5G NTN (Non-Terrestrial Networks)
Satellites for Broadband & Narrowband

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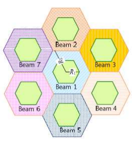
International Mobile Telecommunications (IMT)

- **IMT-2000 (ITU-R M. 1457 – 1st publication 2000)**
  - Technical specifications for satellite Rec. ITU-R M.1850 with 8 radio interfaces (2014)
- **IMT-Advanced (ITU-R M. 2012 – 1st publication 2012)**
  - Technical specifications for satellite Rec. ITU-R M.2047 with 2 radio interfaces SAT-OFDM & BMSat (2013)

SAT-OFDM

Multiple-access scheme	OFDMA (downlink), SC-FDMA (uplink)
Duplex scheme	Frequency division duplexing (FDD)
Sampling rate	A multiple or submultiple of 3.84 Msps
Subcarrier spacing	15 kHz
Carrier spacing	1.4, 3, 5, 10, 15, 20 MHz
Frame length	10 ms
Inter-spot synchronization	No accurate sync. needed (Accurate sync. for inter-beam coordination)
Multi-rate/Variable-rate scheme	Variable modulations and coding rates and multi-layer
Channel coding scheme	Convolutional coding with rate 1/3 Turbo coding with rate 1/3



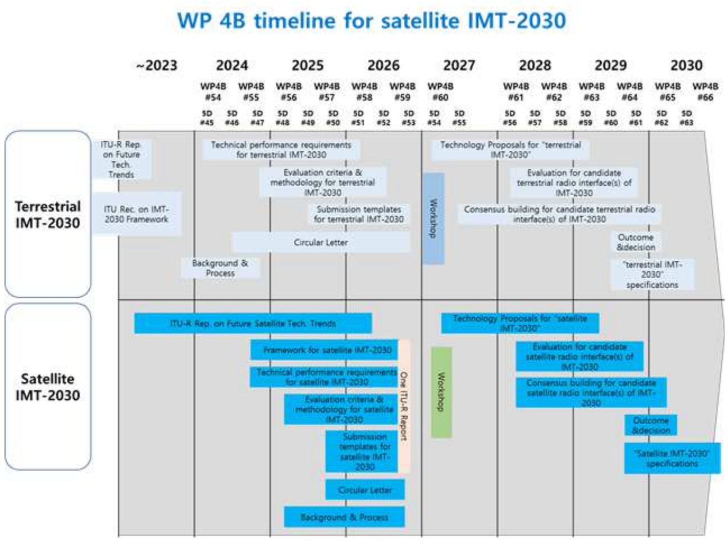
Fractional Frequency Reuse (FFR)

BMSat System

- Conventional OFDM with two low envelope fluctuation transmission modes DFT-spread OFDM (DFTS-OFDM) and offset-modulated single-carrier (OSC)
- 1/3 turbo coding with QPSK, 16QAM, 16APSK
- Bandwidths from 1.4 MHz to 100 MHz
- Carrier aggregation allowing bandwidths larger than 20 MHz with fragmented spectrum allocations
- Channel-dependent scheduling (dynamic), semi-persistent scheduling, and fixed scheduling
- Multi-antenna transmission schemes (spatial multiplexing, transmit diversity in the downlink, autonomous antenna selection diversity in the uplink)

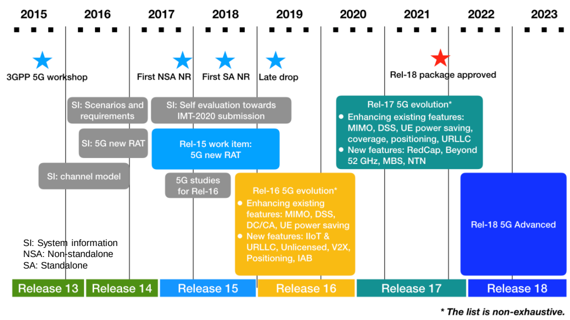
- **IMT-2020 (ITU-R M. 2150 – 1st publication 2021)**
  - Guidelines for satellite radio interface(s) of IMT-2020 Rec. ITU-R M.2514 (2022)

IMT-2030



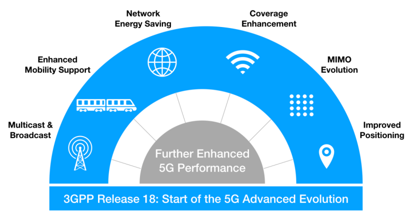
Proposed Work Plan for the Future Development of Satellite IMT-2030, ITU-R 56, April 2024

5G Roadmap



6G Workshop
March 2025

RAT: Radio Access Technology
NR: New Radio
MIMO: Multiple-Input Multiple-Output
DSS: Dynamic Spectrum Sharing
DC/CA: Dual Connectivity / Carrier Aggregation
IIoT: Industrial Internet of Things
URLLC: Ultra Reliable and Low Latency Communications
V2X: Vehicle-to-Everything
IAB: Integrated Access Backhaul
MBS: Multicast and Broadcast Services
NTN: Non-Terrestrial Network

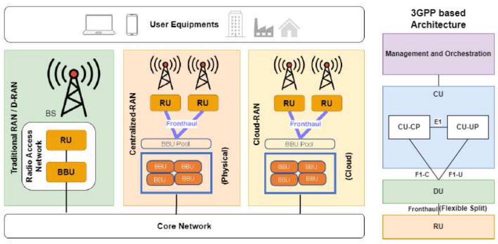


R19 started in 2024
AI/ML, Duplex,
Wake-Up Signal,
Wake-Up Receiver…

An Overview of 5G Advanced Evolution in 3GPP Release 18, X. Lin, Ericsson, 2022

5G System Components

- **User Equipment (UE)**
  - Mobile devices
- **5G Core Network (5GC)**
  - Separation of control (authorization and mobility management) and user (data forwarding, QoS...) planes allowing Network Function Virtualization, Network Slicing, Edge Computing
- **5G Radio Access Network (RAN)**
  - gNB base stations (Base Transceiver Station in 2G, Node B in 3G, eNB in 4G) to connect 5G Core and provide 5G protocol to UE, Integrated Access Backhaul (IAB) using gNB radio resources for backhauling



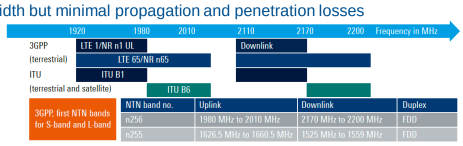
Centralized or Cloud RAN split
Radio Unit (RU) / Base Band Unit (BBU)
Horizontal and Vertical functional splits
H: Distributed Unit (DU) / Central Unit (CU)
V: Control Plane (CP) / User Plane (UP)
AI into RRM
RAN Intelligent Controller (RIC)
Open RAN
Open interfaces for multivendor environment

Source: A Survey on Open Radio Access Networks: Challenges, Research Directions, and Open Source Approaches, W. Azariah & all, Sub. IEEE CST, 2022

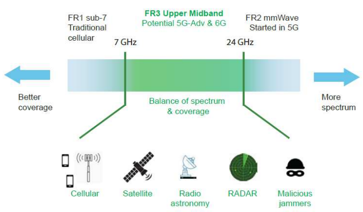
- **Data Network**
  - Application functions (services trusted by the operator) and user functions (Internet or other networks)

5G Frequency Bands

- **FR1: Traditional cellular frequency bands <7.125GHz**
  - Limited bandwidth but minimal propagation and penetration losses



- **FR2: Millimeter wave (mmWave) >24GHz**
  - Massive multi-Gbps peak rates on an often intermittent and limited coverage
- **FR3: Upper Midband (for WRC-27)**
  - Good balance of coverage and bandwidth



Ku-band
10.7-12.75GHz ⇧
12.75-13.25GHz ⇩
13.75-14.5GHz ⇩
Ka-band (GEO)
17.3-20.2GHz ⇧
27.0-30.0GHz ⇩
Ka-band (Non-GEO)
17.7-20.2GHz ⇧
27.0-29.1GHz ⇩
29.5-30.0GHz ⇩
Q/V-band
37.5-42.5GHz ⇧
47.5-47.9GHz ⇧
48.2-48.54GHz ⇧
49.44-50.2GHz ⇧
42.5-43.5GHz ⇩
47.2-50.2GHz ⇩
50.4-52.4GHz ⇩

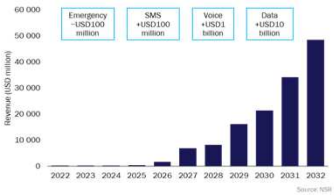
5G NTN Users

	Direct connectivity (< 7 GHz)		Indirect connectivity (above 10 GHz)
Targeted terminals	IoT devices	handset (smart phones) and car/drone mounted devices	VSAT and/or ESIM
Service	Narrowband hundreds of kbps	Wideband few Mbps	Broadband hundred Mbps
Orbit	GSO and NGSO	NGSO	GSO and NGSO
3GPP Radio interfaces	4G NB-IoT/eMTC	5G New Radio	5G New Radio
Example of applications	Professional : utilities (smart grids, water distribution, oil & gas), agriculture	Consumer market Professional markets : Automotive, public safety, utilities, agriculture, Defense	Professional markets: Telco (e.g. Backhaul), IPTV service providers, Satellite News Gathering, Transport (aeronautical, maritime, railway), public safety, defense

NB-IoT: NarrowBand - Internet of Things / eMTC: enhanced Machine Type of Communications
VSAT: Very Small Aperture Terminal / ESIM: Earth Station In Motion

Usage scenarios	Experience data rate DL	Experience data rate UL	Max UE speed	Environment	UE categories
IoT connectivity	2 kbps	10 kbps	0 km/h	Extreme coverage	IoT
Pedestrian	2 Mbps	250 kbps	3 km/h	Extreme coverage	Handheld
Public safety	3.5 Mbps	3.5 Mbps	100 km/h 250km/h	Open area	Handheld Vehicle mounted
Stationary	50 Mbps	25 Mbps	0 km/h	Extreme coverage	Building mounted
Vehicular connectivity	50 Mbps	25 Mbps	250 km/h	Along roads in low population density areas	Vehicle mounted
Airplanes connectivity	360 Mbps	180 Mbps	1000 km/h	Open area	Airplane mounted

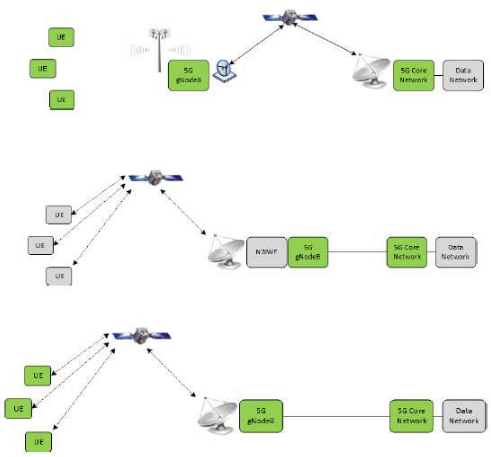
3GPP TR 22.261 and 38.821



Analysis Mason, March 2024

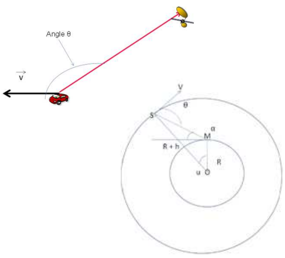
5G NTN Architectures

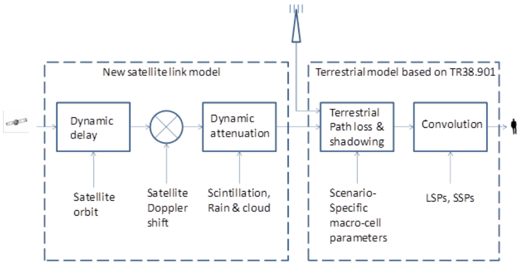
- **Satellite backhauling**
  - Existing satellite air interfaces (as DVB) to link 5GC to gNB
  - Further integration of satellite backhauling into 5G system in R18
- **Satellite non-3GPP access network**
  - Satellite access network connected to 5GC via an interworking function
  - Non-3GPP interworking functions (N3IWF) specified in R15
- **Satellite 3GPP access network**
  - UE connected to Evolved Packet Core by eMTC/NB-IoT access based on satellite access nodes in R17
  - UE connected to 5GC by NR access based on satellite access nodes in R17



5G NTN Channel

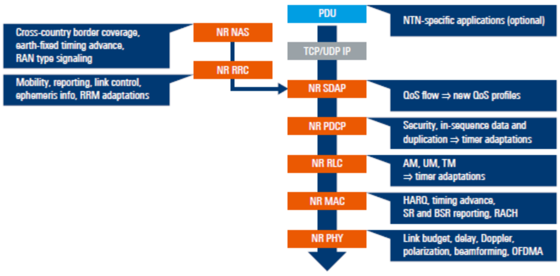
- **Unobstructed link**
  - Line-of-sight (LOS) between the UE and satellite depending on elevation and situation (urban, suburban, rural)
  - Diffuse multipath (non-LOS) with low delay spread due to multipath propagation versus absolute delay
  - Free space path loss, Rain&Cloud attenuation (>6GHz), Scintillation (ionospheric<6GHz, tropospheric>10GHz)
  - Signal depolarization (Faraday rotation)
  - Second-order dynamic effects taking into account fade slope&duration, LEO movement, Doppler shift
- **Doppler shift $f_c v cos(\theta)/c$**
  - f_c carrier frequency, v mobile* velocity, θ angle between mobile* velocity vector V and signal propagation direction (mobile: satellite and/or UE)





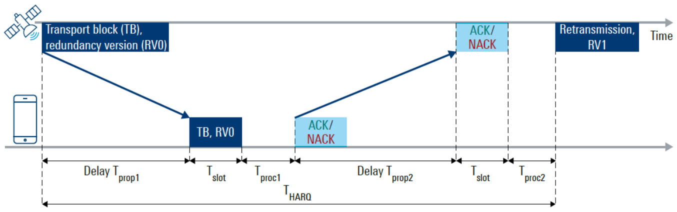
5G NTN Protocol Stack with New Radio (NR)

- **TCP-UDP/IP based on Next Generation Radio Access Network (NG-RAN)**
  - Non-access stratum (NAS): Protocol for dialogue between 5GC and UE
  - Radio resource control (RRC): Configuration of user and control planes, Radio Resource Management (RRM)
  - Service data adaptation protocol (SDAP): Mapping between QoS flows and data radio bearers
  - Packet data convergence protocol (PDCP): Provisioning, Discard functions, Dispatching, Ciphering, Duplication
  - Radio link control (RLC): 3 transport modes (UM: Unacknowledged, AM: Acknowledged, TM: transparent)
  - Medium access control (MAC): Random access (RACH), Discontinuous reception (DRX), Timing advance (TA), scheduling request (SR), Hybrid automatic repeat request (HARQ)



5G NTN and MAC Layer

- **Procedures impacted by longer latency**
  - Random Access taking 2 (or 1) round trip delays redesigned in R17
  - Acquisition window enlarged because of larger differential delays between users
  - Extension of the number of existing HARQ processes to 32 processes in R17
  - HARQ feedback shifted to higher layers, e.g. RLC AM (Radio Link Control Acknowledged Mode)
  - New configuration of automatic retransmission, e.g. TTI (Transmit Time Interval) bundling features

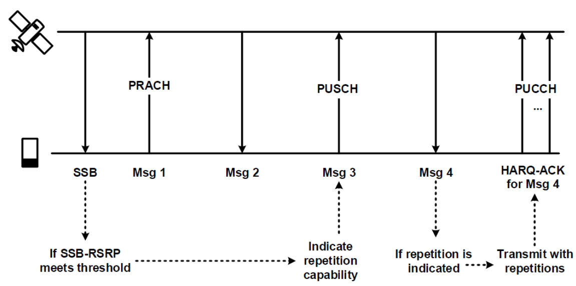


Constellation	T_{HARQ} max.	No. of HARQ processes	UE side feasibility
Terrestrial	16 ms	16	Rel. 15
LEO	50 ms	50 theoretically, 3GPP agrees to 32	HARQ extension
GEO	600 ms	600 theoretically	For future study

Assumption: 15 kHz SCS and 1 ms slot duration [TR 38.811]

5G NTN takes flight: Technical overview of 5G non-terrestrial networks, Rohde & Schwartz White Paper, 2022

5G NTN and Random Access



- **Four-step message exchange**
  - Msg1: PRACH (Physical Random Access CHannel), Repetition to be added in R18
  - Msg2: PDCCH (Physical Downlink Control CHannel)
  - Msg3: PUSCH (Physical Uplink Shared CHannel), Repetition in R17 based on SSB-RSRP (Synchronization Signal Block - Reference Signal Received Power)
  - Msg4: PDSCH (Physical Downlink Shared CHannel)
  - Msg4 HARQ (Hybrid Automatic Repeat request) ACK / PUCCH (Physical Uplink Control CHannel), Repetition added in R18

Non-Terrestrial Networks: Coverage Enhancement in 3GPP Rel-18, G. Prasad, Ofinno, 2023

5G NTN and 5G NR Physical Layer

- **Frequency bands in Frequency Division Duplex (FDD)**
  - S/L in R.17: n255 (UL:1.6265-1.6605GHz, DL: 1.525-1.559GHz), n256 (UL: 1.98-2.01GHz, DL: 2.17-2.20GHz) S/L/Ka in R.18: (UL: 1.61-1.6265GHz, DL: 2.4835-2.5GHz), n510-n512 (UL: 27.5-30GHz, DL: 17.7-20.2GHz)
  - Ku in R.19 (TBC)
- **Physical layer with lower signal-to-interference-and-noise-ratio (SINR) operating points**
  - Reed-Muller codes and CRC assisted polar codes for control channels and LDPC for data channels
  - BPSK/QPSK/16QAM/64/256QAM in DL and UL (π/2 BPSK in UL for reduced PAPR and IoT)
  - OFDMA for DL and UL with SC-FDMA as an option for UL
  - 5/10/15/20MHz with 15/30/60kHz of Subcarrier spacing (SCS)
  - Timing advance autonomous estimation using UE's GNSS capability in addition to satellite ephemeris in R17
- **Performance requirements over a 30MHz carrier for a LEO 600km constellation**
  - 53.3kHz of typical Doppler shift for f_C=2GHz and v_{LEO}=8km/s (~vf_C/c)
  - Peak data rates of 70Mbps at 3bps/Hz (DL) and 2Mbps at 1.5bps/Hz (UL)
  - DL and UL area traffic capacity of 8kbps/km2 and 1.5kbps/km2
  - 500devices/km2 in massive Machine-Type Communications (mMTC)
  - Reliability of 99.9% and latency >10ms for Enhanced Mobile Broadband (eMBB)
  - No Ultra-Reliable Low Latency Communications (URLLC) asking for extremely low latency (1ms) and high reliability

5G NTN and Synchronization

- **Synchronization needs**
  - Inter-Symbol Interference (ISI) in case of time misalignment above the Cyclic Prefix (CP) length
  - Inter-Carrier interference (ICI) increasing in function of the frequency misalignment

Numerology μ	SCS [kHz]	CP [us]
0	15	4.69
1	30	2.34
2	60	1.17
3	120	0.59
4	240	0.29

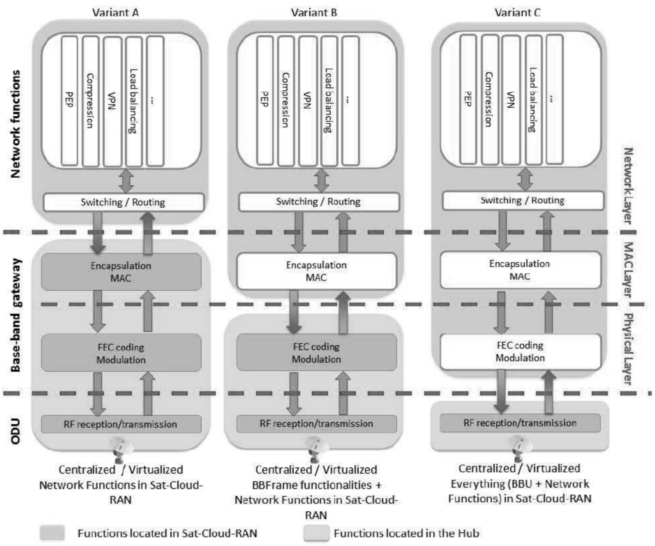
Relative SCS offset [%]	ICI level [dB]
0.5	-41.5
1	-35.5
2	-29.5
5	-21.5
10	-15.5

  - Maximum speeds and accelerations for the different profiles

Label	a $[m/sec^2]$	v $[m/sec]$	Remark
CircAero1	3	300	Circular movement 0.7 to 1.3 G commercial flight
CircAero2	10	100	Circular movement 0 to 2 G with maritime speed
CircAero3	10	300	Circular movement 0 to 2 G with aero speed
CircAero4	100	2400	Circular movement Extreme 10G and Mach7
MaxAero1	3	300	Abrupt a changes 0.7 to 1.3 G commercial flight
MaxAero2	10	100	Abrupt a changes 0 to 2 G with maritime speed
MaxAero3	10	300	Abrupt a changes 0 to 2 G with Aero speed
MaxAero4	100	2400	Abrupt a changes Extreme 10G and Mach7
LeoLow	130	8000	Low altitude (400km) zenital LEO pass
LeoHigh	27	5500	High altitude(1500km) zenital LEO Pass

- **Time and frequency offsets compensation**
  - Use of GNSS and satellite orbit information (R17) with constraints on availability, power consumption, logon time
  - Terminal clocks slaved to the downlink without hub feedback messages only possible for very accurate clocks
  - Loop logic in the terminal with offset compensation estimated by the hub in time (as 5G-NR Timing Advance mechanism) and frequency (as in DVB-S2X/RCS but not with first order closed loops for a better accuracy)

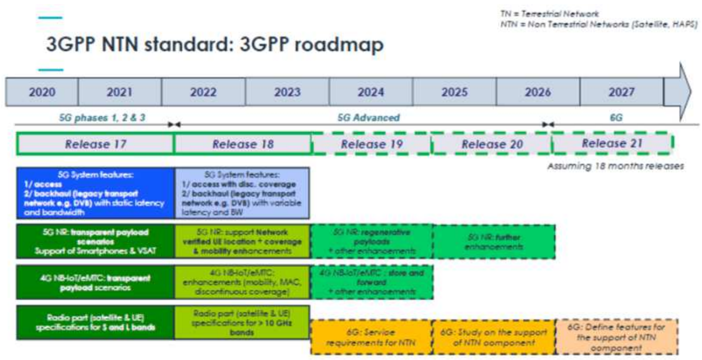
5G NTN Ground Segment Virtualization



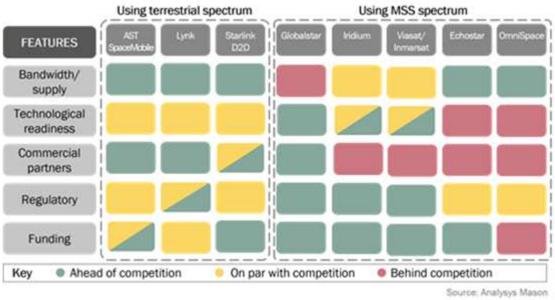
Analyzis based on Cloud-RAN for terrestrial mobile access

5G NTN Standardization Schedule

- 3rd Generation Partnership Project (3GPP) proposed NTN for un/underserved areas
  - R15 TR 38.811: NTN deployment scenarios and related system parameters
  - R16 TR 38.821: Features/Adaptations to operate the New Radio (NR) protocol in NTN
  - R16 TR 22.822: Use cases of satellite access in 5G (roaming, broadcast/multicast, IoT…)
  - R17: Access, Backhaul with static latency and bandwidth, Transparent payload scenarios, S/L radio
  - R18: Access, Backhaul with variable latency and bandwidth, NR and IoT enhancements, Ku/Ka radio



Satellite Systems for Mobile Devices

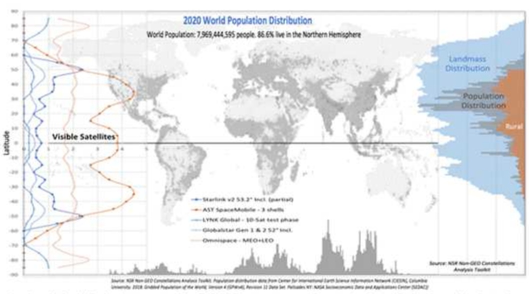


- **Apple (USA) and Globalstar (USA) launched in Nov. 2022**
  - One-way emergency messaging when no cellular or Wi-Fi service is available (SOS feature for iPhone 14)
- **Bullitt (UK) with Inmarsat (UK) and Echostar (US)**
  - SOS, two-way messaging, location sharing, Android Smartphone with MediaTek/Skylo chips and Bullit App
- **eSAT Global (USA) with Inmarsat (UK) and Yahsat (Saudi Arabia)**
  - Two-way texting, IoT vertical markets, chipsets of smartphones to be modified
- **BeiDou (China)**
  - Short text messages, one-way messaging, two-way messaging with Huawei and ZTE smartphones

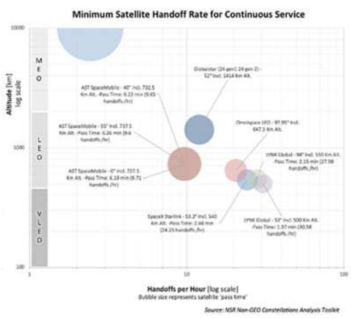
Comparison of 5G NTN NR Constellations

System	Orbit Type	Altitude [km]	Inclination [degrees]	Orbital Planes	Satellites per Orbital Plane	Satellites in Shell	Handheld Minimum Elevation Angle [degrees over the horizon]	Orbital Period [minutes]	Satellite Field of View (FoV) [sq.km]	Satellite Coverage Radius [km]	Maximum Latitude Reached [degrees N/S]
SpaceX Starlink	Inclined	540	53.2	36	11	396	40	95	999,647	564	58
AST SpaceMobile	Equatorial	728	0	1	18	18	20	99	6,047,264	1,379	12
AST SpaceMobile	Inclined	733	40	10	15	150	20	99	6,108,373	1,386	53
AST SpaceMobile	Inclined	738	55	5	15	75	20	99	6,169,593	1,393	68
LYNK Global	Polar	550	98	2	2	4	45	96	748,118	488	90
LYNK Global	Inclined	500	53	1	6	6	45	95	630,962	448	57
Globalstar (24 gen1; 24 gen 2)	Inclined	1,414	52	8	6	48	45	114	3,604,003	1,067	62
Omnispace MEO	Inclined	10,111	44.91	3	5	15	40	351	40,629,204	3,450	78
Omnispace LEO	Polar	648	97.95	10	20	200	40	98	1,370,936	660	90

Source: NSR Non-GEO Constellations Analysis Toolkit 3.0 (NCAT3)

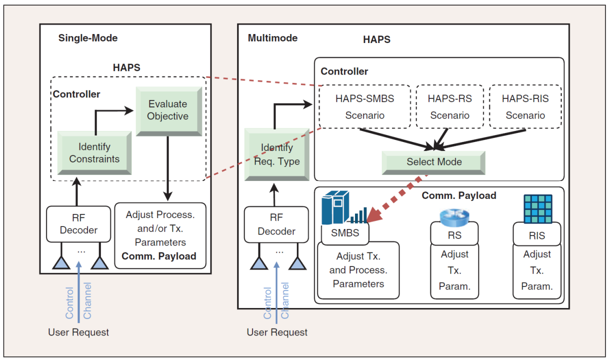


Rural population defined as lower or equal than 300 inhabitants per square kilometer. Landmass distribution excludes Antarctica



5G NTN for High-Altitude Platform Stations (HAPS)

- **Main parameters**
  - Length of 100-200m with wingspans of 35-80m
  - Altitude ~20 km with footprint radius 40-100 km
  - Operation mode: Super Macro Base Station (SMBS) / Relay Station (RS) / Reconfigurable Intelligent Surface (RIS)

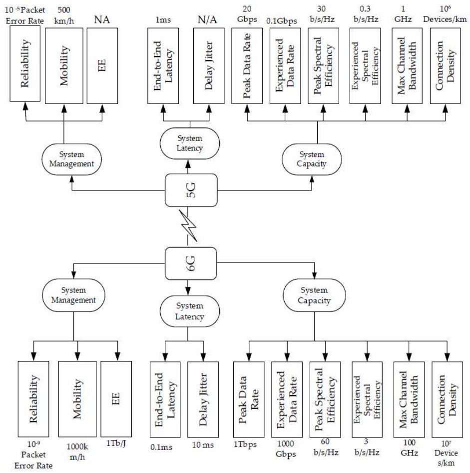


Multimode high-altitude platform stations for next-generation wireless networks,
S. Alfattani & all, IEEE Vehicular Technology Magazine, September 2023

From 1G to 6G

- **"1G short, and 2G long, 3G short, and 4G long"**
  - 2G best solution for voice mobile communication though voice was early defined in 1G
  - 4G best solution for mobile internet though mobile internet was early defined in 3G
  - 70% of the worldwide population, 20% of the global land area, less than 6% of the Earth's surface
- **5G specification and development**
  - 1st papers in 2013, key technologies identified in 2015, standards In 2017/18, pre-commercial networks in 2019
  - 3 scenarii and 8 key performance indexes (eMBB in Gbps, mMTC for 1M/km2 connexions, URLLC in ms…)
  - Wireless technologies: massive MIMO, advanced coding and modulation, mmWave communication, non-orthogonal multiple access, ultra-dense networking, dual connectivity architecture, flexible frame structure…
  - Network technologies: network slicing, multi-access edge computing (MEC), software defined network (SDN), network function virtualization (NFV), customized mobility, service based architecture…
  - 5G NR standardization for eMBB and URLLC, but not for mMTC (based on LTE NB-IoT)
- **Ubiquitous Intelligent Mobile Society**
  - 6G to be the best solution for Internet of Everything (IoE) and vertical applications (vehicles, industry…)
  - 3 scenarii (high fidelity holographic society, connectivity for all things, time sensitive & engineered applications)
  - Higher frequency bands and channel modelling, physical layer optimization, ubiquitous and integrated network with broader and deeper coverage merging communication, sensing, navigation, and computation data

5G vs. 6G



6G Enabled Smart Infrastructure for Sustainable Society: Opportunities, Challenges, and Research Roadmap
A. L. Imoize & all, Sensors, March 2021

6G NTN Technology Directions

6G NTN versus 5G NTN: possible performance targets (TBC)

Target service performances	NTN in 5G (As per 3GPP &/or ITU-R IMT2020 satellite requirements)	NTN in 6G
Peak data rate (DL/UL) wrt Handheld	1/0.1 Mbps (Outdoor only) @ up to 3 km/h	Outdoor conditions: Tens of Mbps @ up to 250 km/h
Peak data rate (DL/UL) wrt Vehicle or drone (flying and surface) mounted devices	[50/25] Mbps @ up to 250 km/h (with 60 cm aperture)	Hundreds of Mbps (Outdoor only) @ up to 250 km/h
Peak data rate (DL/UL) wrt Large Aeronautic, maritime platforms mounted devices	[360/180] Mbps @ up to 1000 km/h	Thousands of Mbps (Outdoor only) @ up to 1200 km/h
Location service (target accuracy and acquisition time) in outdoor conditions only	respectively 1 meter and < 100 seconds (reliability through Network verification)	Respectively 1 meter and < 1 second (95% reliability through Network based positioning method)
Coverage	Outdoor only	Light indoor/In car conditions: At least Short Message Service capability
Reliability	up to 99.9% ($1-10^{-3}$)	up to 99.999% ($1-10^{-5}$)
Over the air Latency for eMBB-s and uRLLC-s	Control plane: 40 ms User plane: 10 ms	Control plane (propagation delay excluded): same as IMT-2030 terrestrial Radio Interface User plane (propagation delay excluded): same as IMT-2030 terrestrial Radio Interface
Connection density	Up to 500 per km2	>1000 per km2

- **Integrated network architecture & TN/NTN frequency sharing**
  - 3D heterogeneous network, with hierarchical control framework for layers having different coverage and quality
  - Interference reduction (space or angle isolation) and co-existence (scheduling-based interference coordination)
- **Service continuity & coverage**
  - Overhead to be minimized for conditional handover (CHO) using location/time-based triggered events
  - Beam footprint size to be adapted by controlling the number of satellite active antenna elements
- **Better link budget & On-Board Processing**
  - High Peak-to-Average Power Ratio (PAPR) and Out of band (OOB) in case of OFDM to be reduced
  - Functional split of Distributed Unit (DU) of the gNB on the satellite payload and Central unit (CU) on the ground