A Sustainable and Intelligent Unified LPWAN-as-a-Service Framework for 6G IoT Using RedCap

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***Abstract*—5G Reduced Capability (RedCap) is a promising technology introduced to bridge the gap between legacy LPWAN technologies (i.e., NB-IoT, LTE-M, URLLC) and full 5G NR. However, 5G RedCap operates with fixed radio parameters and cannot dynamically adapt to changing service requirements. This paper proposes a Unified LPWAN-as-a-Service (ULaaS) framework that leverages existing provision of 5G NR to optimize the RRC parameters, such as bandwidth part, power class, antenna configuration, and modulation scheme, to support legacy LPWAN technologies-inspired operational behaviours within a Single 5G RedCap device and policy-driven network architecture. The framework enables multi-persona operation by dynamically changing configurations through standard 5G management entities—specifically the Network Exposure Function (NEF), Policy Control Function (PCF), and Session Management Function (SMF). This software-driven approach aligns well with the 6G design principles of intelligent control, hardware reuse, and resource-efficient networking, enabling the sustainable and intelligent Green Internet of Things. The implementation of ULaaS is realized on MATLAB-based waveform-assisted evaluation to demonstrate that the adaptive RedCap parameter tuning can effectively approximate the latency, throughput, and energy-efficiency behavior of legacy LPWAN technologies. The results show that ULaaS can serve as a unified layer that enhances RedCap's flexibility for heterogeneous IoT deployments.**

***Index Terms*—5G RedCap, LPWAN-as-a-Service, NB-IoT, LTE-M, URLLC, 6G-IoT connectivity.**

I. Introduction

A. *I. Introduction*

Rapid digitalization and the surge in IoT devices have resulted in a fragmented connectivity landscape. Today's IoT networks rely on specialized, siloed technologies-NB-IoT for low-power sensing, LTE-M for mobile tracking, and URLLC for real-time control-each with its own hardware, spectrum needs, and infrastructure. This separation increases device costs, complicates spectrum management, and hinders unified service orchestration in domains such as smart cities, industrial automation, and connected vehicles [1], [2].

And even with these multiple technologies, some IoT use cases still fall through the gaps. To bridge this, 3GPP introduced 5G Reduced Capability (RedCap), a simplified New Radio device profile with reduced bandwidth, power, and complexity [3], [4]. RedCap sits between legacy LPWANs and full 5G NR, targeting mid-tier IoT applications. But this raises a critical question: As new IoT devices and use cases emerge, should we continue to introduce specialized technologies, or can we develop a single unified technology that can adapt to serve them all?

Prior research has explored how NB-IoT and LTE-M can coexist with or transition toward 5G NR. Gbadamosi et al. [5] list specific features between the 5G NR and NB-IoT numerologies to promote the coexistence. Ratasuk et al. [6] demonstrated that NB-IoT and LTE-M can operate within NR carriers with appropriate guard-band management. Tlake et al. [7] and Liu et al. [8] investigated adjacent-channel interference and power control strategies to maintain performance during 4G-5G coexistence. Beyond analytical coexistence, Jabeen and Haque [9] proposed an ICI-aware scheduler for unified NR/NB-IoT deployments, showing gains in resource allocation fairness. Although these studies demonstrate that LPWAN and NR can coexist at architectural and scheduling levels, most approaches rely on static configurations or interference mitigation. They do not provide true dynamic adaptation at the device or RAN level, nor do they explore persona-based reconfiguration using standardised 5G control-plane functions. Existing research generally treats RedCap as a static mid-tier device rather than an adaptive substrate capable of approximate the operational behaviours of NB-IoT, LTE-M, and [10].

This paper addresses this gap by introducing a Unified LPWAN-as-a-Service (ULaaS) framework that leverages RedCap as a universal substrate for scenario-driven adaptation. Within this architecture, a single RedCap device can transition between NB-IoT-like, LTE-M-like, and URLLC-inspired modes through over-the-air adjustment of RRC parameters, bandwidth parts (BWPs), and QoS profiles. This flexibility enables a single hardware platform to support ultra-low-power sensing, moderate-bandwidth mobility, and latency-sensitive control, thereby reducing the need for multiple chipsets or parallel network deployments.

The key contributions of this paper are summarised as follows:

- A scenario-adaptive RedCap architecture integrated with a ULaaS orchestration layer that provisions radio and core network templates via standard 5G functions.
- The design of three persona profiles-NB-IoT-like, LTEM-like, and URLLC-like-formalised as configurable RedCap

operating modes to address heterogeneous IoT requirements.
- A waveform-level evaluation assessing how adaptive RedCap profiles can approximate the latency, throughput, and energy-efficiency behaviour associated with legacy LPWAN.

The remainder of this paper is organized as follows: **Section II** details the ULaaS architecture and scenario-based configuration profiles. **Section III** outlines the simulation setup and evaluation method. Finally, concluding remarks are drawn in **Section IV**.

II. Proposed ULaaS Architecture

RedCap is well-suited to unify fragmented LPWAN systems, owing to its streamlined physical and MAC-layer design and compatibility with both standalone (SA) and non-standalone (NSA) 5G deployments [3]. It supports flexible numerology (15, 30, and 60 kHz subcarrier spacing), configurable BWPs, and advanced power saving features. Making it possible to approximate the behavior of NB IoT (deep coverage, long sleep), LTE M (moderate speed, mobility), and URLLC (low latency, high reliability) [5], [6].

A. *System Architecture*

The proposed ULaaS framework transforms RedCap into a configurable substrate capable of approximating the behaviour of traditional LPWAN's on a single chipset without hardware modification. As illustrated in Fig. 1, the ULaas defines a multi-layered control and management framework that enables adaptive operation of RedCap devices across heterogeneous 5G environments. It is composed of four main tiers as described below:

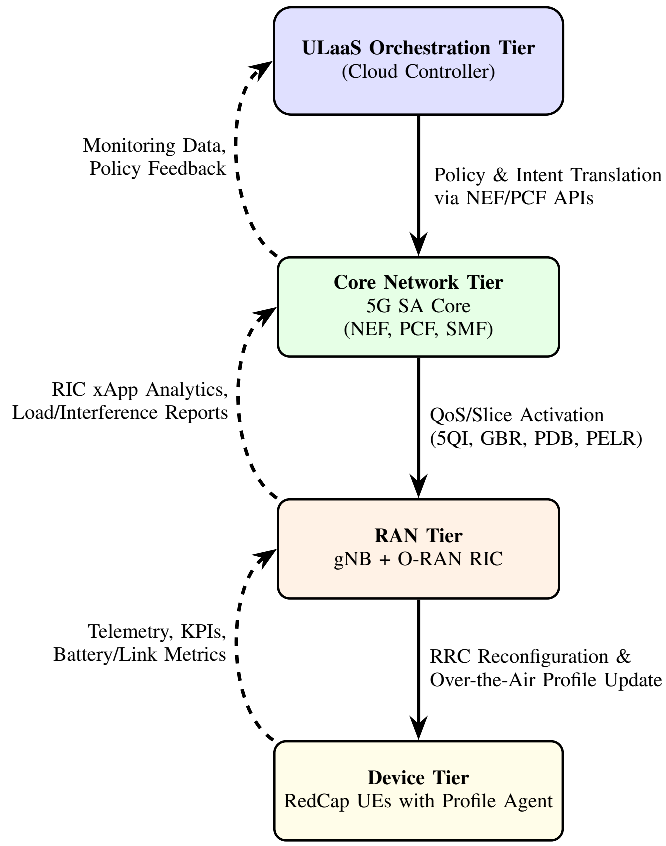

Fig. 1: ULaaS layered architecture showing control (solid) and feedback (dashed) flows between orchestration, core, RAN, and device tiers.

- **Device Tier (RedCap UEs):** This tier comprises RedCap user equipment (UEs) based on the 3GPP Release 17 NR protocol stack. Each device supports multiple subcarrier spacings (15, 30, and 60 kHz) and configurable BWPs ranging from 5 MHz to 20 MHz, providing flexibility to operate under varying network conditions and service classes. It employs standardised low-duty-cycle operation to extend device lifetime and optimise energy use. The firmware integrates a lightweight Profile Agent responsible for receiving over-the-air (OTA) configuration sets corresponding to the selected operational scenario. The agent applies control and QoS parameters received from the network to adjust modulation schemes, scheduling policies, and power states.
- **RAN Tier (gNB and RIC):** The RAN tier serves as the intermediate execution layer between orchestration commands and physical-layer operations. Each gNB maintains predefined RRC configuration templates for all ULaaS persona profiles-NB-IoT-like, LTE-M-like, and URLLC-like. These templates specify numerology, BWP size, scheduling strategy (configured-grant or dynamic), HARQ parameters, modulation and coding schemes, and power-saving timers. The RAN Intelligent Controller (RIC) continuously monitors radio performance indicators, interference levels, and traffic load, triggering near-real-time reconfiguration of RRC parameters when required. This ensures that RedCap devices can transition between personas seamlessly while maintaining service-level quality under varying channel or load conditions.
- **Core Network Tier (5G SA Core):** The 5G standalone core serves as the logical and policy-control hub of the ULaaS system. It provides service differentiation through network slicing and QoS flow management. The Policy Control Function (PCF) and Session Management Function (SMF) assign appropriate QoS parameters-5QI, Guaranteed Bit Rate (GBR), Packet Delay Budget (PDB), and Packet Error Loss Rate (PELR)-according to each persona's performance requirements. The Network Exposure Function (NEF) offers APIs that enable the ULaaS orchestrator to request profile activations, query session states, and retrieve network telemetry. Through these interfaces, orchestration actions can be propagated without modifying the operator's underlying 5G architecture, maintaining compatibility with existing SA deployments. This layer thus bridges the intent-driven orchestration logic and the underlying radio resource behaviour.
- **ULaaS Orchestration Tier (Cloud Controller):** At the

top of the hierarchy, the ULaaS orchestration tier operates as the cognitive control plane that interprets high-level application intents (e.g., smart meter, industrial sensor, wearable, or autonomous vehicle) and maps them to the corresponding RedCap persona profiles. Using standardised NEF and PCF interfaces, the orchestrator pushes configuration updates to the 5G core, which subsequently instructs the RAN to apply the associated RRC and QoS templates to relevant UEs. Beyond static configuration, the orchestrator supports feedback-driven adaptation. It aggregates telemetry from the RIC and NEF to evaluate latency, throughput, and energy-efficiency metrics in real time. These analytics allow dynamic re-selection of personas, ensuring optimal network performance and efficient resource utilisation across IoT, industrial, and vehicular domains.

Each ULaaS profile represents a logical template that aggregates RRC, RAN, and QoS parameters into a single configuration entity. These profiles define how a RedCap device adapts its operation to approximate specific LPWAN service classes under varying latency, throughput, and power constraints. The three baseline scenario profiles used in this study are summarised in Table I.

TABLE I: Scenario-Based Profiles

Profile ID	**Use Case**	**Key Target KPIs**	**Representative Configuration**
NB-IoT-like	Static sensors, smart meters	Latency $\leq$ 3 s, Power $\geq$ 10 years	SCS 15 kHz, BWP 5 MHz, 1×1 MIMO, 5QI 65
LTE-M-like	Wearables, asset tracking	Latency $\leq$ 200 ms, mobility support	SCS 30 kHz, BWP 10 MHz, 5QI 9
URLLC-like	V2X telemetry, industrial control	Latency $\leq$ 20-50 ms, Reliability $\geq$ 99.99 %	SCS 60 kHz, BWP 10 MHz, Configured-Grant UL, mini-slot (2-3 symbols), 5QI 84/85

B. Operational Workflow and Profile Management

The ULaas framework comprises a structured control process based on device onboarding, profile activation, radio configuration, and continuous adaptation as detailed below:

- **Device Onboarding:** Each RedCap UE communicates, via the 5G control plane, its supported capability set (e.g., `supportOfRedCap-r17`) during initial registration. Based on this information, along with the device metadata such as type, mobility class, and service intent, the ULaaS orchestrator assigns a unique Scenario Profile Identifier (SPID). The SPID ensures that the device's operational behavior aligns with the intended use case by associating it with a predefined ULaaS profile.
- **Profile Activation:** Once the SPID is assigned, the orchestrator sends a policy request to the 5G core via NEF. This ensures the synchronization between the intended service, the QoS policy, and the radio configuration. Upon receiving the request, the PCF associates the device IMSI with the selected profile and instructs the SMF to establish the appropriate QoS flow and slice identifier (S-NSSAI). Subsequently, the gNB loads the RRC configuration template corresponding to the SPID.
- **RAN Configuration:** The gNB then initiates the RRC configuration process and sends the relevant settings to the UE. These settings include BWP, subcarrier spacing (SCS), low-duty-cycle setting, and scheduling details. The RedCap device immediately applies these settings to complete the setup. At the same time, RIC monitors and manages configuration in near-real-time using xApps to ensure operational stability and policy compliance.
- **Steady-State Operation and Adaptation:** Once the RRC configuration is complete, the device continues to adhere to the active ULaaS profile until a trigger event is detected. The triggering event can be a mobility event, a low-energy state, or an application update. If there is a need of profile change, the orchestrator initiates a new policy request to 5G core using NEF and the same process repeats. Generally, profile transition takes between 200 and 300 ms, ensuring seamless switching among NB-IoT-like, LTE-M-like, and URLLC-like modes. This results in no session interruption or QoS violations.

C. Implementation Considerations

The proposed ULaaS framework is designed to operate over standardized 3GPP and O-RAN interfaces to ensure interoperability among heterogeneous network deployments. The framework leverages the existing service-based architecture (SBA) functions, specifically the NEF, PCF, and SMF, to integrate the core network. Though RAN parameters are adjusted via O-RAN E2 interface and associated control applications (xApps). The approach is primarily adopted to avoid the need for proprietary signaling extensions or vendor-specific APIs.

The ULaaS profiling templates can be implemented and shared using JSON/YANG data models that represent layer-specific configurations, including RRC parameters, QoS, and scheduling policies. These templates can be readily integrated into orchestration platforms to facilitate efficient deployment and customization across various verticals.

III. Performance Evaluation

The aim of this evaluation is to verify whether the proposed ULaaS framework based on RedCap can achieve the key performance indicators (KPIs) traditionally provided by discrete technologies such as NB-IoT, LTE-M, and URLLC, as defined in Section II. Furthermore, the evaluation will quantify the degree to which RedCap configuration parameters affect the trade-off between latency, throughput, and energy consumption.

This evaluation serves to validate the hypothesis that RedCap, when managed under the ULaaS orchestration framework, can function as a unified substrate for next-generation LPWAN services while operating within representative 3GPP performance regions.

A. Simulation Environment

The proposed ULaaS framework was evaluated using a MATLAB-based NR waveform-assisted simulation environment configured to approximate 5G RedCap operation under the scenario profiles defined in Table I. The simulation setup and key parameters are summarised below.

- **Software Platform:** MATLAB R2025a with the 5G Toolbox, Communications Toolbox, and WLAN/IoT extensions was used to generate, configure, and analyse RedCap and LPWAN-equivalent waveforms.
- **Waveform Configuration:** A single-cell 5G NR carrier operating at 3.5 GHz (FR1) was simulated using standard sub-carrier spacings and BWP allocations corresponding to the ULaaS persona profiles.
- **Channel Model:** A 3GPP TDL-C fading channel was employed with a 100 ns RMS delay spread and Doppler shifts up to 650 Hz to represent moderate vehicular and industrial mobility.
- **User Equipment (UE) Model:** Each RedCap UE was modelled using the MATLAB `nrWaveformGenerator` configuration parameters (`SCS`, `NumRBs`, `NumTxAntennas`, `DuplexMode`), with capability sets aligned to 3GPP Release 17 RedCap specifications.
- **gNB Model:** The base station was implemented using `nrCarrierConfig` and `nrDLCarrierWaveform` objects, together with a custom MATLAB scheduler supporting configured-grant uplink operation and DRX/eDRX cycles.
- **Traffic Generation:** Application-layer traffic was generated through deterministic packet streams using MATLAB's `timeseries` object, providing precise control of inter-packet intervals, payload size, and QoS attributes.
- **Simulation Duration:** Each scenario was executed for 100s of continuous operation to capture steady-state performance and long-term energy behaviour. Independent random seeds were applied for each run to ensure statistical robustness and reproducibility.

B. Simulation Results

Fig. 2 illustrates the autonomous persona transitions between different modes. The URLLC-like persona is activated during high-SNR regions (typically above 15 dB), supporting latency-critical and reliability-sensitive applications. When the SNR remains within a moderate range (5-15 dB), the LTE-M-like configuration becomes dominant, balancing throughput, mobility, and energy efficiency for mid-tier IoT and wearable applications. In contrast, during deep fading or coverage-limited intervals (below 0 dB), the orchestrator seamlessly reverts to the NB-IoT-like mode to sustain connectivity and extend device battery life.

The figure highlights the responsiveness of the ULaaS control plane, where profile transitions complete within approximately 200-300 ms. This ensures service continuity even during rapid channel variations. The observed persona switching confirms the intelligence of the ULaaS orchestration layer in mapping real-time SNR feedback and application policies, achieving unified and context-aware performance across heterogeneous IoT environments.

Latency differentiation across personas under varying network and channel conditions is shown in Fig. 3. The results clearly demonstrate that the ULaaS framework can achieve persona-dependent latency behaviour. The URLLC-like persona achieves low end-to-end latency in high SNR regions, confirming its suitability for time-sensitive use cases such as vehicular communication. As the system switches to a moderate SNR region, the LTE-M-like persona stabilizes the latency between 100-200 ms. In contrast, under low SNR, the NB-IoT-like persona achieves a latency of 2.5-3 seconds. Overall, the results clearly indicate that the ULaaS framework can dynamically achieve each persona's latency profile.

The power consumption trend across the different user personas is shown in Fig. 4, which verifies the ULaaS framework's ability to adaptively control power consumption based on the active user persona. In the URLLC-like scenario, power

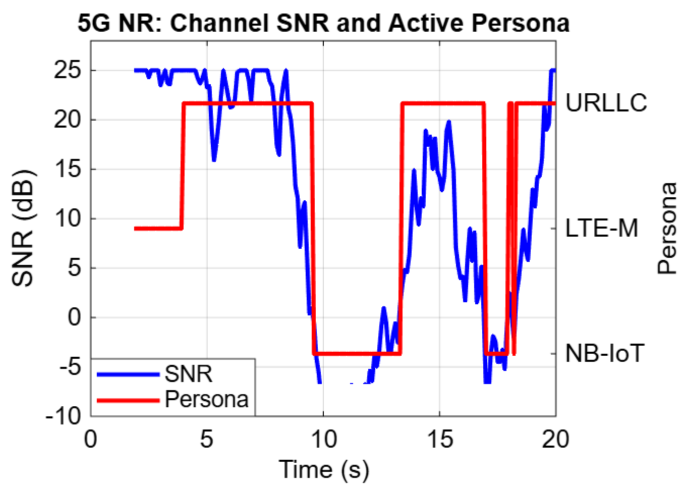

Fig. 2: Dynamic persona switching in ULaaS under varying SNR.

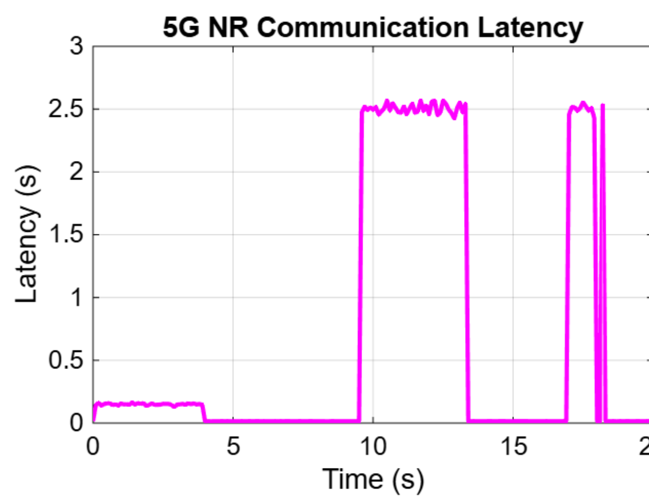

Fig. 3: Latency across ULaaS personas.

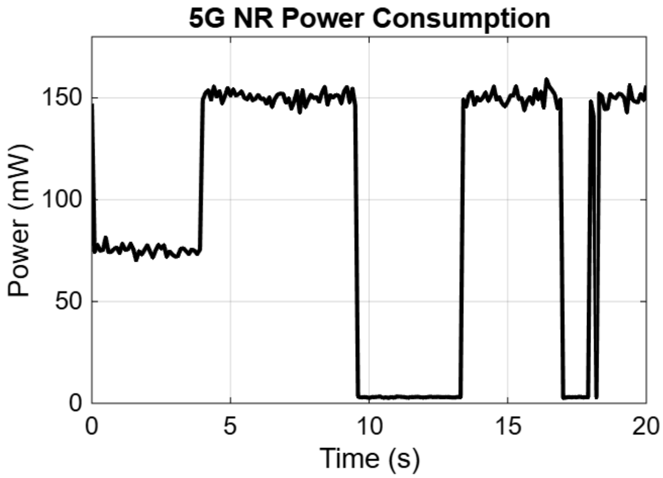

Fig. 4: Power consumption across ULaaS personas.

consumption remains high at 150 mW, as expected due to continuous radio activity and low-latency scheduling. As the system changes to the LTE-M-like communication scenario, average power consumption drops to 75-80mW, as moderate duty cycles and less stringent transmission settings come into practice. However, as SNR values drop further, the orchestrator transitions to an NB-IoT-like scenario, resulting in a drastic reduction in power consumption to below 10 mW, reflecting persona-dependent low-duty-cycle behaviour consistent with extended sleep operation. The analysis verifies the ULaaS framework's ability to achieve adaptive power scaling with preserved energy efficiency and service continuity.

Fig. 5 presents the throughput performance across ULaaS personas. The framework dynamically scales data rates based on the active persona to ensure optimal spectrum efficiency and service continuity in varying channel conditions. During the URLLC-like scenario, the throughput performance reaches a maximum value of approximately 0.12 Mbps. In the LTE-M like scenario, the throughput performance is maintained

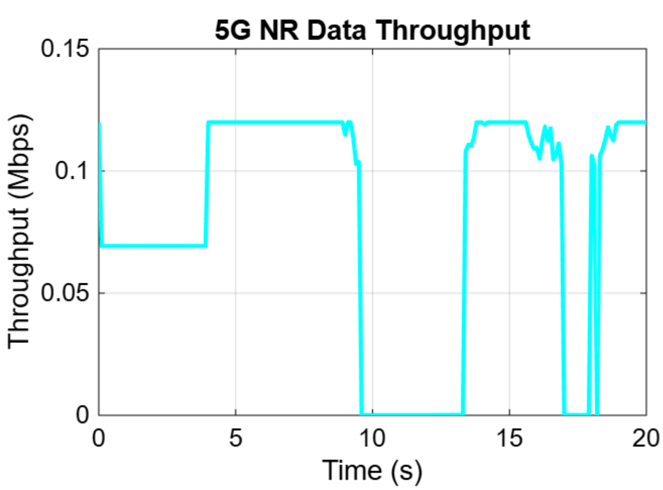

Fig. 5: Throughput performance across ULaaS personas.

between 0.08 Mbps and 0.10 Mbps. This is due to the trade-off between spectral efficiency and energy consumption. In contrast, the throughput performance for the NB-IoT-like user is below 150 kbps, consistent with sparse reporting and extended sleep behaviour.

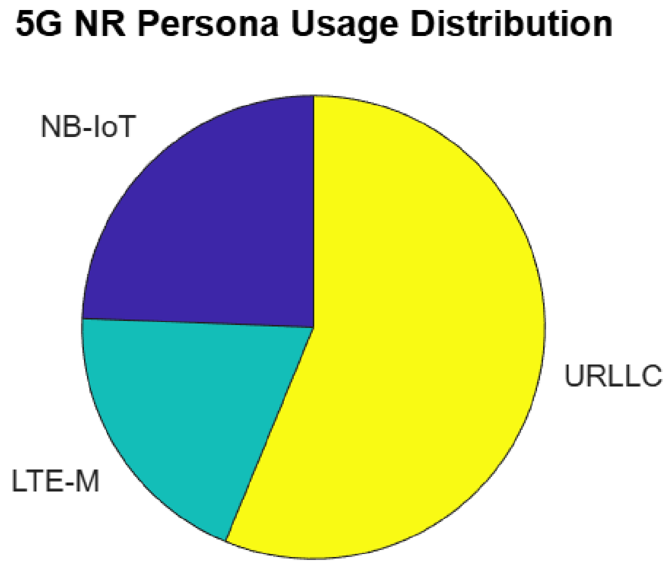

Fig. 6: Persona usage distribution during simulation.

Lastly, the distribution of persona utilization is shown in Fig. 5 based on the changing channel conditions. URLLC-Like is the most utilized mode, which is about 55%, and is used when the SNR is high or when there is a need to meet the latency requirement. The LTE-M-Like mode, which is about 20%, is used to meet the average throughput requirement, and the NB-IoT-Like mode, which is about 25%, is used to increase the coverage and battery life. This intelligent, context-aware switching validates ULaaS can efficiently support diverse IoT use cases on a unified platform.

IV. Conclusion

5G RedCap is a promising technology designed to bridge the gap between traditional LPWAN solutions and full 5G NR capabilities. However, its fixed operational parameters limit its flexibility in dynamic and heterogeneous IoT environments. This paper proposes a Unified LPWAN-as-a-Service (ULaaS) platform that enables dynamic, over-the-air reconfiguration of RedCap devices to support NB-IoT, LTE-M, and URLLC inspired operating modes. Simulation based evaluations show that the proposed platform enables low-latency communication, improved energy efficiency, and reliable connectivity while enabling seamless switching between different operating modes. Overall, ULaaS increases RedCap's adaptability to diverse IoT deployments, reduces hardware fragmentation, and provides a unified and sustainable approach to future 5G-enabled IoT networks.

Declaration

Generative AI and AI-assisted technologies: The author(s) used Grammarly to improve the language and readability. After using this tool, the work is thoroughly reviewed and edited as needed. Therefore, the author(s) take(s) full responsibility for the content of the publication.

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