Mobility Management Enhancements in Non-Terrestrial Networks: A 3GPP Perspective

Shama Noreen[1], Ainur Daurembekova[1], Reiner Stuhlfauth [2] Hans D. Schotten[1,3]

Institute for Wireless Communication and Navigation, University of Kaiserslautern-Landau (RPTU), Germany [1]
Rohde & Schwarz International GmbH, 81671 Munich, Germany [2]
Intelligent Networks, German Research Center for Artificial Intelligence (DFKI), Germany [3]

RPTU Rheinland-Pfälzische Technische Universität Kaiserslautern Landau

Federal Ministry of Education and Research

6G-TakeOff

Introduction

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Mobility Management Challenges in NTNs

- *High propagation delay:* Long signaling delays disrupt timely handovers and updates.
- *Outdated measurement data:* Delayed measurements cause inaccurate handovers in LEO.
- *Weak signal differentiation:* Overlapping beams lead to ping-pong handovers.
- *Dynamic neighbor cells:* Constant satellite movement requires frequent updates.
- *Timing offset:* Propagation delay mismatch affects CSI/SSB detection.
- *ANR limitations:* No direct backhaul hinders satellite neighbor discovery.

Idle Mode Mobility Enhancements

- **Challenges with Tracking Area Update (TAU):**
  - NR TAU is sensitive to satellite-induced delay and beam dynamics.
  - Frequent TAUs can overload the AMF and cause outdated measurement.

- **Solutions for Efficient TAU:**
  - *Predictive Updates:* Leverage satellite orbit data to enable proactive TAUs
  - *Satellite-defined TA:* Moves with the beam, causing frequent updates.
  - *Earth-fixed TA:* Fixed geographic zones decouple TAUs from beam shifts

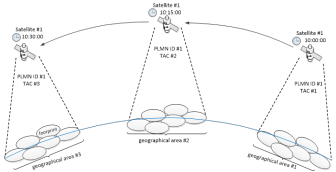

Fig. 1. An example of updating TAC for moving satellite in real-time

Idle Mode Mobility Enhancements

- **Paging Enhancements:**
  - *Optimized Paging Area Grouping:* Clusters TAs to reduce signaling and avoid excessive paging.
  - *Conditional paging triggers:* Use time and location cues to predict UE reappearance.
  - *Reliable Paging:* Maintains delivery despite satellite gaps, e.g., due to beam shifts.
  - *Paging Latency:* Optimizes message timing in GEO/LEO to reduce delay.
  - *Smart Paging Management:* Prioritizes urgent UEs to minimize reconnect congestion.

- **Cell Reselection under NTN Dynamics:**
  - Neighboring cell data is delivered via System Information Blocks (SIBs).
  - LEO satellite movement causes frequent SIB updates and validity concerns.

To handle this, 3GPP introduced: A SIB Validity Timer that informs the UE how long the current system information remains valid — reducing unnecessary reselection attempts while preserving accuracy.

Connected Mode Mobility Enhancements

- **Challenge:** Minimal RSRP differences due to satellite altitude limit the effectiveness of traditional HO triggers.

- **Release 17 Enhancements:**
  - *Event-Based Triggers (A3, A4, A5):*
    - *A3:* Target cell RSRP > Serving cell RSRP + offset.
    - *A4:* Target RSRP > predefined threshold.
    - *A5:* Combines A3 and A4 for robust HO decisions.
  - *Time/Location-Based Triggers:*
    - *T1 (Time-based):* HO triggered if signal condition met within a configured time window.
    - *D1 (Location-based):* Triggered when UE enters a configured proximity to reference points; uses "time to trigger" to avoid flapping.

- **Release 18 Enhancement:**
  - Flexible combinations of triggers: e.g., A4 + T1 or A4 + D1 for context-aware HO.

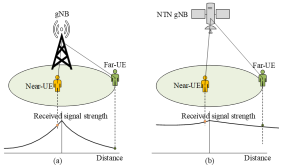

Fig. 2. : A sketch of near-far effect in different scenarios: (a) Terrestrial Network; (b) NTN

Connected Mode Mobility Enhancements

- **Mobility Configuration Enhancements (Rel-18):**
  - *Common Handover Parameters Broadcast:* spCellConfigCommon,enhanced SIB19 to reduce RRC signaling.
  - *Release 18 SIB19 Enhancements:* Include satellite ephemeris, timing advance, and neighbor cell info.
  - *Optimized SIB Transmission:* Uses selective broadcasting and timing control to minimize signaling load.
  - *Indexed Handover Configurations:* UEs apply predefined mobility profiles based on current conditions.
- **Improved Measurement Control (Rel-17):**
  - *Dynamic Measurement Configs:* UEs get adaptive measurement guidance based on satellite movement.
  - *Propagation Delay Compensation:*Timing windows extended to match satellite delays, ensuring accuracy.
  - *Power-Efficient Measurement:* Measurement windows adjust to satellite visibility, conserving UE energy.
  - *Improved Synchronization:*Alignment with moving satellites minimizes handover failures/missed measurem.
- **Proactive Handover Execution:**
  - *Proactive Mobility Management* To address rapid satellite movement and high propagation delays.
  - *Ephemeris data* is used to anticipate beam transitions before signal quality degrades.
  - *Action:* minimizes latency-related risks, avoids frequent ”ping-pong” handovers, improves load balancing.

Feeder Link Switching

Transparent Satellite (gNB on Earth)

- **Different gNBs (via GW1 → GW2):**
  - *Dual Feeder Links (T1.5)*: Satellite relays both gNBs;
    - CD-SSBs from gNB2 use distinct sync raster points to gNB1.
    - **Blind HO** or **CHO**, if measurement based HO than use RTT / Event A5
  - *Single Feeder Link (Hard Switch)*:
    - **CHO with activation time** *Start switching to the new gNB at time T2*
    - **RRC reestablishment via SIB** *If connection drops, try reconnecting to gNB2*
- **Same gNB via different GWs:**
  - *Two Feeder Links*: small or no interruption; may avoid HO.
  - *One Feeder Link*: CTemporary break in downlink signal; fallback to CHO/reestab.

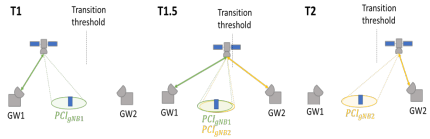

Fig. 3(a). LEO feeder link transition with simultaneous dual gateway support

Fig. 3(b). Single feeder link switch in transparent LEO satellite

Feeder Link Switching

Regenerative Satellite (gNB partially/fully onboard)

- **Full gNB onboard:**
  - Two Feeder Links (Smooth Transition)
    - UE only uses the service link (Uu) — switch is invisible to the UE.
  - One Feeder Link (Temporary Disruption)
    - Satellite must disconnect from Gateway 1 before connecting to Gateway 2.
    - Temporary break in feeder link causes no user scheduling (data paused).
- **gNB-DU on satellite, CU on Earth:**
  - Single Feederlink (CU remains the same)
    - DU briefly loses Earth connection but continues broadcasting system info.
    - UE sees the cell, but no user data is exchanged
  - Single Feederlink (CU changes)
    - DU must disconnect from the old CU and then connect to the new CU
    - Leads to temporary service interruption (Radio Link Failure - RLF).

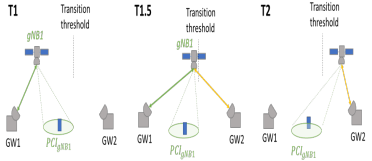

Fig. 4 (a). Feeder link switch in regenerative LEO with onboard gNB using dual gateways for seamless transition.

Impact of Transport Interfaces on Mobility

Seamless mobility in NTN depends on reliable, flexible, and low-latency transport.

- **SRI (Satellite Radio Interface):**
  - *Payload Types:*
    - Transparent: Gateways manage links; soft switch via SRI reduces packet loss.
    - Regenerative: Onboard gNBs require timely NG reconfiguration and proactive mobility handling.
  - *F1 over SRI:* In CU–DU split, high delay across the SRI can cause session loss; mitigated using SCTP multihoming or redundant associations.
  - *Xn over SRI:* Enables gNB coordination via ground gateways; adds delay but supports reliability. Frequent movement in LEO causes XnAP/SCTP churn.
- **ISL (Inter-Satellite Link):**
  - *Satellite-to-Satellite HO:* Regenerative satellites use ISLs for NG/Xn/F1 signaling; 10 ms delay improves handover flexibility.
  - *Backhaul Independence:* Distributing core functions (e.g., AMF, UPF) across satellites with ISL-based routing reduces latency and congestion.
  - *Xn over ISL:* Enables low-latency dual connectivity and fast cell activation across satellites; but increases protocol complexity.

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