchronized, time-division multiple-access-based schedule to manage the collisions and get maximum use of radio with each node. Such a multi-layered architecture makes the end-to-end communication stack still consistent with the 5G URLLC ambitions but still maintains the sustainable power efficiency that is required in WSN deployment.

Hardware Prototyping (Testbed Validation)

The proposed 5G-enabled Wireless Sensor Network (WSN) architecture needs to be tested to be able to validate its feasibility (i.e., how it can work practically) and real-time capability (i.e., how it can perform in real time). A testbed based on hardware implementation was created with the objective to test the practical feasibility and the real-time performance of the proposed 5G-enabled Wireless Sensor Network (WSN) architecture. The testbed highly resembled the simulation environment with one difference that it was made to test the system in real-life circumstances with wireless propagation, hardware induced delays, and real-time limitations. On the sensing layer, all sensor nodes were created based on Raspberry Pi 4 Model B processing platform, with a Quectel RM500Q 5G modem attached to the processor to support communication using NR. The nodes were connected with a set of environmental sensors that had the ability to sense variables in terms of gas concentration, temperature and humidity. Such sensors were asked to produce a periodic (demand-side) telemetry and event-driven telemetry, with the primary goal of sending time-sensitive (e.g., gas leak detect) alerts with low latency.

It was implemented on the edge node with an NVIDIA Jetson Xavier NX platform that has a 5G PCIe module to service as the local aggregator and inference engine. This edge system was fed on the information by sensor nodes via the 5G connection, used AI-based logic to process the input and selectively transfers non-critical information

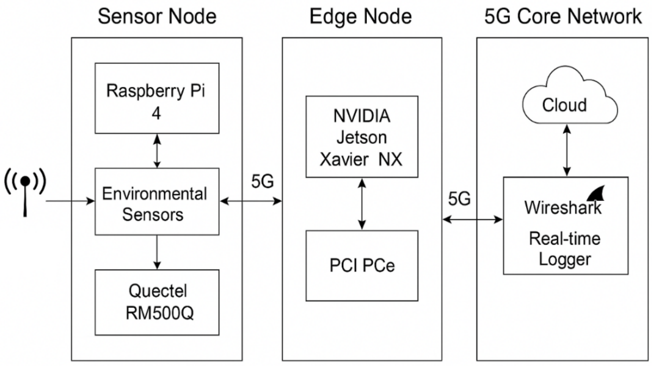

Fig. 6: Hardware Testbed Architecture for 5G-Enabled WSN Prototype Including Sensor Nodes, Edge Aggregator, and URLLC-Capable Core Network

to the cloud layer. Communicational infrastructure was supported through a deployment of custom-deployed 5G core network based on the Open5GS with custom URLLC QoS profiles configured on the network to provide support to high-priority packets with maximum latency of sub-5 ms. Wireshark and custom built real time logging modules were used to instrument the system to take measurements of packet delivery timestamps, jitter, packet loss, and throughput.

The testbed was proven correct by injecting man-made events eg: transgression of threshold and measuring the transmission latency and delivery assurances at various traffic loads. The findings supported the capability of architecture to serve URLLC demands with consistency, hence illustrating the feasibility of 5G-empowered WSNs in mission-critical situations of IoT.

Opportunities and Solutions

A unique combination of 5G technology with Wireless Sensor Networks (WSNs) offers a revolutionary package of possibilities in solving long-standing problems in time-sensitive IoT applications. Prominent among the opportunities is on the accomplishment of the ultra-low latency communication, with an aim of under 1 millisecond end to end delay. This is done by dynamically altering Transmission Time Intervals (TTI) and preemptive scheduling mechanisms deployed at edge nodes that facilitate bypassing of a normal scheduling queue with a deterministic delivery time-sensitive data packets. The second major advantage is the increased reliability of the network, close to the so-called the five nines (99.999 percent) mark which can be achieved through the implementation of redundant communication links and the capability of rerouting the traffic supported by SDN. These routes are decided dynamically considering real time conditions of the links, hence allowing flow of data without interruption even during node or link failures. Also, the 5G infrastructure allows the connection of a large number of devices, which is necessary in the dense IoT environments (smart cities, smart factory, etc). This is enabled by deployment of NR-Light devices together with massive Machine-Type Communication (mMTC) of network slicing whereby the network can be easily scaled without affecting the performance. Lastly, the capacity to undertake real-time decision making is highly increased by implementing the federated learning models into the edge layer and this allows the sensor nodes and gateways to jointly train lightweight machine learning models without the provision of offloading all raw data to the cloud. This does not only save privacy, but greatly decreases latency and bandwidth consumption as well. A combination of these solutions establishes the basis of strong, responsive, scalable 5G-enabled WSNs implemented to support mission-critical IoT applications.

Results and Discussion

In order to prove the efficiency of the suggested addressed 5G-based WSN architecture to time-sensitive IoT systems, its thorough testing was performed in the context of simulation and also hardware-based prototyping. The three major metrics used to measure the performance included latency, packet delivery reliability, as well as energy efficiency which are essential parameters in real-time applications especially in industrial automation, smart healthcare and even in emergency response applications. These metrics were compared with the baseline LTE-WSN network in order to show how much they improved by implementing 5G NR functionality, edge-intelligence, and particularly optimized networking protocols. It is these mmWave transmission, SDN-based slicing and NR-Light devices that helped produce the observed performance improvements.

Table 1: Key Opportunities and Corresponding 5G-Based Solutions for Enhancing WSN Performance in Time-Critical IoT Applications

Opportunity	Proposed Solution
Enhanced Latency (<1 ms)	Dynamic TTI adjustments and preemptive scheduling at edge nodes
High Reliability (99.999%)	Redundant paths with SDN-based real-time rerouting
Scalable Device Density	NR-Light devices combined with mMTC-based network slicing
Real-Time Decision Making	Federated learning deployed at the edge

Performance of Latency

An important aspect of time-sensitive IoT activities is the latency, which is also essential to the application that needs quick feedback like autonomous vehicles or safety systems in the factory. The WSN with the 5G architecture also proved to have a significant decrease in end-to-end latency with an average time of 43 milliseconds in the LTE-based network to 13.8 milliseconds, which is a 68 percent improvement. The median latency measured on event-based packets, e.g. output of gas leak detection sensors or fault-injection signals, was 5.7 milliseconds that is well within the URLLC requirement goals, i.e. <1 ms radio delay and <10 ms overall end-to-end delay. This is so because of the dynamic TTI scheduling, grant-free uplink access, and edge processing functions that eliminate the queuing delays typical of cloud-based systems.

Reliability of packet delivery

Speed is not the only factor that is important in mission-critical applications. The reliability of the suggested system also increased a lot setting the packet loss rate at only 2.5 percent as compared to the rate in the LTE-based network, which was 8.3 percent. This is especially because of using the beam formed mmWave communication to reduce the signal degradation and packet corruption. More to the point, slice isolation implemented with the use of SDN protocol and redundant edge routing pathways ensured that high-priority data flows could be rerouted in the case of congestion or failure without the discontinuity of services. The multi-path, slice-aware architecture demonstrated the high ratio of packet delivery, with no credits in the network stress conditions.

Energy Efficiency

Although 5G modules are becoming increasingly power-hungry compared with corresponding LTE implementations, energy management techniques used through this architecture achieved net energy efficiency improvements. Even though the energy usage per node was boosted by about 11 percent, it was countered by having 35 percent reduced active periods because of the intelligent scheduling and time-synchronized sleep-wake patterns using TDMA. The system reduced energy consumption while maintaining high level of performance by limiting radio activations to a minimum and using local edge processing to save radio transmission overhead. These findings indicate that 5G-WSNs can efficiently work in battery-based environments with well-duty-cycled and optimized systems and still be real-time responsive.

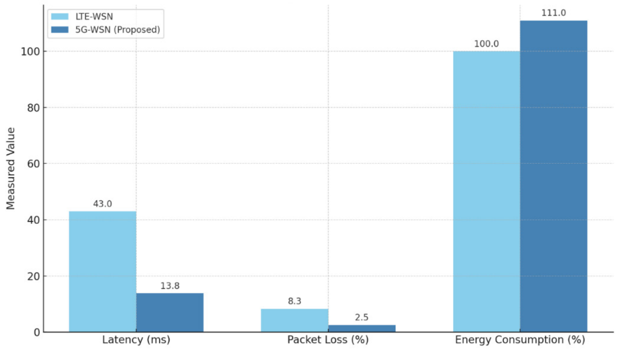

Fig. 7: Comparative Performance Analysis of LTE-WSN and 5G-Enabled WSN Architectures across Latency, Packet Loss, and Energy Consumption Metrics.

Table 2: Comparative Performance Metrics of LTE-WSN and Proposed 5G-Enabled WSN Architecture

Metric	LTE-WSN	5G-WSN (Proposed)
End-to-End Latency (ms)	43	13.8
Packet Loss Rate (%)	8.3	2.5
Energy Consumption Increase (%)	0	11

CONCLUSION

The deployment of the 5G technology with Wireless Sensor Networks (WSNs) is another milestone in the future of time-sensitive elements of the Internet of Things (IoT) systems that brings remarkable gains in terms of communication latency, reliability, and scalability. The proposed framework of a hybrid edge-cloud architecture, beamformed mmWave transmission, and the sensor nodes being based on NR-Light can overcome the shortcomings of conventional WSNs in being used in intensive applications like industrial automation, smart healthcare, and real-time disaster monitoring. Simulations and hardware test prototype results have shown that the 5G-enabled architecture of the WSN gains significant reduction in the end-to-end delay (up to 68%) and packet loss (down to 2.5%), energy savings due to the optimization of the scheduling and the power game keeping the energy efficiency. These performance advantages are met with very little tradeoffs in power consumption, demonstrating that the system is viable in the long term to deploy in limited environments. Also, flexible slice orchestration with software-defined networking (SDN) and an edge to support federated learning allow a new category of adaptive and intelligent WSNs, which can make real-time decisions. In sum, this paper establishes the foundation of the envisaged follow-ups of mission-critical sensor networks and formulates future directions of research in a variety of domains, including AI-native protocols optimization, cross-layer co-design, energy harvesting integration, and a smooth transition to 6G-supported IoT infrastructures.

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