Mobility for 5G NTN: Performance and Challenges of NTN over Mobile Channels

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Nicolò Mazzali, PhD (nicolo.mazzali@ext.esa.int)
Riccardo Tuninato, PhD (riccardo.tuninato@ext.esa.int)
ESA/ESTEC TEC-SEC

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Roadmap

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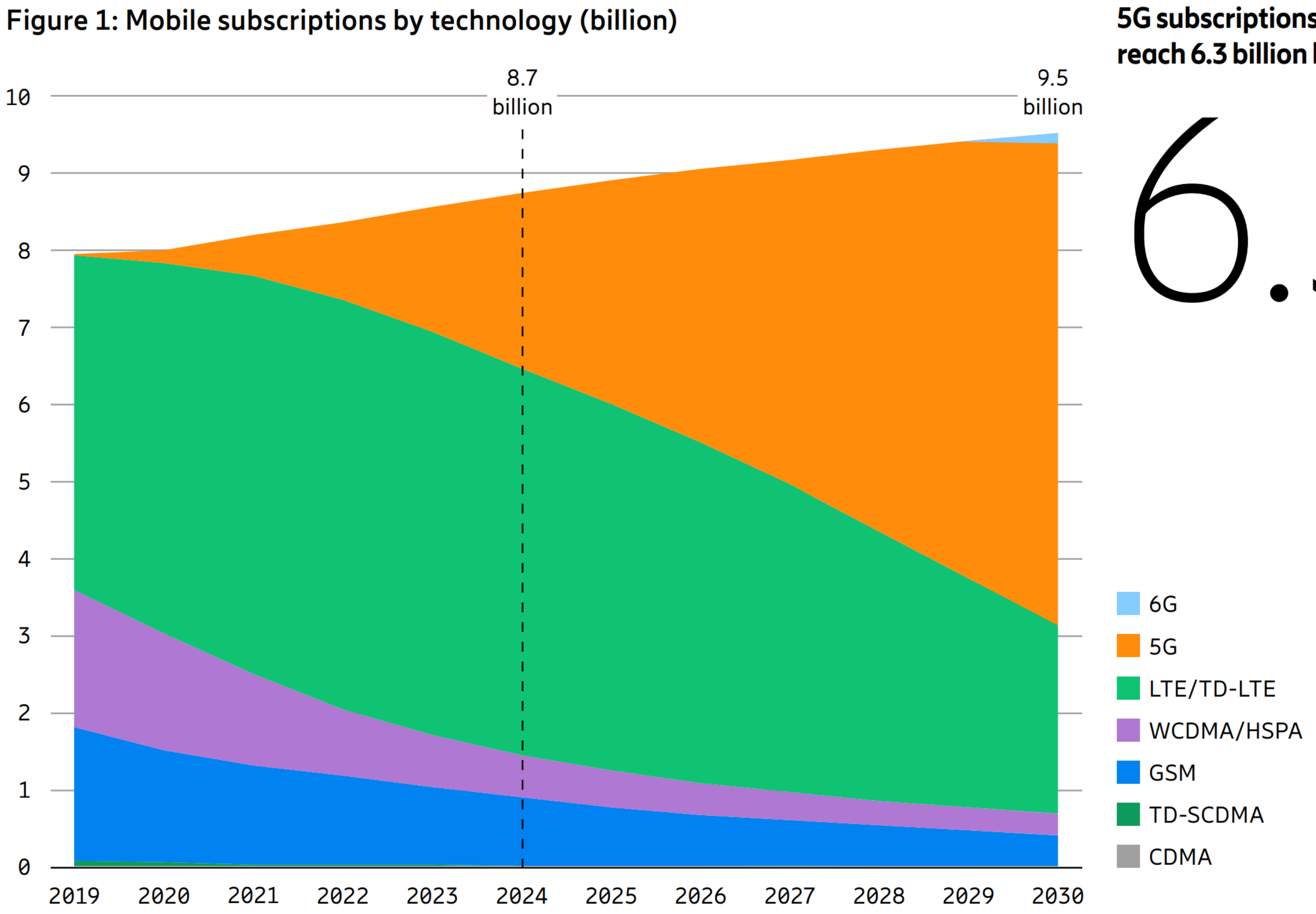
Introduction to 5G NTN

Mobility for 5G NTN: Performance and Challenges of NTN over Mobile Channels

5G today and next years forecasts

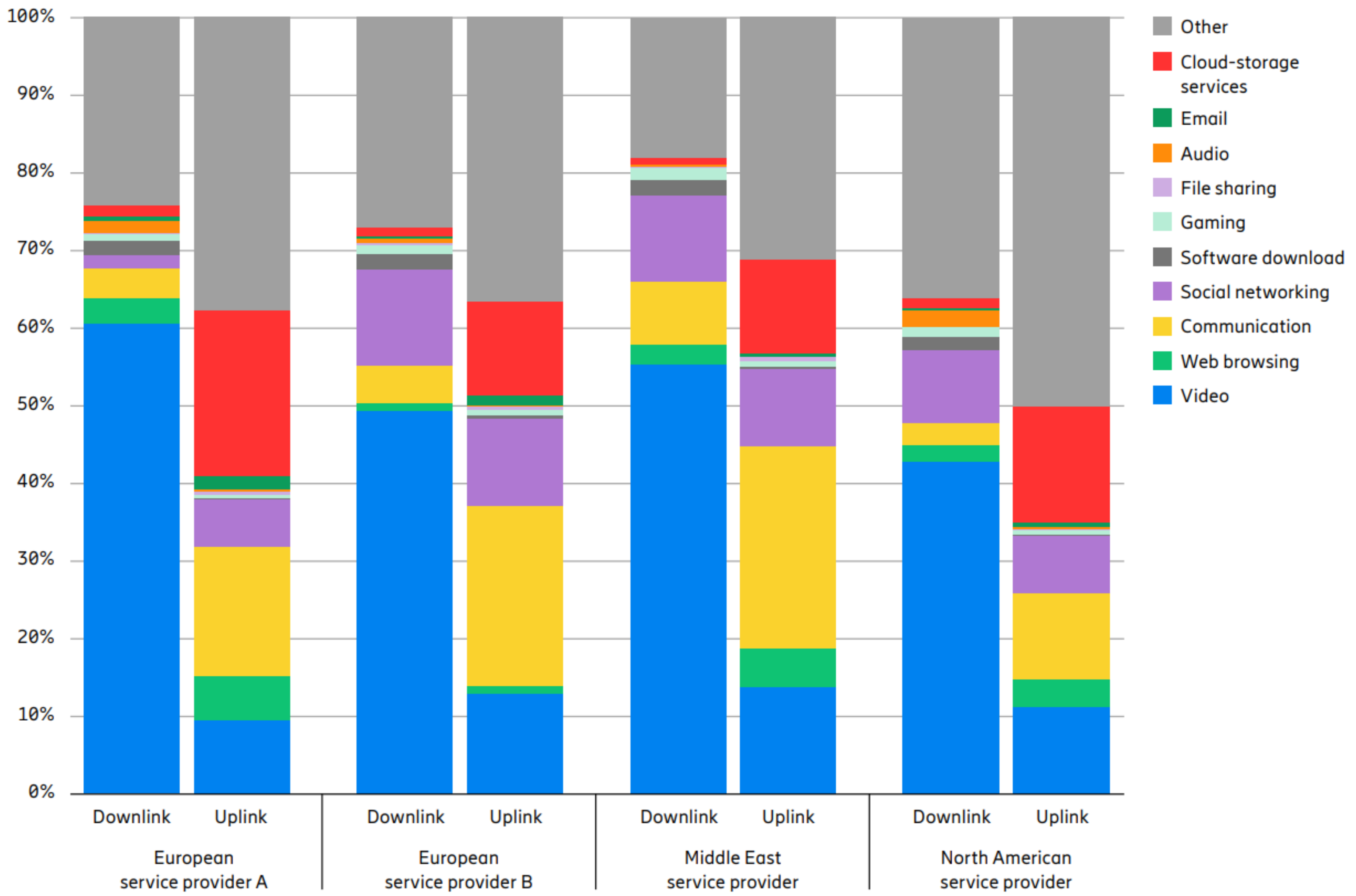


5G subscriptions are forecast to reach 6.3 billion by the end of 2030.

6.3bn

Ericsson, "Ericsson Mobility Report", November 2024

New technologies and traffic share



Ericsson, “Ericsson Mobility Report”, November 2023

Space for pervasive 5G coverage

Since commercial deployment began in 2019, 5G coverage has increased to reach 40% of the world population in 2023

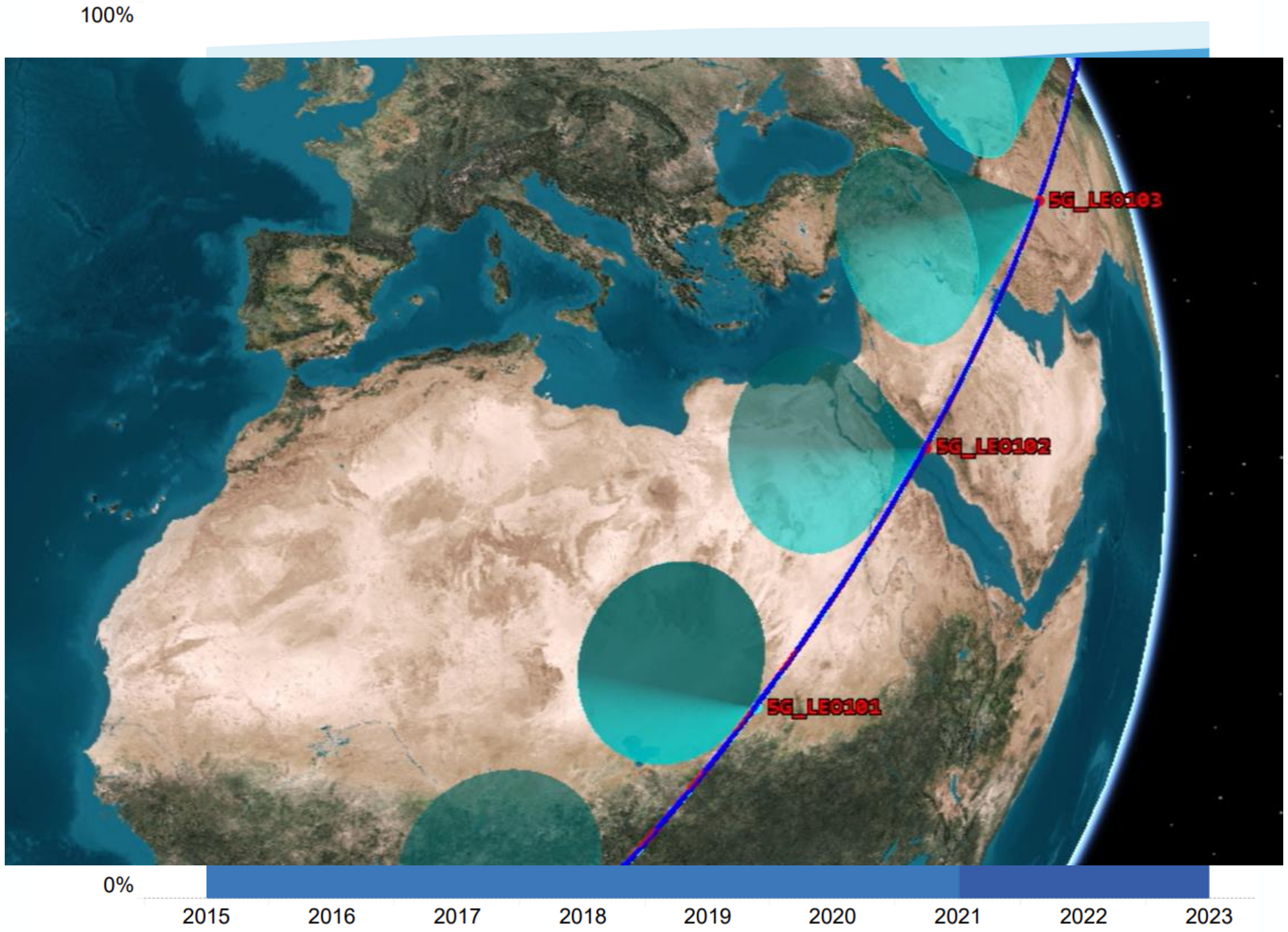
Distribution, however, remains very uneven

- 89% of the population in high-income countries is covered by a 5G network
- Coverage remains limited in low-income countries

Main obstacles to 5G deployment and adoption

- **high infrastructure costs**
- device affordability
- regulatory barriers

Moreover, about one-third of the global population, or 2.6 billion people, remain offline



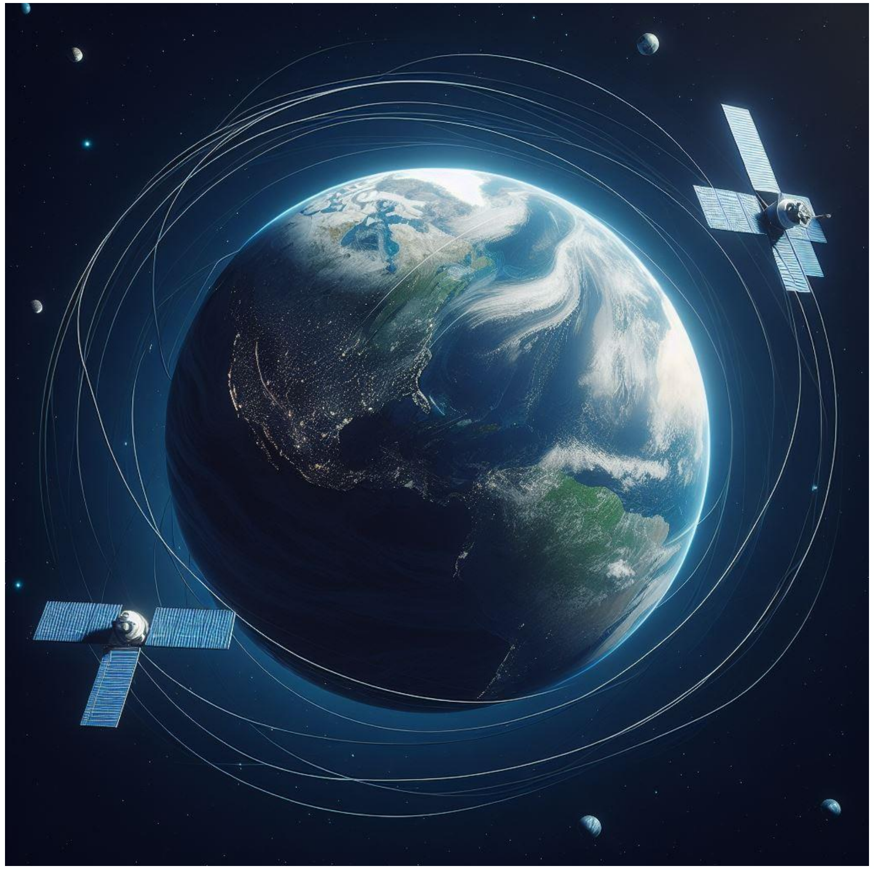
ITU, “Measuring digital development Facts and Figures”, 2023

Non-Terrestrial Network for 5G

3GPP Rel-17 and Rel-18 introduce solutions enabling New Radio to support **Non-Terrestrial Networks (NTN)**

Wide service coverage capability and reduced vulnerability of space vehicles to physical attacks and natural disasters

- Provide **5G service** in **un-served** (isolated/remote areas, on board aircrafts or vessels) or **under-served areas** (e.g. sub-urban/rural areas)
- Reinforce the 5G service **reliability**
    - service continuity for IoT devices or for passengers on board moving platforms
    - critical communications
    - future railway/maritime/aeronautical communications
- Enable 5G network **scalability** by providing efficient multicast/broadcast resources for data delivery towards network edges or even user terminal



5G NTN use cases and scenarios

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Use cases of 5G

Enhanced Mobile Broadband (eMMB)

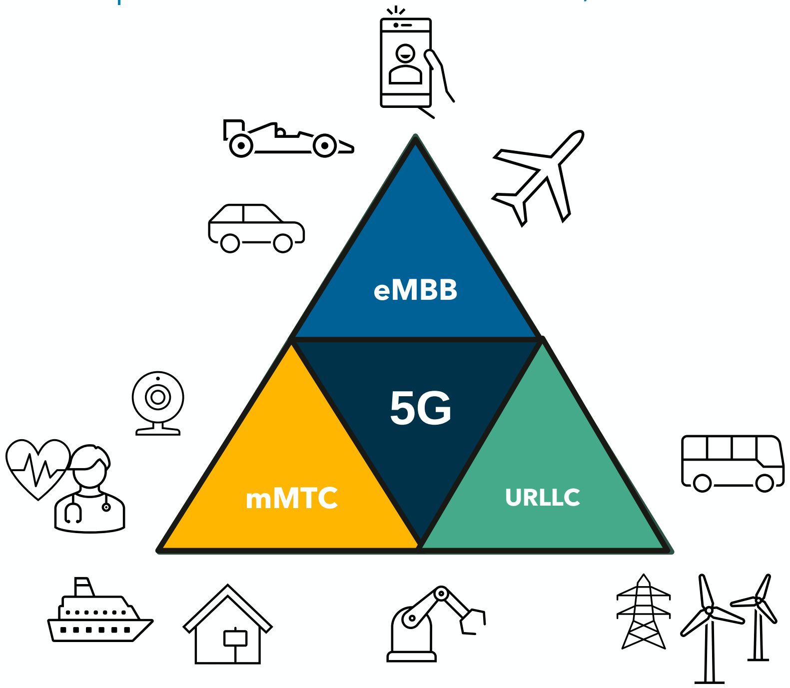
1. Very high system data rates: peak data rates from Gbit/s/km2 up to several Tbit/s/km2 and user data rate of several Mbit/s up to 1 Gbit/s
2. Support to user mobility: Broadband services for devices in high speed vehicles, high speed trains and airplanes
3. Handle different user density: From rural macro up to dense macro scenarios, in broadband access in a crowd

- High quality video streaming
- Virtual reality

massive Machine-Type Communications (mMTC)

1. Scalability to comply very high device density up to million devices/km2
2. Low latency, crucial for timing critical applications
3. Energy efficiency to reduce power consumption of devices, limited by batteries

- Smart home / Smart Cities
- Health care monitoring



Ultra-Reliable Low Latency Communications (URRLC)

1. Ultra-low latency End-to-end latency of few to tens ms
2. Extreme high reliability. For remote control of process automation, a reliability of 99.9999%

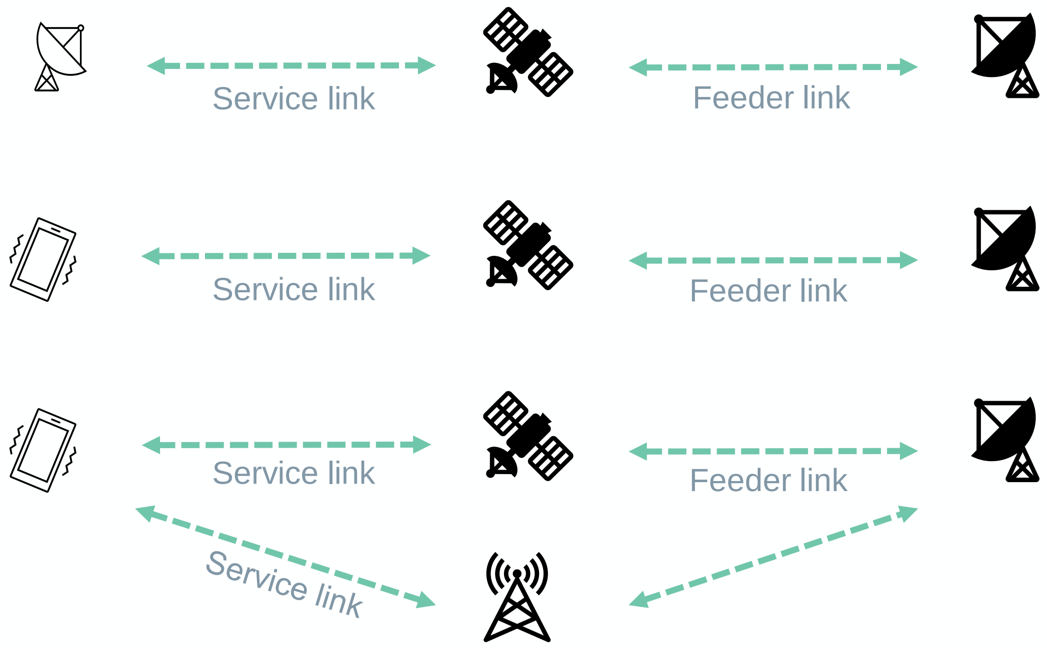
- Public safety
- Autonomous driving

The concept that sum up the main objective of 5G is **flexibility,** to deal with very different use cases and scenarios, that are characterized by very different requirements and systems

The use cases of 5G NTN - eMBB

eMBB

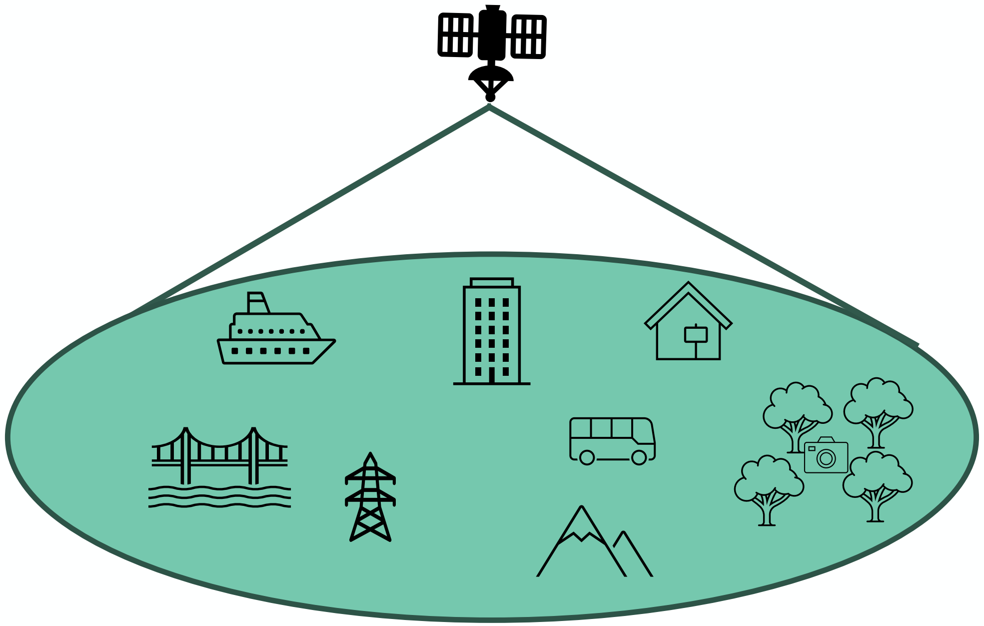
- Users in isolated villages or remote areas
- Passengers on board vessels or aircrafts
- Critical network links as primary or secondary connection
- Live broadcast, ad-hoc broadcast/multicast streams
- Backhauling support for underserved areas with limited user throughput



The use cases of 5G NTN - mMTC

mMTC

- Wide area IoT service: Global continuity of service for telematic applications based on a group of sensors/actuators;
  - Automotive and road transport, Energy distributions infrastructures, agriculture
- Local area IoT service: Group of sensor that collect local information, connect to each other and report to a central point



Orbits delays and applications

- Critical communications < 20 ms
- Online gaming < 50 ms
- Online meetings < 100 ms
- Phone calls < 150 ms
- Cloud storage > 100 ms
- Sensors (non critical) > 100 ms
- Streaming > 100 ms

Orbit [km]	Propagation delay user-satellite [ms]		Latency*
	Elev. 90 deg	Elev. 30 deg	
LEO 600 km	2.00	3.59	~ 20-40 ms
LEO 1200 km	4.00	6.665	
MEO 8000 km	26.66	33.86	
GEO 35,786 km	119.3	128.71	**~ 600 ms**

*End-to-end values from ReliaSat

3GPP frequency bands for NTN

L-band at 1.6 GHz (n255) and **S-band** at 2 GHz (n256), plus a mixed L/S-band (n254), FDD

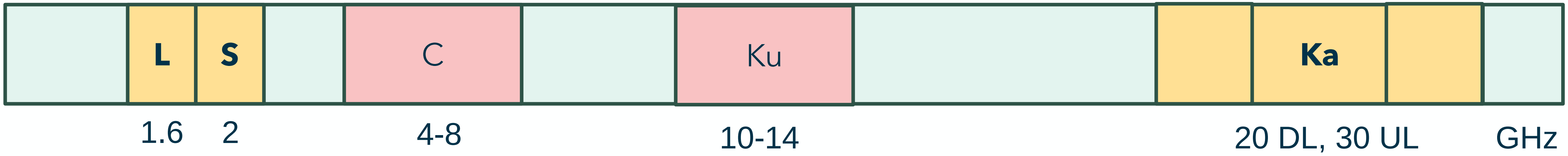
- Min 5 MHz, max 30 MHz transmission bandwidth (FDD)
- Handheld and IoT devices

Ka-band at DL 20 GHz UL 30 GHz (n510 n511 n512), FDD

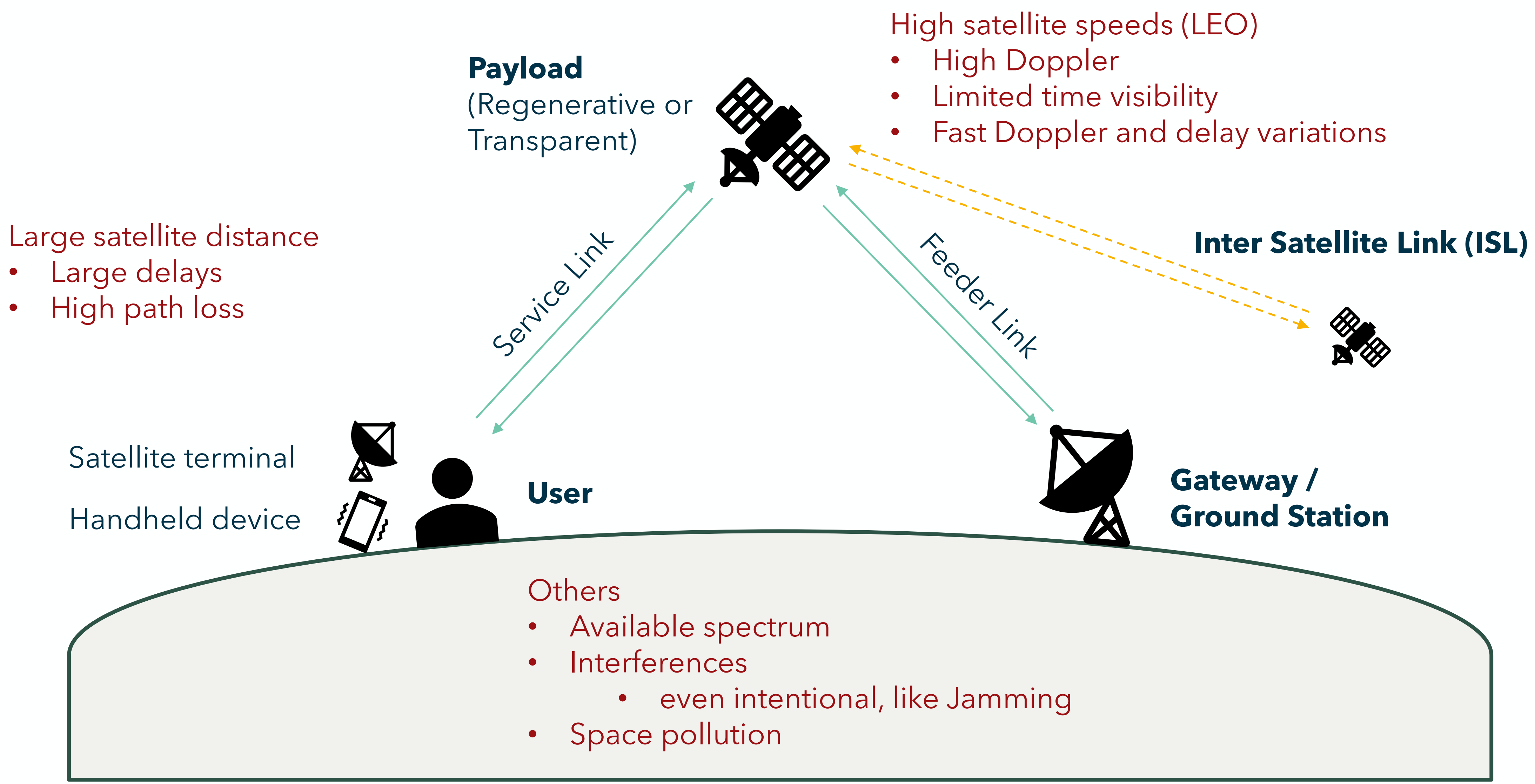
- Min 50 MHz, max 400 MHz transmission bandwidth
- VSAT terminals

Other candidates:

- C-Band (4-8 GHz): band in TDD, which can be much more challenging with satellites (larger guard band). Co-existence with TN and Fixed Satellite Service, requiring strict interference analysis
- Ku-band (10-14 GHz): already used by other satellite services



Baseline architecture and challenges



5G NR data channels and retransmission mechanisms

Mobility for 5G NTN: Performance and Challenges of NTN over Mobile Channels

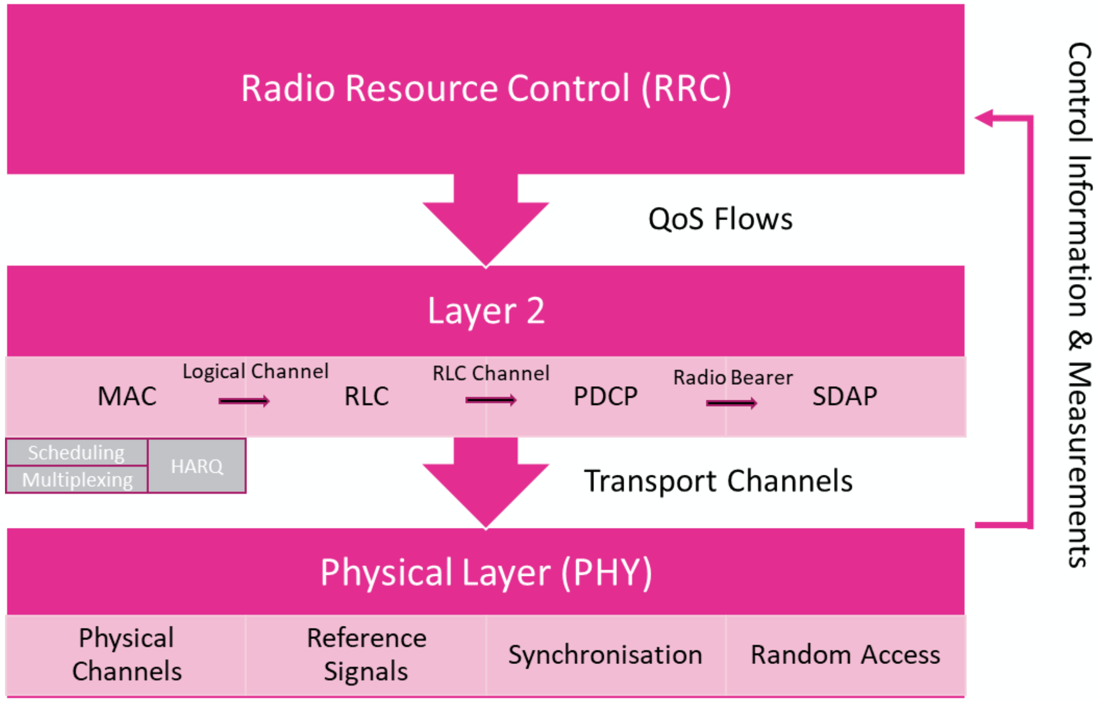
5G Layers 1-3

5G Describes Several Layers, Logical, and Transport Channels

- Layer 1: Physical (PHY)
- Layer 2:
  - Medium Access Control (MAC)
  - Radio Link Control (RLC)
  - Packet Data Convergence Protocol (PDCP)
  - Service Data Adaptation Protocol (SDAP)
- Layer 3: Radio Resource Control (RRC)

We focus on:

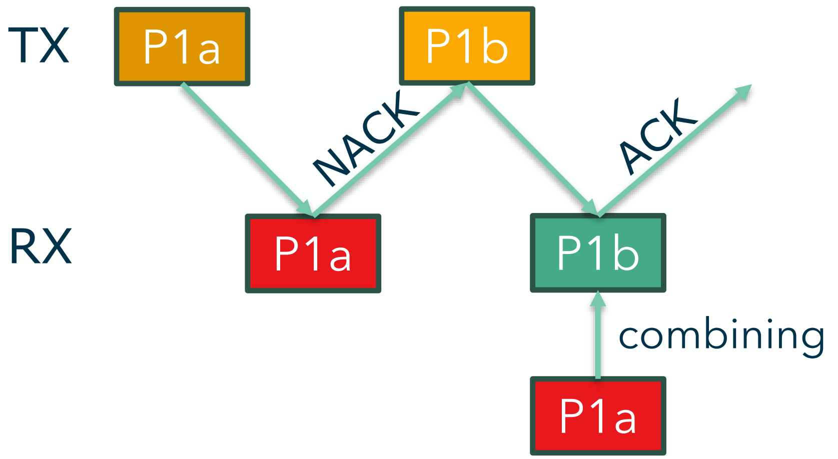
- RLC: Segmentation & Re-Transmission (ARQ)
- MAC: Hybrid ARQ (HARQ), Scheduling, Multiplexing
- PHY: Physical Channels (coding, modulation, reference signals, scrambling, …)



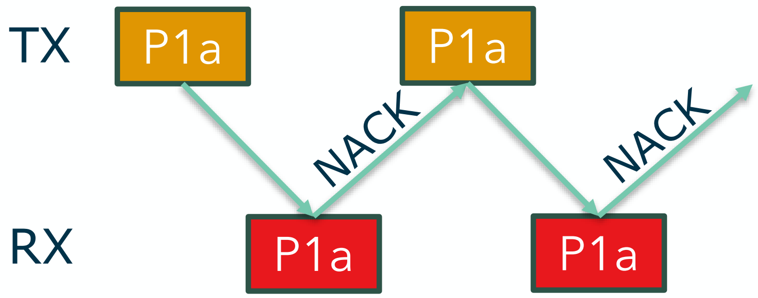
HARQ and RLC ARQ

Hybrid Automatic Repeat Request (HARQ) stores bits of erroneously received packets in buffer memory, and later combines them with the retransmission to obtain a single packet that is more reliable than its constituents

- Higher complexity at receiver side



Radio Link Control (RLC) ARQ operating at the 5G RLC layer, is a simpler retransmission mechanism that does not keep any memory of previous transmissions at the receiver side



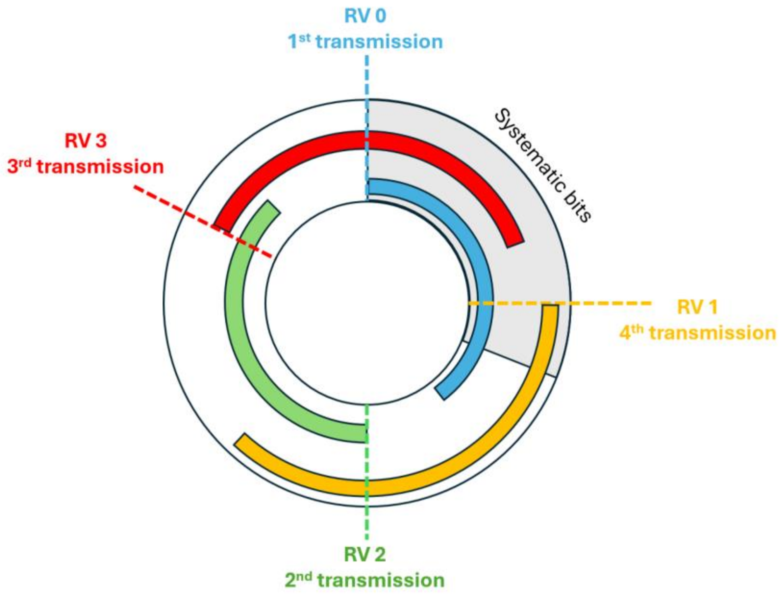
Incremental Redundancy with HARQ

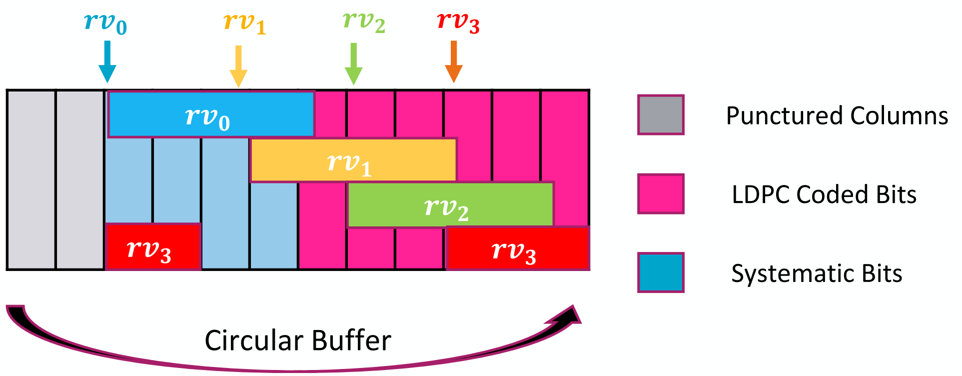
HARQ can improve the decoding at the receiver side via **incremental redundancy**, a technique that allows the transmission of different versions of the same codeword, called **redundancy versions**, that can have overlapping or non-overlapping parts.

- The non-overlapping parts allow the construction of a longer sequence at the receiver side, providing a **coding gain** thanks to the additional redundancy bits.
- The overlapping parts improve the bits likelihood through soft combining, thus producing a **combining gain**.

To obtain a coding gain with HARQ, the encoded bit sequence in the circular buffer must be longer than the codeword length to be transmitted.

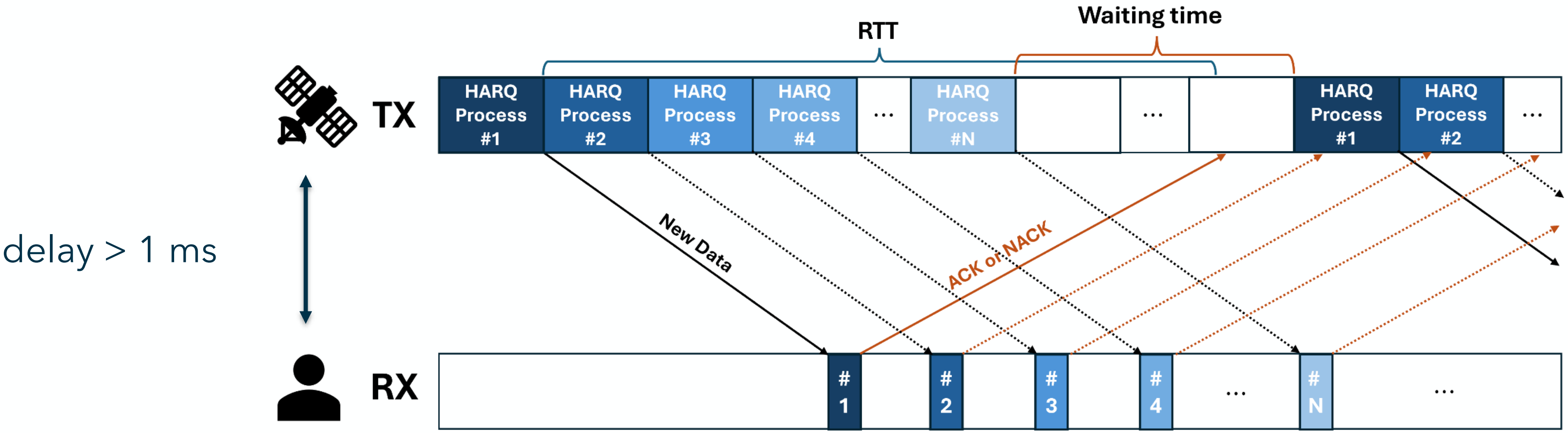
- This is usually true except for very low coding rates.





HARQ in satellite communications – 1/2

- Multiple HARQ processes can be generated to avoid the stop-and-wait typical of retransmission protocols
- In terrestrial networks, propagation latency is relatively small and a limited number of HARQ processes are required to avoid stop-and-wait
- In satellite communications, the propagation delay can be much longer, and the maximum number of HARQ processes designed for terrestrial networks may be insufficient to avoid the stop-and-wait
  - Waiting time means wasted resources and lower SE



HARQ in satellite communications – 2/2

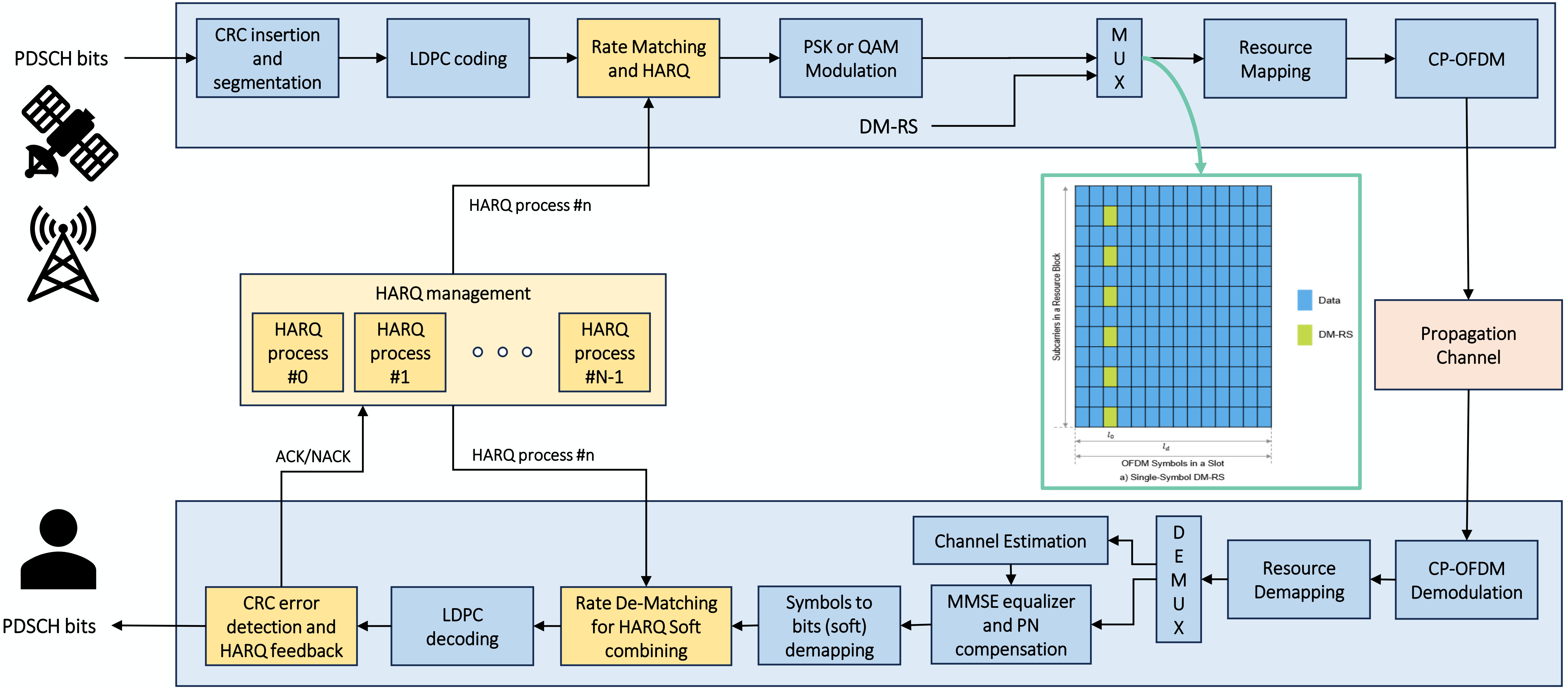
In this table we report the minimum number of HARQ processes required to avoid Stop-and-Wait

SCS [kHz]	T_{slot} [ms]	LEO 1 θ		LEO 2 θ		MEO θ	
		90°	30°	90°	30°	90°	30°
15	1	5	9	9	15	**55**	**69**
30	0.5	9	16	17	28	**108**	**136**
60	0.25	17	30	**33**	**55**	**215**	**270**
120	0.125	**33**	**59**	**65**	**108**	**428**	**539**
240	0.0625	**65**	**116**	**129**	**215**	**855**	**1077**

LEO 1: 600 km altitude
LEO 2: 1200 km altitude
MEO: 8000 km altitude

The receiver **complexity** in terms of memory is proportional to the number of HARQ processes times the number of retransmissions and the transport block size.

Physical Downlink Shared Channel (PDSCH)



Channel models for NTN and mobile terminals

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NTN channel model

3GPP introduces the channel model for link and system level simulations in section 6 of TR 38.811.

The requirements identified for this new channel are:

- **Support a frequency range from 0.5 GHz up to 100 GHz -** Two frequency bands are targeted in particular: below 6 GHz (FR1) and Ka-band (FR2). For Ka-band communications, the UL frequency is around 30 GHz while the DL frequency is around 20 GHz.
- **Accommodate UE mobility -** For satellite channel models, **mobility speed up to 1000 km/h** is supported; this corresponds to aircraft that can be served by satellite access.

The channel model is then characterized by **two different cases**, depending on the frequency selectivity of the channel:

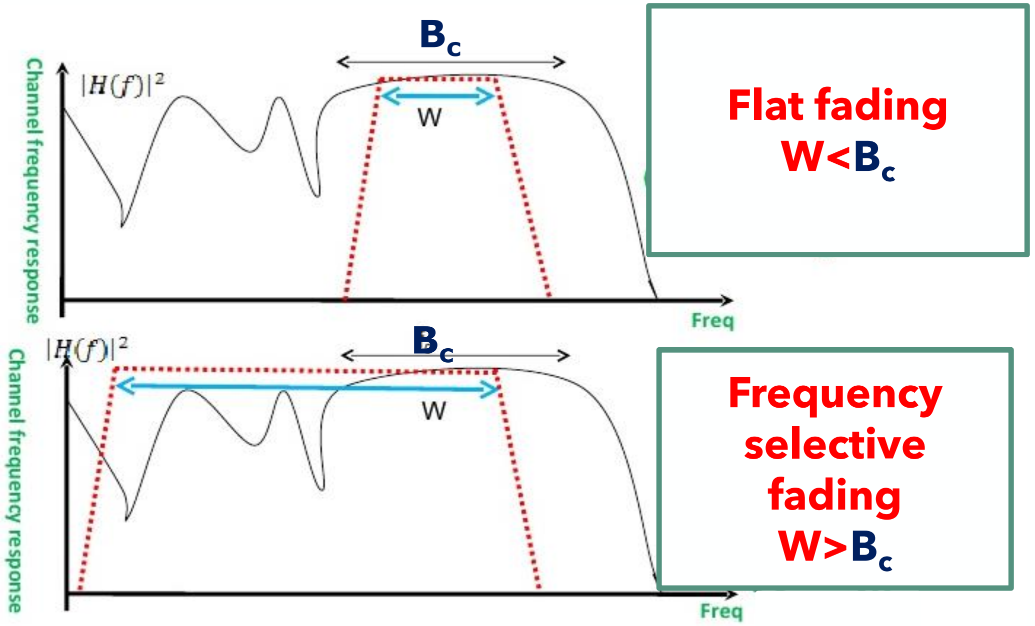
- **Flat fading**: the channel frequency response can be considered flat over the signal bandwidth, i.e. the coherence bandwidth is larger than the signal bandwidth.
- **Frequency selective fading**: the channel frequency response is varying significantly over the signal bandwidth, due to multipath, causing signal distortions.

Frequency selectivity – 1/3

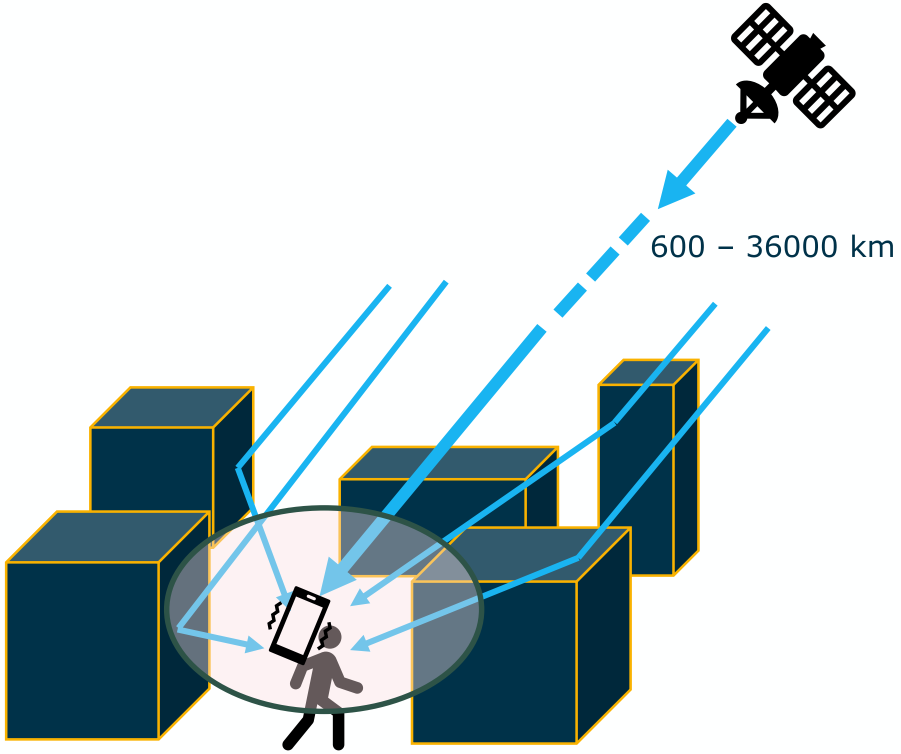
The criteria to determine which case shall be used is based on the channel **delay spread**, resulting in a certain **coherence bandwidth** B_c.

- The delay spread is a measure of the maximum delay of the multipath

The coherence bandwidth then depends on the **environment** where the signal gets scattered (urban, suburban, rural, etc.), the **antenna pattern** and the **satellite elevation.**



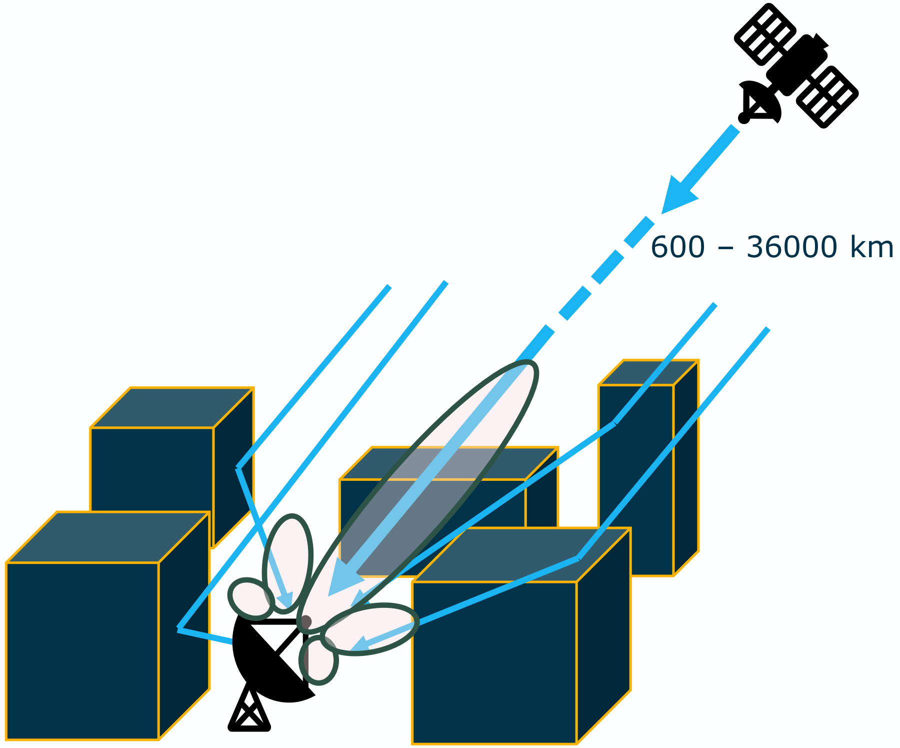
Frequency selectivity – 2/3



Handheld terminal

Quasi-isotropic antenna pattern

(Generally) frequency selective channel



VSAT terminal

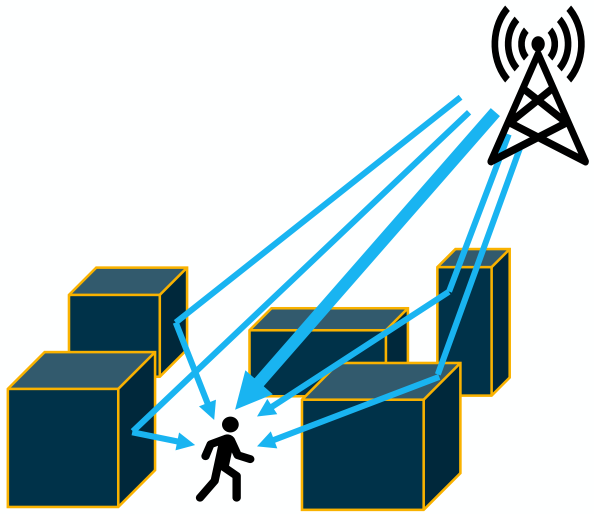
Directive antenna (spatial filtering)

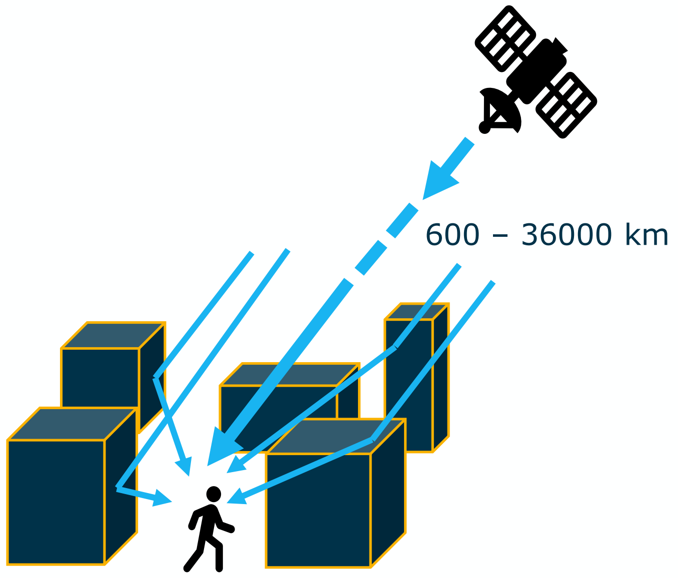
(Generally) flat fading channel

Frequency selectivity – 3/3

The frequency selective model proposed by 3GPP is based on the terrestrial version presented in **TR 38.901**, then adapted for the NTN scenario. Key differences:

1. **New parameters** tables specifically for **NTN** (TR 38.811)
2. **Angular modification** are needed in cluster generation
   - The cluster azimuth angle spread of departure (ASD) can be neglected for the satellite, since all the paths are parallel before reaching the receiver.





Flat fading model – 1/2

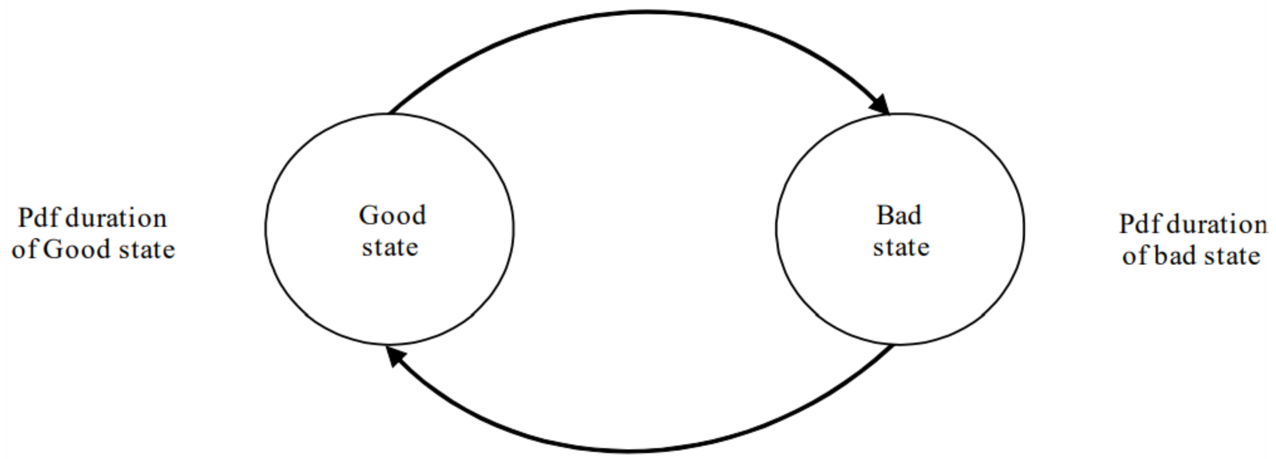
Land Mobile-Satellite (LMS) Flat fading channel model ITU-R P.681-11

In Land Mobile-Satellite Service (LMSS) propagation environments such as rural and urban areas, a mixture of different propagation conditions can occur

1. **GOOD state**: LOS, including slightly shadowed conditions
2. **BAD state**: with more severe shadowed conditions

The long-term variations in the received signal are described by a semi-Markov chain including the two distinct states, GOOD and BAD.

- The duration of each state is log-normally distributed.

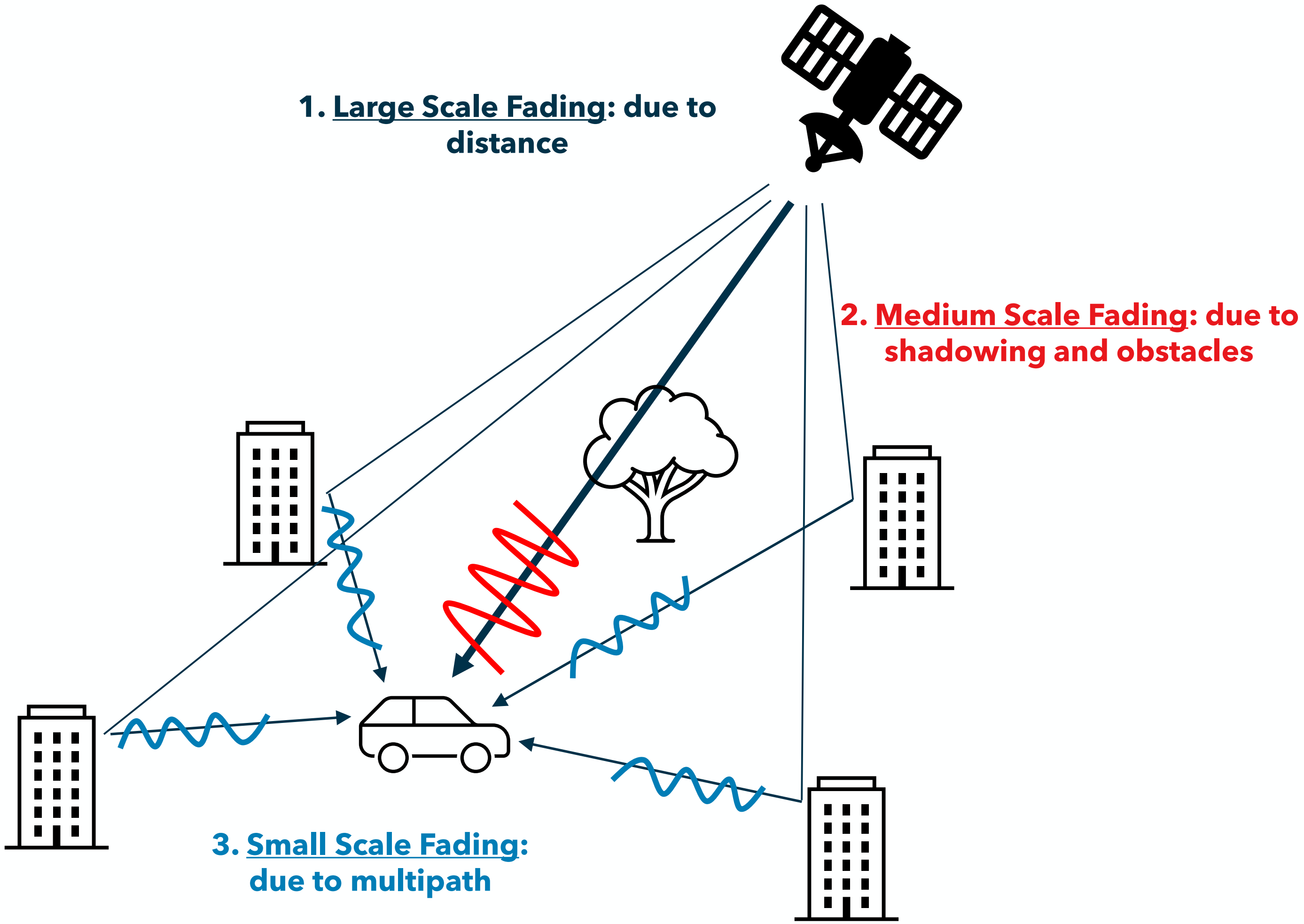


ITU p.681-11: "Propagation data required for the designs systems in the land mobile-satellite service," 08-2019

Flat fading model – 2/2

The signal fading given a state follows a **Loo distribution**, which includes:

1. **Rice** distribution for direct signal (**LOS** or strong reflected path) and multipath
   - The ratio of LOS and multipath powers is the K-factor
   - With mobile users, the multipath produce a Doppler spread, due to the different velocity vectors of the echoes
   - Higher terminal speed means faster fading variations
2. **Lognormal** distribution for the direct signal power (**shadowing**)
   - Negligible at high satellite elevation



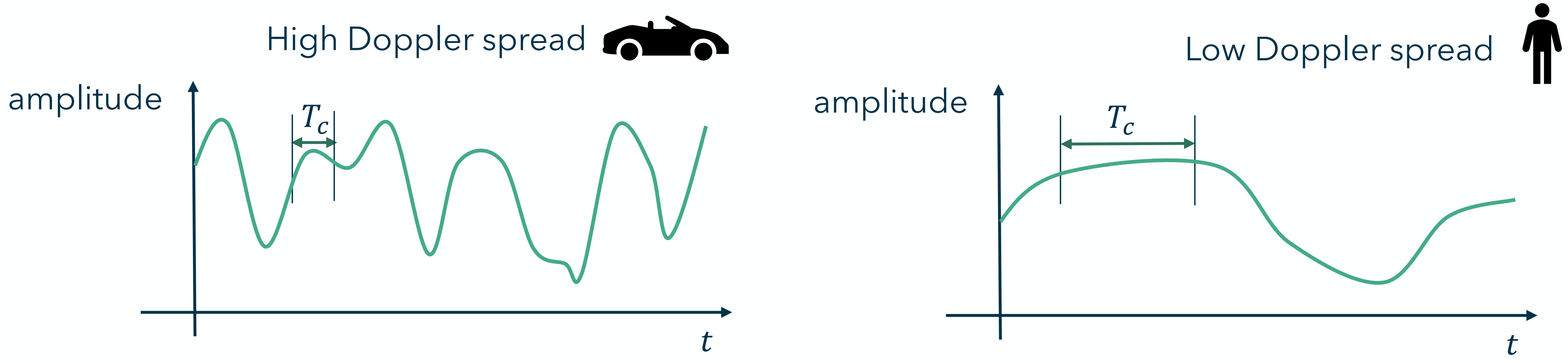
Doppler frequency dispersion

The Doppler frequency dispersion, or **Doppler spread** is defined as twice the largest Doppler shift among the ones affecting the received echos.

- It is a dynamic characteristics of the channel, due to the relative motion between transmitting and receiving antennas.

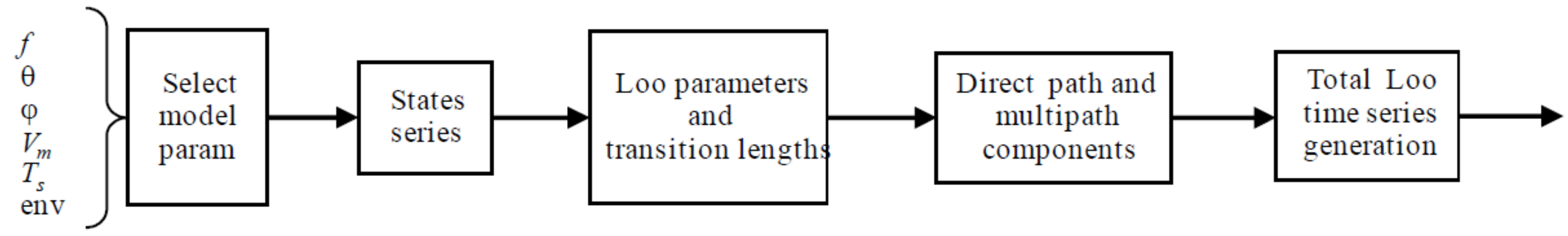
The inverse of the Doppler spread is proportional to the **coherence time** T_c of the channel

- Time interval over which the channel amplitude is considered correlated
- High speeds result in high variability of the channel path delay, phase, and attenuation

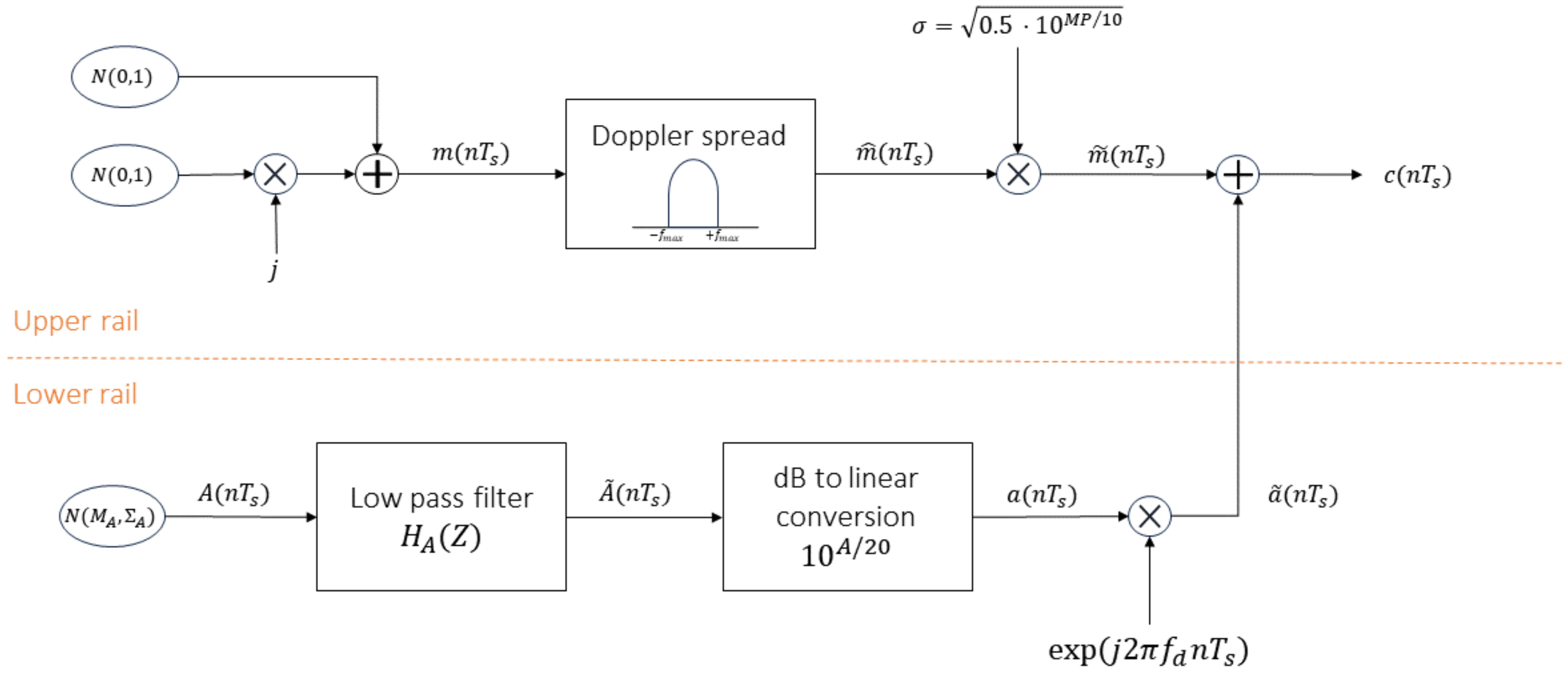


Flat fading generation

ITU-R P.681-11 Section 6.2 Generative model block schemes



multipath

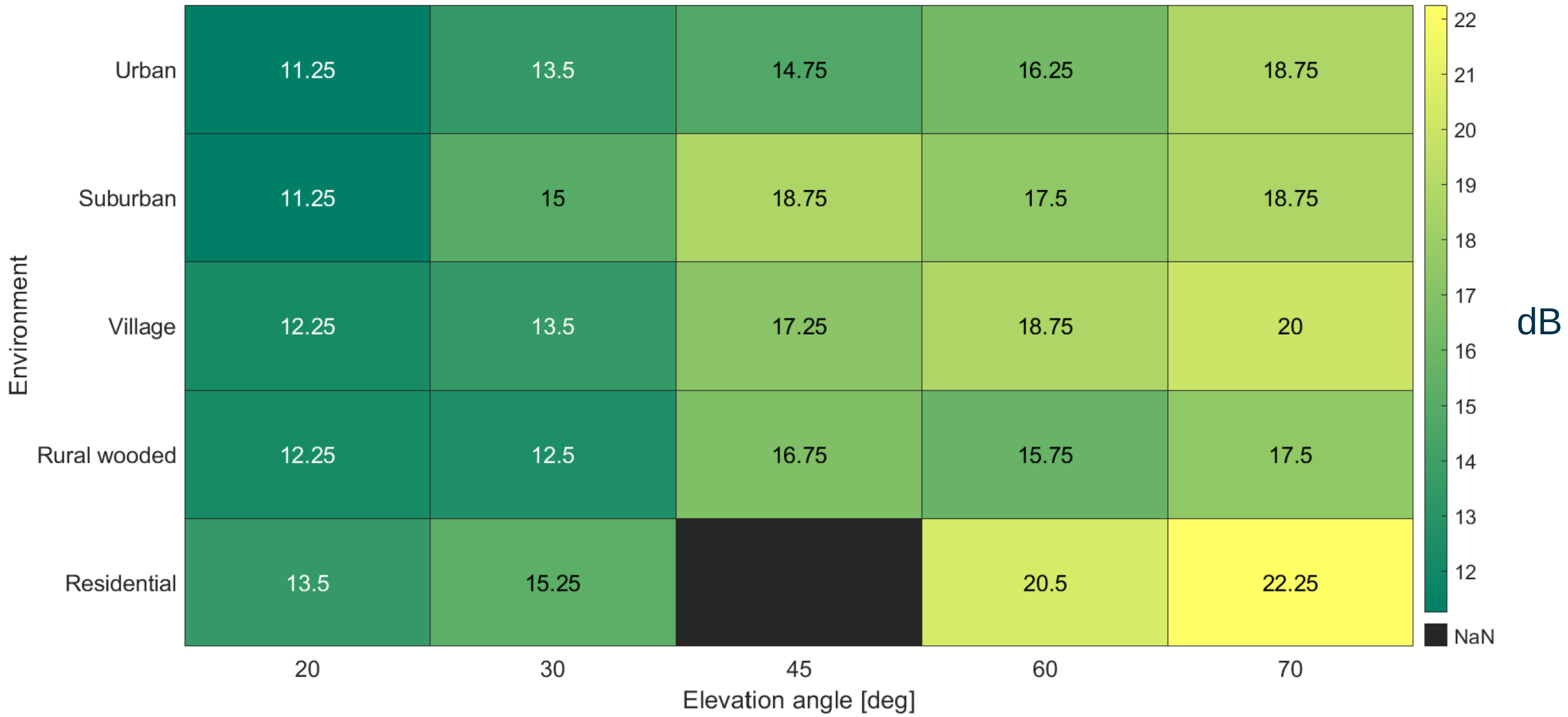


LOS with Doppler shift and shadowing (lognormal distributed)

Flat fading model

ITU-R P.681-11 Section 6.1 provides a statistical characterization of the channel parameters.

It can be used, for example, to derive K-factors in different scenarios.



K-factor for 95% confidence interval for carrier frequency of 2.2 GHz

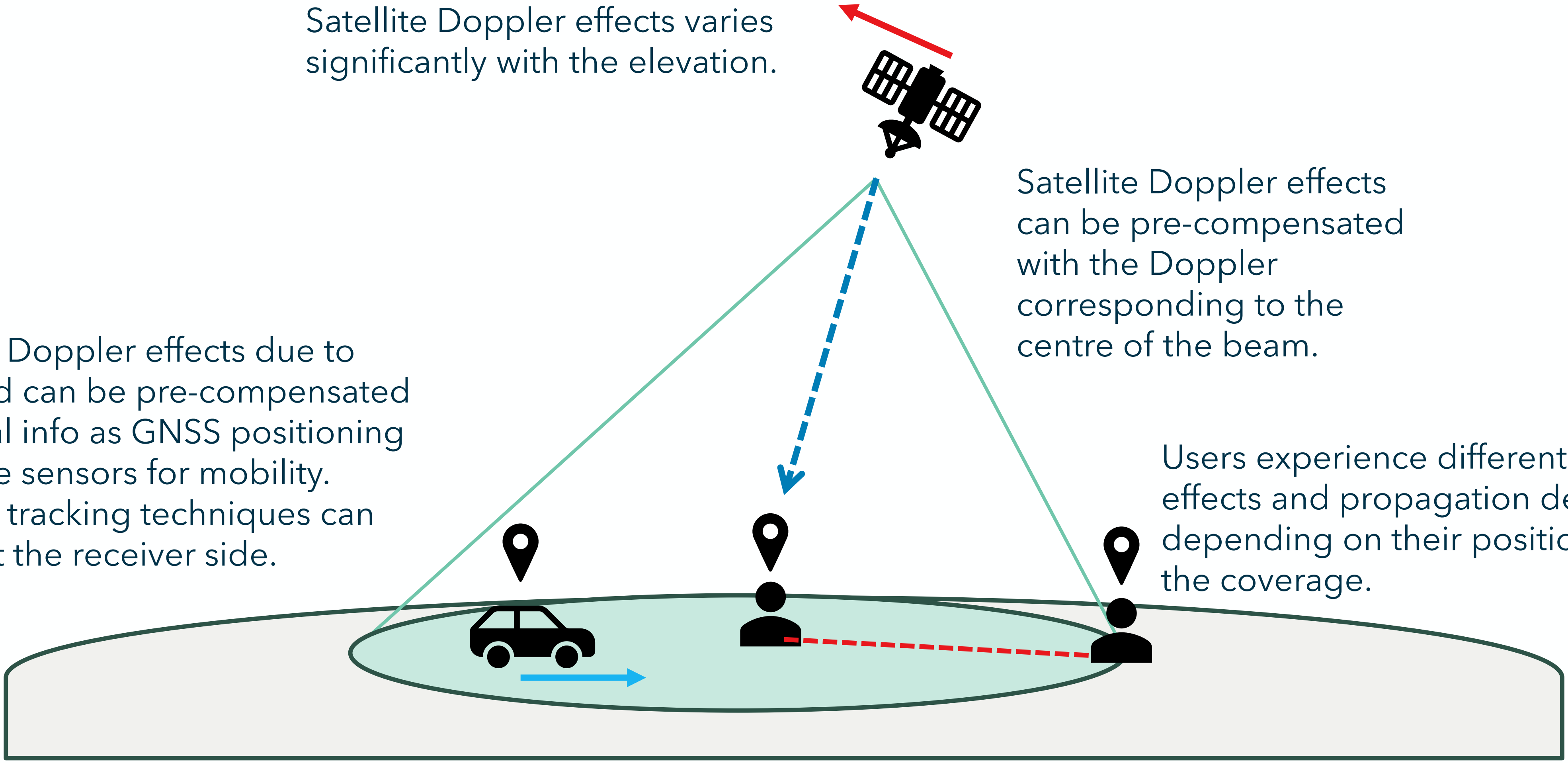
Delay and Doppler shift in NGSO

Satellite Doppler effects varies significantly with the elevation.

Satellite Doppler effects can be pre-compensated with the Doppler corresponding to the centre of the beam.

Delay and Doppler effects due to user speed can be pre-compensated by external info as GNSS positioning and device sensors for mobility. Moreover, tracking techniques can be used at the receiver side.

Users experience different Doppler effects and propagation delays depending on their position within the coverage.



Examples of Doppler and delay differences

Orbit	Max sat Doppler shift	Max tot Doppler shift*	Propagation delay		3dB beamwidth	Max sat diff. Doppler shift**	Max total diff. Doppler shift***	Max differential delay**
LEO			90 deg	30 deg		90 deg	90 deg	90 deg
600 km	+/-465 kHz	+/- 483.5 kHz	2 ms	3.6 ms	1.8 deg	+/- 14 kHz	+/- 32.5 kHz	+/- 1 us
					4.4 deg	+/- 36 kHz	+/- 54.5 kHz	+/-5 us
1200 km	+/-411 kHz	+/- 429.5 kHz	4 ms	6.7 ms	1.8 deg	+/- 12 kHz	+/- 30.5 kHz	+/- 2 us
					4.4 deg	+/- 31.5 kHz	+/- 60 kHz	+/- 10 us

* Total considering additional user max mobility: vmax = 1000 km/h -> max user Doppler shift +/-18.5 kHz

** Static user on the beam edge

*** Mobile user on the beam edge (vmax = 1000 km/h)

Results and discussion

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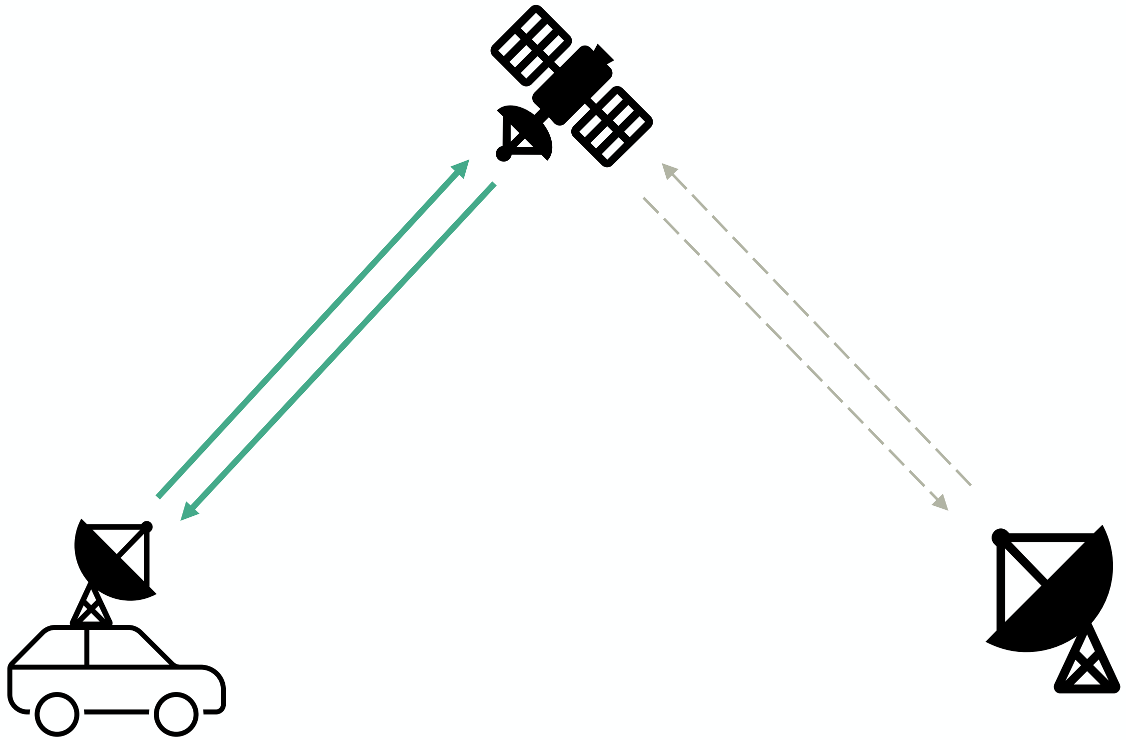
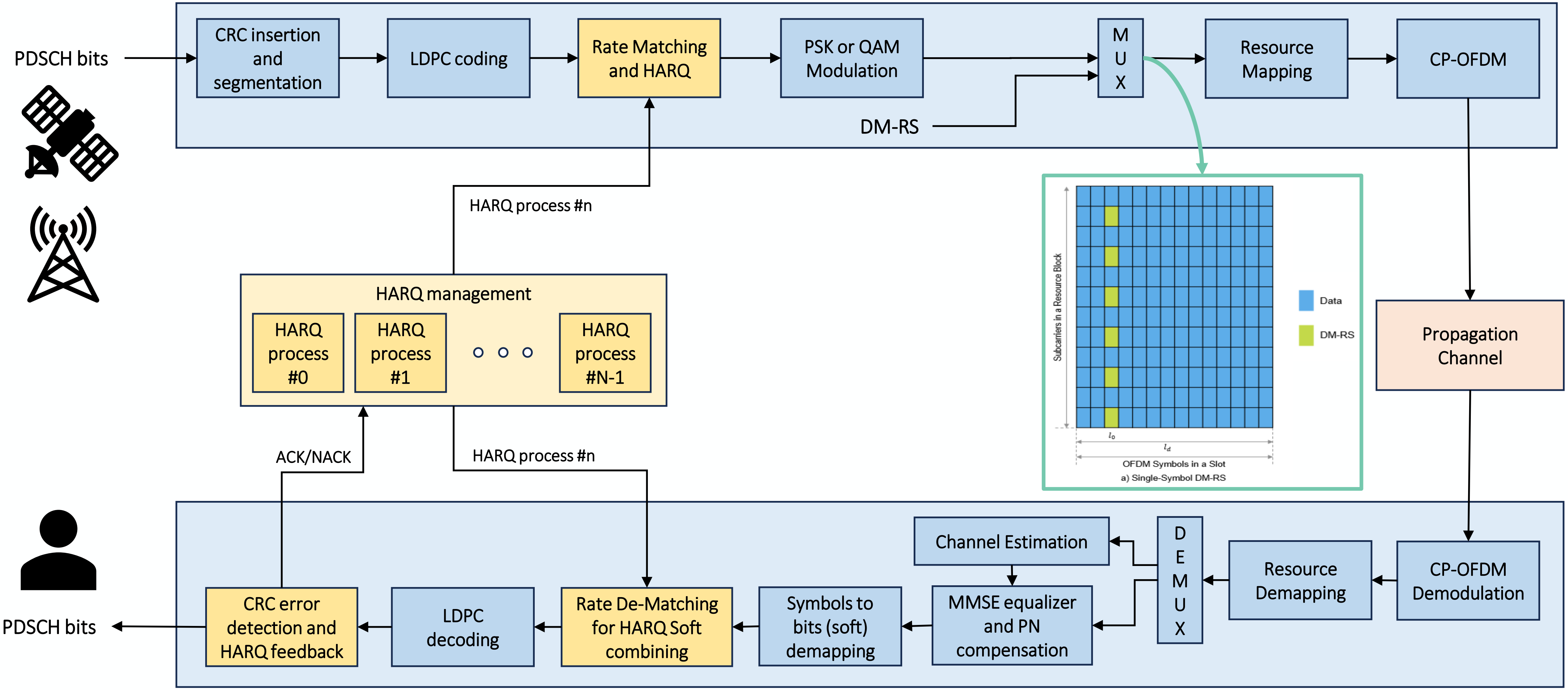
Simulation scenario

- LEO Ka-band (20 GHz DL)
- VSAT user terminal
  - High spatial filtering
- Regenerative Payload
  - Focus on user link
- Broadband communications
- Mobility scenario
  - User speeds up to 1000 km/h
- Compare HARQ vs. RLC ARQ
- PDSCH link level simulator
  - Connected mode
  - Perfect synchronization or residual frequency errors

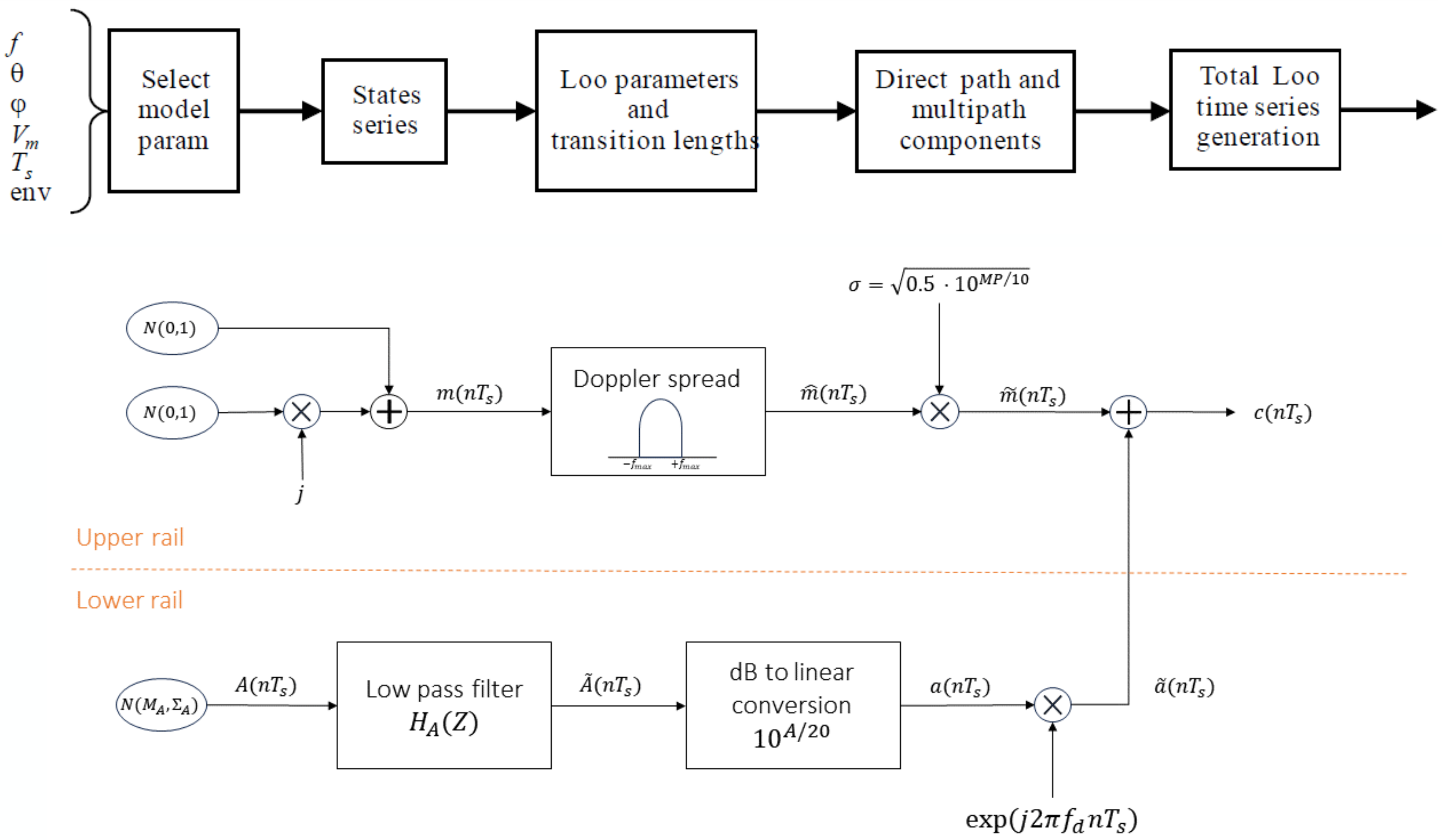


Simulator architecture



Channel generation

ITU-R P.681-11 Section 6.2 Generative model block schemes



System parameters

Parameter	Value
Satellite altitude	600 km
Frequency Band	Ka-Band
Carrier Frequency DL	20 GHz
Carrier frequency UL	30 GHz
Subcarrier Spacing	120 kHz
Transmission Time Interval (TTI)	0.125 ms
Symbol allocation	14 OFDM symbols per slot
NPRB	140 (201.6 MHz)
Terminal type	VSAT
Terminal speed	{0, 50, 150, 900} km/h
Channel model	LMS or AWGN
K factor	{15, 20} dB
LDPC decoding algorithm	Layered belief propagation
LDPC decoder iteration count	25
HARQ redundancy version	[0 2 3 1]
MCS table	TR 38.214 Table 5.1.3.1.-1

Simulation set 1 – HARQ results with LMS

In the next slides, we will consider a specific case of the **LMS channel**:

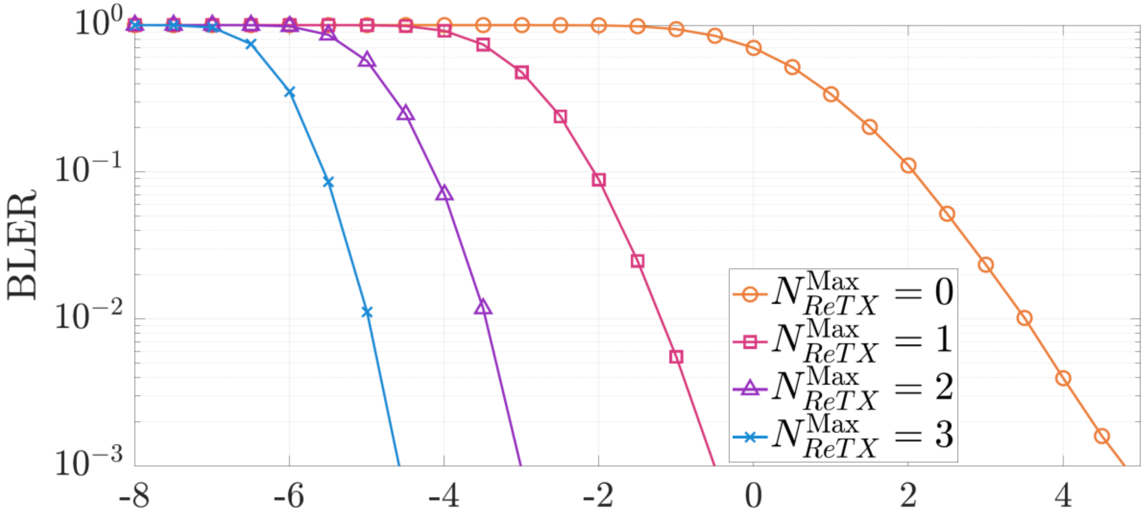
- GOOD state, with 60 cm aperture VSAT
- K-factor 15 dB, which represents a case of high multipath power for a VSAT terminal
- **user speed** of 50 km/h
- no shadowing (high elevation angle).

Different modulation and coding schemes are adopted to show the different effects of 5G HARQ on the BLER and SE depending on the code rate

- QPSK, 16QAM, 64QAM, and 256QAM

Then, we will also consider K = 20 dB and user speeds from 0 up to 900 km/h to evaluate the impact of the terminal speed on the performance.

5G NTN DL – HARQ – QPSK 1/2

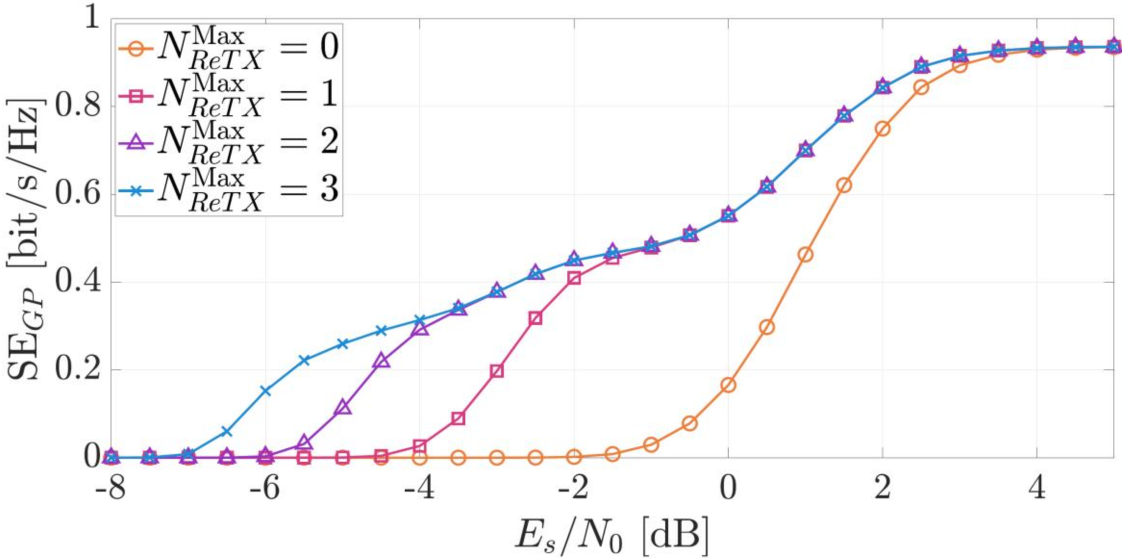


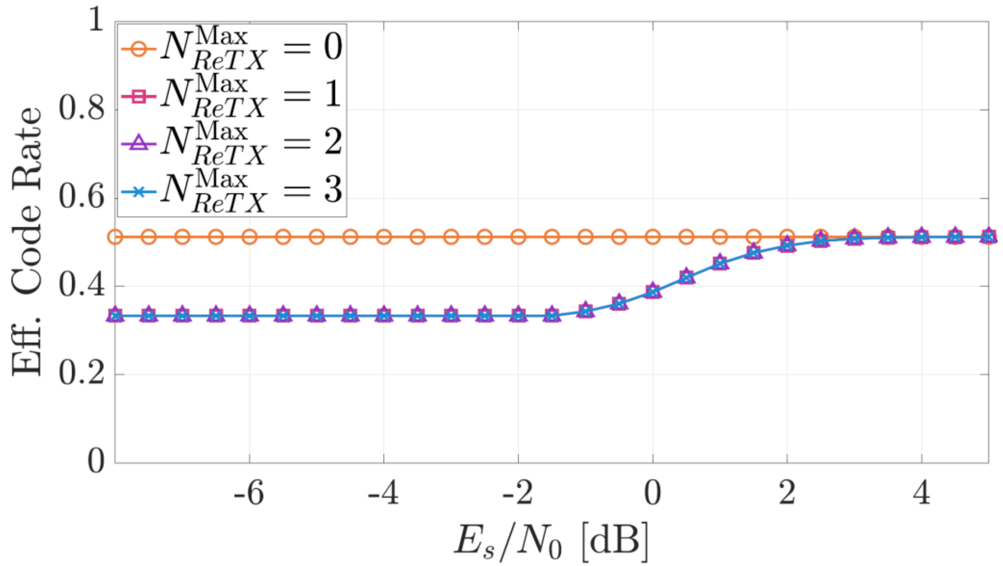
Each retransmission shifts the BLER curve toward lower values of Es/N0, and makes it steeper

- Price to pay: a lower SE

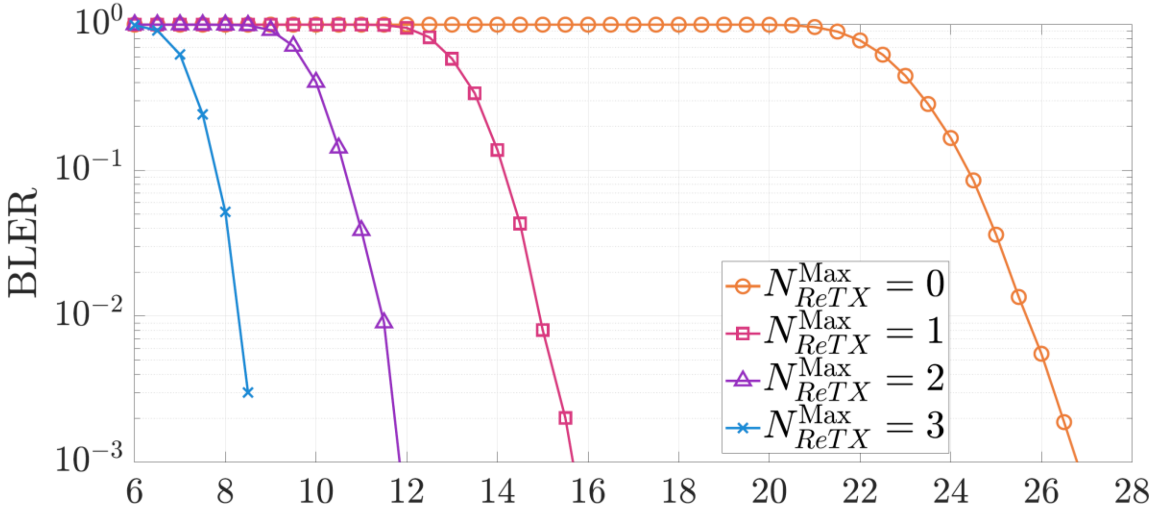
About 8 dB gain for 3 retransmissions.

Coding gain only for 1 retransmission, as can be seen from effective code rate





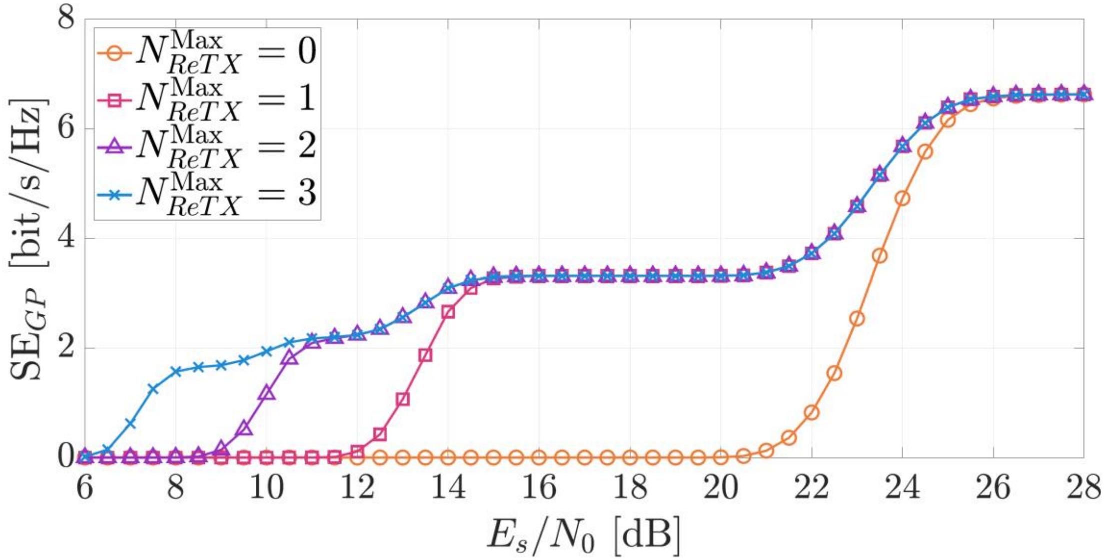
5G NTN DL – HARQ – 256QAM 8/9

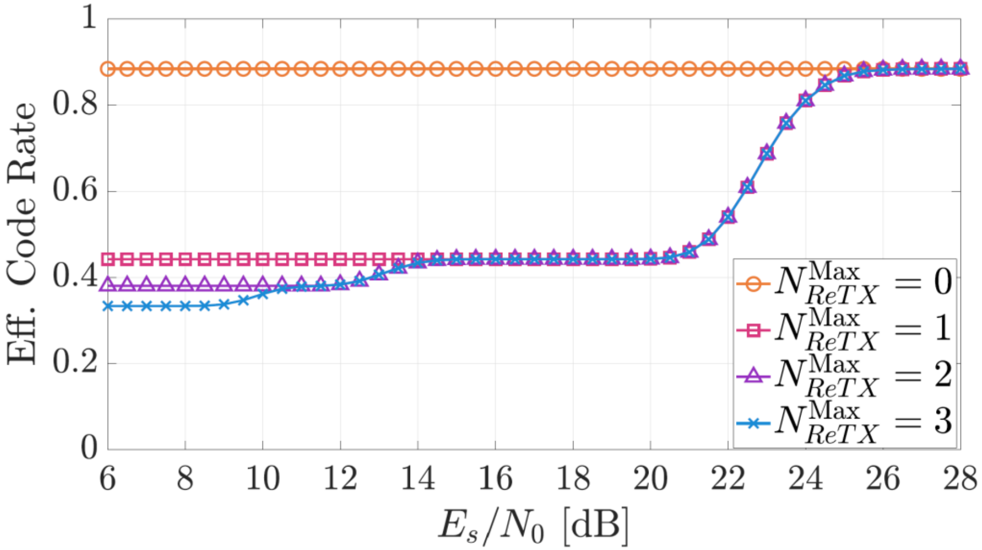


About 18 dB gain for 3 retransmissions

- Higher coding gain

HARQ coding gain depends on the initial (nominal) code rate.



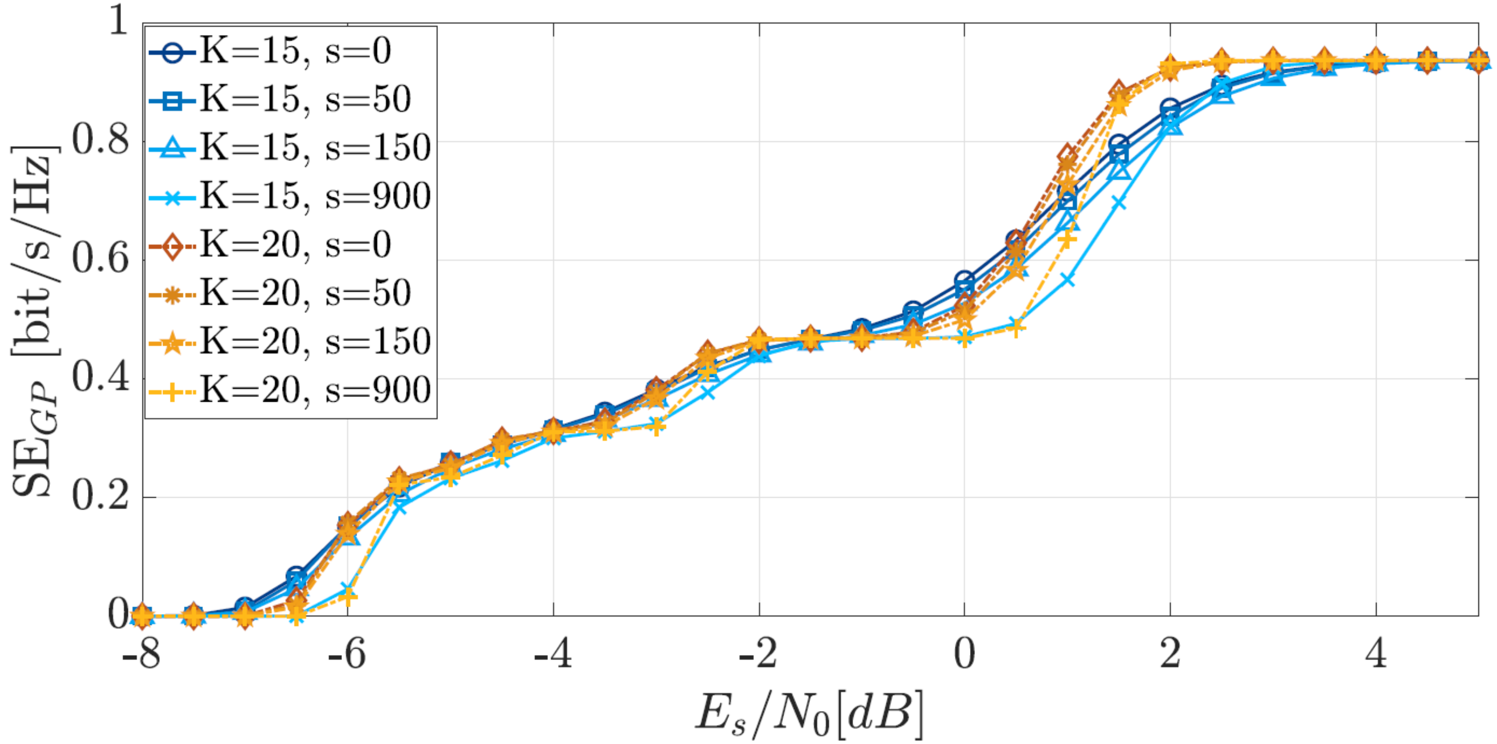


HARQ – Impacts of terminal speed

This set of results adopted different user speeds, **from 0 km/h up to 1000 km/h**, and two different K-factors for the LMS channel, i.e., 15 and 20 dB

- Results for **QPSK 1/2**

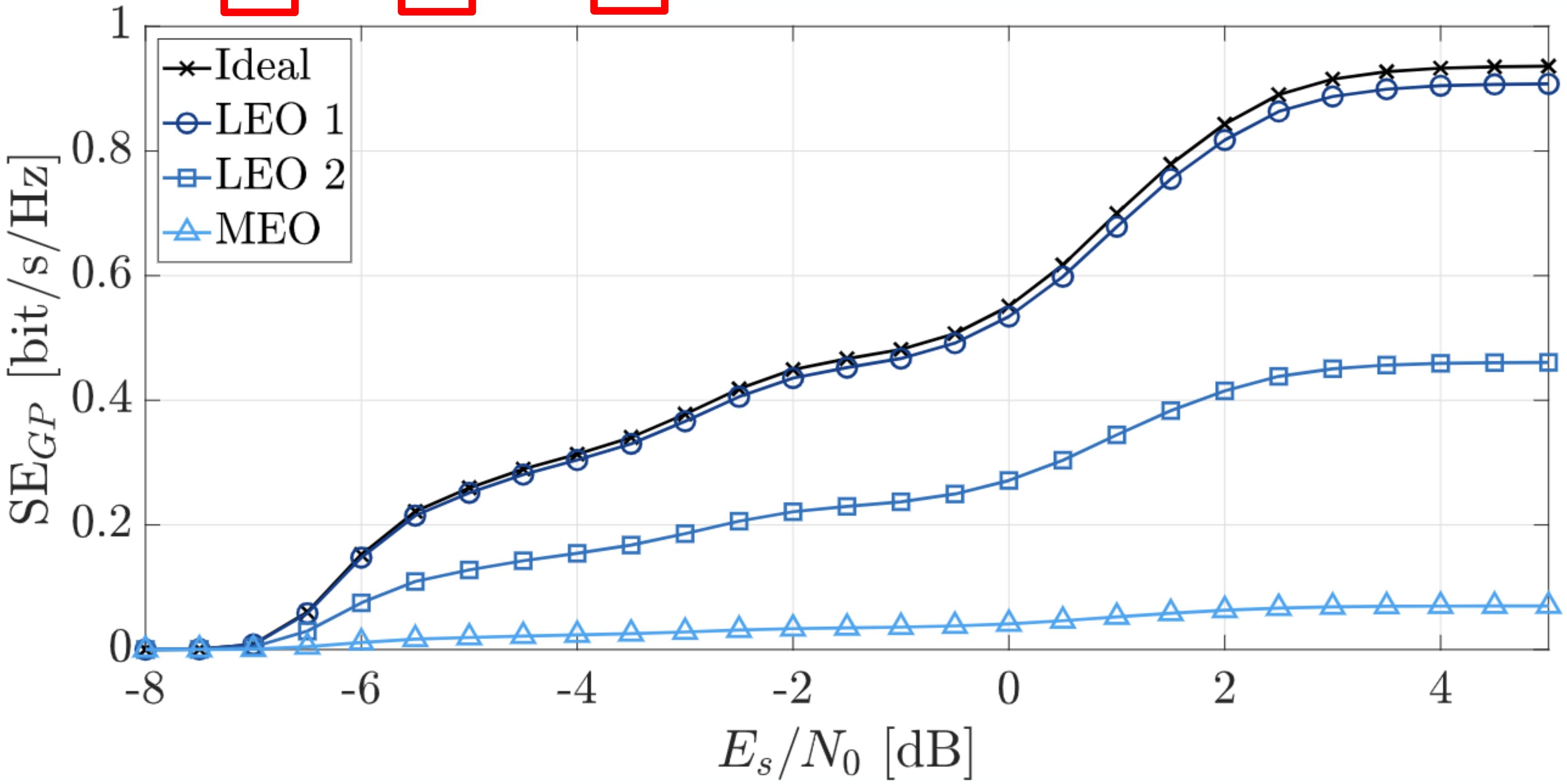
User speed increases the Doppler spread, and produces faster fading which results in steeper curves (shorter coherence time, noise-like behaviour)



HARQ performance with Stop-And-Wait

			Number of HARQ processes					
			LEO 1 θ		**LEO 2** θ		**MEO** θ	
μ	SCS [kHZ]	TTI [ms]	30°	90°	30°	90°	30°	90°
3	120	0.125	**59**	**33**	**108**	**65**	**539**	**428**

LEO 1: 600 km altitude
LEO 2: 1200 km altitude
Medium Earth Orbit (MEO): 8000 km altitude



32 HARQ processes as per 3GPP specifications

QPSK 1/2, LMS K15 s 50

5G MCSs for NTN

In the next set of slides, we will adopt 5G MCSs from Table 5.1.3.1-1 of TR 38 214 for HARQ and RLC ARQ comparison.

- For lower SE MCSs, useful for handheld or IoT devices, look at Table 5.1.3.1-3

We limit our study to **QPSK** and **16QAM** MCSs

- Link Budgets analysis from TR 38821 results in CNR of 8.5 dB for DL (30 deg elevation), limiting the interest to lower order MCSs
    - Support to higher order MCSs is still guaranteed

Table 5.1.3.1-1: MCS index table 1 for PDSCH

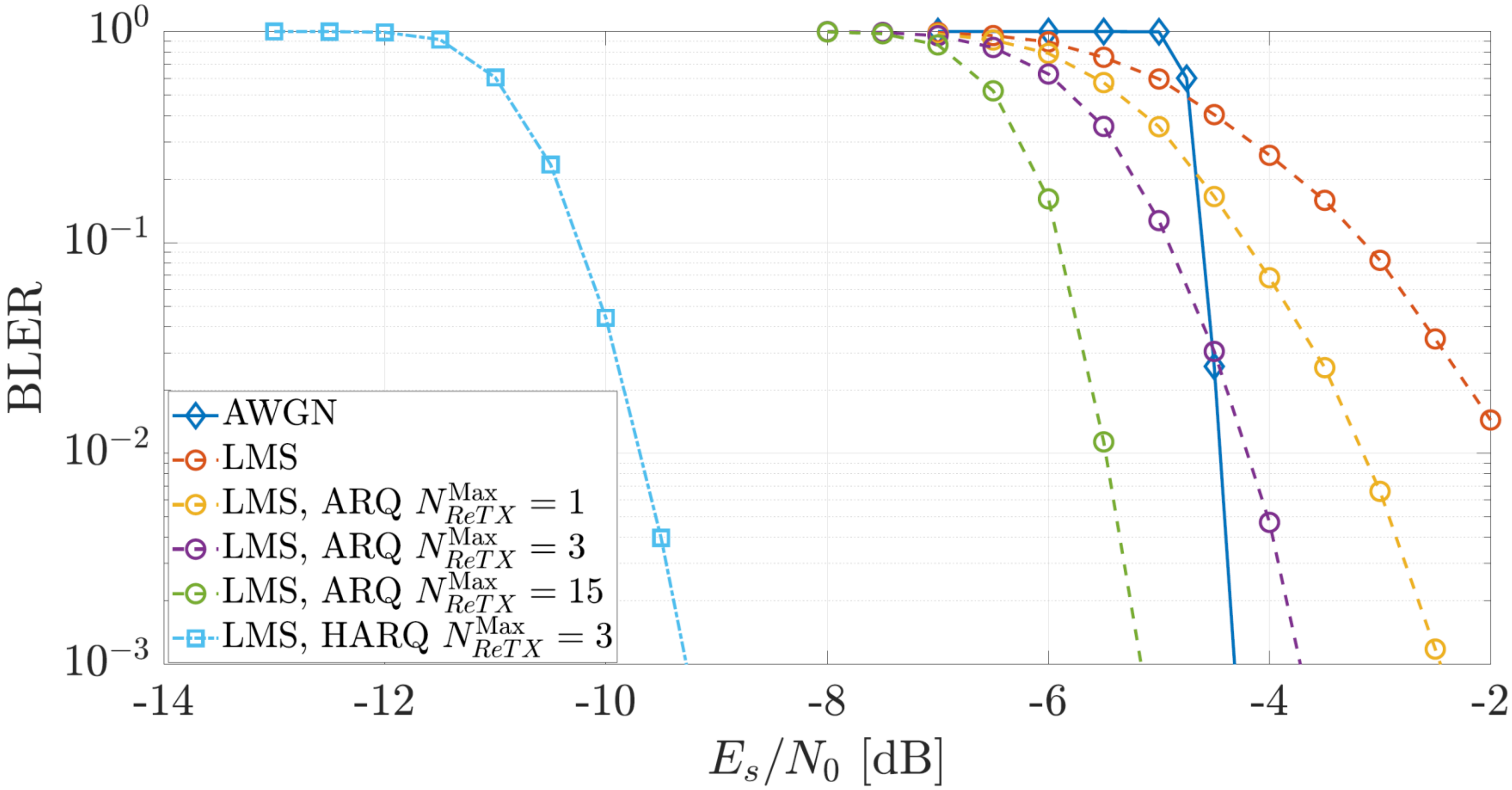
MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate R x [1024]	Spectral efficiency
0	2	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
6	2	449	0.8770
7	2	526	1.0273
8	2	602	1.1758
9	2	679	1.3262
10	4	340	1.3281
11	4	378	1.4766
12	4	434	1.6953
13	4	490	1.9141
14	4	553	2.1602
15	4	616	2.4063
16	4	658	2.5703
17	6	438	2.5664
18	6	466	2.7305
19	6	517	3.0293
20	6	567	3.3223
21	6	616	3.6094
22	6	666	3.9023
23	6	719	4.2129
24	6	772	4.5234
25	6	822	4.8164
26	6	873	5.1152
27	6	910	5.3320
28	6	948	5.5547
29	2	reserved	
30	4	reserved	
31	6	reserved	

HARQ vs RLC ARQ – BLER – single MCS

The two retransmission mechanisms produce different effects on the BLER curve:

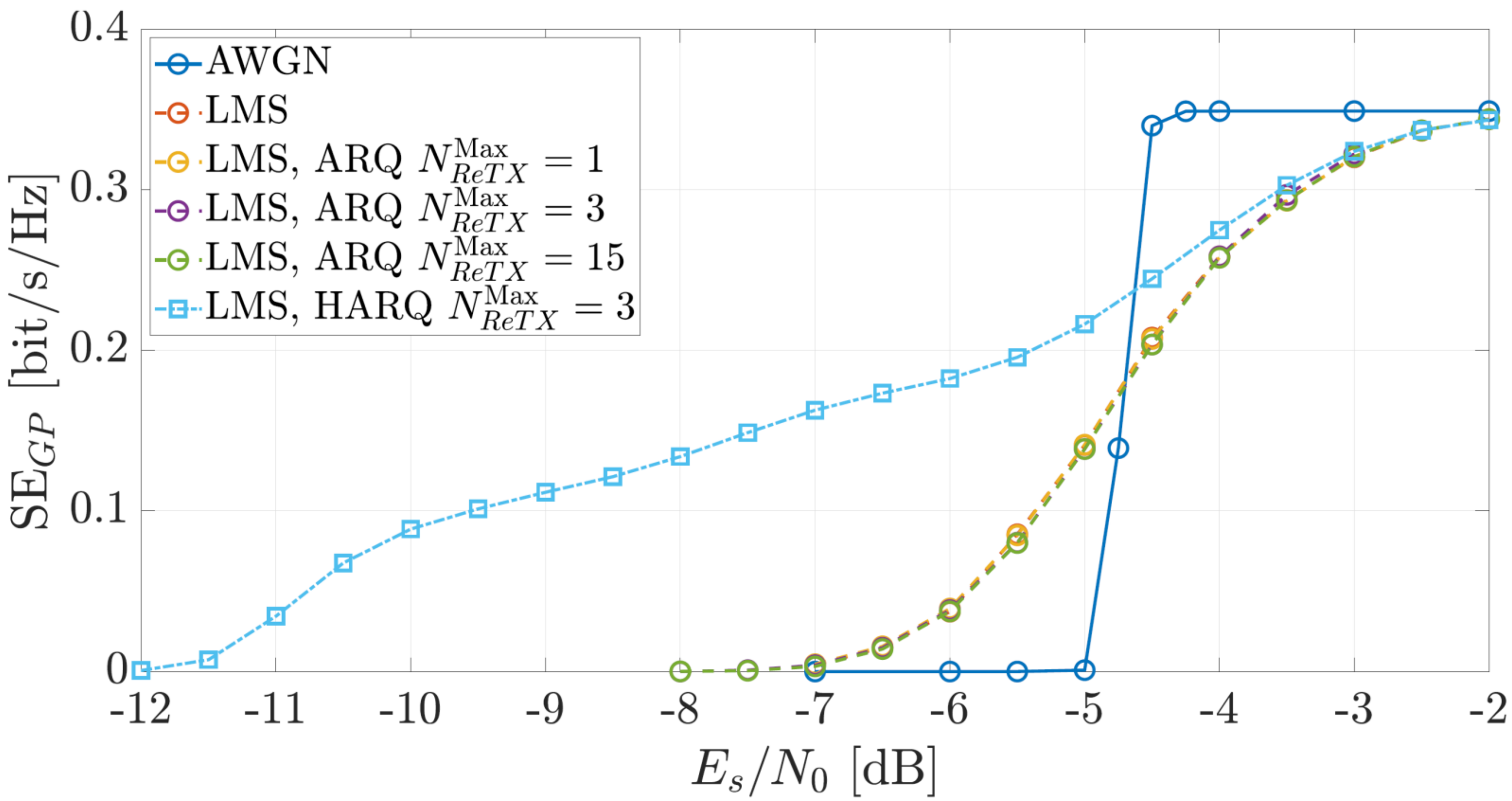
- RLC ARQ increases the steepness of the BLER
- HARQ shifts it to lower SNR

MCS 2 - QPSK 193/1024, LMS K15 s 50



HARQ vs RLC ARQ – SE – single MCS

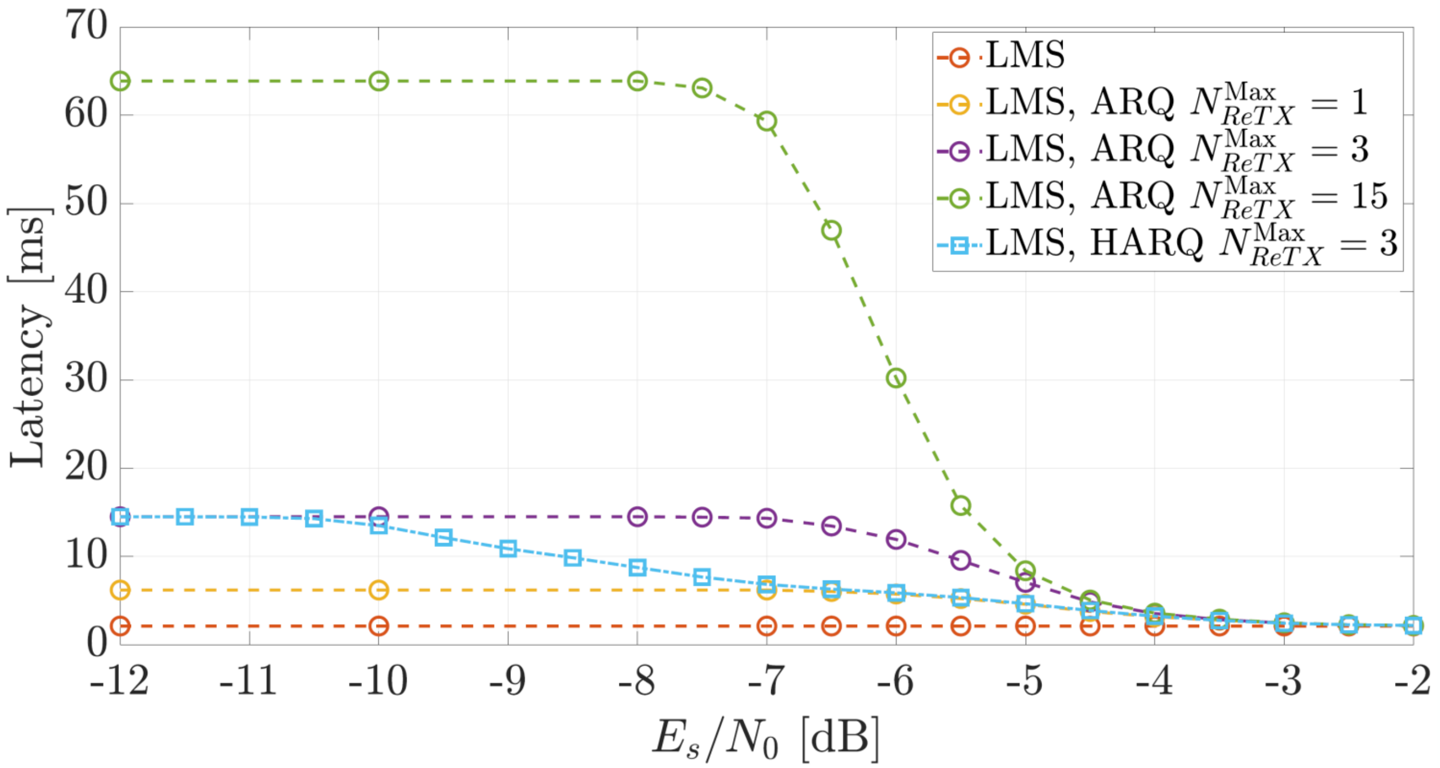
- We are considering the **goodput**, not the throughput
- **Counterintuitive result**: RLC ARQ does not impact the system SE since each decoding attempt is independent of the others, and the total number of correctly decoded blocks does not change, while the single codeword BLER decreases but requires multiple attempts.

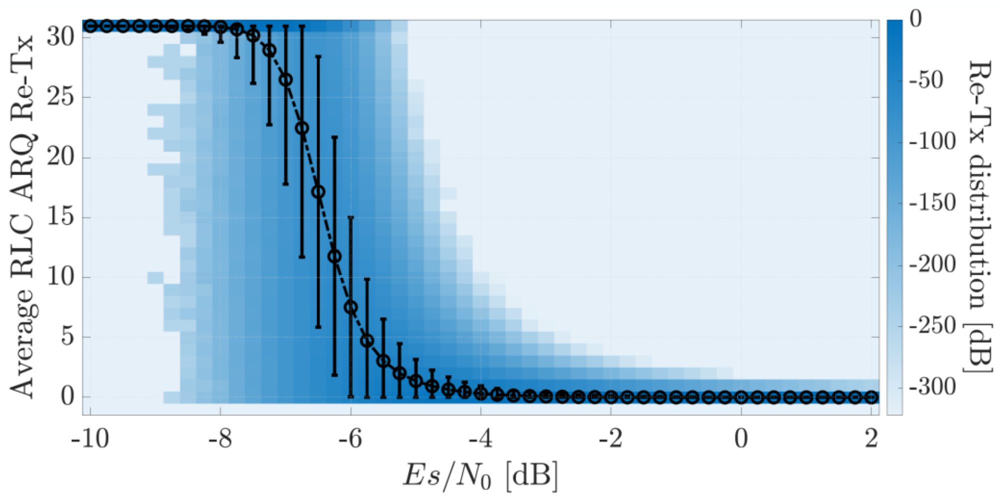


HARQ vs RLC ARQ – Latency – single MCS

Since the decoding events are independent, the number of retransmissions of RLC ARQ can be very high even for small SNR variations, which can be problematic in systems with large delays, such as NTN.

- The max number of retransmissions in RLC ARQ should be carefully chosen.





Latency due to RLC ARC and impact on applications

- We report some values of RLC ARQ delays with a different number of maximum retransmissions
- RLC ARQ latencies should consider the additional propagation delay for the feeder link, and at least 5 ms of network delay

$N_{\text{ReTx}}^{\text{MAX}}$	**LEO 1** θ 90° [ms]	**LEO 1** θ 30° [ms]	**LEO 2** θ 90° [ms]	**LEO 2** θ 30° [ms]	**MEO** θ 90° [ms]	**MEO** θ 30° [ms]
0	2.25	3.75	4.25	6.87	26.87	33.87
1	6.62	11.11	12.62	20.5	80.5	101.5
3	15.37	25.87	29.37	47.75	187.75	236.75
7	32.87	55.37	62.87	102.25	402.25	508.25
31	137.87	232.37	263.87	429.25	1689.25	2130.25

Application	**Maximum latency**
Voice and Videophone	preferred 150 ms, max 400 ms
Interactive games	75 ms
Web-browsing	2-4 sec
Streaming	10 sec
Immersive multi-modal VR	5-10 ms
Remote control robot	1-100 ms
Medical monitoring	100 ms

HARQ and RLC ARQ comparison with ACM

In the last set of simulations, we include an Adaptive Coding and Modulation (ACM) mechanism.

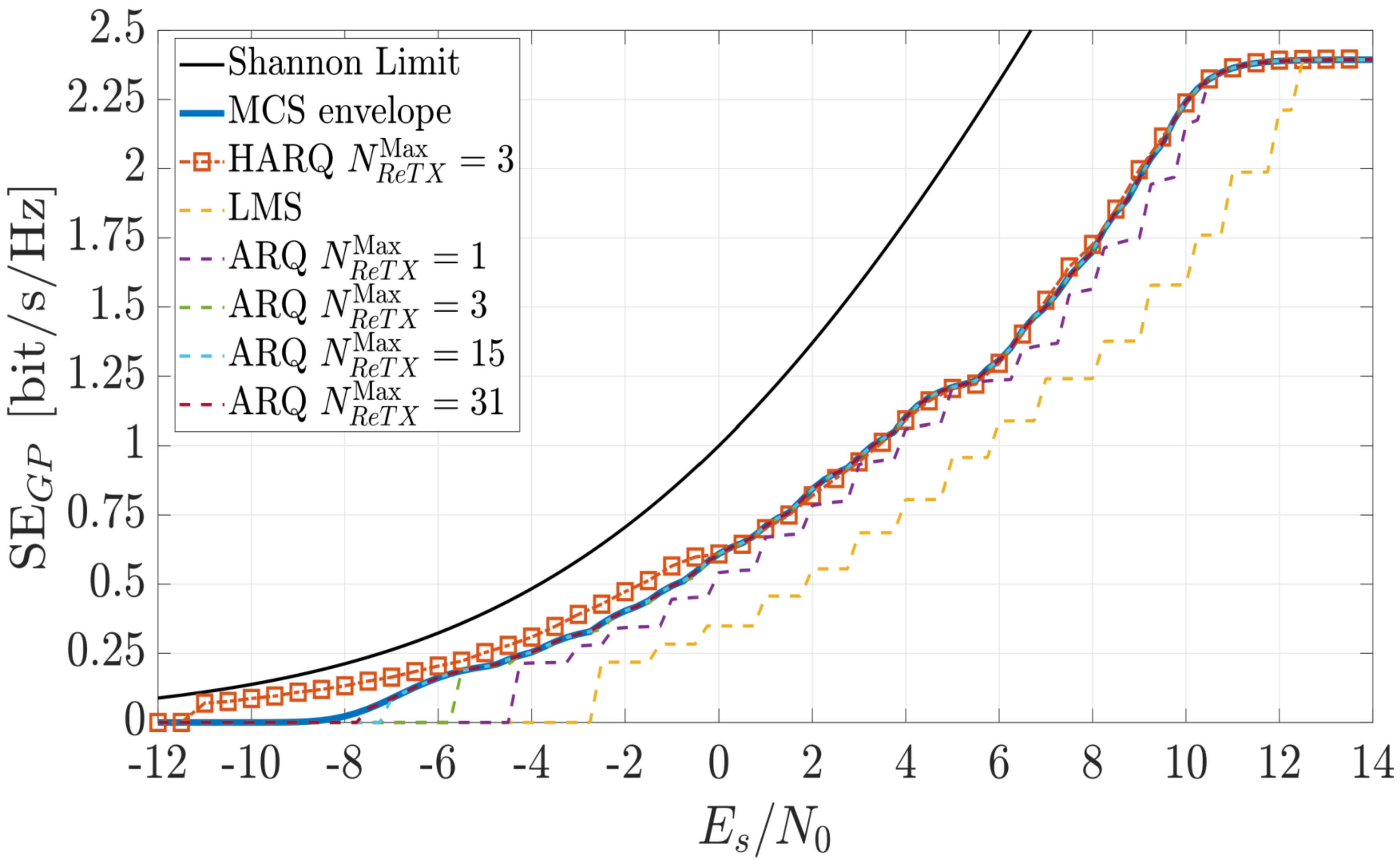
- Given a measured channel quality, ACM selects the MCS providing the maximum SE, given a threshold on the acceptable BLER (usually 10^{-3} or 10^{-5}, depending on the required QoS)

Test: HARQ SE envelope vs RLC ARQ SE envelope

1. Fix a certain target maximum BLER post retransmissions (10^{-3})
2. Determine the SE envelope for the entire SNR range, which is the maximum SE across all the MCSs for a certain SNR

This can provide a new look-up table for the ACM, which shows which MCS should be used at a certain SNR, assuming a particular retransmission mechanism.

HARQ vs RLC ARQ – ACM and LMS channel



RLC ARQ can recover most of the SE loss even with a low number of retransmissions.

Conclusions, open challenges, and future directions

Mobility for 5G NTN: Performance and Challenges of NTN over Mobile Channels

Considerations – 1/2

- HARQ clearly outperforms RLC ARQ in terms of BLER and SE, thanks to the coding and combining gain, allowing the decoding of codewords at SNRs much lower than the nominal MCS operational point.

- However, in typical NTN channels with VSAT terminals, the channel state (GOOD/BAD) variability is limited and the need of HARQ may be relatively low.

Environment	User speed	Average state duration
Train	250 km/h	372 ms
Highway	130 km/h	556 ms
Suburban	70 km/h	1.038 s
Urban	50 km/h	2.652 s

- For handheld and IoT terminals, HARQ may not even be an option considering the additional complexity required to exploit the gains stemming from incremental redundancy.

Considerations – 2/2

- For higher-than-LEO altitudes, HARQ requires an excessive number of parallel processes to limit the SE losses due to the stop-and-wait.
- HARQ may still be useful for extremely low SNRs or environments where LOS conditions may change rapidly.
- IoT devices may tolerate the use of the stop-and-wait strategy.
- A fast-enough ACM and RLC ARQ may guarantee acceptable results in most conditions. Nevertheless, particular care should be put on setting of maximum number of RLC ARQ retransmission, due to the resulting delay.

Conclusions

- The HARQ/RLC ARQ trade-off depends on a broad set of parameters (e.g., environments, terminal features, satellite orbits, elevation angle, etc.)
- 5G NR HARQ may not be a viable solution in several cases:
  - Terminals with limited computational capabilities, energy limitations, memory constraints (e.g., IoT, handheld)
  - Higher altitude orbits, as MEO and GEO, due to the excessive latency.
- RLC ARQ may be a preferable solution when:
  - The channel is approximately LOS only (e.g., very high K-factor)
  - The direct signal power changes slowly (slowly-varying shadowing), so that the ACM can provide an effective MCS selection.
- RLC ARQ must be carefully configured to avoid excessive delays.

Open 5G NTN challenges and future directions

- Tuning the number of HARQ processes for LEO and VLEO orbits
- Channel measurements and performance validation campaigns
- Synchronization without GNSS
- 5G-based positioning
- Support of beam-hopping
- AI for exploitation of non-terrestrial dynamics
- Cheap mass-product terminals
- Autonomous UAV
- Intelligent reconfigurable surfaces

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Q&A

Thank you

Nicolò Mazzali (nicolo.mazzali@ext.esa.int)
Riccardo Tuninato (riccardo.tuninato@ext.esa.int)

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