Toward Federated Cloud Continuum Infrastructures for Smart-City CPS

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***Abstract*—Smart-city applications are becoming distributed cyber-physical systems (CPS) whose behavior depends on sensing, actuation, computation, communication, and control across edge, fog, cloud, and high-performance computing resources. Yet experimentation environments remain fragmented: prototypes are often evaluated on isolated testbeds, ad-hoc deployments, or simplified emulations that are difficult to reproduce, compare, and reuse. This position paper argues that smart-city CPS research requires federated cloud continuum research infrastructures that make heterogeneity, observability, and experiment intent explicit scientific artefacts. Building on the SLICES Cloud Continuum Blueprint, we outline architectural principles for separating infrastructure capabilities from application logic, preserving realistic heterogeneity, and treating reproducibility as a lifecycle property.**

***Index Terms*—Smart cities, CPS, cloud continuum, edge–fog–cloud, reproducibility, research infrastructures, SLICES.**

I. Introduction

Urban challenges such as energy transition, mobility, and environmental monitoring increasingly depend on distributed ICT infrastructures spanning the city from sensor to cloud. Smart-city services are moving beyond centralized data platforms toward CPS organized across the cloud continuum [1], [2], requiring low-latency processing near physical processes, metropolitan aggregation, elastic cloud services, and sometimes HPC-based simulation.

This evolution changes how smart-city systems should be experimentally studied. A single-cluster prototype rarely captures timing, placement, heterogeneity, locality, and operational constraints, while direct experimentation in operational city infrastructure is difficult to repeat, compare, or share. The resulting gap weakens scientific validation and transferability.

This paper advances a position: future smart-city experimentation should rely on federated, programmable research infrastructures that provide reusable cloud continuum substrates. This need aligns with emerging European efforts on federated infrastructures for distributed systems and cloud continuum experimentation. The SLICES Cloud Continuum Blueprint is a promising basis because it emphasizes federation, heterogeneity, programmability, and reproducibility across edge, fog, cloud, network, and HPC.

II. Need for the Cloud Continuum

Modern smart-city applications combine physical proximity with global coordination. Edge nodes ingest sensor streams, enforce local control loops, and reduce data movement. Fog or metropolitan sites aggregate information across neighborhoods and host shared services. Cloud platforms support elastic storage, cross-domain analytics, and service integration, while HPC resources support large-scale simulation, optimization, and digital-twin workloads.

The distribution of computation across the continuum is often intrinsic to CPS semantics rather than a mere deployment optimization. Latency, locality, data ownership, physical interaction, resilience, and cross-domain coordination are part of the scientific problem itself. A centralized deployment can reproduce some application logic, but not the continuum conditions under which smart-city CPS operate.

Research infrastructures must therefore support controlled variation of placement, connectivity, resource capacity, and observability, enabling architectural questions about the continuum rather than only software deployment.

III. Fragmented Experimentation

Current experimental practice remains methodologically fragmented. Resources are heterogeneous and exposed through incompatible interfaces, making it difficult to compose edge devices, network facilities, cloud sites, and HPC resources within one experiment. Observability is usually local to each platform, with logs, metrics, traces, and physical measurements collected using different semantics and time bases. Experiment descriptions often capture deployment scripts but not topology, workload assumptions, timing constraints, control objectives, or provenance.

This fragmentation limits reproducibility because conditions that shape CPS behavior are rarely encoded as first-class scientific artefacts. A smart-city experiment may depend on sampling rates, network impairment, actuator timing, workload bursts, mobility, energy availability, or institutional data boundaries. As a result, findings are hard to compare, transfer, and generalize across infrastructures, domains, and deployment conditions.

IV. Architectural Principles

A cloud continuum research infrastructure for smart-city CPS should follow four principles.

Separate infrastructure and application layers. The infrastructure layer should describe resources, connectivity, monitoring, federation policies, and controllable impairments. The application layer should describe CPS logic, data flows, control policies, and workload behavior. This separation avoids

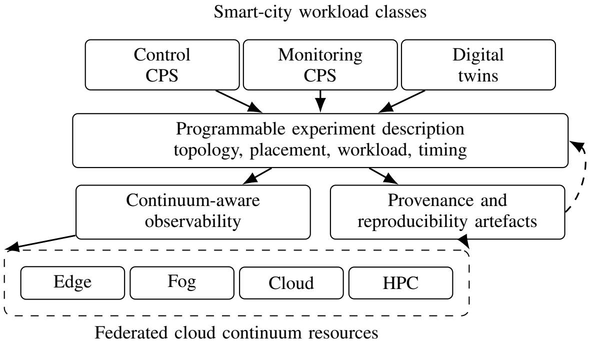

Fig. 1. Conceptual view: workload classes are encoded as experiment descriptions, executed over federated continuum resources, and linked back through observability and provenance.

encoding a single use case into the testbed and enables reuse across domains.

Make programmability reproducible. Programmability is not equivalent to deployment automation. A research infrastructure should expose experiment intent: topology, resource placement, timing assumptions, workload profiles, observability configuration, and termination conditions. Reproducibility then becomes a lifecycle property spanning reservation, configuration, execution, measurement, provenance, and archival [3].

Support federation without hiding heterogeneity. No single site can represent the full smart-city cloud continuum. Federation enables geographically distributed edge nodes, institutional cloud sites, network testbeds, and specialized computing facilities to be combined. The challenge is to provide repeatable abstractions without masking realistic heterogeneity behind oversimplified orchestration models.

Provide continuum-aware observability. Distributed CPS experimentation requires observability across computational and physical boundaries. Metrics should cover infrastructure state, application performance, network behavior, and domain-level CPS indicators. Time synchronization, provenance, and semantic consistency are central to explaining cross-layer effects.

V. SLICES as Research Infrastructure

The SLICES Cloud Continuum Blueprint is an enabling reference model for these principles [5]. SLICES is a European research infrastructure providing federated access to edge, wireless, cloud, and HPC facilities across multiple national sites.

For smart-city CPS research, this provides a middle ground between uncontrolled field deployments and oversimplified emulations. Researchers can instantiate controlled continuum configurations, vary placement and network conditions, collect comparable measurements, and reuse experiment descriptions while preserving realism.

VI. Representative Workload Classes

Representative workload classes illustrate the required capabilities without becoming case studies. *Control-oriented CPS workloads* involve feedback loops between physical processes and distributed computation. Renewable energy community management is a lightweight example: measurements, forecasts, optimization, and actuation may span gateways, fog nodes, cloud services, and simulation resources.

Monitoring-oriented CPS workloads focus on continuous sensing, aggregation, and interpretation of urban phenomena. Urban sensing pipelines may process environmental, mobility, or infrastructure data near the source before forwarding summaries to cloud services. Digital-twin workloads add a third class, linking live observations with simulation and optimization [4]. Across these classes, infrastructures should support reusable experiment patterns rather than domain-specific deployment pipelines. These classes collectively stress different subsets of the four principles: control workloads require timing and placement guarantees; monitoring workloads stress observability; digital twins demand HPC integration and provenance.

VII. Open Directions

Reproducibility under physical-world variability is central [3]. Smart-city CPS experiments cannot assume deterministic repetition: sensor noise, mobility, weather, energy availability, and institutional constraints may change between runs. Reproducibility models should capture controllable conditions, provenance, and uncertainty boundaries, not only software versions.

Further work is needed on intent-aware orchestration that lets researchers express placement, timing, resilience, and observability goals without binding experiments to low-level technologies. Continuum-aware observability must align infrastructure metrics, application traces, network conditions, and CPS indicators. Reusable workload profiles are needed for comparison without rigid benchmarks, while federation requires governance for identity, policy, data protection, resource accounting, and cross-site responsibility.

VIII. Conclusion

Smart-city CPS research increasingly depends on infrastructures spanning edge, fog, cloud, and HPC resources, yet current experimentation environments are fragmented and difficult to reproduce. This paper positions federated cloud continuum research infrastructures, inspired by the SLICES Blueprint, as reusable substrates for CPS experimentation. The central challenge is not deploying applications across resources, but turning experiment descriptions, observability data, provenance, and deployment intent into reusable experimentation knowledge.

References

[1] F. Bonomi *et al.*, "Fog computing and its role in the Internet of Things," in *Proc. MCC*, 2012.
[2] A. Maia *et al.*, "Computing, caching, and communication in the cloud-to-edge continuum," *Comput. Commun.*, 2024.
[3] National Academies, *Reproducibility and Replicability in Science*, 2019.
[4] D. Li *et al.*, "Smart city based on digital twins," *Comput. Urban Sci.*, 2021.
[5] A. Sabbioni *et al.*, "The SLICES Cloud Continuum Blueprint," in *Proc. IFIP Networking*, 2025.