Adroit-6G Proof-of-Concept 2a: Deterministic, Scalable and Energy-Efficient Extreme-mMTC for Industry 5.0 IIoT

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***Abstract*—The Proof of Concept 2a (PoC 2a) of Adroit-6G project demonstrates how terrestrial 6G technologies can sustain extreme massive Machine-Type Communication (mMTC) in industrial Internet-of-Things (IIoT) environments. Three user stories—Robot Operator, Production Manager and Integrator—frame the requirements for ultra-reliable low-latency control of mobile robots, AI-driven predictive analytics, and seamless multi-vendor integration. The validation campaign, executed in Testing Cycle 1, employs a 5G/6G-ready testbed equipped with closed-loop Management and Orchestration (M&O), Belief-Desire-Intention (BDIx) agents, and network-slice lifecycle tooling. Three progressively integrated test cases were performed: 1) Distributed Resource Discovery and Management BDIx agents autonomously discovered and managed edge and RAN resources across $>$ 2 UEs, sustaining 95 % service availability and $\geq$ 90 % resource-use efficiency during simulated node failures. 2) Closed-Loop Service Orchestration and Scalability Slice instantiation time was capped at $\leq$ 5 min while maintaining end-to-end latency $\leq$ 50 ms under loads emulating up to 10 edge nodes; more than 1 000 xApps/rApps could be supported without functional degradation. 3) End-to-End Integration Under Dynamic Load Combined BDIx and closed-loop orchestration preserved $\leq$ 50 ms latency, $\geq$ 95 % availability and $\geq$ 90 % resource utilization while achieving a $\geq$ 30 % energy-consumption reduction and offloading-decision latency $\leq$ 5 s. All interfaces—between BDIx agents, xApps/rApps, the near-real-time RIC, and core network components—were fully validated with no critical issues. Monitoring via Prometheus, Grafana and Wireshark confirmed stable operation and KPI compliance; any minor software-version mismatches were resolved during the campaign. The results substantiate that the ADROIT6G platform can meet Industry 5.0 demands by delivering deterministic, scalable and energy-efficient IIoT connectivity, thereby enabling real-time robot control, predictive maintenance, and flexible production orchestration over extreme-mMTC-capable 6G networks.**

***Index Terms*—Adroit-6G Proof-of-Concept 2a: Deterministic, Scalable and Energy-Efficient Extreme-mMTC for Industry 5.0 IIoT**

I. Introduction

Industry 5.0 envisions collaborative robots and dense sensor fabrics operating alongside humans on flexible manufacturing lines. Such environments require *deterministic* communications (bounded latency and jitter), *scalability* to extreme device densities (mMTC), and *energy efficiency* across RAN, edge, and device domains. PoC 2a of Adroit-6G addresses these challenges over a terrestrial 6G-ready testbed by combining closed-loop Management & Orchestration (M&O), O-RAN-compliant RIC with xApps/rApps, and BDIx agents running at the edge and on user equipment (UE). Three representative user roles—Robot Operator, Production Manager, and Integrator—drive the requirements for low-latency teleoperation, AI-driven predictive maintenance, and seamless multi-vendor integration, respectively.

Scope. This short paper reports Cycle-1 functional-block validation and partial end-to-end integration for PoC 2a. We summarise the architecture under test, the three test cases (TC1–TC3), and the resulting KPIs, providing a concise view of readiness for subsequent end-to-end demonstrations.

II. Related Work

Industry 5.0 research emphasises human–machine collaboration, sustainability, and resilience in manufacturing, driving the need for deterministic and energy-efficient communications in Industrial IoT (IIoT) [4, 7, 9]. Recent works propose human-centric architectures [4], design frameworks for smart manufacturing integrating IIoT, wearables, and edge computing [7], and systematic reviews of trustworthy AI for industrial automation [9]. On the networking side, edge-intelligence frameworks have emerged to support adaptive IIoT analytics and orchestration. Yang and Shami [3] proposed a multi-stage automated analytics pipeline for IIoT data streams, while Fraga-Lamas *et al.* [2] explored human-centred mist and edge computing for safety-critical Industry 5.0 environments. However, these works focus mainly on analytics or cloud-edge integration, lacking a unified control architecture capable of deterministic, scalable orchestration across RAN and edge layers.

In parallel, the rise of AI-native and agentic networks has introduced new paradigms for closed-loop orchestration and autonomy. Feriani and Hossain [1] surveyed single and multi-agent reinforcement learning for 6G control, paving the way for network-level intelligence. Building on this direction, *Symbiotic Agents* [10] combine LLM reasoning with optimisation algorithms for trustworthy AGI-driven networks. *MX-AI* [12] is an agentic observability and control platform for Open and AI-RAN, while *AGORAN* [11] extends this concept to an open marketplace for agent-based RAN automation. Marro *et al.* [6] proposed a scalable protocol for inter-agent communication among LLM networks. Other related works inlcude [14, 16, 15, 5, 13, 8]. Our work differs by implementing and validating a terrestrial 6G-ready testbed with BDIx agents and O-RAN-compliant closed-loop orchestration, demonstrating

TABLE I
CYCLE-1 KPI TARGETS PER TEST CASE

KPI	Target	Applies to
Service availability	$\geq 95\%$	TC1, TC3
Resource utilisation (RAN+edge)	$\geq 90\%$	TC1, TC3
Slice instantiation time	≤ 5 min	TC2
E2E latency under load	≤ 50 ms	TC2, TC3
Energy consumption reduction	$\geq 30\%$	TC3
Offloading decision latency	≤ 5 s	TC3
xApps/rApps scalability	> 10 apps	TC2

deterministic, scalable, and energy-efficient extreme-mMTC connectivity tailored to Industry 5.0 IIoT scenarios.

III. SYSTEM ARCHITECTURE

Fig. 1 situates the building blocks validated in PoC 2a: (i) AI-driven M&O including Closed-Loop Governance (CLG), Service/Slice Orchestration, and Resource Orchestration; (ii) BDIx-driven unified/open control (BDIx agents on UEs and UE-VBS component); and (iii) O-RAN near-RT RIC hosting slice control/monitoring xApps with policies from the Non-RT RIC/rApps. The testbed integrates KPI monitoring via Prometheus/Grafana and trace-level inspection with Wireshark.

Fig. 2 outlines the five-stage slice lifecycle executed by the Slice Monitoring & Lifecycle-Management xApp: *deploy* $\rightarrow$ *init* (RIC connection & SM instantiation) $\rightarrow$ *observe* (KPM) $\rightarrow$ *control* (policy push) $\rightarrow$ *finalise* (KPI harvest). This loop closes through the RIC to gNB while non-RT policies are injected by rApps.

IV. EVALUATION OF POC 2A

A. Methodology and KPIs

Cycle-1 experiments follow a bottom-up path: TC1 validates BDIx/UE-VBS foundations; TC2 validates closed-loop slice orchestration and scalability; TC3 composes both under dynamic load. KPIs and targets are summarised in Table I.

B. Test Case Summaries

TC1 — Distributed Resource Discovery & Management: BDIx agents are deployed on UEs; topology discovery and UE-VBS control are validated. Under emulated failures, service availability remains at 95% with $\geq 90\%$ resource utilisation across RAN and edge. *Outcome:* foundational communication & control layer validated.

TC2 — Closed-Loop Service Orchestration & Scalability: The slice monitoring/control xApp maintains ≤ 50 ms E2E latency while emulating up to 10 edge nodes; slice instantiation time is ≤ 5 min. The platform supports > 10 xApps/rApps without functional degradation. *Outcome:* closed-loop orchestration validated at scale.

TC3 — End-to-End Integration Under Dynamic Load: Combining BDIx and closed-loop orchestration preserves ≤ 50 ms latency, $\geq 95\%$ availability, and $\geq 90\%$ utilisation; energy consumption drops by $\geq 30\%$; offloading decisions complete within ≤ 5 s. *Outcome:* integrated system stability and efficiency under dynamic load.

TABLE II
CYCLE-1 VALIDATION OUTCOMES (SUMMARY)

Metric	Target	Observed
Availability (TC1/TC3)	$\geq 95\%$	95% (with failures)
Utilisation (TC1/TC3)	$\geq 90\%$	$\geq 90\%$
Latency (TC2/TC3)	≤ 50 ms	≤ 50 ms
Slice instantiation (TC2)	≤ 5 min	≤ 5 min
Energy reduction (TC3)	$\geq 30\%$	$\geq 30\%$
Offload decision (TC3)	≤ 5 s	≤ 5 s
xApps/rApps scale (TC2)	> 10	> 10 (no degradation)

C. Representative Traces

Fig. 3 depicts dynamic UE traffic patterns observed during closed-loop operation, illustrating stability of throughput/latency while policies change. Monitoring components (Prometheus, Grafana) captured KPI streams; Wireshark validated message-level exchanges.

D. Consolidated Results

Table II summarises Cycle-1 outcomes against targets.

V. CONCLUSION

PoC 2a demonstrates that terrestrial 6G technologies—when paired with closed-loop orchestration and BDIx-based device/edge intelligence—can sustain extreme mMTC in Industry 5.0 scenarios with deterministic latency and robust availability. Cycle-1 results validate the key functional blocks and their interfaces, confirm scalability to > 10 xApps/rApps, and show material energy savings under dynamic load. Future work will deliver full end-to-end user-story trials and broader KPI benchmarking.

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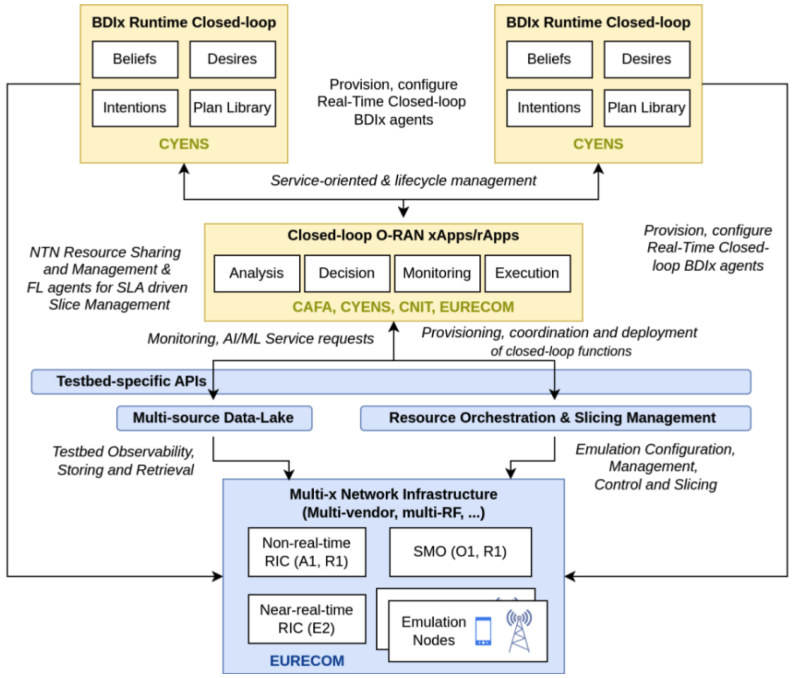

Fig. 1. PoC 2a functional blocks and control loop (illustrative).

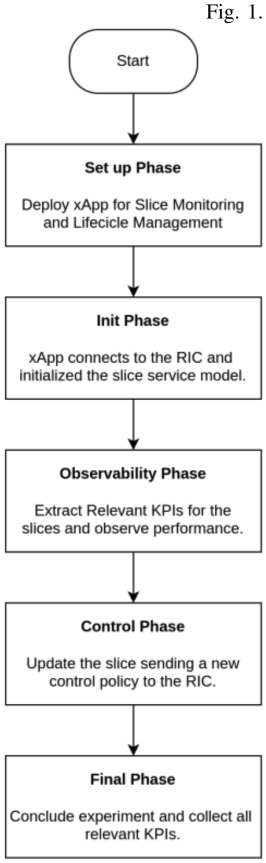

Fig. 2. Closed-loop slice lifecycle (TC2 flow).

Fig. 3. Representative closed-loop traces (TC3).

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