RAIN4C: A Multi-Layer Framework Integrating Satellite and Aerial Networks for Reliable Communications in Emergency Scenarios

Alexandre Heideker, Giovanni Interdonato, Sara Pizzi, and Angelo Trotta

Abstract

Reliable communication infrastructures are critical in emergency management scenarios, as traditional terrestrial networks often suffer severe degradation or failure. To overcome these limitations, integrated multi-layer networks combining satellite systems, Unmanned Aerial Vehicle (UAV) swarms, and terrestrial assets offer promising solutions. In this context, we propose RAIN4C (Reliable Aerial and Satellite Networks for joint Communication, Computation, and Caching for Critical scenarios), a comprehensive framework specifically designed to fulfill communication, computational, and data management requirements in emergency situations. The RAIN4C architecture leverages adaptive drone swarm coordination, intelligent multi-layer caching, and hybrid orchestration strategies, effectively addressing the limitations of isolated network segments. Through a representative use case on enhanced Mobile Broadband (eMBB) offloading, our evaluations validate the proposed RAIN4C framework and demonstrate significant improvements in terms of network reliability, latency reduction, and resource efficiency compared to traditional approaches.

Introduction

The increasing frequency of large-scale emergencies, including natural disasters and infrastructure disruptions, underscores the critical importance of reliable and resilient communication systems [1]. Traditional terrestrial networks, although widespread and robust under normal conditions, often experience partial or complete outages during emergencies due to physical damage, power failures, or severe congestion [2]. Consequently, emergency response operations require flexible and adaptive communication solutions capable of rapidly overcoming infrastructure limitations to support timely decision-making and coordination among responders.

Non-Terrestrial Networks (NTNs), notably satellite constellations, have emerged as compelling alternatives that ensure global connectivity regardless of terrestrial network conditions [3]. However, satellite systems inherently suffer from high communication latency, limited bandwidth, and substantial deployment and operational costs. Complementarily, Unmanned Aerial Vehicle (UAV) networks offer low-latency and adaptive communication capabilities, providing rapid deployment and extensive coverage flexibility in challenging environments [4]. Yet, UAV-based solutions introduce their own set of challenges, including limited battery life, restricted computational capacity, and the complexity of dynamically managing highly mobile network topologies.

Effectively addressing these intertwined challenges requires an integrated, multi-layer architecture that simultaneously harnesses terrestrial robustness (when available), satellite connectivity for global backhaul, and UAV swarms for rapid and adaptive coverage. Motivated by these requirements, we introduce the Reliable Aerial and satellite Networks for joint Communication, Computation, and Caching for Critical scenarios (RAIN4C) framework. RAIN4C uniquely integrates the complementary strengths of terrestrial, aerial, and satellite segments, providing a comprehensive communication and computational solution tailored explicitly for emergency scenarios. The architecture leverages advanced technologies, including hybrid resource orchestration, multi-layer intelligent caching, adaptive UAV swarm management, and next-generation networking technologies, e.g., multiple-input multiple-output (MIMO) and millimeter wave (mmWave).

The main contributions of this paper are as follows:
- A detailed analysis of communication and computational requirements inherent to emergency scenarios.
- A comprehensive multi-layer framework, referred to as RAIN4C, that integrates terrestrial, aerial, and satellite segments, explicitly addressing identified requirements and limitations.
- Identification and description of key enabling technologies, particularly emphasizing hybrid orchestration approaches, advanced wireless

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communication techniques, and intelligent data caching strategies.
- Insights into practical implementation using modern orchestration platforms, supported by real-time monitoring and visualization tools.
- Validation through a realistic enhanced Mobile Broadband (eMBB) offloading use case, demonstrating performance improvements over traditional single-layer solutions.

The remainder of this paper is structured as follows. The "Related Work" section critically reviews related work, clearly positioning our contributions. The "Motivation and Requirements" section discusses motivations, identifies specific system requirements, and introduces the RAIN4C concept. The detailed RAIN4C architecture is described in the "RAIN4C System Architecture" section, followed by an overview of implementation strategies in the "RAIN4C Implementation and Deployment" section. The "Use Case: eMBB Offloading in Emergency Scenarios" section presents the representative eMBB offloading use case, including performance evaluations. Finally, the "Conclusion" section summarizes our contributions and discusses potential directions for future research.

Related Work

This section reviews existing literature in the field of integrated terrestrial, satellite, and aerial networks, focusing on communication, computation offloading, resource orchestration, and caching strategies tailored for critical and emergency scenarios.

Recent developments in integrated terrestrial and NTNs have primarily focused on leveraging the complementary characteristics of these systems. The integration of satellite and terrestrial networks has been extensively explored, as future sixth-generation (6G) networks will be undoubtedly based on a three-dimensional (3D) architecture encompassing jointly optimized terrestrial and non-terrestrial components [3]. In [5], an opportunistic federation strategy among satellite constellations is proposed to enhance Internet of Things (IoT) service capabilities in areas with limited terrestrial coverage. Integration of UAVs into terrestrial networks has emerged as another promising strategy due to their rapid deployment capabilities and flexibility in dynamic environments [6].

UAV-based communications face distinct challenges related to mobility, energy constraints, and dynamic network topologies. Trotta et al. [4] propose a framework for persistent crowd monitoring using UAV swarms, incorporating energy and mobility management techniques to ensure continuous operation. In [2], joint coverage, connectivity, and charging strategies for UAV networks are explored, highlighting how collaborative swarm behaviors can mitigate the inherent limitations of UAV systems.

Computation offloading is an essential technique enabling devices with limited computational resources to leverage external processing capabilities. Edge computing, particularly through UAV-assisted edge clouds, has been widely explored to facilitate near-user processing and minimize latency [7]. The papers in [8] and [9] propose edge-enabled cell-free massive MIMO systems to reduce computational offloading delays, emphasizing the significant improvements in user power consumption and quality-of-service (QoS) delivery. Furthermore, resource orchestration in UAV-aided networks is pivotal for maximizing system performance. Recent research in [10] investigates 5G sidelink communication techniques to facilitate cooperative multi-hop UAV swarm communications, aiming to optimize resource usage, minimize interference, and improve overall system reliability in harsh environments.

Data caching plays a vital role in alleviating bandwidth pressure and reducing access latency in integrated terrestrial and non-terrestrial systems. Reference [11] explores UAV caching strategies in hybrid satellite-terrestrial networks, demonstrating significant improvements in outage performance. The intelligent management of cached resources, particularly at aerial and satellite layers, is critical for delivering high-QoS applications, a topic increasingly gaining research attention [12].

Despite these advancements, existing research often addresses these aspects separately, without a unified approach integrating terrestrial, satellite, and UAV segments simultaneously for optimized communication, computation offloading, and caching in emergency scenarios. To address this gap, the RAIN4C framework presented in this paper proposes a cohesive and integrated solution explicitly tailored to support robust operations during critical events, significantly advancing the current state of the art.

Despite these advancements, existing research often addresses these aspects separately, without a unified approach integrating terrestrial, satellite, and UAV segments simultaneously for optimized communication, computation offloading, and caching. Moreover, the challenges that arise in emergency scenarios require further investigation to provide a truly reliable service in such situations. To address this gap, the RAIN4C framework presented in this paper proposes a cohesive and integrated solution explicitly tailored to support robust operations during critical events, significantly advancing the current state of the art. Unlike prior works on Space-Air-Ground Integrated Network (SAGIN) and Aerial Ad-hoc Network (AAN) that treat orchestration, caching, or UAV control separately, RAIN4C integrates these functions and validates them in a real testbed, bridging the gap between concept and deployable practice.

Motivation and Requirements

Modern emergency scenarios impose unique and stringent demands on communication infrastructures. Terrestrial networks, despite their ubiquity and reliability under normal conditions, often face partial or complete outages during emergencies due to physical damage, congestion, or power disruptions, critically impairing emergency response operations [2]. In contrast, satellite-based NTNs offer global connectivity that remains unaffected by local terrestrial failures. However, inherent satellite characteristics, such as relatively high communication latency, limited throughput, and considerable operational costs, restrict their practical application for latency-sensitive emergency tasks [5]. Complementarily, UAV networks promise rapid deployment, high adaptability, and flexible coverage; nevertheless, UAV systems face constraints including limited energy reserves, computational resource scarcity, and complex dynamic network coordination [4].

Addressing these combined terrestrial, aerial, and satellite challenges necessitates a carefully integrated multi-layer architecture, designed explicitly to leverage the complementary strengths of each layer while compensating for their individual limitations. Such a multi-layered emergency communication infrastructure must satisfy the following key requirements:

- *Reliable and Seamless Connectivity:* Ensuring uninterrupted network availability and robust connectivity is crucial. The integrated architecture must maintain stable communication links among terrestrial nodes, UAVs, and satellite segments, even in the presence of potential terrestrial disruptions or failures.
- *Efficient Computational Offloading:* Emergency operations increasingly require computationally intensive tasks such as real-time data analytics, machine learning-based decision support, and situational awareness applications. Hence, the architecture must effectively orchestrate computational workloads among terrestrial edges, UAV nodes, and satellite-based resources, forming an efficient edge-to-satellite computation continuum.
- *Adaptive UAV Swarm Management:* Given the highly dynamic and unpredictable nature of emergency scenarios, intelligent management of UAV resources is essential. UAV swarms should be capable of autonomously adapting their positioning and resource allocation strategies to optimize network coverage, extend battery life, and effectively respond to evolving conditions.
- *Multi-Layer Intelligent Data Caching:* To enhance reliability and responsiveness, critical data must be proactively cached across multiple layers—terrestrial, aerial, and satellite—ensuring rapid access and minimizing data retrieval latency, especially under intermittent connectivity conditions.
- *Hybrid Centralized-Distributed Orchestration:* A flexible orchestration approach is essential to dynamically balance centralized control and distributed decision-making. Such hybrid orchestration should offer scalability, responsiveness, and resilience, rapidly adapting to changing network states and resource availabilities inherent in emergency contexts.

To effectively address these critical requirements, we propose the RAIN4C framework that synergistically integrates terrestrial, aerial, and satellite network components into a cohesive multi-layer architecture specifically tailored for emergency response scenarios. As illustrated in Figure 1, RAIN4C leverages satellite networks for global backhaul connectivity, UAV swarms for dynamic, local network coverage and flexibility, and terrestrial infrastructures for baseline reliability. Computational resources are strategically distributed across terrestrial edges, aerial nodes, and satellites to achieve efficient computation offloading. Concurrently, multi-layer intelligent caching mechanisms proactively manage data resources, significantly enhancing system resilience and reducing service latency during emergencies.

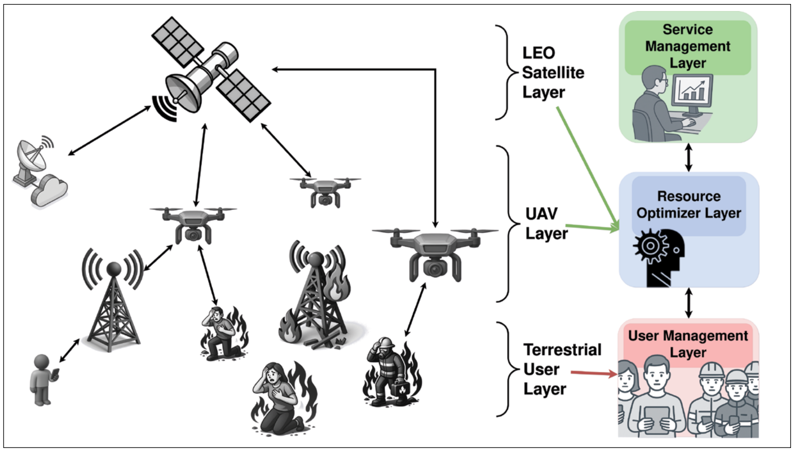

FIGURE 1. Scenario overview with integrated architectural roles. The figure highlights User, Resource Optimizer, and Service layers and their interactions across terrestrial, UAV, and satellite segments.

RAIN4C System Architecture

Traditional Infrastructure-as-a-Service (IaaS) systems typically adopt deployment strategies focused on optimizing resource usage and satisfying application constraints. Although such deployment schemas can dynamically respond to scaling needs or failures, emergency scenarios impose additional complexities such as UAV mobility, battery constraints, and highly dynamic communication demands. To address these specific demands, we propose the RAIN4C multi-layer system architecture (depicted in Figure 1, right part) explicitly designed for robust emergency and critical communications. Its innovation lies in seamlessly integrating terrestrial, UAV-based, and satellite segments into a coherent, resilient, and adaptive infrastructure, facilitating reliable support for demanding communication and computational tasks. The architecture comprises three interconnected logical layers: User Management Layer (UML), Service Management Layer (SML), and Resource Optimizer Layer (ROL).

User Management Layer

The UML is responsible for managing interactions with ground users, IoT sensors, and emergency response teams. It captures and categorizes data, tasks, and service requests, continuously tracking mobility patterns and communication link quality. Key UML functionalities include task and data request monitoring, real-time communication quality estimation, and context-aware event detection. By dynamically capturing user-centric information and environmental conditions, the UML provides essential input data to the upper layers, informing adaptive optimization and service management decisions.

Service Management Layer

The SML acts as a centralized administration layer, providing overall system control, status

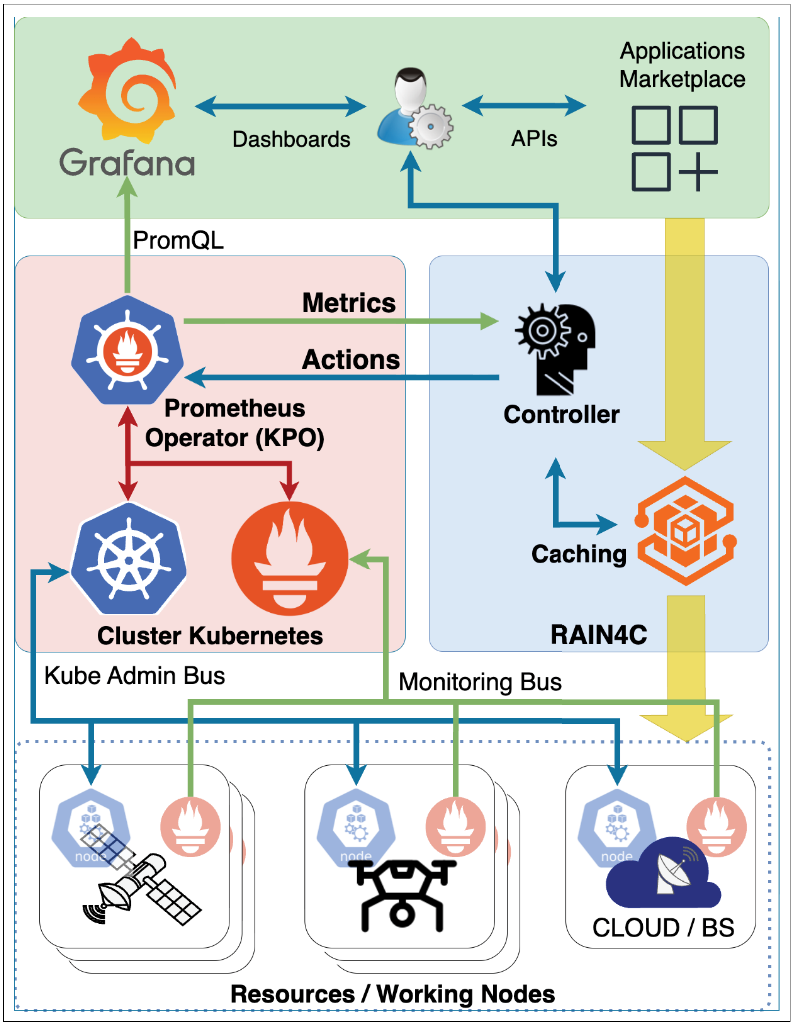

FIGURE 2. RAIN4C software components and interactions. Prometheus collects UAV/edge telemetry; the RAIN4C Controller orchestrates resources via Kubernetes; MQTT enables lightweight state dissemination; Grafana provides operational visibility through PromQL queries to the Prometheus.

monitoring, and strategic configuration. It maintains up-to-date information about available physical and virtual resources, including satellite links, UAVs, and terrestrial infrastructure. Through integrated visualization tools such as customized dashboards, the SML enables network administrators to monitor system status and make informed operational decisions promptly.

A key component of SML is the hybrid orchestration capability enabled by containerized frameworks. The orchestration strategy dynamically combines centralized control with distributed deployments, providing rapid adaptability to evolving emergency scenarios. Administrators can swiftly reconfigure services, manage QoS policies, and prioritize computational tasks based on real-time operational insights. Thus, the SML provides strategic administrative oversight, translating monitoring data into effective, adaptive network management actions suitable for highly dynamic scenarios.

Resource Optimizer Layer

The ROL constitutes the intelligent core of RAIN4C, responsible for dynamic and efficient resource optimization across the network. This layer comprises several integrated functional modules:

- **Drone Swarm Management:** This module dynamically optimizes UAV positions to maximize network coverage, balance energy consumption, and minimize latency. UAV mobility decisions must adapt in real-time to changing emergency conditions. Thus, trajectory control is crucial to ensure reliable service continuity. Strategic management of UAV recharging stations further enhances operational longevity.
- **Task Management and Computational Offloading:** closely interacting with the UML and SML, this module allocates computational tasks dynamically across terrestrial edges, UAV nodes, and satellite resources. It supports flexible transitions between centralized satellite-based computation and distributed UAV or terrestrial-edge processing, creating a hybrid computational continuum responsive to varying demands.
- **Network Configuration Optimization:** this module systematically manages network parameters such as transmission power, channel selection, and antenna configurations (e.g., MIMO technology). Real-time adjustments accommodate changing channel states, mobility patterns, and user demands, ensuring resilient, high-performance connectivity.
- **Intelligent Data Caching:** this component implements proactive multi-layer caching strategies, strategically distributing critical data across UAVs and satellite nodes to minimize latency and bandwidth usage. Employing predictive analytics and machine learning methods, caching decisions are dynamically adjusted to anticipate data demand patterns, enhancing system responsiveness and reliability.

By integrating UAV mobility management, computational task orchestration, adaptive network optimization, and intelligent caching, the ROL ensures effective cross-layer resource utilization. As a result, the RAIN4C architecture substantially enhances overall network reliability and performance, meeting the critical communication requirements inherent in emergency and disaster-response scenarios. The design of RAIN4C draws on SAGIN/AAN architectures and extends them by explicitly combining orchestration, intelligent caching, and UAV swarm management in a single layered workflow validated on a Kubernetes-based UAV testbed.

RAIN4C Implementation and Deployment

This section describes the practical implementation strategy adopted to realize the RAIN4C architecture and achieve the functionalities envisioned in the previous sections. While the RAIN4C framework defines a multi-layered conceptual structure, its effective deployment leverages carefully selected software solutions and integration strategies, enabling robust orchestration, efficient resource management, and comprehensive system monitoring.

Prometheus-Based System Information Collection

Prometheus is adopted as the monitoring backbone for UAV-based execution nodes. Its time-series data model and pull-based scraping mechanism enable continuous collection of critical UAV metrics such as position, CPU, memory, and battery, supporting intelligent deployment and scheduling decisions.

A key advantage of Prometheus lies in its ability to handle multidimensional data through labels, which aligns well with UAV nodes' heterogeneous and ephemeral characteristics. For example, metrics like UAV position (latitude, longitude, altitude) and resource status can be tagged and queried efficiently using Prometheus Query Language (PromQL), allowing RAIN4C to make informed orchestration choices in near real-time. Prometheus also supports a wide range of exporters, i.e., modular components that expose system and application metrics in a standardized format. In our context, exporters enable seamless integration with UAV telemetry (e.g., battery levels, CPU load, and geographic position) as well as with Kubernetes resource indicators, ensuring that heterogeneous data sources can be uniformly monitored and leveraged for orchestration decisions. Prometheus federation and alerting allow RAIN4C to detect anomalies (e.g., low battery, node failures) across distributed UAVs, enhancing reliability. Combined with Grafana, this supports intuitive operator monitoring.

The RAIN4C controller consumes the metrics monitored by Prometheus through the Prometheus HTTP API, specifically leveraging the endpoints to retrieve real-time or historical time-series data. The controller periodically sends HTTP requests to Prometheus to fetch critical metrics, such as UAV battery levels, CPU usage, and geographic positions (GIS), using PromQL to filter and aggregate the data based on specific criteria (e.g., geographic area, battery thresholds). RAIN4C may also use Prometheus's alerting features, subscribing to specific alert rules, which are exposed as webhooks, enabling proactive decision-making and orchestration adjustments.

Hybrid Task Orchestration via Kubernetes

Our custom controller interacts with Kubernetes and Prometheus API to retrieve real-time telemetry, such as energy consumption, GIS position, and CPU load. These operational metrics inform dynamic scheduling decisions across a heterogeneous infrastructure of UAVs, terrestrial edge nodes, and satellite-linked terminals. The RAIN4C Controller extends the default Kubernetes scheduling behavior through a modular plugin interface, allowing us to prioritize energy efficiency and latency sensitivity in task allocation [13].

Support for custom resource definitions allows domain-specific orchestration policies [14]. The hybrid strategy combines centralized scheduling with localized execution, improving resilience and responsiveness. The integration of the custom controller into the Kubernetes ecosystem is accomplished using the controller-runtime library from the Kubernetes Special Interest Group (SIG) project using the Go language. The controller watches for changes in custom resource definitions that encapsulate workload specifications and associated constraints, such as energy budgets or latency thresholds, as well as the future state, like the final trajectory of UAVs. The controller reconciler periodically queries Prometheus through its HTTP API (e.g., /api/v1/query) to retrieve up-to-date metrics such as node-cpu-seconds-total, node-network-receive-bytes-total, and node-power-draw-watts. This data is parsed and normalized before being fed into a scoring function that extends the Kubernetes Scheduler Framework, specifically by implementing a custom Score and Filter plugin.

During scheduling, the Kubernetes scheduler invokes the custom plugin, which evaluates node suitability by computing a composite score based on real-time metrics. These scores are then used to rank candidate nodes for pod placement. The plugin is registered by modifying the scheduler's configuration file (typically kube-scheduler-config.yaml), where the custom scheduler name and plugin weights are specified under the profiles and plugins sections. To ensure high availability and scalability, the controller is deployed as a Kubernetes Deployment and uses leader election to manage failover. This architecture allows our system to dynamically and intelligently adapt task placement decisions across heterogeneous edge environments in real time while fully compliant with Kubernetes's native orchestration mechanisms.

Monitoring and Visualization via Grafana

The SML includes a centralized visualization and monitoring component built using Grafana, a widely adopted open-source analytics and visualization platform. Grafana provides dashboards for real-time monitoring of UAV metrics, energy, and caching efficiency, enabling operators to supervise complex deployments.

Grafana is configured to work directly with Prometheus, which collects and stores time-series data, while Grafana queries this data to generate dynamic dashboards, offering a centralized and interactive overview of system metrics. This integration is through the HTTP API, allowing it to retrieve metrics data through PromQL expressions, enabling real-time visualization of key telemetry, including UAV positions via GPS coordinates, CPU and GPU utilization of edge computing nodes, battery levels, network throughput, and latency figures. Grafana's data source configuration allows setting up Prometheus as a back-end, specifying query intervals, and using templating to filter data per UAV or node cluster. Additionally, Grafana supports annotations to mark events like task deployments or UAV handovers, enriching the temporal context of data visualization. Using the RESTful HTTP API, dashboards can be programmatically created, updated, and deleted, allowing for dynamic generation based on application mission parameters or operator roles. For instance, each UAV can have a dedicated dashboard generated through API calls using a dashboard JSON schema. This approach reduces manual configuration and supports infrastructure-as-code paradigms [15].

Caching Implementation and Data Flow Management

Efficient data caching and flow management are crucial for mitigating latency and ensuring service continuity under emergency conditions. The proposed RAIN4C implementation leverages distributed in-memory caching solutions such as Redis or Hazelcast to facilitate rapid access to frequently requested data items across different layers of the network. UAV nodes are equipped with local caching instances to reduce latency for ground users, while selected UAVs periodically synchronize their caches to maintain consistency and efficiency across the swarm.

Predictive caching algorithms, integrated within UAV nodes, proactively distribute and update data caches based on anticipated demand patterns derived from historical and real-time usage analytics. Cached data are also periodically synchronized with satellite repositories to enable data persistence and redundancy. Such a multi-layer caching strategy significantly reduces data retrieval latency and bandwidth consumption, thus enhancing overall system responsiveness and reliability.

System Information Sharing via Lightweight Protocols

Reliable system-wide information dissemination is critical for dynamic decision-making, network adaptation, and optimization. RAIN4C implements lightweight, publish-subscribe communication protocols, such as the Message Queuing Telemetry Transport (MQTT), to facilitate efficient and reliable sharing of network state and status information among devices and orchestration layers.

MQTT, in particular, is well-suited to RAIN4C scenarios due to its minimal overhead, scalability, and robustness in constrained and intermittent network conditions. UAVs, ground devices, and satellites publish status updates—including energy consumption, channel quality indicators, mobility information, and computational loads—to MQTT brokers deployed within the aerial swarm or on selected ground nodes. Subscribing modules within ROL and SML receive real-time data updates, continuously adjusting their optimization strategies, mobility coordination, and computational offloading decisions accordingly. Moreover, the adoption of MQTT's QoS mechanisms ensures reliable delivery of critical system information, even under challenging and dynamic conditions typical of emergency scenarios. This lightweight and reliable information-sharing solution supports agile and adaptive operations across the entire RAIN4C architecture.

Fig. V illustrates the software architecture of the RAIN4C framework. Users and operators interact with the system by submitting applications and monitoring the environment via Grafana dashboards, which are seamlessly integrated with the Kubernetes Prometheus Operator (KPO). Leveraging the API exposed by the KPO, the optimization and management algorithms within the RAIN4C Controller orchestrate resources across a Kubernetes-based infrastructure. This infrastructure incorporates UAVs, satellites, base station (BS) resources, and cloud continuum components as cluster nodes. On each of these nodes, specialized agents collect and expose custom metrics to Prometheus, enabling fine-grained and adaptive resource orchestration.

Use Case: eMBB Offloading in Emergency Scenarios

To concretely demonstrate the benefits and practicality of the RAIN4C architecture introduced in the "RAIN4C System Architecture" section, we present an eMBB offloading scenario explicitly designed for emergency communications. This representative scenario emphasizes the critical role of the RAIN4C orchestration mechanism—primarily the ROL—in effectively managing resources across terrestrial, UAV, and satellite networks, particularly when terrestrial 5G infrastructure faces congestion or disruptions.

Scenario Description

We consider a three-layered network scenario comprising ground eMBB users, UAV swarms, and a hybrid terrestrial-satellite communication infrastructure. Ground users, such as emergency response teams and first responders, require robust, high-throughput communication links managed via the UML. We assume the terrestrial 5G BS is operational but heavily congested or partially impaired, limiting its capacity to serve all ground users adequately.

In this scenario, each ground user, whose requests and connectivity statuses are monitored by the UML, has three potential connectivity options:

- Direct terrestrial 5G-BS connectivity.
- UAV connectivity in *relay mode*, in which UAVs forward user traffic to the terrestrial 5G-BS.
- UAV connectivity in *satellite-offloading mode*, in which UAVs forward traffic directly to the satellite network.

We assume UAV positions are dictated by mission requirements external to the RAIN4C orchestration process; therefore, the orchestrator (implemented within the ROL) is responsible solely for the allocation of UAV communication and computational resources rather than their flight trajectories or physical positions. This choice is motivated by the will to isolate orchestration effects from trajectory control, which will be a future research direction.

Orchestration Mechanism

The orchestration mechanism within the ROL continuously monitors critical Key Performance Indicators (KPIs) obtained through the UML, such as ground-to-BS (G2BS), ground-to-air (G2A), air-to-BS (A2BS), and air-to-satellite (A2Sat) link qualities, alongside user QoS requirements. Additionally, the orchestrator integrates real-time telemetry provided by the UAV swarm management module, including battery status, computational resource availability, and UAV positions; however, in this analysis, we primarily focus on bandwidth availability and QoS requirements.

Based on these metrics collected by the SML through Prometheus and visualized in Grafana dashboards (as detailed in the "RAIN4C Implementation and Deployment" section), the orchestrator dynamically configures UAV nodes into:

- *Relay mode*, leveraging the Line-of-Sight (LoS) connections between UAVs and the terrestrial 5G-BS to alleviate congestion.
- *Satellite-offloading mode*, forwarding user data directly via satellite links, thus reducing terrestrial network load and enhancing communication robustness.

The orchestrator (i.e., ROL) aims to maximize the proportion of ground users whose QoS requirements are fully satisfied. Formally, the orchestration logic is expressed as follows:

- Let $\mathcal{E} = \{e_1, \ldots, e_{N_e}\}$ represent the set of the ground eMBB users, whose cardinality is N_e. Each user e_j, $j = 1, \ldots, N_e$, is characterized by a required bandwidth req_{e_j} in bytes/s, managed by the Task Request Monitor module within the UML. The set of the N_u UAVs available in the network is denoted by $\mathcal{U} = \{u_1, \ldots, u_{N_u}\}$. Each UAV is capable of operating in both 5G relay and satellite-offloading modes.
- The subset $\mathcal{E}_{\text{off}} \subseteq \mathcal{E}$ includes ground users inadequately served directly by the terrestrial BS, becoming candidates for UAV-supported offloading.
- We define $\mathcal{E}_{\text{off}}^{u_i} \subseteq \mathcal{E}_{\text{off}}$ as the subset of the ground users served by the UAV u_i, $i = 1, \ldots, N_u$, ensuring the condition $\bigcup_{u_i \in \mathcal{U}} \mathcal{E}_{\text{off}}^{u_i} \subseteq \mathcal{E}_{\text{off}}$.
- We define the *effective bandwidth* for user e_j, bw_{e_j}, as the maximum achievable bandwidth considering all the possible end-to-end connection paths (i.e., direct terrestrial, UAV-relay, and UAV-satellite offload). For each candidate path, the effective bandwidth is computed as the *minimum* bandwidth among its constituent links, since the end-to-end capacity is constrained by the bottleneck link along the route.
- The binary decision variable $\text{ol}_{\text{sat}}^{u_i}$ indicates the operational mode for UAV u_i: satellite-offloading mode (1) or relay mode (0).
- The optimization problem solved by the ROL's optimization module is concisely formulated as:

$$\text{find}: \quad \left\{\mathcal{E}_{\text{off}}^{u_i}, \text{ol}_{\text{sat}}^{u_i}\right\} \ \forall u_i \in \mathcal{U}$$

$$\text{maximize}: \quad \Phi = \frac{1}{|\mathcal{E}|} \sum_{e_j \in \mathcal{E}} s_{e_j}$$

$$\text{subject to}: \quad s_{e_j} = \begin{cases} 1 & \text{if } \text{bw}_{e_j} \geq \text{req}_{e_j}, \\ 0 & \text{otherwise.} \end{cases}$$

Due to real-time constraints and the computational complexity of optimal decision-making, heuristic methods such as genetic algorithms are employed within the optimization module of the ROL to efficiently derive near-optimal solutions. We intentionally keep the formulation concise to emphasize practical implementation feasibility and empirical validation through both simulation and real-world testbed experiments, rather than extended mathematical modeling.

Performance Evaluation

We validate RAIN4C through two complementary approaches: (i) a simulation-based analysis employing the *LL-Sim5G* simulator[1], and (ii) an experimental validation through a real-world UAV-based orchestration setup. The SML and ROL support both evaluation environments by monitoring relevant metrics and dynamically managing resource allocations.

Key performance metrics analyzed include:

- *Maximization Index* (Φ): the fraction of eMBB users whose QoS requirements are satisfied by RAIN4C compared to baseline strategies.
- *Average Service Downtime:* the time during which a service is unavailable while the orchestrator (ROL) reconfigures workloads across UAV nodes, reflecting responsiveness.

Parameter	Value
Scenario area	1000 × 1000 m, urban
Links	Downlink, satellite backhaul
Carrier frequencies	28 GHz (5G-BS), 3.5 GHz (UAV), 2 GHz (satellite)
Channel bandwidth	≈ 36MHz per link
Numerology / SCS	$\mu = 2$ (60 kHz subcarrier spacing)
TX power	20 dBm (5G-BS/UAV), 45 dBm (satellite)
Antenna gain	10 dBi (5G-BS), 12 dBi (UAV), 50 dBi (satellite)
Propagation model	LOS/NLOS, shadowing, fast fading (Jakes)
Users	Varied across runs, height 1.5 m
User mobility	Random Waypoint, 0.4–1.2 m/s
UAV relays	Varied across runs, height 100 m
Satellite altitude	~5.3 × 10^5 m, elev. angle 85°

TABLE 1. Simulation setup (main parameters).

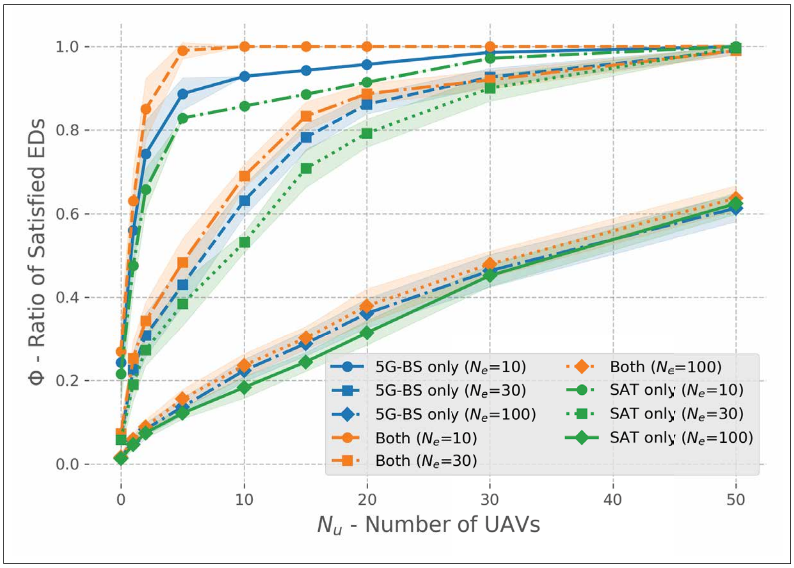

FIGURE 3. Ratio of satisfied eMBB ground users under different orchestration strategies.

1) Maximization Index Analysis: In the simulation-based experiment, we vary the number of ground users to evaluate the effectiveness of the orchestration mechanism in maximizing user satisfaction. The implemented genetic algorithm serves as the optimization strategy within the ROL, focusing on bandwidth allocation efficiency across terrestrial, UAV, and satellite segments. Table 1 summarizes the main simulation parameters used in the orchestration evaluation.

Fig. 3 compares the maximization index (Φ) obtained by RAIN4C with baseline approaches, including direct terrestrial (no offloading), relay-only, and satellite-only solutions. The results clearly demonstrate RAIN4C's capability to dynamically leverage UAV resources managed by the ROL, substantially outperforming isolated baseline strategies. Moreover, the results highlight the importance of exploiting the presence of UAVs for eMBB offloading.

[1] https://github.com/EFontesP90/LLSim5G

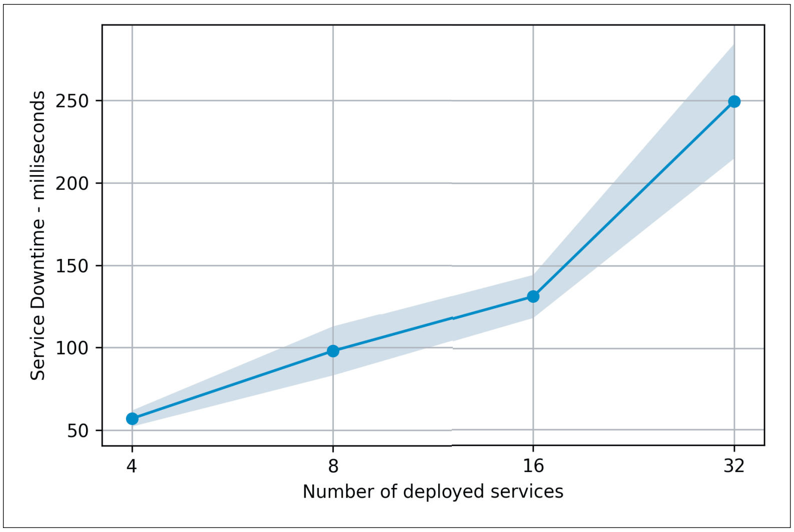

FIGURE 4. Average service downtime after a battery failure vs. the number of deployed services, illustrating RAIN4C orchestration responsiveness.

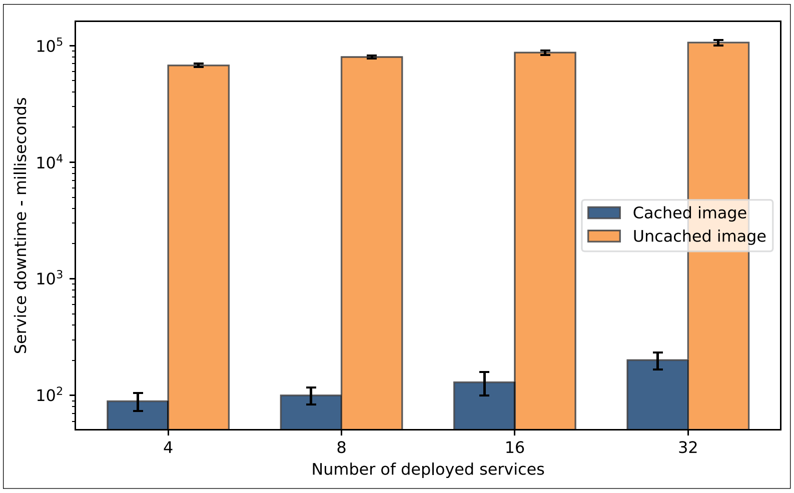

FIGURE 5. Impact of image caching on re-orchestration downtime. Bars show mean values with 99% confidence intervals over 30 runs.

2) Average Downtime Analysis (Experimental Validation): For the real-world experimental validation, we implement a Kubernetes-based orchestration setup (managed through the SML) with two quadcopter UAVs (*Holybro X650*[2]), each equipped with a Raspberry Pi 5 node, coordinated from a Dell XPS-13 acting as the control station. This setup assesses the system's responsiveness, specifically in scenarios involving UAV battery depletion events, triggering rapid re-orchestration by the ROL.

Fig. 4 illustrates the average service downtime versus the number of microservices deployed. Results confirm that the orchestration logic of RAIN4C maintains fast and predictable response times suitable for emergency scenarios, demonstrating scalability and responsiveness managed by the SML and ROL layers. The experimental procedure involved emulating 10 battery depletion events, with 30 repetitions executed per workload. The resulting data are presented with a 99% confidence interval.

To further validate the role of multi-layer caching, we conducted an additional experiment explicitly comparing the re-orchestration downtime with and without cached container images. As illustrated in Fig. VI-C2, when a 50 MB image is forced to be re-pulled during pod migration, the service downtime increases from less than 0.2 seconds to more than one minute, depending on the workload. This corresponds to an improvement of more than two orders of magnitude across different pod counts. The results confirm that caching is a first-order mechanism to guarantee responsiveness under emergency conditions.

These caching results complement the maximization index analysis (Fig. 3) and the downtime validation (Fig. 4), providing a multi-dimensional evaluation aligned with RAIN4C's reliability and responsiveness goals.

Conclusion

In this paper, we introduced RAIN4C, a novel multi-layer architecture that integrates terrestrial, UAV, and satellite communication segments to address critical communication needs in emergency scenarios. By leveraging advanced technologies, including hybrid orchestration, UAV-based edge computing, intelligent caching, and adaptive network management, RAIN4C ensures reliable, robust, and responsive communication even when terrestrial infrastructure is impaired or overloaded. We demonstrated the effectiveness of the proposed architecture through a representative use case focused on eMBB offloading. Simulation and experimental evaluations highlighted RAIN4C's capability to significantly enhance user satisfaction and maintain rapid service deployment, consistently outperforming traditional single-layer strategies. The results underscore the importance of dynamic resource orchestration, particularly the strategic allocation of UAV communication resources between terrestrial relay and satellite offloading modes. The combination of simulation-based orchestration analysis and real-world testbed validation, including the new caching experiments, highlights the practical contribution of RAIN4C beyond theoretical frameworks.

Future research will explore further optimization of orchestration strategies, incorporating predictive and AI-driven mechanisms for improved UAV resource management and QoS-aware service allocation. Additionally, large-scale experiments with extended UAV swarms and integration of diverse IoT devices will further validate RAIN4C's scalability and practical applicability to real-world emergency response operations. An additional research direction will be the integration of UAV trajectory optimization with the orchestration logic already embedded in the ROL to jointly coordinate connectivity, caching, and positioning in highly dynamic scenarios.

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