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Integrated UAV-Satellite Communication Architecture with NOMA-based Multi-link Connectivity for Secure and Resilient Wireless Networks

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Abstract

This paper proposes an integrated UAV–satellite communication architecture designed to improve wireless connectivity in dynamic, infrastructure-limited, and contested environments. The framework combines UAV relay platforms, satellite communication, LTE links, cloud-based coordination, and NOMA mechanisms to enhance coverage, spectral efficiency, and service continuity. It also addresses security risks such as interception, interference, and communication disruption. The proposed architecture is applicable to tactical communications, emergency response, critical infrastructure protection, and future beyond-5G/6G networks.

Keywords:
UAV Communication; Satellite Communication; NOMA;
Tactical Networks; Secure Communication; 6G.

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1. Introduction

The rapid development of wireless technologies has significantly transformed modern information exchange, enabling continuous connectivity across civilian, industrial, and defense sectors. In recent years, Unmanned Aerial Vehicles (UAVs) have emerged as an important component of next-generation wireless systems due to their mobility, rapid deployment capability, and ability to operate in environments where conventional infrastructure is unavailable, damaged, or operationally limited. UAV-assisted platforms can provide temporary or persistent network coverage in remote geographic regions, disaster-affected zones, military operations, and emergency response scenarios where traditional terrestrial systems cannot ensure reliable service availability (Vinogradov et al. 2019; Liu et al. 2020).

The integration of UAV platforms into wireless networks has attracted considerable attention from both the research community and industry because of their ability to support adaptive network deployment and dynamic resource management. UAVs can function as aerial base stations, relay nodes, or wireless gateways that extend the reach of terrestrial infrastructure and enhance service delivery in challenging operational conditions. Their capability to maintain line-of-sight links with ground terminals and neighboring aerial nodes makes them suitable for high-data-rate transmission, reduced propagation loss, and improved signal stability in urban, rural, and infrastructure-constrained environments (Cui et al. 2020; Greenberg, Bar, and Klodzh 2019).

The continuous evolution of fifth-generation (5G) and future sixth-generation (6G) wireless systems has further increased the importance of UAV-assisted architectures. Modern wireless environments require high spectral efficiency, low latency, reliable connectivity, and flexible network management to support large numbers of connected devices and mission-critical services. UAV-enabled platforms contribute to these requirements by providing adaptive network structures capable of dynamically allocating resources according to environmental conditions, user distribution, and operational demands (Duong et al. 2022; Lu et al. 2021).

Beyond extending network coverage, UAV platforms facilitate the integration of heterogeneous wireless technologies within a unified networking framework. Hybrid architectures may combine terrestrial cellular infrastructure, satellite systems, and local wireless data links to ensure uninterrupted service under varying operational conditions. Satellite systems provide wide-area and long-distance connectivity, while cellular infrastructure offers high-capacity access in urban and semi-urban regions. The combination of these technologies with UAV relay platforms enables the development of resilient networking solutions capable of supporting both civilian and defense-related missions, including tactical operations and critical infrastructure protection (Xu, Kishk, and Alouini 2023; Xiong, Chen, and Ying 2025).

Recent research has also emphasized the importance of advanced multiple-access mechanisms for improving network efficiency in dense wireless environments. Non-Orthogonal Multiple Access (NOMA) has been proposed as an effective technique for enhancing spectral efficiency and supporting simultaneous access by multiple users within the same frequency resources. Unlike conventional orthogonal schemes, NOMA allows multiple users to share identical channels through power-domain multiplexing and differentiated power allocation. This approach increases network capacity and throughput while improving spectrum utilization. The integration of NOMA with UAV-assisted systems enables aerial platforms to support larger numbers of connected users and achieve higher performance in dynamic operational scenarios (Shen and Ochiai 2021; Kieu-Xuan and Le-Thi 2024).

Despite these advantages, several technical and security challenges remain associated with the deployment and management of UAV-assisted wireless systems. One of the major challenges involves efficient resource coordination in highly dynamic environments characterized by UAV mobility, changing network topologies, and variable user distribution. Effective interaction between aerial relay nodes, terrestrial infrastructure, satellite systems, and centralized management platforms is required to maintain stable connectivity and optimize resource utilization (Qian et al. 2023; Jung et al. 2023).

Security represents another critical concern. Due to the broadcast nature of wireless channels and the exposed operational characteristics of aerial platforms, UAV-enabled networks are vulnerable to signal interception, jamming, malicious interference, and unauthorized access. Adversarial entities may attempt to disrupt network operations, intercept sensitive information, or degrade service availability during tactical and mission-critical activities. Consequently, the development of secure and resilient UAV communication architectures has become an important research direction in both civilian applications and defense-oriented network environments (Michailidis et al. 2022; Mustafovski 2025).

The integration of satellite systems, UAV relay platforms, and advanced wireless access mechanisms provides a promising approach for addressing many of these operational and security challenges. Multi-layer architectures combining aerial, terrestrial, and satellite segments can enhance network robustness, extend coverage, and maintain dependable service delivery in complex environments. Such solutions are particularly applicable to emergency response coordination, environmental monitoring, intelligent transportation systems, wireless sensor networks, border surveillance, tactical communications, and operations conducted in infrastructure-degraded regions (Hu et al. 2024; Gao et al. 2025).

In this context, the development of integrated UAV-assisted networking architectures represents an important research direction for future wireless systems. By combining heterogeneous communication technologies, advanced user-access mechanisms, and centralized coordination, it is possible to create scalable and adaptive infrastructures capable of supporting diverse operational requirements. Recent research efforts have focused on enabling efficient interaction between UAV platforms, satellite systems, terrestrial infrastructure, and cloud-based management solutions in order to improve reliability, operational effectiveness, and overall network performance (Hu et al. 2026; Eskandari and Savkin 2024; Mustafovski, Risteski, and Shuminoski 2025a).

This paper presents an integrated UAV-satellite communication architecture that incorporates multi-link connectivity, centralized network control, and NOMA-based user access mechanisms within a unified networking environment. The proposed framework is designed to support reliable and secure wireless services in tactical operations, emergency response scenarios, disaster-affected regions, and infrastructure-limited environments. In addition, the study introduces a conceptual threat-aware model that considers signal interception, malicious interference, and service continuity within heterogeneous wireless networks.

2. Security and Defense Relevance

Reliable communication infrastructure represents one of the fundamental operational requirements in modern security and defense environments. Military operations, crisis response activities, border surveillance missions, and critical infrastructure protection increasingly depend on the availability of secure, adaptive, and resilient wireless communication systems capable of maintaining operational continuity under dynamic and contested conditions. Conventional terrestrial communication infrastructure may become unavailable or degraded due to natural disasters, cyber-attacks, physical destruction, electronic warfare activities, or geographic limitations. In such environments, the ability to rapidly establish communication links and maintain uninterrupted information exchange becomes essential for command coordination, situational awareness, and operational decision making (Li and Shang 2025).

The integration of Unmanned Aerial Vehicles into wireless communication architectures provides important operational advantages for defense and security-related applications. UAV platforms can be rapidly deployed as aerial relay nodes, temporary communication gateways, or airborne access points capable of extending wireless coverage in areas where fixed infrastructure is damaged or inaccessible. Their mobility and elevated operational position enable the establishment of line-of-sight communication links between dispersed operational units, command centers, emergency response teams, and mobile users operating in complex terrain conditions. This capability is particularly important in tactical communication environments where communication continuity must be preserved despite rapidly changing operational conditions and limited infrastructure availability (Guo and Yang 2022).

The proposed UAV-satellite communication architecture is especially relevant for mission-critical communication scenarios that require resilient multi-layer communication support. By integrating satellite communication systems, LTE communication infrastructure, local digital communication links, and UAV-based aerial relay platforms, the architecture enables communication redundancy and adaptive communication routing across heterogeneous wireless technologies. Such integration allows operational communication traffic to be redirected through alternative communication pathways when primary communication links experience degradation, interference, or physical disruption. This capability supports communication continuity during military operations, disaster response coordination, search and rescue activities, and emergency management scenarios. Similar multi-link UAV communication concepts integrating satellite, cellular, and cloud-based communication infrastructures have been explored in practical UAV communication architectures such as MAVNet (Oak Ridge National Laboratory 2020). Furthermore, the integration of NOMA mechanisms with UAV communication platforms has been shown to improve spectral efficiency and support simultaneous multi-user communication in wireless environments characterized by increasing communication demand (Thi Tam et al. 2023).

Another important aspect of the proposed framework is its relevance to communication security and operational resilience in contested wireless environments. Modern defense communication systems are increasingly exposed to threats such as communication jamming, signal interception, malicious interference, and unauthorized network access. Adversarial entities may attempt to disrupt communication availability or compromise sensitive operational information transmitted through wireless communication channels (Michailidis et al. 2022; Mustafovski 2025). The architecture presented in this study incorporates conceptual threat-aware communication modeling that considers interference sources, eavesdropping scenarios, and communication disruption attempts within the wireless environment. The integration of multiple communication technologies and centralized network coordination improves the ability of the communication system to maintain operational functionality even under degraded or hostile communication conditions (Qian et al. 2023; Jung et al. 2023; Mustafovski, Risteski, and Shuminoski 2025b).

The incorporation of Non-Orthogonal Multiple Access mechanisms further enhances the operational applicability of the framework in dense communication environments where large numbers of users and communication devices require simultaneous network access. Tactical operations, emergency response deployments, and critical infrastructure monitoring systems often involve communication congestion caused by multiple active users operating within limited communication resources. NOMA-based communication improves spectral efficiency and enables more efficient utilization of wireless communication channels, thereby supporting increased communication capacity and improved operational coordination (Shen and Ochiai 2021; Kieu-Xuan and Le-Thi 2024; Thi Tam et al. 2023).

Overall, the proposed integrated UAV-satellite communication architecture provides a scalable and operationally relevant framework for supporting secure and resilient wireless communication in defense, security, and crisis management environments characterized by dynamic operational conditions, infrastructure limitations, and increased communication security challenges (Xu, Kishk, and Alouini 2023; Eskandari and Savkin 2024; Mustafovski, Risteski, and Shuminoski 2025c).

3. Research Hypotheses

The increasing integration of Unmanned Aerial Vehicles, satellite communication systems, heterogeneous wireless technologies, and advanced multiple access mechanisms within modern wireless communication environments has introduced new opportunities for improving communication resilience, operational continuity, and network flexibility in complex operational scenarios. However, the effectiveness of such integrated communication architectures depends on the ability of the system to maintain reliable connectivity, efficiently allocate communication resources, and preserve communication continuity under dynamic environmental and operational conditions. In order to examine the operational capabilities and communication performance of the proposed UAV-satellite communication architecture, this study establishes a set of research hypotheses associated with communication availability, spectral efficiency, network resilience, and communication security.

The first research hypothesis assumes that the integration of UAV relay platforms with satellite communication systems, LTE communication infrastructure, and local digital communication links improves communication availability and operational continuity compared with conventional single-link communication architectures. The proposed framework incorporates multiple communication pathways capable of supporting adaptive communication routing and communication redundancy in environments where terrestrial infrastructure may be unavailable, degraded, or exposed to operational disruptions. This hypothesis is particularly relevant for tactical communication environments, emergency response operations, and infrastructure-limited scenarios where communication continuity represents a critical operational requirement.

The second research hypothesis is associated with the implementation of Non-Orthogonal Multiple Access mechanisms within the proposed communication framework. The hypothesis assumes that NOMA-based communication improves spectral efficiency and increases communication capacity by enabling simultaneous communication among multiple users within shared communication resources. The integration of NOMA-based access mechanisms with UAV-assisted communication platforms is expected to support more efficient utilization of available communication bandwidth and improve communication performance in dense wireless communication environments characterized by large numbers of connected users and communication devices.

The third research hypothesis focuses on the operational resilience of the integrated communication architecture under dynamic communication conditions and potential communication disruptions. The hypothesis assumes that the combination of satellite communication systems, UAV relay platforms, and centralized network coordination reduces communication outage probability and improves communication stability in environments exposed to interference, communication congestion, or infrastructure degradation. The proposed multi-layer communication architecture is expected to provide adaptive communication support through alternative communication pathways capable of maintaining operational connectivity during communication failures or degraded network conditions.

The fourth research hypothesis examines the role of centralized network management and adaptive communication coordination within the proposed framework. This hypothesis assumes that cloud-based network coordination and dynamic communication link selection improve communication reliability, optimize communication resource allocation, and reduce the operational impact of communication interference and malicious disruption attempts. The integration of centralized network control mechanisms is expected to support efficient interaction between aerial communication nodes, terrestrial communication infrastructure, and satellite communication systems under varying operational conditions.

The final research hypothesis is related to the security and operational applicability of the proposed architecture within defense and mission-critical communication environments. The hypothesis assumes that the integration of heterogeneous wireless communication technologies and threat-aware communication modeling enhances communication resilience against signal interception, malicious interference, and communication disruption attempts. The proposed framework is expected to support secure and reliable communication operations in tactical environments, disaster response coordination, critical infrastructure protection, and other mission-critical communication scenarios requiring continuous and resilient wireless connectivity.

4 Proposed Architecture and Methodology

4.1. Architecture Overview

The methodological framework proposed in this study is focused on the design and analytical evaluation of an integrated UAV-satellite communication architecture intended to support secure, adaptive, and continuous wireless connectivity in dynamic operational environments. The proposed architecture combines satellite communication systems, aerial relay platforms, terrestrial wireless infrastructure, and Non-Orthogonal Multiple Access-based communication mechanisms within a unified multi-layer communication environment. The framework is developed to support communication continuity in scenarios characterized by infrastructure degradation, communication congestion, operational mobility, and potential communication threats. Particular emphasis is placed on tactical communication environments, emergency response operations, disaster-affected regions, and infrastructure-limited areas where reliable communication services are essential for operational coordination and information exchange (Liu et al. 2020; Xu, Kishk, and Alouini 2023; Mustafovski 2025).

The proposed communication architecture is structured as a multi-layer wireless communication environment composed of interconnected aerial, terrestrial, and satellite communication segments coordinated through centralized network management. UAV platforms operate as adaptive aerial relay nodes capable of establishing communication links between mobile users, terrestrial communication infrastructure, and satellite communication systems. By integrating heterogeneous wireless communication technologies within a common operational architecture, the framework enables communication traffic to be dynamically distributed across multiple communication pathways according to network conditions, communication requirements, and operational constraints (Eskandari and Savkin 2024; Hu et al. 2024; Jung et al. 2023).

Within architecture, UAV relay platforms perform an important operational role by extending communication coverage and supporting communication continuity in environments where direct communication between users and fixed communication infrastructure may not be possible. The elevated operational position of UAV platforms enables the establishment of line-of-sight communication links with ground devices and neighboring communication nodes, thereby reducing signal obstruction and propagation loss caused by buildings, terrain irregularities, vegetation, or infrastructure limitations (Cui et al. 2020; Greenberg, Bar, and Klodzh 2019). In addition to extending communication range, UAV relay nodes facilitate the interaction between terrestrial communication infrastructure and satellite communication systems, allowing communication services to remain operational under changing environmental and operational conditions (Hu et al. 2026; Xiong, Chen, and Ying 2025; Li and Shang 2025).

The integrated architecture incorporates satellite communication systems as a long-range communication layer responsible for supporting beyond line-of-sight connectivity and communication continuity in remote or infrastructure-degraded environments. Satellite communication links provide operational redundancy by enabling UAV platforms and centralized network control systems to maintain communication even when terrestrial communication infrastructure experiences disruption or limited coverage (Li and Shang 2025; Hu et al. 2024; Gao et al. 2025). LTE communication channels and local digital communication links are additionally incorporated within the framework to support short-range and medium-range wireless communication between aerial nodes, mobile users, and terrestrial communication infrastructure. The combination of multiple communication technologies within a unified operational environment improves communication flexibility, enhances network resilience, and enables adaptive communication routing according to current network conditions and operational requirements (Xu, Kishk, and Alouini 2023; Xiong, Chen, and Ying 2025; Hu et al. 2026).

The architecture also incorporates centralized cloud-based network coordination responsible for monitoring communication conditions, managing communication resources, and coordinating communication flows between UAV relay nodes, terrestrial communication infrastructure, satellite systems, and mobile users. This centralized management approach enables dynamic communication link selection, adaptive routing, and operational coordination across heterogeneous communication technologies (Qian et al. 2023; Jung et al. 2023). Through the integration of multi-link communication support, centralized network coordination, and aerial relay communication mechanisms, the proposed framework is intended to maintain reliable and continuous wireless communication in complex operational environments exposed to mobility, infrastructure limitations, and potential communication disruptions (Eskandari and Savkin 2024; Mustafovski, Risteski, and Shuminoski 2025a).

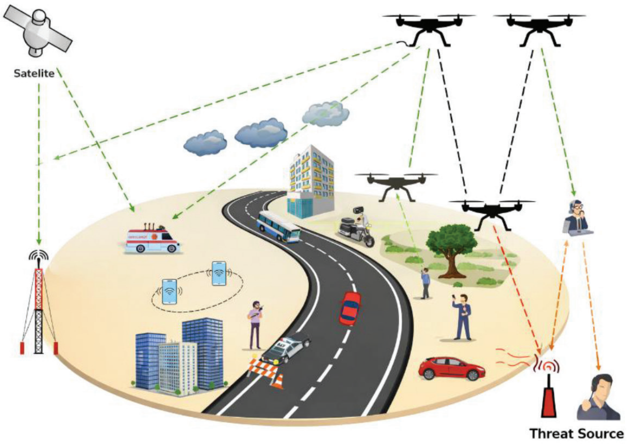

Figure 1 Integrated UAV-satellite Communication Environment for Multi-Layer Wireless Connectivity and Threat Monitoring
Source: Author made.

The figure illustrates an integrated communication environment in which UAV platforms interact with satellite systems, terrestrial infrastructure, and mobile users to support wireless connectivity across urban and road environments. UAVs operate as aerial relay nodes that extend communication coverage and enable data transmission between ground users, communication towers, and centralized network systems. Architecture also represents potential threat sources and eavesdropping activities within the communication environment, highlighting the importance of resilient and secure wireless communication frameworks in complex operational scenarios.

4.2. UAV Relay Communication Layer

Within the proposed communication architecture, UAV platforms operate as adaptive aerial relay nodes responsible for extending wireless communication coverage, supporting communication continuity, and facilitating data transmission between heterogeneous communication layers. The UAV relay communication layer is designed to enable reliable wireless connectivity in operational environments where direct communication between users and terrestrial infrastructure may be limited, degraded, or temporarily unavailable. By functioning as airborne communication relays, UAV platforms provide dynamic communication support for mobile users, terrestrial communication systems, and centralized network infrastructure operating within complex and changing operational conditions (Liu et al. 2020; Vinogradov et al. 2019; Mustafovski, Risteski, and Shuminoski 2025a).

One of the primary operational advantages of UAV relay platforms is their ability to establish line-of-sight communication links with ground terminals, neighboring aerial nodes, and terrestrial communication infrastructure. The elevated operational position of UAV platforms reduces the impact of physical obstacles such as urban buildings, terrain irregularities, vegetation, and infrastructure obstructions that may degrade communication performance in conventional terrestrial wireless environments (Cui et al. 2020; Greenberg, Bar, and Klodzh 2019). The establishment of line-of-sight communication pathways contributes to reduced signal attenuation, improved signal propagation conditions, and enhanced communication reliability across the wireless communication environment (Duong et al. 2022; Eskandari and Savkin 2024).

The UAV relay communication layer also enables dynamic communication deployment and adaptive network extension according to operational requirements and environmental conditions. UAV platforms can be positioned in areas affected by infrastructure degradation, communication congestion, or limited wireless coverage in order to support temporary or continuous communication services. This capability is particularly important in tactical communication environments, disaster response operations, emergency coordination scenarios, and remote geographic regions where rapid communication deployment and operational mobility are essential. The aerial communication layer, therefore, provides operational flexibility by allowing communication resources to be repositioned dynamically according to mission requirements and communication demand distribution.

Within the proposed framework, UAV relay nodes are additionally responsible for facilitating communication interaction between terrestrial communication infrastructure and satellite communication systems. The aerial communication layer enables data traffic generated by ground users to be transmitted toward centralized network infrastructure through LTE communication channels, local digital communication links, or satellite communication pathways, depending on communication conditions and network availability. This relay functionality enables communication continuity even when one or more communication pathways experience degradation, operational disruption, or limited availability.

The UAV relay communication layer also contributes to communication resilience through multi-node aerial communication coordination. Multiple UAV platforms can operate simultaneously within the communication environment to support communication redundancy, increase operational coverage, and improve communication reliability across large geographic areas. Communication traffic may be dynamically distributed between aerial relay nodes according to communication quality indicators, operational requirements, and network load conditions. Through the integration of adaptive aerial relay functionality, line of sight communication support, and multi-link communication coordination, the proposed UAV communication layer improves operational connectivity and enables stable wireless communication in dynamic and infrastructure-constrained operational environments.

4.3. Satellite and LTE Communication Integration

The proposed communication architecture integrates satellite communication systems, LTE communication infrastructure, and local digital communication links within a unified multi-layer wireless communication environment designed to support reliable and continuous operational connectivity. The integration of heterogeneous communication technologies enables the architecture to maintain communication availability across varying operational conditions, geographic environments, and infrastructure limitations. By combining multiple communication pathways within the same operational framework, the proposed system supports adaptive communication routing, communication redundancy, and dynamic network coordination between aerial relay platforms, terrestrial communication infrastructure, and centralized network management systems (Xu, Kishk, and Alouini 2023; Eskandari and Savkin 2024).

Satellite communication systems represent the long-range communication component of the proposed framework and provide beyond-line-of-sight communication support between UAV relay platforms and centralized cloud-based infrastructure. Satellite communication links enable operational connectivity in remote geographic regions, disaster-affected environments, rural areas, maritime environments, and tactical communication scenarios where terrestrial communication infrastructure may be unavailable or degraded. Through the integration of satellite communication systems, UAV relay nodes are capable of transmitting operational data, communication traffic, and network status information directly toward centralized communication infrastructure regardless of terrestrial network availability. This communication capability improves operational continuity and supports resilient wireless communication in infrastructure-constrained operational environments (Li and Shang 2025; Hu et al. 2024; Gao et al. 2025; Xiong, Chen, and Ying 2025).

The architecture additionally incorporates LTE communication infrastructure in order to support medium-range wireless communication and integration with existing terrestrial communication networks. LTE communication channels provide connectivity between UAV platforms, mobile users, and ground access infrastructure operating within urban and semi-urban communication environments. The integration of UAV relay nodes with LTE infrastructure enables wireless coverage extension in regions characterized by weak signal propagation, communication congestion, or limited terrestrial communication access. LTE communication pathways also support rapid communication deployment and enable operational interaction between aerial communication nodes and existing wireless communication infrastructure without requiring dedicated standalone communication systems (Lu et al. 2021; Liu et al. 2020).

Local digital communication links are incorporated within the architecture to support short-range and high-speed communication between UAV relay platforms and nearby communication devices. These communication links provide low-latency communication support for operational environments where aerial nodes operate in close proximity to mobile users, emergency response units, or tactical communication teams. Local digital communication pathways enable rapid data transmission and support efficient communication exchange between operational nodes requiring immediate information transfer and localized communication coordination.

The integration of satellite communication systems, LTE infrastructure, and local digital communication links enables the establishment of a multi-link communication environment capable of supporting adaptive communication routing and communication redundancy. Communication traffic generated by ground users or operational devices may be dynamically redirected through alternative communication pathways according to network availability, communication quality indicators, operational priorities, and environmental conditions. In situations where LTE communication infrastructure becomes unavailable, or communication quality degrades due to interference or infrastructure disruption, UAV relay nodes can redirect communication traffic through satellite communication channels or local digital communication links in order to preserve operational connectivity.

The proposed architecture also incorporates centralized network coordination mechanisms responsible for monitoring communication conditions and managing communication link selection across heterogeneous communication technologies. The centralized network management system evaluates communication parameters such as signal quality, communication latency, link availability, and operational communication status in order to determine the most suitable communication pathway for data transmission. This adaptive communication coordination improves communication stability, enhances operational flexibility, and enables communication continuity during dynamic operational conditions and communication disruption scenarios.

Through the integration of satellite communication systems, LTE communication infrastructure, and local digital communication pathways, the proposed framework establishes a resilient multi-layer communication architecture capable of supporting secure and continuous wireless communication in tactical operations, emergency response environments, disaster recovery scenarios, and infrastructure-limited operational conditions.

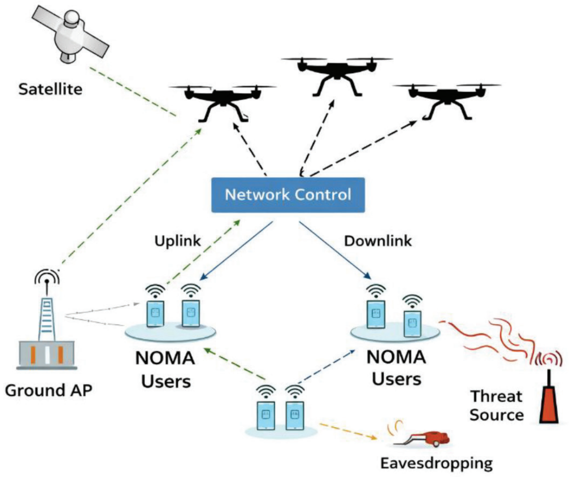

Figure 2 UAV-satellite Communication Architecture with NOMA-Based User Access and Network Control
Source: Author made

The figure presents the proposed UAV-assisted communication architecture that integrates satellite connectivity, aerial relay platforms, ground access infrastructure, and centralized network control. UAV nodes facilitate uplink and downlink communication between NOMA-based users and the network infrastructure, while satellite links support extended connectivity. The architecture also illustrates potential security threats such as interference sources and eavesdropping, highlighting the need for secure and resilient wireless communication frameworks.

4.4. Centralized Cloud-Based Network Coordination

The proposed communication architecture incorporates a centralized cloud-based network coordination layer responsible for communication monitoring, resource allocation, communication routing, and operational management across the integrated wireless communication environment. The centralized coordination mechanism functions as the primary network control component that supervises communication interaction between UAV relay platforms, satellite communication systems, LTE infrastructure, local digital communication links, and mobile user devices. Through centralized operational coordination, the architecture enables adaptive communication management capable of maintaining stable and continuous communication services under dynamic network conditions and varying operational requirements (Qian et al. 2023; Jung et al. 2023; Eskandari and Savkin 2024).

The centralized network management platform continuously collects communication-related information from aerial relay nodes, terrestrial infrastructure, and connected communication devices in order to evaluate current network conditions and operational communication status. Communication parameters, including signal quality, communication latency, communication link availability, traffic load distribution, packet transmission conditions, and operational network status, are monitored in real time through the cloud-based coordination environment. The continuous monitoring of communication conditions enables the centralized management system to identify communication degradation, communication congestion, infrastructure limitations, and potential operational disruptions affecting communication performance (Qian et al. 2023; Lu et al. 2021; Jung et al. 2023).

An important function of the centralized coordination layer involves adaptive communication resource allocation across heterogeneous communication technologies. The network management platform dynamically allocates communication resources according to communication demand, operational priorities, user distribution, and communication quality indicators within the network environment. Communication traffic generated by mobile users and operational devices can be distributed between LTE communication infrastructure, local digital communication pathways, and satellite communication channels according to current network conditions and operational requirements. This adaptive resource allocation mechanism improves communication efficiency and supports balanced utilization of available wireless communication resources.

The centralized coordination framework additionally supports dynamic communication routing between communication nodes operating within the integrated network architecture. UAV relay platforms function as intermediate communication nodes that receive communication traffic from ground users and transmit data through the most suitable communication pathway selected by the centralized network management system. Communication routing decisions are based on operational communication parameters, including communication latency, signal quality, communication availability, network congestion, and communication link stability. In situations where primary communication links experience degradation or become unavailable, the centralized coordination layer can redirect communication traffic through alternative communication pathways in order to maintain communication continuity and operational connectivity.

The cloud-based network management system also contributes to operational communication resilience through coordinated multi-link communication control and network redundancy management. Communication links operating within the architecture are continuously evaluated in order to detect communication interruptions, degraded transmission conditions, or abnormal operational behavior. Through centralized communication coordination, the network management platform can initiate adaptive communication link selection and dynamic routing adjustments that improve operational stability and reduce the impact of communication disruptions caused by infrastructure failure, environmental conditions, or malicious interference.

In addition to communication management and routing coordination, the centralized cloud-based framework enables operational synchronization between aerial communication nodes and terrestrial communication infrastructure. The network management system coordinates communication interaction between UAV relay platforms operating within different geographic regions and communication layers, thereby supporting scalable communication deployment and efficient operational coordination across large communication environments. This centralized operational approach improves communication reliability, enhances network flexibility, and enables efficient management of integrated UAV-satellite communication environments characterized by mobility, infrastructure variability, and heterogeneous wireless communication technologies.

4.5. NOMA-Based Multi-User Communication

The proposed communication architecture incorporates Non-Orthogonal Multiple Access (NOMA) as the primary multi-user access mechanism between UAV relay platforms and ground users. The purpose of integrating NOMA within the UAV-assisted communication layer is to improve spectral efficiency, increase simultaneous user access, and support efficient communication in dense operational environments where multiple users require connectivity through limited wireless spectrum resources. In contrast to orthogonal multiple access techniques, where users are separated through different time, frequency, or code resources, NOMA enables multiple users to share the same frequency resource by assigning different power levels according to their channel conditions (Shen and Ochiai 2021; Kieu-Xuan and Le-Thi 2024; Thi Tam et al. 2023).

Within the proposed architecture, UAV platforms operate as aerial access points that serve multiple ground users through power-domain NOMA. Users located within the coverage area of a UAV relay node are grouped into NOMA clusters according to their channel quality, distance from the UAV, and communication requirements. A user with weaker channel conditions, usually located farther from the UAV or affected by stronger propagation loss, is assigned a higher transmission power coefficient. A user with stronger channel conditions, usually located closer to the UAV or experiencing better signal quality, is assigned a lower transmission power coefficient. This power allocation principle enables both users to share the same communication resource while maintaining decodable signal separation at the receiver side (Shen and Ochiai 2021; Kieu-Xuan and Le-Thi 2024).

For a NOMA cluster with N users, the transmitted signal from the UAV relay node can be represented as:

$$x = \sum_{i=1}^{N} \sqrt{a_i P_t}\, s_i \qquad (1)$$

where x denotes the superimposed transmitted signal, P_t is the total

transmission power of the UAV relay node, a_i is the power allocation coefficient assigned to the user i, and s_i represents the information signal intended for the user i.
The power allocation coefficients must satisfy the following condition:

$$\sum_{i=1}^{N} a_i = 1, 0 < a_i < 1 \tag{2}$$

In this model, higher power allocation is assigned to users with weaker channel gains, while lower power allocation is assigned to users with stronger channel gains. If user j has weaker channel conditions than the user k, the allocation follows:

$$| h_j |^2 < | h_k |^2 \Rightarrow a_j > a_k \tag{3}$$

where h_j and h_k represent the channel coefficients of the corresponding users.
The received signal at the user i can be expressed as:

$$y_i = h_i x + n_i \tag{4}$$

where y_i is the received signal, h_i is the channel coefficient between the UAV relay node and the user i, and n_i represents additive noise. The received signal, therefore, contains the superimposed data streams of all users within the same NOMA cluster.

In order to recover the intended user data, Successive Interference Cancellation (SIC) is applied at the receiver side. Users with stronger channel conditions decode and remove the signals of weaker users before decoding their own information. This decoding process enables efficient separation of superimposed signals and supports simultaneous communication within the same wireless resource block.
The Signal-to-Interference-plus-Noise Ratio (SINR) for the user i can be generally expressed as:

$$SINR_i = \frac{a_i P_t |h_i|^2}{\sum_{k=i+1}^{N} a_k P_t |h_i|^2 + N_0} \tag{5}$$

where N_0represents the noise power, and the interference term corresponds to the remaining non-cancelled user signals within the NOMA cluster.

Based on the achieved SINR, the data rate for the user i can be expressed as:

$$R_i = B\log_2(1 + SINR_i) \tag{6}$$

where B denotes the available communication bandwidth.

The total achievable throughput of the NOMA cluster can then be represented as:

$$R_{sum} = \sum_{i=1}^{N} R_i \quad (7)$$

These equations provide a formal basis for evaluating the spectral efficiency and communication capacity of the NOMA-based UAV communication layer. The integration of NOMA enables the proposed architecture to support multiple users within the same bandwidth resource, which is particularly important in tactical communication environments, emergency response deployments, and critical infrastructure monitoring scenarios where communication demand may increase rapidly, and available spectrum resources may be limited.

The NOMA-based communication layer also supports adaptive communication management through centralized network coordination. The cloud-based network control system can use channel quality indicators, user distance, traffic demand, and link availability to support user grouping and power allocation decisions. By combining UAV relay communication with power domain NOMA, the proposed architecture improves simultaneous user access, enhances spectral efficiency, and supports reliable communication service delivery in dynamic multiuser wireless environments.

4.6. Channel Model and Simulation Parameters

The proposed communication framework incorporates multiple wireless communication links operating across aerial, terrestrial, and satellite communication layers. In order to evaluate the operational behavior of the integrated architecture, the communication environment is represented through a multi-layer channel model that considers communication interaction between UAV relay platforms, mobile users, LTE communication infrastructure, and satellite communication systems. The communication model is intended to represent realistic operational conditions characterized by mobility, variable communication quality, infrastructure limitations, and heterogeneous communication technologies (Xu, Kishk, and Alouini 2023; Hu et al. 2024; Xiong, Chen, and Ying 2025; Eskandari and Savkin 2024).

The first communication segment within the proposed framework consists of UAV-to-user communication links established between aerial relay platforms and ground users operating within the communication coverage area of the UAV nodes. These communication links primarily support short-range and medium-range wireless communication between UAV relay platforms and mobile devices, tactical units, emergency response teams, and operational communication terminals. Due to the elevated operational position of UAV platforms, the communication environment is characterized predominantly by line-of-sight signal propagation conditions. However, communication quality may still be affected by environmental obstacles, urban infrastructure density, terrain irregularities, signal attenuation, and user mobility. The UAV-to-user communication layer also incorporates NOMA-based user access mechanisms in order to support simultaneous communication among multiple users sharing identical communication resources.

The second communication segment involves UAV to LTE communication links established between aerial relay platforms and terrestrial cellular communication infrastructure. LTE communication pathways provide medium-range wireless connectivity and enable UAV relay nodes to integrate with existing terrestrial communication networks. This communication layer supports communication traffic exchange between aerial platforms and ground-based communication infrastructure operating in urban, semi-urban, and partially infrastructure-constrained environments. LTE communication quality may vary according to network congestion, communication load distribution, signal propagation conditions, and infrastructure availability. The integration of LTE communication channels within the proposed architecture enables adaptive communication routing and improves operational communication flexibility by allowing UAV relay platforms to utilize existing wireless communication infrastructure whenever available.

The third communication segment consists of UAV-to-satellite communication links responsible for long-range and beyond line-of-sight communication between aerial relay nodes and centralized cloud-based network infrastructure. Satellite communication systems provide communication continuity in operational environments where terrestrial communication infrastructure is unavailable, degraded, or operationally inaccessible. This communication layer is particularly important for remote geographic regions, disaster-affected environments, maritime communication scenarios, and tactical operations requiring resilient long-distance communication support. Although satellite communication introduces a higher propagation delay compared with terrestrial communication systems, it significantly improves communication availability and operational coverage across large geographic regions.

The integrated communication environment additionally incorporates local digital communication links operating between nearby UAV nodes and operational devices within localized communication areas. These communication links support low-latency data exchange and rapid communication interaction between aerial communication platforms and nearby operational units requiring high-speed communication services. The integration of local digital communication pathways further contributes to communication redundancy and enables adaptive multi-link communication support within the operational environment.

The simulation environment considers dynamic communication conditions in which communication quality, link availability, and operational network conditions may vary according to user mobility, UAV positioning, communication congestion, environmental interference, and infrastructure availability.

Communication interaction between network nodes is evaluated through uplink and downlink communication flows established across aerial, terrestrial, and satellite communication layers. The integrated channel model, therefore, enables the analysis of communication continuity, adaptive routing behavior, operational communication resilience, and multi-link connectivity within heterogeneous UAV-assisted wireless communication environments.

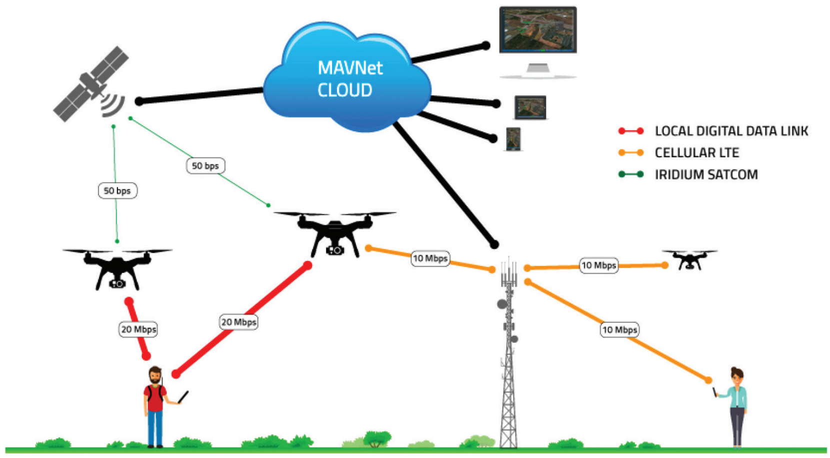

Figure 3 MAVNet Cloud-Based Multi-Link Communication Architecture for Global UAV Connectivity

Source: Adapted by the author from Horizon31 LLC and Oak Ridge National Laboratory (ORNL), "Horizon31 Startup Licenses ORNL Global Communication System for Drones" (2020), for academic and research purposes, with full source attribution provided. Available at: https://www.ornl.gov/news/horizon31-startup-licenses-ornl-global-communication-system-drones

The figure illustrates the MAVNet communication architecture developed at Oak Ridge National Laboratory, which enables global control and monitoring of unmanned aerial vehicles through a cloud-based communication system. The architecture integrates multiple communication pathways, including local digital data links, cellular LTE networks, and Iridium satellite communication. UAV platforms connect to a centralized MAVNet cloud server that enables remote operation, data transmission, and coordination of multiple drones through internet connectivity. The use of redundant communication links improves reliability and ensures continuous control of UAV systems even in environments with limited network coverage.

4.7. Threat-Aware Multi-Link Selection Algorithm

The proposed communication framework incorporates a threat-aware multi-link selection mechanism intended to support adaptive communication routing and communication continuity within dynamic wireless communication environments exposed to infrastructure degradation, interference, and potential malicious communication activity. The primary objective of the algorithm is to continuously evaluate the operational status of available communication pathways and dynamically select the most suitable communication link for data transmission according to current communication conditions and operational requirements. The algorithm operates within the centralized cloud-based network coordination layer and supervises communication interaction between UAV relay platforms, LTE communication infrastructure, satellite communication systems, and local digital communication links (Qian et al. 2023; Jung et al. 2023; Michailidis et al. 2022; Mustafovski, Risteski, and Shuminoski 2025b).

The threat-aware communication model is developed to address operational challenges associated with wireless communication environments characterized by signal attenuation, communication congestion, malicious interference, communication jamming, and potential signal interception attempts. Since the proposed architecture integrates heterogeneous communication technologies operating under varying communication conditions, the communication management system must continuously determine which communication pathway can provide the highest operational communication stability and communication availability. The multi-link selection process, therefore, evaluates communication links according to communication quality indicators and threat-related operational conditions detected within the communication environment.

The algorithm continuously monitors operational communication parameters, including signal quality, communication latency, communication link availability, packet transmission conditions, communication congestion levels, and detected interference intensity across all available communication pathways. LTE communication links, satellite communication channels, and local digital communication pathways are periodically evaluated through the centralized network coordination system in order to identify communication degradation or abnormal operational behavior that may affect communication continuity. Communication links experiencing excessive communication delay, signal degradation, increased packet loss, or detected interference are classified as degraded communication pathways and assigned a lower operational communication priority during the communication routing process.

Within the operational communication environment, UAV relay nodes transmit communication status information and network condition indicators toward the centralized cloud-based coordination system. The centralized management platform processes the collected communication information and dynamically determines the most appropriate communication pathway for operational data transmission. In situations where terrestrial LTE communication infrastructure remains operational, and communication quality indicators satisfy required communication thresholds, communication traffic is primarily routed through LTE communication channels in order to reduce communication delay and improve communication efficiency. However, if LTE communication conditions deteriorate due to infrastructure disruption, network congestion, malicious interference, or communication outages, the algorithm redirects operational communication traffic toward satellite communication systems or local digital communication pathways in order to maintain communication continuity.

The threat-aware communication model also considers the presence of passive and active communication threats operating within the wireless communication environment. Passive threats include unauthorized signal interception and communication monitoring attempts, while active threats include communication jamming, malicious interference generation, and communication disruption attempts targeting wireless communication links. Communication pathways exposed to increased interference intensity or abnormal communication activity are dynamically deprioritized during the communication selection process in order to reduce the operational impact of malicious communication behavior. This adaptive communication coordination improves communication resilience and enables the architecture to maintain operational functionality under degraded or contested wireless communication conditions.

The operational flow of the proposed multi-link selection mechanism can be summarized through several sequential communication management stages. First, the centralized network coordination layer continuously monitors all available communication links and collects communication performance indicators from UAV relay platforms and network infrastructure components. Second, communication quality parameters, including signal quality, communication latency, communication availability, and detected interference levels, are evaluated for each communication pathway. Third, communication links that fail to satisfy operational communication requirements are temporarily deprioritized within the communication routing process. Fourth, the communication pathway exhibiting the highest operational communication stability and communication quality is selected for data transmission. Finally, the communication routing process is dynamically updated whenever communication conditions change or communication degradation is detected within the operational environment.

The integration of the threat-aware multi-link selection mechanism significantly improves the operational resilience of the proposed UAV-satellite communication architecture. By combining adaptive communication routing, centralized communication coordination, and multi-link communication redundancy, the framework supports continuous wireless communication in tactical operations, emergency response deployments, infrastructure-degraded environments, and operational scenarios exposed to communication interference and malicious communication threats.

5. Results and Discussion

The analytical and conceptual evaluation of the proposed UAV-satellite architecture highlights the operational advantages of integrating UAV relay platforms, satellite systems, LTE infrastructure, local digital links, and NOMA-based user access mechanisms within a unified wireless networking framework. The proposed solution enables adaptive coordination across heterogeneous technologies and supports reliable service delivery in environments characterized by infrastructure limitations, network congestion, operational mobility, and potential security threats. It should be emphasized that the present study provides an analytical assessment of the proposed framework rather than a full numerical simulation. The evaluation focuses on service continuity, multi-link connectivity, adaptive routing capabilities, spectral efficiency, and operational robustness in comparison with conventional architectures that rely primarily on fixed terrestrial infrastructure.

One of the most significant outcomes of the proposed framework is the establishment of a multi-layer networking environment that integrates aerial relay nodes, terrestrial wireless infrastructure, and satellite systems within a single operational architecture. In conventional wireless networks, connectivity frequently depends on fixed infrastructure such as cellular base stations, communication towers, or wired backbone systems. In contrast, the proposed framework incorporates UAV relay platforms as adaptive aerial nodes capable of dynamically extending coverage and maintaining network operation in environments where terrestrial infrastructure may be degraded, unavailable, or physically inaccessible. Due to their elevated operational position, UAV relay platforms maintain line-of-sight links with both ground users and infrastructure components, thereby reducing signal attenuation and improving service quality in urban, rural, and infrastructure-constrained environments.

The integration of satellite systems further enhances operational robustness by enabling beyond-line-of-sight connectivity between UAV relay platforms and centralized network infrastructure. Satellite links support long-range connectivity and provide redundancy during scenarios characterized by LTE degradation, infrastructure disruption, or service outages affecting terrestrial wireless networks. When terrestrial infrastructure becomes unavailable, the adaptive multi-link coordination mechanism redirects traffic toward satellite channels in order to preserve network operation. Although satellite links introduce higher latency compared with terrestrial technologies, their integration significantly improves service availability and reduces outage probability in remote geographic regions, disaster-affected environments, and defense-oriented operational scenarios.

Another important outcome of the proposed framework is the integration of heterogeneous multi-link technologies, including local digital links, LTE channels, and satellite systems operating simultaneously within the same networking environment. Each layer provides distinct operational characteristics in terms of latency, coverage, and capacity. Local digital links support low-latency and high-speed data exchange between nearby UAV nodes and operational devices. LTE channels provide medium-range connectivity and integration with existing terrestrial infrastructure, while satellite systems offer long-range support and redundancy across large geographic areas. The availability of multiple transmission paths enables adaptive routing and improves overall network robustness by compensating for degradation or interruption affecting individual links.

The implementation of NOMA-based access mechanisms also contributes significantly to the efficiency of the proposed architecture. In conventional orthogonal systems, resources are allocated separately to individual users, limiting simultaneous access and reducing spectral utilization efficiency in dense environments. Within the proposed framework, NOMA enables multiple users to share identical resources through power-domain multiplexing and adaptive power allocation. Users experiencing weaker channel conditions receive higher transmission power coefficients, while users with stronger channel conditions apply Successive Interference Cancellation to separate superimposed signals. This approach improves spectral efficiency, increases system capacity, and enables UAV relay platforms to support a larger number of connected devices within limited spectrum resources. These advantages are particularly relevant in tactical operations, emergency response deployments, and infrastructure-constrained scenarios characterized by increased traffic demand.

The comparative analysis indicates that the proposed framework differs from existing UAV communication architectures through the integration of UAV relay communication, satellite communication support, LTE connectivity, NOMA-based

TABLE 1. Comparative Analysis of UAV Communication Architectures

Feature	MAVNet Cloud Architecture	UAV-satellite NOMA Architecture	Integrated Proposed Framework
Communication Control	Cloud-based centralized control	Network control center	Integrated cloud and network control
UAV Role	Remote drone operation and monitoring	Aerial relay nodes for NOMA users	Multi-functional aerial communication relays
Communication Links	Local digital link, LTE, satellite	Satellite, UAV links, ground access points	Local digital link, LTE, satellite, UAV relay
User Access Mechanism	Conventional communication access	NOMA-based user communication	NOMA-based multi-user connectivity
Coverage Range	Global connectivity through the internet	Extended coverage through UAV relay	Multi-layer coverage, including satellite and aerial networks
Network Resilience	Redundant communication pathways	UAV relay communication redundancy	Multi-link redundant communication architecture
Security Consideration	Not explicitly modeled	Includes threat source and eavesdropping scenarios	Integrated threat awareness and resilient communication design
Application Domains	UAV fleet management and remote control	Wireless communication research and user access modeling	Emergency response, smart infrastructure, tactical communication

multiuser communication, centralized cloud-based network coordination, and threat-aware adaptive routing within a unified operational communication architecture. Unlike conventional communication frameworks primarily focused on isolated communication functionalities, the proposed architecture incorporates communication redundancy, adaptive multi-link routing, and operational threat awareness intended for tactical and infrastructure-constrained communication environments.

Conclusions

The increasing dependence on continuous wireless connectivity across civilian, emergency response, and defense environments has intensified the need for architectures capable of maintaining reliable network operation under dynamic and infrastructure-constrained conditions. This study presented an integrated UAV-satellite architecture that combines UAV relay platforms, satellite systems, LTE infrastructure, local digital links, centralized cloud-based coordination, and NOMA-based multiuser access within a unified networking framework. The proposed solution was designed to support adaptive routing, network redundancy, and operational continuity in environments characterized by congestion, infrastructure degradation, mobility, and potential security threats.

The analytical and conceptual evaluation demonstrated that the integration of UAV relay platforms with heterogeneous wireless technologies enhances operational flexibility and enables service continuity across multiple networking layers. UAV relay nodes function as adaptive aerial platforms capable of extending coverage and maintaining line-of-sight connectivity between mobile users, terrestrial infrastructure, and centralized network systems. The incorporation of satellite support further enables beyond-line-of-sight connectivity and improves service availability in remote geographic regions, disaster-affected environments, and tactical scenarios where terrestrial infrastructure may be unavailable or degraded.

The proposed multi-link architecture also demonstrated significant operational advantages through the simultaneous integration of LTE channels, satellite systems, and local digital links. The availability of multiple transmission paths enabled adaptive routing and enhanced network robustness through redundant connectivity mechanisms. During LTE degradation or infrastructure disruption, the threat-aware coordination mechanism redirected traffic toward satellite pathways, thereby preserving network operation and reducing the probability of service interruption. This capability is particularly important for defense operations, emergency response missions, and critical infrastructure protection, where uninterrupted information exchange is essential for operational effectiveness.

The implementation of NOMA-based access mechanisms further improved system efficiency. Through power-domain multiplexing and adaptive power allocation, multiple users were able to share identical spectrum resources while maintaining efficient bandwidth utilization. Users experiencing weaker channel conditions received higher transmission power coefficients, whereas users with stronger channel conditions applied Successive Interference Cancellation to separate superimposed signals. As a result, the proposed framework improved spectral efficiency and increased system capacity in dense operational environments characterized by high traffic demand and limited spectrum resources.

The study additionally addressed security and resilience through the incorporation of threat-aware coordination mechanisms. The proposed architecture considered challenges such as signal interception, malicious interference, communication jamming, and unauthorized eavesdropping. The threat-aware routing mechanism continuously evaluated network conditions and dynamically adjusted path selection according to link availability, latency, signal degradation, and detected interference levels. Links exposed to adverse conditions were deprioritized, while alternative paths maintained uninterrupted service delivery. This adaptive behavior enhanced network resilience and reduced the operational impact of disruption attempts within contested wireless environments.

The comparative analysis demonstrated that the proposed framework differs from existing UAV networking architectures through the integration of UAV relay functionality, satellite support, LTE connectivity, NOMA-based access, centralized cloud coordination, and adaptive threat-aware routing within a unified operational architecture. Unlike conventional solutions that focus primarily on isolated functionalities or standalone UAV management, the proposed framework incorporates redundancy, adaptive coordination, and security-oriented design principles intended for tactical operations, emergency response coordination, disaster recovery environments, and infrastructure-constrained scenarios.

Overall, the analytical evaluation indicates that the proposed UAV-satellite architecture improves service availability, spectral efficiency, adaptive routing capability, and operational resilience within heterogeneous wireless environments. The framework demonstrates strong applicability for tactical communication systems, emergency response operations, infrastructure monitoring, disaster recovery coordination, and mission-critical environments exposed to infrastructure degradation, network congestion, and potential security threats.

It should be emphasized that the present study provides an analytical and conceptual assessment of the proposed architecture rather than a full numerical simulation. Future research will focus on simulation-based performance validation and comparative evaluation of UAV-only, LTE-only, SATCOM-only, and integrated multi-link architectures using metrics such as latency, throughput, packet loss, service availability, and resilience under interference conditions. Additional research directions include optimization of adaptive routing strategies, experimental validation in realistic operational environments, and the integration of artificial intelligence-based network management mechanisms for beyond-5G and 6G wireless systems.

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