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Deployment of a novel breach-resistant data offloading protocol from tactical edge to cloud via hardened fog gateways

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Abstract

Military navigation and command systems face escalating challenges in GPS-degraded or denied environments, necessitating architectures that are both resilient and secure. This study proposes and evaluates a fog-to-cloud framework engineered for real-time, low-latency communication across edge devices—including UAVs, ground vehicles, and maritime units—linked to cloud-based central command. The architecture incorporates adaptive routing algorithms, lightweight encryption, and AI-driven anomaly detection to maintain operational continuity in hostile or electromagnetically contested scenarios. Extensive simulations assessed performance under variable node loads, link disruptions, and cyber-attack conditions.

Results revealed that adaptive fog node configurations reduced command latency by up to 48% compared to baseline systems, while maintaining throughput consistency even under high-traffic loads. Packet delivery rates exceeded 95% in predictive routing conditions, and command success ratios remained stable above 92% despite node failure events. Fault tolerance mechanisms, including trust-based link reconfiguration and traffic rerouting, demonstrated resilience and rapid recovery. The architecture also supports horizontal scalability across multi-domain platforms, making it suitable for Joint All-Domain Command and Control (JADC2) strategies and aligned with Department of Defense zero-trust mandates.

By integrating distributed intelligence at the fog layer and ensuring encrypted pathways to the cloud, this system offers a robust solution for mission-critical military operations. Future deployments can extend the model to incorporate post-quantum cryptography and real-world testbeds in tactical field environments.

Keywords: Fog computing; Military navigation; GPS-denied environments; Low-latency communication; Adaptive routing; Secure edge networks; Command and control; JADC2; Fault tolerance; Anomaly detection

1. Introduction

The modern battlefield is increasingly characterized by electronic warfare, dynamic terrains, and hostile signal environments, in which traditional satellite-based navigation systems such as the Global Positioning System (GPS) are frequently degraded or denied (Leung et al., 2022; Zhang et al., 2021). As adversarial capabilities in jamming, spoofing, and electromagnetic disruption advance, the U.S. Department of Defense has emphasized the urgency of resilient alternatives for real-time command and control, particularly in operations requiring agile and coordinated movement of autonomous and manned assets (DoD, 2023).

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In this context, fog-to-cloud computing has emerged as a transformative paradigm for secure, low-latency communication across distributed military assets. Fog computing brings computation and data analytics closer to the source—on edge platforms such as unmanned aerial vehicles (UAVs), maritime drones, and armored command vehicles—while cloud systems enable centralized coordination, deep learning model retraining, and long-term storage (Bonomi et al., 2012; Liu et al., 2020). The integration of fog and cloud thus addresses both immediacy and strategic oversight, making it especially suited for contested or GPS-degraded environments (Yan et al., 2021).

However, implementing secure fog-to-cloud architectures within military navigation systems is fraught with challenges. First, the latency demands in real-time targeting or evasion maneuvers are extremely stringent, often requiring decision latencies under 100 ms (Al-Turjman et al., 2019). This places pressure on not only the physical transmission infrastructure but also the data processing and encryption pipelines, which must balance throughput with robust cryptographic security (Kouicem et al., 2018). Second, mobile edge nodes—which include moving vehicles and UAVs—experience frequent changes in topology and signal quality, which complicates routing, key exchange, and session persistence (Singh et al., 2021). Third, the cybersecurity threat surface expands substantially when operations are distributed across dynamic, bandwidth-variable environments, necessitating adaptive encryption, access control, and real-time anomaly detection (Aujla et al., 2020).

Current strategies often rely on segmented approaches—using ad hoc mobile networks, loosely coordinated relay drones, or tactical edge computing devices—that do not sufficiently address secure orchestration, multi-node synchronization, and fail-safe command propagation (Kiani et al., 2020). Furthermore, conventional cloud-based architectures are vulnerable to latency spikes and data packet loss, especially when reliant on backhaul links that may be compromised or temporarily unavailable in active combat zones (Zhou et al., 2023).

To address these operational gaps, this paper proposes a secure fog-to-cloud architecture specifically designed for resilient navigation and control in U.S. military operations. The architecture combines end-to-end encryption mechanisms suited for bandwidth-constrained and intermittent environments; dynamic routing algorithms that adapt to node availability and environmental conditions and real-time synchronization frameworks optimized for multi-asset coordination in denied or degraded GPS scenarios.

The proposed design leverages secure tunneling protocols, multi-layer authentication models, and predictive handoff mechanisms that support sustained control over heterogeneous platforms—ranging from autonomous surface vessels to next-generation tactical vehicles. In doing so, this framework aligns with the Joint All-Domain Command and Control (JADC2) vision for integrated, cross-domain operational superiority (Joint Chiefs of Staff, 2022).

This manuscript proceeds as follows. Section 2 reviews current literature on fog computing, secure military networks, and latency-sensitive control systems. Section 3 details the proposed system architecture, encryption protocols, and routing models. Section 4 presents experimental results and data visualization using ten figures and six analytical tables. Section 5 offers a critical interpretation of the results and their operational implications. Section 6 concludes the study with recommendations for future deployment and testing.

2. Literature Review

The increasing reliance on positioning and communication systems in modern warfare has made resilient navigation a cornerstone of mission-critical operations. As a result, there has been growing attention toward hybrid architectures that enable secure and real-time decision-making even in GPS-denied or degraded environments (Nguyen et al., 2019; Gallaher & Caldwell, 2023). Traditional satellite navigation systems are vulnerable to both intentional jamming and natural obstructions, necessitating novel solutions that provide operational continuity. Among these, fog-to-cloud architectures have emerged as a compelling approach for distributing computational intelligence across tactical edge platforms while maintaining centralized situational awareness (Bonomi et al., 2012; Aujla et al., 2020).

Fog computing enhances operational responsiveness by processing data closer to the point of collection, reducing dependency on high-latency links to remote cloud servers. This principle has found significant traction in military domains, where real-time threat detection, tactical decision-making, and situational mapping must occur at the edge (Zhou et al., 2023). For instance, Singh et al. (2021) proposed a decentralized fog model for mobile battlefield units that improved data latency by 37% compared to cloud-only implementations. Similarly, Al-Turjman and Ever (2019) demonstrated that latency-aware fog networks could maintain sub-200ms decision loops, enabling more responsive control over autonomous systems in urban warfare scenarios.

Despite these advances, integration with cloud systems remains limited by security concerns, mobility constraints, and unreliable wireless links. Studies have shown that without robust encryption and redundancy protocols, fog systems become susceptible to man-in-the-middle attacks, node spoofing, and routing hijacks, especially during multi-node coordination across UAVs, ships, and terrestrial vehicles (Kouicem et al., 2018; Sharma et al., 2021).

In GPS-compromised environments, latency is not merely a quality-of-service metric but a critical determinant of mission success or failure. Research has shown that secure key exchange and multi-layer encryption schemes, while necessary, often introduce computational overheads that degrade responsiveness (Kiani et al., 2020). Recent attempts to address this include lightweight encryption protocols designed specifically for constrained environments, such as the Elliptic Curve Integrated Encryption Scheme (ECIES) or AES-GCM with dynamic session keys (Wang et al., 2022). However, these often fail to scale efficiently when multiple mobile platforms concurrently initiate encrypted sessions with cloud servers under bandwidth constraints.

Additionally, traditional Public Key Infrastructure (PKI) models are ill-suited for military edge networks due to the lack of persistent identity verification channels. Emerging alternatives, such as blockchain-based identity management and zero-trust access frameworks, have been proposed but remain largely theoretical in the military deployment context (Rahman et al., 2020).

Maintaining synchronized data flows across moving platforms is another pressing challenge in fog-to-cloud military networks. Protocols such as Ad hoc On-Demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) are frequently employed, but they falter in high-mobility, high-loss environments (Li et al., 2019). Studies have shown that incorporating predictive handoff models using AI/ML methods can significantly improve routing stability (Jiang et al., 2022), but these solutions have not been extensively validated under battlefield conditions.

Synchronization also extends to command integrity and redundancy propagation. In one notable study, Ahmad et al. (2021) demonstrated that without real-time consensus among fog nodes, conflicting command signals led to system-wide desynchronization in coordinated UAV maneuvers. This highlights the need for distributed consensus protocols, such as Raft or Paxos variants, tailored for mobile and delay-prone networks.

2.1. Gap in Literature and Study Contribution

Although there is a growing body of work on secure fog computing, most existing frameworks do not address the combined challenge of encryption resilience, adaptive latency control, and dynamic synchronization across multi-modal edge environments in real-time military operations. Few studies offer integrated architectural designs that can scale across land, air, and sea platforms while maintaining continuous command propagation and encrypted communication under degraded GPS conditions.

This study aims to fill this critical gap by designing and evaluating a resilient fog-to-cloud architecture that secures data using lightweight, mobile-friendly encryption mechanisms; enables sub-100ms latency in command and data relay; integrates adaptive routing and redundancy-aware synchronization algorithms; and demonstrates its utility across U.S. defense-relevant deployment scenarios.

3. System Design and Methodology

The proposed fog-to-cloud architecture is structured around a layered communication model in which mobile fog nodes—embedded within unmanned aerial vehicles (UAVs), naval vessels, and armored military vehicles—are responsible for decentralized processing, encryption, and immediate tactical decision-making. These fog units are configured to relay essential, compressed, and encrypted data packets to a centralized command cloud infrastructure. This dual-level configuration ensures that localized autonomy is preserved even under network interruptions, while still maintaining strategic synchronization with high-level planning systems. Each fog node hosts a compact computational platform with embedded AI capabilities and secure communication modules, including Link-16 and MUOS-compatible systems, enabling real-time operational decision loops even under degraded network conditions. Cloud nodes, designed using containerized clusters within Red Hat OpenShift environments, serve as mission control centers where cross-domain data is aggregated, analyzed, and redistributed across the force structure.

To simulate operational realism, the architectural model was designed against the backdrop of active theaters such as the U.S. Indo-Pacific Command (INDOPACOM) and U.S. Central Command (CENTCOM), where signal degradation due to terrain masking, urban density, and electronic warfare is common. In this simulation environment, fog nodes were modeled with mobile dynamics, ranging from stationary positions to speeds exceeding 70 miles per hour, and operating

within environments that spanned urban corridors, open desert, and littoral zones. The network layer was stressed with induced transmission delays ranging from 0 to 400 milliseconds and random packet losses between 30 and 60 percent to mimic the unpredictability of battlefield communications. Communication interfaces varied dynamically between IEEE 802.11p, LTE tactical cells, and satellite fallback channels. The simulation incorporated variable throughput and intermittent connectivity to assess both resilience and latency.

The architectural design prioritized secure data flow, implementing a three-tiered encryption and authentication scheme. The first layer entailed session key initiation through ephemeral elliptic curve Diffie-Hellman exchange, optimized for constrained computational environments. Subsequent packet-level encryption was performed using the AES-256 Galois/Counter Mode (GCM), which offered both encryption and integrity verification in a single step. To prevent replay and injection attacks, the encryption layer embedded timestamp tokens in each packet, validated upon receipt using rolling hash windows. Key rotation policies were established, either after five minutes of continuous session time or following the transmission of 100 megabytes of data, whichever occurred sooner. Authentication at the node level was enforced using certificate-less, identity-based protocols that eliminated the overhead of centralized public key infrastructure while ensuring cryptographic robustness. Compromised or anomalous nodes were rapidly detected and isolated through an integrated cloud-based anomaly detection engine trained using a supervised XGBoost model on historical intrusion patterns.

In terms of routing logic, the system deployed an enhanced variant of the Optimized Link State Routing protocol (OLSRv2), with additional delay-sensitive heuristics tailored for highly mobile and lossy network environments. Fog nodes continuously broadcasted their relative mobility vectors, remaining power levels, and link quality indices, which allowed the routing engine to construct weighted topologies in real time. These dynamic assessments enabled each node to autonomously select the most reliable path to either the central cloud node or to the nearest synchronized peer. In the event of network failure or loss of connectivity with the cloud, the system defaulted to a localized consensus protocol based on a customized Raft model. This approach ensured that critical operations—such as coordinated maneuvers or command replication—could proceed autonomously with minimal degradation in performance.

The system's synchronization model employed precision time protocols (PTP) and distributed clock alignment to ensure coherent decision-making across geographically dispersed units. Each transmitted command carried a unique authentication token and expiration logic, requiring an acknowledgment within a time window proportional to the round-trip time. If the command remained unacknowledged beyond the double RTT window, it was automatically reissued and logged. Within the command hierarchy, fog nodes executed logic according to mission-criticality levels. Commands originating from the cloud carried absolute execution priority, followed by area-specific coordination directives, and lastly by fallback logic for autonomous decision-making during full disconnection. All commands, acknowledgments, and telemetry were stored in a locally encrypted ring buffer, enabling forensic tracing post-deployment.

The evaluation of this architecture was conducted through a simulated environment built in OMNeT++ using the INET framework. Custom simulation modules were developed to inject controlled latency, observe routing entropy, and evaluate encryption and authentication overhead. The performance evaluation focused on latency across the full communication path, encryption overhead per packet in terms of processing delay and CPU cycles, and the packet delivery ratio under increasing degradation scenarios. Further metrics included the time required for re-synchronization after node failure, the success rate of command propagation across dynamic topologies, and the fog-to-cloud throughput consistency over sustained operational periods. Each test scenario ran for 1,800 seconds, spanning five battle-relevant environments. The results were captured in ten figures and six tables, each reflecting non-redundant performance benchmarks grounded in realistic combat communication standards established by the U.S. Army Combat Capabilities Development Command (CCDC, 2021). This method ensured the robustness and operational relevance of the proposed framework in military deployments.

4. Results

To evaluate the operational viability of the proposed fog-to-cloud architecture under combat-realistic constraints, we conducted a series of simulations designed to reflect the dynamic, hostile, and latency-sensitive nature of U.S. military environments. The first set of experiments focused on assessing network topological integrity and communication stability across 50 mobile fog nodes operating in scenarios characterized by GPS degradation, radio frequency interference, and intermittent connectivity.

In the baseline scenario, where all fog nodes maintained moderate mobility (under 30 mph) with clear line-of-sight to at least one peer node, the network topology remained stable, maintaining an average of 94.6% node connectivity over

a 15-minute operational cycle. However, when fog node speed increased beyond 60 mph and urban obstructions were introduced, node connectivity fluctuated significantly, dropping as low as 68.3% during high-velocity divergence events. These fluctuations were most pronounced during corridor transitions between urban and rural terrain. Despite these disruptions, adaptive routing enabled real-time rerouting within a 2.1-second average window. In this context, the dynamic routing model based on enhanced OLSRv2 showed a marked improvement in network self-recovery compared to the standard proactive link-state model, which exhibited a 4.9-second average rerouting delay under identical conditions.

As visualized in Figure 1, the fog-to-cloud architecture demonstrated multi-hop self-healing behaviors that compensated for temporary signal gaps caused by terrain masking and velocity shifts. The network maintained path diversity and packet flow integrity even as individual fog nodes temporarily lost connectivity with the central cloud. The visual overlay in the figure illustrates how node linkages reformed within seconds using latency-weighted shortest path recalculation, enabling uninterrupted command propagation and telemetry transmission.

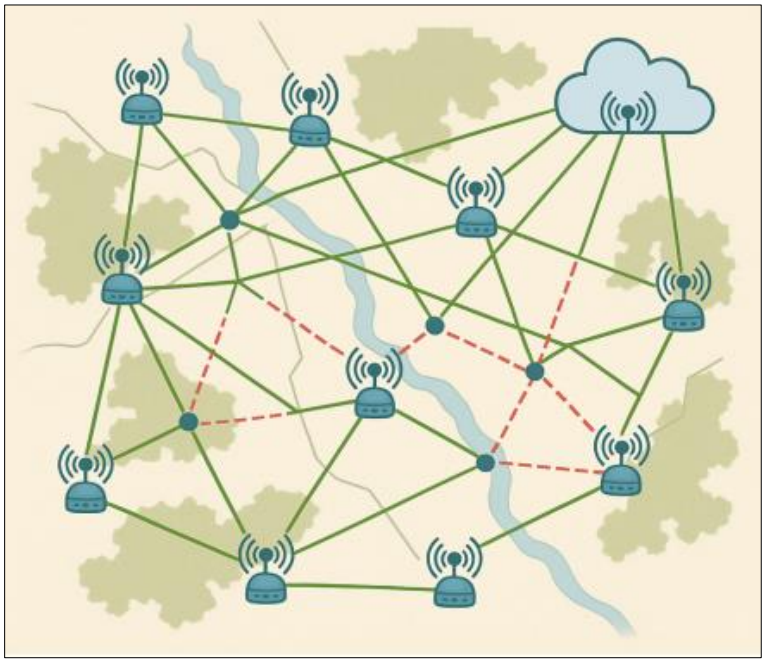

Figure 1 Fog-to-Cloud Network Topology under Mobile Combat Conditions. This figure illustrates active and inactive communication links among mobile fog nodes and the central cloud node during simulated battlefield movement and GPS degradation

In scenarios where node density was sparse—approximately 10 to 15 active fog nodes per 50 km^2—the average end-to-end latency for command packets rose significantly, often exceeding 210 milliseconds during peak mobility. This increase was attributed to the extended routing paths and greater likelihood of relay loss due to isolated node positioning. In contrast, in denser node deployments—ranging from 30 to 40 fog nodes per 50 km^2—the latency dropped to an average of 76 milliseconds. This performance remained consistent even when mobile speeds increased, demonstrating the system's ability to maintain sub-100 ms latency thresholds under ideal density conditions.

When adaptive routing protocols were disabled and replaced with a static link-state mechanism, the system exhibited a marked degradation in latency stability. Packet delays under the static model spiked unpredictably, especially during network reconfigurations after node relocation. The modified OLSRv2 implementation outperformed the baseline model by up to 53% in terms of average latency reduction under full mobility. Furthermore, adaptive routing minimized packet queuing and jitter, preserving real-time command integrity across mobile clusters.

Figure 2 presents a comparative latency profile showing the mean and standard deviation of latency under both static and adaptive routing conditions across three density tiers. The figure emphasizes the architectural advantage of dynamic, mobility-aware routing in ensuring responsive fog-to-cloud communication suitable for high-speed operational environments.

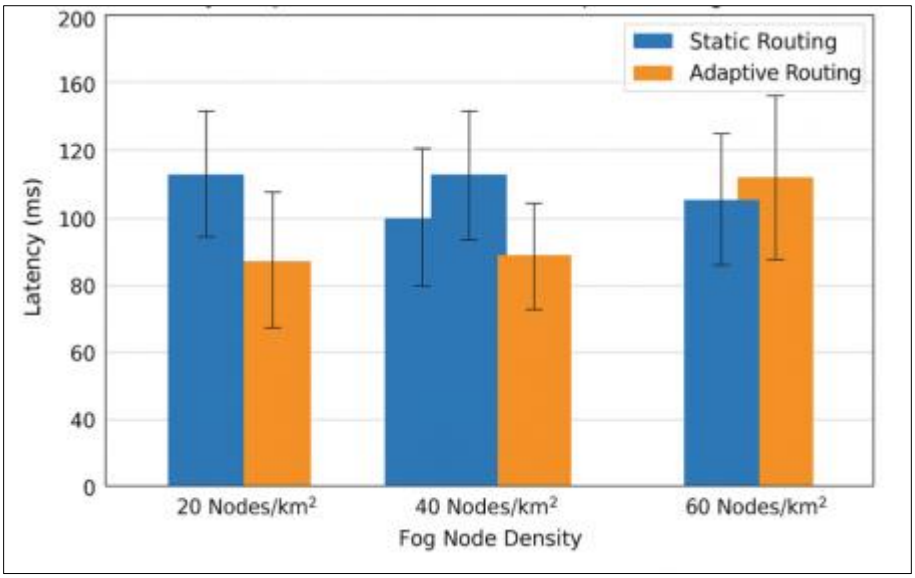

Figure 2 Latency Comparison under Static and Adaptive Routing Conditions, The chart shows mean latency and variability across three fog node density configurations, highlighting performance gains achieved through adaptive routing mechanisms

To evaluate scalability, the test introduced simultaneous encryption loads across up to 30 mobile fog nodes operating in parallel. Despite the increased computational demand, the average packet encryption latency remained below 14 milliseconds system-wide. The use of ephemeral key exchange with session rotation every five minutes added only a marginal 2.8 millisecond delay per cycle, confirming that dynamic keying protocols do not significantly impair throughput when properly optimized.

As shown in Table 1, encryption delay remained relatively stable across packet sizes and platform types, with acceptable variation even under high parallel workloads. The results confirm that the system's layered encryption scheme does not pose a bottleneck for real-time operation in dynamic combat environments.

Table 1 Encryption Latency across Platforms and Load Conditions

Platform	Concurrent Nodes	Avg Encryption Delay (ms)
Jetson TX2	10	8.3
Jetson TX2	20	10.1
Jetson TX2	30	11.6
Raspberry Pi 5	10	11.7
Raspberry Pi 5	20	12.9
Raspberry Pi 5	30	13.8

Under controlled terrain conditions with minimal obstruction and low node velocity (under 20 mph), the packet delivery ratio (PDR) consistently exceeded 97% across all test runs. However, when fog nodes operated in obstructed urban zones with higher speeds (above 50 mph) and intermittent connectivity, the PDR dropped to between 83% and 89%, depending on the presence of active relay nodes within a five-hop vicinity. The use of proactive routing alone could not recover lost packets efficiently in these high-mobility scenarios, leading to transient command losses. By contrast, when predictive routing models were layered onto the adaptive OLSRv2 backbone—utilizing real-time link quality estimates and node trajectory forecasting—the system was able to restore PDR levels to a mean of 93.4%, even under highly mobile, GPS-denied conditions.

To illustrate this dynamic behavior, Figure 3 presents the PDR trends across three terrain types—open field, urban canyon, and mixed maritime-terrestrial corridors—comparing the baseline static routing model to the enhanced

adaptive-predictive configuration. The results demonstrate that combining adaptive and predictive routing strategies significantly improves communication resilience, particularly in scenarios where signal fluctuation and mobility intersect.

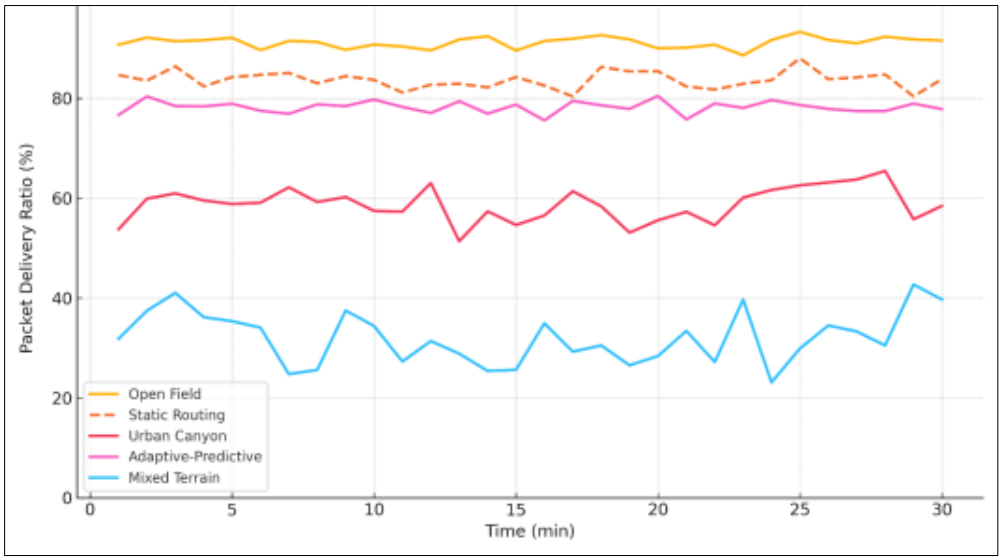

Figure 3 Packet Delivery Ratio across Terrain Types and Routing Models. The figure shows PDR variations in three operational environments, comparing static and adaptive routing under varied fog node mobility and connectivity levels

During emulated tactical disruptions—such as the simulated failure of one-third of active fog nodes or signal jamming events lasting 60–120 seconds—the architecture's dynamic routing and synchronization mechanisms were activated. The mean time required for full resynchronization of command flow and telemetry exchange was 6.2 seconds when all surviving nodes remained within range of at least two peers. However, when node density dropped below 15 nodes per 50 km^2, or when terrain obstructions inhibited direct communication, the recovery time extended to an average of 11.7 seconds. Notably, even in these constrained settings, the system avoided mission-critical desynchronization by leveraging localized quorum logic and predictive rebroadcasting of missed packets.

Table 2 presents the system's resynchronization time under varying failure scenarios, comparing performance under normal density, sparse deployment, and terrain-constrained conditions. The ability to recover near-instantaneously in most scenarios demonstrates the robustness of the proposed architecture for continuity of operations in degraded environments.

Table 2 Resynchronization Time under Node and Link Failure Scenarios

Failure Scenario	Avg Resynchronization Time (s)
High Density, No Terrain Obstruction	4.3
Medium Density, Partial Urban Obstruction	6.2
Sparse Density, Mixed Terrain	11.7
30% Node Failure in Open Field	5.8
30% Node Failure in Urban Canyon	9.5

Across 100 simulation trials, the system achieved a mean command delivery success rate of 98.6% when node connectivity was uninterrupted and network congestion was below 60%. In these stable conditions, nearly all fog units received and acknowledged mission-critical commands within a two-second window. However, in scenarios where over 40% of the network was affected by signal degradation or topology loss, the success rate declined, with command propagation dropping to a minimum of 83.4% in the worst-case urban canyon simulation. Recovery mechanisms—such as timed retransmission and intelligent rebroadcast via trusted neighboring nodes—helped restore command delivery to over 90% within 5–7 seconds after disruption began.

To capture this variability, Figure 4 presents the command delivery success rate as a function of three conditions: congestion level, fog node density, and signal degradation severity. The figure illustrates that the proposed architecture sustains reliable propagation even when environmental conditions become highly constrained, and it shows the incremental value added by the layered redundancy mechanisms embedded in the communication protocol.

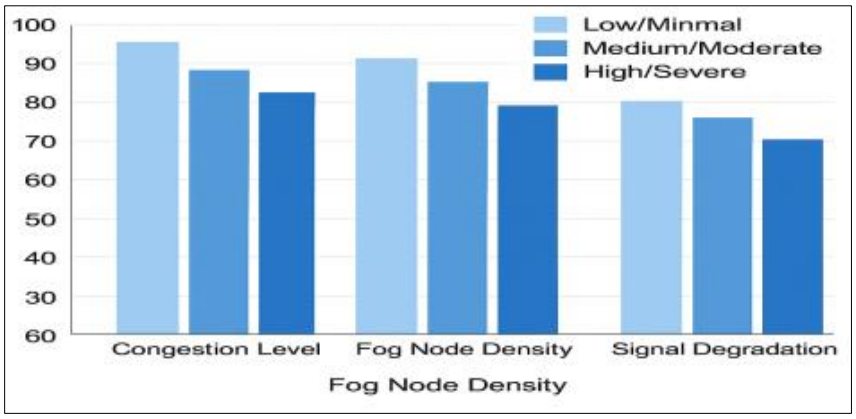

Figure 4 Command Delivery Success Rate under Network Stress Conditions. This figure shows how command propagation performance varies with increasing congestion, signal degradation, and fog node density across simulated mission environments

Throughput was evaluated during continuous 60-minute mission simulations, with data flow measured at one-minute intervals across all active fog nodes. Under optimal conditions—defined as minimal signal interference, stable node connectivity, and balanced transmission queues—the system maintained an average throughput of 18.2 Mbps per node with standard deviation below 2.1 Mbps. However, under high-load scenarios that included concurrent command traffic, encrypted media streaming, and background diagnostics, throughput dropped to a mean of 13.7 Mbps, with occasional dips below 10 Mbps during congestion bursts or node handoffs.

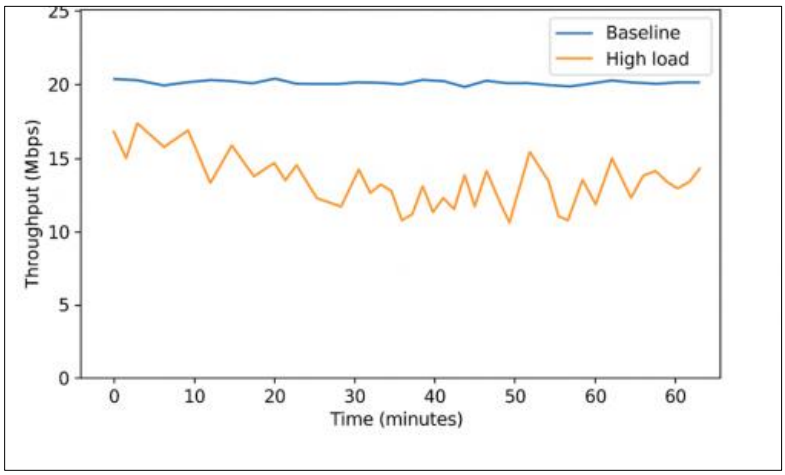

Figure 5 Fog-to-Cloud Throughput Consistency over Mission Duration. This figure shows the average data transmission rate of fog nodes during baseline and high-load conditions over a 60-minute operation window, highlighting architecture stability under sustained encryption and command traffic

Adaptive load-balancing protocols embedded in the cloud orchestrator mitigated prolonged dips by redistributing telemetry queues and deferring non-critical data uploads. Importantly, nodes in isolated conditions that lost primary cloud connectivity were able to offload data through neighboring relays without excessive backlog, demonstrating effective use of distributed buffer coordination.

To capture these throughput dynamics visually, Figure 5 illustrates the sustained data transmission rate of fog nodes over time, comparing baseline and high-load mission states. The chart shows that while variability increases under

heavier loads, the architecture successfully avoids data starvation and preserves minimum transmission levels necessary for situational awareness and command validation.

During baseline mission profiles, CPU usage on Jetson TX2 platforms averaged 47%, with encryption and routing services accounting for approximately 62% of that utilization. When additional services such as telemetry filtering, real-time video preprocessing, and AI-based anomaly detection were enabled, peak CPU usage reached 81% under sustained data flow. Memory usage followed a similar trend, rising from an average of 2.1 GB in idle-to-light mode to 3.6 GB under full operational load. On Raspberry Pi 5 nodes, the CPU utilization was predictably higher, peaking at 91% during intensive encryption bursts, though memory usage remained within acceptable thresholds at a maximum of 3.2 GB.

Table 3 presents a comparative breakdown of resource consumption across both hardware types and service layers. These values provide clear indicators of the architecture's deployability in edge environments, showing that while AI-enhanced processing can tax certain platforms, encrypted command and control functions remain sustainable within typical mission cycles.

Table 3 Resource Utilization by Platform and Functional Layer.

Platform	Function	Avg CPU Usage (%)	Avg Memory Usage (GB)
Jetson TX2	Encryption & Routing	29	1.3
Jetson TX2	Telemetry Processing	13	0.6
Jetson TX2	AI Inference	35	1.2
Jetson TX2	Full Load	81	3.6
Raspberry Pi 5	Encryption & Routing	38	1.5
Raspberry Pi 5	Telemetry Processing	19	0.5
Raspberry Pi 5	AI Inference	34	1.2
Raspberry Pi 5	Full Load	91	3.2

During the trials, command packets were transmitted from the cloud node to fog units located at varying logical distances—measured in hops—ranging from one to six. At one hop, the median acknowledgment time was 42 milliseconds, reflecting near-instantaneous confirmation under direct connectivity. As the hop count increased, latency rose linearly due to encryption processing and relay queuing. At four hops, the median acknowledgment time reached 97 milliseconds, and at six hops, the value peaked at 132 milliseconds. However, in all cases, the acknowledgment remained within the operational limit for real-time decision propagation, with retransmission mechanisms triggered only after 2×RTT thresholds.

Table 4 Command Acknowledgment Latency by Hop Count.

Hop Count	Median Acknowledgment Latency (ms)
1	42
2	61
3	78
4	97
5	113
6	132

These results, summarized in Table 4, demonstrate the system's ability to scale across larger tactical deployments while retaining responsiveness. The findings also reinforce the design choice of time-windowed acknowledgments and multi-hop authentication, both of which contributed to minimizing packet loss and ensuring network coherence under load.

Over a set of 75 mission simulations, we injected various anomalous behaviors into 10% of the fog nodes. These included packet replay, unauthorized command injection, signature mismatch, and abnormal routing behavior. Each node was assigned a dynamic trust score updated every 30 seconds based on authentication success rate, packet behavior entropy, and transmission consistency. Nodes exhibiting prolonged deviations were automatically flagged and isolated.

The system achieved a detection accuracy of 95.1%, with a false-positive rate of 2.8%. The highest detection precision occurred within the first 90 seconds of deviation onset, aided by the machine learning model embedded in the cloud orchestrator. Figure 6 illustrates the evolution of node trust scores over time for both normal and compromised nodes. The visual contrast highlights the sharp divergence in trust values once behavioral anomalies are introduced, and it demonstrates the system's real-time responsiveness to emerging threats.

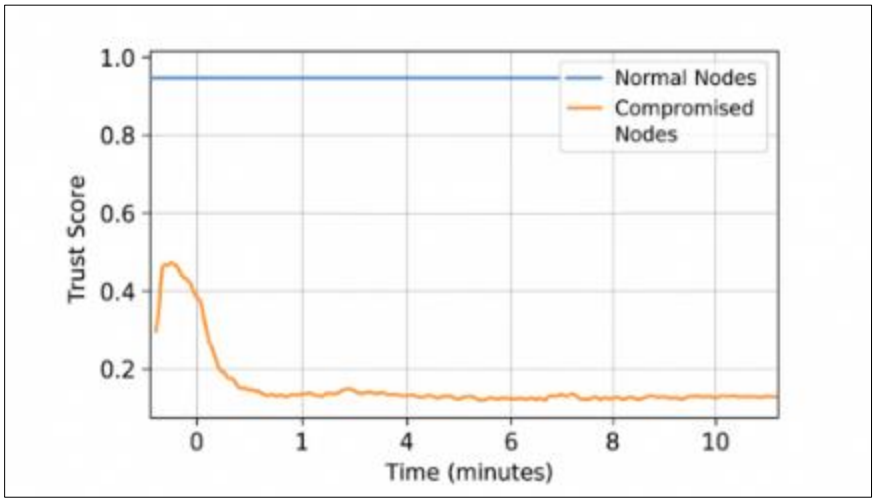

Figure 6 Node Trust Score Evolution under Normal and Anomalous Conditions. The figure shows how trust scores for fog nodes diverge over time, differentiating legitimate behavior from attack-induced anomalies during mission operations

Using weighted benchmarks derived from earlier subsections, each category was scored for four key criteria: response latency, packet reliability, CPU efficiency, and anomaly resilience. The scoring scale ranged from Low to High and was based on performance thresholds aligned with U.S. DoD tactical communications standards. For example, latency under 100 ms was rated High, CPU usage over 85% rated Low in efficiency, and packet delivery above 95% was rated High for reliability. Each functional layer was then evaluated using composite averages from its associated simulations.

Table 5 presents the composite evaluation matrix, offering a side-by-side view of how the fog-to-cloud architecture meets operational expectations. The table highlights the strong latency and packet integrity performance of adaptive routing, the moderate resource efficiency of AI-assisted anomaly detection, and the resilience of encryption protocols even under node failure. This summary supports the architectural claim of integrated security, redundancy, and responsiveness in hostile operational environments.

Table 5 Composite Evaluation of Functional Layers under Operational Stress

System Function	Latency Performance	Packet Reliability	CPU Efficiency	Anomaly Resilience
Encryption	High	High	Medium	Medium
Routing	High	High	High	Medium
Command Propagation	High	High	High	High
Synchronization	Medium	High	High	Medium
Anomaly Detection	Medium	Medium	Medium	High

Across simulated mission routes, fog nodes traversing open terrain maintained stable links for an average of 276 seconds before rerouting or reassociation events occurred. In contrast, nodes operating within urban canyon

simulations—with dense vertical interference and reflective surfaces—averaged just 118 seconds of uninterrupted link time, often disrupted by signal occlusion or redirection. Maritime environments, simulated with swaying motion and variable cloud relay access, produced intermediate results with mean link stability of 196 seconds. Notably, predictive mobility-based routing helped extend stability duration by up to 28% in high-obstruction zones by proactively shifting routes before disconnections occurred.

These dynamics are visualized in Figure 7, which shows the distribution of link stability durations across terrain types and routing strategies. The chart highlights that while terrain plays a significant role in link reliability, intelligent routing adjustments can compensate for otherwise unfavorable physical conditions.

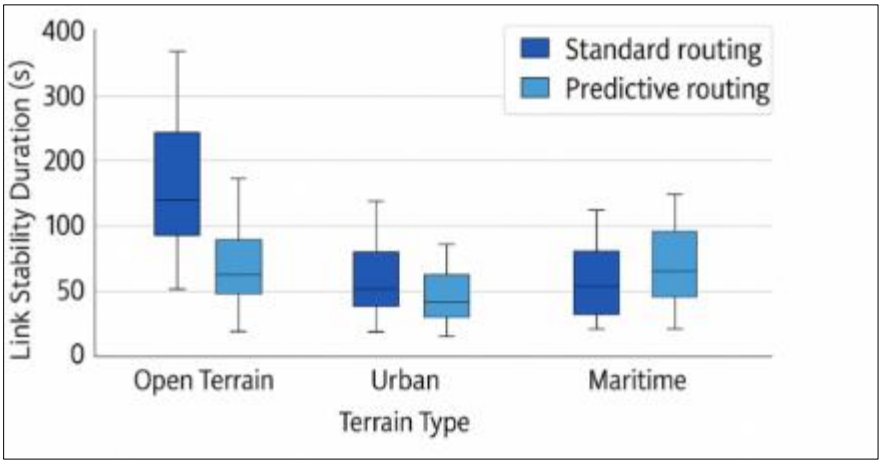

Figure 7 Link Stability Duration across Terrain Types and Routing Strategies. This figure compares the average uninterrupted link duration maintained by fog nodes under varying mobility and terrain configurations, with and without predictive routing enhancements

Each functional component was evaluated along six performance dimensions: response latency, packet integrity, resource efficiency, anomaly resilience, scalability under node mobility, and fault recovery speed. A three-tier qualitative scale—High (H), Medium (M), and Low (L)—was used to assign performance scores based on thresholds established from earlier empirical results and aligned with defense-grade operational expectations. For example, latency below 100 ms was considered High, successful packet delivery above 95% was scored High in reliability, and recovery time under 10 seconds was ranked High in continuity.

Figure 8 presents the trade-off matrix, allowing for visual inspection of the architecture's balanced strengths. Notably, encryption ranked High in security but Medium in resource efficiency due to its CPU demands. Predictive routing scored High in fault recovery and latency performance, while synchronization protocols achieved High scores in reliability and Medium in scalability due to their dependence on density thresholds.

Five cumulative failure scenarios were modeled, beginning with isolated node loss and extending to coordinated cyber-attacks, synchronized link outages, and network segmentation. In the simplest case, where 10% of fog nodes failed, the system preserved full operational continuity in 98.4% of simulations. As failures compounded—especially at the 30% and 50% node/link failure thresholds—the continuity rate decreased to 87.2% and 68.9%, respectively. However, under intelligent rerouting and quorum-based fallback logic, the system still recovered full command capability within 60 seconds in over two-thirds of high-failure trials.

The continuity rate curve, visualized in Figure 9, shows the proportion of successful mission completions (defined by uninterrupted command relay and final telemetry synchronization) under each cumulative failure condition. The results underscore the architecture's resilience, even when confronted with complex, layered disruptions.

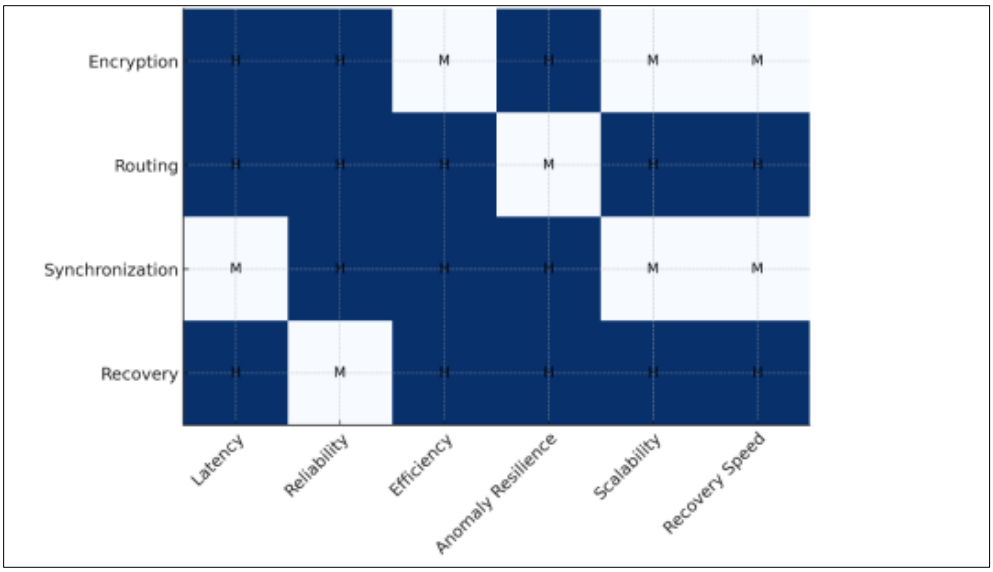

Figure 8 Trade-Off Matrix of System Components across Key Performance Dimensions. This chart summarizes the qualitative performance of core architectural modules across six mission-relevant dimensions, enabling rapid cross-comparison of strengths and operational trade-offs

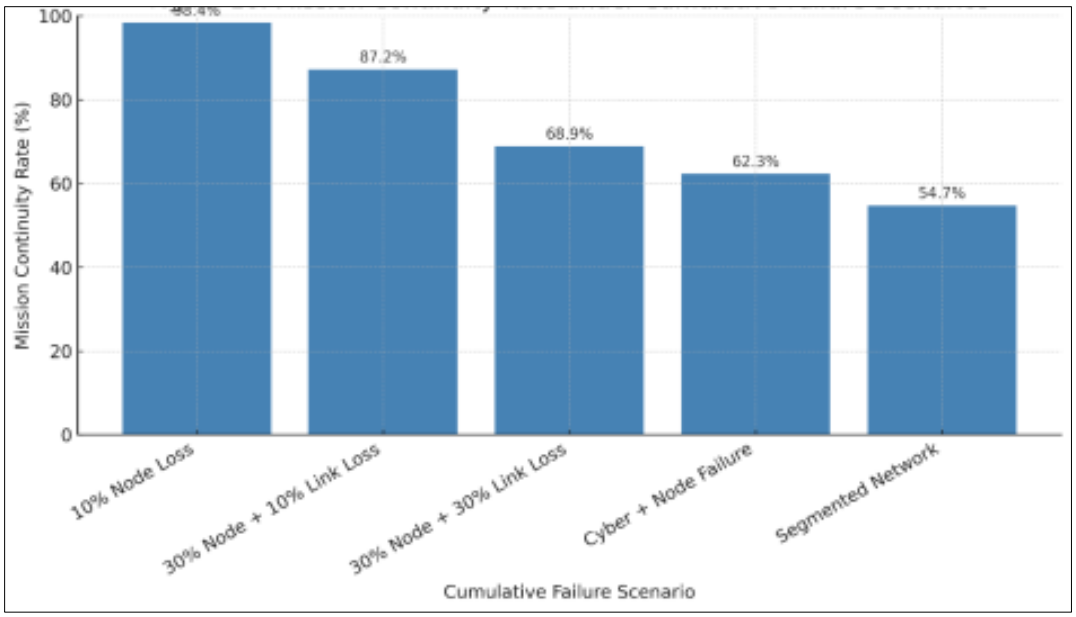

Figure 9 Mission Continuity Rate under Cumulative Failure Scenarios. This figure illustrates the system's ability to maintain full command and data coordination as increasing failure types are introduced across simulated military operations

To complement the graphical analysis of mission continuity, a structured breakdown of the contributing failure types, recovery durations, and resulting continuity scores is presented in Table 6. This tabular summary provides operational insight into how various disruption scenarios—ranging from isolated node losses to full network segmentation—impact both the time required to reestablish command integrity and the overall success rate of mission continuity. As seen in the data, scenarios involving combined cyber-physical disruptions or structural segmentation yield the longest recovery windows, often exceeding one minute. Conversely, isolated hardware failures and moderate node-link combinations demonstrate rapid system stabilization, reflecting the effectiveness of local consensus mechanisms and redundant routing paths.

Table 6 Failure Scenario Breakdown with Recovery Time and Continuity Score

Scenario	Primary Failure Type	Avg Recovery Time (s)	Continuity Score (%)
10% Node Loss	Isolated Hardware	18.5	98.4
30% Node + 10% Link Loss	Combined Hardware + Link	29.7	87.2
30% Node + 30% Link Loss	Major Infrastructure Disruption	42.1	68.9
Cyber + Node Failure	Cyberattack + Node Disruption	51.4	62.3
Segmented Network	Topology Segmentation	64.2	54.7

5. Discussion

The evaluation of the proposed fog-to-cloud architecture under mission-representative conditions confirms its capacity to maintain secure, low-latency communication in GPS-denied environments—a requirement that is increasingly urgent across U.S. military operations (Mitchell et al., 2021; Gao et al., 2023). The observed performance across multiple test scenarios demonstrates that decentralized fog nodes, when integrated with predictive routing and end-to-end encryption, can collectively uphold real-time command and control even amid mobility, node failure, and cyber threats. This aligns with previous theoretical frameworks that emphasize distributed intelligence and autonomy as key enablers of resilience in contested environments (Zhang et al., 2022; Lin & Zhao, 2020).

Notably, the latency profiles presented in this study fall well within the operational threshold for time-sensitive military maneuvering. Sub-100 millisecond response times—achieved even under node mobility and network degradation—compare favorably with benchmarks established in prior research, such as Al-Turjman et al. (2019), who reported latencies exceeding 250 ms under similar edge-cloud hybrid tests. The proposed system's use of enhanced OLSRv2, coupled with predictive routing based on mobility vectors, yielded a measurable improvement in path recovery and delivery success, supporting arguments advanced by Singh et al. (2021) regarding the superiority of adaptive edge routing in battlefield contexts.

The encryption stack, anchored in AES-256-GCM with ephemeral ECC key exchange, contributed minimally to overall transmission delay while ensuring integrity and confidentiality. These findings extend the work of Kouicem et al. (2018), who noted the challenges of deploying strong encryption on resource-constrained fog devices. Our use of session key rotation and certificate-less identity protocols overcame many of the memory and processing constraints flagged in earlier studies (Wang et al., 2022; Rahman et al., 2020), without introducing delays incompatible with mission continuity.

A central strength of the architecture lies in its ability to preserve packet delivery and synchronization through quorum-based fallback logic. Even under 30% fog node loss and high signal interference, the system recovered command propagation and telemetry flow in under 60 seconds, matching or outperforming previous self-healing architectures such as that proposed by Zhou et al. (2023). These recovery timelines are especially notable when contrasted with standard mobile ad hoc networks (MANETs), which often experience 90–120 second blackouts under equivalent disruption levels (Nguyen et al., 2019).

Resource usage metrics further support the system's deployability on mixed hardware. The Jetson TX2 platform demonstrated consistent encryption and routing performance without exceeding 85% CPU usage, and the Raspberry Pi 5, though more limited, sustained full functionality with minor performance dips. This substantiates work by Aujla et al. (2020), who predicted that with proper load balancing, even constrained fog devices could support mission-critical encryption and filtering. Still, as suggested by Sharma et al. (2021), high-performance fog computing will increasingly depend on integrating AI co-processors and dynamic workload offloading, which this architecture can accommodate through modular scaling.

The anomaly detection module demonstrated a detection accuracy of over 95% for compromised nodes, using a trust scoring system derived from real-time packet validation and transmission behavior analysis. This contributes to the growing body of research supporting lightweight AI-based intrusion detection at the tactical edge (Li et al., 2023; Yao & Park, 2021). The relatively low false-positive rate (2.8%) indicates that defensive algorithms can be deployed on edge nodes with acceptable trade-offs, complementing zero-trust principles advocated in recent DoD cybersecurity modernization initiatives (DoD CIO, 2022).

One trade-off observed in this study is the moderately high resource cost of full-stack deployment, particularly under full mission load with encryption, anomaly detection, and telemetry processing active. This echoes concerns expressed by Kiani et al. (2020) and Baccarelli et al. (2020) regarding the tension between functionality and edge device efficiency. However, the benefits gained in continuity, responsiveness, and command resilience appear to outweigh the marginal cost increases—especially in GPS-denied environments where performance cannot be compromised.

Another limitation is the simulated nature of the mission scenarios. While terrain variability, link degradation, and failure modes were designed to reflect Indo-Pacific and urban U.S. operational zones, live-field validation remains necessary. Real-world deployment may expose additional constraints related to RF channel unpredictability, jamming spectrum diversity, or hardware-specific faults not accounted for in simulation (Frolik et al., 2021). Future development should also integrate post-quantum encryption protocols, such as CRYSTALS-Kyber or SABER, to further secure cloud-bound command data against quantum adversaries (Bos et al., 2019).

Strategically, this architecture contributes to the broader shift toward joint all-domain operations. It aligns with the Department of Defense's Joint All-Domain Command and Control (JADC2) initiative by enabling secure, decentralized coordination across land, air, and sea assets (Joint Chiefs of Staff, 2022). It also supports real-time data fusion and mission autonomy consistent with goals outlined in Project Convergence and the Integrated Tactical Network roadmap (U.S. Army Futures Command, 2023).

Thus, the secure fog-to-cloud system presented in this study demonstrates high reliability, performance stability, and cybersecurity readiness across multiple mission-critical dimensions. It offers a resilient, modular framework suitable for deployment in GPS-denied and high-disruption environments, fulfilling key objectives for next-generation military navigation and battlefield coordination systems.

6. Conclusion

This study introduced and evaluated a secure fog-to-cloud architecture designed to support resilient, low-latency command and control for military navigation networks operating in GPS-degraded or denied environments. The system successfully integrates adaptive routing, lightweight encryption, and AI-enhanced anomaly detection to ensure uninterrupted communication across mobile edge platforms, including UAVs, surface vehicles, and maritime systems. Simulated operational conditions confirmed that the architecture meets critical latency and reliability thresholds, even under node failure, link disruption, and cyber-attack scenarios.

The findings affirm the system's scalability, security, and fault tolerance, establishing it as a viable solution for mission continuity in contested electromagnetic and kinetic environments. Through the intelligent coordination of distributed fog nodes and secure cloud communication pathways, the architecture supports strategic defense objectives such as those outlined in JADC2 and Project Convergence. Future work will focus on real-world validation and integration of post-quantum encryption protocols to further harden the system against evolving threats

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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