TECHNICAL INSIGHTS INTO IMPLEMENTING 5G NTN USER EQUIPMENT

POL HENAREJOS, MARIUS CAUS

CENTRE TECNOLÒGIC DE TELECOMUNICACIONS DE CATALUNYA-CERCA (CTTC-CERCA)

Centre Tecnològic de Telecomunicacions de Catalunya

Horizon Europe research and innovation programme
[grant agreement No 101081983]

Smart Networks and Services Joint Undertaking (SNS JU)
[Grant Agreement No 101096573]

CTTC ORGANIZATION

CTTC is working on satellite communications for 15 years

The performance evaluation has been carried out in the Space and Resilient Communications and Systems (SRCOM) research unit

The main goal of SRCOM is to contribute to defining the evolution of future new space communication systems, spanning from inter-satellite links to fixed and mobile space-to-Earth communication towards intelligent space systems with autonomous operation integrated with the terrestrial telecom infrastructure and cloud and storage services.

Research and Development Team

Pol Henarejos

Erislandy Mozo

Amedeo Giuliani

Marius Caus

Head of SRCOM

Miguel A. Vázquez

OUTLINE

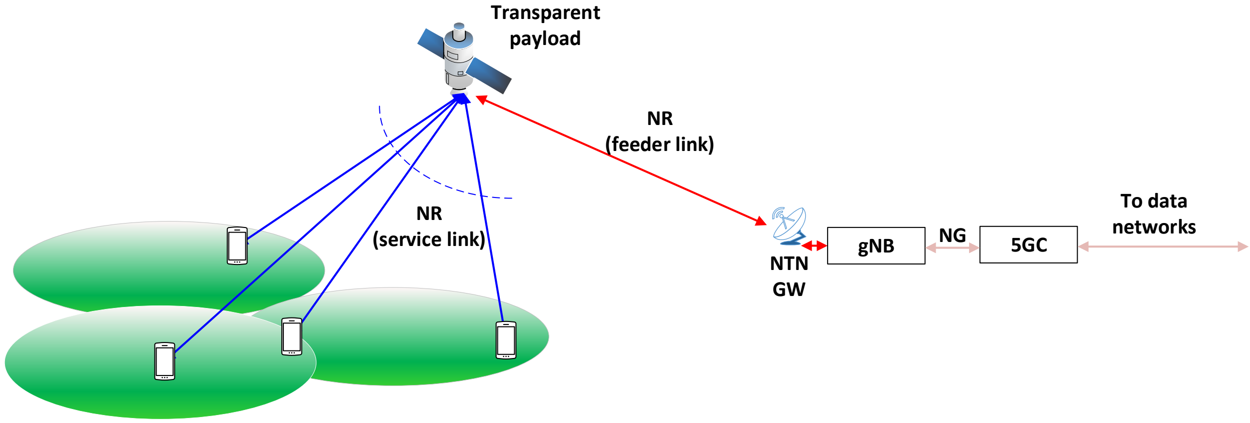
- ARCHIECTURE DEFINITION
- SATELLITE CHANNEL IMPAIRMENTS
- ATTACHMENT PROCEDURE
- OVERVIEW
- LAB SETUP
- LAB RESULTS
- FIELD TRIALS
- PLANNED TRIALS

ARCHITECTURE DEFINITION

ARCHITECTURE OPTIONS FOR DIRECT CONNECTION

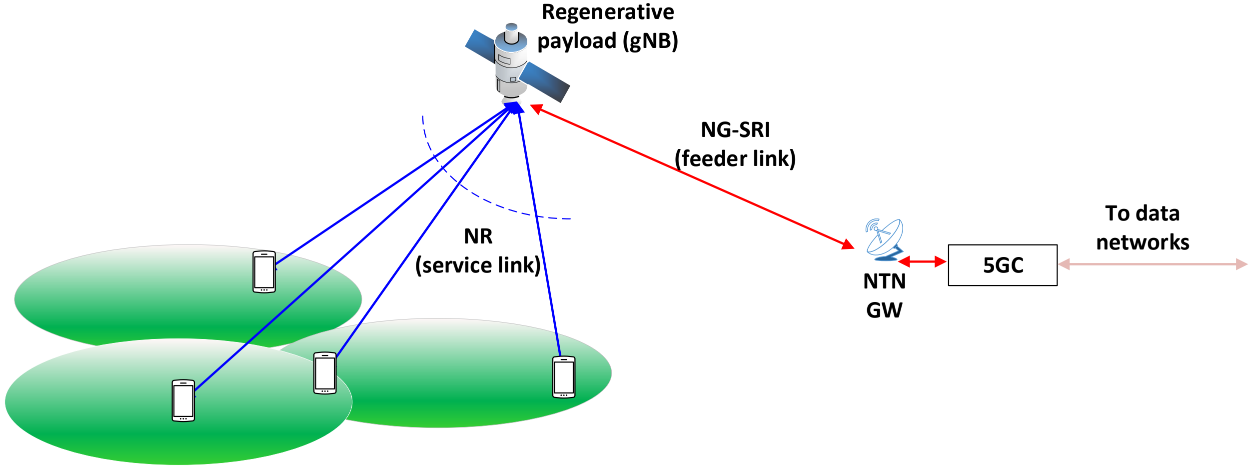
Transparent architecture (Rel. 17 & Rel. 18)

- The NR protocol stack terminates on-ground
- NR is transmitted over service and feeder links
- The gNB is located at the gateway
- Longer propagation delays in the network
- Low complexity



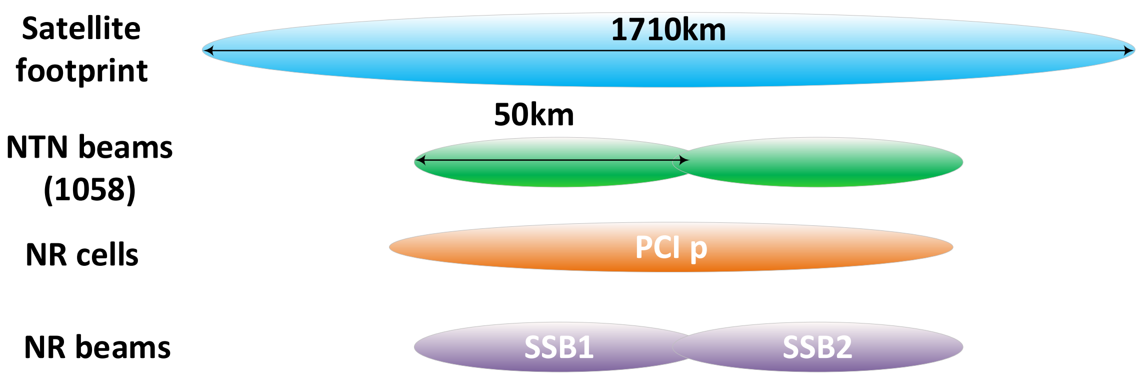
Regenerative architecture (Rel. 19)

- The NR protocol stack terminates on-board
- NR is transmitted over service links
- The link between the gNB and the 5GC can use any suitable air interface, e.g., the DVB-S2X
- Shortest propagation delays in the networks
- High complexity

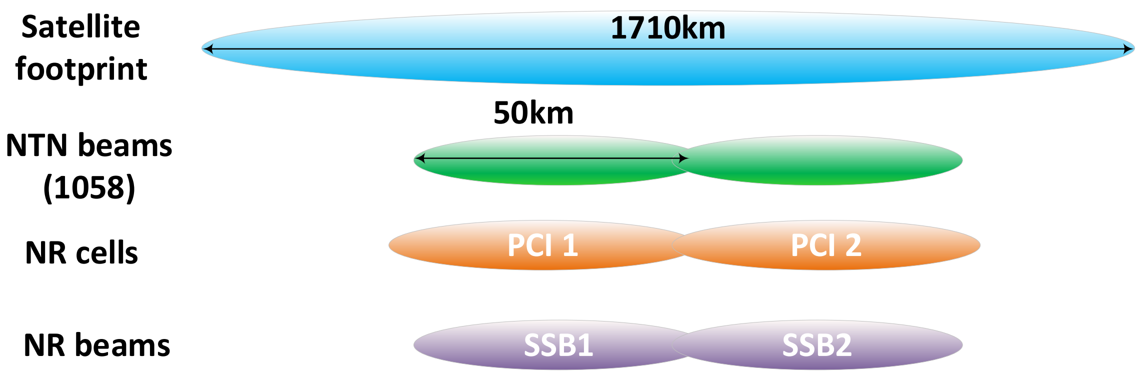


CELL MAPPING SCHEMES

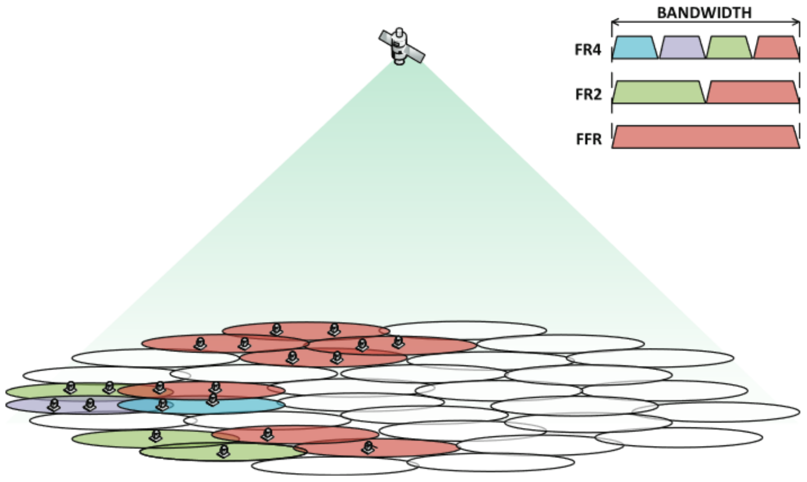
Multi-Satellite beam cell and multi NR beam cell



Single NR cell per satellite beam and single NR beam cell



- The satellite coverage area is divided into multiple beams
- Full frequency reuse setup would require all beams to operate on the same frequencies, leading to potential interference issues
- Adopting beam hopping or frequency reuse can minimize inter-beam interference



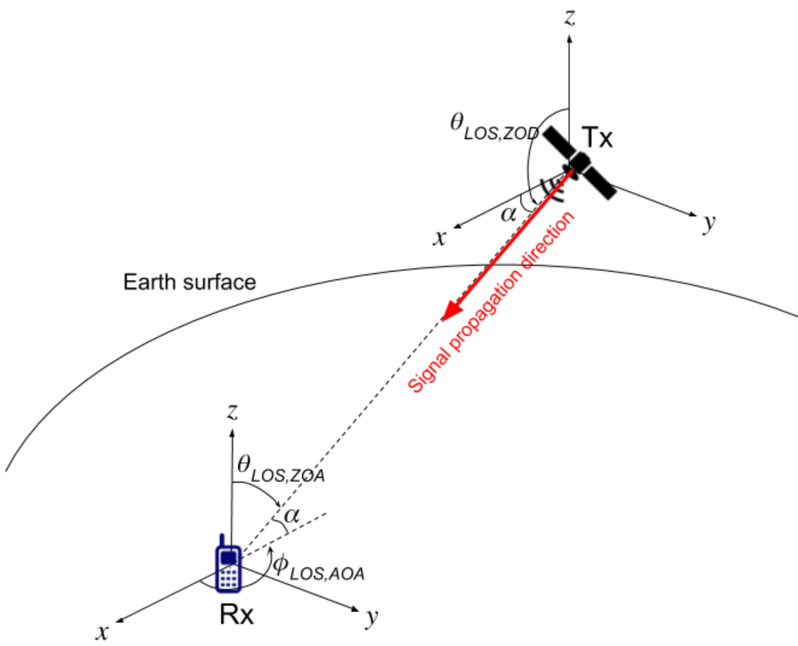
SATELLITE CHANNEL IMPAIRMENTS

PATH LOSS

In 3GPP NTN specifications, the channel model to be considered for system-level analyses and link budget calibration assumes UEs always in LOS conditions

The overall path loss is computed as:

$$L = L^{(fs)} + L^{(sha)} + L^{(atm)} + L^{(sci)}$$



- **Free Space Loss:** $L^{(fs)} = 32.45 + 20\log_{10} f[\text{GHz}] + 20\log_{10} d[\text{m}]$
- **Shadowing:** $L^{(sha)}[\text{dB}] \sim \mathcal{N}\left(0, \sigma_{sha}^2\right)$
- **Atmospheric losses:** $L^{(atm)} = \frac{A_{zenith}(f)}{\sin \varepsilon}$
- **Scintillation losses:** In S-band, ionospheric scintillation is considered only for latitudes within $\pm 20°$ and neglected in all other cases. When considered, it is fixed at $L^{(sci)} = 2.2$ dB.

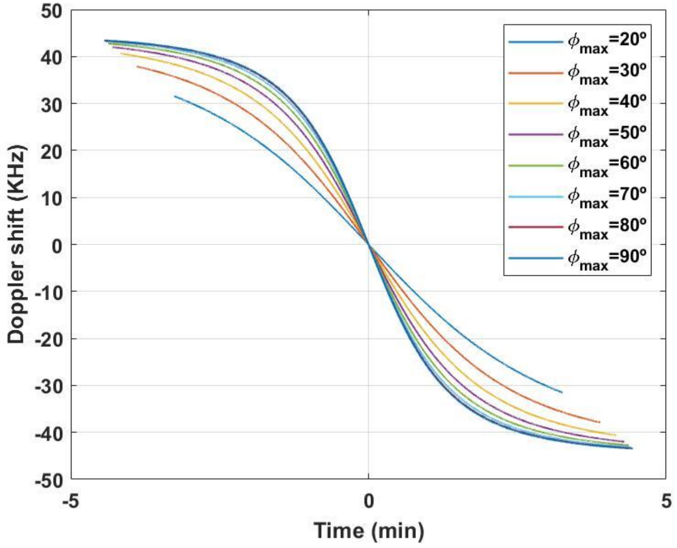
CARRIER FREQUENCY OFFSET AND DELAY

The effects that contribute to the DL CFO are divided into:

- UE and satellite oscillator offsets
- UE and Satellite Satellite Doppler frequency shifts

Constellation	LEO 600 km		LEO 1200 km	
Scenario	Airway	Stationary	Airway	Stationary
CFO (KHz)	70.6	69	62.6	61

Doppler frequency shift at LEO 600 km



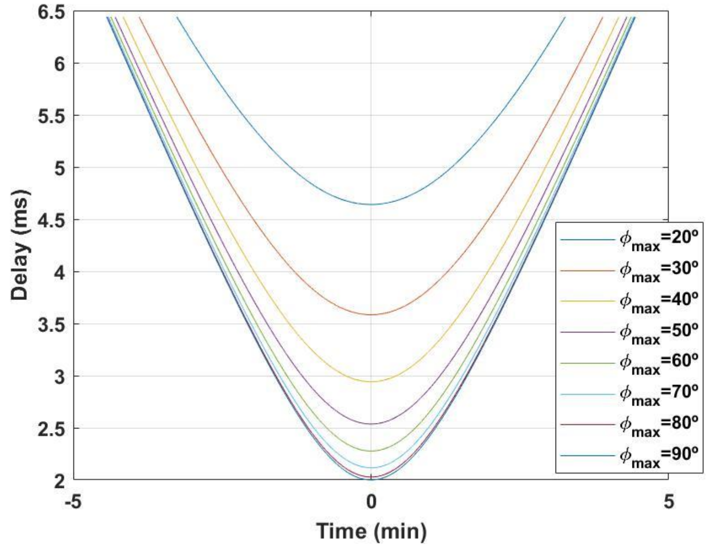
In most of the terrestrial deployments: Doppler<1KHz

To estimate the delay, a pessimistic scenario is assumed:

- $\theta_{GW-SAT} = 5º$
- $\theta_{SAT-UE} = 10º$

Constellation	GEO	LEO 600 km
One-way (ms)	272.37	14.2
RTT (ms)	544.75	28.4

SAT-UE propagation delay at LEO 600 km

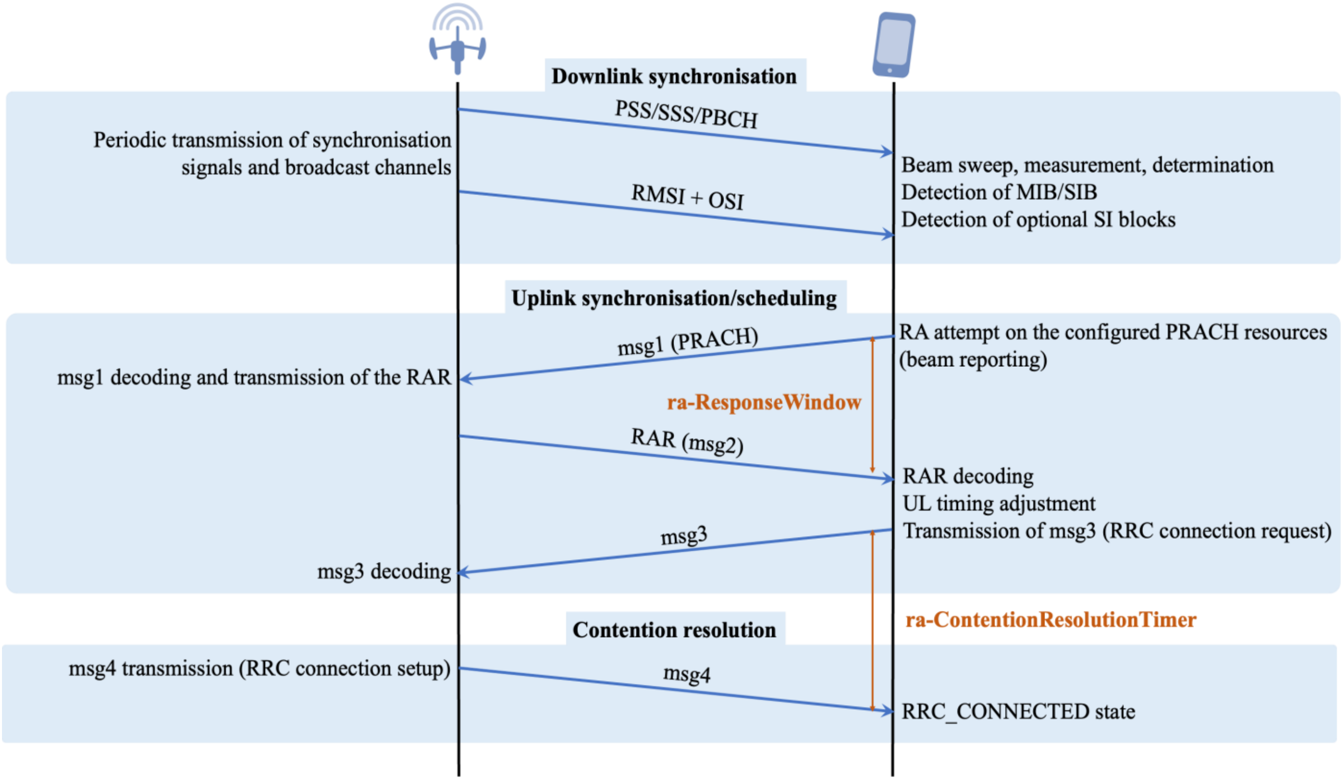


In most of the terrestrial deployments: Delay<0.66ms

ATTACHMENT PROCEDURE

CONNECTION ESTABLISHMENT

Exchange of messages to go from the idle to the connected state



Connection establishment:

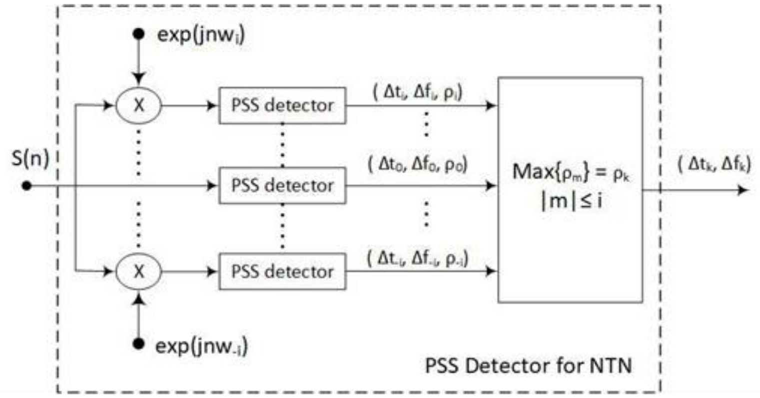
- Broadcast transmission
- Cell search
- UE reads SIBs
- Pre-compensation
- Preamble transmission
- Random access response
- Connection request
- Contention resolution

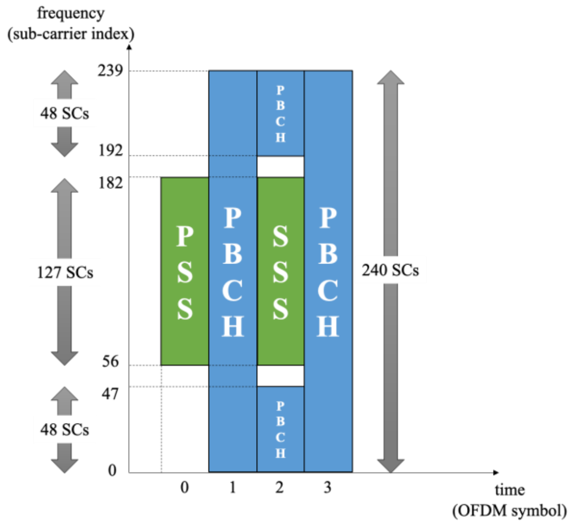
CELL SEARCH

The Cell Search procedure is used by the UE to acquire the time and frequency synchronisation in the cell and to detect the physical cell ID (PCI)

To this aim, a signal synchronization bock (SSB) is periodically transmitted in the DL of each cell. The SSB consists of: PSS, SSS and PBCH

- If the CFO is lower than the subcarrier spacing (SCS), the synchronization performed in terrestrial deployments can be reused
- Otherwise, a parallel correlator with multiple hypothesis testing shall be implemented





PSS: used for the detection of the initial symbol boundary and initial frequency synchronisation

SSS: used for the identification of the radio frame boundary and of the PCI; (together with the PSS, there are $3 \cdot 336 = 1008$ PCIs), obtained as the combination of two BSPK modulated m-sequences

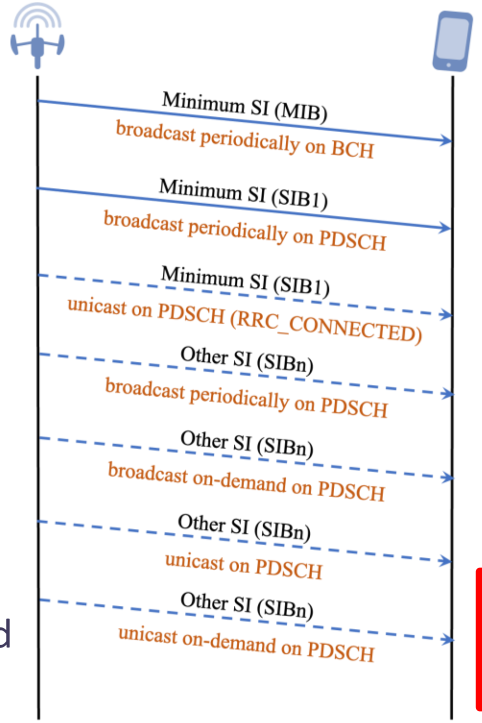
PBCH: provides the System Frame Number (SFN), Sub-Carrier Spacing (SCS) and information on how to detect the system information block 1 (SIB1)

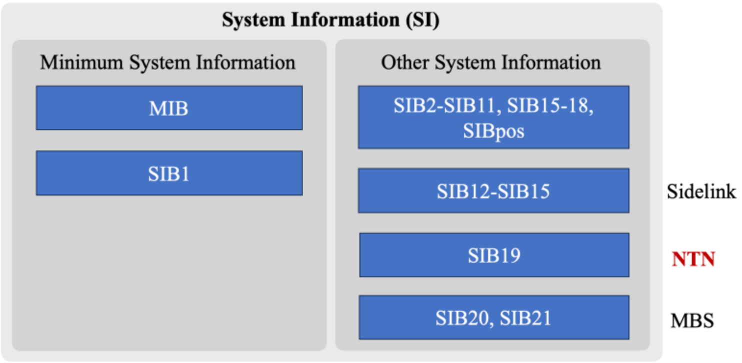
UE READS SIBS

SIB1 contains information about random access configuration that the UE needs in order to carry out random access procedure. SIB1 provides the scheduling of the other information blocks

There are many SIB types, but SIB19 has been specifically introduced in Rel. 17 for NTN and it provides:

- **Ephemeris data**
  ECEF coordinates or orbital coordinates
- **Common-TA parameters**
  Delay between GW and payload
- **K-offset, Kmac**
  Larger than maximum Service link and Common-TA sets offset between DL & UL
- **Epoch time**
  The time at which this ephemeris & Common-TA is valid
- **Validity duration**
  The duration for which the ephemeris & Ta are valid
- **List of NTN neighbouring cells**
  Including their ntn-Config, carrier frequency and PCI



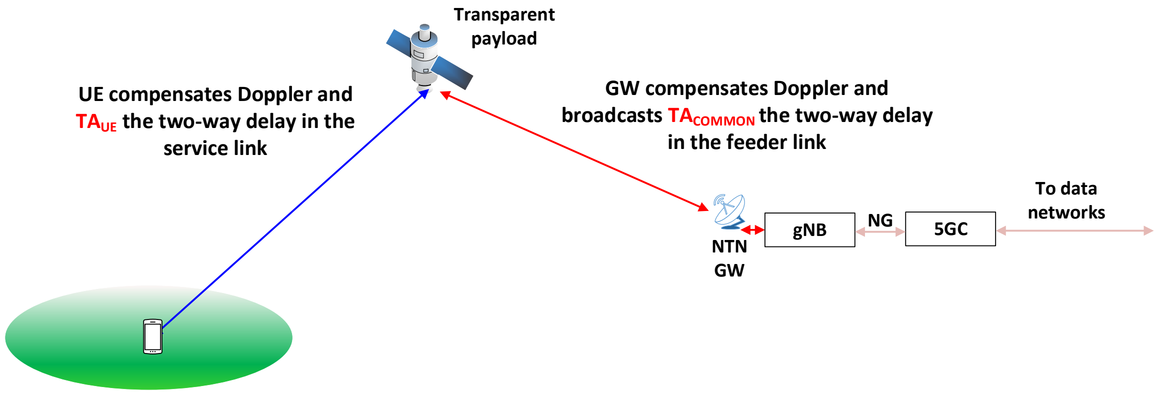


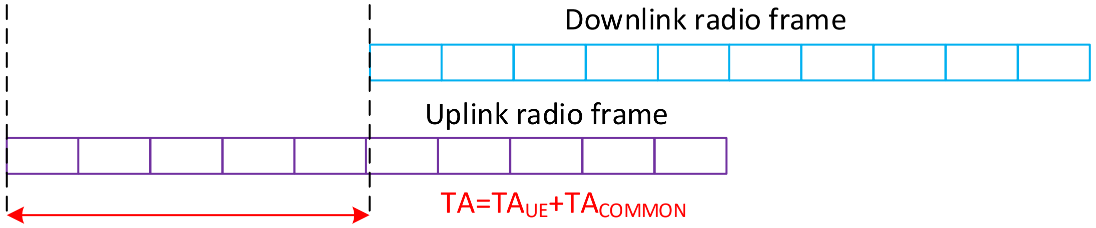
MOST IMPORTANT PARAMETERS:
K-OFFSET & UE DELAY

PRE-COMPENSATION

Legacy UEs cannot cope with the large round trip delays and Doppler shifts experienced in NTN. To this aim, the standard has introduced enhancements:

- UE shall be able to self-acquire its position via GNSS assisted information
- UE shall be capable of predicting a satellite orbit (position and velocity) based on ephemeris information and common delay broadcasted in SIB19





Using GNSS and SIB19 the UE is able to involve the RTT delay in all procedures and compensate the Doppler frequency shift in the service link

The Doppler effects in the feeder link are handled by the gateway

RANDOM ACCESS RESPONSE

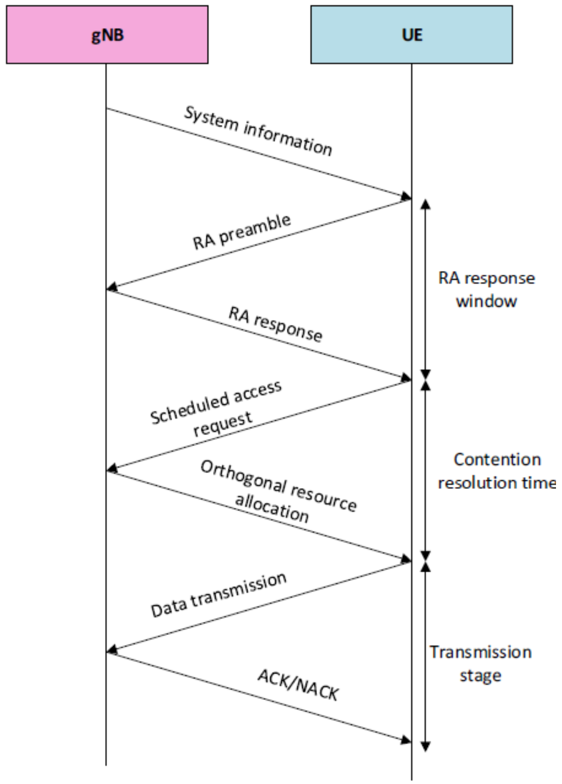
The UE starts monitoring the PDCCH for the RA Response (RAR) or msg2) based on the RA-RNTI

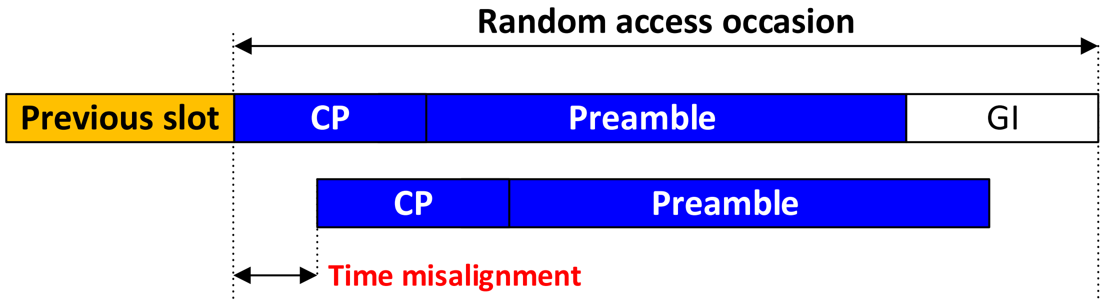
This time window starts at a predefined time interval after the transmission of msg1

In case no RAR is received by the UE within the RAR window, it is assumed that the RA procedure failed and a new attempt can be made

The start of the window in NTN is delayed by an additional offset corresponding to the estimated UE-gNB RTT

Decoding the msg2 allows the UE to define the resources to be used for msg3 on the PUSCH and whether it shall use the TA command for timing adjustment





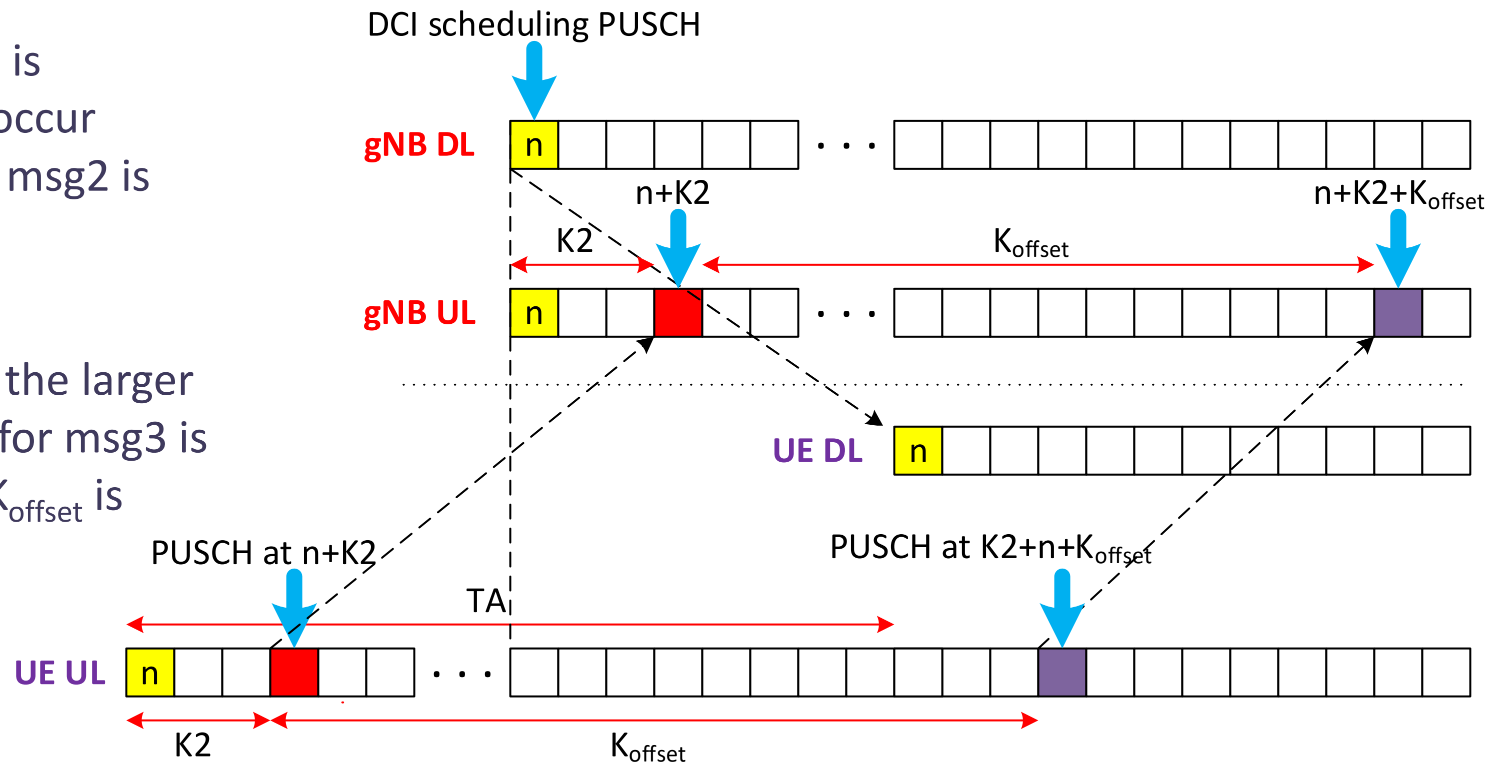
CONNECTION REQUEST

- Prior to Rel. 17, assuming that msg2 was received in slot n, the uplink slot where the UE shall transmit the msg3 is determined as slot n+k2

- In NTN, the UE needs to apply a timing advance (TA) to compensate the RTT between UE and the gNB

- The uplink slot $n+K2$ where msg3 is supposed to be transmitted may occur before the downlink slot n where msg2 is received

- For NTN access, to accommodate the larger propagation delays, the start slot for msg3 is computed as n+k2+K_{offset}, where K_{offset} is usually set as the maximum RTT



CONTENTION RESOLUTION

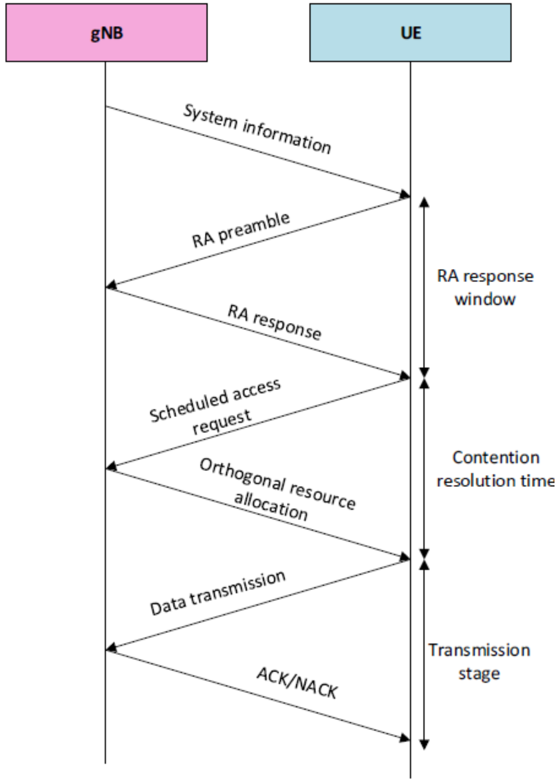
Once msg3 has been transmitted, the UE starts another timer and start monitoring the PDSCH for msg4

The maximum value of the Timer defined for TNs is sufficient to accommodate the large RTT over NTN channels

In order to reduce the power consumption of the UE, the behaviour of the contention resolution timer has been modified in Rel. 17 NTN so as to start with a delay equal to TA

After processing msg3, the gNB sends msg4 which contains the UE's identity, confirming that the gNB has correctly identified the UE, and that potential contentions have been resolved.

At this step, the network assigns to the UE a Cell RNTI (C-RNTI)



HARQ

The hybrid automatic repeat request (HARQ) functions as a stop-and-wait protocol

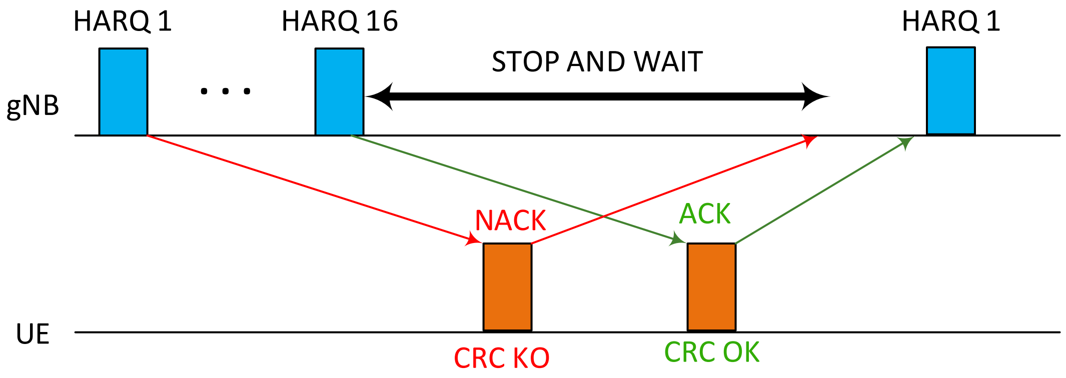
5G TN allows for 16 parallel transmissions. After transmission, each HARQ ID waits for either ACK or NACK

The time to wait for feedback in a transparent-payload GEO satellite is excessively long, and during this time, a particular HARQ ID will not be unavailable

HARQ stalling. The scheduler has to wait until one of the active HARQ processes is released.

To remedy these issues with HARQ, the following solutions have been proposed:

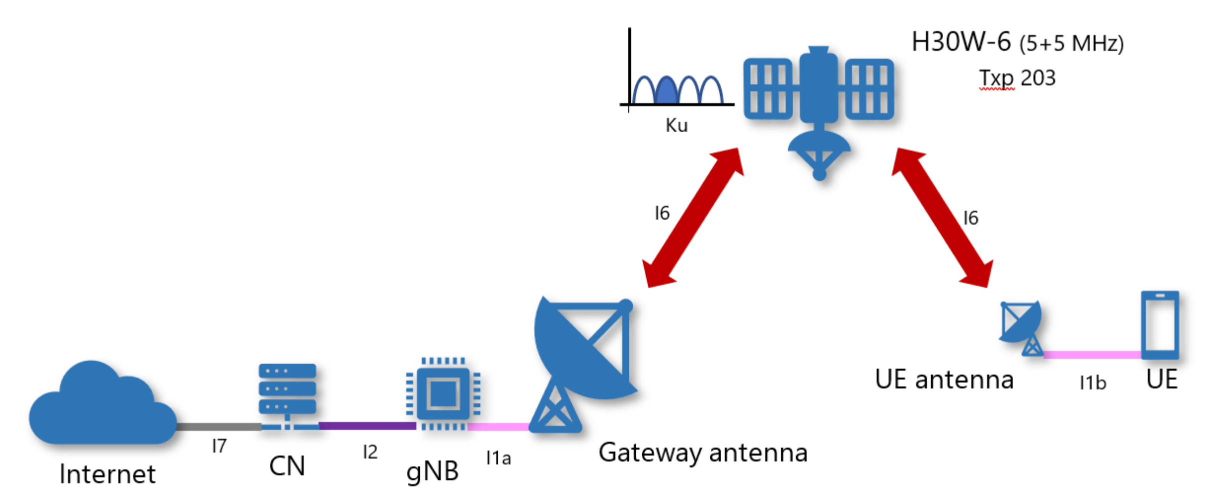
- Increasing the number of HARQ processes to 32 (only suitable for LEO)
- disabling HARQ entirely and relying on radio link control acknowledgement mode for re-transmissions



OVERVIEW

OVERVIEW

Baseline scenario



- **Interface I1a**: (air) gateway ←→ gNB-A developed by **CTTC** and **HIS**. This interface will work in the L band, and it will convey the enhanced 5G waveform.
- **Interface I1b**: UE-A antenna ←→ UE-A, developed by **CTTC** and **HIS**. This interface will work in the L band, and it will convey the enhanced 5G waveform. Besides, it will also convey the necessary information to perform beam management procedures for accurate antenna pointing.
- **Interface I2**: (wire) gNB ←→ CN, developed by **SRS**. This interface conveys the messages between the CN and UE, via the selected gNB-A.
- **Interface I6**: (wire) Satellite ←→ gateway/UE antenna, developed by **HIS**. This interface will convey the waveform generated by the gNB to the satellite and to the UE antenna.
- **Interface I7**: (wire) CN ←→ Internet, already developed by common CN. This interface communicates the CN with the internet. It is IP based. Implementation: parts in lab or in house

OVERVIEW
Ground segment

LAB SETUP

LAB TESTS

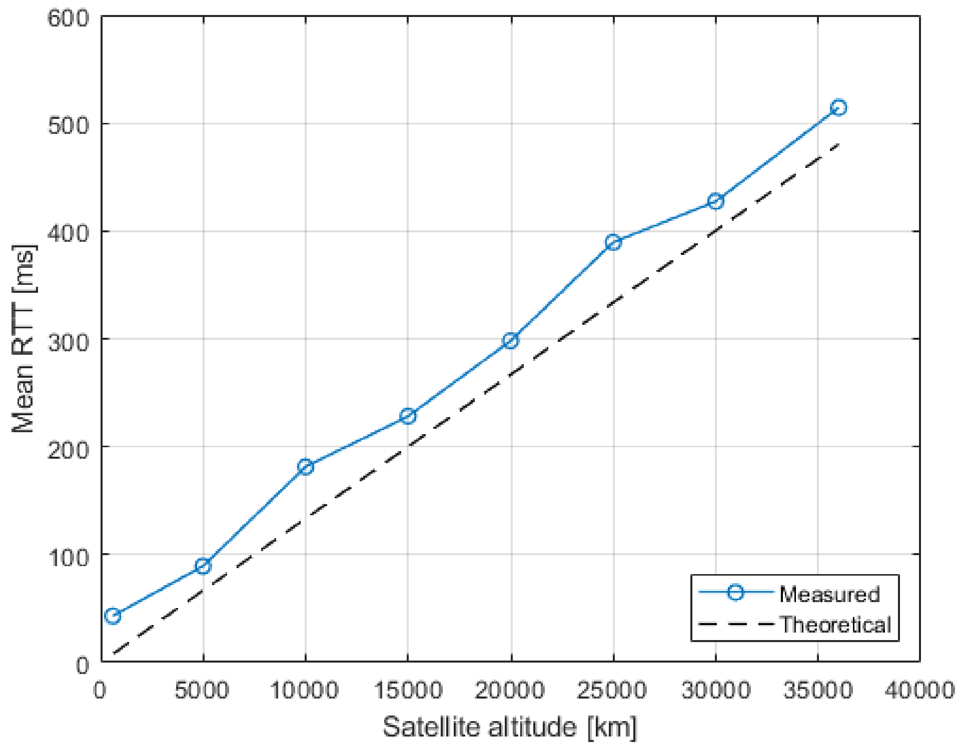
Specification	Description
RF ports	Up to: ➤ 16 bidirectional TRX ports ➤ 16 unidirectional TX and RX ports SMA-female connectors at all ports Bidirectional and unidirectional fading
Frequency range	3 MHz to 6 GHz With unit E7770A: 6 GHz to 12 GHz or 7 GHz to 15 GHz With unit M1740A: 24.25 GHz to 29.5 GHz and 37 GHz to 43.5 GHz
Doppler emulation	Up to ±1.5 MHz, requires F8820ACEA option
Channel models	3GPP 5G NR TDL LTE, WCDMA, GSM, and Static Butler
Fast fading profiles	Constant, Rayleigh, Rice, Nakagami, Lognormal, Suzuki, Pure Doppler, flat, rounded, Gaussian, Jakes, Butterworth, user-defined, and CIR data from 3rd party simulation tools
Delay profiles	Constant, sliding delay, 3GPP birth-death, 3GPP sliding delay group, user- defined, delay profiles from 3rd party simulation tools, ray-tracing applications
Interference sources	CW ➤ Independent uncorrelated sources at each output port ➤ Adjustable frequency offset ➤ Absolute and SNR based level settings AWGN ➤ Independent uncorrelated sources at each output port ➤ User adjustable BW and frequency offset ➤ Absolute and SNR based level settings Arbitrary Waveform interference PathWave Signal Generation generated waveforms
CA support	Contiguous up to 1200 MHz (TDD or FDD) Non-contiguous up to 8 CA bands
Independent RF oscillators	Up to 8
Minimum delay	2.6 µs
Maximum delay	1000 ms, requires F8820ACEA option

Parameter	Value
Frequency	DL: 1842.50 MHz, UL: 1747.5 MHz
Bandwidth	5 MHz
Delay	Variable, depends on satellite altitude

LAB RESULTS

RESULTS LAB TEST

Measured RTT

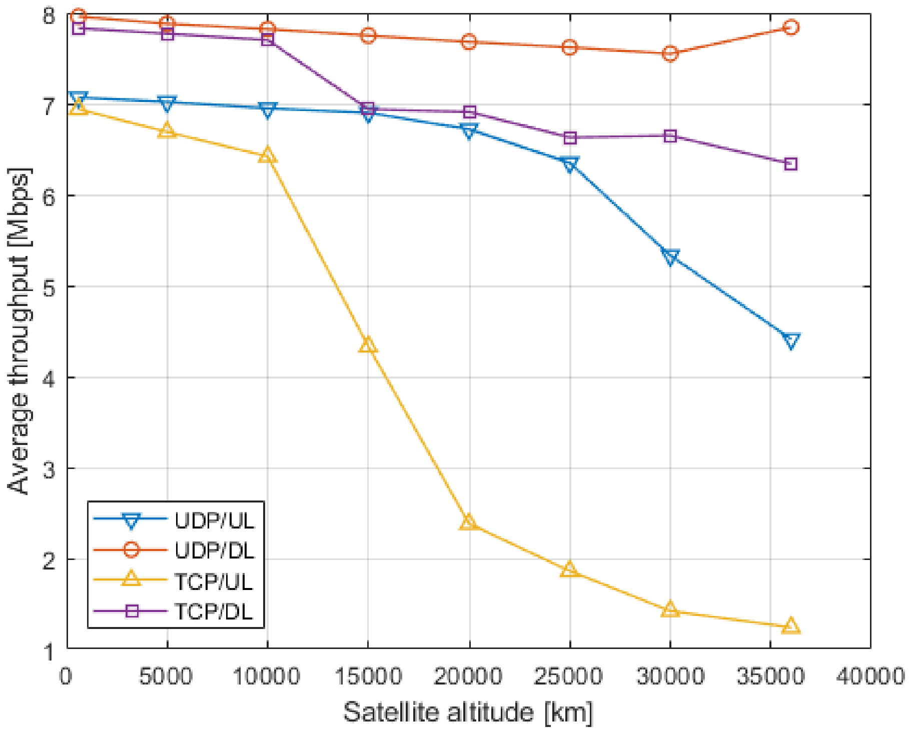


Theoretical $d = \frac{2(l_{service}+l_{feeder})}{c}$

Measured using ping tool

RESULTS LAB TEST

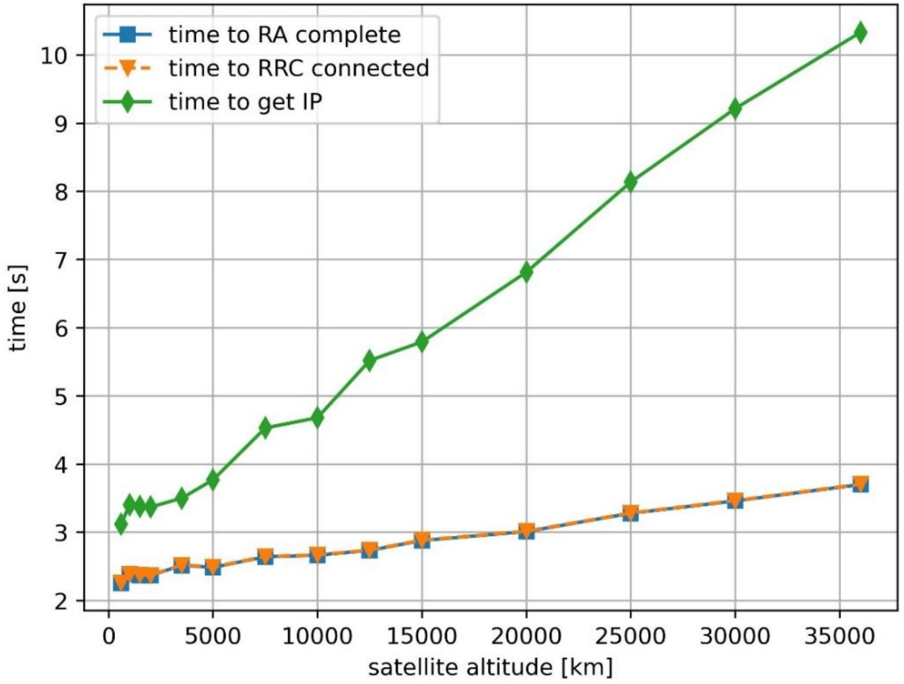
Throughput



Throughput using iperf3 tool with TCP and UDP in DL and UL.

RESULTS LAB TEST

Latency



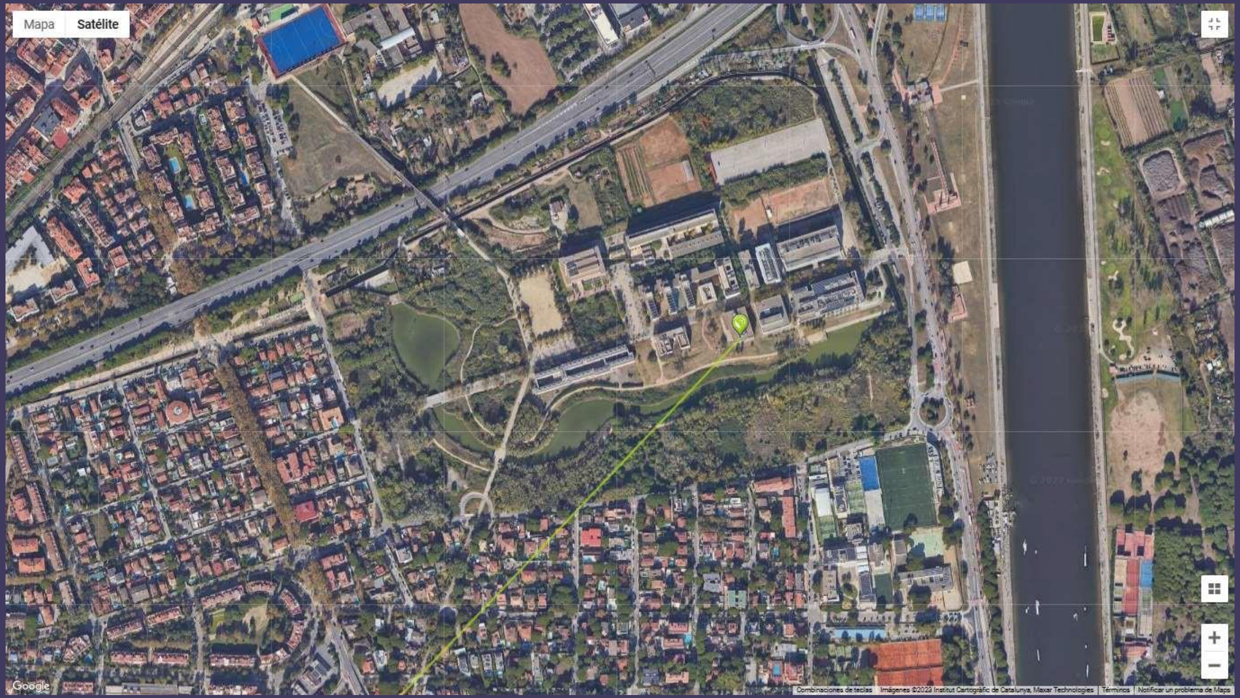
Time to RA: involves SSB, SIB1, SIB19 and PRACH (Msg1)

Time to RRC: involves RAR (Msg2), Msg3 and Msg4.

Time to get IP: involves multiple RRC procedures up to set up of PDN.

FIELD TRIALS

FIELD TRIALS

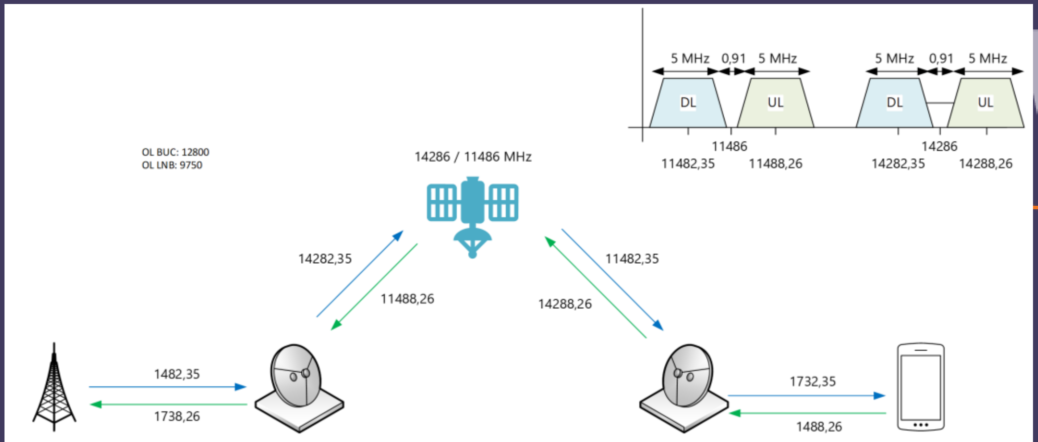


Parameter	Value
Effective Antenna	2.4 m
Operating Frequency	Tx 13.75 -14.50 GHz Rx 10.7 - 12.75 GHz
Polarization	Linear
Gain	Tx 49.1 dBi at 14.3GHz Rx 47.7 dBi at 12 GHz
Typical G/T (EL = 10º)	26.7 dB/K (70 K LNA)

FIELD TRIALS

1. The signal generated at UE side (which is contained in the "UL" slot, green color) will first be upconverted from 1488.26 MHz (L band) to 14288.26 MHz (Ku band)
2. It reaches the satellite, which, before relaying the signal to the gNB antenna, it will translate the frequency to 11488.26 MHz, thus shifting the center frequency by 3 GHz
3. When the signal reaches the gNB antenna, it will be downconverted to 1738.26 MHz (again L band)

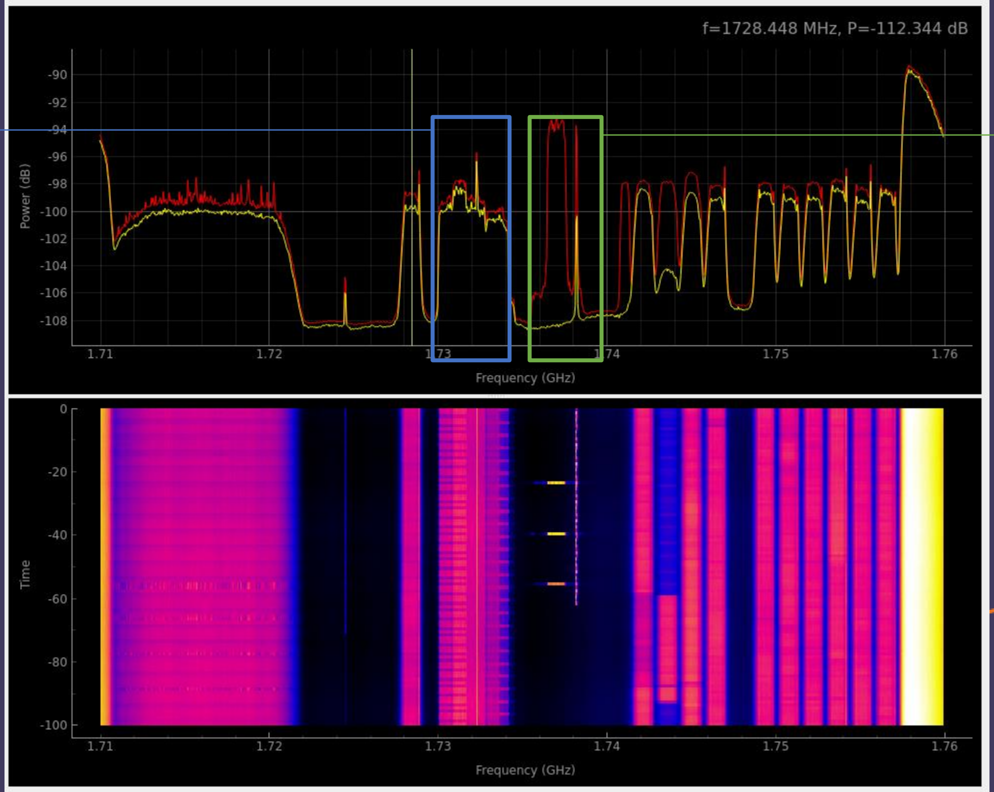
Parameter	Value
Manufacturer	Space System Loral
Launch date	2017
Launcher	SpaceX
Orbital Position	30ºW
Coverage	Europe, North Africa and America
Operational transponders	40 Ku + 10 C + 7 Ka spots
Transponder Bandwidth	Ku and C: 36MHz - 72 MHz Ka: 225 MHz



FIELD TRIALS

Spectrum received by gNB

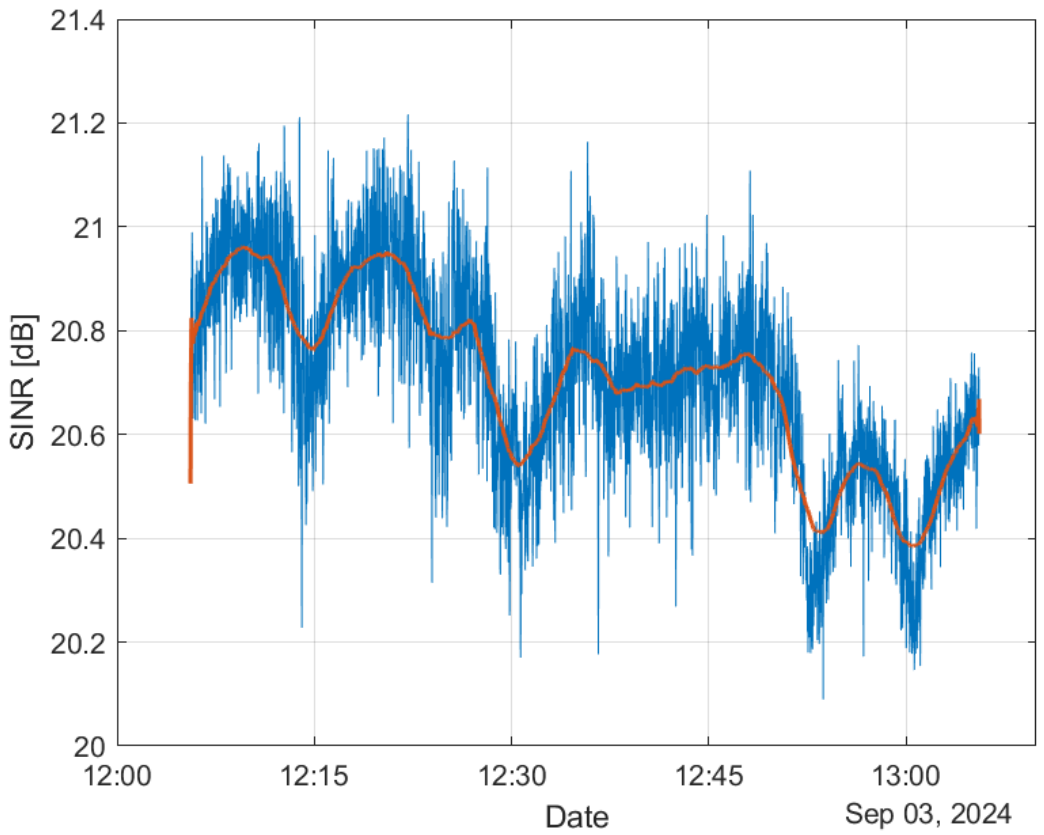
Downlink
gNB → UE

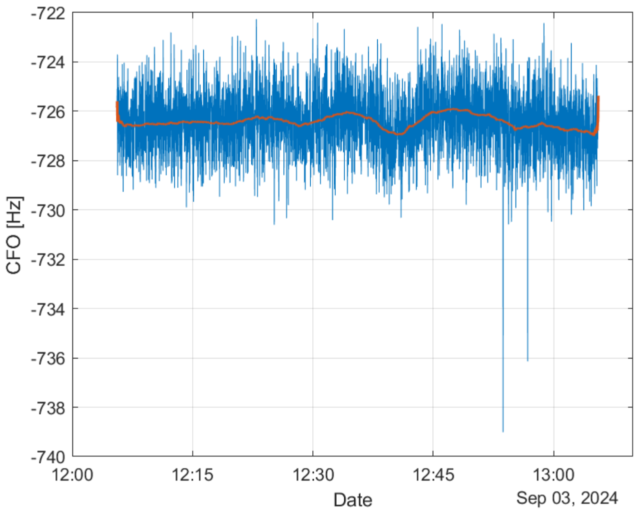


Uplink
UE → gNB

RESULTS LAB TEST

Signal strength (SINR)

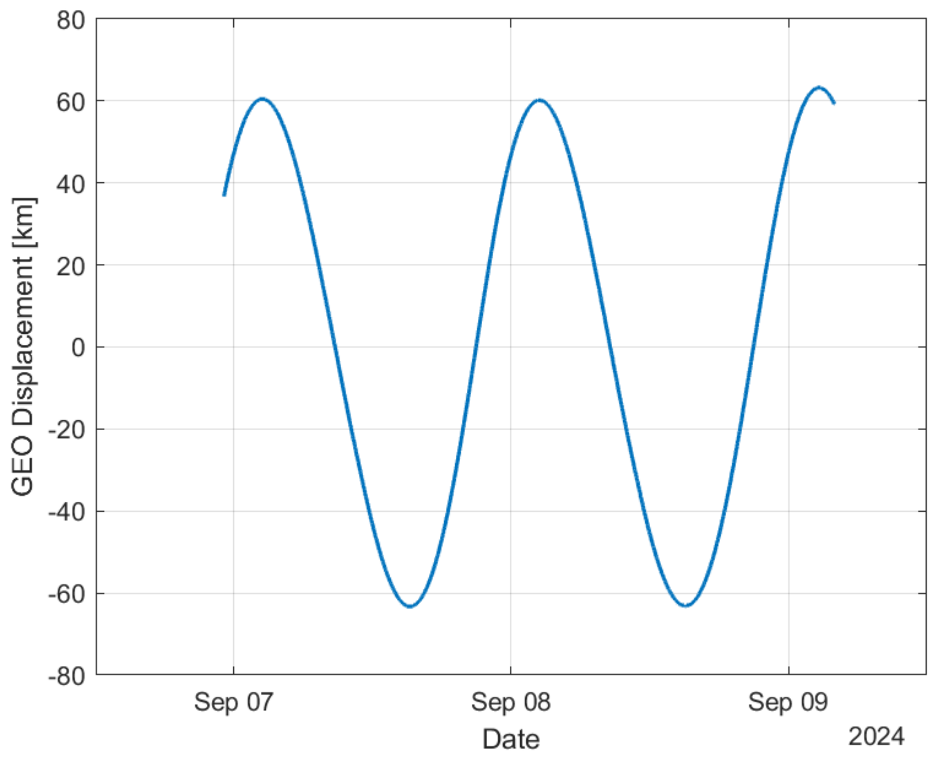




RESULTS LAB TEST

Delay variation due to GEO movement

$$d = \frac{c}{4} \frac{16}{15000 \times 2048} \mathrm{TA} \approx 39 \times \mathrm{TA}\ [m]$$



RESULTS LAB TEST

5G stardust

TRANTOR

Delay measurement

Metric	Value	Description
Time to Cell Search	262.946 ms	Time elapsed searching for the cell
Msg2-Msg1	1052.003 ms	Time elapsed between RACH and RAR (Msg1 and Msg2)
Msg4-Msg3	3189.811 ms	Time elapsed between Msg4 and Msg3.
RA Procedure	4241.814 ms	Overall time of Random Access procedure.
Session Attachment	5012.258 ms	Time of RRC configuration.
Time to IP	9497.703 ms	Overall time between boot and get an IP.

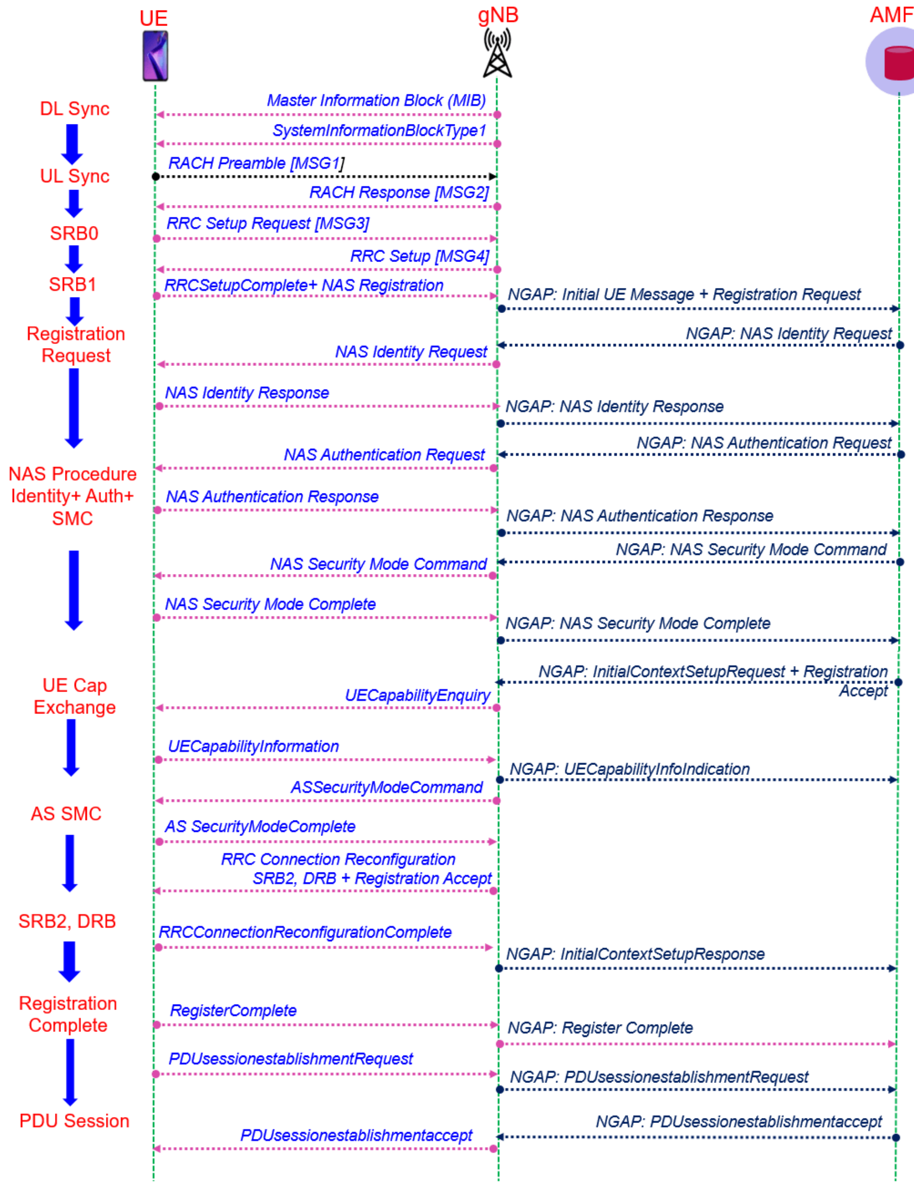
```
phenarejos@castle-jupiter:~$ ping 10.45.0.1 -c 15
PING 10.45.0.1 (10.45.0.1) 56(84) bytes of data.
64 bytes from 10.45.0.1: icmp_seq=1 ttl=64 time=1080 ms
64 bytes from 10.45.0.1: icmp_seq=2 ttl=64 time=553 ms
64 bytes from 10.45.0.1: icmp_seq=3 ttl=64 time=1153 ms
64 bytes from 10.45.0.1: icmp_seq=4 ttl=64 time=617 ms
64 bytes from 10.45.0.1: icmp_seq=5 ttl=64 time=578 ms
64 bytes from 10.45.0.1: icmp_seq=6 ttl=64 time=697 ms
64 bytes from 10.45.0.1: icmp_seq=7 ttl=64 time=818 ms
64 bytes from 10.45.0.1: icmp_seq=8 ttl=64 time=938 ms
64 bytes from 10.45.0.1: icmp_seq=9 ttl=64 time=1058 ms
64 bytes from 10.45.0.1: icmp_seq=10 ttl=64 time=1161 ms
64 bytes from 10.45.0.1: icmp_seq=11 ttl=64 time=640 ms
64 bytes from 10.45.0.1: icmp_seq=12 ttl=64 time=600 ms
64 bytes from 10.45.0.1: icmp_seq=13 ttl=64 time=720 ms
64 bytes from 10.45.0.1: icmp_seq=14 ttl=64 time=840 ms
64 bytes from 10.45.0.1: icmp_seq=15 ttl=64 time=960 ms

--- 10.45.0.1 ping statistics ---
15 packets transmitted, 15 received, 0% packet loss, time 14040ms
rtt min/avg/max/mdev = 553.224/827.459/1161.212/209.995 ms, pipe 2
```

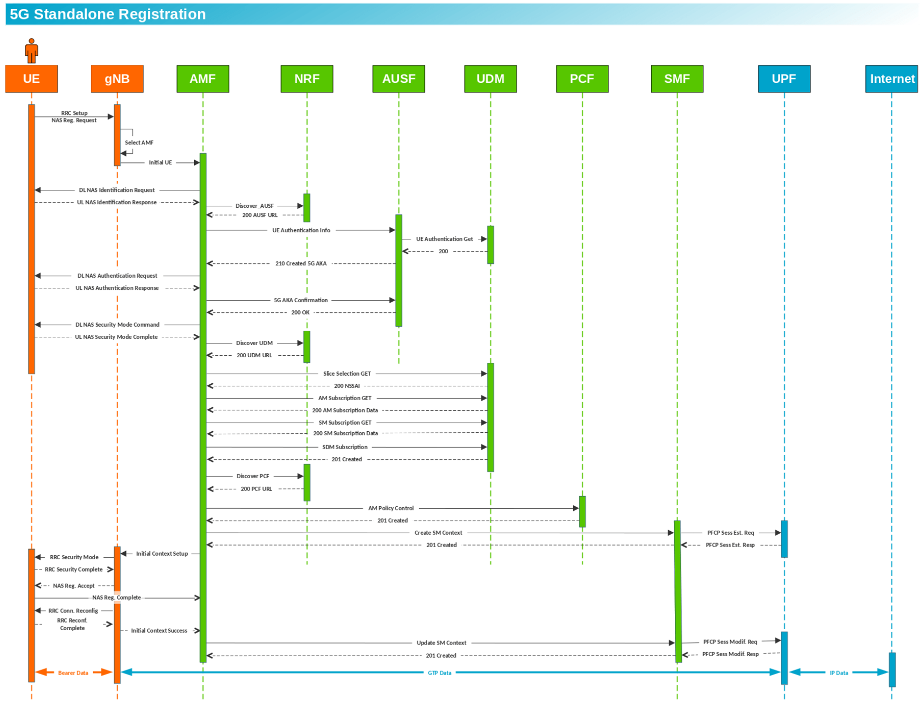
UE → CN

```
phenarejos@castle-sun:~$ ping 10.45.0.11 -c 15
PING 10.45.0.11 (10.45.0.11) 56(84) bytes of data.
64 bytes from 10.45.0.11: icmp_seq=1 ttl=64 time=1183 ms
64 bytes from 10.45.0.11: icmp_seq=2 ttl=64 time=657 ms
64 bytes from 10.45.0.11: icmp_seq=3 ttl=64 time=656 ms
64 bytes from 10.45.0.11: icmp_seq=4 ttl=64 time=616 ms
64 bytes from 10.45.0.11: icmp_seq=5 ttl=64 time=575 ms
64 bytes from 10.45.0.11: icmp_seq=6 ttl=64 time=617 ms
64 bytes from 10.45.0.11: icmp_seq=7 ttl=64 time=654 ms
64 bytes from 10.45.0.11: icmp_seq=8 ttl=64 time=615 ms
64 bytes from 10.45.0.11: icmp_seq=9 ttl=64 time=575 ms
64 bytes from 10.45.0.11: icmp_seq=10 ttl=64 time=617 ms
64 bytes from 10.45.0.11: icmp_seq=11 ttl=64 time=655 ms
64 bytes from 10.45.0.11: icmp_seq=12 ttl=64 time=615 ms
64 bytes from 10.45.0.11: icmp_seq=13 ttl=64 time=575 ms
64 bytes from 10.45.0.11: icmp_seq=14 ttl=64 time=616 ms
64 bytes from 10.45.0.11: icmp_seq=15 ttl=64 time=653 ms

--- 10.45.0.11 ping statistics ---
15 packets transmitted, 15 received, 0% packet loss, time 14008ms
rtt min/avg/max/mdev = 574.610/658.477/1182.867/143.056 ms, pipe 2
```

CN → UE

RESULTS LAB TEST



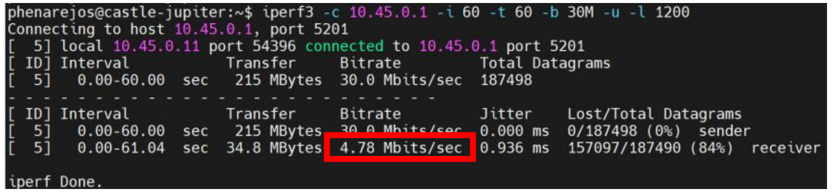


RESULTS LAB TEST

Throughput (iperf3)

Mode	TCP/UDP	Result [Mbps]
UE→CN	UDP	4.78
CN→UE	UDP	8.02
UE→CN	TCP	2.61
CN→UE	TCP	5.54

UE → CN (UDP)

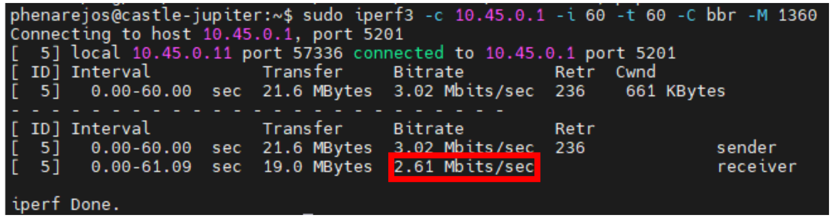


```
phenarejos@castle-jupiter:~$ iperf3 -c 10.45.0.1 -i 60 -t 60 -b 30M -u -l 1200
Connecting to host 10.45.0.1, port 5201
[  5] local 10.45.0.11 port 54396 connected to 10.45.0.1 port 5201
[ ID] Interval           Transfer     Bitrate         Total Datagrams
[  5]   0.00-60.00  sec   215 MBytes  30.0 Mbits/sec  187498
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-60.00  sec   215 MBytes  30.0 Mbits/sec  0.000 ms  0/187498 (0%)  sender
[  5]   0.00-61.04  sec  34.8 MBytes  4.78 Mbits/sec  0.936 ms  157097/187490 (84%)  receiver

iperf Done.
```

CN → UE (UDP)

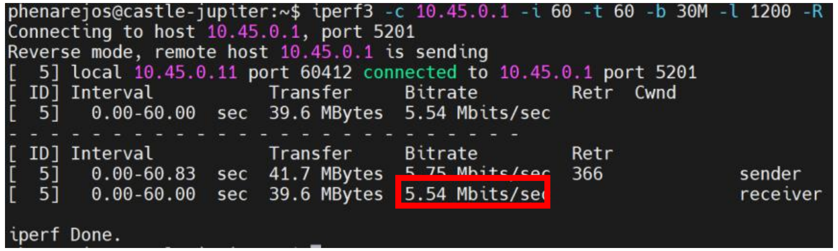
```
phenarejos@castle-jupiter:~$ iperf3 -c 10.45.0.1 -i 60 -t 60 -b 30M -u -l 1200 -R
Connecting to host 10.45.0.1, port 5201
Reverse mode, remote host 10.45.0.1 is sending
[  5] local 10.45.0.11 port 38368 connected to 10.45.0.1 port 5201
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-60.00  sec  57.4 MBytes  8.02 Mbits/sec  1.411 ms  129613/179752 (72%)
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Jitter    Lost/Total Datagrams
[  5]   0.00-60.64  sec   217 MBytes  30.0 Mbits/sec  0.000 ms  0/189498 (0%)  sender
[  5]   0.00-60.00  sec  57.4 MBytes  8.02 Mbits/sec  1.411 ms  129613/179752 (72%)  receiver

iperf Done.
```

UE → CN (TCP)



```
phenarejos@castle-jupiter:~$ sudo iperf3 -c 10.45.0.1 -i 60 -t 60 -C bbr -M 1360
Connecting to host 10.45.0.1, port 5201
[  5] local 10.45.0.11 port 57336 connected to 10.45.0.1 port 5201
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[  5]   0.00-60.00  sec  21.6 MBytes  3.02 Mbits/sec  236    661 KBytes
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-60.00  sec  21.6 MBytes  3.02 Mbits/sec  236             sender
[  5]   0.00-61.09  sec  19.0 MBytes  2.61 Mbits/sec                  receiver

iperf Done.
```

CN → UE (TCP)

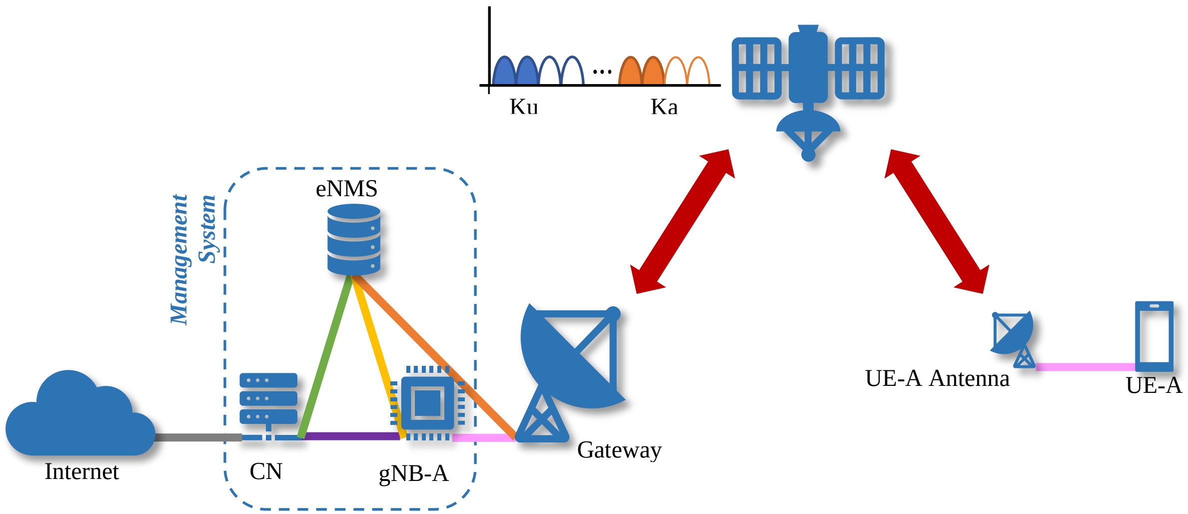


```
phenarejos@castle-jupiter:~$ iperf3 -c 10.45.0.1 -i 60 -t 60 -b 30M -l 1200 -R
Connecting to host 10.45.0.1, port 5201
Reverse mode, remote host 10.45.0.1 is sending
[  5] local 10.45.0.11 port 60412 connected to 10.45.0.1 port 5201
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[  5]   0.00-60.00  sec  39.6 MBytes  5.54 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-60.83  sec  41.7 MBytes  5.75 Mbits/sec  366             sender
[  5]   0.00-60.00  sec  39.6 MBytes  5.54 Mbits/sec                  receiver

iperf Done.
```

PLANNED TRIALS (2025)

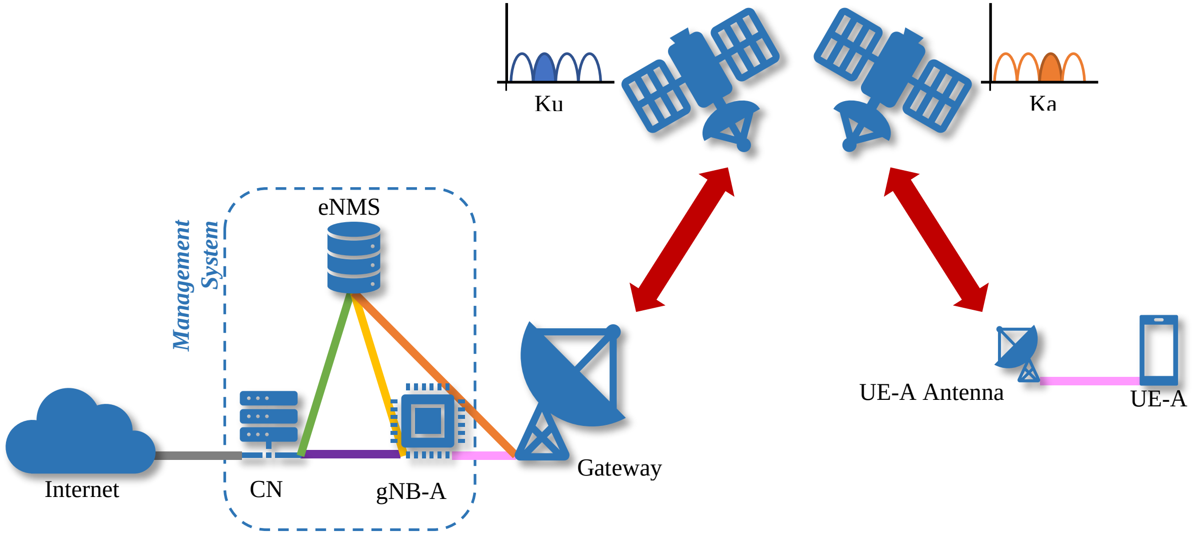
PLANNED TRIALS

Multiband



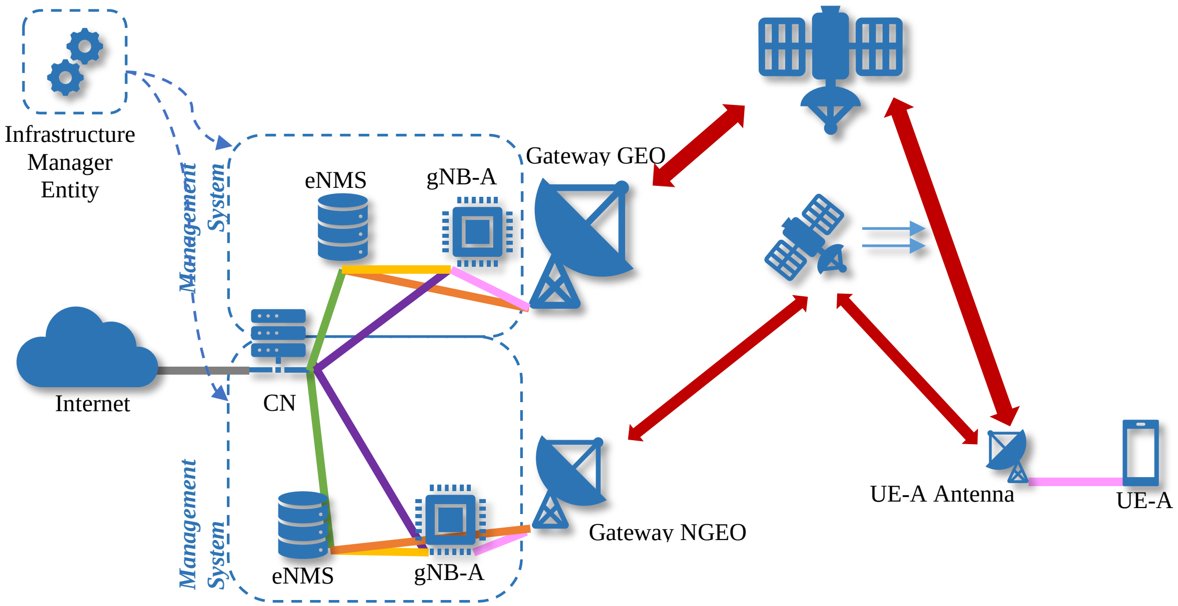
PLANNED TRIALS

Multisatellite



PLANNED TRIALS

Multiorbit



TRANTOR

Ad Spatium Pro Omnibus

https://www.trantor-he.eu/

Horizon Europe research and innovation programme
[grant agreement No 101081983]

5G stardust

https://5g-stardust.eu/

Smart Networks and Services Joint Undertaking (SNS JU)
[Grant Agreement No 101096573]

cttc

Advanced research for everyday life

tecnio catalonia

Fins a 31/12/2023

ACCIÓ

Generalitat de Catalunya

AENOR

Gestión I+D+i

UNE 166002

IDI-0024/2011

HR EXCELLENCE IN RESEARCH