

A Case for Stateless Mobile Core Network Functions in Space

Yuanjie Li, Hewu Li, Wei Liu, Lixin Liu, Yimei Chen, Jianping Wu, Qian Wu, Jun Liu, Zeqi Lai
Institute for Network Sciences and Cyberspace, BNRist, Tsinghua University, Beijing 100084, China

ABSTRACT

Is it worth and feasible to push mobile core network functions to low-earth-orbit (LEO) satellite mega-constellations? While this paradigm is being tested in space and promises new values, it also raises scalability, performance, and security concerns based on our study with datasets from operational satellites and 5G. A major challenge is today's *stateful* mobile core, which suffers from signaling storms in satellites' extreme mobility, intermittent failures in outer space, and attacks when unavoidably exposed to untrusted foreign locations. To this end, we make a case for a *stateless* mobile core in space. Our solution, SpaceCore, decouples states from orbital core functions, simplifies location states via geospatial addressing, eliminates unnecessary state migrations in satellite mobility by shifting to geospatial service areas, and localizes state retrievals with device-as-the-repository. Our evaluation with datasets from operational satellites and 5G shows SpaceCore's 17.5× over existing solutions signaling reductions and resiliency to failures/attacks.

CCS CONCEPTS

• **Networks** → **Mobile networks**; **Network protocol design**.

KEYWORDS

Mobile network, space network, low-earth-orbit satellite mega-constellations, stateless core network functions, 5G and beyond.

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1 INTRODUCTION

Mobile networks (5G and beyond) have successfully served billions of users. But their heavy deployment and operation costs (10s–100s billions of dollars [1, 2]) in rural areas, developing countries, aircraft, or oceans limit them from covering the remaining 3.7 billion “unconnected” global users [3]. Their fixed deployment limits regional operators from expanding to international services for more revenues. Their terrestrial infrastructure is also vulnerable to disasters (earthquakes, tornados, or wars).

Hewu Li is the corresponding author.

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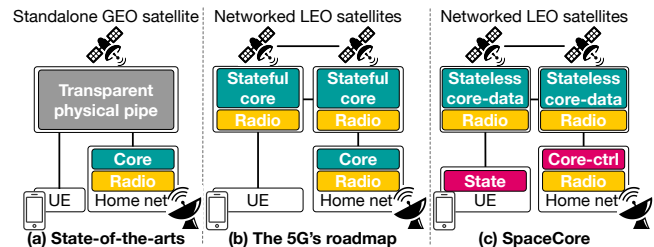


Figure 1: Mobile function and state divisions in space.

Pushing mobile networks to space is a promising solution. Satellite communications via 2G–5G have been operational for decades [4–11]. They complement terrestrial networks' coverage to remote areas at lower costs. The recent low-earth-orbit (LEO) satellite mega-constellations (Starlink [12], OneWeb [7], Amazon Kuiper [13], Boeing [14], and more) further promise competitive bandwidth and latency to terrestrial networks. To this end, the industry is actively extending 5G (and beyond) to LEO constellations with standardizations [15–18] and early adoptions [19–24].

Early mobile satellites are standalone, transparent physical pipes in the geostationary orbit with broad coverage yet low performance (Figure 1a). In LEO mega-constellations, this model suffers from low coverage and single-point bottlenecks [25, 26]. Instead, operators and infrastructure vendors have started to experiment with LEO satellites as 5G radio access [19–21] and core network [22–24, 27] functions (Figure 1b). This paradigm, if feasible, could solve the above issues *and* potentially boost new values like global mobile service expansions, ubiquitous connectivity to massive terrestrial IoT devices, seamless space-terrestrial 5G integration, lightweight satellite devices, and orbital edge computing [28–32] (§2.2).

Despite so, pushing mobile core functions to space is still controversial. Unlike fixed terrestrial infrastructure, LEO satellites move fast in unreliable, untrusted outer space on a global scale. This challenges basic assumptions in mobile networks. In §3, we analyze various options of pushing mobile core to space based on our signaling datasets from operational satellites and terrestrial 5G (Table 2, released in [33]). If placed in LEO satellites, today's mobile core would suffer from signaling storms (10^4 signaling/s per satellite, 10^5 signaling/s per ground station), repetitive mobility registrations for numerous *static* users (every 165.8s), service disruptions in space failures [34–36], and sensitive state leakages (e.g., security keys) in satellite attacks [37–41]. These issues are exacerbated with more satellites and users served by each satellite.

We show these issues are rooted in the *stateful* mobile cores today. To offer carrier-grade services, the mobile network establishes sessions between user equipment (UE) and infrastructure with states of traffic delivery, mobility, QoS, billing, and security. As the UE moves, the core migrates these states to the new infrastructure node to retain continuous services. These state operations must succeed before activating data services. While feasible for fixed terrestrial infrastructure, this design incurs excessive state

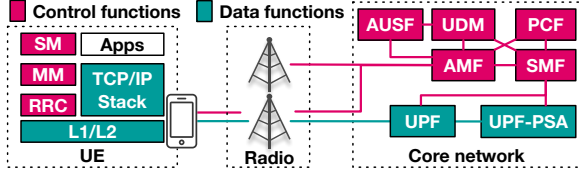


Figure 2: Terrestrial mobile network functions in 5G.

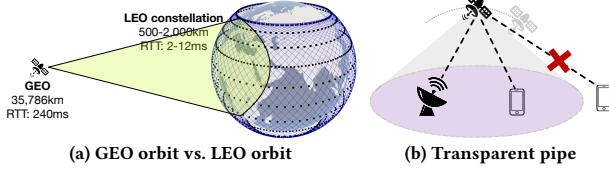


Figure 3: Coverage of standalone mobile satellites.

migrations in LEO satellite mobility for *static* UEs. These state migrations are vulnerable to failures that are not uncommon in space ($\approx 3\%$ in Starlink [34]). Moreover, the stateful orbital core is unavoidably exposed to foreign locations, thus threatened by attacks and sensitive state leakages (e.g., security keys). This issue demotivates applying recent proactive state replications [42–44] to space.

To this end, we make a case for a *stateless* mobile core in space. The basic idea is simple: Decouple core functions from states to mitigate exhaustive state migrations, failures, and attacks on satellites. The challenge, however, is how to retain carrier-grade services after this decoupling. This results in three fundamental questions:

Q1: What session states are “must-haves” for orbital core?

Q2: Where are these states placed (if not in satellites)?

Q3: How can orbital core functions work with these states?

Our solution, SpaceCore, solves Q1–Q3 with *localized, geospatial state management*. Its key observation is that the *local* UEs naturally form a scalable, resilient, secure state repository for the fast-moving satellites. They have replicated session states during the initial registration. SpaceCore utilizes this readily available feature to decouple states from the orbital core, simplify location states via geospatial addressing, eliminate state migrations in satellite mobility by shifting to *geospatial* service areas, and localize state retrievals with device-as-the-repository. SpaceCore is lightweight for satellites, decentralized without bottlenecks from space-terrestrial asymmetry, and supports seamless integration with terrestrial 5G and commodity UEs.

We prototype SpaceCore with open5gs [45] on commodity hardware used by 5G LEO satellites. Compared to existing solutions, SpaceCore reduces $17.5\times$ – $122.2\times$ signaling costs, removes bottlenecks from remote gateways, and is more resilient to satellite failures/attacks in the harsh outer space at low costs.

Ethics: This work does not raise any ethical issues.

2 MOTIVATION

We introduce the terrestrial mobile network (§2.1) and motivate why and how it is currently expanded to space (§2.2).

2.1 Terrestrial Mobile Networks

The mobile network (5G and beyond) is the largest terrestrial wireless infrastructure for wide-area data access. It consists of the radio access network and core network (Figure 2). The radio access network offers wireless access to user equipments (UEs, such as phones and IoT devices) with base stations. The core network relays traffic

	Satellites per orbit n	Total orbits m	Total satellites $n \cdot m$	Altitude H (km)	Inclination angle ϕ	Speed
Starlink [12]	22	72	1,584	550	53°	7.6 km/s
OneWeb [7]	40	18	720	1,200	87.9°	7.3 km/s
Kuiper [13]	34	34	1,156	630	51.9°	7.5 km/s
Iridium [57]	11	6	66	780	86.4°	7.4 km/s

Table 1: LEO satellite mega-constellations today.



(a) Baoyun LEO satellite as 5G core + orbital edge [22–24, 27]

(b) Satellite devices in our tests

Figure 4: Mobile communication satellites & devices.

between base stations and runs diverse functions for carrier-grade services, such as user profile management, authentication, mobility control, session management, policy control, traffic forwarding, and anchor gateway¹. These functions interact with each other in a distributed environment via signaling exchanges (§3).

The mobile network tracks a UE’s location and service by its two-tier *service areas*. At the fine granularity, each base station runs one or more small service areas called *cells*. As the UE moves, the serving cell migrates its service to the new cell via *handover*. At the coarse granularity, base stations are grouped as a larger *tracking area* (managed by an AMF). When crossing tracking areas, the UE updates its new location to the core via *mobility registration update*.

2.2 Mobile Satellites Today & Limitations

A satellite can run in geostationary orbit (GEO, at the altitude of $\approx 35,786$ km) or non-geostationary orbit, such as low-earth orbits (LEO, $\leq 2,000$ km). As shown in Figure 3a, LEO satellites promise shorter RTT and more bandwidth, but at the cost of lower coverage. So LEO *mega-constellations* are deployed for global coverage with 100s–1,000s of satellites (Table 1). LEO satellites have microwave radio for terrestrial users and inter-satellite links in space.

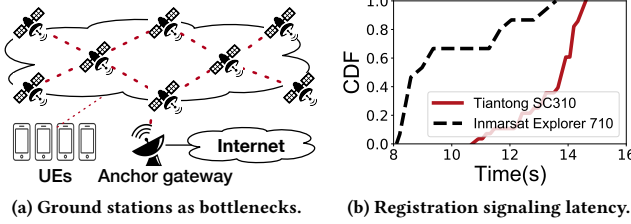
Today, most satellite communications use 2G–5G mobile network technologies, such as OneWeb [7], Inmarsat [8, 9], Boeing [14], Iridium [6], Thuraya [11], Tiantong [52], Lockheed Martin [19], Lynk [20], and AST SpaceMobile [21]. These satellites use diverse wireless spectrums (some being overlapped with terrestrial 5G spectrums [53]), such as 845–849 MHz and 788–798 MHz by AST SpaceMobile [54], sub-1 GHz by Lynk [55], 2 GHz by Lockheed Martin [19], 450 MHz–6 GHz and 24.25–52.6 GHz by 5G NTN [56]. They can be classified into three categories by their roles:

Satellites as transparent pipes: This is the *de facto* mode for most satellites today. Satellites only relay physical radio signals between terrestrial nodes without further processing. In 2G GMR [4], 3G BGAN [58], 4G SES [5], and 5G NTN [15, 16], geostationary satellites (at 35,786 km altitude) relay the radio signals between devices (e.g., satellite phones) and terrestrial ground stations. Mobile operators also rent satellites from OneWeb [7, 59] or Starlink [60, 61] as backhauls to relay signaling/data traffic between base stations and core, which saves their fiber deployments in rural areas.

¹In 5G jargons, they are called UDM, AUSF, AMF, SMF, PCF, UPF, and PDU session anchor UPF (PSA-UPF) [46–51]. See Appendix A for the acronyms.

	Mobile satellites			Terrestrial 5G		
	Inmarsat	Tiantong		China	China	China
	Explorer 710	SC310	T900	Telecom	Unicom	Mobile
L1/L2	56,231	1,744,094	3,887,429	3,828,083	1,475,393	8,405,587
RRC	40,800	4,226	1,340	28,841	14,833	69,782
MM	57,264	43,555	12,626	605	970	4,194
SM	53,868	4,586	1,670	203	338	925
Others	762,957	310,455	376,671	N/A	N/A	N/A
Total	971,120	2,106,916	4,279,736	3,857,732	1,491,534	8,480,488

Table 2: Overview of dataset from our experiments.



(a) Ground stations as bottlenecks. (b) Registration signaling latency.

Figure 5: Bottlenecks by space-terrestrial asymmetry.

Trace 1 Session establishment in Inmarsat Explorer 710.

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11:25:10.074 UMTS-GMM:Initiating service request
11:25:15.709 UMTS-GMM:Signalling connection secured
11:25:18.612 UMTS-GMM:Initiating RAU procedure
11:25:18.613 UMTS-MM:MM_LOCUPDPEND
11:25:18.615 UMTS-MM:MM_WAITRRLOCUPD
11:25:18.615 UMTS-MM:MM_LOCUPDINIT
11:25:19.264 UMTS-SM:AL State:DATA_CONN_ACTIVE
11:25:20.141 UMTS-GMM:Authentication request received
11:25:20.221 UMTS-SM:Qos:transferdelay:22, maxSDU:1500
11:25:20.221 UMTS-SM:Qos:bitRateUp:512/896, Down:512/896
11:25:20.222 UMTS-SM-GW:pdp new state Active

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Early geostationary communication satellites are mostly standalone bent pipes to support local communications between nodes within their coverage (Figure 3). This is not effective for LEO satellites with small coverage [62]. Instead, modern LEO mega-constellations have adopted networked satellites to expand their coverage. Despite so, networked physical pipes suffer from bottlenecks from *space-terrestrial asymmetry*. As transparent physical links, satellites redirect all data and signaling to remote ground stations for further processing. Since remote ground stations are fewer than LEO satellites in mega-constellations, they become the bottleneck (Figure 5). At the data plane, [26] reports that Starlink’s ground stations limit the LEO network’s total capacity despite mega-constellations. At the control plane, [63] shows Starlink ground stations should process 5 TB signaling traffic per day, and [25] reports each OneWeb’s ground station must process 10,000 terminal handovers per second. From our experiments, Figure 5b and Trace 1 show 9.5s and 13.5s average registration delays in Inmarsat and Tiantong (detailed in §3). Such latency cannot meet 5G’s stringent radio baseband processing (≤ 10 ms [64–67]) and signaling deadlines. Deploying more ground stations can alleviate this bottleneck, but lowers satellites’ advantages over terrestrial networks.

Satellites as radio access: To alleviate both issues, recent efforts seek to offload mobile network functions to satellites. The first step is to enable the radio base station functionalities in the satellites (Figure 6a). This option has been used by satellites from Lockheed Martin [19], Lynk [20], and AST SpaceMobile [21], and standardized as the regeneration mode in 5G [15, 16]. It localizes radio processing to alleviate signaling delays and bottlenecks from ground stations.

Moreover, recent 5G radio satellites in [19–21] allow direct access by today’s commodity smartphones without modifications. These satellites share wireless spectrums with terrestrial 5G, and modify

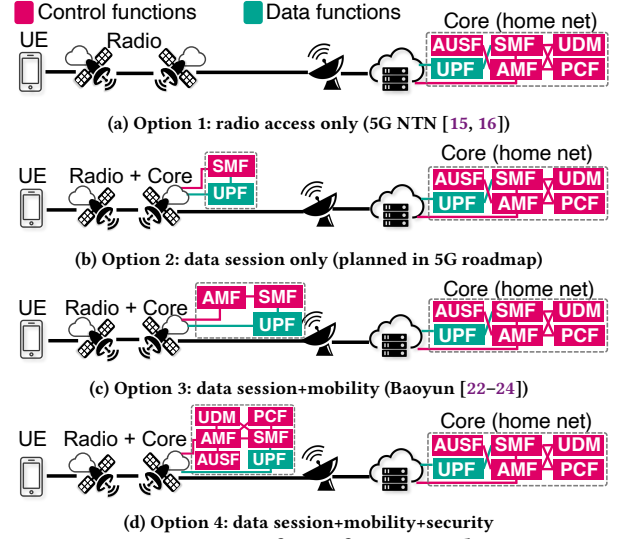


Figure 6: A taxonomy of core function splits in space.

their radio signals to disguise themselves as “terrestrial” base stations [68, 69]. This facilitates *lightweight* mobile devices without additional antennas or baseband chips for satellite communications.

However, satellites as radio access only do not suffice to eliminate bottlenecks from space-terrestrial asymmetry. First, link-layer radio access cannot route network data. All user traffic from satellites should still be relayed to the remote terrestrial home for forwarding (Figure 5). Second, splitting radio access and core between space and ground incurs new signaling storms as we will analyze in §3.1. **Satellites as core networks:** On December 7, 2021, an LEO satellite called *Baoyun* (in *Tiansuan* orbital edge computing constellation [22–24, 27] from China Mobile, Huawei, and BUPT) was successfully launched and tested as a 5G core (Figure 4a and 6c). This satellite consolidates 5G mobility (AMF), session management (SMF), and user plane (UPF) functions. Satellites with radio and core network functions can potentially eliminate the above bottlenecks by routing traffic among satellites without ground stations and localizing signaling processing. They also promise new value propositions, including (but not limited to):

(1) *Global service expansion:* Satellites let local operators expand to international services *without* relying on competitive operators’ expensive, slow, and sometimes untrusted foreign roaming [70].

(2) *Ubiquitous IoT connectivity:* LEO satellites offer broader coverage than terrestrial base stations. They are closer to terrestrial devices than GEO satellites and thus more energy-efficient for space-terrestrial communications with ≈ 30 dB higher signal-to-noise ratios [71]. So 5G favors LEO satellites for massive connectivities to delay-tolerant, low-energy Internet-of-Things (IoTs) [15–17].

(3) *Orbital edge:* Edge computing in LEOs has attracted interest from academia [31, 32, 72] and industry [28, 73–75]. It is beneficial to expand terrestrial CDNs to remote areas [13, 28, 31, 74], localize computations of earth observations [32, 72], empower space AI [73], and provide secure storage from space [75]. Orbital edge needs space networking (thus orbital core functions) for functionality.

(4) *Emergency communications:* In disasters or wars, the terrestrial mobile infrastructure can be destroyed. In this case, satellites as radio and core functions can offer complementary services for emergency communications [42].

3 STATEFUL MOBILE CORE IN SPACE?

Unlike fixed terrestrial infrastructure or classic GEO satellites, LEO satellites move fast in unreliable, untrusted outer space on a global scale. This challenges today's *stateful* mobile core network functions. We study options of pushing stateful core to space and analyze their deficiencies in session establishment (§3.1), mobility (§3.2), and their resiliency to attacks/failures (§3.3).

Methodology: We run what-if emulations to analyze four options of orbital core from 3GPP standards [15, 16] and 5G satellites [22–24, 27] by progressively adding radio, session, mobility, and security functions to satellites (Figure 6). Rather than spread these functions to multiple satellites, we focus on consolidating them to each satellite that is coherent with today's 5G satellites [15, 16, 22–24]. This approach saves signaling costs [42, 43, 76]. Our emulations study LEO mega-constellations in Table 1 based on real orbital information from [77] and ground stations in [78]. It considers the standard grid satellite network topology [6, 79] with inter-satellite links. We run 5G protocol procedures in [15, 16, 46–48, 50] on these constellations and ground stations, assuming the global distributions of UEs from the World Bank [80]. For each option in Figure 6, we replay datasets from operational satellites and terrestrial 5G (Table 2 and Figure 4b) in a testbed running open5gs [45] on two commodity hardware used by real LEO satellites (detailed in §5–6).

Overview: Figure 10–8 compares the options of orbital cores in Figure 6 in LEO mega-constellations. We make three observations:

(1) *Exhaustive signaling storms:* All options incur signaling storms. Each LEO satellite must process $10^4 \sim 10^5$ signaling messages/s (depending on satellite capacity, location, and constellations). This cost is worsened at the ground stations by one order of magnitude due to space-terrestrial asymmetry (except for Option 4). It exhausts satellite hardware for Option 3 and 4 (Figure 7), congests ground stations, and delays user services (Figure 8). Spreading functions to multiple satellites will incur even more signaling costs [42, 43, 76].

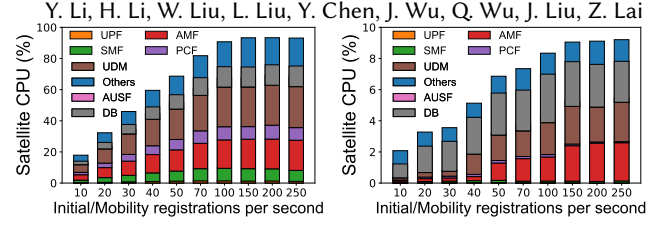
(2) *Diverse causes of signaling storms:* Without mobility functions in satellites (Figure 6a–6b), signaling storms arise from the stateful session establishment (§3.1). Adding mobility functions to satellites alleviates this deficiency (Figure 6c), but incurs more signaling storms for *static* users due to LEO satellites' extreme mobility (§3.2).

(3) *Vulnerability to failures/attacks:* Stateful procedures are vulnerable to satellite failures (e.g., due to radiation and unreliable wireless links) and attacks (e.g., physical collisions, jamming, hijacking, and eavesdropping [37–41]). Pushing stateful core to satellites is also at risk of sensitive state leakages (e.g., security keys).

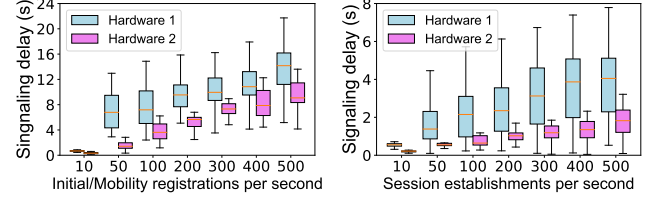
3.1 Session Establishment

To use data services, the UE should first establish a session with the infrastructure. This session is stateful to enforce carrier-grade services. It involves signaling exchanges between core functions. Session establishment is frequent for each UE (every 106.9s [44]) since inactive connections will be released after 10–15s for power saving [82]. In LEO networks, this procedure suffers from bottlenecks from space-terrestrial asymmetry.

Stateful sessions in terrestrial networks: Today's mobile network enforces carrier-grade services on a per-session basis between a UE and its fixed anchor gateway. Each session has five categories of states according to standards [46–51]: (1) *S1: identifiers*, including



(a) Satellite hardware 1 [22–24] (b) Satellite hardware 2 [28, 81]
Figure 7: Breakdown of CPU usages by core functions.



(a) Initial/Mobility registration (b) Session establishment
Figure 8: Signaling latency in hardware by satellites.

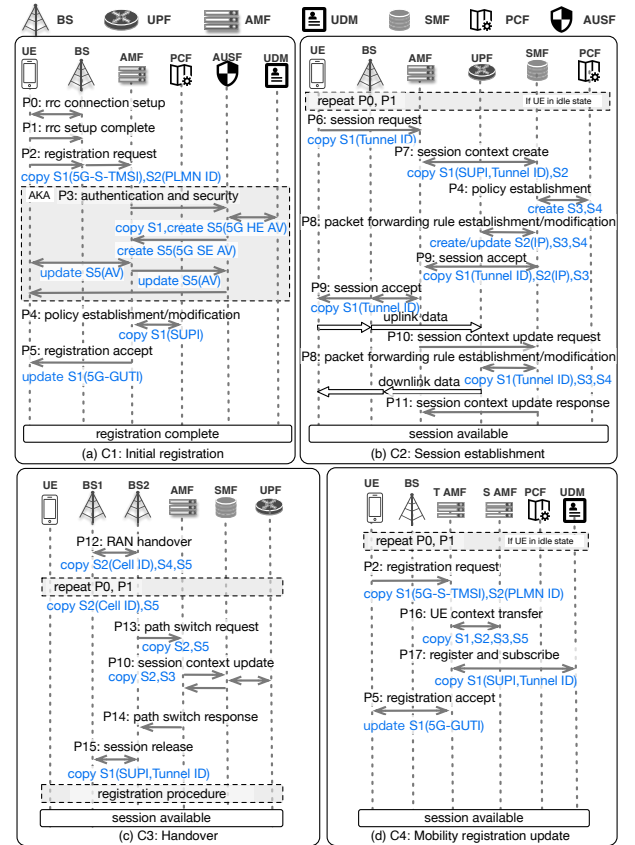


Figure 9: Terrestrial 5G signaling procedures [46–51].

the UE and session identity; (2) *S2: UE locations*, including the UE's service area IDs (cell ID and tracking area ID) and IP address; (3) *S3: QoS*, including the QoS class, priority, and forwarding rules; (4) *S4: Billing*, including the network usage report rules; and (5) *S5: Security*, including keys, authentication vectors, and access policies.

Figure 9a–b shows procedures for the initial registration and session establishment. When the UE registers to 5G for the first time, AMF authenticates the UE and notifies SMF with QoS/billing profiles. Then the SMF selects a UPF as the anchor gateway to form a session. Later, to send uplink data, the UE first establishes a radio

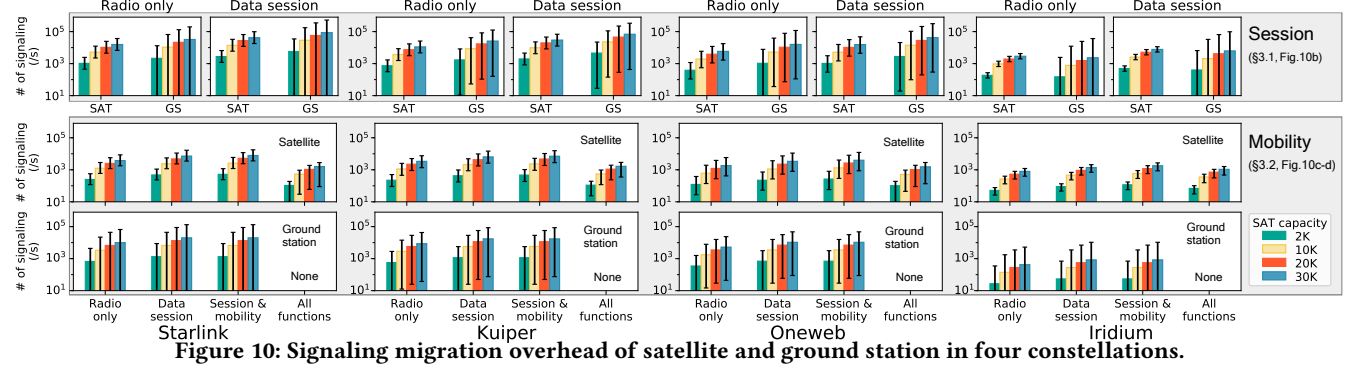


Figure 10: Signaling migration overhead of satellite and ground station in four constellations.

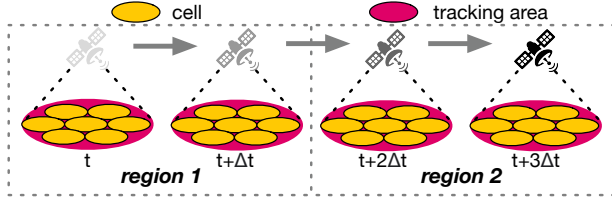


Figure 11: Moving service areas in satellite mobility.

connection with the base station. Then the base station sends a service request to AMF, which copies the session states to the base station for QoS enforcement. To deliver downlink traffic, the anchor gateway should notify AMF of the data arrival. Then AMF notifies the base station to run paging for the UE. If successful, the device repeats the above procedure to establish the session. From the state management perspective, these procedures synchronize session states between the UE, base station, and core network functions.

Bottlenecks from space-terrestrial asymmetry: Stateful sessions in space experience bottlenecks at the data and control plane. At the data plane, each session is coupled to a remote anchor gateway on the ground. As shown in Figure 5a and §2.2, this anchor gateway becomes the single-point bottleneck since the global users' traffic would be redirected to it. At the control plane, session establishment incurs signaling exchange between network functions. If LEO satellites only have radio or session functions (Figure 6a–6b), they need to fetch session states from ground stations (P6/P9 in Figure 9b) and incur signaling overhead. Due to the space-terrestrial asymmetry and satellite routing, such signaling overhead will aggregate at satellite links and ground stations to form signaling storms. While moving AMF to satellites (Figure 6c) can avoid this issue in static scenarios, this option incurs even more state migrations in satellite mobility and offsets its merits, as we will see in §3.2.

Validation: Figure 10 shows the cost of session establishments in satellites and ground stations. Each satellite suffers from 1,035–41,559 signalings/s from session establishments, depending on the satellite's maximal user capacity. Each remote ground station aggregates signaling messages from all satellites and thus causes up to an order of magnitude more messages. Option 3 and 4 do not suffer from this deficiency but experience more deficiencies below.

3.2 Infrastructure Mobility from Space

Unlike fixed terrestrial infrastructure, orbital core network functions experience extreme mobility from LEO satellites (up to 7.6 km/s, Table 1). While the legacy core supports seamless *user mobility*, it requires fixed infrastructure (as anchors) and cannot support *infrastructure mobility*. If placed into fast-moving LEO satellites, the

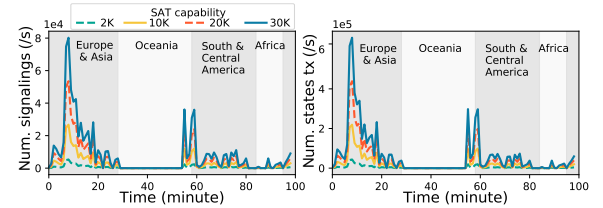


Figure 12: Temporal dynamics of a fast-moving LEO satellite's signaling overhead in Option 3 (Figure 6c).

legacy stateful mobility functions will trigger *fast-moving service areas* and thus exhaustive signaling costs for even *static* UEs.

Stateful mobility control in terrestrial networks: The legacy mobile network tracks a UE's location and services by its service area IDs (S2 in §3.1). As the UE moves to a new service area (cell/tracking area), its session states in §3.1 should be migrated to the new service area to retain continuous services. Figure 9c–d illustrates how this works between fine-grained cells (via handovers) and coarse-grained tracking areas (via mobility registration). In handovers, the old base station migrates its session states to the new base station via AMF or direct tunnels. In mobility registrations, the device reports its arrival to the new location to the new AMF. The new AMF migrates states from the old AMF, after which the old AMF deletes the states. The new SMF updates the session and possibly gateways to resume data service.

Moving service areas for static users: The legacy mobile network design binds its service area ID (cell/tracking area ID) and its *logical* function node IDs (base station/AMF) on the premise that they are fixed anchors. While feasible for terrestrial infrastructure, such logical service areas would be unstable if pushing mobility functions to LEO satellites. As shown in Figure 11, as a logical base station or AMF, a satellite will result in fast-moving “cells” and “tracking areas”. Note each LEO satellite only has transient coverage (≈ 165.8 s in Starlink) for its 1,000s–10,000s of terrestrial users. These static users have to initiate procedures in Figure 9c–d and trigger signaling storms for satellites and ground stations.

Validation: Figure 10 compares the cost of mobility events. If only radio functions are in space (Option 1–2), LEO mobility triggers 248–7,169 (662–19,927) handover messages/s for each satellite (ground station) depending on each satellite's capacities in Starlink. With mobility functions in space (Option 3–4), the mobility registrations are also triggered and result in 105–7,801 (1,324–19,927) signaling messages/s for each satellite (ground station). As exemplified in Figure 12, such signaling overhead is *bursty* as static users in the same area simultaneously enter an incoming satellite's coverage. It also varies over time as each satellite traverses different global

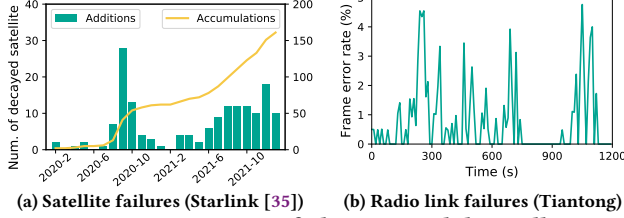


Figure 13: Intermittent failures in mobile satellites.

locations. For all options in Figure 6, this signaling storm delays all users' mobility registrations by queuing (Figure 8). In Option 3–4, it further exhausts satellites' CPUs (Figure 7). This signaling storm is worsened between neighboring satellites without direct links (due to opposite moving directions at polars). It causes multi-hop (up to 48) signaling delivery with more latencies and bandwidth costs.

3.3 Resiliency in Harsh Foreign Space

Unlike fixed terrestrial infrastructure, mobile LEO satellites are unavoidably exposed to unreliable, untrusted outer space with intermittent failures and malicious attacks. All stateful procedures in §3.1–3.2 are vulnerable to both threats and thus threatened by sensitive state leakages and failures (out of services).

Resiliency in terrestrial stateful core: The resiliency of the terrestrial mobile network mainly relies on the premise of *trusted, untampered, and reliable* infrastructure. Most terrestrial infrastructure nodes are fixed and fully controlled by the operator. They are isolated from external entities via dedicated hardware, IPsec-protected domains [51], private clouds, or public clouds with high security/availability ($\geq 99.999\%$ [83]). They are assumed to store, update, and migrate all states in §3.1 in a secure and reliable environment. Without this assumption, all procedures in Figure 9 can be insecure (e.g., user authentication vector or key leakage) or unreliable (e.g., signaling loss/error to block the entire procedure).

Why not resilient in space: The above premise in terrestrial mobile networks does not hold for LEO satellites. If pushed to satellites, stateful functions in Figure 6 will suffer from two threats:

- *Satellite failures:* LEO satellites are prone to failures from radiation and debris in outer space. As shown in Figure 13a, every 1 out of 40 Starlink satellites may have failed since they use low-cost commodity CPUs without hardening against radiations [34, 35]. A recent geomagnetic storm in space also destroyed 40 Starlink satellites [84]. Moreover, all satellite links are wireless and thus prone to intermittent disconnections (e.g., out-of-alignment for laser satellite links in mobility², and atmospheric attenuation for space-ground radio links [89] as exemplified in Figure 13b from our datasets). All procedures in Figure 9 are prone to these failures since any signaling loss/error can block the entire procedure.

- *Satellite attacks:* Attacking satellites has been hardly the news [39] and recently active during the Russia-Ukraine war [90]. When exposed to foreign locations, satellites face hijacking [37, 38], eavesdropping [41], jamming [39], or physical collisions [36, 40] by terrestrial nodes or satellites from adversarial countries. Stateful functions in these satellites should maintain sensitive states (e.g., authentication vectors in Option 3–4, and permanent keys in UDM in Option 4) from numerous users and traverse globally (Figure 12), thus at

²Neighboring satellites in different orbits exhibit relative motions and complicate their laser link alignment. Moreover, satellite vibrations (e.g., due to atmospheric drags in LEO satellites) also cause the misalignment of the satellites' laser links [85–88].

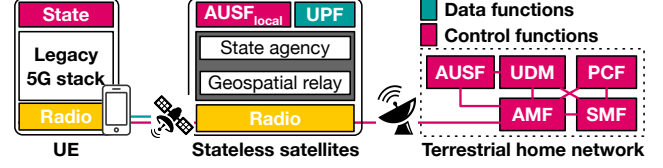


Figure 14: An overview of SpaceCore.

risk of leakages to adversaries. Jamming satellite links can also block the stateful procedures in Figure 9 and disrupt services.

Implications for proactive state management: Recent efforts seek to optimize the mobile core network functions by pre-fetching states (e.g., authentication vectors in UAVs [42]) or proactively replicating/broadcasting them among nearby nodes [42–44]. Option 4 in Figure 6 also proactively places all functions in satellites to avoid state fetching/migrations between space and ground. These optimizations excel for terrestrial mobile networks in well-protected areas with superior performance. Unfortunately, they are at risk of security context leakages if used by LEO satellites. We thus seek alternative secure, scalable, and performant cores in space.

4 A CASE FOR STATELESS ORBITAL CORE

To solve issues in §3, we make a case for *stateless, decentralized, lightweight* mobile core network functions in space. If achievable, this paradigm could eliminate bottlenecks from space-terrestrial asymmetry, mitigate exhaustive state migrations from LEO satellite mobility, and prevent sensitive security state leakages in unreliable, untrusted foreign environments. It also simplifies the exploitation of the redundancies of computing/networking in LEO satellite *mega-constellations* for fault/attack tolerance. However, the challenge is retaining carrier-grade services for traffic delivery, mobility, QoS, billing, and security after the function-state decoupling.

Our solution, SpaceCore, copes with this challenge with the following insight: *The devices naturally form a distributed state repository for core functions in satellites.* After registering to the home, a UE has replicated and stored its session states by itself (Figure 9a). These states are locally accessible to new satellites to enable carrier-grade services for this UE, thus avoiding exhaustive multi-hop state migrations from home (§3.1). They remain local despite LEO satellite mobility, thus avoiding unnecessary invocations of procedures for mobility in §3.2. Without being exposed to foreign locations, they are resilient to failures/attacks (§3.3). SpaceCore utilizes these replicas to decouple states from the orbital core.

Figure 14 overviews SpaceCore. It consists of the remote terrestrial home, LEO satellites as decentralized cores, and UEs. The terrestrial home is a legacy mobile core and runs all control functions. As we will see soon, the terrestrial home serves three purposes: (1) it seamlessly integrates the space infrastructure with the legacy terrestrial mobile networks; (2) it allows the operators to retain their complete control when pushing core functions to space; and (3) it serves as the root of trust when pushing session states to UEs. The decentralized, networked satellites push data functions and gateways from remote ground stations to the edge, thus eliminating bottlenecks from space-terrestrial asymmetry in §3.1. Satellites can relay data and signaling traffic via inter-satellite links (ISLs). SpaceCore decouples session states from data functions in satellites. Satellites directly fetch states from local UEs during the session establishment or mobility events. We next detail SpaceCore's state-function-location decoupling (§4.1), how its benefits procedures in

Figure 9 in space (§4.2–4.4), and supports seamless integration of satellites and legacy terrestrial mobile networks (§4.5).

4.1 State-Function-Location Decoupling

SpaceCore enables a stateless satellite core via *localized, geospatial state management*. It takes three steps. First, SpaceCore decouples the basic concept of service areas (cells/tracking areas) in legacy mobile network designs from the fast-moving LEO satellites. It shifts from today’s *logical* service areas to *geospatial* ones, which remain stable in satellite mobility. Next, SpaceCore simplifies most location states in §3.1 and unifies a UE’s logical and physical locations. Last, SpaceCore delegates satellite core’s other states to local UEs, thus forming a distributed geospatial local state repository³. Any authorized stateless satellite that enters a service area can serve its UEs with local states. We next explain each step.

Step 1: Geospatial service area-satellite decoupling. Recall the legacy mobile network tracks a UE’s location and service by its service area (cell/tracking area). In the terrestrial mobile network, each cell (tracking area) is tightly coupled and identified by the fixed anchor base station (AMF) and remains stable. But in LEO mega-constellations, this design causes moving service areas in satellite mobility (Figure 11), incurs exhaustive state migrations for even static UEs (§3.2), and thus complicates the state management.

SpaceCore decouples the service areas from the fast-moving satellites. It redefines a cell/tracking area as a *geospatial* area, rather than a logical area by a functional node (e.g., satellite). This ensures each service area remains stable despite satellites’ extreme mobility.

Figure 15 showcases SpaceCore’s geospatial cell division for LEO mega-constellations in Table 1. Unlike most geospatial systems (latitude/longitude, Google S2 [94], or Uber H3 [95]), SpaceCore defines its cells based on LEO constellations’ orbital parameters to facilitate data session, mobility, and security functions in satellites (detailed in §4.1). As shown in Table 1, Most operational LEO constellations (Starlink, Kuiper, and OneWeb) are *uniform*: Each constellation has m circular orbits (all with inclined angle β) that are uniformly spanned across the Equator. Each orbit has n satellites that are uniformly placed on this orbit. For such a uniform LEO constellation, we define an affine spherical coordinate system in Figure 15a. Each terrestrial location is uniquely identified by a coordinate (α, γ) , where α is the longitude and γ is a generalized *inclined latitude* as the angular distance on a great circle with inclined angle β . At the constellation initialization ($t = 0$), SpaceCore projects all satellites’ initial location to the earth and connects them along with the (α, γ) coordinate system. Afterward, it uses this inclined grid cell division in Figure 15b to track a UE’s location. This cell division is resilient to later satellite orbit perturbations (e.g., due to atmospheric drag and earth oblateness) since it is fixed at the $t = 0$.

Step 2: Simplify location states (S2). Once decoupled from the geospatial cells, the fast-moving LEO satellites no longer need to track a UE’s location and service, thus eliminating most logical location states (cell/tracking area IDs) in §3.1. Instead, SpaceCore only keeps a UE’s IP address as its location state but redefines its addressing scheme to unify the UE’s logical and physical location. As shown in Figure 15c, SpaceCore’s geospatial IP address is a

³We note 5G also has an infrastructure-side state repository (UDSF [91, 92]), which is slow [93] and suffers from issues in §3 in satellites (Figure 7).

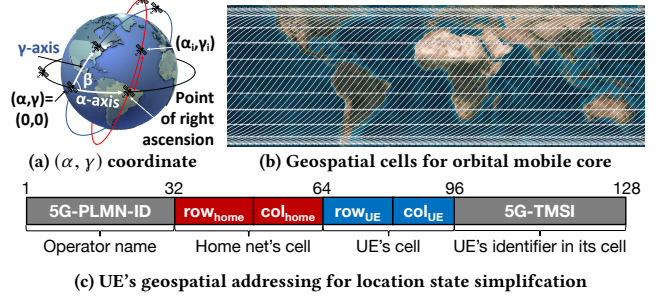


Figure 15: SpaceCore’s geospatial service area & state.

	Num. satellites	Min. cell size (km ²)	Max. cell size (km ²)	Avg. cell size (km ²)
Starlink	1,584	93,382	1,616,366	471,476
Kuiper	1,296	116,716	1,685,950	526,697
OneWeb	720	336,294	4,508,080	1,573,215

Table 3: SpaceCore’s cells in real LEO constellations.

concatenation of prefix, hierarchical geographical ID, and the UE suffix. The prefix is used for networking with external networks. The per-UE suffix ensures the globally unique address inside each cell. A UE’s address remains fixed unless it moves to a new cell (which is rare due to the cell size in Table 3).

Step 3: Delegate other states to local UEs. For other states (S1, S3–S5), SpaceCore delegates them from LEO satellites to the local UEs. This results in a stateless satellite core and a *distributed geographical state repository by local devices*. Most of these states are readily available in UEs today once registered to the core network (Figure 9a). They are locally stored in UEs and thus free of exhaustive state migrations (§3.1–3.2) or leakage (§3.3) in satellite mobility. In the following, we detail how it enables localized state management for the data sessions, mobility control, and security.

Step 4: UE-assisted local state management. With the UEs as distributed state repositories, SpaceCore localizes the state management for session establishments, mobility, and security functions in Figure 9 to address the concerns in §3. We next describe how SpaceCore achieves so for each procedure.

4.2 Localized Session Establishment

SpaceCore localizes most session establishments from space and mitigates single-point bottlenecks from the remote home (§3.1). Its core idea is that, after successful initial registration, each UE has replicated most states in §3.1 from the home. It can assist satellites in establishing local sessions *without* redirecting to the home.

Initial registration: Each UE follows the standard procedure in Figure 9a for the authentication, security key agreement, state creations, and session setup with the remote terrestrial home. In this process, the home network retains full control of each UE’s data forwarding, QoS, billing, and security by generating session states based on these policies. After the successful registration, the home network allocates the geospatial IP address in Figure 15c to the UE, encrypts these states based on its satellite access control policies (detailed in §4.4), and delegates them to the local UE.

Uplink session establishment: This procedure is invoked when the UE wants to send data but has no active radio connection to its serving satellite. Its legacy workflow in Figure 9b incurs state copies and data relays with the remote terrestrial home network, both causing bottlenecks due to space-terrestrial asymmetry and

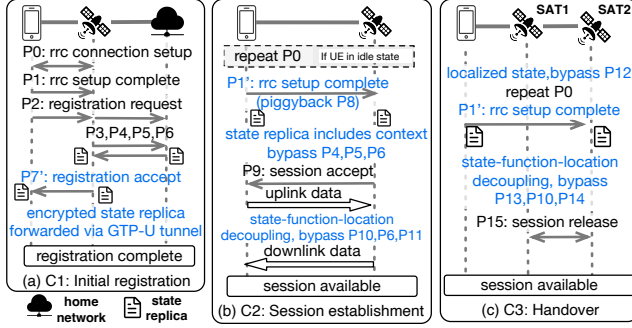


Figure 16: Localized state management in space (C4 is eliminated by geospatial mobility management).

triangular routing (Figure 5). Instead, SpaceCore leverages the UE's state replica to localize the session establishment. As shown in Figure 16a, the UE piggybacks its state replica to its serving LEO satellite during the radio connection setup (which can be achieved by reusing UE's AT commands, as detailed in §5). If authorized to access these local states by the home (detailed in §4.4), the serving satellite can successfully decrypt and install them into its local radio access and UPF functions for immediate data services. Otherwise, the serving satellite fails to decrypt these states and rolls back to the legacy procedure in Figure 9b by contacting the home network. **Downlink session establishment:** This procedure occurs when a UE should receive its data but has no active radio connection to satellites. Compared to the uplink case, the new challenge is how satellites can deliver this UE's data to the correct location *without* maintaining UE's location states. To avoid single-point bottlenecks in §3.1, SpaceCore pushes data services to edge satellites and removes the fixed anchor gateway (Figure 5). But without this anchor, the network has no reference point to relay the data to the fast-moving edge satellite covering the UE at runtime, notify the UE to set up the radio connection via paging, and deliver the data.

To this end, SpaceCore adopts stateless data forwarding between satellites by *geospatial cells*. In §4.1, we decouple the geospatial service areas from fast-moving satellites and embed the UE's geospatial cell into its IP address. By comparing the destination UE's address and its runtime location, each satellite can estimate its physical distance to the destination and decide the next-hop satellite.

Algorithm 1 shows how satellites in SpaceCore forward traffic via inter-satellite links based on geospatial cells. Each satellite has 4 inter-satellite links (2 for intra-orbit neighbors, and 2 for inter-orbit neighbors). As explained in §4.1 and exemplified in Figure 15, SpaceCore locates each terrestrial location with a uniquely coordinate (α, γ) based on LEO constellations' orbital parameters. This coordinate system facilitates routing between satellites: Forwarding packets through each satellite results in a *constant* $\pm\Delta\alpha$ (for inter-orbit links) or $\pm\Delta\gamma$ (for intra-orbit links) physical distance traversal in SpaceCore's (α, γ) coordinate system. Therefore, Algorithm 1 selects the physically closest next-hop satellite to forward data. If the current satellite has covered the destination UE, it runs paging to notify the UE. Then the UE repeats the procedure in Figure 16a to set up downlink services with its local states. Algorithm 1 is resilient to satellite orbit perturbations (e.g., due to atmospheric drag and earth oblateness), since each satellite uses its runtime coordinate $(\alpha_s(t), \gamma_s(t))$ to calibrate the orbit errors/perturbations.

Algorithm 1 Stateless geospatial relaying in Grid topology.

Input: The satellite's runtime location $S = (\alpha_s(t), \gamma_s(t))$, coverage radius ΔS , and distance to its neighboring satellites $\Delta\alpha, \Delta\gamma$
Output: The next hop for a data packet destined to $D = (\alpha_d, \gamma_d)$

```

1: if  $\alpha_d \in [\alpha_s - \Delta S, \alpha_s + \Delta S]$  and  $\gamma_d \in [\gamma_s - \Delta S, \gamma_s + \Delta S]$  then
2:   Run paging and forward packet to  $D$ ; return;
3:   ▷ The satellite covers destination
4: else if  $|\alpha_d - \alpha_s| > |\gamma_d - \gamma_s|$  then
5:   if  $|\alpha_d - \alpha_s| > m/2 \cdot \Delta\alpha$  or  $(\alpha_d \leq \alpha_s \text{ and } \alpha_s - \alpha_d \leq m/2 \cdot \Delta\alpha)$ 
6:     then next_hop=S.left; end if
7:   ▷ Forward to left neighbor
8:   if  $|\alpha_d - \alpha_s| > m/2 \cdot \Delta\alpha$  or  $(\alpha_d \geq \alpha_s \text{ and } \alpha_d - \alpha_s \leq m/2 \cdot \Delta\alpha)$ 
9:     then next_hop=S.right; end if
10:  ▷ Forward to right neighbor
11: else
12:   if  $(\gamma_d > \gamma_s \text{ and } \gamma_d - \gamma_s > n/2 \cdot \Delta\gamma)$  or  $(\gamma_d \leq \gamma_s \text{ and } \gamma_s - \gamma_d \leq n/2 \cdot \Delta\gamma)$  then
13:     next_hop=S.down; end if
14:   ▷ Forward to bottom neighbor
15:   if  $(\gamma_d < \gamma_s \text{ and } \gamma_s - \gamma_d > n/2 \cdot \Delta\gamma)$  or  $(\gamma_d \geq \gamma_s \text{ and } \gamma_d - \gamma_s > n/2 \cdot \Delta\gamma)$  then
16:     next_hop=S.up; end if
17:   ▷ Forward to upper neighbor
18: end if
19: return next_hop;
```

Analysis: SpaceCore offers three merits: (1) *Performance:* SpaceCore removes the single-point bottleneck from the remote home (Figure 5). It speeds up the session establishment via local state operations; (2) *Scalability:* SpaceCore mitigates state migrations between satellites and the home (§3.1); (3) *Resiliency:* By localizing session establishments, SpaceCore prevents sensitive state leakages. After successful registration, SpaceCore can retain services even with unreliable inter-satellite links or intermediate satellite failures.

4.3 Geospatial Mobility Management

SpaceCore shifts from logical to *geospatial* mobility management. It decouples the service areas from fast-moving satellites (§4.1). It avoids unnecessary state migrations in satellite mobility (§3.2) and retains the legacy functions for UE mobility. It is also backward compatible with legacy 5G and facilitates seamless space-terrestrial integration in §4.5. We next describe how SpaceCore achieves so in handovers and mobility registrations.

Handovers by satellite mobility: A static UE in the idle mode (i.e., no active connections) does not run handovers as satellites move. Even if the static UE reselects the satellite, no state updates are needed because SpaceCore decouples geospatial cells from satellites and adopts Algorithm 1 for paging and data delivery.

A static UE with active radio connections may face two types of handovers: (1) *Beam handover*, where the UE switches from one antenna to another from the same satellite. This occurs at the physical layer without core state operations; (2) *Inter-satellite handover*, in which the UE switches from one satellite to another. The new satellite should install the UE states to retain seamless ongoing data services. The standard handover achieves so by migrating the old satellite's states to the new satellite, which suffers from multi-hop delivery in satellite networks (§3.2). Instead, SpaceCore offers another option with UE's local states (Figure 16): Once switching to the new satellite, the UE piggybacks its state replica in the handover acknowledgment message to the new satellite. This results in an equivalent but shorter state migration path.

No mobility registrations by satellite mobility: Unlike legacy stateful designs, SpaceCore eliminates track area updates due to moving satellites since it decouples geospatial tracking areas from satellites (§4.1). A static UE's tracking area remains unchanged regardless of its serving satellite and is thus free of updates. In this way, SpaceCore avoids exhaustive state migrations in §3.2.

Handovers/mobility registrations in UE mobility: Both only occur if the UE crosses geospatial cells (uncommon due to large cell sizes in Table 3). In this case, the UE should update its location to the

remote terrestrial home. The home follows the standard procedure in Figure 9d to re-authenticate the UE, re-allocate its geospatial IP address, and possibly update QoS/billing states based on the new location's policies (e.g., roaming in new countries). The UE will receive an updated state from home for later services in this cell.

Analysis: SpaceCore eliminates unnecessary handovers and mobility registrations in satellite mobility, thus scalable and performant in LEO satellite mobility. It also reduces the state migrations between satellites and therefore the risks of attacks (e.g., state leakages) or failures (traversing fewer intermittent wireless satellite links and space-ground links). Moreover, SpaceCore's stateless core is also a necessary first step to simplify the fault/attack tolerance for the orbital edge computing in §2.2: Upon satellite attacks/failures, the UE can quickly migrate to other available satellites and recover from failures/attacks with its local state replicas.

4.4 Home-Controlled State Updates

Despite its aforementioned benefits, a stateless orbital core is not without costs. By offloading states from infrastructure to devices, the stateless orbital core may lower the operator's controllability of critical mobile network functions such as dynamic QoS or billing policies for some UEs (e.g., "unlimited data speed for the first 15GB data, and throttled to 128Kbps afterward"). Moreover, some devices can be compromised, selfish, or even malicious. They may manipulate the offloaded states and raise security risks.

We resolve these limitations with *home-controlled* state updates. In SpaceCore, the home is the only entity that can update all states except S2 and S5. It receives the dynamic data usage reports from the remote satellites, runs its policy control functions, and updates session states to the local UE and serving satellites using the session modification procedure. For S2, the UE notifies its new locations to the home network if it moves to the new geospatial cell (§4.3). Local state updates by UEs or satellites are prohibited (except S2 and S5) since states have been signed by the home (detailed below).

Meanwhile, to mitigate sensitive security state leakages (S5 in §3.3), SpaceCore delegates most authentication and key agreements to local UEs and edge satellites. The legacy mobile network's security relies on symmetric key-based shared secret states [51]. Instead, SpaceCore's stateless design implies UEs and satellites should establish mutual trust *without* mutual states. Therefore, it adopts public-private key cryptography⁴ for local security and state protection with home-controlled attributed-based encryption (ABE [96, 97]). It allows the home to specify the access control policies based on UEs and satellites' attributes, thus resilient to unauthorized state access or modifications by local UEs/satellites.

Algorithm 2 shows SpaceCore's local authentication, key agreement, and state access. At the initialization, the home network prepares secret key pair (pk, msk), generates keys for authorized satellites (UEs) based on its attribute sets S_{sat} (S_{UE}), and install them to satellites (before their launches to space) and UEs (in SIM cards). For the first-time registration (C1), the UE and home network follow the legacy protocol in P3 in Figure 9a for mutual authentication. In this process, the home encrypts the UE states with its private key pk and an access tree structure $\mathbb{A}$ (in the form of a

Algorithm 2 Home-controlled local mutual authentication.

```

1: Initialization:
2:   Home: (pk, msk) ← Setup( $1^\lambda$ ); ▷ Master key initialization
3:   Home → Satellite:  $CERT_{sat}, sk_{sat} \leftarrow KeyGen(pk, msk, S_{sat})$ ;
4:   Home → UE:  $sk_{UE} \leftarrow KeyGen(pk, msk, S_{UE})$ ; ▷ Pre-stored in SIM card.
5: Initial registration (C1):
6:   Home: state $_{UE} \leftarrow (ver, TTL, IP, QoS, billing, p, g)$ ; ▷ State initialization
7:   Home → UE:  $msg_{UE} \leftarrow Encrypt(pk, state_{UE}, \mathbb{A})$ ; ▷ Encryption by policy
8:   UE: state $_{UE} \leftarrow Decrypt(msg_{UE}, sk_{UE})$ ; ▷ Keep state until TTL expiry
9: Later service establishments (C2–C3): ▷ Piggybacked in connection setup
10:  UE → Satellite:  $X \leftarrow g^x \bmod p, msg_{UE}$ ;
11:  Satellite: state $_{UE} \leftarrow Decrypt(msg_{UE}, sk_{sat})$ ; ▷ Successful if  $\mathbb{A}(S_{sat}) = true$ 
12:  Satellite:  $Y \leftarrow state_{UE} \cdot g^y \bmod p, K \leftarrow X^y \bmod p$ ;
13:  Satellite → UE: Y,  $CERT_{sat}$ ;
14:  UE: Verify( $CERT_{sat}, pk_{sat}$ ),  $K \leftarrow Y^x \bmod p$ ;

```

Boolean formula). $\mathbb{A}$ is specific to this UE with $\mathbb{A}(S_{UE}) = true$ and defines the satellites' access control policies. For example, $\mathbb{A}(S) = \{(S \text{ is UE and } S.SUPI == UE.SUPI) \text{ or } (S \text{ is satellite and } S \text{ supports QoS and } S.bandwidth \geq 10Gbps)\}$. For later services (C2–C3 in Figure 16), the UE and its serving satellite run local authentication and key agreement by verifying their states/certificates. Note the satellite can successfully decrypt the UE's states if and only if its attributes satisfy the home's access control policy ($\mathbb{A}(S_{sat}) = true$). Otherwise, the satellite rolls back to the legacy procedure in Figure 9. In Appendix B, we analyze Algorithm 2 and show it retains the same security as the legacy terrestrial mobile network.

4.5 Seamless Space-Terrestrial Integration

SpaceCore natively supports seamless integration of satellites and legacy terrestrial 5G mobile networks. The reason is two-fold. First, SpaceCore is built on top of standard 5G core network functions and signaling procedures, thus backward compatible with legacy terrestrial 5G. Second, SpaceCore's terrestrial home core network is accessible to both satellites and terrestrial 5G base stations, thus serving as a natural coordinator for space-terrestrial integration.

We next show how SpaceCore integrates satellites and terrestrial 5G. SpaceCore reuses terrestrial mobile core as its home network. Operators connect the existing terrestrial mobile core with the satellite ground stations, update their IP address allocation policy to satellite UEs based on geospatial cells (§4.1), and add support for policy-based UE state encryption (§4.4). The initial registration and session establishment in §4.2 does not involve interactions between satellites and terrestrial 5G. For the mobility management between space and terrestrial infrastructure, we first integrate SpaceCore's terrestrial home core network into today's terrestrial 5G infrastructure. This integration is readily achievable since SpaceCore's terrestrial home follows legacy 5G. Then this terrestrial home coordinates satellites and terrestrial base stations if the UE should switch its wireless access between them. When the UE has no active connectivity to infrastructure (i.e., idle state), it runs the standard cell re-selection [98] to switch its association between space and terrestrial base stations. Otherwise (i.e., connected state), note that SpaceCore's home (core) network is a natural controller for both space and terrestrial nodes. Handovers from space to terrestrial base stations (and vice versa) follow the standard 5G handovers [47, 48, 50] controlled by SpaceCore's terrestrial home.

5 IMPLEMENTATION

Figure 14 shows SpaceCore's deployment in 5G. For backward compatibility, we realize SpaceCore as an external proxy for the legacy

⁴We note 5G has also adopted public-private key cryptography to encrypt user identity (SUCI) in the initial registration to protect user privacy [51].

5G functions. This proxy is implemented with readily available features in commodity UEs, satellites, and terrestrial infrastructure. The terrestrial 5G core can be extended as SpaceCore's home network to facilitate seamless space-terrestrial network integration.

- **Satellites:** LEO satellites run the legacy 5G radio, UPF, and SpaceCore proxy. At the control plane, the SpaceCore proxy follows §4.1–4.4 to fetch and decrypt states from local UEs upon legacy 5G requests (P1, P2, and P8 in Figure 16). If unsuccessful (e.g., no UE-side support or state decryption failure), it rolls back to legacy 5G procedures in Figure 9 by relaying signaling messages to the remote home. At the data plane, the SpaceCore proxy activates local radio paging in 5G [50, 99], realizes Algorithm 1 using the satellites' switching or routing, relays packets to the upper-layer legacy UPF to enforce QoS/billing, and piggybacks UE states in the FutureExtensionField (FEF) in the 5G GTP-U tunnel header [100, 101] for packets to the next-hop UPFs in the same session.

- **UEs:** SpaceCore can be realized in today's commodity UEs without hardware or 5G standard changes. It runs a local state proxy as a system app in commodity UEs. At the initial registration, the SpaceCore proxy stores the UE states from the home network. For later session establishments, the proxy leverages 5G's standard UE-initiated PDU session setup request [48] to piggyback local states to the satellites, as shown in Figure 16a. The proxy initiates this procedure with local UE states via AT+CGQREQ command [102], which is piggybacked in the RRC connection setup complete message (thus saving signaling and round trips). The satellite-side SpaceCore agency re-intercepts this message to extract local UE states and runs procedures in Figure 16.

- **Terrestrial home:** As detailed in §4.5, SpaceCore reuses terrestrial mobile core as its home network for seamless space-terrestrial integration. Each UE uses the same identity to register to the space and terrestrial mobile network, and seamlessly switches between them via mobility registration in Figure 9d.

SpaceCore prototype: We prototype SpaceCore on commodity hardware used by 5G LEO satellites. For the satellites, we prototype SpaceCore with open5gs [45] on two hardware: (1) Raspberry Pi 4 used by Baoyun 5G LEO satellite [22, 29] and; (2) Precision 7920 Workstation with Xeon E5-2630 (20 cores, 2.2GHz), which is similar to (weaker than) Hewlett Packard Enterprise EL 8000s (24 cores, 2.4GHz) used by OrbitsEdge in satellites [28, 81]. For the UEs, we prototype its local state proxy with UERANSIM [103]. For the terrestrial home, we run the open5gs protocol stacks in a ThinkStation P910 workstation. We implement SpaceCore's home-controlled state updates with OpenABE [104] cryptography library.

6 EVALUATION

We assess and compare SpaceCore with existing satellite 5G scenarios with state-of-the-art satellite 5G optimizations.

Experimental setup: We validate SpaceCore's functionality in a small prototype (§6.1), and assess it in LEO mega-constellations via emulations driven by operational 5G and satellites datasets (§6.2).

- **Satellite and 5G dataset:** As shown in Table 2, we collect over-the-air signaling messages between operational geostationary satellites and three terminals (Figure 4b): Inmarsat Explorer 710 satellite terminal [105] (based on 3G UMTS [5, 58]), China Telecom's Tiantong SC310 satellite terminal [106] and T900 satellite phone

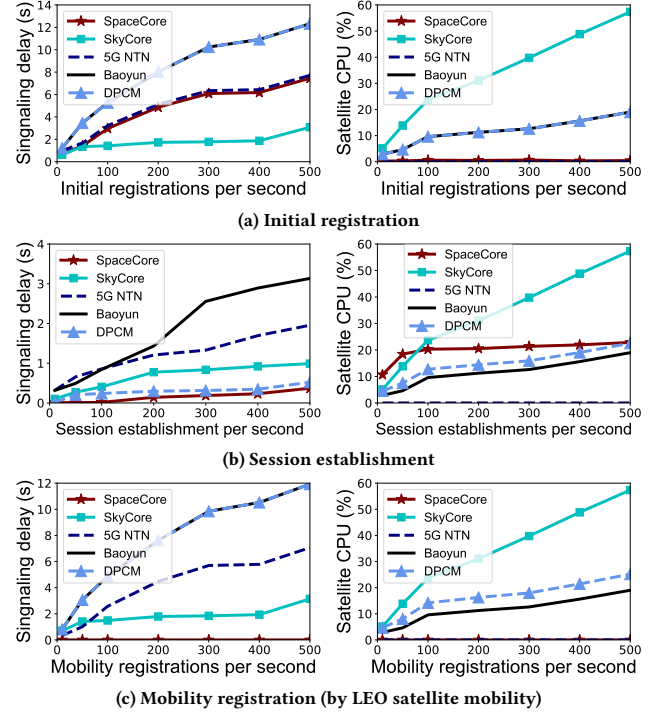


Figure 17: Prototype results in hardware platform 1.

[107] (2G GMR [4, 108]). For each terminal, we enable the diagnostic mode for its satellite baseband and collect signaling messages of radio resource control (RRC), mobility management (MM), and session management (SM) protocols. We also collect operational 5G signaling messages from China Unicom, China Mobile, and China Telecom with Xiaomi 10/11 and OnePlus 9 running MobileInsight [109] with our extension to support 5G message collection.

- **Testbed:** To assess SpaceCore at scale, we replay the above operational satellite and terrestrial 5G signaling datasets in the prototype in §5. We evaluate this prototype with the real orbital information in the LEO mega-constellations in Table 1 from [77], the distribution of ground stations (terrestrial homes) follows [78], and the global terrestrial UE density follows the statistics from [80]. We consider the standard grid satellite network topology [6, 79] with inter-satellite links. Note that SpaceCore's designs and merits are independent of the specific wireless spectrums. So our results in this section based on the legacy wireless channel model in UERANSIM also hold for satellite spectrums in §2.2 as well.

6.1 Prototype Evaluation

We first examine SpaceCore's functionality with a home running full-fledged 5G protocol stacks in a ThinkStation P910, a SpaceCore satellite with Raspberry Pi 4, and terrestrial UEs emulated by UERANSIM. We initiate procedures in Figures 9 and 16 with a varying number of users to evaluate SpaceCore's performance and cost.

We compare SpaceCore with four satellite solutions: (1) **5G NTN** [15, 16], which is the legacy *baseline*. We evaluate its regeneration mode (Figure 6a); (2) **SkyCore** [42], which is the representative non-terrestrial mobile core (currently for UAV). It precomputes and stores all users' security contexts and policies in UAV/satellite to

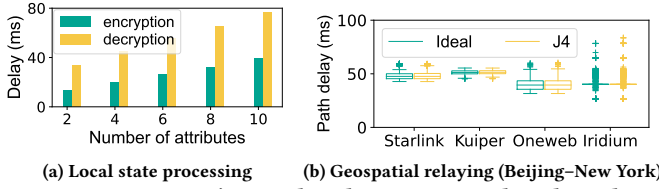


Figure 18: SpaceCore's signaling latency micro-benchmark.

minimize state transfers from the ground, and proactively synchronize states between UAVs via broadcast. (3) **Baoyun** [23], which is the first 5G core in real LEO satellites (Figure 4a and 6c); (4) **DPCM** [44], which leverages device-side state replica to accelerate the legacy signaling procedures (Figure 6c). Figure 17 shows the signaling delays and satellite CPU usage in these solutions.

- **Initial registration:** SpaceCore follows the legacy 5G in this scenario with reasonable delay and negligible satellite CPU (§4.2). SkyCore has the lowest latency since it has pre-stored all states to localize the initial registration, but at the cost of satellite CPU and security state leakages (§3.3). Baoyun and DPCM have the highest latency due to their interplays with the terrestrial home, and their in-orbit functions slow down the satellite processing (Figure 7).

- **Session establishment:** SpaceCore localizes it with UE-side states for faster state migrations and decentralized state processing loads, thus achieving the lowest latency (§4.2). It is slightly faster than DPCM due to its lighter satellite CPU with fewer functions (mainly used by its attribute-based state decryption for security enforcements in §4.4, as quantified in Figure 18a). Instead, while SkyCore also localizes this procedure, its heavy functions in satellites slow down its processing. Meanwhile, other solutions require interplays with remote ground stations and thus incur long delays.

- **Mobility registration by LEO mobility:** SpaceCore avoids this procedure with its geospatial mobility management (§4.3), thus enjoying negligible delays and satellite CPU. Instead, others suffer from such signaling costs due to their logical service areas.

6.2 Emulation in LEO Mega-Constellations

We next assess SpaceCore's scalability, performance, and resiliency with large-scale emulations in LEO satellite mega-constellations and ground stations. We run SpaceCore in LEO mega-constellations in Table 1 (based on real orbital information from Space-Track [77]) and ground stations in [78]. We assume the LEO mega-constellations use the grid satellite topology [6, 79] with inter-satellite traffic delivery capability. We run UERANSIM [103] with SpaceCore to emulate global mobile subscription density according to World Bank [80], and replay signaling datasets in Table 2 to trigger their signaling procedures. We repeat this experiment in SpaceCore and other solutions in §6.1 under varying LEO satellite capacities. Figure 20 shows the signaling costs without failures/attacks, and Figure 19 shows the resiliency to satellite attacks.

Scalability: SpaceCore's localized, geospatial state management significantly saves signaling costs. SpaceCore reduces 122.2×, 17.5×, 40.3×, and 49.3× signaling costs for satellites compared to 5G NTN, SkyCore, Baoyun, and DPCM, respectively in Starlink where the capability of the satellite is 30,000 users. By pushing data-plane functions to edge satellites, SpaceCore eliminates the remote ground stations' performance bottlenecks due to space-terrestrial asymmetry. By shifting to geospatial service areas, SpaceCore also saves

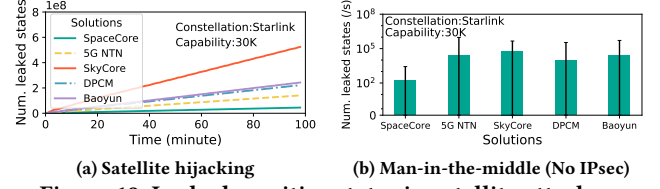


Figure 19: Leaked sensitive states in satellite attacks.

	5G NTN	SkyCore	DPCM	Baoyun
Starlink	122.2×	17.5×	40.3×	49.3×
Kuiper	87.7×	19.3×	33.8×	42.8×
Oneweb	49.8×	20.1×	6.8×	25.8×
Iridium	34.5×	25.8×	7.7×	16.7×

Table 4: SpaceCore's satellite signaling cost reduction.

the signaling costs from mobility registrations, and avoids state synchronizations between satellites (e.g., in SkyCore).

Performance: We examine SpaceCore in three aspects:

- **Signaling latency:** As shown in Figure 17, SpaceCore's lightweight, localized state management reduces 1,008 ms (7.33×), 1,529 ms (11.12×), 139 ms (1.01×), and 477 ms (3.47×) signaling delays in session establishment compared to the legacy 5G NTN, Baoyun, DPCM, and SkyCore, respectively. Its signaling latency overhead mainly arises from the local state processing in §4.4 but is marginal compared to its latency reductions (Figure 18a).

- **Geospatial relay via inter-satellite links:** We evaluate SpaceCore's stateless geospatial relaying in Algorithm 1 under the ideal satellite orbits and the realistic J4 orbit propagator [110, 111]. Compared to the ideal orbits in §4.1, J4 considers satellite orbit perturbations and secular variations due to the earth's oblateness. Figure 18b showcases the delay between Beijing and New York. Under both ideal and realistic orbits, Algorithm 1 guarantees traffic delivery. The path delays are similar in both scenarios since Algorithm 1 calibrates orbit perturbations as explained in §4.2. In Iridium, SpaceCore sometimes incurs $\geq 100ms$ longer path delays in realistic J4 orbits than ideal orbits with $\leq 0.5\%$ probabilities. This arises from the detours due to the granularity of the geospatial cells and can be avoided with finer-grained cells (thus more bits in the addressing in Figure 15c).

- **User-level performance:** We showcase ping and TCP data transfer between Beijing and New York and assess their stalling time due to satellite mobility in §4.3. For SkyCore, Baoyun, and DPCM, the mobility registrations will update the UE's logical IP addresses and thus terminate TCP connections and ping. 5G NTN avoids this by binding the logical IP address to the remote home core, but experiences long stalling due to slow signaling. Instead, as shown in Figure 21, SpaceCore avoids TCP/ping terminations with its geospatial addressing, and saves 5G NTN's stalling time for TCP and ping with its localized state management. Both user-level stalling durations are usually longer than the duration of the mobility registrations due to the higher-layer recovery (e.g., TCP retransmission timeout).

Resiliency to attacks/failures: Figure 19 shows the state leakages under satellite hijacking and man-in-the-middle passive listening of wireless inter-satellite links. SpaceCore is resilient to satellite hijacking due to its stateless nature; only the active serving users' keys are leaked in this case (which is unavoidable and can be counter-measured by disabling this satellite's access control, detailed in Appendix B). For comparison, other solutions leak more authentication vectors and keys due to proactive state replication

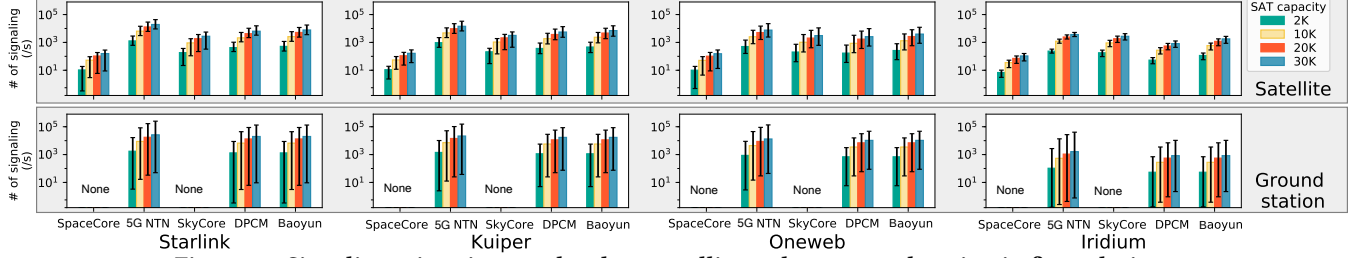


Figure 20: Signaling migration overhead per satellite and per ground station in five solutions.

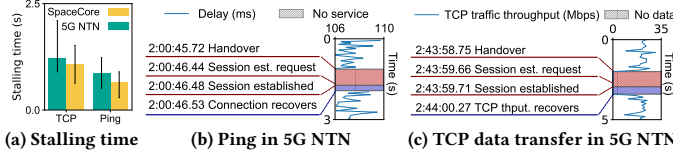


Figure 21: User-level performance in satellite mobility.

or state migrations with remote terrestrial home. SpaceCore is also resilient to link failures and man-in-the-middle attacks since it localizes most state operations with few migrations. Other solutions may leak states during the migration since backend encryption (IPsec) is not mandatory in standards [51]. Enabling encryptions can mitigate man-in-the-middle attacks, but still cannot mitigate state leakages in satellite hijacking.

7 DISCUSSION

On radio access network (RAN): This work focuses on mobile core functions and assumes standalone RAN functions for each satellite (consistent with current 5G satellites [19–21]). It is possible to split RAN functions among satellites, similar to recent O-RAN/C-RAN [112–115]. Similar state management issues would occur and SpaceCore’s general lessons can be generalized to RAN.

Implications for 5G and beyond: This study is based on the current 5G. While 5G has started to extend its support for satellites [15, 16], its architecture is unlikely to change dramatically due to backward compatibility requirements (which results in our SpaceCore design). Looking forward, we believe a native stateless architecture in 5G and beyond would be necessary to unleash the potential of LEO mega-constellations.

Will mobile networks win this space race? Besides mobile networks, there are other options for satellite networks, such as DTN [116], IP [79, 117, 118], MPLS [119, 120], DVB-S [121], CCSDS [122], to name a few. Mobile satellite networks are competitive with these alternatives, because they can potentially support seamless integration with terrestrial 5G and beyond and thus readily serve billions of mobile and IoT devices today (§2.2). Even so, which option will win this space race is beyond this paper’s scope. Instead, this paper uses mobile networks to showcase the challenges of stateful functions in space. Its lessons are generally applicable to other network architecture and stateful functions as well.

8 RELATED WORK

Mobile networks are experiencing a technical leap due to the recent global 5G deployments and function openness to academia and industry. For radio access, extensive studies have been made based on O-RAN/C-RAN for function split [112, 113] and resource optimizations [114, 115]. For core networks, recent work refines core functions and state managements for Internet-of-Things [76], UAVs

[42], programmable core [123], cloudified function [83], to name a few. Some proposals also shift core network states to UEs for low-latency access [44] and network democratization [70], but they still rely on fixed infrastructure and thus cannot tackle issues from extreme LEO satellite mobility in §3. Instead, SpaceCore complements these efforts by exploring core network function redesigns in LEO satellite mega-constellations.

Enabling mobile network functions in space is still in the early stages. Despite being the *de facto* for satellite communications for decades [4–9], mobile networks have not migrated their core functions to satellites (§2.2) until the emergence of LEO mega-constellations in 2018. Recent LEO satellites from Lockheed Martin [19], Lynk [20], AST [21] (as radio access), China Mobile, and Huawei [22–24] (as core) have demonstrated the feasibility of enabling mobile network functions in a *single* satellite. Our work takes one step further to explore scalable, performant, and resilient mobile core functions in networked LEO mega-constellations. Besides LEO satellites, some work has also explored placing mobile network functions in other non-terrestrial platforms such as UAVs [42] and Loons [124, 125]. LEO satellites differ from them since they are unavoidably exposed to harsh foreign locations on a global scale, thus raising reliability and security concerns in §3.3 and motivating SpaceCore’s stateless designs.

9 CONCLUSION

This work explores the feasibility of enabling mobile core functions in low-earth-orbit mega-constellations. We show today’s stateful mobile core suffers from LEO satellites’ extreme mobility and exposure to unreliable, insecure outer space. This motivates us to make a case for SpaceCore, a stateless mobile core in space. SpaceCore decouples states from orbital core functions, reduces state migrations by shifting to geospatial service areas, and localizes state management with device-as-the-repository for fewer failures/attacks.

In a broader context, SpaceCore follows the end-to-end principle to simplify stateful core network functions for the devices and by the devices. Since its origin, the mobile network has followed the infrastructure-centric design with heavy signaling and states. This method becomes expensive when infrastructure must move in harsh outer space. We hope our lessons can inspire and stimulate user-centric, lightweight mobile networks in the space era.

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A ACRONYMS IN THIS WORK

ABE	Attribute Based Encryption
AKA	Authentication and Key Agreement Protocol
AMF	Access and Mobility Management Function
BS	Base station
CN	Core Network
CP	Control Plane
GEO	Geostationary Earth Orbit
GSL	Ground-Space Link
HN	Home Network
IMSI	International Mobile Subscriber Identity
ISL	Inter-Satellite Link
LEO	Low Earth Orbit
MEC	Multi-access Edge Computing
MM	Mobility Management
NAS	Non-Access Stratum
NTN	Non-Terrestrial Network
PCF	Policy and Charging Function
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
RAN	Radio Access Network
RRC	Radio Resource Control
SM	Session Management
SMF	Session Management Function
SUCI	Subscription Concealed Identifier
SUPI	Subscription Permanent Identifier
TMSI	Temporary Mobile Subscriber Identity
UDM	Unified Data Management
UDSF	Unstructured Data Storage Function
UE	User equipment
UPF	User Plane Function

B SECURITY ANALYSIS

This section analyzes how SpaceCore ensures security with its local authentication, key agreement, and state verification in §4.4. We study SpaceCore’s security under various threats and show that (1) for threats that can be defended by the legacy mobile networks, SpaceCore should also defend it; (2) for threats that the legacy mobile network cannot defend, SpaceCore should not exacerbate them; and (3) SpaceCore does not create new security vulnerabilities.

Threat model: We follow the standard threat model for the mobile network [51, 126] but extend it in three aspects. First, we assume unreliable satellites that are vulnerable to intermittent wireless links and attacks in harsh foreign locations (§3.3). Second, we consider 3rd-party malicious satellites in outer space (e.g., from adversarial countries) that may actively fake as the legacy satellites or passively listen to the wireless links to intercept UEs and legacy satellites. Third, we assume *compromised, selfish or malicious UEs* that may attempt to manipulate SpaceCore’s local states for their own merits (e.g., higher QoS or lower billing). We assume the home network is well-protected and trusted in the homeland.

UE state leakages/failures: SpaceCore is resilient to state leakages since satellites do not maintain permanent session states. Under satellite hijacking, only the current serving users’ states may be leaked (which is unavoidable for any solutions). Its localized authentication also mitigates state migrations between satellites, thus more resilient to satellite node/link failures and man-in-the-middle passive listening by adversary satellites.

Authenticity: SpaceCore offers mutual authentication in the initial registration (Figure 9a) and Algorithm 2 based on UE’s encrypted states (from home) and satellites’ certificates. When a satellite is hijacked, the home network detects it and invalidates its authenticity by updating the access structure $\mathbb{A}$ and refreshing UEs’ encrypted states such that $\mathbb{A}(S_{sat}) = \text{false}$. In this way, hijacked satellites can no longer decrypt UEs’ states to negotiate the keys according to Algorithm 2 (line 12).

Authorization: Algorithm 2 adopts the attribute-based encryption [96, 97] to let the home customize access control policies $\mathbb{A}$ for satellites (S_{sat}) and UEs (S_{UE}). This facilitates fine-grained access control based on QoS, billing, satellites and UEs’ hardware capability, and other attributes.

Confidentiality: Algorithm 2 negotiates the security key K for signaling/data traffic encryption over the air and updates this security key for every session establishment (thus resilient to key leakages or satellite hijacking).

State integrity: Without the home network’s key pair (pk, msk), neither the UE nor satellite can fake or modify the states.

Man-in-the-middle attacks: Algorithm 2 negotiates the security key K based on the station-to-station protocol [127], which is resilient to man-in-the-middle attacks. The attacker cannot derive the keys K or decrypt the UE states by passively listening SpaceCore’s message exchange.

Replay attacks: Without knowing the UE or satellite’s secret keys sk_{sat}/sk_{UE} (pre-stored in trusted satellite hardware and UE’s SIM), an attacker replaying the previous encrypted states cannot derive the keys K or decrypt UE states. Moreover, each encrypted state is associated with a version number ver and time-to-live TTL . The home network can specify both fields to determine the lifetime of a UE-side state. On TTL expiry, the edge satellite will update states from the terrestrial home instead of using UE-side states (line 11 in Algorithm 2).

Denial-of-service attacks: The legacy mobile network is inherently vulnerable to DoS. The legacy mobile network [51, 126] decides not to fully address DoS due to the high cost. Similar attacks can appear in SpaceCore but are not worsened by SpaceCore. Its signaling piggyback in §4.2 and 5 also mitigates signaling costs and thus DDoS attacks.

UE-side state manipulation. Since SpaceCore offloads session states to local devices, a compromised, selfish or malicious UE may modify its local states to manipulate the control procedures (e.g., lower its data billing or increase its QoS). SpaceCore defends this security threat with home-controlled state updates. In SpaceCore, local state updates by UEs or satellites are prohibited (except S_2 and S_5) since states have been signed by the home network’s private key pk (Algorithm 2). Without the private key, any local UEs cannot fake or locally manipulate the states. At runtime, the local UE should piggyback these encrypted states to the satellites. The satellites can verify the states’ integrity with the public key

sk_{sat} . Any illegal local state manipulations will thus be detected by the satellites. Moreover, if the UE manipulates its location (S2) or security (S5) states, its serving satellites will also detect these modifications during the local service establishments in Algorithm 2. Upon detection of these manipulations, SpaceCore rolls back to the legacy 5G's home-controlled procedures, which guarantees the same security level as the legacy 5G.