Vertical Handover Delay Minimization in Non-Terrestrial Networks: A Review and the Ateles Time-Adaptive Search Framework

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***Abstract*—Non-terrestrial networks (NTN) are increasingly recognized as a critical enabler of 5G and beyond, providing ubiquitous coverage, enhanced mobility support, and resilience in challenging environments. However, seamless vertical handover (VHO) between terrestrial and non-terrestrial segments remains a major challenge due to high propagation delays, Doppler effects, and dynamic satellite topologies. Existing optimization approaches, including mobility prediction, reinforcement learning, and topology-aware scheduling, provide partial solutions but suffer from scalability and signaling overhead issues. This review paper systematically analyzes recent advancements in NTN handover management, with particular emphasis on transparent and regenerative payload architectures. Furthermore, it highlights the potential of the Ateles Time-Adaptive Search (TAS) framework as a promising solution to minimize handover delays by dynamically adapting timer configurations (TTT, T304) to mobility and link variations. The paper consolidates the state-of-the-art, identifies key research gaps, and proposes future directions for implementing TAS-enabled handover mechanisms in 6G NTN.**

Keywords—Non-Terrestrial Networks (NTN); Vertical Handover (VHO); 5G and Beyond; Transparent Payload; Regenerative Payload; Handover Delay Minimization; Ateles Time-Adaptive Search (TAS); Mobility Management.

I. INTRODUCTION

The integration of non-terrestrial networks (NTNs) with 5G and beyond technologies has become essential for achieving global connectivity and bridging coverage gaps left by traditional terrestrial networks (TNs)[1]. Despite advancements, current wireless infrastructure covers only about 20% of land and 5% of oceans, leaving significant areas underserved[2]. NTNs—including low earth orbit (LEO) satellites, high-altitude platforms (HAPs), and unmanned aerial vehicles (UAVs)—are increasingly recognized as enablers of ubiquitous, scalable, and resilient communications, complementing TNs in both routine and mission-critical scenarios[3].This integration is motivated by both commercial and societal demands. Forecasts project that by 2028, the number of 5G subscriptions will surpass 5 billion, with an additional 300 million fixed wireless access (FWA) connections[4]. At the same time, the exponential growth of the massive Internet of Things (mIoT)—expected to exceed 75 billion devices by 2025—requires unprecedented levels of connectivity, reliability, and spectrum efficiency. NTNs are therefore envisioned as a cornerstone of 6G networks, enabling advanced use cases such as autonomous transportation, precision agriculture, remote healthcare, disaster recovery, and global industrial automation[5].

However, supporting such large-scale, high-mobility environments introduces significant mobility management (MM) challenges[6]. In both TNs and NTNs, handover (HO) and cell (re)selection (CS) are crucial procedures for ensuring seamless connectivity as user equipment (UE) and IoT devices traverse coverage areas[7]. In NTNs, these procedures are far more complex due to dynamic topologies, long propagation delays, intermittent line-of-sight, and frequent link quality variations[8]. Among mobility challenges, vertical handover (VHO)—transitioning between heterogeneous access technologies such as satellite-to-terrestrial or UAV-to-satellite links—has emerged as particularly critical[9]. Improper VHO execution often results in excessive latency, packet loss, service interruption, and the ping-pong effect, which severely degrade user experience in delay-sensitive applications[10].Recent surveys have emphasized these concerns. Alsaeedy and Chong (2024) highlighted that power constraints, signaling overhead, and high handover latency are key bottlenecks for mobility management in NTN-based 5G networks[11]. Similarly, Azari et al. (2022) noted that seamless VHO will be central to the evolution of integrated ground–air–space (GAS) networks, requiring adaptive algorithms and intelligent decision-making frameworks to meet stringent 6G requirements[12]. Despite numerous proposed solutions—including optimization algorithms, machine learning-based decision models, fuzzy logic systems, and software-defined networking (SDN)—the literature reveals persistent gaps in energy efficiency, scalability, and reliability under real-world NTN conditions[13].

Against this backdrop, this review provides a comprehensive analysis of vertical handover delay minimization techniques in NTNs, synthesizing current methods, identifying open research challenges, and exploring emerging directions[14]. In particular, the review highlights the potential of bio-inspired and adaptive algorithms, such as the proposed Ateles Time Adaptive Search Algorithm, as promising candidates for achieving seamless mobility with minimized handover delays in next-generation NTNs[15].

II. LITERATURE REVIEW

The design and development of a vertical handover (VHO) delay minimizing framework for non-terrestrial networks (NTNs) using the Ateles time adaptive search algorithm is a complex task due to the high mobility of Low Earth Orbit (LEO) satellites, frequent link disruptions, and the stringent requirement for seamless connectivity[16]. Literature from 2021–2025 provides valuable insights into network topology optimization, handover mechanisms, and resource management, all of which directly influence handover delays. This section synthesizes state-of-the-art research to establish the foundation for the proposed framework[17].

A. Network Topology and Optimization

The dynamic nature of LEO constellations demands efficient topology optimization. Ron et al. (2025) introduced the Dynamic Time-Expanded Graph (DTEG)-based Optimal Topology Design (DoTD) algorithm, which maximizes network capacity and minimizes latency by using a time-dependent scoring function[18]. Similarly, Ei et al. (2024) applied a deep reinforcement learning (DDPG) framework for integrated terrestrial-NTN systems to jointly optimize user association, trajectory, and power allocation[19]. These works highlight the importance of predictive and adaptive algorithms to support seamless mobility.

B. Handover Mechanisms

Frequent handovers in LEO satellite networks introduce significant signaling storms and latency. Dahouda& Joe (2023) proposed machine learning-based clustering and classification to optimize handover decision-making, reducing signaling overhead[20]. Lee et al. (2023) developed a deep reinforcement learning-based handover protocol (DHO) that bypasses the Measurement Report phase, reducing access delays and collision rates[21]. These innovations demonstrate the trend toward AI-driven, delay-minimizing VHO protocols.

C. Resource Management and Optimization

Resource management in NTNs is constrained by large round-trip delays (RTDs) and limited onboard processing. Sheemar et al. (2023) optimized RLC/PDCP timers and buffers, reducing delays for regenerative payload satellites[22]. In parallel, Cao et al. (2024) proposed collaborative computing with multi-time-scale deep reinforcement learning, enabling joint optimization of radio resources between LEO satellites and user equipment (UEs)[23].

D. Future Directions and Challenges

As NTNs evolve toward 6G, new paradigms such as dynamic network slicing, beamforming, and Generative AI-based CSI estimation are emerging. Wang et al. (2024) highlighted the criticality of mobility-aware SDN/NFV architectures for seamless TN-NTN handovers[24]. Guo et al. (2024) focused on Age of Information (AoI) modeling, showing how satellite visibility and cross-traffic directly impact data freshness and timeliness in NTN scenarios[25].

III. APPLICATIONS AND SCENARIOS OF 5G NON-TERRESTRIAL NETWORKS (NTNS)

1) Background Context – NTNs extend 5G connectivity to underserved, remote, and disaster-hit areas using GEO, MEO, LEO, and vLEO satellites. While GEO/MEO provide coverage with higher latency, LEO/vLEO enable low-latency communication but require advanced mobility management due to frequent handovers.

2) LEO Constellations – Operating at 500–2000 km, LEO satellites power global broadband systems like Starlink, OneWeb, and Project Kuiper. They offer low latency, reduced attenuation, and scalable deployment, making them central to NTN integration with 5G and beyond.

3) vLEO Constellations – Positioned at 100–350 km, vLEO satellites further cut latency, enabling real-time disaster monitoring, autonomous operations, and mission-critical services. However, their rapid movement intensifies handover frequency, requiring optimization frameworks such as the Ateles Time-Adaptive Search (TAS) to minimize service interruptions and manage signaling overhead.

IV. NTN-ENABLED 5G RAN ARCHITECTURE

The integration of NTNs into 5G extends NG-RAN by enabling both LTE and 5G UEs to seamlessly access the 5GC. Unlike terrestrial networks, NTNs face higher delays, Doppler effects, and frequent beam transitions, making adaptive gNB functional splits essential for efficient vertical handover management.

A. gNB Functional Units and NTN Relevance

1) Central Unit (CU): Hosts higher-layer protocols; CU-CP manages signaling and mobility updates under satellite dynamics, while CU-UP handles payload forwarding to minimize delay during TN↔NTN handovers.

2) Distributed Unit (DU): Manages lower-layer functions (RLC, MAC, PHY) to ensure radio link reliability amid rapid beam switching in LEO/vLEO constellations

3) Relevance to NTNs: The CU–DU split enables virtualization, load balancing, and flexible deployment, making adaptive handover control feasible under high-latency NTN conditions.

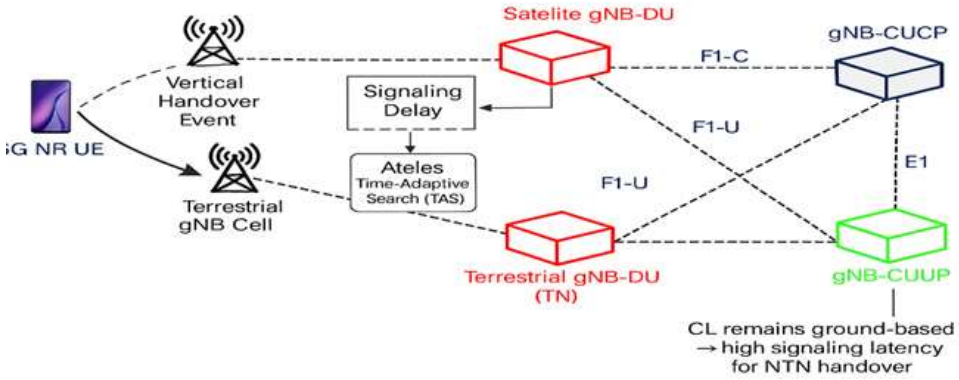


Fig. 1. Proposed NTN-TN integrated gNB architecture showing vertical handover scenario.

The UE transitions between a satellite NTN cell and a terrestrial gNB cell, where signaling over the F1-C interface introduces delay. The Ateles Time-Adaptive Search (TAS) algorithm is integrated to minimize vertical handover delay.

B. Satellite Payload Architectures for 5G NTN Access

1) Transparent Payload: Satellites act as bent-pipe relays, forwarding signals to gateways with low onboard complexity. While protocol consistency is maintained, reliance on ground processing increases latency due to gateway-dependent terminations.

2) Regenerative Payload: Satellites host partial NG-RAN functions (e.g., gNB-DU), performing onboard processing. This reduces latency, avoids repeated gateway round-trips, and enhances handover management in dynamic LEO/vLEO scenarios.

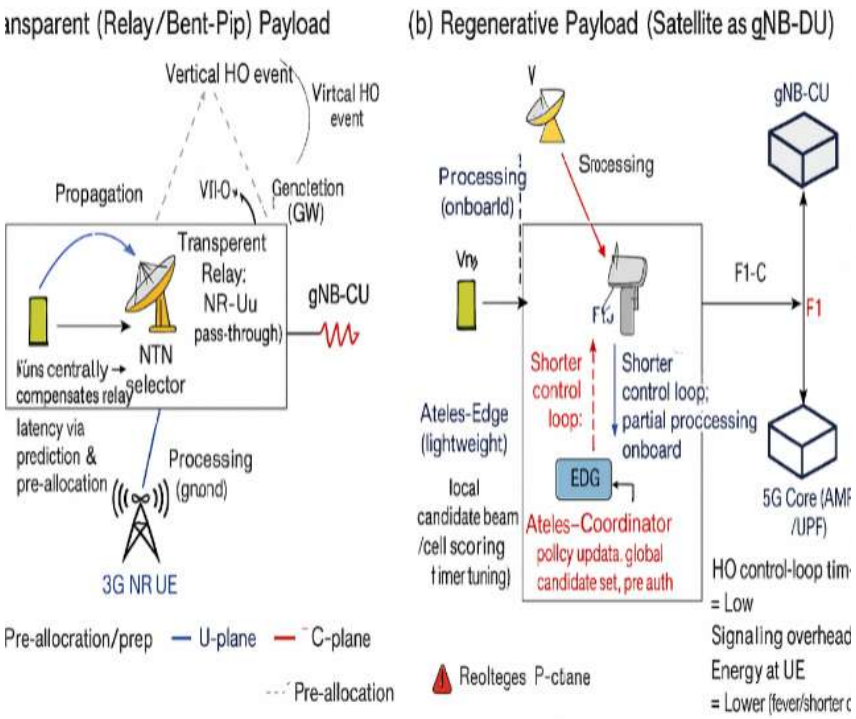


Fig. 2. Transparent vs. regenerative NTN payloads and their impact on vertical handover delay. (a) In relay (transparent) payloads, (b) In regenerative payloads

Regenerative payloads + split Ateles (edge+coordinator) provide the lowest vertical HO delay for LEO/vLEO, while transparent payloads rely on stronger prediction and pre-authentication to hide RTT.

V. KEY ELEMENTS OF NG-RAN IN 5G NON-TERRESTRIAL NETWORKS (ALIGNED WITH ATELES TAS FRAMEWORK)

1) Core NTN Elements: Sat-gNBs in LEO/vLEO extend coverage and support predictive handovers, while gateways (GWs), feeder links, and service links (NR-Uu) form the backbone of NTN–5GC integration. TAS adapts timers at CU level to mask feeder delays and accelerates UE-driven handover triggers.

2) Satellite Payloads: Transparent payloads act as relays, relying on ground CUs where TAS compensates for higher RTT. Regenerative payloads perform onboard processing (gNB-DU), enabling TAS to run as an edge-agent for faster handovers.

*3) Beam Management:*Multibeam footprints increase handover frequency; TAS dynamically tunes beam-switching timers to reduce failures in fast mobility scenarios (ships, aircraft, trains).

4) Inter-Satellite Links (ISLs): ISLs distribute TAS decision data across satellites, maintaining predictive handover continuity and reducing interruptions during inter-satellite mobility.

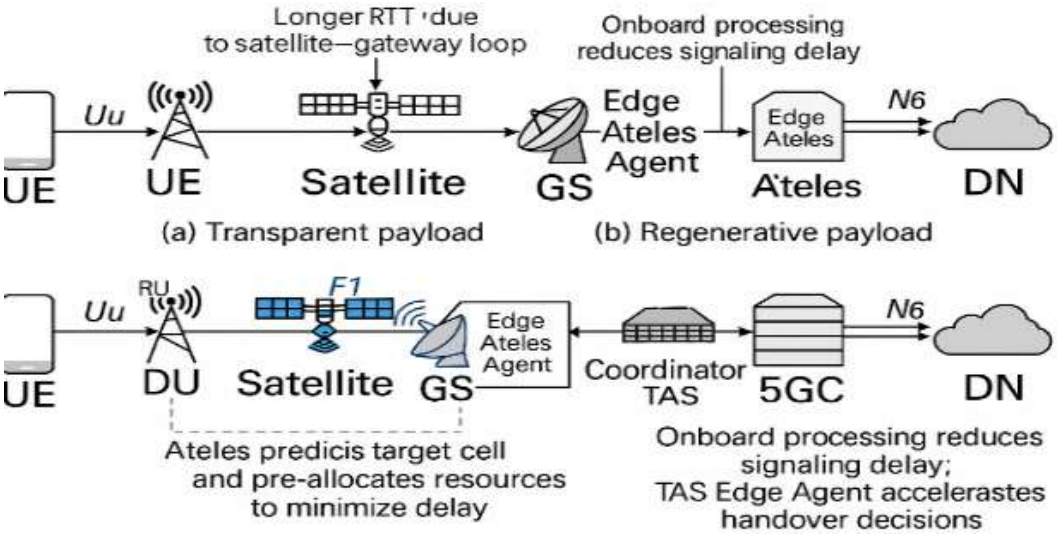


Fig. 3. 5G NTN Architectures with Transparent and Regenerative Payloads

VI. SURVEY OF HANDOVER OPTIMIZATION APPROACHES

Vertical handover (VHO) in NTNs has prompted diverse solutions. We organize the literature into five families of methods and evaluate them specifically against NTN constraints (fast-moving LEO/vLEO beams, long feeder delays in transparent payloads, limited satellite compute, UE energy constraints).

A. Optimization & Metaheuristic Methods

1) Metaheuristic Approaches in NTN: Techniques like cuckoo search, GA, hybrid metaheuristics, simulated annealing, and PSO treat VHO as a multi-objective optimization problem but face high computational cost, slow convergence, and heavy parameter tuning, limiting real-time applicability in short LEO pass windows.

2) Ateles TAS Advantage: Unlike population-based searches, TAS employs a time-adaptive, lightweight strategy that narrows exploration as deadlines approach, enabling faster, near-optimal handover decisions with minimal iterations and measurement overhead.

B. Machine Learning (Supervised / Unsupervised)

1) ML-Based Handover in NTNs – Techniques such as clustering, supervised classifiers, and feature ranking predict optimal beams/cells and group UEs to cut signaling. While effective (e.g., Dahouda& Joe, 2023), they depend on quality labeled data, frequent retraining, and struggle to generalize across varying constellations and mobility regimes, with added challenges of data-sharing and privacy.

2) Advantage of Ateles TAS – Unlike data-heavy ML models, Ateles TAS can optionally use ML scores as input but remains dataset-independent. Its adaptive, lightweight search refines handover decisions in real time from recent observations, avoiding retraining overhead while ensuring robustness across diverse NTN environments.

C. Reinforcement Learning

Deep reinforcement learning (DQN, DDPG, actor-critic, multi-agent schemes) has been applied to NTN handovers, enabling predictive decisions but suffering from high training complexity, sample inefficiency, and satellite resource constraints. In contrast, the Ateles TAS framework avoids heavy training, using a lightweight bio-inspired search with split deployment to deliver fast, adaptive, and practical handover decisions.

D. Topology / Graph-Based & Time-Aware Approaches

1) Graph-Based Approaches in NTN: Techniques such as dynamic graphs, time-expanded graphs, and shortest-path algorithms optimize ISL/feeder link selection and global routing to reduce latency and link churn (e.g., Ron et al., DoTD 2025).

TABLE I. COMPARITIVE PERSPECTIVE AFTER TAS PLACEMENT

Architecture	TAS Placement	Key Adaptations	Expected HO Delay	Strength
Transparent	Centralized CU/AMF	TTT↓, T304↑, pre-allocation	High (RTT-bound)	Simple satellite design
Regenerative	Split: Edge Agent + Coordinator	TTT↓, T304↓, real-time edge decision	Low (fast loops)	Best for vLEO/LEO mobility

2) Ateles TAS Advantage: While graph models handle global topology control, Ateles focuses on per-UE, per-beam handovers. Its time-adaptive search minimizes VHO delay dynamically at the user level, complementing topology optimization with lightweight, practical decision-making.

E. Protocol-Level and PHY-aware Fixes

1) Protocol and PHY-Level Optimizations in NTN: Adaptive timers (RLC/PDCP T304), buffer sizing, numerology tuning, and beamforming improvements help mitigate RTT and Doppler effects, reducing retransmissions and timer-related false handovers. However, they mainly address link reliability and protocol delays, without accelerating target cell/beam selection.

2) Ateles TAS Advantage: Unlike standalone fixes, Ateles integrates adaptive timer control into its time-adaptive search, combining protocol-level adjustments with proactive target selection to achieve more effective handover latency reduction.

VII. ATELES TIME-ADAPTIVE SEARCH

1) Rationale and Objective: Vertical handovers in NTNs face challenges from fast-moving LEO/vLEO beams, high delays, and diverse payloads. The Ateles Time-Adaptive Search (TAS) offers a lightweight, bio-inspired solution that adapts search intensity to strict handover deadlines.

2) Time-Adaptive Search Concept: TAS adjusts exploration dynamically—broad candidate probing in the early phase, refined selection mid-phase, and rapid convergence in the late phase—balancing accuracy with execution speed.

3) Timer Adaptation Mechanism: TAS adapts key timers for efficiency: TTT is shortened with high confidence/urgency and extended to prevent ping-pong; T304 is lengthened for transparent payloads (high RTT) and shortened for regenerative payloads (low RTT).

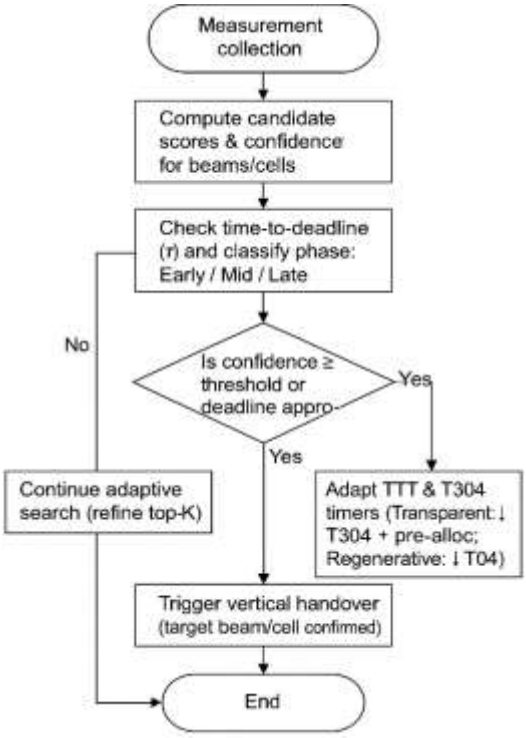


Fig. 4. Conceptual workflow of the Ateles Time-Adaptive Search (TAS) algorithm for vertical handover in NTNs

VIII. PROPOSED FRAMEWORK

A. *Transparent Payload with Centralized TAS*

In transparent payload NTNs, TAS is centralized at the gNB-CU/AMF, using predictive handover with resource pre-allocation and adaptive timer tuning. This reduces control latency by overlapping pre-authentication with ongoing sessions.

B. *Regenerative Payload with Split TAS*

In regenerative payload NTNs, TAS splits between an onboard edge agent for rapid local HO execution and a ground coordinator for global updates.

C. *Comparative Perspective*

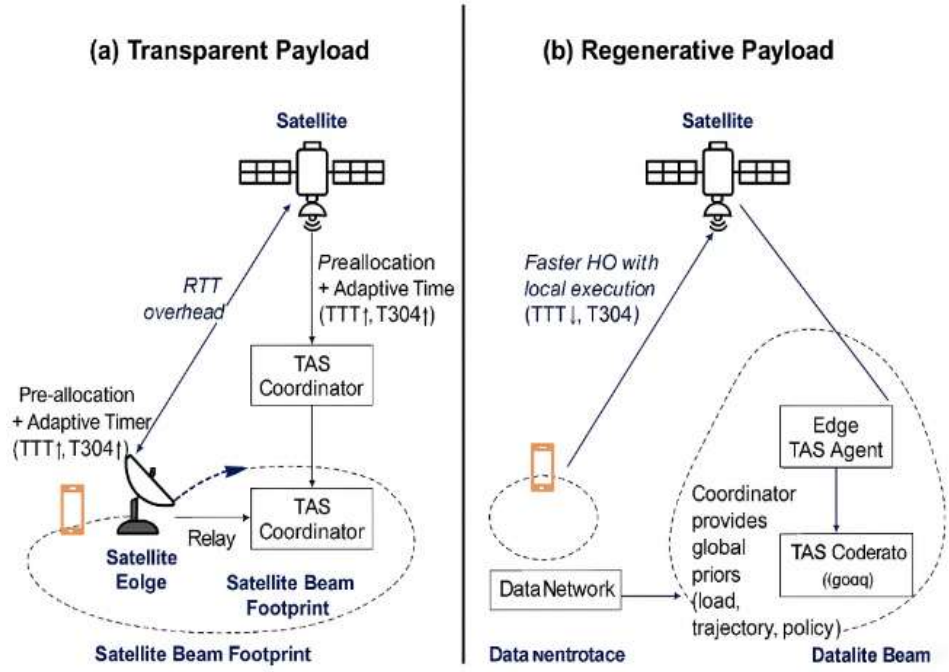


Fig. 5. Call flow of Ateles Time-Adaptive Search (TAS) integration under Transparent and Regenerative NTN payload architectures.

IX. CHALLENGES AND OPEN ISSUES

1) Scalability in Mega-Constellations – Managing TAS across tens of thousands of satellites and millions of UEs requires efficient distributed logic, cooperative beam management, and cross-satellite coordination to avoid overwhelming control channels.

2) Doppler & PHY-Level Impairments – Severe Doppler shifts in LEO/vLEO demand joint PHY–MAC–RRC optimization, integrating TAS with adaptive numerology, beam forming, and CSI estimation for robust mobility support.

3) Multi-Connectivity Complexity – 6G's parallel TN/NTN links complicate handover due to inter-satellite routing and UE battery drain; TAS must selectively manage multi-links, balancing redundancy and signaling overhead.

4) Edge–Coordinator Synchronization – In regenerative payloads, TAS needs reliable coordination between satellite

edge agents and ground coordinators, addressing consistency, backhaul delays, and conflict resolution.

5) Energy, Security & Realistic Validation – TAS must minimize UE power drain, align with security/standardization efforts (3GPP Rel-18+), and be validated through hybrid emulation, cross-layer testbeds, and hardware-in-the-loop experiments.

X. FINAL REMARKS AND CONCLUSION

This review has examined the state-of-the-art in vertical handover (VHO) optimization for non-terrestrial networks (NTNs), emphasizing the challenges of LEO/vLEO constellations and 5G–6G mobility management. Existing approaches—spanning metaheuristics, machine learning, reinforcement learning, and protocol-level enhancements—offer partial improvements but remain constrained by computational complexity, dataset dependence, and limited adaptability to dynamic NTN topologies. To address these gaps, the Ateles Time-Adaptive Search (TAS) framework is proposed as a lightweight, adaptive strategy that dynamically tunes search intensity and timers, while differentiating between transparent and regenerative payload architectures. TAS centralizes predictive resource allocation in transparent payloads and leverages edge–coordinator cooperation in regenerative payloads to reduce latency and improve resilience. Despite its promise, TAS remains conceptual; key challenges persist in scalability, Doppler mitigation, multi-connectivity, synchronization, energy efficiency, and standardization. Future research must pursue implementation through simulations, hybrid emulators, and testbeds to advance TAS toward practical, deployable NTN mobility solutions.

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