Democratizing Direct-to-Cell Low Earth Orbit Satellite Networks

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Abstract

Multi-tenant Low Earth Orbit (LEO) satellites emerge as a cost-effective win-win solution for direct 4G/5G access to our regular phones/IoTs anywhere on Earth. However, the current hop-by-hop stateful cellular session impedes this effort due to its need for tight functional coupling and stable service relationships among satellite operators, mobile operators, and users. Our empirical study with real satellite data shows that, it restricts LEO satellites' serviceable areas, limits the use of available (possibly competitive) satellites, and suffers from signaling storms and dynamic many-to-many relationships in extreme LEO mobility. We thus devise MOSAIC to strive for *self-serve multi-tenant* LEO satellites. MOSAIC defines policy-embedded one-time tokens for *pay-as-you-go* local satellite access. These tokens allow satellites to self-serve users anywhere without relying on remote mobile operators, alleviate inter-satellite coordinations to enjoy competitive satellites, and simplify many-to-many service relationships for on-demand multi-tenancy. MOSAIC is attack-resilient and incrementally deployable using our SIM-based solution. Our evaluations with the real satellite data and commodity 3GPP NTN protocol stack validate MOSAIC's viability.

1 Introduction

Space is the new business growth point for cellular networks. The emergent direct-to-cell LEO satellites, such as SpaceX's Starlink [1, 2], Iridium [3, 4], Globalstar [5], AST [6, 7], and Lynk [8] complement terrestrial networks to eliminate their coverage holes for 2.7 billion "unconnected" global users [9] and offer their regular phones/IoTs direct satellite access via 4G, 5G, and beyond. They can significantly save operators' infrastructure costs in under-served areas and expand their service to anywhere on Earth for new subscribers and revenues. So, mobile network operators (MNOs) and satellite network operators (SNOs) have actively partnered to deploy [10–15] and standardize [16–27] direct-to-cell LEO satellite services.

Rather than owning dedicated satellites by every MNO, building *multi-tenant* direct-to-cell satellites for sharing is a more practical and favorable win-win solution for MNOs *and* SNOs [1] (Figure 1). On the one hand, satellites are a scarce and competitive resource for MNOs. The highly congested near-Earth space leaves insufficient orbital slots for all MNOs' satellites [28–30]. LEO satellites' capital expenses are also prohibitive for MNOs [31, 32]. Instead, renting satellites is more affordable and lowers the barriers to entry for MNOs. On the other hand, SNOs also have incentives to partner with MNOs due to their lack of licensed 4G/5G spectrums to serve

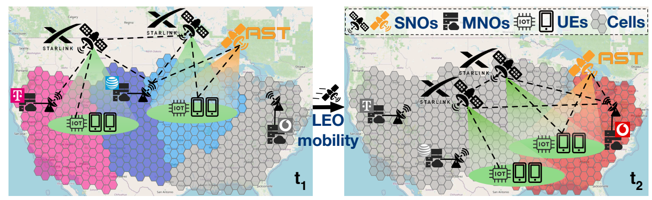


Figure 1: Dynamic multi-tenant direct-to-cell LEO satellites.

regular phones/IoTs independently. Akin to cloud computing, leasing satellites to more MNOs increases SNOs' revenues and return on investment through economies of scale.

Sharing satellite access has been a decades-old practice. Traditional geostationary satellites are single-hop physical pipes that are easily sharable using the infrastructure-as-a-service model. While ideal for multi-tenancy, this transparent pipe model suffers from low service coverage, missed radio processing deadlines, and unaffordable bandwidth demands in 4G/5G due to its heavy reliance on remote ground stations (§3.1). To this end, modern LEO satellites like Starlink, AST, and Lynk have adopted onboard cellular network functions for scalable and performant direct-to-cell services [8, 33–36].

However, cellular network functions in LEO satellites are not easily sharable due to their requirement for tight functional coupling and stable service relationships among SNOs, MNOs, and user equipment (UEs). This requirement is rooted in the cellular architecture's stateful hop-by-hop session that assumes fixed, always-on, and trusted infrastructure. It is hard to meet in multi-tenant LEO satellites due to their fast mobility, intermittent accessibility to MNOs for remote control, and 3rd-party nature as intermediate session nodes. Our empirical study with real satellite data shows that (§3), this defect is detrimental to everyone: It impedes UEs' flexible use of *any* available satellites, restricts MNOs' serviceable areas, complicates MNOs' use of diverse (potentially competitive) SNOs' satellites, and exhausts SNOs' satellites with signaling storms and dynamic many-to-many relationship management.

We explore an alternative cellular scheme for *self-serve multi-tenant* direct-to-cell satellites. Our solution, MOSAIC (**M**ulti-**O**perator **S**atellite **A**ccess via **I**n-band **C**ontrol), adopts the *pay-as-you-go* paradigm that is more suitable than hop-by-hop stateful sessions for sharing the mobile infrastructure like LEO satellites (§5): Akin to mobile bike sharing [37], each MNO supplies its UEs with self-certified one-time tokens (a satellite version of restrictive blind signatures from the offline cash system [38]) as "coins" to pay for local satellite access on demand. These tokens embed UE-specific roaming, billing, and QoS policies to let *any* authentic satellite self-serve UEs without contacting remote MNOs. This UE-initiated in-band state provision enables near-stateless/sessionless satellites for transparent pipe-like multi-tenancy. It also simplifies inter-satellite coordination and dynamic many-to-many service relationships to avoid signaling storms and encourage the use of competitive SNOs' satellites. MOSAIC's tokens retain the same security level as the legacy 4G/5G and are incrementally deployable using our SIM card-based deployment (§6).

We prototype MOSAIC and evaluate it using real satellite data and Amarisoft's commodity 3GPP non-terrestrial network (NTN) protocol stack. Compared to the NTN [16–27] and Starlink [34–36], MOSAIC scales to a large number of satellites, COTS UEs, and MNOs with signaling storm freedom, 116% serviceable area expansion to the LEO constellation's entire coverage, and 4.71–14.25× service resumption latency reduction in LEO mobility at negligible costs.

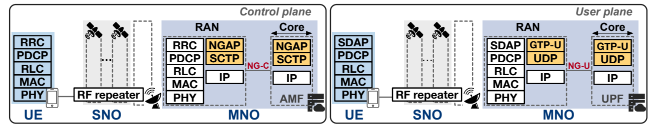
2 Why Multi-Tenant LEO Mobile Satellites?

In this section, we motivate the need for direct-to-cell LEO satellites (§2.1) and the incentives for sharing them among MNOs from the MNO, SNO, and UE perspectives (§2.2).

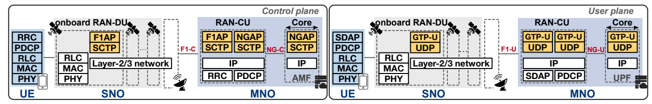
2.1 The Need for Direct-to-Cell LEO Satellites

Direct-to-cell satellites originate as a complementary method to connect phones/IoTs where the terrestrial infrastructure cannot reach. To offer ubiquitous access, terrestrial cellular networks should deploy radio access networks (RANs) with numerous radio base stations to cover broad geographic areas and bridge them to the Internet via core networks (Figure 2a). While profitable in urban areas with sufficient subscribers, such capital-intensive infrastructure loses revenues when covering rural areas with few subscribers [39, 40] and is even undeployable in oceans and airplanes, thus leaving 2.7 billion global users unconnected [9, 41]. Instead, direct-to-cell satellites can complement terrestrial networks with their broad coverage, offer direct cellular access to phones/IoTs, and save MNOs' capital and operation costs in under-served areas.

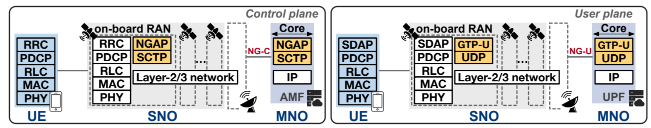
Traditional direct-to-cell satellites, such as Inmarsat [42], Thuraya [43], and Tiantong [44], operate in the geostationary orbit (GEO) at an altitude of 35,786 km. While excellent for broad coverage, GEO satellites are unfriendly to commodity phones/IoTs since their distant transmission is power-hungry, slow, and noisy. Dedicated satphones with high-gain antennas can alleviate this issue, but they are not widely available or affordable to most consumers. Instead, modern satellites like Starlink [1, 2], Iridium [3, 4], Globalstar [5], AST [6, 7], and Lynk [8] operate in LEOs at the altitude of 340–2,000 km to be closer to phones/IoTs for faster network speed, lower energy costs, and more affordable hardware. Due to each LEO satellite's smaller coverage, a *constellation* with 10s–1,000s satellites is typically adopted for global coverage.



(a) Transparent satellite pipe [20, 44] (option 8 in Fig.5a)



(b) Onboard RAN-DU [20] (option 2 in Fig.5a, also used in Starlink [33–36])



(c) Onboard RAN [20] (option 1 in Fig.5a, full-fledged satellite base stations)

Figure 2: State-of-the-art cellular network function splits in 3GPP NTN and Starlink for direct-to-cell satellites.

2.2 Incentives for LEO Satellite Multi-Tenancy

The traditional satellite network market is monopolistic: Each SNO independently launches its own satellites (most of which reside in the GEO) to operate its own network services using dedicated satellite-specific radio spectrums. While feasible for standalone GEO satellites for customized terminals, this dedicated mode is not technically feasible or commercially profitable for both MNOs and SNOs in direct-to-cell LEO constellations due to three fundamental constraints:

1. MNOs: Scarce orbital slots. LEOs are highly crowded, with about 8,300 satellites [29] and 27,000 space junks [28], leading to 3,500–60,000 conjunction events per month [45, 46] and 24,410 collision avoidance maneuvers per year [47]. The recent mega-constellation deployment further congests LEOs and raises collision risks [30] and RF interferences [48]. This situation leads to more stringent and time-consuming orbit allocations (typically years) by ITU [49]. There are insufficient orbital slots to accommodate all MNOs' satellites.

2. SNOs: Shortage of licensed 4G/5G spectrums. To be compatible with commodity phones/IoTs, direct-to-cell satellites should use the legacy 4G/5G spectrums, most of which have been allocated to terrestrial MNOs by ITU/FCC. SNOs alone do not have sufficient licensed cellular spectrums to offer direct-to-cell services.

3. MNOs & SNOs: Prohibitive capital costs. Despite advances in satellite miniaturization and rocket reusability, deploying a LEO constellation is still capital-intensive for both MNOs and SNOs [31, 32]. Building dedicated direct-to-cell LEO constellations raises the barrier to entry for MNOs and lowers the commercial return on investment for SNOs.

To this end, SNOs like Starlink [10–12, 33, 50], AST [6, 7, 51], and Lynk [8] have recently partnered with global MNOs (e.g., T-Mobile, AT&T, Vodafone, and KDDI) to advocate *multi-tenant* direct-to-cell satellite services. FCC has recently proposed a regulatory framework to foster collaborations between SNOs and MNOs, allowing SNOs to utilize spectrum previously allocated only to MNOs through lease

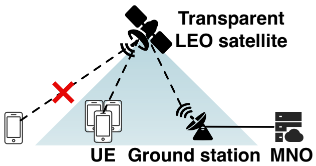
(a) Direct-to-cell UEs

(b) Open probes [54]

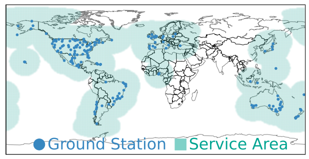
Dataset	Scale	Description
TLEs [55]	50,922,755 Two-Line Elements	Real LEO satellites' ephemeris
Iridium RF	943,003 RF link measurements	From our Iridium RF receivers
RIPE open probes [54]	7,800,177 ping and 382,464 traceroute logs	From 50 open Starlink dishes as network probes
GEO direct-to-cell	3,903,065 PHY, MAC, RLC, RRC, & NAS logs	From Thuraya X5-Touch and Tiantong T900 satphones

(c) Real satellite dataset

Figure 3: Equipment and satellite data in our empirical study.



(a) Reliance on ground stations (GS)



(b) Servicable areas limited by GS

Figure 4: Limited coverage for transparent LEO satellites.

agreements or partnerships [52]. Each MNO rents SNOs' satellites and grants its licensed 4G/5G spectrums to them for direct phone/IoT connection. The SNO's satellites can host multiple MNOs' direct-to-cell services, while each MNO can rent diverse SNOs' satellites for coverage and cost optimizations. Akin to cloud computing, LEO multi-tenancy yields a win-win situation: it lowers the barrier to entry for MNOs, complements MNOs' terrestrial coverage in under-served areas at low costs, and increases SNOs' revenues and return on investment through economies of scale. UEs also benefit from it through a more open, competitive market that offers cheaper satellite data plans and complementary coverage[1].

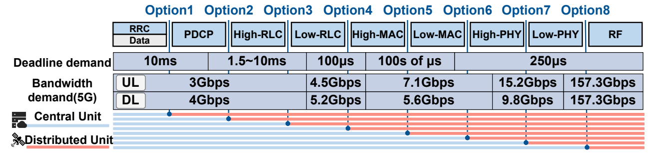
3 Challenges for Multi-Tenant LEO Satellites

While appealing to SNOs, MNOs, and UEs, multi-tenant direct-to-cell LEO satellites are still in their infancy. The ongoing direct-to-cell satellite solutions under development, such as Starlink [34–36] and 3GPP NTN [16–27], have not started to support multi-tenancy. Our empirical study driven by real satellite data in Figure 3 shows that traditional 2G/3G GEO transparent pipe sharing model is not feasible for LEOs due to its incomplete coverage, 4G/5G deadline violations, and unaffordable bandwidth demands (§3.1). While moving 4G/5G functions to LEO satellites can resolve this issue, its multi-tenancy can be impeded by the cellular hop-by-hop stateful session's need for tight functional coupling and stable service relationships among SNOs, MNOs, and UEs (§3.2).

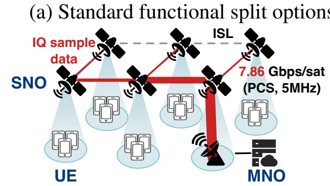
3.1 Transparent Satellite Pipe as a Service?

Sharing satellite access is a decades-old practice. Most GEO satellites today are transparent physical pipes that can multiplex radio signals from diverse MNOs. Similar to fiber rentals, it is easy for MNOs to rent these satellites to relay raw RF signals (IQ samples) between UEs and terrestrial infrastructure, as shown in Figure 4a. This physical network slicing has

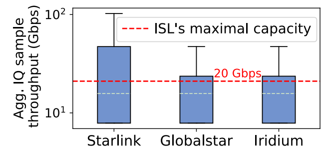
[1]The latest Huawei Mate 60 Pro+ smartphone has supported both Tiantong and Beidou satellites for messaging services [53].



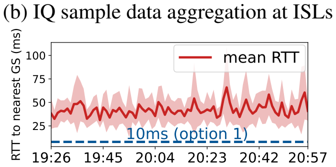
(a) Standard functional split options in 4G/5G radio functions [56–58]



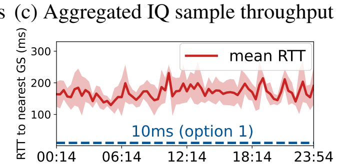
(b) IQ sample data aggregation at ISLs



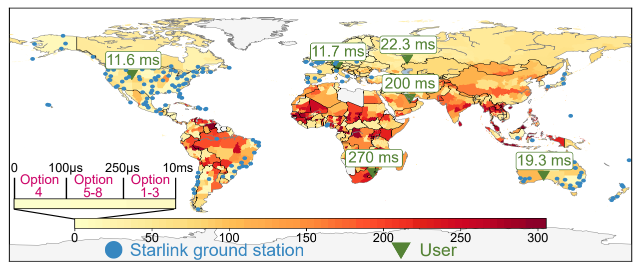
(c) Aggregated IQ sample throughput



(d) Starlink terminal's RTT w/o ISLs



(e) Starlink terminal's RTT w/ ISLs



(f) RTT between the user and its nearest ground station (w/ ISLs)

Figure 5: Transparent satellite pipes cannot meet 4G/5G's deadline and throughput requirement for basic functionality.

been successful in direct-to-cell GEO satellites for low-speed 2G/3G. It is a preferable multi-tenancy model for both MNOs and SNOs due to its *simplicity* and *transparency*: MNOs can rent satellites on demand as plug-and-play pipes without exposing their internal network functions to SNOs, thus retaining complete control of their mobile services. SNOs can transparently accommodate and isolate diverse (potentially competitive) MNOs without deploying or maintaining complex, per-MNO cellular functions in satellites.

Unfortunately, while excellent for low-speed 2G/3G GEO satellites, this transparent pipe sharing becomes technically infeasible for faster 4G/5G LEO satellites for three reasons:

(1) Incomplete coverage: For a standalone satellite, UEs and ground stations must concurrently reside in its coverage for functional direct-to-cell services. While acceptable for GEO satellites with broad coverage, this issue limits low-coverage LEO satellites' globally serviceable areas (Figure 4b). Most "unconnected" UEs today [9] reside in remote areas with sparse or no ground stations, thus leaving them still disconnected by bent-pipe satellites. This prevents MNOs from expanding their services to these UEs for more revenue.

(2) Missed 4G/5G radio deadlines: To expand coverage, LEO satellites can be networked via inter-satellite links (ISLs) to reach remote ground stations. However, such a networked physical pipe still cannot meet 4G/5G's basic functional requirements. From the functional split view, networked trans-

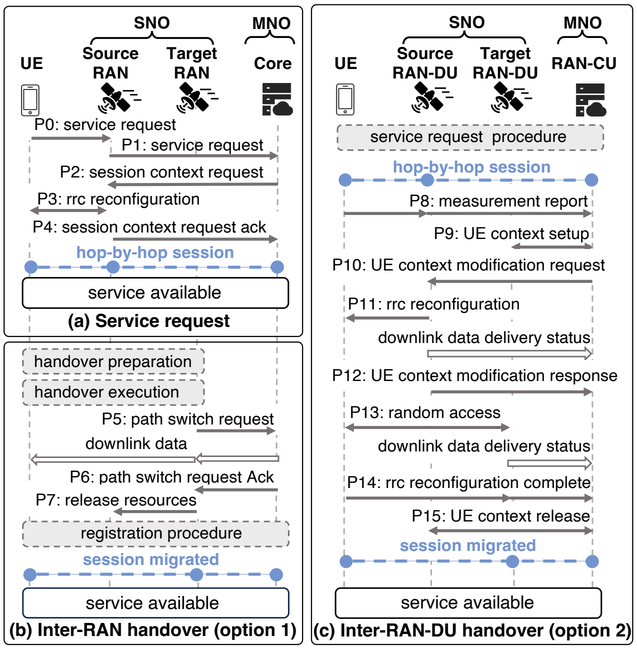


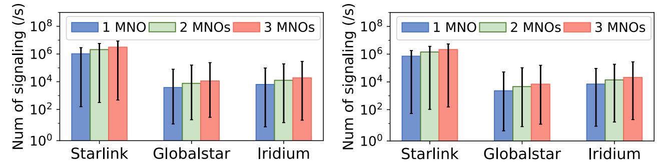
Figure 6: Signaling procedures in 4G/5G satellites [61].

parent LEO satellites essentially follow the standard 3GPP option-8 split [56–58] in Figure 5a: Each satellite relays all serving UEs' RF IQ samples to remote ground stations for processing. For functional correctness, each 4G/5G IQ sample should be delivered to the ground station within 250μs, which accounts for $\leq$80 km distance between the satellite and ground station [56]. This stringent deadline is unsatisfiable for LEO satellites, whose distance to ground stations is at least 340 km. Figure 5d–5e quantify real Starlink dish terminals' ping RTTs to ground stations with/without multi-hop ISL traversals based on the RIPE's global open Starlink dish probes [54]. Both RTTs exceed the 250-μs deadline by 1–2 orders of magnitude, thus crashing the basic 4G/5G radio functions if the transparent satellite pipe model was used.

(3) Unaffordable bandwidth demands: Each transparent LEO satellite relays all serving UEs' IQ samples to ground stations for processing, which requires 7.86 Gbps for a typical 5 MHz radio channel [58]. As shown in Figure 5b–5c, all these satellites' IQ samples to remote ground stations will accumulate and congest ISLs (typically with $\leq$20 Gbps capacity [59, 60]), thus further impeding the 4G/5G functionality.

3.2 In-Orbit Cellular Function as a Service?

To avoid the transparent LEO satellite pipe's constraints for functional 4G/5G in §3.1, SNOs have started to offload terrestrial cellular network functions to LEO satellites. Starlink Gen 2 satellites have equipped medium access control (MAC) and radio link control (RLC) protocols [33, 34], resulting in an option-2 split in Figure 5a. 3GPP also extends its 4G/5G standards to place partial (option-2) or complete (option-1) radio functions to satellites [20] (Figure 2b–2c). Due to the stringent 4G/5G radio deadlines in Figure 5a, only option-



(a) RAN (Option 1 in Fig.6b) (b) RAN-DU (Option 2 in Fig.6c)

Figure 7: Signaling storms in satellites under LEO mobility.

1 and 2 split are feasible for LEO satellites. Both localize the radio processing to avoid missing deadlines and wasting ISL bandwidth, thus enabling functional direct-to-cell 4G/5G LEO satellite services for commodity phones/IoTs.

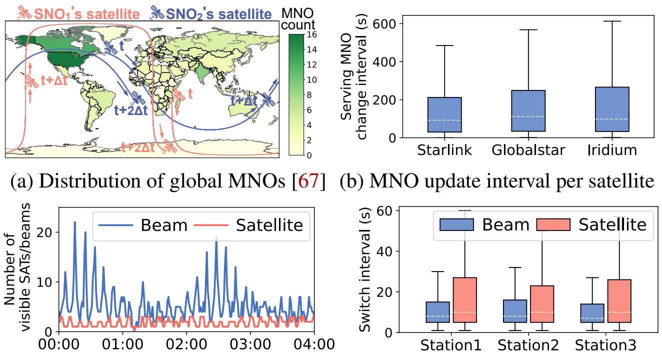
However, in-orbit cellular functions are not easily sharable from the multi-tenancy perspective. Localizing radio processing in satellites in Figure 2 requires exposing MNOs' internal cellular functions to SNOs' fast-moving, intermittently accessible, and potentially untrusted LEO satellites. This functional split among SNOs, MNOs, and UEs becomes burdensome in LEO satellites due to two fundamental issues:

Tight functional coupling: Today's cellular network adopts a stateful session-based architecture for carrier-grade services. To activate services for each UE, it should set up a hop-by-hop session across the UE, base station, and core network that binds this UE's ID, QoS, billing, and security states. As the UE moves, it should migrate this hop-by-hop session to the new infrastructure node to retain services. This stateful session implies a tight coupling and trust among the UE, base station (SNO), and core network (MNO) to coordinate for successful network services, which is not flexible or efficient for LEO multi-tenancy from all participants' perspectives:

◦ *SNOs: Signaling storms.* The exposure of MNOs' stateful cellular functions can exhaust the SNO's satellites. Each LEO satellite has a short-lived coverage for each area due to its fast mobility (e.g., ≈3 minutes for a Starlink satellite at 7.6km/s). When entering a new area, each LEO satellite should take over all active UEs' sessions from the previous LEO satellite for continuous services. The session migration procedures differ between functional split options (F1AP [62] for option-2 between local and remote radio functions in Figure 6c, and NGAP [63] for option-1 between RAN and core network in Figure 6b). We evaluate the number of signaling processed by each satellite per second in Figure 7. Since each satellite can cover multiple MNOs (each having 1,000s of UEs), both incur signaling storms for LEO satellites.These signaling storms can consume up to 15.75% of total ISL bandwidth.

◦ *MNOs: Restricted serviceable areas.* Due to the tight functional coupling, the radio functions in SNOs' satellites in Figure 2b–2c still rely on the remote ground station to contact the terrestrial MNO and fetch each UE's session states for functioning. Note that most LEO satellites today do not have active or reliable ISLs[2]. Similar to transparent pipes in §3.1, they cannot serve UEs in remote areas without ground stations even if physically covering them (Figure 4). To independently

[2]For example, Starlink's ISLs have just started to operate in limited areas [64, 65], while AST, Globalstar, and Lynk's satellites have no ISLs.



(a) Distribution of global MNOs [67] (b) MNO update interval per satellite

(c) Visible satellites/beams (Iridium RF) (d) Switch interval (Iridium RF)

Figure 8: Dynamic SNO-MNO-UE service relationship.

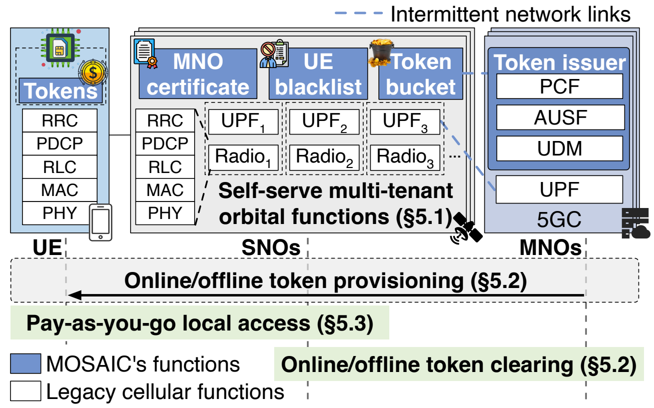


Figure 9: Overview of MOSAIC.

function without MNOs, SNOs' satellites should equip the MNO's full-fledged radio and core network functions, which becomes out of the MNO's control due to satellites' intermittent accessibility and is vulnerable to attacks in space [66].

○ *MNOs & UEs: Inflexible use of competitive SNOs.* As explained in §2.2, both MNOs and UEs have incentives to employ diverse LEO satellites from multiple SNOs. However, the hop-by-hop session in Figure 2 limits this flexibility due to its tight coupling among the UE, SNO, and MNO. As the LEO satellite moves, the UE and its MNO should re-establish or migrate the session among *competitive* SNOs' satellites that are unlikely to coordinate directly. Re-establishing the session requires the new satellite to fetch UE states from the ground station, thus limiting its serviceable area without ISLs (Figure 4). Migrating the session from the old SNO's satellite to the new SNO's satellite is prohibitive due to its competitive nature. While the MNO's terrestrial core can bridge these satellites for indirect migration, its reliance on remote ground stations again limits LEO satellites' serviceable area.

Dynamic SNO-MNO-UE service relationship: Due to the extreme LEO mobility, the many-to-many relationship among SNOs, MNOs, and UEs fluctuates and challenges everyone:

○ *SNOs: Exhaustive MNO reconfigurations.* Each SNO aims to host as many MNOs as possible for higher revenue. As its LEO satellite moves, it should repeatedly reconfigure its serving MNOs in the current coverage (Figure 1 and 8a–8b). With its cellular functions coupled to MNOs, this reconfiguration is more exhaustive than transparent pipes in §3.1 since it should manage MNOs' per-UE stateful sessions (Figure 7).

○ *MNOs & UEs: Dynamic trust establishment.* As shown in Figure 8c–8d, the LEO satellites that each MNO and UE can employ change over time due to their transient coverage, some of which can be untrusted. They must frequently re-establish trust with the new incoming satellite to maintain the hop-by-hop stateful session (thus signaling storms), which is hardly scalable to LEO constellations from diverse SNOs.

4 Overview

We propose an alternative cellular network scheme for multi-tenant direct-to-cell LEO satellites to address issues in §3. Our solution, MOSAIC, adopts in-orbit cellular functions for functional direct-to-cell 4G, 5G, and beyond (§3.1). As shown in §3.2, these functions are not easily sharable due to their tight functional coupling and demands for stable service relationships among SNOs, MNOs, and UEs. Both are hard to meet in SNOs' LEO satellites due to their fast mobility, intermittent accessibility to remote MNOs when ISLs are not reliable or active, and 3rd-party nature for MNOs and UEs.

To this end, MOSAIC shifts from the hop-by-hop session-based cellular service to **pay-as-you-go satellite self-service**. We note that, the need for tight cellular functional coupling and stable service relationships stems from the hop-by-hop stateful session for carrier-grade services. These sessions are inherently vulnerable to extreme LEO mobility, intermittent satellite connectivity, and untrusted satellites. Instead, the pay-as-you-go paradigm is more suitable for sharing mobile infrastructure like LEO satellites[3]: Analogous to bike-sharing systems [37], each UE pays for its runtime satellite access on-demand using one-time digital tokens ("coins") provisioned by its MNO. *Any* SNO's authentic local satellite can accept these tokens to serve this UE without pre-establishing sessions or contacting MNOs. When this satellite can reach the remote MNO (e.g., using ISLs immediately if available or geographically covering the MNO's ground station afterward), it uses these tokens as a proof of service to charge the MNO for on-demand satellite leasing. This scheme departs from the session-based cellular architecture today in three aspects:

○ *Loose coupling:* Each satellite locally self-service UEs without contacting remote ground stations or other satellites. This alleviates the coordination among satellites and ground stations, prevents signaling storms for SNOs under fast LEO mobility, lets the MNO employ remote satellites for more coverage and revenue, and facilitates the UE to take advantage of diverse (potentially competitive) SNOs' satellites.

○ *Simple SNO-MNO-UE relationship:* The pay-as-you-go tokens eliminate stateful sessions and decouple the SNO, MNO, and UE to benefit everyone. SNOs' in-orbit cellular

[3] Although the pay-as-you-go paradigm has also existed in terrestrial mobile networks (e.g., prepaid SIM cards [68]), it is still based on hop-by-hop stateful session. It is infeasible for multi-tenant LEO satellites (§3.2).

functions become near-stateless, thus more transparent and friendly for multi-tenancy (similar to pipes in §3.1). MNOs and UEs can rent SNOs' satellites on demand, which is more cost-effective and flexible to use competitive satellites.

◦ *Retain carrier-grade services:* Despite near-stateless, this scheme can still retain carrier-grade services. Its pay-as-you-go paradigm naturally enforces the billing and even avoids traditional 4G/5G's exhaustive charging data signalings [69]. The MNO can embed the roaming, QoS, and other policies into its digitally signed tokens. When accepting these tokens from the UE, the SNO's satellite locally learns these policies to enforce them without directly contacting remote MNOs.

Figure 9 overviews MOSAIC. It comprises multi-tenant satellites from SNOs, the remote terrestrial home network from MNOs, and UEs. Satellites equip full-fledged radio and data-plane functions to meet the 4G/5G deadline and bandwidth requirements in §3.1. These functions' states are decoupled from satellites and provisioned by UEs' tokens, resulting in near-stateless satellites for transparent multi-tenancy. To foster self-service, MOSAIC does *not* mandate ISLs in these satellites for immediate access to ground stations. Each MNO's terrestrial home maintains its subscriber database and provisions its UEs with self-certified, policy-embedded tokens online or offline. For compatibility and integration with terrestrial 4G/5G, the MNO can reuse its core network to manage these tokens. The UEs store these tokens in their SIM cards and feed them to the satellites via runtime in-band signaling for pay-as-you-go services.

5 Design of MOSAIC

This section addresses three key issues to realize MOSAIC:

1. How can SNOs arrange cellular functions in satellites to enable self-serve multi-tenancy for MNOs (§5.1)?
2. How can MNOs generate pay-as-you-go tokens for UEs to leverage these 3rd-party satellites, while still retaining full (remote) control of carrier-grade services (§5.2)?
3. How can UEs consume these tokens to access any local authentic satellites without mutual trust (§5.3)?

5.1 Self-Serve Multi-Tenant Orbital Functions

The first step for MOSAIC is to enable multi-tenant direct-to-cell LEO satellites for SNOs that are (I) as easily sharable by MNOs as the classic transparent pipe in §3.1 but (II) free of their incomplete global coverage, 4G/5G deadline violations, and bandwidth exhaustion in §3.1. The challenge arises from the tension between both goals: (II) requires pushing 4G/5G functions to LEO satellites, which, however, suffers from tight coupling with MNOs and complex SNO-MNO-UE service relationship dynamics to meet (I). As explained in §3.2, this tension is rooted in the hop-by-hop stateful cellular session.

To this end, MOSAIC rearranges orbital cellular functions to be self-contained for (II) and decouples them from stateful sessions for (I). Each satellite deploys self-contained 4G/5G radio and user-plane functions, so that it can independently serve local UEs in case its ISLs are unavailable/disrupted and remote ground stations are unreachable. These orbital cellular functions are near-stateless and decoupled from MNOs: At runtime, they are locally driven by UE-paid tokens in §5.2 provisioned by MNOs that have embedded session states, thus free of signaling coordination (storms) among satellites and ground stations. This design allows the satellite to serve MNOs and UEs on demand and approximates the transparent pipes in §3.1. We next elaborate on the design details.

Step 1: Self-contained cellular functions in satellites. As shown in Figure 9, each satellite in MOSAIC runs full-fledged 4G/5G radio functions as standalone base stations, thus free of deadline violations and bandwidth exhaustion in §3.1. It also integrates the core network's user-plane functions to enforce self-serve traffic forwarding, QoS, and billing. To decouple these functions from stateful sessions, MOSAIC adopts a session state proxy in each satellite. This local proxy emulates control-plane core network functions for radio and user-plane functions through the standard interface (e.g., NGAP [70] and GTP-U [71] in 5G). It provisions session states to these functions using the UE-paid tokens rather than contacting remote MNOs. Even without ISLs or access to ground stations in the worst case, each satellite can still independently offer the minimum 4G/5G access and local communications (e.g., voice calls, short messaging, and emergency SoS) for UEs inside its coverage[4]. In this case, each satellite can still serve a considerable number of users due to its wide coverage area (covering 10–100s km^2). When the ground stations or ISLs are available, it can also roll back to the legacy 4G/5G to fetch states from MNOs (though not necessary in most cases).

Step 2: Transparent MNO multi-tenancy. To serve a MNO in a given geographic area, each LEO satellite should be (1) granted the use of this MNO's licensed 4G/5G spectrum in this area for the radio access; (2) paid by UE-side tokens for runtime on-demand access; and (3) paid by MNOs offline by showing these tokens as a proof of service. To achieve this, the MNO signs a digital certificate for each authorized satellite that binds its spectrum grant with this satellite's identity and geographic areas to use these spectrums. The satellite stores this certificate as a proof for UEs and global spectrum regulators to offer services when covering the target areas. At runtime, it accepts UE-side tokens with session states to drive its stateless 4G/5G functions, and saves these tokens into its bucket for offline financial clearing with the MNO (detailed in §5.2). Its stateless functions can easily accommodate multiple MNOs with their certificates for multi-tenancy.

Step 3: Dynamic multi-tenancy under LEO mobility. As the LEO satellite rapidly moves over time, its serving MNOs also update frequently in response to its terrestrial coverage change. MOSAIC's stateless nature simplifies this process: Except for 4G/5G spectrums and cell broadcast information,

[4] Services that mandate ground stations (e.g., emergency calls) may be unavailable but are also impossible for *any* solutions without the connectivity.

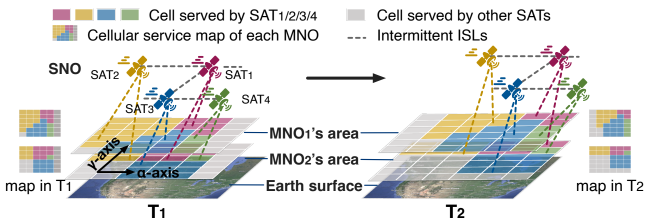


Figure 10: MOSAIC's dynamic multi-tenancy.

no other stateless cellular functions need to be reconfigured since they are decoupled from MNOs. To further simplify spectrum and cell information updates, MOSAIC inherits the idea of Earth-fixed geographic cells from SpaceCore [66] that are stable despite satellite mobility and coupled with each MNO's location-dependent roaming, QoS, billing, and spectrum policies. As shown in Figure 10, for each MNO, MOSAIC defines its 4G/5G cells by their geography rather than their fast-changing service satellites. MOSAIC uses SpaceCore's affine spherical coordinate to align these cells with satellites' orbital parameters, thus linearizing each satellite's runtime mapping of cells it covers. Each satellite tracks its runtime coverage to these cells, determines the MNOs to be served using its local certificates, and reconfigures its radio with these MNOs' 4G/5G spectrums and geographic cell identity. If a LEO constellation is used, the successive satellite takes over a cell's service when the previous satellite leaves, while retaining the same geographic cell and service area IDs for UEs to prevent unnecessary handover signalings.

5.2 Pay-as-you-go Satellite Access Tokens

The key enabler of MOSAIC's pay-as-you-go satellite access is its self-certified, policy-embedded one-time tokens. These tokens are generated by MNOs, provisioned to each UE online or offline based on its data plan, consumed by UEs for runtime local satellite access, and deposited by SNOs back to MNOs online or offline to close the financial transaction. The issue is that, UEs in remote areas may have to pay these tokens for access to SNOs' satellites out of the MNO's reachability. This threatens the MNO's controllability of its carrier-grade services and the security of the token-based satellite access.

To this end, MOSAIC adopts the idea of cryptographic "restrictive blind signatures" from the offline cash system [38] as provably secure one-time tokens, embeds MNO-controlled carrier-grade service policies into these tokens for remote enforcement, locally restrains the UE-side token misuses using MNO-issued tamper-resistant SIM cards, and lets the MNO detect and penalize token misuses as the ultimate defense.

Semantics of policy-embedded tokens: Each one-time token represents a unit of satellite access defined by each MNO based on its billing granularity (e.g., by time, data volume, message count, satellite access count, or even flat rate). The MNO embeds each UE's location-dependent roaming, QoS, billing, access control, and other policy states into its token to enforce its carrier-grade services. The UE should consume the corresponding token to enjoy the carrier-grade satellite services in the target location. Some MNOs may want to offer multi-stage data plans (e.g., "\$10/GB for the first 5GB data, then free data throttled at 128Kbps afterward"). MNOs can enforce them by generating and provisioning a corresponding quota of differentiated tokens for each stage for the UE.

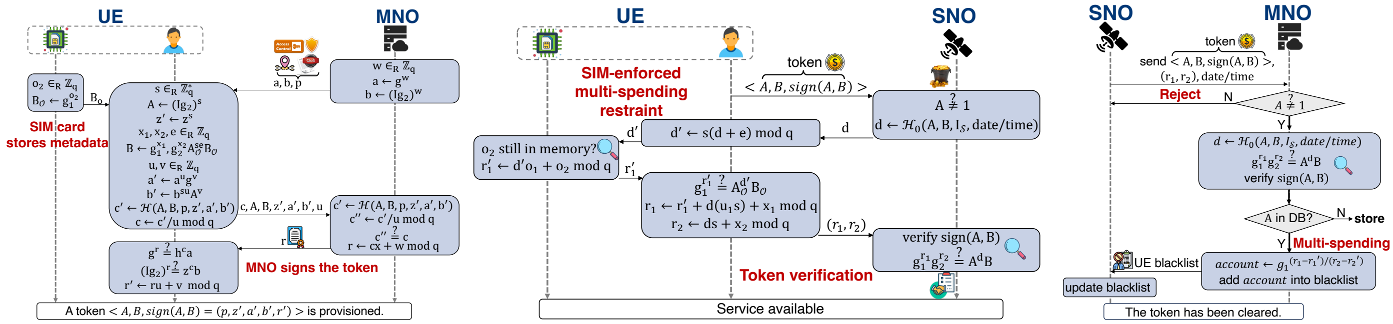
Token generation/provision: Figure 11a illustrates how each MNO generates and provisions tokens for each UE. It can occur *offline* (e.g., the user purchases the prepaid SIM card with pre-generated tokens) or *online* (e.g., the MNO offers tokens to the UE after the initial registration over a secure channel). It involves the MNO, the UE, and the MNO-issued tamper-resistant SIM card to the UE. There are two steps:

(1) Preparation: The MNO maintains two databases for the UE subscription and the consumed token, both of which can reuse the legacy cellular functions (detailed in §6). Following the one-time restrictive blind signature [38], the MNO generates tokens using a function pair $\langle x, (G_q, g, g_1, g_2, \mathcal{H}, \mathcal{H}_0)\rangle$, where x is its private key, (G_q, g, g_1, g_2) is its public key for UEs/SNOs based on the classic discrete logarithm challenge [72], $\mathcal{H}$ is a public hash function for token generation and verification, and $\mathcal{H}_0$ is a public hash function for SNOs for runtime challenge-response token verification.

(2) Token generation: To create a token, the MNO generates a random number pair (a,b) to the UE. The UE with the SIM card generates a third random number o_2, and computes a number pair (A,B) based on (a,b,o_2) and MNO's public key in Figure 11a. To restrain the UE-side token manipulation, the SIM card stores o_2 for later token consumptions below. To retain MNOs' control of carrier-grade services, MOSAIC extends [38] to bind (A,B) with each UE's session states p (including but not limited to location-dependent roaming, QoS, billing, and access control profile) using the hash function $\mathcal{H}$ and digitally signs this binding as $sign(A,B)$ using the private key x. The UE stores the tuple $\langle A, B, sign(A,B)\rangle$ as a token.

SIM-enforced one-time token consumption: At runtime, the UE should consume a token to "pay" for the satellite access (whose detailed workflow will be introduced in §5.3). For correctness, each token should be used at most once. This can be threatened by selfish or malicious UEs that attempt to gain free or unauthorized satellite access by spending a used token multiple times. The issue is that such token misuse may occur for SNOs' satellites in remote areas without ISLs or ground stations to reach the MNO for detection. MOSAIC must mitigate it locally *without* the remote MNO's assistance.

MOSAIC mitigates this threat using SIM card-assisted token consumption. Recall that SIM cards are MNO-issued, trusted, and tamper-resistant hardware that are resilient to UE manipulations. They are mandatory for UEs to gain network services. Although the MNO may not be able to remotely detect the UE's token multi-spending, it can delegate this task to SIM cards for local enforcement. A side benefit of this approach is that its local nature also saves time and signaling overhead among satellites and remote ground stations.



(a) Token generation/provision (MNO–UE) (b) One-time token consumption (UE–SNO) (c) Token clearing (SNO–MNO)

Figure 11: MOSAIC's self-certified, policy-embedded one-time tokens for pay-as-you-go local satellite access.

Figure 11b shows how the SIM card enforces the local one-time token consumption. To use a token $\langle A, B, sign(A,B)\rangle$, the UE should correctly respond to the serving satellite's runtime challenge. The computation of this response must rely on this token's random number o_2, which has been stored in the SIM card and never exposed to the UE. After computing the response and receiving the token acknowledgment from the satellite, the SIM card deletes this token's o_2. In case the UE double-spends the same token, its random number o_2 has been lost in the SIM card, thus failing to pass the satellite's challenge and access network services. If the token packet from the UE to the satellite is lost over the air, the UE will not receive the token acknowledgment. After the timeout, the UE will retransmit the token for loss recovery.

Token clearing and misuse penalty: Upon the successful token validations, the SNO's satellite obtains the token as proof of its service to remote UEs. It can use this token to charge the corresponding MNO by usage, as shown in Figure 11c. This token-clearing process can happen either *online* (if the satellite has ISLs or direct ground station coverage to contact the MNO) or *offline* otherwise. For the latter case, the LEO satellite should maintain a token bucket to hold and clear these tokens when it eventually moves to cover the MNO's accessible ground station. On receiving the satellite's tokens, the MNO records them in its consumed token database. In the extreme case when the UE manages to crack the SIM card to bypass its local one-time consumption enforcement (though we are unaware of such attacks for commercial SIM cards in reality), the MNO can still eventually detect it by comparing the multi-spent token with those in this database. In this case, the MNO notifies this UE to the satellite. The satellite blacklists this UE and later denies its service as a penalty. In practice, this process is responsive due to the considerable ground station availability, as we will evaluate in §7.

5.3 Local Self-Service via In-Band Control

We last present how the UE can use tokens in §5.2 to enjoy self-serve satellites in §5.1. Its policy-embedded tokens can locally drive the stateless satellite to establish and enforce carrier-grade services via *in-band control*, thus alleviating the need to redirect to MNOs via ISLs (which may not always exist in LEO satellites today) or ground stations (unavailable in remote areas in Figure 4b) and minimizing the amount of signaling. To maximize the number of phones/IoTs (thus higher revenue) to enjoy MOSAIC, this in-band control requires no changes for the UE hardware or the standard 4G/5G interfaces between UE and infrastructure.

Preparation: Each UE should prepare tokens in §5.2 in advance for later satellite access. There are various ways to achieve this. For example, the UE can purchase prepaid SIM cards with tokens, retrieve tokens from the MNO offline through a secure out-of-band channel (e.g., WiFi or terrestrial 4G/5G when available), or fetch tokens from the MNO online through an end-to-end secure channel if the serving satellite has active ISLs or direct coverage to the ground station.

Service establishment: There are two scenarios:

• *Uplink service:* When the UE needs to send data but has no active connectivity, it should establish the service with a satellite. As shown in Figure 12, the UE first selects *any* authentic satellite based on its broadcasted identity and sets up an insecure radio connectivity. It then performs identity-based cryptography [73, 74] to authenticate this satellite using its certificate in §5.1 and negotiates local security keys for this connection, thus preventing the invocation of signaling procedures with the remote MNO. After the successful satellite authentication, it follows the procedure in Figure 11b to consume token. For backward compatibility, the UE and satellite piggyback the necessary information using standard transparent ULInformationTransfer and DLInformationTransfer message containers in 4G/5G [26, 27]. After the token consumption, the satellite extracts the UE's session states from the token to enforce carrier-grade services. If any of these procedures fails, the satellite will terminate the service or roll back to the legacy procedure in Figure 6 if it can reach the MNO.

• *Downlink service:* When a satellite receives data destined for the UE, it should forward the data to satellites covering this UE or establish downlink services if covering the UE by itself. The challenge is that MOSAIC's stateless satellite has no prior knowledge of the UE's location. 4G/5G resolves this issue by paging the UE through all base stations in the service area through the downlink broadcast channel, which, however, is expensive for satellites due to their broad global coverage and many more UEs to serve in these areas.

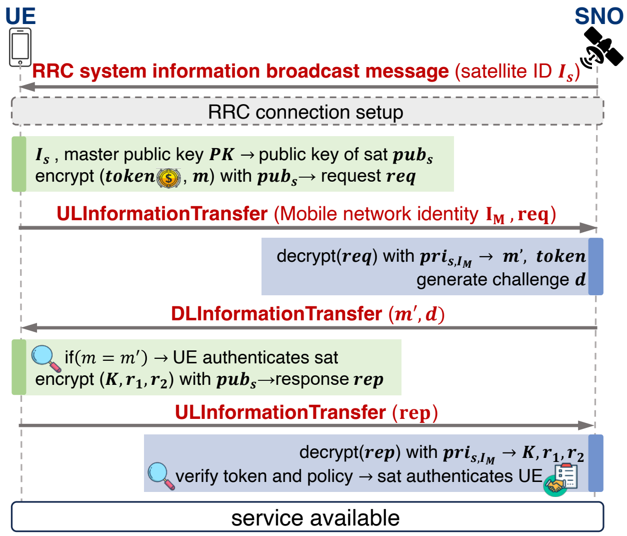


Figure 12: MOSAIC's in-band control for local self-service.

Instead, MOSAIC leverages the Earth-fixed geographic cells in §5.1 and Figure 10 as the UE's location reference for downlink services. MOSAIC assigns each UE's IP address as PLMN.cell-ID.UE-identity, where PLMN is the UE's serving MNO's 4G/5G Public Land Mobile Network identity, cell-ID is this UE's residing geographic cell's identity, and UE-identity is this UE's globally unique identity (e.g., IMSI in 4G and SUCI in 5G). This IP address is globally unique and locates this UE at the cell granularity. For each geographic cell, MOSAIC assigns one satellite per MNO that fully covers this cell to serve it. This is achieved in the LEO constellation through an initial bipartite matching between satellites and geographic cells per MNO and linear cell mapping update over time in Figure 10. For multiple MNOs, the SNO runs this matching separately to distribute MNOs among multiple satellites. Given the UE's packet with its geographic IP address, the satellite can easily detect if it is responsible for this cell for paging or locates the satellite serving this cell for geographic satellite routing. Upon receiving the paging message, the UE follows Figure 12 to establish the connectivity to this satellite and receive the downlink data.

Carrier-grade service enforcement: With the MNO-signed token from the UE, the serving satellite can extract the session states p from each token to locally enforce various carrier-grade services per UE, including but not limited to:

- *Billing:* The pay-as-you-go nature readily enforces it;
- *QoS:* The token embeds the 4G/5G QoS indicator for the satellite to run MAC-layer QoS-aware radio scheduling;
- *Location-based service:* The MNO can embed the applicable location in each token to let the satellite enforce location-specific roaming and access control; and
- *Customized service:* Some services (e.g., emergency calls) mandate redirecting data to specific infrastructure. The MNO can embed these rules into the corresponding token for the satellite to guide its traffic forwarding.

UE-driven mobility support: MOSAIC's pay-as-you-go paradigm implicitly moves the mobility support out of the infrastructure. The extreme LEO satellite mobility does not trigger any signaling procedures for a static UE, thus avoiding signaling storms in §3.2. The UE's in-band state provision also prevents inter-satellite coordination for handovers, letting the UE access any available and even competitive satellites. When the UE roams to a new geographic cell, it does not have to update its location to the remote core network like the legacy 4G/5G or SpaceCore [66]. Instead, it can immediately gain services using the tokens tailored to this new cell.

Security analysis: MOSAIC's pay-as-you-go paradigm departs from today's stateful session-based cellular architecture. It does not require the strong trust among the SNOs, MNOs, and UEs that is a must-have for hop-by-hop stateful sessions (§3.2), thus more dependable for multi-tenancy in untrusted satellites. Appendix A details how MOSAIC is resilient to threats from UEs, SNOs, MNOs, and external attackers to retain at least the same security as the legacy cellular network.

6 Practical Deployment

We focus on three issues for MOSAIC's practical large-scale deployment: (1) How to minimize SNOs' satellite changes for MOSAIC? (2) How to integrate MOSAIC satellites with MNOs' terrestrial 4G/5G for coexistence? (3) How to enable MOSAIC for commercial off-the-shelf (COTS) phones/IoTs?

Our deployment resolves these issues with three principles:

(I) *MOSAIC as a plug-and-play proxy:* For the minimal changes for SNO's satellites, we realize MOSAIC as an external proxy for the unmodified cellular functions.

(II) *Seamless integration with terrestrial 4G/5G:* MOSAIC reuses and incrementally upgrades terrestrial cellular core networks to integrate pay-as-you-go satellites.

(III) *SIM-based deployment for UEs:* Rather than changing the COTS UE hardware, we realize MOSAIC's UE-side logic as SIM applet and mobile app. UEs can readily enjoy MOSAIC with a new SIM card.

Figure 9 shows MOSAIC's practical deployment scheme based on these principles. It spans three participants:

• **SNO-side satellites:** Each satellite installs the legacy cellular RAN and user-plane function (UPF). It further installs a proxy that emulates the cellular core network's control-plane functions. This proxy packages MOSAIC's self-serve multi-tenant functions in §5.1. It maintains this satellite's certificates from MNOs, accepts tokens from each UE through ULInformationTransfer messages, extracts the UE's session states from tokens, and feeds these states to RAN and UPF to enforce carrier-grade services. As the LEO satellite moves, this proxy also updates its mapping to cells and MNOs (§5.1 and §5.3). To facilitate this proxy's deployment with minimal satellite changes, we can reuse operational satellites' built-in software-defined telemetry, tracking, and control (TT&C) features to remotely upgrade onboard satellite software/firmware[5].

[5] For instance, Starlink has demonstrated its quick satellite software up-

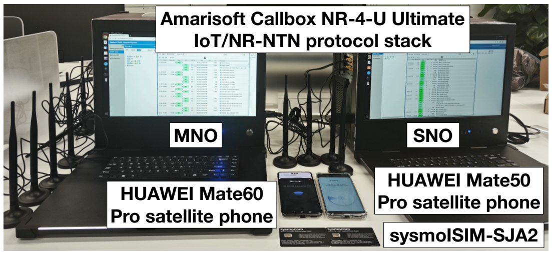


Figure 13: Our MOSAIC prototype and testbed setup.

• **MNO-side terrestrial infrastructure:** For tokens in §5.2, MOSAIC reuses the standard subscription server (HSS in 4G [77] and UDM in 5G [78]) as the user profile database and charging function (OCS/OFCS in 4G [77] and CHF in 5G [78]) as the consumed token database. It offers tokens to UEs and their SIM cards through the standard APDU interface for remote over-the-air update [79]. This unifies the management between satellite and terrestrial cellular networks. It also uses this core network to bridge the handover between satellites and terrestrial base stations using procedures in Figure 6. This integration requires no changes for terrestrial base stations.

• **UE-side SIM card:** MOSAIC requires no hardware changes for COTS phones/IoTs. Instead, each UE just needs to (1) get a SIM card from the MNO with MOSAIC's token capabilities in §5.2 as an applet and (2) install a mobile app to store tokens in §5.2 and invoke the in-band control in §5.3. This app coordinates with the SIM/eSIM via TelephonyManager APIs [80] to jointly perform procedures in §5.2–5.3. MNOs can remotely upgrade SIMs/eSIMs and provision tokens using the standard over-the-air update interfaces [81, 82].

Proof-of-concept prototype (Figure 13): We follow the above methodology to prototype MOSAIC with Amarisoft Callbox NR-4-U Ultimate [83], one of the first available 3GPP NTN software protocol stacks on the market for direct-to-cell satellite communication testing. This suite realizes full-stack 3GPP-R17 IoT/NR-NTN protocols and standard-compliant LEO satellite RF channel emulators [19]. We use one Amarisoft node to emulate the SNO's LEO satellite, one Amarisoft node to emulate the MNO's terrestrial 4G/5G core, and COTS phones/IoTs with programmable sysmoISIM-SJA2 SIM cards [84] and an Android app to realize MOSAIC's pay-as-you-go paradigms. We test various COTS UEs, including the Huawei Mate 60 Pro with direct-to-cell communication with the Tiantong GEO satellite via 2G GMR, and Huawei Mate 50 with messaging services via Beidou GEO satellites.

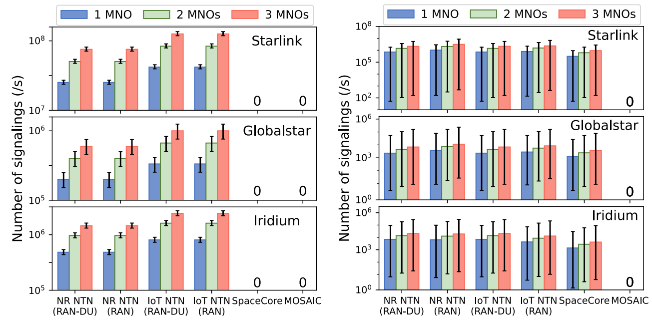
7 Evaluation

We evaluate MOSAIC using a combination of qualitative analysis, quantitative micro-benchmark test with our prototype in Figure 13, and large-scale what-if emulations driven by satellite data in Figure 3. We compare MOSAIC with state-of-the-art in Figure 2, assess its modules in §5.1–5.3, and show how it addresses issues in §3.2 for SNOs, MNOs, and UEs.

grade capability [75] to defend against jamming attacks. Spire Global deployed software-defined satellites to facilitate remote firmware upgrade [76].

	COTS UEs?	4G/ 5G?	Self-service?	Multi-tenancy?	Competitive satellites?
Transparent pipe	√	×	×	√	√
Starlink [33–36]	√	√	×	Partial	Partial
NR NTN (5G) [20]	√	√	×	×	×
IoT NTN (4G) [23]	√	√	×	×	×
SpaceCore [66]	×	√	√	×	×
MOSAIC	√	√	√	√	√

Table 1: Comparison of direct-to-cell satellite solutions.



(a) Service establishment (b) Satellite handover in LEO mobility

Figure 14: MOSAIC reduces signalings for satellites.

7.1 Qualitative Advantages over SOTAs

Table 1 compares MOSAIC with existing work in Figure 2 regarding their support for multi-tenant LEO satellites to directly connect COTS phones/IoTs. By offloading cellular functions to satellites, MOSAIC avoids the transparent satellite pipes' shortage of enabling satellite 4G/5G for UEs (§3.1). By replacing the stateful hop-by-hop cellular sessions with the pay-as-you-go paradigm, MOSAIC also overcomes the limitations in §3.2 to enable self-serve satellites for SNOs for transparent multi-tenancy. Its near-stateless nature lets UEs and MNOs flexibly use competitive SNOs' satellites for complementary coverage and lower costs. While SpaceCore [66] achieves similar stateless 5G core functions in LEO satellites with UE-driven state management, it cannot readily support multi-tenancy or competitive satellites because it assumes all satellites belong to a single MNO (i.e., no trust concerns). Moreover, unlike MOSAIC, SpaceCore requires modifying 4G/5G radio resource control (RRC) messages to piggyback UE states, thus not applicable to COTS phones/IoTs.

7.2 Self-Serve Multi-Tenant Orbital Functions

We assess how MOSAIC's self-service paradigm in §5.1 frees SNOs' satellites from signaling storms, expands their global serviceable areas for more revenues, and simplifies their dynamic many-to-many mapping to MNOs and UEs.

Self-contained orbital cellular functions: MOSAIC's function split in §5.1 lets each satellite independently serve UEs without interacting with other satellites or ground stations, thus free of signaling storms in §3.2. Figure 14a counts the signalings for each fast-moving LEO satellite to establish services for incoming UEs using the procedure in Figure 6a. It confirms that MOSAIC avoids the signaling storms with its

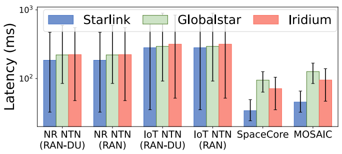


Figure 15: Service setup latency.

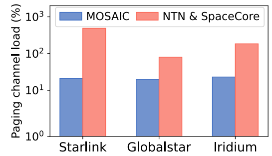


Figure 16: DL paging cost.

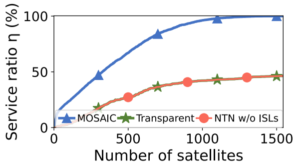


Figure 17: Serviceable areas.

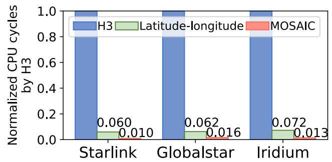


Figure 18: Mapping overhead.

pay-as-you-go tokens. Note that SpaceCore also saves signalings with its UE-driven state fetching but requires modifying 4G/5G standards, thus not applicable to COTS UEs.

A side benefit of MOSAIC's self-contained orbital cellular functions is that it saves UE-perceived service latencies. Figure 15 shows that, compared to NTN, MOSAIC's localized service setup reduces signaling latency by up to 5.19×, 1.33×, and 2.33× in Starlink, Globalstar, and Iridium, respectively. Its service setup latency is slightly higher than SpaceCore by 0.33× as a tradeoff for compatibility with COTS UEs with additional standard-compliant signalings (Figure 12).

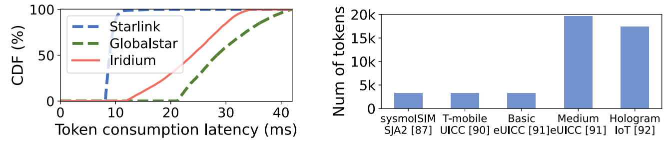
Expansion of serviceable areas: MOSAIC's self-service nature eliminates satellites' reliance on ground stations for broader serviceable areas. We define each LEO constellation's cellular service ratio as $\eta = \frac{\text{Areas with functional satellite 4G/5G}}{\text{Total areas covered by all satellites}}$. Figure 17 showcases Starlink Phase II satellites' service ratio as a function of activated satellites. When ISLs are not reliable, NTN's serviceable areas are constrained by ground stations similar to transparent pipes in §3.1. More satellites do not suffice to fulfill serviceable areas due to the non-uniform distribution of ground stations in Figure 4b. Instead, MOSAIC is free of this deficiency. It expands these satellites' serviceable areas with up to 116% increment and achieves 100% service ratio within this LEO constellation's terrestrial coverage.

Simplified dynamic many-to-many mapping: MOSAIC adopts the orbit-aligned geographic cell division in §5.1 to simplify the dynamic SNO-MNO-UE service relationships. Figure 18 compares this method with H3 hexagonal cells [85] (likely used by Starlink [86]) and the latitude-longitude rectangular cells in terms of their computation cost of dynamic re-mapping. MOSAIC reduces CPU cycles by 100×, 63×, and 73× in Starlink, Globalstar, and Iridium, respectively.

7.3 Pay-as-you-go Satellite Access Tokens

We next evaluate the efficiency, scalability, and resiliency of MOSAIC's pay-as-you-go tokens in §5.2 for MNOs and UEs.

Efficiency of token consumption: MOSAIC's localized token consumption in Figure 11b slightly incurs extra delays between the UE and satellite. As shown in Figure 19a, each token's consumption latency is ≤ 16.4 ms, 41.9 ms, and 34.8 ms in Starlink, Globalstar, and Iridium, respectively. They are marginal compared to MOSAIC's savings in Figure 15.



(a) Token consumption latency (b) Num. tokens each (e)SIM can support

Figure 19: MOSAIC token's system overhead.

Scalability of SIM-enforced tokens: MOSAIC's SIM-enforced one-time token requires storing per-token metadata o_2 in the SIM card. Figure 19b quantifies the number of available 1024-bit tokens that each commercial standard-compliant SIM card (with 64KB–384KB RAM [84,87–89]) can support. Each SIM card can store 3,279-19,661 tokens' 160-bit metadata o_2. If the MNO lets each token represent 1 minute, 1 text, or 1 MB of data quota, then the quota of MOSAIC based on today's SIM card is comparable to prepaid SIM cards on the market today (e.g., 250 units/month SIM [68])[6].

Scalability of token generation and verification: Both are scalable to many UEs. Our test with a workstation using a single core of 2.30GHz Intel Xeon Gold 5218 shows that, each MNO in this setup can generate 1,175 tokens/s (Figure 11a) and verify 1,401 tokens/s (Figure 11c) on average.

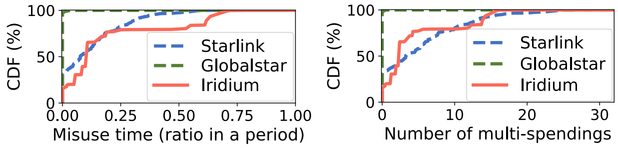
Resiliency to token manipulations: MOSAIC's SIM-enforced token consumption locally restrains most token misuse since the SIM is tamper-resistant. In the extreme case where the MNO-controlled SIM is cracked *and* remote LEO satellites have no ISLs to reach remote MNOs, the token misuse is still detected when the LEO satellites eventually move to the ground station to interact with MNOs in Figure 11c. Figure 20 quantifies this worst-case token multi-spending by a misbehaved UE before it is detected by blacklisted by SNOs and MNOs. Due to LEO satellites' fast mobility and considerable ground station availability (exemplified in Figure 4b), even this worst-case misuse time is still bounded by 0.2–0.88 satellite orbital periods (22.8–87.7 minutes). It can be further shortened if ISLs exist for timely token clearing in Figure 11c.

7.4 Local Self-Service via In-Band Control

We last assess how MOSAIC's UE-driven procedures in §5.3 localize satellite access, simplify signalings in LEO mobility, and facilitate the use of competitive SNOs' satellites.

Service establishment: MOSAIC's uplink service establishment has been studied in §7.2. Its downlink service is similar to the uplink one except for the additional paging procedure, which could overload the 4G/5G broadcast channel given numerous UEs in satellites' broad coverage [91]. Figure 16 compares the paging load assuming 5MHz 4G/5G radio bands for each satellite and 400 UEs/km^2 by following [91]. Compared to NTN and SpaceCore, MOSAIC reduces paging channel load by 23×, 4×, 8× in Starlink, Globalstar, and Iridium, respectively. Note that NTN and SpaceCore's paging load can even exceed the 4G/5G channel capacity, thus unable to support numerous UEs. Instead, by mapping each

[6] Besides, existing SIM cards allow for 100,000–500,000 read/write operations during their lifetime [90], so the number of writes won't be a bottleneck.



(a) Misuse time per token (b) Misuse count per token

Figure 20: Worst-case token misuse when SIMs are cracked.

geographic cell to a corresponding satellite in §5.3, MOSAIC reduces the areas to page for functional 4G/5G services.

UE-driven mobility support: As explained in §5.3, MOSAIC's UE-driven primitive avoids procedures triggered by extreme LEO satellite mobility. As shown in Figure 14b, this helps MOSAIC eliminate the signaling storms in §3.2: Rather than coordination between satellites, each new satellite directly fetches each UE's states from its one-time tokens.

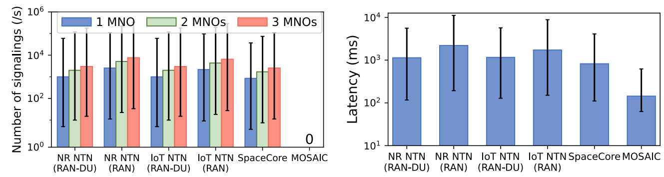
Use of competitive SNOs' satellites: By minimizing the coordination among satellites and ground stations, MOSAIC's in-band control lets UE freely choose *any* authentic satellite for use. Instead, existing solutions require the MNO's involvement to indirectly coordinate competitive SNOs' satellites, which require ISLs to remote ground stations and incur signaling storms. Figure 21 quantifies these costs assuming two SNOs (Starlink and Iridium) with ISLs. Compared to the state-of-the-art, MOSAIC saves 850–7,640× signaling costs and 4.71–14.25× latencies due to its local in-band control.

8 Limitations

MOSAIC is our first step to enable self-serve multi-tenant direct-to-cell satellites for our regular phones/IoTs. While encouraging, we believe that it could be further improved in at least three aspects in the future work: *(1) For SNOs*, while MOSAIC's pay-as-you-go token grants service access, it does not guarantee *verifiable* carrier-grade service. Selfish SNOs may not offer carrier-grade services after gaining tokens, thus causing overbilling. This issue could be resolved using recent two-sided measurement and negotiation mechanisms [69, 92]. *(2) For MNOs*, while MOSAIC's policy-embedded tokens let MNOs retain cellular policy control, the offloaded cellular functions to satellites still cannot be directly managed by MNOs. How to enhance MNOs' configurability and manageability of on-board satellite cellular functions deserves further research. *(3) For UEs*, MOSAIC's tokens suppress signaling overhead at the cost of some UE-to-satellite bandwidths due to its in-band control. It is worth exploring how to compress tokens for more bandwidth-efficient pay-as-you-go services.

9 Related Work

We are witnessing a boom in LEO networks. Extensive efforts have been made on LEO physical topology [30, 93], link-layer scheduling [94, 95] and handovers [96, 97], network-layer routing [98–100], edge computing applications [101, 102], and real-world measurements [103–105]. Instead, enabling direct-to-cell satellites for commodity phones/IoTs has gained less



(a) Handover signaling message costs (b) Service resumption latency

Figure 21: Inter-SNO satellite handover under LEO mobility.

attention until recently. These LEO satellites differ from other non-terrestrial 4G/5G via balloons [106] or UAVs [107–109] due to their extreme mobility and scale in foreign outer space. Recent studies [20, 66, 110] focus on coping with these challenges for functional satellite 4G/5G. Our work complements them by exploring the sharing of direct-to-cell satellites among SNOs and MNOs as a cost-effective win-win solution.

Cellular network multi-tenancy has been a long-standing desire and is becoming a reality in terrestrial networks with the maturity of standards [111–113], cloudified 5G [114, 115], and decentralized architecture [92, 116, 117]. But these terrestrial efforts cannot support sharing the extremely mobile LEO satellite infrastructure (§3), which motivates our design. MOSAIC borrows the idea of UE-driven state management from SpaceCore [66] but extends it as pay-as-you-go tokens for multi-tenancy. MOSAIC's SIM-based solution also avoids SpaceCore's incompatibility with regular phones/IoTs.

10 Conclusion

We present MOSAIC, a pay-as-you-go solution to enable self-serve multi-tenant LEO direct-to-cell satellites for our regular phones/IoTs in under-served areas via 4G, 5G, and beyond. MOSAIC departs from today's hop-by-hop stateful cellular session that impedes multi-tenancy due to its need for tight functional coupling and stable relationships among SNOs, MNOs, and UEs. Instead, it adopts policy-embedded one-time tokens for on-demand satellite services. This paradigm realizes near-stateless satellites for transparent multi-tenancy, alleviates their reliance on remote ground stations for self-service, and alleviates inter-satellite coordinations to encourage the use of diverse satellites from competitive SNOs.

In a broader context, MOSAIC is an attempt to democratize cellular networks from space. While cellular democratization has been nice-to-have in terrestrial networks to foster market competition, it has become a must-have in space due to the mutual need for scarce orbital slots from satellite operators, licensed spectrums from mobile operators, and lowered capital costs of LEO constellations for both participants. We hope our lessons can spur this effort toward a win-win sharing of space networks *by* the community and *for* the community.

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A Security Analysis

MOSAIC's pay-as-you-go paradigm departs from traditional stateful session-based cellular architecture. It does not require the strong trust among the SNOs, MNOs, and UEs that is a must-have for conventional hop-by-hop stateful sessions (§3.2), thus more feasible for multi-tenancy over untrusted satellites. We next show how MOSAIC is resilient to various threats from UEs, SNOs, MNOs, and external attackers to retain at least the same security as the legacy cellular network.

Mitigating threats from UEs: A selfish UE is incentivized to forge, manipulate, or multi-spend a token for unauthorized satellite access. MOSAIC avoids so with its cryptographically restrictive blind signature-based tokens (whose security has been formally proved in [38]) and SIM-assisted protection. Without the MNO's secret key x in §5.2, the UE cannot forge or modify a valid token. The MNO-issued tamper-resistant SIM locally denies the UE's token multi-spending. In the worst rare case that the SIM is cracked, the MNO can still detect the multi-spending and permanently blacklists this UE for later services in the clearing phase in Figure 11c.

Mitigating threats from MNOs: A selfish MNO may want to save its rental bill to SNOs by underclaiming its usage of satellites. MOSAIC's pay-as-you-go tokens offer undeniable proof of service for SNOs to mitigate this threat: Each satellite can only gain the token if serving the UE. By showing the ownership of these tokens to trusted third parties (e.g., court), the SNO can prove the MNO's satellite usage for charging.

Mitigating threats from SNOs: An unauthorized satellite without the certificate from the MNO cannot legally use this MNO's licensed 4G/5G spectrums; otherwise, it fails to pass the authentication in Figure 12 and can be detected by spectrum regulators (e.g., ITU/FCC). Besides, a selfish SNO may refuse to offer carrier-grade services after gaining the UE's token, thus overbilling the UE and MNO. This issue has existed in terrestrial cellular networks for decades [69, 92, 117] due to the lack of verifiable accounting and QoS. To avoid this attack, MOSAIC can leverage the two-sided measurement and negotiation in [69, 92] between the UE and satellite to form an undeniable, publicly verifiable proof of service enforcement. The SNO can only convincingly charge the MNO when both this proof and token are available.

Mitigating threats from external attackers: MOSAIC retains at least the same security as the legacy 4G/5G. Like 4G/5G, it adopts authentication and key agreement in Figure 12 to protect its over-the-air signaling and data. Its tokens and certificates are exchanged afterward over the encrypted channel, thus resilient to eavesdropping or manipulation by man-in-the-middle attackers. MOSAIC's in-band control also localizes the UE's state retrieval to mitigate potential leaks during the state migrations between satellites and ground stations in the outer space filled by untrusted 3rd-party satellites.

B Acronyms in This Work

AMF	Access and Mobility Management Function
AUSF	AUthentication Server Function
COTS	Commercial Off-The-Shelf
CU	Central Unit (in radio access networks)
DU	Distributed Unit (in radio access networks)
F1AP	F1 Application Protocol [62]
GEO	Geostationary Earth Orbit
GTP-U	GPRS Tunneling Protocol–User plane [71]
HSS	Home Subscriber Server
IMSI	International Mobile Subscriber Identity
ISL	Inter-Satellite Link
LEO	Low Earth Orbit
MNO	Mobile Network Operator
MM	Mobility Management protocol
NAS	Non-Access Stratum
NGAP	Next Generation Application Protocol [20, 70]
NTN	Non-Terrestrial Network
OCS	Online Charging System
OFCS	OFfline Charging System
PCF	Policy and Charging Function
PDU	Protocol Data Unit
PDCP	Packet Data Convergence Protocol
PLMN	Public Land Mobile Network
RAN	Radio Access Network
RLC	Radio RLC Control protocol
RRC	Radio Resource Control protocol
SCTP	Stream Control Transport Protocol
SM	Session Management protocol
SMF	Session Management Function
SNO	Satellite Network Operator
SUCI	Subscription Concealed Identifier
SUPI	Subscription Permanent Identifier
UDM	Unified Data Management
UE	User equipment
UP	User Plane
UPF	User Plane Function