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5G From Orbit: NTN Engineering and the Direct-to-Device Race

How 3GPP taught a terrestrial radio to survive a 541-millisecond round trip, why your phone now computes its own timing from GPS and satellite ephemeris — and an honest map of who is actually selling connectivity from space in 2026.

AUTHOR
5G/6G Academy Research

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***Abstract*—5G needed no new waveform to work from orbit — it needed new clocks. This paper walks the engineering first: the four things that break when the cell moves to 600 km or 35,786 km (timing, Doppler, HARQ, random access), quantified from 3GPP's own study; the Rel-17 toolkit that fixes them, including a quiet inversion in which the handset computes most of its own timing advance from GNSS and broadcast ephemeris; and the Rel-19 decision to put a full gNB on board after, by one vendor's account, a year of debate. Then the market: two distinct direct-to-device architectures went commercial — standards-native NB-IoT NTN over GEO on satellite spectrum (Skylo/Verizon, fall 2024) and terrestrial spectrum re-radiated from LEO under the FCC's 2024 SCS framework (T-Mobile/Starlink, July 2025; AST SpaceMobile targeting 2026). The link budget of a 23 dBm handset explains both the 223 m^2 antennas and why the first mass-market service was, counter-intuitively, GEO messaging.**

1. Why NR Almost Works From Orbit

The remarkable thing about 5G in space is how little of it had to change. The waveform, the channel coding, the protocol stack — all survive the trip. What does not survive is every number that quietly assumed the base station was a few kilometers away. 3GPP's foundational study, TR 38.821, put figures on the violence: a transparent GEO path — phone to satellite to ground station — has a maximum round trip of **541.46 ms**; even a 600 km LEO costs 25.77 ms through the bent pipe, or 12.89 ms if the base station rides on the satellite itself [1]. NR's terrestrial design assumed round trips under a millisecond.

Four mechanisms break first, and Table 1 pairs each with its dose of physics. HARQ — the stop-and-wait retransmission engine with 16 parallel processes — stalls when the acknowledgment takes hundreds of times longer than a slot. Random access breaks more subtly: within one GEO beam, the *difference* in delay between the near and far edge reaches 10.3 ms, so a response window built for 10 ms cannot even span one cell [1]. Doppler at LEO reaches 24 parts per million — about ±48 kHz at 2 GHz, derived — drifting at up to 0.27 ppm per second as the satellite sprints overhead at 7.56 km/s [1]. And the humble RLC retransmission timer, dimensioned for terrestrial echoes, stretches to seconds: the study's own worst-case arithmetic lands at 3.0 s for GEO [1].

TABLE 1 · The delay ladder (3GPP TR 38.821) — and what each rung breaks [1]

Scenario	Max round trip	What it breaks first	The Rel-17 answer
LEO 600 km, regenerative	12.89 ms	HARQ stop-and-wait stalls	32 HARQ processes (up from 16)
LEO 600 km, transparent	25.77 ms	scheduling timelines	K_offset added to timing relations
LEO 1,200 km, transparent	41.77 ms	RLC retransmission timers	extended MAC/RLC/PDCP timers
GEO, regenerative	270.73 ms	HARQ entirely	per-process HARQ feedback disable → RLC ARQ
GEO, transparent	541.46 ms	everything above at once	all of the above + 10.3 ms differential delay forces extended random-access windows

2. The Rel-17 Toolkit: Your Phone Knows Where the Satellite Is

Rel-17's most elegant fix is an inversion of forty years of cellular practice. Terrestrially, the network measures a phone's delay and commands a timing advance. From orbit, that loop is too slow and the spread too large — so the phone now does the work itself. The network broadcasts, in system information, the satellite's **ephemeris** (where it is and where it is going) plus a **common timing-advance** component covering the feeder side; the UE combines that with its own GNSS position to compute the service-link delay, and applies the total per the timing equation of TS 38.211/38.213 (Fig. 1) [2]. The working assumption is printed plainly in the specs: NTN devices are GNSS-capable. It works — and it makes satellite 5G's timing dependent on another satellite system, a single-point dependency worth knowing about.

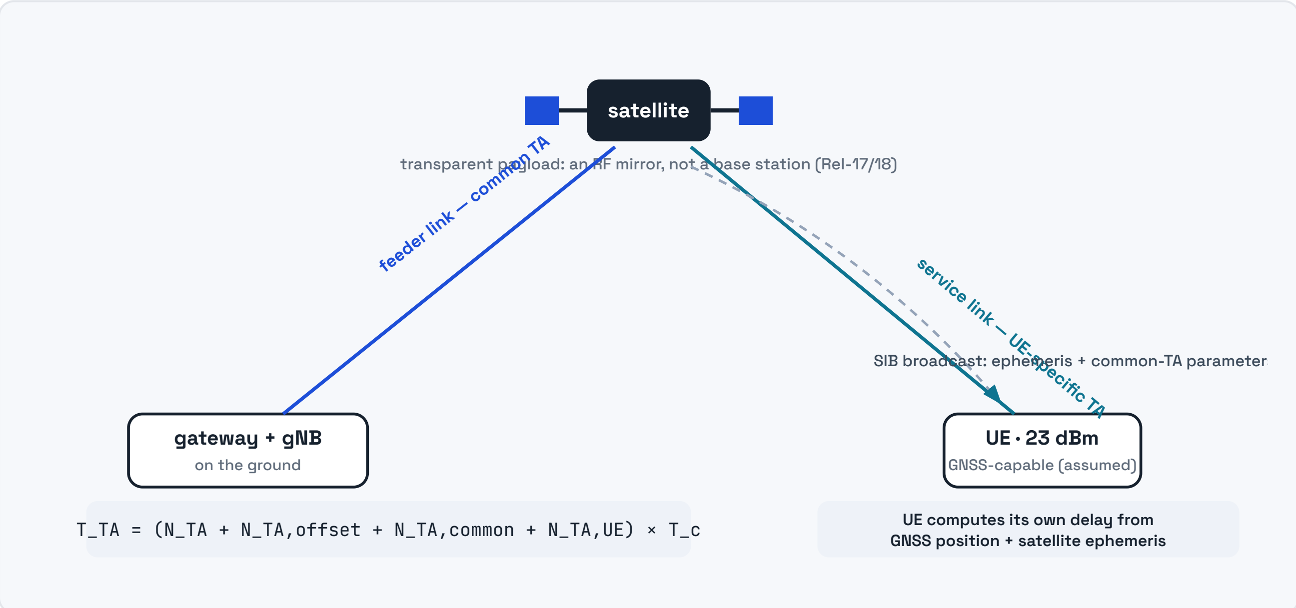

Fig. 1. Rel-17 timing-advance anatomy: the network broadcasts ephemeris and the common (feeder-side) component; the device self-computes the service-link component from GNSS. The classical measure-and-command loop is gone. Per TS 38.213 §4.2 / TS 38.211 §4.3.1 [2].

The rest of the toolkit follows the same philosophy — stretch, don't redesign. **K_offset**, a configured offset added to NR's scheduling relationships, absorbs the round trip (dimensioned, as a rule of thumb, near the service-link RTT plus the common TA) [3], [4]. HARQ gets two escape hatches: extend to **32 processes** so LEO pipelines keep flowing, or **disable feedback per process** and lean on RLC retransmission — the GEO-friendly option [3]. MAC, RLC and PDCP timers all gained NTN ranges. None of it is glamorous; all of it is why a standard phone can now register through a repeater 600 kilometers up.

3. Bent Pipe Was a Choice — Until Rel-19

Everything above assumes the satellite is a mirror: the "transparent" architecture, where the gNB stays on the ground and the spacecraft just translates frequencies and re-radiates. That was a deliberate scoping decision — 3GPP studied regenerative payloads (a base station in orbit) as far back as the 2019 study, then shipped Rel-17 and Rel-18 transparent-only to keep payloads simple and deployment early [5].

Rel-19 changes the answer. After what Ericsson describes as a full year of debate across four TSG RAN meetings, 3GPP chose in December 2023 to specify the **full gNB on board** — not a partial DU split [5]. The engineering question underneath is a beautiful one: where do you cut a RAN whose fronthaul is a feeder link? A full gNB in orbit natively supports inter-satellite links, satellite-to-satellite mobility, and **store-and-forward** — a satellite collecting IoT data over the ocean with no ground station in view, delivering it on the next pass. It also halves the worst delays: GEO's 541 ms transparent round trip becomes 271 ms when the gNB rides along [1], [5]. The Rel-19 package — regenerative payloads, store-and-forward, RedCap devices in NTN, downlink coverage enhancements, even phone-to-phone calls relayed by a single satellite — was completed with implementable specifications at the end of December 2025 [6], [7].

4. Spectrum: Two Lanes to the Sky

Direct-to-device runs in two legally distinct lanes, and the distinction explains the whole market map. The **MSS lane** uses spectrum licensed for satellite service all along: Rel-17 defined the first NR-NTN bands in TS 38.101-5 — n255 in L-band (uplink 1626.5–1660.5 MHz, downlink 1525–1559 MHz) and n256 in S-band (uplink 1980–2010, downlink 2170–2200 MHz) — with further MSS bands added later [8]. IoT-NTN — NB-IoT over satellite — was standardized in parallel as a Rel-17 feature, with its radio band specification (TS 36.102) published as a Rel-18 document [9]. Rel-18 also opened Ka-band for NR-NTN — bands n510/n511/n512, uplink 27.5–30 GHz, downlink **17.3–20.2 GHz** — strictly for VSAT-class, steered-antenna terminals, not handsets [8].

The **terrestrial lane** did not exist legally until the FCC created it: the Supplemental Coverage from Space framework, adopted March 14, 2024 — the first of its kind worldwide, effective that May — lets satellite operators re-use a terrestrial carrier's licensed mobile spectrum from orbit [10], [11]. That single regulatory act is the foundation under T-Mobile/Starlink and AST SpaceMobile: ordinary phones, ordinary bands, extraordinary cell altitude.

5. The 2026 Scoreboard: Two Religions, Both Commercial

Fig. 2 places the players on the two axes that actually matter — orbit and spectrum lane. The standards-native religion went first: Verizon and Skylo announced in August 2024 and were live that fall with emergency messaging over **NB-IoT NTN on GEO satellites** — billed as the first commercial supplemental smartphone connectivity from a mobile carrier [18]. Note the contrarian fact: the first mass-market D2D service runs on the orbit with the *worst* latency on Table 1. For messaging, latency is nearly irrelevant; link closure and one-satellite-covers-a-continent economics decide. The same lane hosts the Apple-Globalstar arrangement — $1.5 billion committed in November 2024 for iPhone satellite features on Globalstar's L/S-band — which took a sharp turn on April 14, 2026, when **Amazon agreed to acquire Globalstar** (a deal valued around $10.8–11 billion at announcement, not yet closed at this writing), folding the iPhone's satellite lifeline into Amazon Leo [19]–[21].

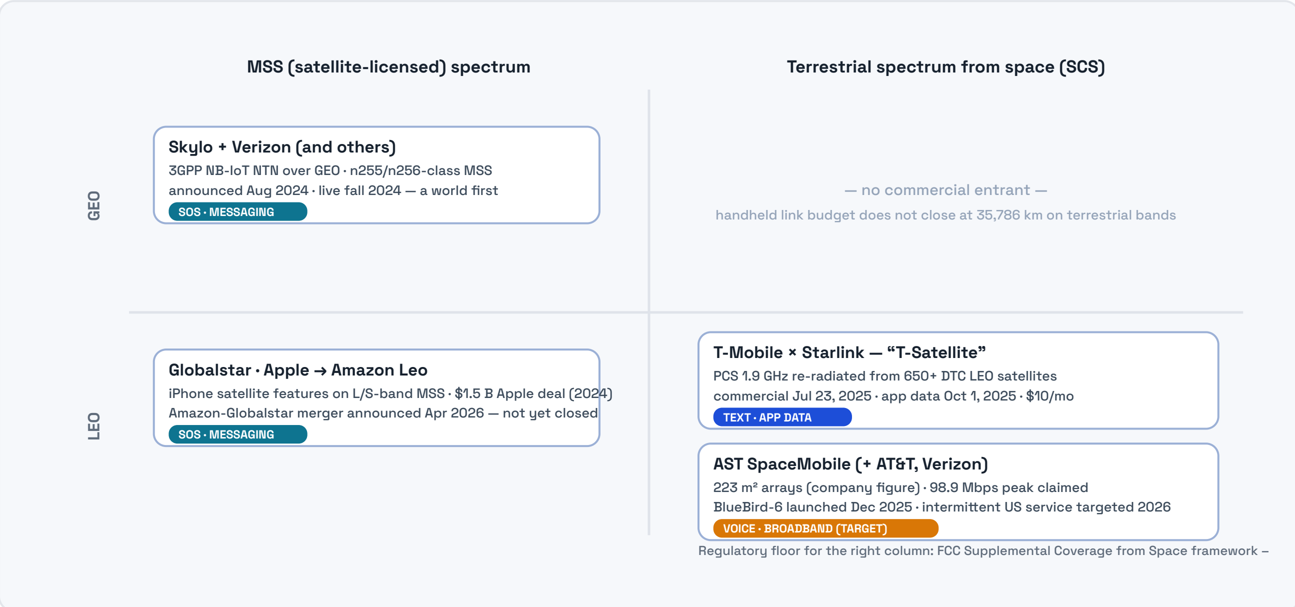

Fig. 2. The direct-to-device map, mid-2026: orbit versus spectrum lane. Capability tiers are cumulative (SOS → messaging → app data → voice/broadband). AST's array size and peak rate are company-reported figures; Starlink's "V2" broadband-from-space claims are forward-looking plans and are deliberately not plotted. Sources: [10]–[21].

The brute-force religion followed. T-Mobile's "T-Satellite" with Starlink went commercial on July 23, 2025 — texting first, satellite data for approved apps from October 1 — at $10 a month, over 650-plus direct-to-cell LEO satellites re-radiating T-Mobile's 1.9 GHz PCS spectrum; One NZ had run the first nationwide Starlink texting service in December 2024 [12]–[14]. AST SpaceMobile is the maximalist: arrays around 223 m^2 (a company figure), a claimed 98.9 Mbps peak on test hardware, an FCC SCS authorization, the BlueBird-6 launch in December 2025, and a target of intermittent US service in early 2026 with AT&T and Verizon agreements in hand [15]–[17]. Treat the right column of Fig. 2's ambitions accordingly: the texting tier is shipped reality; the broadband tier is, as of June 2026, a funded plan.

6. The Link Budget Is the Product

Why do the architectures diverge so sharply? Because the handset refuses to change. The standardized assumption is merciless: 23 dBm — a fifth of a watt — into a 0 dBi omnidirectional antenna, with a 7 dB noise figure [1]. Free-space loss at 2 GHz runs about 154 dB straight up to a 600 km satellite and about 164 dB at the 1,932 km slant range of a low pass (derived from the study geometry); GEO adds another 25 dB on top [1]. Every decibel must come from somewhere else, and there are only three suppliers: aperture, bandwidth, and cooperation. Aperture is the visible arms race — from ~64 m^2 test arrays to AST's reported 223 m^2 — because collecting area is the one thing you can keep buying. Narrowband is the quiet supplier: NB-IoT's tones and repetitions are why GEO messaging closes its link with no drama. Cooperation is the research frontier — distributed beamforming across satellites adds up to 6 dB with two spacecraft and 12 dB with four, per published analysis [22].

Read the tiers of Fig. 2 as link-budget statements, not marketing tiers: SOS and messaging fit today's physics on any orbit; app data fits LEO with big arrays; phone-grade broadband from space awaits the next aperture generation — Starlink's V2 plans claim it, and plans are what they remain [23]. For 6G NTN planning, assume the handset stays a 23 dBm omni — history says it will — and budget everything else around that fixed point.

7. What To Watch, and What To Do

Five markers will tell you where this market actually is by 2027. **(1)** First Rel-19 regenerative payloads in commercial constellations — the moment store-and-forward IoT and satellite-relayed calls stop being slideware [5], [6]. **(2)** AST's transition from intermittent to continuous US service, on schedule or not [15], [16]. **(3)** Whether Starlink's V2 generation turns "5G speeds from space" from plan into measured fact [23]. **(4)** The Amazon-Globalstar closing and what Amazon Leo does with the iPhone franchise [20], [21]. **(5)** SCS-style regulatory frameworks appearing outside the US — the right column of Fig. 2 is currently an American invention.

For engineers: treat D2D as three products, not one — emergency/messaging (deployable today, either lane), IoT including store-and-forward (watch Rel-19 hardware), and broadband (watch apertures, not announcements). Audit the GNSS dependency in any NTN device plan — Rel-17 timing assumes it. And when a vendor quotes you a satellite latency figure, ask the Table 1 question: which scenario, which payload, which path? The difference between 12.89 and 541.46 milliseconds is not a rounding error — it is the difference between an architecture and an apology.

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