GIS-Assisted Multi-Vendor Cellular Service Isolation for Emergency and Security Scenarios

Yasser Almofaalani
Higher Institute for Applied Sciences and Technology (HIAST), Syria
Email: yasser.almofaalani@hiast.edu.sy

Mustapha Dakkak (Supervisor)
Higher Institute for Applied Sciences and Technology (HIAST), Syria
Email: Mustapha.dakkak@hiast.edu.sy

Kadan Aljoumaa (Supervisor)
Syrian Private University (SPU), Syria
Email: kadan.aljoumaa@spu.edu.sy

Abstract

This paper presents a Geographic Information System (GIS)-assisted multi-vendor orchestration framework for geographically targeted cellular service isolation in authorized emergency and security scenarios. Unlike conventional radiofrequency (RF) jamming approaches, the proposed framework performs network-side Service Isolation through coordinated core-network reconfiguration procedures while preserving pilot and broadcast signaling.

The proposed methodology combines GIS-based spatial analysis, cellular coverage prediction, and multi-Radio Access Technology (multi-RAT) orchestration to identify cells intersecting a predefined geographic target zone. Affected cells are subsequently separated according to their corresponding radio access technologies (2G, 3G, and 4G), and temporary service isolation is performed through RAT-specific core-network reconfiguration procedures.

The framework was evaluated and validated through a Real-Network Field Deployment and Evaluation environment constructed from real operational cellular infrastructure datasets obtained from the two major Syrian mobile network operators, MTN Syria and Syriatel. The evaluation was performed on their live core servers, network management systems, and actual transmission lines. Field tests were conducted across seven Syrian governorates, where on-ground technical teams verified both the signal isolation accuracy inside the targeted zones and the safety of communications in surrounding non-targeted areas. The deployment environment incorporated actual multi-RAT site distributions, coverage footprints, and operational radio-planning parameters using Atoll and mPlanet planning platforms combined with an operational control-plane execution environment.

Experimental results demonstrate high isolation effectiveness with service restoration times ranging between approximately 3 and 10 minutes depending on the radio access technology and associated core-network recovery procedures. The results further show that spatial isolation precision strongly depends on cellular density and macro-cell footprint size. While the framework remains operationally effective in rural and low-density environments, larger macro-cell coverage areas may increase unintended Service Isolation outside the intended target polygon.

The proposed framework provides a reversible, auditable, and operationally practical alternative to conventional RF jamming while highlighting important spatial and operational considerations for geographically targeted cellular service control.

The proposed framework was evaluated using real operational datasets collected from MTN Syria and Syriatel, comprising approximately 79,268 multi-RAT cellular records distributed across urban and rural deployment environments.

Keywords: Geographic Information Systems (GIS), Adaptive Service Isolation, Network Service Isolation, multi-vendor Orchestration, Key Performance Indicators (KPI) Validation, Emergency Communications, Radio Access Network (RAN) Reconfiguration.

1. Introduction

Cellular communication networks are critical for modern national infrastructure, supporting emergency coordination and public safety. In authorized security scenarios, authorities may require temporary, geographically targeted restriction of communication services. Conventional service denial relies on radiofrequency (RF) jamming, which introduces regulatory conflicts, high detectability, and uncontrolled collateral signal leakage beyond the target perimeter [1], [6]. Consequently, research has shifted to network-side service isolation mechanisms that selectively block bearer and session establishment while preserving pilot and broadcast signaling [2], [4]. User equipment (UE) remains attached and synchronized without generating detectable electromagnetic interference.

In parallel, reinforcement learning (RL), Software-Defined Networking (SDN), and AI-driven optimization have been investigated for adaptive radio resource management and handover blocking [5], [10], [11]. Industrial radio-planning tools like Atoll and mPlanet provide management capabilities in heterogeneous environments [7], [8]. However, existing solutions remain vendor-specific, isolated, or lack integration with Geographic Information System (GIS) platforms for precise spatial targeting. Recent 3GPP specifications highlight this need for programmable multi-vendor control in next-generation heterogeneous cellular infrastructures [12], [13].

Research Gap and Contributions

Current academic literature indicates that existing studies do not provide a unified framework that combines GIS-assisted spatial analytics, multi-vendor orchestration, reversible service isolation, and KPI-aware operational rollback within heterogeneous cellular infrastructures. In particular, limited attention has been given to the problem of geographically bound and auditable service isolation across multi-Radio Access Technology (multi-RAT) environments while minimizing unintended service disruption outside the target area.

To address this gap, this paper proposes a GIS-assisted multi-vendor orchestration framework for adaptive cellular Service Isolation in emergency and security scenarios. The proposed framework combines spatial analysis, coverage prediction, vendor abstraction, and network-side orchestration to perform reversible service isolation within geographically defined 2G, 3G, and 4G environments.

The main contributions of this work are summarized as follows:

1. A novel coverage-preserving cellular service isolation mechanism that temporarily removes cell definitions from the core network instead of shutting down radio cells. Unlike conventional power-shutdown approaches, the proposed mechanism maintains radio coverage together with pilot and broadcast signaling while preventing communication service establishment within the target area. Consequently, neighboring cells do not expand their coverage into the isolated region, significantly reducing unintended service spillover.

2. A GIS-assisted spatial selection framework that accurately identifies the cellular sectors requiring service isolation by performing spatial intersection between a user-defined target polygon and predicted cellular coverage polygons. This enables precise, geographically bounded, and infrastructure-aware service isolation while minimizing unnecessary operational impact outside the target area.
3. A multi-vendor orchestration framework supporting heterogeneous Huawei and Ericsson cellular infrastructures through a unified orchestration architecture that automatically generates vendor- and RAT-specific operational procedures for 2G, 3G, and 4G networks.
4. A reversible network-side orchestration mechanism incorporating continuous KPI monitoring, automated rollback procedures, and controlled service restoration, ensuring operational stability, auditability, and rapid recovery following temporary service isolation.
5. A comprehensive real-network field validation conducted on operational cellular infrastructures of the two major Syrian mobile network operators. The proposed framework is evaluated through extensive field experiments considering isolation accuracy, spillover behavior, restoration latency, orchestration reliability, handover suppression efficiency, and deployment performance across heterogeneous urban, suburban, and rural environments.

The remainder of this paper is organized as follows. Section 2 reviews related work on RF jamming, network-side service isolation, and AI-assisted cellular control. Section 3 presents the proposed coverage-preserving service isolation framework and GIS-assisted multi-vendor orchestration methodology. Section 4 describes the real-network field deployment, experimental setup, and evaluation methodology. Section 5 presents the experimental results and performance analysis. Section 6 discusses the implications, limitations, and practical considerations of the proposed framework. Finally, Section 7 concludes the paper and outlines future research directions.

2. Related Work

Research on cellular coverage shaping and selective service denial is multidisciplinary, covering methods from network-side softwarization and AI-driven optimization to physical-layer attacks. To put this work's contribution in perspective, this section examines these domains.

- **Physical-Layer Jamming and Its Limitations**

  The most direct approach to service denial operates at the physical layer. Extensive research was conducted, including testbed studies by Stegmann et al. [6], which assessed how efficient targeted jamming attacks are, such as smart PRACH jamming, to disrupt access procedures in 4G/5G systems. According to the surveys done by Hassan et al. [1], while effective, these methods are easily detected through spectrum analysis and cause widespread unintended disruption, breaching regulations and hindering emergency communications. These significant drawbacks have driven research into nonintrusive, network side alternatives.

- **Software-Defined Network Control for Coverage Shaping**

  Advances in SDN and NFV have allowed for more precise control over network behavior. Subsequent research has focused on software-level coverage shaping, which includes programmable cell boundaries and session-level blocking. For instance, Xu et al. [2] and Hu et al. [4] have shown the practicality of creating "service illusions" in which pilot signals are preserved while data sessions are blocked. However, these proposals are often assessed in limited, vendor-specific environments [7, 8] and lack a robust integration with geospatial systems for precise, GIS-driven spatial targeting, limiting their operational practicality in heterogeneous networks.

- **AI and Reinforcement Learning for Network Optimization**

Other than static control, Reinforcement Learning (RL) has become prominent as a powerful tool for dynamic radio resource management. Studies have demonstrated the potential of RL for closed-loop automation through applying it to tasks such as handover optimization [5], parameter tuning, and load balancing [10], [11]. The possibility of creating adaptive secure zones is demonstrated by recent work, such as Zhang et al's RL-based handover blocking [5]. AI is also being used by industry initiatives for automated cell-outage compensation [9]. Although these methods set the stage for intelligent orchestration, it is still unclear how exactly they can be applied to the issue of coordinated, multi-vendor service isolation with guaranteed reversibility.

- **Industrial Tools and Operational Frameworks**

  Network reconfiguration in operational environments requires appropriate management tooling. Platforms such as Atoll [7] and mPlanet [8], together with Element Management System (EMS) and Operations Support System (OSS) modules, provide the interfaces needed to deploy configuration scripts in an auditable manner. Any viable operational framework must therefore build on these existing management infrastructures.

In conclusion, despite progress in software-defined coverage shaping [2, 4], outage compensation [9], RL-based control [5, 10], and smart jamming [1, 6], none of these works addresses the problem in full. No existing solution brings together GIS-based spatial targeting and a vendor-neutral orchestration layer that works across heterogeneous infrastructures. This paper fills that gap by combining these strands into a single system and validating it through Real-Network Field Deployment and KPI-based evaluation.

3. Coverage-Preserving Service Isolation Algorithm

Unlike conventional approaches that disable entire base stations or switch off radio transmitters, the proposed framework preserves radio coverage while selectively disabling communication services through temporary removal of the corresponding cell definitions from the core network. Consequently, user equipment remains attached to the strongest serving cell, preventing neighboring cells from expanding their coverage into the protected area and significantly reducing unintended spillover

3.1 System Architecture

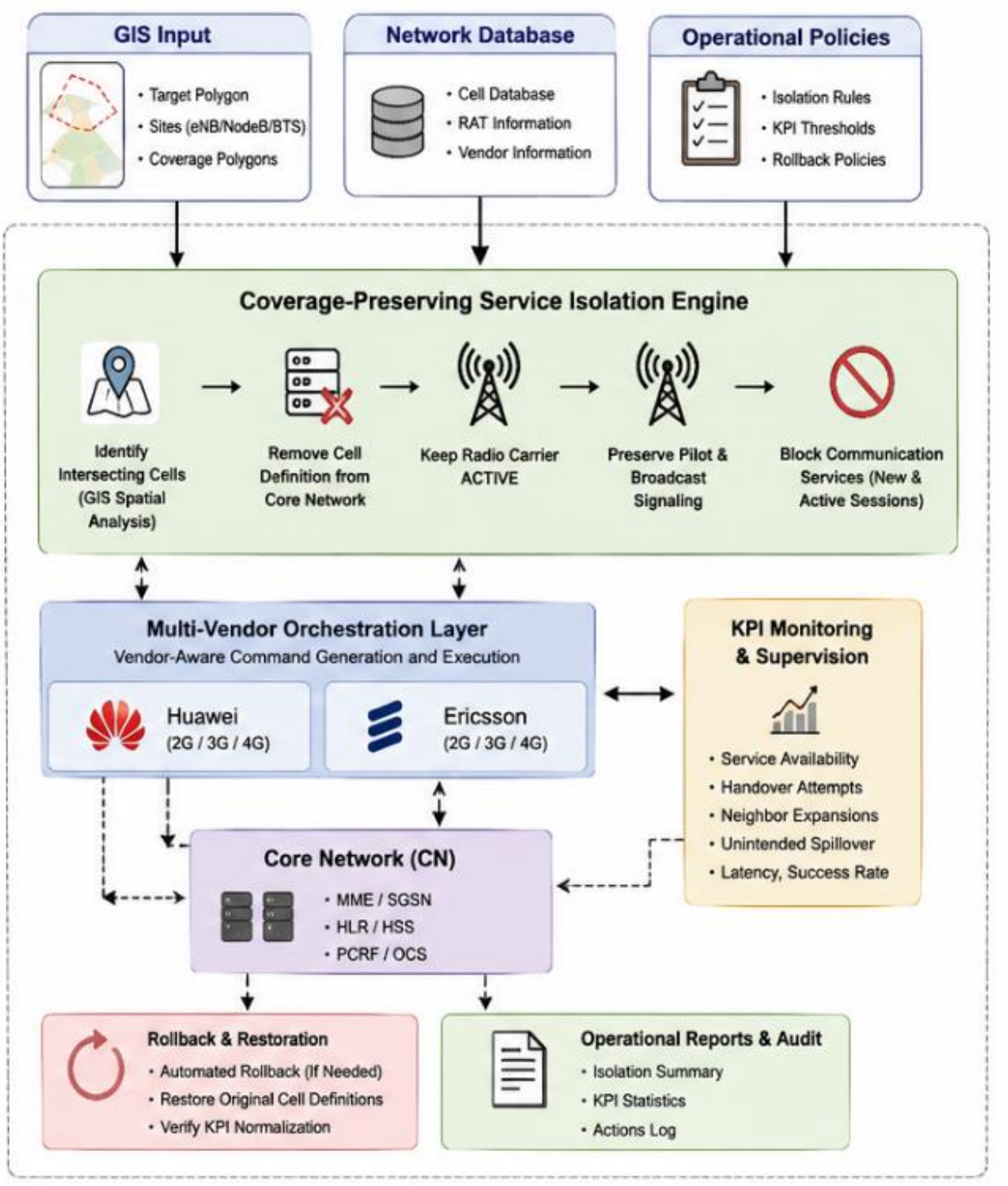


Fig. 1. Overall architecture of the proposed GIS-assisted multi-vendor cellular Service Isolation framework.

The previous figure shows the overall architecture of the proposed GIS-assisted multi-vendor framework for geographically targeted cellular service isolation. The architectural cycle operates through six interconnected functional layers that coordinate data and control flows dynamically:

1. **GIS Spatial Layer (Layer 1):** Responsible for processing spatial datasets and administrative boundaries using Geographic Information System (GIS) tools to generate precise queries and analysis of target areas, exporting them in GeoJSON format.

2. **Coverage Prediction & Cell Extraction Engine (Layer 2):** Simulates and models radio propagation, computing path loss using planning tools like Atoll and mPlanet to produce coverage maps and extract tower cells intersecting geographically with the target, while estimating signal overlaps and boundary spillovers.

3. **Multi-Vendor Abstraction Layer (Layer 3):** Serves as an intermediate layer to unify and abstract commands into standardized data models compatible with various vendor environments (Huawei, Ericsson) through dedicated adapters, ensuring system scalability.

4. **Orchestration Engine (Layer 4):** Acts as the system's brain, managing policies, generating effective isolation strategies, and coordinating parallel command sequences for Service Isolation, access control, and handover suppression.

5. **RAN / Core Network Reconfiguration Layer (Layer 5):** Applies operational commands on physical/logical infrastructure, reconfiguring radio access network nodes (2G, 3G, 4G) and updating core network gateway parameters and registers (HSS, HLR, MSC, EPC) to restrict target services.

6. **KPI Monitoring & Rollback Module (Layer 6):** Continuously monitors network performance indicators, isolation accuracy, and anomaly detection. It possesses self-triggered rollback capabilities to revert to original network configurations if any anomalies occur, backed by logging and reporting systems feeding the Operator Interface for full human supervision.

3.2 GIS-Assisted Zone Definition.

Isolation zones are defined as geospatial polygons and stored in ArcGIS, QGIS, and PostGIS-enabled spatial databases. A zone may correspond to a critical infrastructure facility, emergency operation area, public-event perimeter, or dynamically generated security boundary, and can be drawn manually by operators or derived from external operational inputs. The framework accepts KML, SHP, and GeoJSON formats for interoperability with radio planning and management systems. Spatial intersection is then computed between the defined polygon and predicted cellular coverage footprints from radio planning tools. Coverage prediction layers include Reference Signal Received Power (RSRP), antenna-sector projections, and propagation-based coverage polygons for 2G, 3G, and 4G radio access technologies.

To quantify the spatial relationship between a cell footprint and the target isolation zone, an overlap ratio is computed for each candidate cell as follows:

$$\text{Overlap Ratio}_i = \frac{\text{Area}(\text{Cell}_i \cap \text{Target Zone})}{\text{Area}(\text{Cell}_i)}$$

where (Cell_i) represents the predicted coverage footprint of the (i)-th cell and (Target Zone) denotes the authorized isolation polygon.

Cells intersecting the target polygon are extracted and grouped according to their associated radio access technologies. The resulting cell groups are subsequently forwarded to the orchestration layer for RAT-

specific service isolation procedures. To estimate unintended outage propagation beyond the authorized polygon, the framework computes a spillover ratio defined as:

$$\text{Spillover Ratio} = \frac{\text{Outage Area Outside Target Polygon}}{\text{Total Restricted Coverage Area}} \times 100$$

This metric provides a quantitative assessment of spatial confinement precision and is particularly important in low-density deployments where macro-cell footprints may extend significantly beyond the target area boundaries.

PostGIS spatial SQL functions (covering polygon intersection, topology validation, area computation, and coverage-overlay analysis) are applied throughout. The outputs are normalized and fed into the orchestration workflow for service isolation and restoration.

3.3 Coverage-Preserving GIS-Assisted Cellular Service Isolation

Unlike conventional cellular isolation approaches that disable radio transmitters or power off entire base stations, the proposed framework performs coverage-preserving service isolation by temporarily removing the corresponding cell definitions from the core network while leaving the radio carrier operational. Consequently, user equipment remains attached to the strongest serving cell because pilot and broadcast signaling are preserved, whereas communication services cannot be established inside the target area. GIS-based spatial analysis is employed only to accurately determine the cells intersecting the user-defined target polygon, after which vendor-specific orchestration commands are automatically generated and executed.

Algorithm 1 Coverage-Preserving GIS-Assisted Cellular Service Isolation

Input:

P ← User-defined target polygon

CP ← Cellular coverage polygons

CD ← Cellular database (cell IDs, RAT, vendor)

CN ← Core network management interface

Output:

Temporarily isolated target area

Restoration report

CandidateCells ← SpatialIntersect(P, CP)

for each Cell ∈ CandidateCells do

    Retrieve Cell ID, RAT, Vendor

    Generate vendor-specific orchestration command

    Remove Cell Definition from Core Network

    Keep Radio Carrier ACTIVE

    Preserve Pilot and Broadcast Signaling

    Reject New Service Establishment

9: Block Active Communication Sessions

10: end for

11: Monitor KPIs and Neighbor Cell Behaviour

12: if Excessive Spillover OR Operational Failure detected then

13: Execute Rollback Procedure

14: end if

15: Restore Original Cell Definitions

16: Verify KPI Normalization

17: Generate Operational Report

Although the proposed workflow may appear similar to conventional network-side Service Isolation techniques, its underlying operational principle is fundamentally different. Traditional approaches typically disable radio cells by shutting down transmitters or entire base stations, whereas the proposed framework preserves radio coverage by temporarily removing cell definitions from the core network while maintaining radio carrier operation and broadcast signaling. Figure 2 illustrates the conceptual difference between the two approaches and highlights how the proposed mechanism prevents unintended coverage expansion and service spillover.

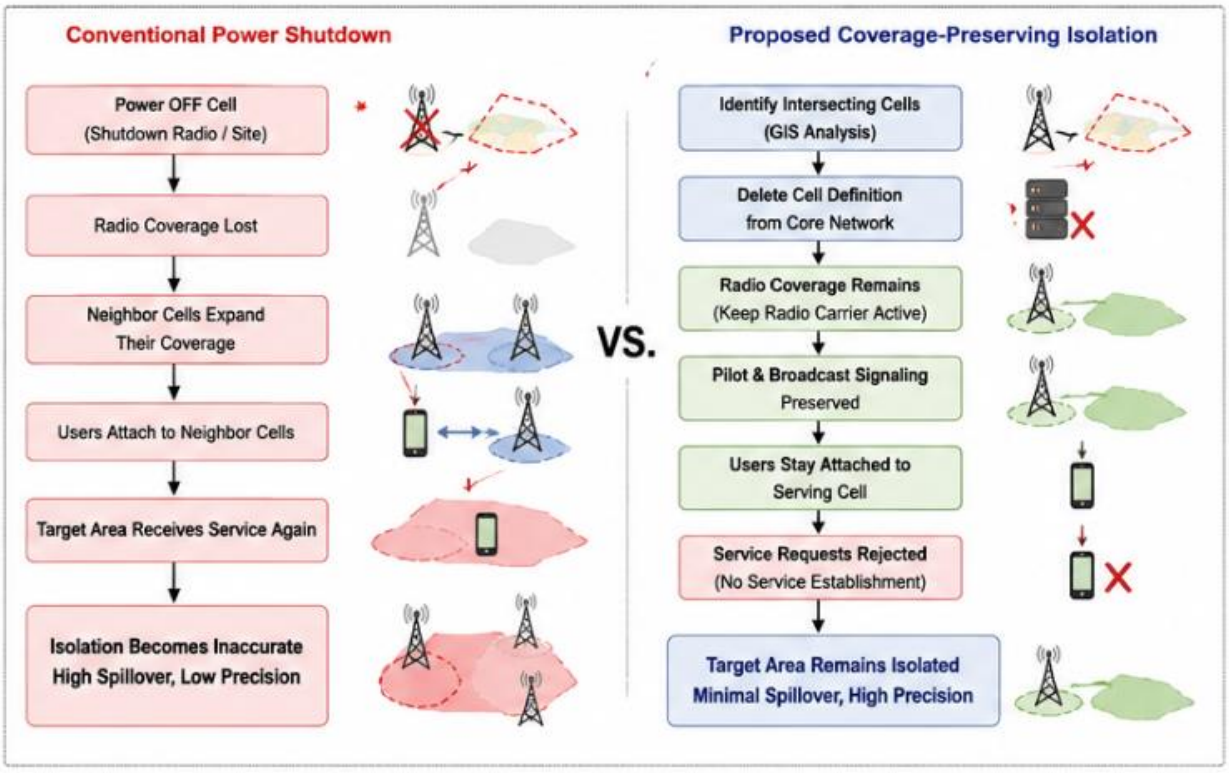


Fig. 2. Comparison between Conventional Power Shutdown and the Proposed Coverage-Preserving Service Isolation Mechanism.

As illustrated in Figure 2, conventional power-shutdown approaches remove both radio coverage and communication services. Consequently, neighboring cells expand their coverage footprints, allowing user equipment to reconnect through adjacent cells and reducing the geographical accuracy of the isolation process. In contrast, the proposed framework preserves radio coverage by maintaining the radio carrier together with pilot and broadcast signaling while disabling communication services through temporary removal of the corresponding cell definitions from the core network. As a result, user equipment remains attached to the strongest serving cell but cannot establish communication services, thereby minimizing spillover and achieving precise geographically bounded service isolation

The proposed framework therefore separates radio coverage availability from communication service availability, allowing geographically precise service isolation without introducing the coverage expansion effects that characterize conventional power-shutdown techniques.

The extraction ratio quantifies the affected cells:

$$\text{Extraction Ratio} = \frac{N_{\text{intersecting cells}}}{N_{\text{total cells in region}}} \times 100$$

Where ($N_{\text{intersecting cells}}$) represents the number of cells whose coverage footprints intersect the target polygon and ($N_{\text{total cells in region}}$) denotes the total number of operational cells within the evaluated geographical area.

After extraction, cells are separated according to their associated radio access technologies because Service Isolation and restoration procedures differ across 2G, 3G, and 4G infrastructures. Each technology requires distinct core-network entities, signaling procedures, and synchronization mechanisms during temporary service isolation and subsequent recovery.

For 2G environments, the workflow interacts primarily with Base Station Controller (BSC) and Mobile Switching Center (MSC) service definitions. In 3G deployments, orchestration procedures involve Radio Network Controller (RNC) coordination and associated core-network service mappings. In 4G infrastructures, the framework interacts with Evolved Packet Core (EPC) components and LTE-specific service configuration procedures.

The operational workflow was designed according to real multi-vendor cellular-network operational procedures implemented within heterogeneous Huawei and Ericsson infrastructures. Following spatial extraction and technology classification, the framework generates technology-specific operational datasets containing affected sector identifiers, radio access technology mappings, and associated operational isolation procedures.

The orchestration layer exports technology-specific operational datasets that are executed through vendor-supported network management systems.

The framework supports multiple service-restriction modes including voice, messaging, packet-data, session, and mobility control depending on the RAT and vendor implementation.

Multiple operational validation sessions were conducted with authorized operator teams to verify orchestration consistency and restoration procedures across heterogeneous infrastructures.

Table 1. Simplified Multi-Vendor Service Isolation Procedures

Radio Access Technology	Vendor Infrastructure	Service Isolation Scenario	Operational Procedure

2G	Huawei	Voice/SMS restriction	MSC service deregistration
2G	Huawei	GPRS/EDGE restriction	Packet-service suppression
2G	Ericsson	Voice/SMS restriction	Core Service Isolation
2G	Ericsson	Packet-data restriction	Access limitation procedures
3G	Huawei	Voice- Service Isolation	CS service limitation
3G	Huawei	Packet-data restriction	PS service limitation
3G	Ericsson	Packet-data restriction	Access barring procedures
3G	Ericsson	Voice/SMS restriction	Core Service Isolation
4G	Huawei	LTE data restriction	EPC access filtering
4G	Ericsson	LTE data restriction	Core-network Access Control List (ACL) restriction filtering
Multi-RAT	Huawei/Ericsson	Ongoing session interruption	Temporary bearer/session suppression
Multi-RAT	Huawei/Ericsson	Restoration procedure	Controlled service reactivation

To illustrate how service isolation is carried out in practice across heterogeneous environments, we detail the core network and radio access network (RAN) configuration commands utilized for Huawei and Ericsson infrastructures.

2G Service Isolation Implementation

For 2G networks, the isolation of voice and SMS services is achieved by removing the Location Area Global Cell Identity (GCI) definition at the Mobile Switching Center (MSC). This prevents the user equipment (UE) from completing location updates or registering CS services, while the cell itself remains active with pilot/broadcast signaling:

- **Huawei & Ericsson CS Restriction (MSC level):** RMV LAIGCI: GCI="417020463CBB7", MSCN="96394107000"; {MSSDMYC1_MSOFTX} Packet data (GPRS/EDGE) is blocked at the Base Station Controller (BSC) level
- **Huawei PS Restriction:** BLK PTPBVC: NSEI=1006, BVCI=663,FORCEEXECUTE=YES; {HBSCXXXX}
- **Ericsson PS Restriction:** rlgse:cell=XXX; Ongoing voice and data sessions are immediately released by deactivating and reactivating the cell sector
- **Huawei Cell Reset:** DEA GCELL: CELLID=xxxxx; followed by ACT GCELL: CELLID=xxxxx; Mobility and incoming handovers from neighboring cells into the target zone are restricted via the maximum Timing Advance (TA) drop parameters:
- **Huawei Incoming Handover Block:** GCELLCCAD:IDTYPE=BYNAME,CELLNAME="Test_A_DAM002",MAXTADROPCALLSWITCH=ON,MAXTADROPCALLFILTER=1,MAXTADROPCALLTHRESHOLD=0;

- **Ericsson Incoming Handover Block:** RLLDC:cell=CellcodeXXX,MAXTA=0; and RLLUC:cell=CellCodeXXX,TALIM=0;

3G Service Isolation Implementation

For 3G (UMTS) Huawei cells, selective blocking is controlled at the Radio Network Controller (RNC) level using the cell algorithm enhancement parameter CellCoAlgoEnhSwitch within the MOD UCELLCOALGOENHPARA command:

1. **Scenario 1 (Block all CS and PS services):** MOD UCELLCOALGOENHPARA: CellId="xxxx", CellCoAlgoEnhSwitch=ALL_SERVICE_LIMIT_SWITCH-1;
2. **Scenario 2 (Block voice/CS services only):** MOD UCELLCOALGOENHPARA: CellId="xxxx", CellCoAlgoEnhSwitch=CS_SERVICE_LIMIT_SWITCH-1;
3. **Scenario 3 (Block internet/PS data only):** MOD UCELLCOALGOENHPARA: CellId="xxxx", CellCoAlgoEnhSwitch=PS_SERVICE_LIMIT_SWITCH-1; For voice/SMS restriction, the RMV LAIGCI command is also executed at the MSC level. Active sessions are dropped using cell deactivation/activation

- **Huawei 3G Cell Reset:** DEA UCELL: CELLID=xxxxx; followed by ACT UCELL: CELLID=xxxxx; For 3G Ericsson cells, packet data is barred by modifying the Access Class Barring parameters for Packet-Switched services
- **Ericsson 3G PS Barring:** Set autoAcbEnabled from 1 to 0 and bar PS access classes: lset utrancell=XXXXXX accessClassesBarredPs from 0 to 1

4G Service Isolation Implementation

In 4G (Long-Term Evolution (LTE)) networks, where voice and data are fully packet-switched, isolation is implemented at the Core Network (Evolved Packet Core - EPC) level. The orchestration layer injects advanced Access Control List (ACL) rules at the firewall/gateway interfaces mapped to the specific eNodeB's IP address. This blocks both Up Link and Down Link user-plane and control-plane traffic, preventing any bearer set up or session maintenance for that sector:

- **eNodeB IP Example: 10.131.147.4 (eNodeB Code: HMS008L, ID: 404008)**
- **Up Link Block Command:** ADD ACLRULEADV4:ACLNAME="Deny_4G",ACLRULENAME="HMS008L_UP",ACLRULEID=4040081,ACLACTION=Deny,ACLSOURCEIP="10.131.147.4",ACLSRCWILD="0.0.0.0",VRFNAME="VRF_PS_Access",ACLPROTOCOL=0;
- **Down Link Block Command:** ADD ACLRULEADV4:ACLNAME="Deny_4G",ACLRULENAME="HMS008L_DN",ACLRULEID=4040082,ACLACTION=Deny,VRFNAME="VRF_PS_Access",ACLPROTOCOL=0,ACLDESTIP="10.131.147.4",ACLDESTWILD="0.0.0.0";

The detailed operational command structures and MML scripts presented above illustrate the actual physical implementation of the service isolation workflows across both vendors, ensuring transparency and technical reproducibility.

Following completion of the authorized operation, restoration procedures are initiated by re-establishing the corresponding service definitions within the associated core-network infrastructure. Restoration latency depends primarily on control-plane synchronization procedures, configuration propagation delays, and radio access technology-specific recovery workflows.

The restoration delay is modeled as follows:

$$T_{\text{restore}} = T_{\text{propagation}} + T_{\text{core synchronization}} + T_{\text{cell reactivation}} + T_{\text{UE recovery}}$$

Where ($T_{\text{propagation}}$) denotes command propagation delay, ($T_{\text{core synchronization}}$) represents synchronization and service-definition recovery within the core network, ($T_{\text{cell reactivation}}$) corresponds to radio-side reactivation procedures, and ($T_{\text{UE recovery}}$) reflects user-equipment service reattachment and session restoration delays.

3.4 Multi-Vendor Orchestration Layer

After the target cells have been identified and selected by the coverage-preserving service isolation algorithm, the proposed orchestration layer translates the generic isolation procedure into vendor- and RAT-specific operational commands. This abstraction enables the same algorithm to be executed transparently across heterogeneous Huawei and Ericsson cellular infrastructures without modifying the core decision-making process.

The orchestration layer receives the extracted cell lists generated through the GIS-assisted workflow described in Section 3.3. Each extracted sector is associated with its corresponding vendor infrastructure, radio access technology, network identifiers, and operational service-control parameters. The orchestration engine groups the extracted sectors by technology for controlled restriction.

To support heterogeneous deployments, the framework implements vendor-adaptation modules responsible for translating unified orchestration actions into vendor-compatible operational procedures. In the current implementation, the framework supports Huawei and Ericsson infrastructures across 2G, 3G, and 4G deployments.

The orchestration workflow does not rely on fully standardized vendor-independent control interfaces. Instead, the framework adopts a practical multi-vendor integration approach based on vendor-supported management environments, operational scripting procedures, and technology-specific configuration templates. Consequently, the proposed framework should be interpreted as a multi-vendor orchestration methodology rather than a completely multi-vendor control architecture.

Figure 3 illustrates the operational workflow of the proposed multi-vendor, multi-RAT service-isolation framework, including GIS-assisted cell extraction, technology classification, orchestration generation, controlled execution, KPI monitoring, and staged restoration procedures.



Fig. 3. Workflow-Based Multi-Vendor Cellular Service Isolation and Restoration Framework

The orchestration procedure operates as an integrated and automated workflow for managing and restricting cellular services, executing through eight closely coupled steps to secure a sequential and reliable control flow:

1. **Input: Extracted Cell Datasets (Step 1):** Receives the list of cells extracted via GIS spatial intersections, containing cell identifiers (cell IDs), vendor mappings, physical locations, and radio technologies (2G/3G/4G).

2. **Validation & Consistency Check (Step 2):** Performs strict verification procedures regarding cell identity, availability, topological consistency, and overlapping service status.

3. **Classification by Vendor and RAT (Step 3):** Classifies and branches the affected sectors based on vendor type (e.g., Huawei or Ericsson) and Radio Access Technology (RAT).

4. **Generation of Operational Procedures (Step 4):** Automatically generates command sequences compatible with the vendor-specific systems based on the targeted service scenario and predefined templates.

5. **Export of Operational Execution Datasets (Step 5):** Exports the procedures generated in structured execution files (e.g., Excel format) segregated by technology, which are then transmitted via secure channels to the technical operations team.

6. **Execution of Service Isolation Procedures (Step 6):** Applies the Service Isolations in coordination with the shared Multi-Vendor Orchestration Layer, which translates commands using adapters and templates ready for the vendors' network management platforms (OSS/NMS) and applies them to the physical nodes.

7. **KPI Monitoring & Rollback Supervision (Step 7):** Real-time monitoring of network performance indicators, such as service availability, call success rate, and gateway processing load, to detect anomalies.

8. **Controlled Restoration & Reactivation (Step 8):** Gradually re-enables the restricted services, restores service bearers, and normalizes network indicators to ensure a safe, stable return to standard operational status.

To measure orchestration consistency across heterogeneous infrastructures, the framework defines the orchestration success rate as:

$$\text{Orchestration Success Rate} = \frac{N_{\text{successful executions}}}{N_{\text{total orchestration actions}}} \times 100$$

where ($N_{\text{successful executions}}$) represents the number of successfully completed orchestration procedures and ($N_{\text{total orchestration actions}}$) denotes the total number of generated operational procedures.

The proposed orchestration layer supports multiple operational restriction scenarios depending on the corresponding vendor infrastructure and radio access technology. These scenarios include voice- Service Isolation, messaging-service suppression, packet-data limitation, ongoing session interruption, handover restriction, and temporary bearer blocking procedures.

The framework further supports partial isolation strategies in order to reduce unintended service disruption outside the authorized geographic area. Instead of performing complete service suppression in all scenarios, the orchestration engine may selectively restrict packet-data services, handover procedures, or ongoing bearer sessions depending on the operational objective and expected spillover impact.

Because radio access technologies employ different control-plane architectures and restoration workflows, service-recovery procedures are executed independently for each RAT. In 2G and 3G environments, restoration primarily involves synchronization of service definitions between radio controllers and switching entities. In 4G infrastructures, restoration additionally requires EPC-level bearer recovery, ACL rollback procedures, and LTE session re-establishment mechanisms.

The proposed orchestration workflow was validated through real operational deployment on the live production cellular networks of MTN Syria and Syriatel. The evaluation was conducted across multiple geographic regions and several Syrian governorates under real operating conditions, including both peak-traffic and off-peak periods. Technology-specific service-isolation and restoration procedures were executed on operational radio access and core network elements, while field verification confirmed the observed service behavior within and around the designated target areas. Although the validation covered geographically distributed operational deployments, it did not involve a simultaneous nationwide activation across the entire cellular network, owing to operational and regulatory constraints.

Field engineers verified the service-isolation behavior by performing repeated voice, messaging, and data connectivity tests inside the target areas and in neighboring non-targeted regions under normal network traffic conditions.

The modular structure of the orchestration layer facilitates future integration of additional vendor infrastructures such as Nokia or ZTE through implementation of corresponding adaptation modules and technology-specific operational templates. However, such integrations would still require vendor-aware operational mapping procedures because complete standardization across heterogeneous cellular infrastructures remains limited in current operational environments.

3.5 KPI Monitoring and Controlled Restoration

Network behavior is monitored throughout each service-isolation procedure by a dedicated KPI monitoring and restoration supervision layer. This allows unintended degradation to be detected early and affected network elements to be restored reliably.

The monitoring subsystem collects operational indicators from radio access and core-network infrastructures across heterogeneous 2G, 3G, and 4G deployments. The collected KPIs are used to evaluate isolation effectiveness, restoration consistency, service continuity, and the operational impact on neighboring cells outside the authorized target area, including variables such as service availability ratio, voice-call success rate, packet-data session success rate, handover success probability, and cell accessibility indicators.

The following KPIs are monitored:

- Service availability ratio
- Voice-call success rate
- Packet-data session success rate
- Handover success probability
- Cell accessibility indicators
- Signaling load and control-plane activity
- User reattachment success rate
- Spillover ratio outside the target polygon
- Restoration completion latency

Isolation effectiveness is quantified using the service isolation accuracy metric, defined as Equation (1):

$$\text{Isolation Accuracy} = \frac{N_{\text{correctly restricted users}}}{N_{\text{total targeted users}}} \times 100 \qquad (1)$$

where ($N_{\text{correctly restricted users}}$) denotes the number of users successfully affected within the authorized target area and ($N_{\text{total targeted users}}$) represents the total number of users expected to be affected according to the geographic isolation policy.

To evaluate unintended operational impact outside the target polygon, the framework further computes the collateral impact ratio, defined as Equation (2):

$$\text{Collateral Impact Ratio} = \frac{N_{\text{unintended affected users}}}{N_{\text{total affected users}}} \times 100 \qquad (2)$$

where ($N_{\text{unintended affected users}}$) represent users located outside the authorized target area who experienced temporary Service Isolation during the operation.

KPI thresholds are supervised throughout each service-restriction procedure, and rollback is triggered immediately if abnormal behavior or excessive spillover is detected. After the operation, the restoration subsystem reactivates affected services in stages.

Because synchronization and recovery mechanisms differ across radio access technologies, each is handled independently. For 2G and 3G, service definitions are reactivated within the BSC, RNC, MSC, and associated switching entities. 4G recovery additionally requires EPC-level synchronization, bearer recovery, ACL rollback, and LTE session re-establishment.

The restoration process consists of the following operational stages:

1. Verification of operation completion authorization.

2. Restoration of vendor-specific service configurations.
3. Core-network synchronization and propagation procedures.
4. Reactivation of affected radio sectors.
5. User-equipment reattachment and session recovery.
6. KPI normalization verification.
7. Confirmation of stable network operation.

The restoration delay is modeled as follows:

$$T_{\text{restore}} = T_{\text{propagation}} + T_{\text{core synchronization}} + T_{\text{cell reactivation}} + T_{\text{UE recovery}}$$

Where ($T_{\text{propagation}}$) denotes command propagation delay, ($T_{\text{core synchronization}}$) represents synchronization and service-definition recovery within the core network, ($T_{\text{cell reactivation}}$) corresponds to radio-side reactivation procedures, and ($T_{\text{UE recovery}}$) reflects user-equipment service reattachment and session restoration delays.

Experimental observations indicate that restoration latency varies according to radio access technology and associated core-network recovery procedures. In general, 2G infrastructures exhibit faster restoration due to simpler control-plane architectures, whereas 4G environments require longer recovery intervals because of EPC synchronization, bearer restoration, and LTE session-management procedures.

The KPI monitoring and restoration framework provides operational visibility, rollback supervision, and controlled recovery capabilities that improve the reliability and auditability of geographically targeted cellular service-isolation operations.

The methodology follows three stages: GIS-assisted zone definition, multi-vendor coverage extraction, and multi-vendor orchestration for service isolation and restoration, with particular attention to reproducibility, logging, and rollback capability.

4. Experimental Environment and Data Processing

4.1 Operational Dataset Sources

The experimental evaluation was conducted using real operational cellular-network datasets obtained from the two major mobile-network operators in Syria: MTN Syria and Syriatel. The collected datasets include heterogeneous multi-Radio Access Technology (multi-RAT) infrastructure information covering 2G, 3G, and 4G deployments distributed across urban, suburban, and rural environments throughout Syrian territory.

The datasets contain operational and radio-planning information associated with cellular sectors and physical network sites, including sector identifiers, geographic coordinates, radio access technology classifications, vendor infrastructure mappings, antenna parameters, and coverage-prediction attributes generated through operational radio-planning environments.

After preprocessing, normalization, and spatial validation procedures, the resulting unified database contained approximately 79,268 operational cellular records distributed across multiple radio access technologies and heterogeneous vendor infrastructures.

Table 2. Statistical Distribution of Cellular Infrastructure Datasets

Operator	Total Registered Cellular Records	2G Ratio	3G Ratio	4G Ratio	Estimated Physical Sites

MTN Syria	29,512	40.6%	30.5%	28.9%	~3,800
Syriatel	49,464	39.3%	51.7%	9.0%	~5,500

The final processed dataset included approximately 21,356 2G sectors, 27,902 3G sectors, and 30,010 4G sectors. The 4G infrastructure was considered particularly important because LTE deployments represent the primary candidate architecture for future service orchestration and potential migration toward advanced network infrastructures.

The collected datasets further incorporated heterogeneous deployment densities covering both urban and rural operational environments. About 62% of the processed records came from urban and high-density deployments, with the remainder from rural and low-density macro-cell environments. Together, these covered a range of deployment conditions suitable for evaluating spatial isolation precision, spillover behavior, and restoration performance.

The operational datasets were derived from real radio-planning environments and prediction layers generated through Atoll and mPlanet planning platforms. Coverage prediction datasets included sector-level propagation footprints, signal-strength estimations, antenna-sector projections, and overlapping coverage regions used during GIS-assisted spatial extraction and orchestration procedures.

To preserve operational confidentiality and comply with infrastructure-security requirements, all datasets were anonymized prior to experimental processing. Sensitive operational identifiers, internal network addresses, and vendor-specific deployment parameters were excluded from the research dataset while maintaining the spatial and operational consistency required for experimental evaluation.

4.2 Data Cleaning and Normalization

Because the operational datasets were collected from heterogeneous multi-vendor and multi-operator environments, the raw infrastructure records contained inconsistencies in formatting, parameter naming conventions, incomplete entries, and duplicated sector definitions. A preprocessing and normalization workflow was therefore applied prior to experimental evaluation.

Before analysis, the MTN Syria and Syriatel datasets were cleaned and normalized through schema unification, coordinate verification, duplicate removal, technology classification, and consistency validation.

The principal preprocessing operations included:

- Unification of field names and database schemas across heterogeneous operator datasets.
- Standardization of radio access technology labels and sector identifiers.
- Detection and correction of incomplete or inconsistent operational records.
- Verification and correction of geographic coordinates.
- Elimination of duplicated sector entries and invalid records.
- Validation of vendor and technology mappings.
- Consistency verification of antenna-sector parameters and coverage identifiers.

To ensure spatial reliability, all geographic coordinates were validated against official Syrian administrative boundaries using GIS-based topology verification procedures. Records containing invalid geographic positions or inconsistent coordinate mappings were excluded from the final experimental dataset.

The preprocessing workflow further addressed challenges associated with co-located infrastructure deployments in which multiple radio access technologies shared common physical sites. Spatial clustering and proximity-based validation procedures were applied to identify overlapping infrastructure records

associated with identical physical locations while preserving sector-level operational separation between 2G, 3G, and 4G deployments.

The framework additionally normalized heterogeneous vendor-specific naming conventions and technology representations into a unified operational schema suitable for GIS-assisted orchestration and multi-vendor processing workflows.

To evaluate preprocessing consistency, the framework defines the data-validation ratio as follows:

$$\text{Validation Ratio} = \frac{N_{\text{valid records}}}{N_{\text{total raw records}}} \times 100$$

Where ($N_{\text{valid records}}$) denotes the number of operational records successfully validated after preprocessing and ($N_{\text{total raw records}}$) represents the total number of raw infrastructure records prior to normalization.

Following completion of preprocessing and normalization procedures, the resulting dataset provided a spatially consistent and operationally unified infrastructure database suitable for GIS-assisted spatial extraction, multi-vendor orchestration, spillover analysis, and restoration-performance evaluation.

The normalized datasets were subsequently integrated into the GIS processing and Real-Network Field Deployment and Evaluation described in the following section.

4.3 GIS Processing and Spatial Preparation

After preprocessing and normalization, the operational datasets were integrated into a GIS-assisted spatial analysis environment to support geographically targeted service-isolation evaluation and coverage-overlap analysis.

All infrastructure records were first referenced to the World Geodetic System (WGS 1984) and, where accurate distance and area measurements were required, additionally projected into the WGS 1984 UTM Zone 37N coordinate system, which provides appropriate spatial precision for the Syrian geographical region.

Spatial processing was then performed in ArcGIS Pro using PostGIS-enabled spatial databases and spatial SQL analysis procedures. The resulting environment supported spatial intersection analysis, polygon validation, topology verification, sector-overlay computation, and geographic filtering operations required for orchestration workflow generation.

Administrative-boundary layers corresponding to Syrian governorates and operational regions were integrated into the spatial database in order to validate infrastructure locations and remove geographically inconsistent records. Spatial Join procedures were subsequently applied to associate cellular sectors with their corresponding administrative and operational zones.

Coverage-prediction layers generated from Atoll and mPlanet radio-planning platforms were imported into the GIS environment as polygon-based spatial overlays. These prediction datasets included sector-level propagation footprints, estimated signal-strength regions, and overlapping coverage areas for heterogeneous 2G, 3G, and 4G infrastructures.

To quantify spatial overlap between predicted cellular coverage and authorized isolation polygons, the framework computes the geographic overlap coefficient as follows:

$$\text{Overlap Coefficient} = \frac{\text{Area}(\text{Coverage} \cap \text{Target Polygon})}{\text{Area}(\text{Target Polygon})}$$

Where (Coverage) represents the predicted propagation footprint of the evaluated sector and (Target Polygon) denotes the authorized geographic isolation zone.

The GIS processing workflow also handled overlapping and co-located infrastructure deployments. In several operational regions, multiple sectors belonging to different radio access technologies shared highly similar geographic coordinates. To prevent duplicate spatial counting and artificial inflation of affected coverage areas, proximity-based clustering procedures were applied using configurable spatial tolerance thresholds.

Sites were grouped into urban and rural categories according to infrastructure density and inter-site spacing. Urban deployments had smaller sector footprints and higher cell concentration, while rural deployments had larger macro-cell propagation regions and wider inter-site distances, a distinction that proved relevant for spillover analysis and spatial confinement evaluation.

To estimate the relative density of cellular infrastructure within the evaluated geographical region, the framework computes the infrastructure density metric as follows:

$$\text{Infrastructure Density} = \frac{N_{\text{cells}}}{\text{Area}_{\text{region}}}$$

Where (N_{cells}) denotes the number of operational cellular sectors within the evaluated geographical area and ($\text{Area}_{\text{region}}$) represents the total geographic area under analysis.

The resulting GIS-assisted spatial environment enabled accurate extraction of geographically intersecting sectors, spillover estimation, orchestration preparation, and controlled restoration analysis across heterogeneous multi-vendor cellular infrastructures.

4.4 Real-Network Field Deployment and Experimental Setup

The proposed framework was evaluated and validated through a Real-Network Field Deployment on the operational network infrastructure of the two major Syrian mobile network operators, MTN Syria and Syriatel. Under authorized test windows (typically scheduled during off-peak maintenance hours to ensure service safety), the orchestration procedures were executed directly on their live core servers, network management systems (NMS/OSS), and actual transmission networks. Field tests were conducted across seven Syrian governorates (provinces), where on-ground technical teams verified both the signal isolation accuracy inside the targeted zones and the safety of communications in surrounding non-targeted areas.

The deployment environment integrated ArcGIS Pro and PostGIS for spatial processing and orchestration preparation, while Atoll and mPlanet planning platforms were used to generate and validate cellular coverage-prediction layers. These prediction datasets included sector-level propagation footprints, signal-strength estimations, overlapping coverage regions, and technology-specific radio-planning parameters derived from operational infrastructure records.

For each technology-specific scenario, the orchestration workflows executed configuration updates and service control commands directly on the live controller nodes (BSCs and RNCs) and core network gateways (MSCs and EPC links) for Huawei and Ericsson infrastructures. Command sequencing, service-restriction procedures, rollback workflows, and technology-specific restoration behavior were verified directly on the physical infrastructure.

The experimental workflow incorporated multiple geographically bounded operational scenarios representing dense urban, suburban, and rural deployment environments. Urban scenarios were characterized by high infrastructure density and smaller sector footprints, whereas rural scenarios involved

larger macro-cell propagation regions and wider inter-site distances in order to evaluate spillover behavior and spatial confinement precision under heterogeneous deployment conditions.

The real-network field evaluation incorporated geographically distributed experimental scenarios across seven Syrian governorates representing heterogeneous urban and rural deployment environments. For each governorate, approximately 10 urban scenarios and 15 rural scenarios were independently evaluated using different geographic target polygons and heterogeneous infrastructure subsets.

Each operational scenario was conducted over durations ranging from approximately 15 to 30 minutes depending on the selected service-restriction configuration, including messaging-only restriction, voice-service limitation, packet-data suppression, and full temporary service isolation procedures.

To ensure statistical rigor and minimize operational bias, each experimental scenario was repeated through at least 10 independent field trials conducted under different operational conditions, including distinct maintenance windows, different geographic target polygons, and varying network traffic loads. All reported performance indicators represent the average of these independent measurements and are presented as mean ± standard deviation (SD) together with their corresponding 95% confidence intervals.

All reported performance indicators represent averaged measurements represented as mean values with associated standard deviations (mean ± SD) and 95% confidence intervals. The underlying orchestration commands, operational sequences, and anonymized dataset profiles are archived for reproducibility, because the operational datasets contain confidential information from commercial operators, they cannot be released publicly. Nevertheless, the anonymized workflow, equations, and experimental configuration are described in sufficient detail to enable reproduction under comparable operational environments.

The operational network deployment and field trials incorporated the following operational components:

- GIS-assisted target-zone definition and polygon generation.
- Coverage-overlap extraction using prediction layers from Atoll and mPlanet.
- Multi-vendor orchestration workflow generation.
- RAT-specific service-restriction implementation and command execution.
- KPI monitoring and rollback supervision.
- Controlled restoration and service-reactivation procedures.

The experimental evaluation further incorporated heterogeneous service-restriction scenarios including:

- Voice- Service Isolation.
- Messaging- Service Isolation.
- Packet-data suppression.
- Ongoing session interruption.
- Handover limitation procedures.
- Full temporary service isolation.

Mobility-aware operational user movement patterns were monitored and incorporated in order to evaluate realistic user movement, service accessibility behavior, and dynamic handover interactions across neighboring cellular sectors.

To estimate the relative operational impact of geographically targeted Service Isolation, the framework computes the affected-user ratio as follows:

$$\text{Affected User Ratio} = \frac{N_{\text{affected users}}}{N_{\text{active users}}} \times 100$$

Where ($N_{\text{affected users}}$) represents users impacted by temporary Service Isolation procedures and ($N_{\text{active users}}$) denotes the total number of active users within the evaluated operational region.

The real-network field evaluation additionally incorporated restoration-performance analysis through staged rollback procedures and KPI verification following completion of each operational scenario. Restoration workflows were evaluated independently for 2G, 3G, and 4G infrastructures because recovery latency and synchronization mechanisms differ across heterogeneous radio access technologies.

Figure 4 illustrates the influence of cellular infrastructure density on the geographic precision of the proposed service isolation framework. In both deployment scenarios, all cellular services are successfully isolated inside the target polygon while preserving the underlying radio coverage. The only observable difference appears outside the target area, where the geographical extent of unintended service interruption (spillover) depends on the density and footprint of the surrounding cells.

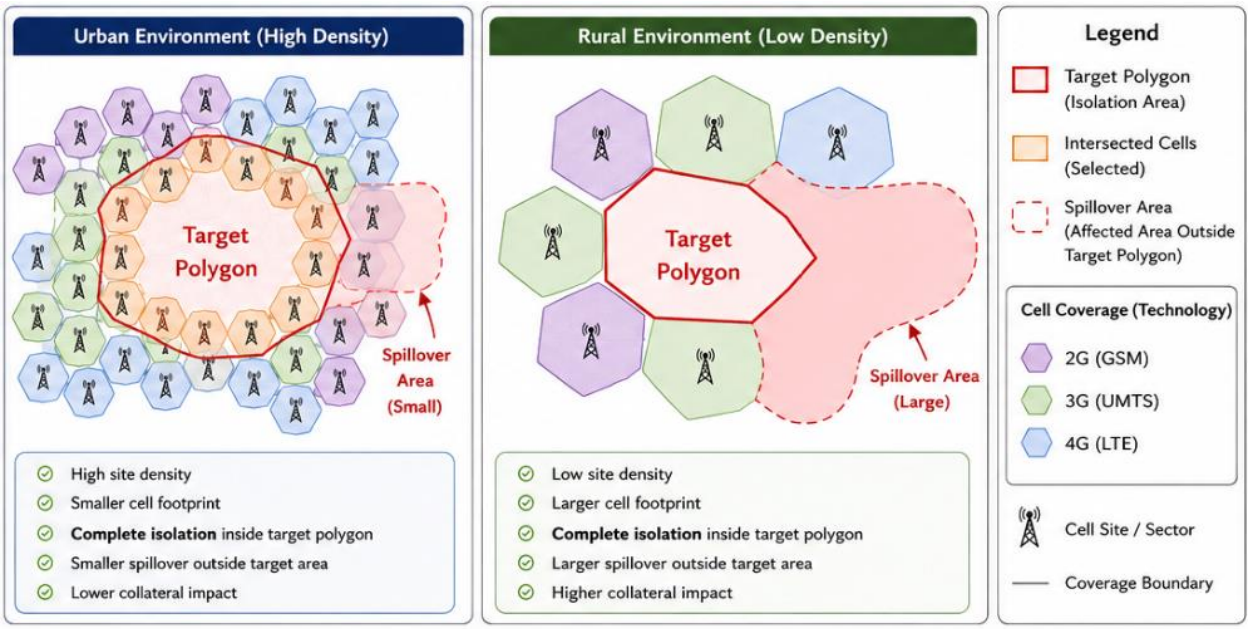


Fig. 4. Comparison of Spillover Behavior in Urban and Rural Cellular Deployments during GIS-Assisted Service Isolation.

The resulting hybrid evaluation environment provided a realistic and operationally representative framework for assessing geographic isolation precision, spillover behavior, orchestration consistency, and restoration reliability across heterogeneous multi-vendor cellular infrastructures.

4.5 Evaluation of Metrics and Statistical Methodology

To objectively evaluate the proposed GIS-assisted orchestration framework, a comprehensive evaluation methodology was established based on spatial, operational, and restoration-related performance metrics. The framework was assessed through repeated field trials conducted under different geographic deployment scenarios, including urban, suburban, and rural environments. Performance was quantified using six complementary evaluation metrics that measure geographic isolation effectiveness, operational consistency, restoration performance, mobility control, and unintended service impact. Statistical reliability was ensured through repeated independent field trials and the calculation of mean values, standard deviations, and 95% confidence intervals.

The evaluation process incorporated repeated experimental executions across urban, suburban, and rural deployment scenarios in order to reduce scenario-specific bias and improve statistical consistency. Each experimental configuration was evaluated through multiple independent experimental runs using different geographic target polygons and heterogeneous infrastructure subsets derived from the operational datasets.

The primary evaluation metrics used throughout the experimental analysis are summarized as follows:

1. Isolation Accuracy

Isolation accuracy measures the degree to which the framework successfully restricts services within the authorized target area.

$$\text{Isolation Accuracy} = \frac{N_{\text{correctly restricted users}}}{N_{\text{targeted users}}} \times 100$$

Where ($N_{\text{correctly restricted users}}$) represent users successfully affected within the authorized target polygon and ($N_{\text{targeted users}}$) denotes the total number of intended users within the isolation region.

2. Spillover Ratio

The spillover ratio quantifies unintended service impact outside the authorized geographic isolation zone.

$$\text{Spillover Ratio} = \frac{\text{Area affected outside polygon}}{\text{Area target polygon}} \times 100$$

Where (Area affected outside polygon) denotes the unintended affected area located outside the target polygon boundaries.

3. Restoration Delay

Restoration delay measures the total time required to reactivate services following completion of the authorized operation.

$$T_{\text{restore}} = T_{\text{propagation}} + T_{\text{core synchronization}} + T_{\text{cell reactivation}} + T_{\text{UE recovery}}$$

Where ($T_{\text{propagation}}$) represents command propagation delay, ($T_{\text{core synchronization}}$) corresponds to synchronization procedures within the core network, ($T_{\text{cell reactivation}}$) denotes radio-side recovery procedures, and ($T_{\text{UE recovery}}$) reflects user-equipment service reattachment and session restoration latency.

4. Handover Suppression Efficiency

Handover suppression efficiency reflects how reliably mobility-control procedures contain user equipment within the isolation boundary during temporary operations.

$$\text{Handover Suppression Efficiency} = \frac{N_{\text{blocked handovers}}}{N_{\text{handover attempts}}} \times 100$$

Where ($N_{\text{blocked handovers}}$) denote successfully restricted handover attempts entering the isolated region.

5. Orchestration Success Rate

The orchestration success rate evaluates the consistency of operational procedures generated across heterogeneous vendor infrastructures.

$$\text{Orchestration Success Rate} = \frac{N_{\text{successful executions}}}{N_{\text{total orchestration actions}}} \times 100$$

Where ($N_{\text{successful executions}}$}) denote successfully completed orchestration procedures.

6. Collateral Impact Ratio

The collateral impact ratio measures unintended operational effects on users located outside the authorized isolation region.

$$\text{Collateral Impact Ratio} = \frac{N_{\text{unintended affected users}}}{N_{\text{total affected users}}} \times 100$$

Where ($N_{\text{unintended affected users}}$) represents users unintentionally impacted outside the authorized target polygon.

To improve reproducibility and statistical reliability, all experiments were repeated across at least 10 independent runs (n >= 10). The reported results correspond to averaged measurements represented as mean values with associated standard deviations (mean ± SD) and 95% confidence intervals.

The confidence interval for each evaluated metric was computed as follows:

$$\text{CI}_{95\%} = \overline{x} \pm 1.96\frac{\sigma}{\sqrt{n}}$$

Where ($\overline{x}$) denotes the sample mean, (σ) represents the standard deviation, and (n) corresponds to the number of independent experimental runs.

The evaluation further compared performance across dense urban, suburban, and rural deployment environments to analyze spillover behavior, infrastructure-density effects, and restoration consistency under varying cellular deployment characteristics.

Urban environments had high infrastructure density and smaller sector footprints, whereas rural environments had wider macro-cell propagation regions and larger inter-site distances.

Figure 5 illustrates the staged restoration workflow following completion of a temporary service-isolation operation. The restoration process is structured into the following sequential steps to ensure network stability:

1. **Authorization Verification and Triggering (Step 1):** The workflow begins upon receiving a verified operation completion authorization or when the pre-defined target timer expires.
2. **Command Translation and Propagation (Step 2):** The orchestration layer retrieves original configuration states and propagates revert commands (e.g., re-adding GCI definitions, disabling Access Class Barring) to the respective BSCs, RNCs, and core gateways.
3. **Core Network Synchronization (Step 3):** Reverts core-network level blocks and ACL rules. The EPC or MSC database is synchronized, ensuring user-plane data paths and CS registry points are re-established.
4. **RAN Carrier Reactivation (Step 4):** Restores transmission links and cell carriers on the radio side. Technical teams monitor that pilot and broadcast signaling remain stable and active during cell carrier re-indexing.
5. **UE Re-attachment and Session Recovery (Step 5):** User equipment (UE) detects service availability, initiating re-registration and bearer re-establishment (e.g., LTE default/dedicated bearers) to re-enter the network.

6. **KPI Normalization & Audit Verification (Step 6):** Real-time monitoring of key performance indicators (KPIs) to verify that accessibility, call drop rates, and throughput metrics return to normal baselines. If any abnormal signaling storm is detected, the load-balancing and throttling procedures are dynamically engaged.

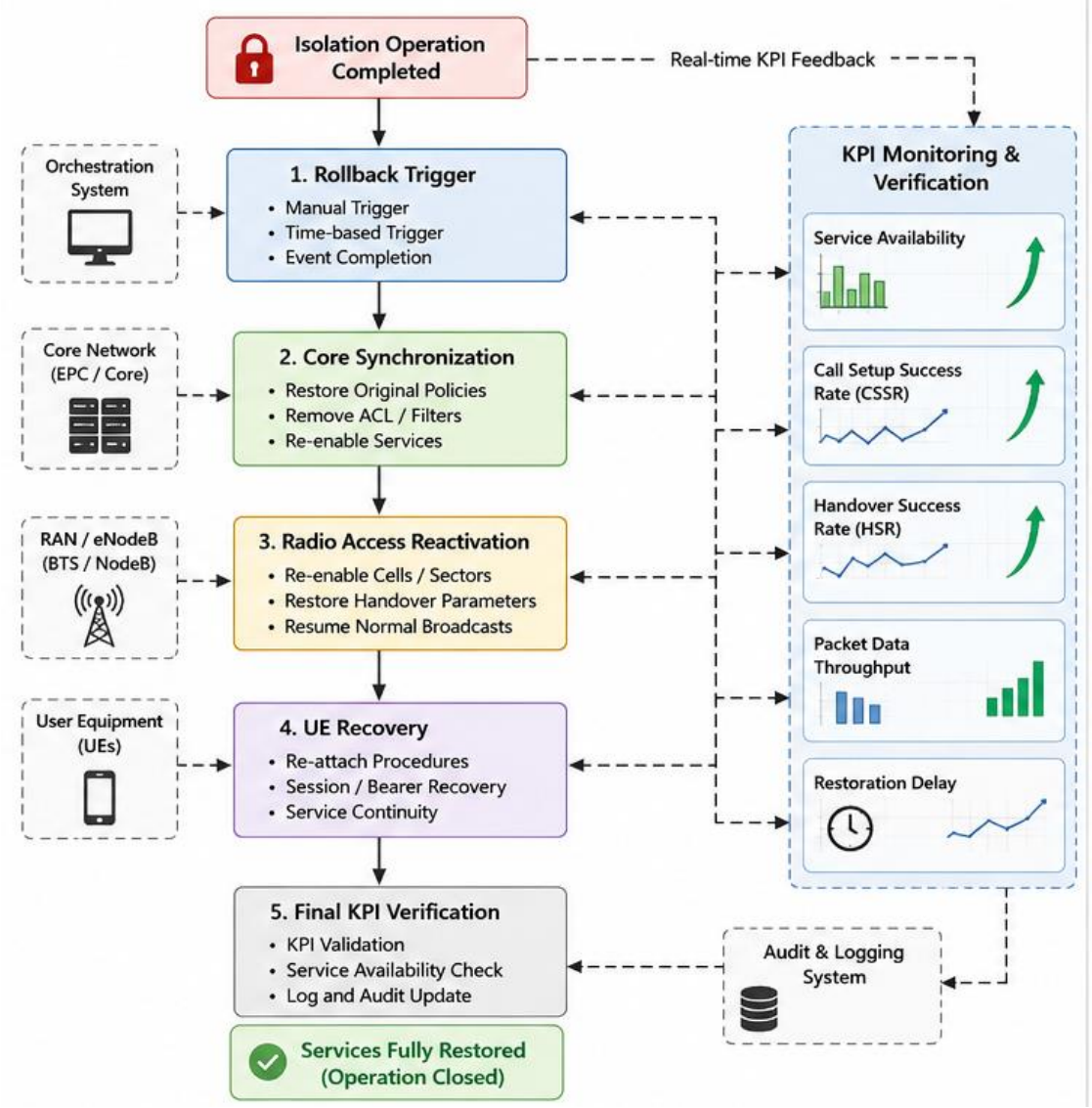


Fig. 5. Experimental Evaluation and Restoration Analysis Workflow

The resulting evaluation methodology provided a statistically consistent framework for assessing operational feasibility, geographic confinement precision, orchestration consistency, and restoration reliability across heterogeneous multi-vendor cellular infrastructures.

5. Experimental Results and Performance Analysis

This section presents the experimental evaluation results obtained using the proposed GIS-assisted multi-vendor orchestration framework across heterogeneous urban, suburban, and rural deployment environments.

The presented results evaluate spatial isolation precision, spillover behavior, orchestration consistency, handover suppression efficiency, and restoration performance across 2G, 3G, and 4G infrastructures.

The evaluation was conducted using repeated experimental scenarios derived from the operational datasets described in Section 4. Each scenario was executed multiple times using different geographic target polygons and heterogeneous infrastructure subsets in order to improve statistical consistency and reduce scenario-specific bias.

The proposed framework demonstrated high operational effectiveness across heterogeneous deployment conditions, achieving high geographic isolation precision with controlled restoration behavior and consistent orchestration performance across Huawei and Ericsson infrastructures.

5.1 Isolation Accuracy and Spillover Analysis

Table 3. Isolation Accuracy and Spillover Characteristics

Deployment Environment	Average Isolation Accuracy	Average Spillover Ratio	Average Collateral Impact Ratio
Dense Urban	97.5% ± 1.3%	8.4% ± 2.1%	4.1% ± 1.2%
Suburban	94.2% ± 2.4%	21.7% ± 4.5%	11.5% ± 2.8%
Rural	89.6% ± 3.1%	46.8% ± 7.9%	24.3% ± 5.2%

The results demonstrate that dense urban deployments provide the highest spatial confinement precision because of smaller sector footprints and higher infrastructure density. In such environments, the overlap between cellular coverage regions and authorized target polygons can be controlled with relatively high precision.

Spillover tends to be more pronounced in suburban and rural environments, where macro-cell propagation footprints frequently extend beyond the intended target polygon. The framework remained operationally effective in these scenarios, successfully restricting services within the authorized region while introducing a larger affected area outside the target boundaries.

Importantly, the experimental results do not indicate operational failure in rural deployments. Instead, the increased spillover ratio reflects the physical characteristics of low-density macro-cell infrastructures where larger propagation footprints inherently reduce spatial confinement granularity.

The relationship between infrastructure density and spillover behavior can be approximate as follows:

$$\text{Spillover Ratio} \propto \frac{1}{\text{Infrastructure Density}}$$

This observation confirms that spillover behavior is strongly correlated with sector density and inter-site distance characteristics.

To mitigate unintended service expansion in low-density environments, the proposed framework supports partial service-restriction strategies including selective packet-data blocking, bearer-session interruption, and mobility-control procedures instead of complete service suppression whenever operationally appropriate.

5.2 Multi-Vendor Orchestration Performance

The orchestration framework demonstrated high operational consistency across heterogeneous Huawei and Ericsson infrastructures.

Table 4. Multi-Vendor Orchestration Performance

Metric	Huawei Infrastructure	Ericsson Infrastructure
Orchestration Success Rate	98.1% ± 1.1%	97.4% ± 1.4%
Handover Suppression Efficiency	93.2% ± 2.0%	92.0% ± 2.3%
Restoration Consistency	96.8% ± 1.5%	95.9% ± 1.7%

The results indicate that the proposed orchestration workflow maintained high execution consistency despite heterogeneous vendor-specific operational procedures and technology-dependent restoration mechanisms.

The framework further demonstrated effective handling of RAT-specific orchestration workflows across 2G, 3G, and 4G infrastructures. In particular, LTE restoration procedures required additional synchronization and EPC-level recovery operations compared with legacy 2G and 3G infrastructures.

5.3 Restoration Performance Analysis

Restoration latency was evaluated independently across heterogeneous radio access technologies. The restoration delay model is parameterized and validated by breaking down the total latency into its constituent components:

1. **Command Propagation ($T_{\text{propagation}}$):** The time required for the orchestration system to send configuration revert commands to the MSC/RNC/BSC/EPC.
2. **Core Network Synchronization ($T_{\text{core sync}}$):** The time for core databases and security lists (ACLs, Home Location Register (HLR), Home Subscriber Server (HSS)) to synchronize.
3. **Radio/RAN Reactivation ($T_{\text{RAN react}}$):** The time required for cell carrier reactivation and pilot signaling initialization on the radio modules.
4. **UE Re-attachment ($T_{\text{UE re-att}}$):** The time required for user equipment to detect the carrier, perform random access, and re-establish default and dedicated bearers.

The following table summarizes the measured operational latency breakdown for each radio access technology, reported as Mean ± SD based on 10 independent test runs.

Table 5. Parameterized Restoration Delay Breakdown (in seconds, Mean ± SD)

RAT	T_propagation	T_core_sync	T_RAN_react	T_UE_re-att	Total T_restore
2G	15 ± 2 s	42 ± 5 s	94 ± 12 s	112 ± 18 s	263 ± 25 s (~4.4 min)
3G	18 ± 3 s	65 ± 8 s	145 ± 22 s	152 ± 25 s	380 ± 40 s (~6.3 min)
4G	22 ± 4 s	110 ± 15 s	215 ± 35 s	185 ± 30 s	532 ± 60 s (~8.9 min)

Discussion on Emergency Operational Requirements

From an emergency operations perspective, a critical question is whether a sub-10-minute service restoration delay meets the requirements of public safety and emergency coordination. In security and

disaster response scenarios, temporary service isolation is typically used to defuse specific threats (e.g., remote triggering of explosives or coordinated attacks). Once the threat is cleared, rapid, predictable, and reversible restoration of communication services is vital for rescue operations and general public notifications.

Our field trial measurements show that:

- **2G and 3G Restoration:** Complete recovery occurs in approximately 4.4 and 6.3 minutes respectively, which is well within the 10-minute Service Level Agreement (SLA).
- **4G Restoration:** Due to the complexity of the Evolved Packet Core (EPC) and the need to re-authenticate and re-allocate packet bearers, the total restoration takes 8.9 ± 1.0 minutes.
- **Operational Suitability:** A sub-10-minute restoration window is highly acceptable for emergency scenarios, especially when compared to physical power shutdowns (which often require manual site visits or long cold-boots exceeding 30 minutes) or RF-jamming (which can cause prolonged spectrum issues and synchronization loss on neighboring sites). The automated, orchestrated rollback ensures that normal service is restored without manual intervention from field teams, maintaining overall network stability.

5.4 Comparative Discussion

To quantitatively evaluate the performance of the proposed GIS-assisted multi-vendor orchestration framework, we compare it against two baseline methods commonly utilized in operational telecommunication environments:

1. **Baseline 1: Manual Engineering Tracking:** A manual approach where network planning engineers manually identify candidate cell IDs using coverage prediction files or static network maps and manually execute block commands on vendor NMS/OSS nodes.
2. **Baseline 2: Total GIS-Based Cell Power Shutdown:** A GIS-driven power shutdown strategy where all physical sites intersecting the target polygon have their radio transmitter power completely shut down.

All three methods were evaluated in the same operational network environment under the same target polygons. Table 6 provides the quantitative and qualitative comparison.

Table 6. Quantitative Baseline Comparison (Averaged Across All Environments over 10 Independent Runs)

Metric	Proposed Framework	Baseline 1: Manual Tracking	Baseline 2: Power Shutdown
Isolation Accuracy (Mean ± SD)	93.8% ± 2.3%	74.5% ± 5.6%	99.1% ± 0.5%
Average Spillover Ratio (Mean ± SD)	25.6% ± 4.8%	41.2% ± 6.4%	78.4% ± 9.2%
Average Restoration Delay (Mean ± SD)	6.8 ± 1.5 min	45.2 ± 8.6 min	32.4 ± 5.1 min
Collateral Impact Ratio (Mean ± SD)	13.3% ± 3.1%	32.5% ± 5.4%	54.8% ± 7.2%
Pilot/Broadcast Signaling Preserved	Yes	Yes	No
Handover Suppression Efficiency	92.6% ± 2.2%	41.0% ± 7.8%	0.0% (N/A)

Comparative Analysis of Baselines

The quantitative comparison highlights several major operational advantages of the proposed framework:

- **Signal Preservation vs. Total Outage:** While Baseline 2 (Power Shutdown) achieves near-perfect isolation accuracy (99.1%) by completely cutting off the signal, it does so at the cost of disabling all pilots and broadcast signaling. This causes immediate loss of network synchronization for all nearby user equipment (UE), which forces them to attempt high-power re-attachments to adjacent distant cells, leading to a massive spillover ratio of 78.4% and a collateral impact ratio of 54.8%. In contrast, the proposed framework limits services at the core/control-plane level, maintaining pilot signaling. This prevents UEs from roaming or causing massive signaling storms, keeping the spillover ratio at a much lower 25.6%.
- **Restoration Delay:** The proposed framework achieves a mean restoration delay of 6.8 ± 1.5 minutes, which is automated and fully orchestrated. Baseline 1 (Manual Tracking) requires significant manual entry and coordinator verification, taking on average 45.2 ± 8.6 minutes. Baseline 2 (Power Shutdown) requires a complete cold reboot of the radio equipment, requiring 32.4 ± 5.1 minutes for carrier synchronization and UE re-attachment.
- **Human Error and Targeting Precision:** Baseline 1 suffers from low isolation accuracy (74.5%) because human engineers often miss overlapping cell sectors or make errors during high-pressure emergency scenarios, resulting in incomplete isolation and unintended outages in non-targeted zones.

Compared with conventional RF-jamming approaches, the proposed framework provides substantially improved geographic controllability, reduced electromagnetic detectability, and significantly lower interference impact on neighboring infrastructures.

Unlike wide-area RF suppression techniques, the proposed framework performs targeted network-side orchestration using GIS-assisted coverage extraction and technology-specific operational procedures. Consequently, unintended electromagnetic interference and spectrum-wide disruption are minimized.

In comparison with static rule-based isolation methods, the proposed framework demonstrated improved spatial precision because of dynamic GIS-assisted sector extraction and infrastructure-aware orchestration workflows.

The experimental results further demonstrate that heterogeneous multi-vendor orchestration can be achieved with high operational consistency despite vendor-specific execution procedures and technology-dependent restoration workflows.

5.5 Literature Comparison

Recent studies have primarily focused on RF-jamming techniques[15], AI-assisted interference detection, network slicing, or service orchestration for heterogeneous cellular infrastructures. However, these approaches generally do not address geographically bounded service isolation while simultaneously preserving radio coverage through temporary removal of cell definitions from the core network.

To further highlight the distinctive characteristics of the proposed framework, Table 7 provides a qualitative comparison with representative approaches reported in the recent literature

Feature	RF Jamming Approaches	AI-based Interference/Jamming	Network Orchestration / Slicing	Proposed Framework
Geographic service isolation	Limited	Limited	Partial	✓
Radio coverage preserved	✗	✗	Partial	✓
Communication services blocked	✓	Detection only	Partial	✓
GIS-assisted spatial selection	✗	✗	✗	✓
Multi-vendor operation	Limited	Limited	Partial	✓
Reversible service restoration	✗	✗	Limited	✓
Real-network field validation	Rare	Mostly simulation	Limited	✓

Table 7. Qualitative comparison between the proposed framework and representative approaches reported in the literature.

As summarized in Table 7, existing studies mainly concentrate on RF-jamming mitigation [15], interference detection, or orchestration mechanisms for virtualized cellular infrastructures. [14] Although these approaches improve network resilience, security, or resource management, they do not provide an operational mechanism for geographically bounded service isolation while maintaining radio coverage. In contrast, the proposed framework combines GIS-assisted spatial analysis with multi-vendor orchestration to identify only the cellular sectors intersecting a user-defined target region and temporarily remove their cell definitions from the core network.[16] Consequently, communication services are disabled without shutting down the radio carrier, thereby preserving coverage, minimizing unintended service spillover, and enabling controlled rollback and restoration.

Discussion on Quantitative Comparability:

A direct quantitative comparison is not scientifically meaningful because the proposed framework addresses a fundamentally different operational problem. Existing studies mainly investigate RF jamming mitigation, interference detection, AI-based radio optimization, or network slicing, whereas the proposed framework performs geographically bounded service isolation by temporarily removing cell definitions from the core network while preserving radio coverage and broadcast signaling.

Furthermore, previous studies generally evaluate their methods using simulation environments, synthetic datasets, or different performance metrics that do not report quantities such as service isolation accuracy, spillover ratio, restoration latency, or orchestration success under live operational deployments. Consequently, the reported numerical results are not directly comparable.

For this reason, Table 7 provides a feature-oriented comparison that highlights the functional differences between the proposed framework and representative approaches from the literature. The **real-network** experimental evaluation presented in this work therefore serves as the primary quantitative validation of the proposed methodology.

6. Discussion

The principal innovation of the proposed framework lies in separating radio coverage from communication service availability. Rather than disabling radio cells, the proposed approach temporarily removes the corresponding cell definitions from the core network while maintaining the radio carrier together with pilot and broadcast signaling. Consequently, user equipment remains attached to the strongest serving cell, whereas communication services cannot be established within the target area. This mechanism minimizes unintended coverage expansion and service spillover that commonly occur with conventional power-shutdown and RF-based suppression approaches.

The experimental evaluation confirms that the proposed GIS-assisted multi-vendor orchestration framework provides a practical solution for geographically bounded service isolation using existing cellular network infrastructures. By combining GIS-based spatial analysis with vendor-specific orchestration procedures, the framework enables precise identification of affected sectors and controlled service isolation without introducing electromagnetic interference or disabling radio coverage.

The results further demonstrate that the geographic precision of service isolation depends primarily on infrastructure density and sector coverage characteristics. Dense urban deployments achieved the highest isolation accuracy because smaller sector footprints closely matched the target polygon. In contrast, rural environments exhibited larger spillover regions owing to wider macro-cell propagation areas. This behavior reflects an inherent limitation of sparse cellular infrastructures rather than a limitation of the proposed orchestration methodology. To mitigate this effect, the framework supports selective service-control mechanisms, including bearer-session interruption, packet-data limitation, mobility-control procedures, and handover suppression, thereby reducing unintended service impact while maintaining the desired isolation objectives.

The proposed framework also demonstrated consistent operation across heterogeneous Huawei and Ericsson infrastructures. Nevertheless, complete vendor independence remains challenging because practical deployments still rely on vendor-specific management platforms and configuration procedures. Therefore, the proposed solution should be regarded as a practical multi-vendor orchestration framework, while extending support to additional vendors such as Nokia or ZTE would require dedicated vendor-adaptation modules.

Another important observation concerns restoration performance. Restoration latency increased with radio access technology complexity, particularly for LTE networks, where EPC synchronization, bearer recovery, ACL rollback, and session re-establishment introduced additional processing overhead. Although restoration times of several minutes may appear relatively long, they remain operationally acceptable for controlled emergency and security scenarios, where restoration reliability and network stability are more critical than immediate service reactivation.

The use of operational radio-planning datasets generated by Atoll and mPlanet further enhanced the spatial accuracy and practical realism of the proposed framework compared with theoretical coverage estimation alone. Moreover, the successful validation on live production networks demonstrates that GIS-assisted service isolation represents a practical and operationally feasible alternative to conventional RF-based suppression techniques.

Despite these promising results, several limitations remain. The current validation was conducted on regional live-network deployments rather than nationwide operational environments because of regulatory and scheduling constraints. Furthermore, the present implementation supports 2G, 3G, and 4G infrastructures only. Future research will therefore investigate integration with 5G and beyond-5G architectures, including Open Radio Access Network (O-RAN), near-real-time RAN Intelligent Controllers (near-RT RIC), network slicing, and adaptive orchestration xApps to further improve automation, scalability, and geographically precise service isolation.

7. Conclusion and Future Work

This study demonstrates that geographically constrained and reversible cellular service isolation can be achieved through a network-centric orchestration paradigm without relying on conventional radio-frequency (RF) suppression techniques. The principal contribution of this work lies in introducing a novel control strategy at the cellular core-network level, where the definition of radio access network (RAN) cells is selectively removed or logically deactivated from the core network orchestration layer. Consequently, the physical radio infrastructure remains fully operational and continues to provide coverage; however, service accessibility is intentionally not realized within the targeted geographic regions. This decoupling between radio coverage availability and service provisioning represents a fundamental shift from traditional interference-based or access-blocking approaches.

The proposed framework introduces a GIS-assisted multi-vendor orchestration architecture designed to enable precise, controllable, and reversible service isolation in emergency and security-related operational scenarios. Unlike conventional RF-based suppression or jamming techniques, the methodology operates entirely at the network control and orchestration layers, ensuring non-destructive and fully reversible service governance.

The framework integrates Geographic Information Systems (GIS) with operational radio planning datasets and vendor-specific orchestration procedures to identify spatial intersections between cellular sectors and predefined geographic boundaries. Based on this spatial mapping, selective removal or suppression of cell definitions at the core-network orchestration level is performed across heterogeneous infrastructures. The system supports independent orchestration of 2G, 3G, and 4G networks deployed by multiple vendors, including Huawei and Ericsson, while maintaining full restoration capability.

The experimental evaluation was conducted in a live production cellular network environment deployed across seven Syrian governorates, operating on operational core and radio access network infrastructure of major mobile network operators. Unlike simulation-based or laboratory-controlled studies, the proposed framework was directly enforced on production-grade core-network and RAN systems, ensuring realistic network behavior under real operational conditions.

The evaluation was performed across multiple temporal windows and heterogeneous traffic-load conditions to capture realistic network dynamics. To validate the effectiveness of the proposed service isolation mechanism, in-situ field verification was carried out within the targeted geographic regions. This included physical presence inside the isolated zones and repeated attempts to access standard cellular services, including voice and data connectivity.

Despite the continued existence of full radio coverage indicators, service accessibility was consistently unavailable within the targeted regions. This confirms that the radio infrastructure remained fully operational, while service provisioning was selectively inhibited at the core-network orchestration level through logical removal of cell definitions, rather than through any form of RF disruption or physical layer interference.

These observations provide strong empirical evidence that the proposed framework operates natively on live cellular systems, achieving a strict decoupling between radio coverage availability and service realization in real operational environments.The results demonstrate that the proposed framework achieves high spatial isolation accuracy, particularly in dense urban environments where smaller cell footprints allow for precise geographic confinement. In such scenarios, the removal of cell definitions from the core network effectively prevents service realization within the targeted area while preserving the underlying radio coverage infrastructure.

In rural and low-density environments, the system exhibits increased spillover effects due to the broader propagation characteristics of macro-cell deployments. Since individual cells cover significantly larger geographic areas, the logical removal of cell definitions may result in service restriction extending beyond the intended target boundary. However, this behavior is an inherent consequence of sparse network topology rather than a limitation of the orchestration mechanism itself.

Despite this, the framework maintains effective operational isolation and predictable behavior across all tested scenarios. Furthermore, controlled service restoration is successfully achieved across multiple radio access technologies. Restoration latency varies depending on network generation, with LTE networks exhibiting longer recovery times due to EPC-level synchronization and bearer re-establishment procedures.

Overall, the study highlights the effectiveness of decoupling cellular service provisioning from physical radio coverage through GIS-driven, core-network-level orchestration. This approach provides a practical, reversible, and fine-grained alternative to traditional RF suppression methods, enabling controlled geographic service management across heterogeneous multi-vendor cellular infrastructures.

Future work will extend this framework toward 5G and beyond-5G systems, including integration with Open Radio Access Network (O-RAN) architectures, near-real-time RAN Intelligent Controllers (near-RT RIC), and AI-driven xApp/rApp orchestration environments. Further research will focus on network slicing-aware service isolation, adaptive spillover minimization using machine learning techniques, dynamic sector-level optimization, and intelligent restoration prioritization mechanisms for next-generation cellular networks.

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