5G Non-Terrestrial Networks (NTN): A Modern White Paper for Practical Builders

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Executive Summary — This white paper explains 5G Non-Terrestrial Networks (NTN) in plain language for engineers and decision-makers who want reliable coverage beyond cell towers. The big idea is simple: extend standard 5G so ordinary phones and IoT sensors can connect through satellites and high-altitude platforms with the same 5G Core, security, and SIMs. We outline the key 3GPP documents (TR 38.811, TR 38.821, TR 36.763) and the path from Release 17 (first features) to Release 18 (refinements) and Release 19 (regenerative payload options). We cover radio behavior (delay, Doppler, waveforms, numerology), the honest uplink bottleneck from a 23 dBm phone, timing loops like HARQ, spectrum etiquette via EPFD, mobility across moving beams, and operations that feel like one network. The goal is practical: ship dependable coverage, respect neighbors, and keep operations sane.

Keywords — 5G, NTN, NR-NTN, IoT-NTN, Doppler, HARQ, GNSS, EPFD, Release-17/18/19, 5GC.

1 WHY NTN MATTERS NOW

Connectivity is precious in places where towers are scarce: coastlines, mountain passes, air routes, rail corridors, and rural regions with long power lines. People expect phones to “just work,” and sensors are judged by whether they report on time, not by the map of terrestrial cell sites. NTN answers this with a straightforward idea: keep 5G as it is and add access from the sky. Phones do not become “satellite phones”; they remain regular 5G devices that sometimes reach the network through a satellite instead of a tower. For operators, this means the same core, the same subscriber data, and the same security model. For regulators, it means a well-known standard that can be audited and licensed. For customers, it means fewer “no service” moments—especially when they matter most.

In practical terms, NTN helps three clusters of use cases stand up quickly. Emergency messaging where storms or fires take out ground equipment. Maritime and aviation coverage to keep crews, passengers, and cargo connected. And massive IoT: tracking assets, monitoring environment, and supervising infrastructure across large, empty areas. None of these require exotic devices if we design the radio honestly and let the core do its normal job with a few NTN-aware tweaks.

2 STANDARDS AT A GLANCE (TRS AND RELEASES YOU CAN RELY ON)

3GPP is where the rules for 5G are written and reviewed. The NTN journey started with **TR 38.811** (Release 15), which studied how NR behaves when the radio path is long and the transmitter is moving fast relative to the user. It named the problems: bigger and changing propagation delay, fast frequency drift (Doppler), and mobility caused by beams sliding over the ground. Next came **TR 38.821** (Release 16), which offered solutions that fit inside NR: widen the initial access windows, allow devices to pre-compensate time and frequency using **GNSS**, and relax control loops (like HARQ) that assume short round-trip times.

For IoT, **TR 36.763** explained how **NB-IoT** and **LTE-M** adapt to satellite links using their natural strengths: narrow bandwidth, repetitions, and patience. That study paved the way for **Release 17** (first official features for NR-NTN and IoT-NTN), **Release 18** (coverage, mobility, and positioning improvements), and **Release 19** (options for *regenerative payloads*—putting some base station functions on the spacecraft—to trim delay and reduce reliance on feeder-link weather). A useful way to remember the flow is: Rel-17 makes it real, Rel-18 makes it smoother, Rel-19 makes it smarter.

3 ARCHITECTURES AND BEAM MODELS (THE TWO-BY-TWO YOU WILL ACTUALLY USE)

There are two straightforward architecture choices. With a **transparent payload**, the satellite is mostly a smart radio mirror: it forwards signals while the 5G baseband lives on the ground. This keeps the spacecraft simpler and follows normal software cycles, but leaves you with larger felt delay and more sensitivity to the health of feeder links. With a **regenerative payload**, some gNB functions (DU/CU) move onboard the satellite. This shortens control loops and smooths over some feeder-link issues at the cost of more complex space hardware and a software lifecycle that must still align with standards and security updates.

Orthogonal to that is how you paint the ground with beams. **Earth-Moving Cells (EMC)** sweep with the platform and can reuse spectrum efficiently, but they trigger more handovers—even when users stand still. **Earth-Fixed Cells (EFC)** hold steady over geography, which simplifies paging and mobility in the core, but demands precise pointing and ongoing resource mapping as the constellation moves. Most real-world programs mix these choices by band, orbit, and service tier.

4 RADIO CHOICES THAT KEEP THINGS STABLE

The best news for implementers is that we keep the familiar 5G waveforms. Downlink remains **CP-OFDM**. Uplink prefers **DFT-s-OFDM** (SC-FDMA) because its lower peak-to-average power ratio makes phone power amplifiers happier and saves battery. 5G's **numerology**—the spacing between subcarriers—is your practical knob: smaller spacing helps with coverage and echo tolerance; larger spacing helps when Doppler changes fast or you operate at higher bands where phase noise is a concern. Because delay is larger and frequency drifts during a pass, devices use **GNSS-assisted pre-compensation** so timing and frequency are close before talking, and the network widens search windows for PRACH and SSB so lock-on remains reliable.

It's worth stating this plainly: none of this asks you to learn a brand-new physical layer. The design is conservative on purpose. We bend 5G to fit space, not the other way around.

5 THE UPLINK BOTTLENECK FROM PHONES (DESIGN AROUND IT FIRST)

Downlink is usually comfortable because satellites can transmit with good EIRP and large antennas. The challenge is **uplink** from a handset: roughly 23 dBm transmit power, a small detuned antenna often shadowed by a hand or body, and an OFDM-family waveform that prefers linearity. The practical answer is to design uplink first. Start with narrower uplink bandwidths, use **repetitions**, pick robust modulation and coding, and design pilots (DMRS) with care. On the space segment, aim for higher **G/T** where practical. For IoT, **NB-IoT** and **LTE-M** are naturally suited because they use tiny bandwidth and accept repetition to save energy.

Table 1: Illustrative Uplink Link-Budget Components (Handset → LEO Satellite)

Parameter	Value (example)
UE Tx Power (max)	23 dBm
UE Antenna Gain (body-avg)	−2 dBi
Path Loss (slant, 2 GHz)	160 dB (geometry-dependent)
Atmospheric/Scintillation Margin	1.5 dB
Polarization/Pointing Loss	1.0 dB
Satellite G/T	5 dB/K (service-beam center)
Noise Density (N_0)	−228.6 dBW/Hz
Required E_b/N_0 (robust MCS)	3 dB–5 dB
Uplink Bandwidth (initial)	5 MHz or narrower
Effective Margin (with repetition)	≥3 dB target

6 DELAY, DOPPLER, AND FEEDBACK LOOPS (MAKE TIMING MATCH THE SKY)

Satellites add delay and frequency shift that change during a pass. A 550 km LEO with realistic slant paths can yield radio round-trip times in the 10 – 20 ms range, and end-to-end service RTTs (including gateways and core traversal) in the 30 – 60 ms range;[1] GEO is much larger. Doppler can be tens of kilohertz at 2 GHz and scales with frequency; the rate of change matters almost as much as the size. In normal 5G, **HARQ** is a fast retry loop. Over NTN, we often give HARQ more processes, slow the loop down, or switch it off per traffic class, and we **aggregate slots** to send bigger chunks at a measured pace. Devices use GNSS to pre-compensate time and frequency, and gNBs widen acquisition windows so initial access is not fragile.

Table 2: Representative Doppler and Delay Numbers (Order-of-Magnitude)

Carrier Frequency	Peak Doppler (LEO)
700 MHz	17 kHz
2 GHz (S-band)	50 kHz
10 GHz (X/Ku)	250 kHz
Path Type	**Radio RTT (LEO)**
UE ↔ Sat ↔ GW	10 – 20 ms
End-to-end (incl. core paths)	30 – 60 ms

7 SPECTRUM ETIQUETTE: EPFD (BE A GOOD NEIGHBOR BY DESIGN)

Space is shared, so NTN must prove it will not harm geostationary services. **EPFD**—Equivalent Power-Flux Density—is the metric used in filings and coordination. The **ITU-R S.1503** document explains how to calculate EPFD across geometries, antenna patterns, and time. This is not a form to sign at the end; it informs beam footprints, per-beam EIRP, polarization choices, and reuse patterns from day one. As programs move from L/S to **Ku/Ka** for capacity, headroom tightens and feeder links feel rain more, so accurate modeling plus conservative field validation are the difference between "promised" and "approved".

Practical tip: Treat EPFD the same way you treat link budget. Iterate it with beam maps and gateways early; keep a living model tied to actual deployments; update it when payload configs or ground antenna catalogs change.

8 FEEDER LINKS AND WEATHER (BACKHAUL IS PART OF THE RAN NOW)

Transparent payloads rely on feeder links between satellites and gateways, often at Ku/Ka/E bands where rain and scintillation can bite. The fix is not a single trick but a bundle: **gateway diversity** across weather patterns, **adaptive coding and power** that step up when clouds arrive,

[1] Values are illustrative and vary with geometry, feeder routing, and processing.

and **buffering/traffic shaping** so short fades do not bubble up to users. Operations should watch feeder health like RAN health, because for NTN they are the same story.

Table 3: Example Feeder-Link Design Levers and Targets

Lever	Typical Target/Note
Gateway diversity	$N \geq 2$ per region with uncorrelated rain zones
Adaptive coding	≥2 fallback profiles within 50 ms switch time
Power control	Limited by EPFD/EIRP masks; prefer coding first
Buffering	Short-fade absorption 200 – 800 ms without head-of-line blocking
Monitoring	Per-beam SNR, FER, and weather overlay in NOC

9 MOBILITY AND THE 5G CORE (KEEP IT ONE NETWORK)

NTN should feel like normal 5G to the **5G Core**. Paging, authentication, policy, slicing, and emergency services must work without special detours. Because beams move, the RAN maps them to stable **service areas** on the ground; the core reasons about those areas as if they were cells that do not wander. For handovers, **Conditional HO** uses time/location triggers and satellite ephemeris so the next cell is armed before it is needed. Cross-border beams require careful PLMN broadcasts and compliance with local emergency and lawful intercept rules. The test of success is operational boredom: the NOC should not need a second playbook just because the radio sometimes looks up.

10 SECURITY BASICS FOR THE SKY (LAYERED AND REALISTIC)

Longer paths and moving coverage change a few security dials. Keys and identities may live longer between refreshes; set timers with real coverage in mind. **GNSS** is helpful but can be jammed or spoofed; add integrity checks and alarms. Wide-area signals can invite jamming; monitor spectrum health and be ready to fall back to profiles that ride through trouble. None of this is exotic—just good hygiene, adjusted for altitude.

11 A PHASED PLAN THAT SHIPS (FROM LAB TO LINE)

Phase 1 — Uplink-first budgets. Model phones, IoT tags, and larger terminals at low elevation with body loss. Choose numerology, uplink bandwidth, repetition, DMRS, and satellite G/T from those numbers. Turn on GNSS pre-compensation and wide search windows on day one so no one “re-does” RACH later.

Phase 2 — Make mobility boring. Pick EMC or EFC on purpose. Use Conditional HO with ephemeris, and map beams to service areas so paging and billing stay sane in the core. Test cross-border behavior early with multi-PLMN broadcasts and emergency call cases.

Phase 3 — Weather-proof feeders. Add gateway diversity; enable adaptive coding/power with tight switching times; buffer intelligently so users do not feel drizzle as packet loss. Instrument the NOC with per-beam SNR/FER and weather overlays.

Phase 4 — Prove coexistence. Model EPFD before hardware is frozen. Design beams and EIRP to pass in each region; tie filings to test plans and share results with regulators and neighbors. Keep the model live as configurations evolve.

Phase 5 — Operational polish. Right-size security timers, add GNSS spoof/jam detection, and rehearse emergency and intercept workflows. Document "runbooks" so handovers, paging, and failovers are muscle memory.

12 DATA BENCHMARKS (SO TEAMS HAVE NUMBERS TO START WITH)

The following tables offer *illustrative* data points you can adapt. They are conservative on purpose and aim to be a safe starting point rather than a record-setting target.

Table 4: Starter Numerology and Timing Profiles (Illustrative)

Profile	Band	SCS	PRACH Win	HARQ Mode
Coverage-first	≤2GHz	15 kHz	Wide	Relaxed (8–12 proc)
Balanced	2 – 4 GHz	30 kHz	Medium	Relaxed (12–16 proc)
Fast-Doppler	≥10 GHz	60 kHz	Medium	Partial-disable + SA

Table 5: NR-NTN Uplink MCS Ladder for Handheld (Illustrative)

Tier	Modulation	Code Rate	Repetition	Target BLER
Very robust	QPSK	1/3	4–8	10 %
Robust	QPSK	1/2	2–4	10 %
Moderate	16-QAM	1/2	2	10 %
Stretch	16-QAM	3/4	1	10 %

Table 6: IoT-NTN Operational Envelope (NB-IoT/LTE-M)

Item	NB-IoT UL BW	Reps	Sleep	Link Budget Gain
Baseline	180 kHz	1×	Minutes	Reference
Deep coverage	180 kHz	8×	Hours	+9–12 dB
Extreme	180 kHz	16×	Days	+12–15 dB

13 COSTS, KPIS, AND WHAT "GOOD" LOOKS LIKE

A white paper should help leaders judge success before the first site is live. For coverage-first NR-NTN, we suggest these **KPIs**: attach success rate > 98 % in open-sky tests; page success

> 97 % within target windows; message delivery > 99 % under light rain at cell center; and smooth degradation under edge geometry with visible repetition engagement. For IoT-NTN, focus on energy per successful report, not raw throughput; the best system wins on battery years, not peak bits. Costs center on payload complexity (transparent vs regenerative), gateway siting and backhaul, spectrum filings, and NOC tooling that watches beams and weather as first-class signals. The cheapest system is the one that is easiest to run, not the one with the largest single link budget on a slide.

Table 7: KPI Starters (Field Acceptance Targets)

KPI	NR-NTN Target	IoT-NTN Target	Notes
Attach success	≥ 98 %	≥ 97 %	Open-sky; device mix
Paging success	≥ 97 %	≥ 96 %	Within agreed window
Msg delivery (light rain)	≥ 99 %	≥ 99 %	Center-of-beam
Energy/report	n/a	≤ 200 mJ	NB-IoT, deep sleep
Service availability	≥ 99.5 %	≥ 99.5 %	With gateway diversity

14 LIMITS TO EXPECT (AND WHY THEY ARE FINE)

Phones are power-limited, so early direct-to-device services will focus on **messaging, alerts, and modest data**. That still delivers huge value in emergencies and remote work. Ultra-interactive apps belong on terrestrial cells; NTN's first job is coverage and resilience, not speed records. **GNSS** is helpful but not universal indoors; devices should try it and fall back gracefully. Feeder-link weather never disappears; we engineer it into invisibility most days. Being honest about limits keeps roadmaps real and helps teams choose where to push next.

15 CASE SNAPSHOTS (CONDENSED AND INSTRUCTIVE)

Rural highway corridor (NR-NTN). Goal: keep standard phones reachable every 5 km along a 400 km stretch. Approach: transparent payload at S-band, EFC beams aligned to geography, GNSS pre-compensation mandatory on UEs, HARQ relaxed with 12 processes. Result: 99 % message delivery under clear sky; 98 % in light rain with two-gateway diversity.

Cold-chain trackers (IoT-NTN). Goal: temperature reports every 30 min with ≥3 years battery life. Approach: NB-IoT, 8× repetition, deep sleep, GNSS-once-per-day for drift control. Result: average 140 mJ/report; ≥99 % delivery in open-sky; indoor handoff to terrestrial NB-IoT where available.

Coastal emergency alerts (mixed). Goal: broadcast alerts to boats within 30 s. Approach: NR-NTN downlink broadcast, IoT-NTN for acknowledgement from beacons, EFC beams over shoreline, feeder diversity across dry microclimates. Result: ≥99 % alert reach; acknowledgements at 95 % within 45 s during heavy rain.

16 WHAT THE RELEASES BRING, IN PRACTICE

Release 17 lets you light up the basics: UE attach, paging, messaging, and early IoT, using standard devices and a 5G Core you already know. **Release 18** smooths coverage and mobility, improves positioning, and reduces operational roughness so scaled deployments are realistic. **Release 19** explores moving more brainpower onto the spacecraft, trimming delay and making the access less sensitive to feeder-link weather, while adding tools that improve uplink and coverage. The theme is steady: start simple, learn in the field, and add sophistication where data says it pays off.

17 WHAT TO DO NEXT (TOMORROW MORNING LIST)

Pick an uplink-honest baseline for handheld and IoT coverage. Tie mobility to geography and ephemeris instead of hoping handovers land on time. Co-design EPFD and reuse before hardware orders. Instrument for jamming, spoofing, and weather so you are never surprised. Write one runbook that covers both the tower and the sky. If you do those few things well, users will just notice that coverage gaps are smaller and that messages arrive when they matter. That is the real point.

Mini-glossary: *NR-NTN* (5G NR via satellites/HAPS for phones); *IoT-NTN* (NB-IoT/LTE-M via satellites for sensors); *CP-OFDM* (downlink waveform); *DFT-s-OFDM* (uplink with lower peaks); *Numerology* (subcarrier spacing dial); *HARQ* (fast retry loop, relaxed in NTN); *GNSS* (timing/location assist, e.g., GPS); *EMC/EFC* (moving vs fixed beams); *EPFD* (satellite coexistence metric); *5GC* (5G Core).

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APPENDIX A: ADDITIONAL DATA TABLES (ILLUSTRATIVE)

Table 8: Beam Geometry and User Elevation Bins (S-band, Illustrative)

Elevation Bin	Notes
> 60°	Best link margin; minimal body loss; short slant.
30 —-60°	Good link; moderate Doppler rate; robust for handheld.
10 —-30°	Challenging; plan repetitions; conservative MCS.
< 10°	Edge cases; consider barge/gateway diversity for service.

Table 9: HARQ and Scheduler Levers for NTN (Per-Traffic-Class Suggestions)

Traffic Class	Suggested Setting
Emergency alerts	HARQ partially disabled; slot aggregation; highest repetition tier.
Messaging/IoT telemetry	Relaxed HARQ (12–16 proc); moderate repetition; periodic scheduling.
Background sync	Best-effort; low repetition; defer under feeder stress.
Interactive voice	Prefer terrestrial when available; otherwise Balanced profile.

Table 10: EPFD Design Hooks to Tune Early

Hook	Practical Note
Beam edge taper	Sacrifice edge EIRP for margin against EPFD masks.
Polarization plan	Align with incumbent patterns to reduce victim coupling.
Gateway siting	Separate by rain zones and GSO arc geometry; reduce worst-case overlap.

Hook	Practical Note
Duty cycle caps	Enforce per-beam duty factors during dense constellation passes.