The challenges of testing NTN

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Viavi Solutions develops the TM500 UE (User Equipment) simulator product family that can be used for protocol and capacity test for both conventional Terrestrial and Non-Terrestrial Networks (NTN).

This paper looks at the technical challenges that occur when the network architecture expands to include satellites.

Introduction.

The mobile phone or UE has become an ubiquitous and essential part of our daily lives. We rely on being connected to the internet for information and a range of services where increasingly there is very little alternative.

In most countries, service levels can generally be considered good in metropolitan or urban areas, but when we travel outside those areas mobile service can be frustratingly patchy at times. This can range from being mildly annoying such as the inability to pay a parking fee via an app, to life threatening if an accident occurs outside the terrestrial network coverage area.

Imagine if we lived in a Science Fiction TV world where we took our communicator out of our pocket and were able to make a call or request data wherever we were on the planet?

The Science Fiction spaceship technology is beyond our technical capability, but shortly you will be able to take out your mobile phone and connect to a satellite network that's part of the global internet.

Background

Satellite phone technology had its first inception with the launch of the Iridium System back in the late 1990s. This used a bespoke mobile handset and a constellation of sixty-six Low Earth Orbit Satellites.

These handsets found applications by various government and NGO agencies where global coverage was extremely important, as well as by customers living in large countries where the mobile phone network was still in its infancy and lacked the geographical coverage.

Outside of those areas the take-up was limited compared with standard cellular mobile phones.

The Iridium constellation was extremely expensive to construct and launch. Each launch could only orbit somewhere between two to seven satellites at a time. Until relatively recently there has been little interest in expanding NTN based networks.

Four factors have now changed the NTN landscape.

1. The 'New Space Age' driven by commercial launch developers where the first stage of the launch vehicle can land and be reused for another flight. This has had a significant impact on the launch cost per kilogram. Each launch is capable of carrying up to sixty satellites at a time also greatly reducing the launch cost per satellite.

2. Automated Satellite manufacturing techniques where factories can build thirty plus lightweight satellites a month. The impact of these techniques and increased volume is to greatly reduce the unit price per satellite.
3. The desire to have a ‘standard’ mobile capable of being connected to either a terrestrial network or a non-terrestrial network with the same range of applications rather than having a bespoke satellite phone.
4. The adoption by 3GPP of standards for NTN operation in Release 17 and Release 18. Standardisation is key for widespread adoption.

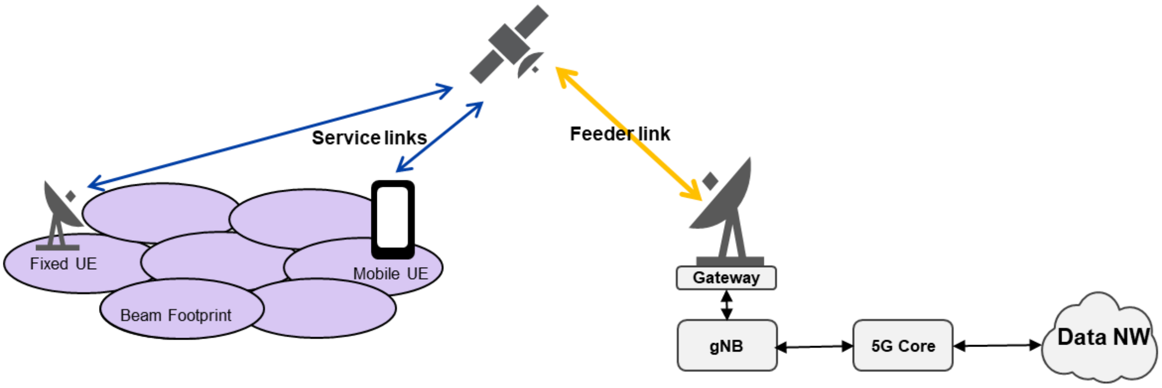
NTN Architectures

The 3GPP specification covers a wide range of architectures, but in practice only a few subsets of the specification are currently being adopted although that may change in the future.

Transparent Satellite or Regenerative Satellite?

There are two main types of satellite in the specification.

Transparent Satellite.



In this configuration the gNB or Gateway is on the ground and the satellite is simply heterodyning the Uplink and Downlink signals. The link to the mobile is called the Service Link and the link between the Gateway and the Satellite is called the Feeder Link.

The advantage of this type of system is that the gNB is on the ground where it can be updated easily.

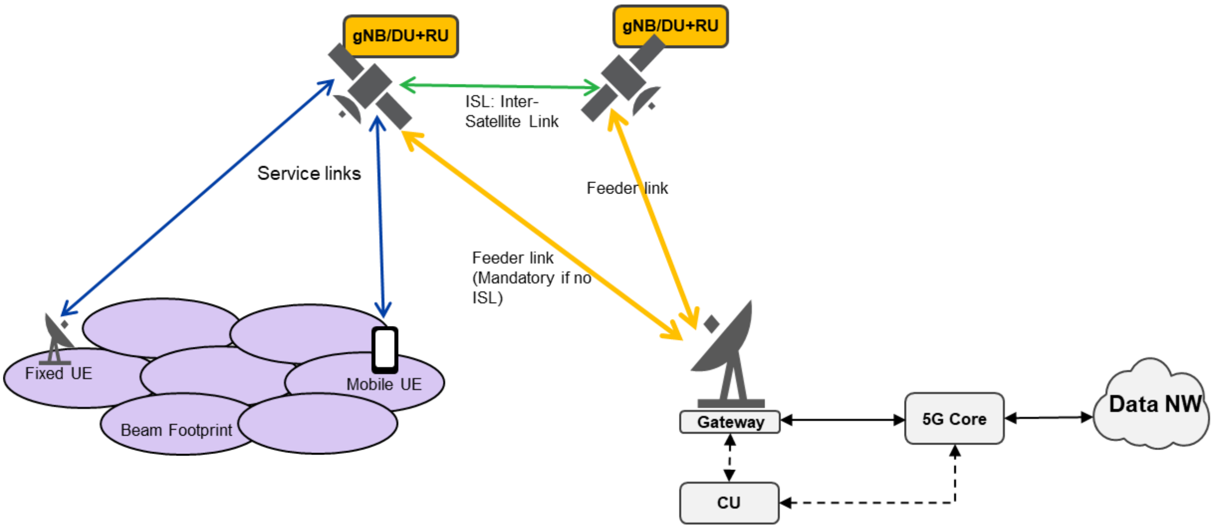
The disadvantages are that the satellite always has to be in view of a ground station or be connected via an intersatellite link which adds extra complexity. The intersatellite link is more complicated since the orbital network has to be designed to transmit analogue signals from the feeder and service links as well as the routing control signals for the analogue feeds.

The system may require more ground stations than a corresponding regenerative system and coverage over the oceans is restricted to littoral waters if there are no Intersatellite links.

The Round Trip Time for an acknowledgement is now twice that of the regenerative architecture.

Calculating and compensating for some of the orbital impairments is now more complicated as both the Service and Feeder signals have to be taken into account.

Regenerative Satellite



In this configuration the base station is orbiting on the satellite. In 5G the base station architecture can be split into the RU (Radiohead Unit), the DU (Distributed Unit: the baseband processing) and the CU (Centralised or Cloud Unit, the higher layers). In Release 18 the architecture can be split with just the RU on the satellite and the rest on the ground, or any other combination. Although Release 18 is still in draft form, the early adopters have already chosen their architectures.

The advantages of this type of system are that the impairment compensation is easier with the regenerative satellite, the intersatellite links are easier to implement as it’s all digital and the Round Trip time for acknowledgements is less than the transparent design. Beam management is easier to manage in this design as the controlling intelligence is on board the satellite.

The disadvantages are that the satellite is more complicated, the software will need to be updated on the satellite more frequently, the system will probably have more base stations compared to a transparent system where a single ground station could service several satellites.

3GPP Reference scenarios

3GPP defines scenarios based on the type of orbit, the satellite architecture, and the type of beam pattern.

Orbit

There are two types of orbit covered in the reference cases.

LEO, Low Earth Orbit.

This covers orbits from typically 500km to 2000km altitude, although there are some proposals to orbit as low as 330km.

The advantages of a LEO orbit are that it provides the lowest loss link budget and the lowest latency.

The disadvantages are high doppler shift, short observable time with consequences of complexity in beam steering and handover. There is also some atmospheric drag in the 300km+ region of space which ultimately will reduce the lifespan of the satellites.

GEO, Geostationary Orbit

The classic ‘Clarke’ geostationary orbit altitude is 35786km above the equator, and the furthest distance from the mobile to the satellite is approximately 40,500km.

The advantages of this orbit are that there is little doppler and only a few satellites are needed in theory to cover the globe.

The disadvantages of this orbit are that the path loss is very high compared with a LEO system, the Round Trip time is much higher, and the system cannot be configured to cover the globe near the poles.

Alternative Orbits.

Although not specifically covered in the 3GPP reference scenarios, there are alternative orbital configurations using elliptical orbits and/or geosynchronous timings that enable specific regions of the globe to be covered with a much smaller constellation of satellites. At present these orbital configurations are used for some GNSS systems, but there is no reason why they couldn't be used to provide mobile phone coverage.

Beam Pattern.

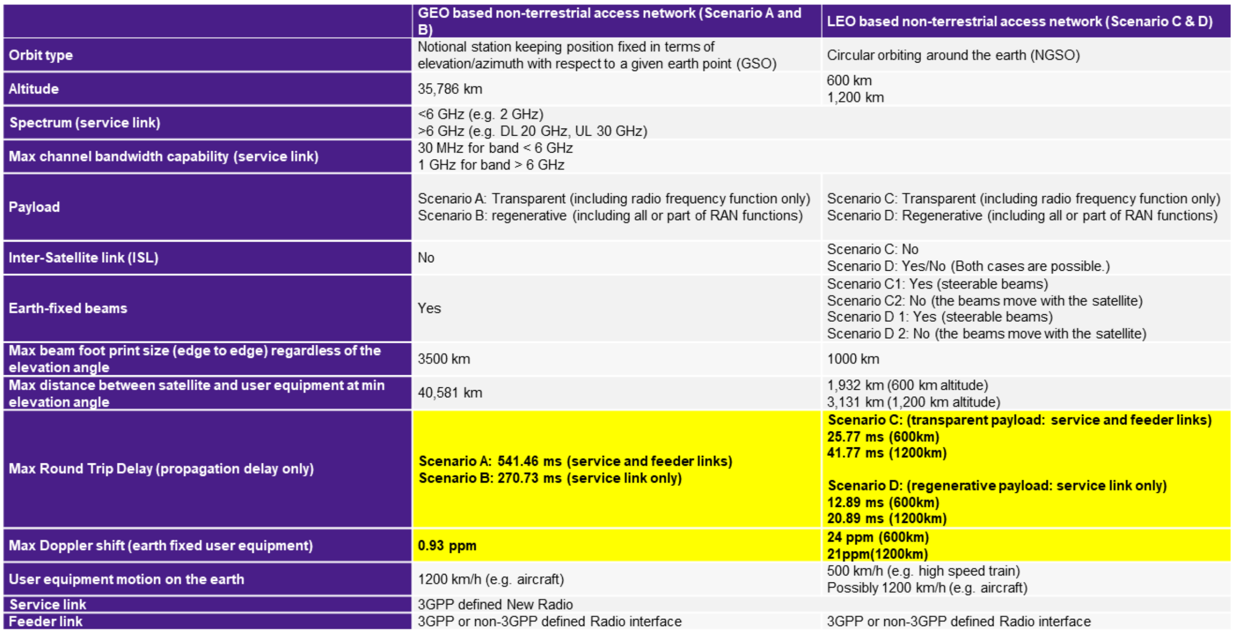
There are two types of beam pattern defined in the 3GPP specification.

Satellite Steerable Beams

In this configuration the satellite can steer the beam. This enables the beam to be fixed on a specific location on the globe as the satellite passes overhead. This provides a quasi-earth fixed cell.

Satellite Fixed beams

In this configuration the beam direction on the satellite is fixed and the beam sweeps across the globe. In this case the cell moves across the earth.



	GEO based non-terrestrial access network (Scenario A and B)	**LEO based non-terrestrial access network (Scenario C & D)**
Orbit type	Notional station keeping position fixed in terms of elevation/azimuth with respect to a given earth point (GSO)	Circular orbiting around the earth (NGSO)
Altitude	35,786 km	600 km 1,200 km
Spectrum (service link)	<6 GHz (e.g. 2 GHz) >6 GHz (e.g. DL 20 GHz, UL 30 GHz)	
Max channel bandwidth capability (service link)	30 MHz for band < 6 GHz 1 GHz for band > 6 GHz	
Payload	Scenario A: Transparent (including radio frequency function only) Scenario B: regenerative (including all or part of RAN functions)	Scenario C: Transparent (including radio frequency function only) Scenario D: Regenerative (including all or part of RAN functions)
Inter-Satellite link (ISL)	No	Scenario C: No Scenario D: Yes/No (Both cases are possible.)
Earth-fixed beams	Yes	Scenario C1: Yes (steerable beams) Scenario C2: No (the beams move with the satellite) Scenario D 1: Yes (steerable beams) Scenario D 2: No (the beams move with the satellite)
Max beam foot print size (edge to edge) regardless of the elevation angle	3500 km	1000 km
Max distance between satellite and user equipment at min elevation angle	40,581 km	1,932 km (600 km altitude) 3,131 km (1,200 km altitude)
Max Round Trip Delay (propagation delay only)	**Scenario A: 541.46 ms (service and feeder links)** **Scenario B: 270.73 ms (service link only)**	**Scenario C: (transparent payload: service and feeder links)** **25.77 ms (600km)** **41.77 ms (1200km)** **Scenario D: (regenerative payload: service link only)** **12.89 ms (600km)** **20.89 ms (1200km)**
Max Doppler shift (earth fixed user equipment)	**0.93 ppm**	**24 ppm (600km)** **21ppm(1200km)**
User equipment motion on the earth	1200 km/h (e.g. aircraft)	500 km/h (e.g. high speed train) Possibly 1200 km/h (e.g. aircraft)
Service link	3GPP defined New Radio	
Feeder link	3GPP or non-3GPP defined Radio interface	3GPP or non-3GPP defined Radio interface

Table 1: 3GPP Use Case Scenarios

RF Challenges

There are four main impairments to the RF link which have a significant factor in the design and architecture of the system.

1. Delay
2. Doppler
3. Path Loss

Delay.

In 5G NR, the permitted delay (K values) in the round trip time (RTT) was reduced from 10ms in 4G to increments of 1ms for 5G NR sub 6GHz frequencies. Typically the K values (K1,2) should be no more than 2 or 3 ms.

The RTT (delay only) for a regenerative satellite operating at say 1200km and at a maximum slant range of 3131km is 20.89ms. It is twice that for a transparent satellite.

The 3GPP specification adds Timing Advance (K offset) to the Uplink signal which is equal to the delay of the system. The value of this is derived from data in the SIB-19 block transmitted from the satellite.

An additional factor to take into account is that the delay experienced by all UEs within a beam will be different depending upon their location as well as changing over time as the satellite travels in its orbit.

Doppler

The Doppler on a LEO satellite is quite significant at +/-48kHz on a 2GHz link at 600km orbit. This exceeds the current 5G NR receiver specification.

Uplink.

The strategy for Doppler on the Uplink is that each UE pre-compensates for the predicted doppler shift. To do this the UE needs to know its own geographical coordinates and the orbital ephemeris of the satellite. This is broadcast in the SIB-19 block from the satellite.

From the satellite perspective the doppler shift from each UE is almost zero, regardless of where the UE is located within the beam coverage. This architecture mitigates for situations where the satellite would have to a receive signals from UEs from opposite sides of the beam where the doppler shift is the opposite of each other.

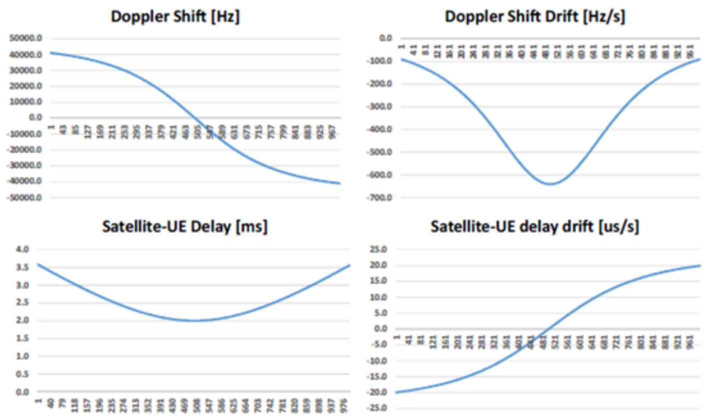
The residual frequency error on the UL needs to be less than ±0.1ppm, and the contribution from the doppler needs to be <20% of this i.e. ±0.02ppm. To achieve this the UE needs to know the position of the satellite to within ±120m and the velocity to within ±1.5m/s. This is achievable through the use of GPS.

Downlink.

There are two strategies available for the Downlink.

The first is to do no compensation on the downlink and let the receiver in the UE handle the full doppler shift. This approach is essential with a satellite using a fixed beam, moving earth cell configuration.

The second strategy is to apply some coarse pre-compensation for the centre of the beam in a fixed earth cell configuration. As the satellite knows its own location and the approximate location of the centre of the beam this is a viable approach. UEs which are located at successive distances from the centre of the beam will experience small doppler shifts as a consequence.



Graphs showing Doppler Shift and Delay

Path Loss.

Most mobiles are expected to operate within a few kilometres of a gNB Basestation where the path loss might be expected to be within the 100-125dB range. The loss over the satellite path is much higher for example at 2GHz the freespace loss at 1000km distance is 158.5dB.

The 3GPP organisation provides a couple of test studies for the satellite link which can be used to evaluate the system.

Test study conditions

Orbit	**Satellite DL Tx Power**	**Satellite Antenna Gain**	**Link Frequency**	**Bandwidth**
600km	34.69dBm	30dB	2GHz	5MHz

Using these figures, we can see that for the downlink reasonable SNRs can be achieved on a standard mobile and with a relatively modest power from the Satellite Transmitter

Distance km	**Free Space Path loss (dB)**	**Transmit power (dBm)**	**DL PWR (dBm)**	**DL SNR (dB)**
300	-148.1	-128.1	-83.4	21.6
600	-154.1	-134.1	-89.4	15.6
1200	-160.1	-140.1	-95.4	9.6
2400	-166.1	-146.1	-101.4	3.6

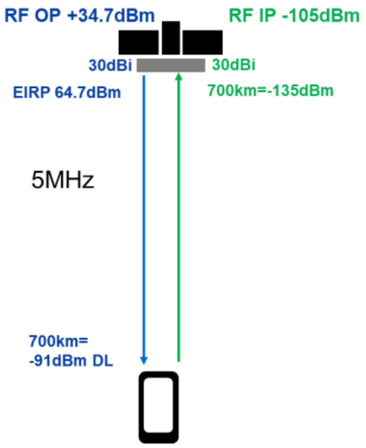


Table 2: Example Downlink Signals using 3GPP test study

Example Downlink and Uplink Signals using 3GPP test study conditions

However for the uplink it is a different story. The Mobile will be transmitting about +20dBm and the SNR at the Satellite receiver is nearly 14dB lower than the uplink due to the disparity between the UL and DL transmitter powers.

The Uplink is the limiting factor. Terminals that have higher power than a standard pocket mobile and can incorporate beamforming with some antenna gain will have a significant advantage.

The Uplink data rate can also be reduced and transmitted in a reduced bandwidth to improve the SNR at the satellite receiver as described in table 3.

The alternative is to have a higher gain on the satellite beamforming antenna and some companies have opted for that approach.

The Downlink table also shows the advantages of having the lowest possible orbit for the satellite. This is why there are some proposals to orbit LEO constellations at circa 350km altitude despite the impact of atmospheric drag on the lifecycle of the satellite.

Usage scenarios	Experience data rate (note 2)		Overall UE density per km2	Activity factor (note 3)	Max UE speed	Environment	UE categories
	DL	UL					
IoT connectivity (note 4)	2 kbps	10 kbps	400	1,00%	0 km/h	Extreme coverage	IoT
Pedestrian	2 Mbps	60 kbps	100	1,50%	3 km/h	Extreme coverage	Handheld
Pedestrian 2	2 Mbps	250 kbps	100	1,50%	3 km/h	Extreme coverage	Handheld
Public Safety	3.5 Mbps	3.5 Mbps	TBD	N.A	100 km/h	Open area	Handheld
Public Safety	3.5 Mbps	3.5 Mbps	TBD	N.A	250 km/h	Open area	Vehicle mounted
Stationary	50 Mbps	25 Mbps	TBD	N.A.	0 km/h	Extreme coverage	Building mounted
Vehicular connectivity	50 Mbps	25 Mbps	TBD	N.A.	250 km/h	Along roads in low population density areas	Vehicular mounted
Airplanes connectivity	360 Mbps	180 Mbps	TBD	N.A.	1 000 km/h	Open area	Airplane mounted

Table 3: Example Downlink and Uplink use cases from 3GPP

Multi path and other propagation impairments.

Although free space loss has been considered as the primary loss mechanism the new standard 3GPP model also includes additional direct loss deriving from ionospheric scintillation, rain and cloud cover as well as standard terrestrial multi path and fading factors.

For the first generation of constellations the mobile will be operating outside urban areas with a clear line of sight view of the satellite, generally somewhere between 20-30° above the horizon. The SNR is likely to be around the 10dB region and multi path in that environment is considered to be below the level of the noise floor.

This will change when NTN becomes an integral part of an urban and metropolitan cellular network.

What about my 4G Mobile?

This paper has looked at some of the changes in the 3GPP specification in release 17 and release 18 for NTN. Some of these changes will require new mobile phones to accommodate the NTN technology such as the frequency tolerance required for the high LEO doppler shift.

However there are some companies that are experimenting with developing satellites that will work with a standard LTE phone. In these scenarios, the complications arising from the orbital impairments are being dealt with in the satellite/ gateway.

To counter the low output power on the Uplink from the mobile, the satellites are deploying large phased array antennas. The overall bit rate supported in these systems is likely to be about 3-5Mb/s within a quasi fixed earth cell. This is enough to support messaging services such as text or internet chat applications but voice and video are unlikely to be supported.

This level of service is also suitable for IOT applications where there are widely distributed sensors which have a low data rate and only need to connect to the network on an intermittent basis.

Test Solutions: Test with confidence on the ground in advance of launch

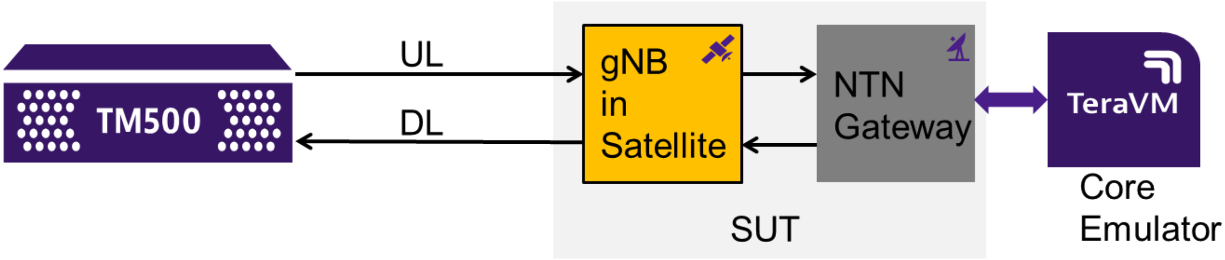
To ensure confidence in the system under development the best way is to set up an end to end test where the changes to the 3GPP protocol can be tested in the laboratory. As the development of chipsets for UEs lags behind the 3GPP specification, an ideal way to do this involves a UE simulator like the Viavi TM500.

The Viavi TM500 uses a combination of X86 server and FPGA CoPro cards for the baseband processing and the protocol stack is updated twice a week to keep pace with changes to the 3GPP specification.

The UE simulator can simulate over a thousand UEs on a single carrier which ensures capacity and throughput testing on the target system.

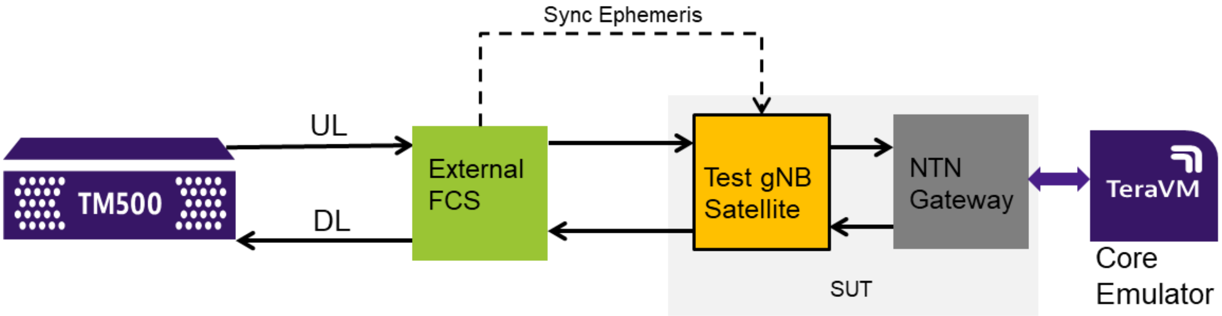
Another advantage of using a UE simulator is that it can be programmatically controlled which means that all the test cases can be run automatically easing regression and validation.

Once the satellite system is in operation, the UE simulator can be part of the protocol stack CI/CD machine and can be used to test new features before they are deployed live.



An example of a basic protocol test system for a Regenerative Satellite in the lab

A basic protocol system like this can test 32UEs with 50MHz BW with the Rel-17 protocol NTN changes including decoding the SIB-19 block. The setup shown is for a regenerative satellite.

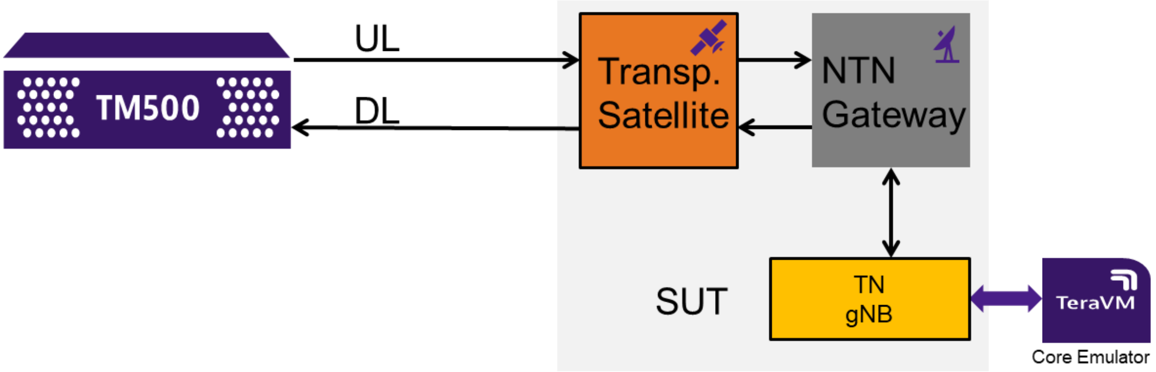


An example of a protocol test system with a Fading Channel Simulator for a Regenerative Satellite

An extended protocol system with a Fading Channel Simulator added can test 32UEs with orbital impairments such as Doppler, delay and simulated path loss SNR.

The orbital models in the test satellite (SIB-19) and the fading channel simulator need to be synchronised so that the UE simulator correctly calculates the doppler pre-compensation.

The path loss is simulated with AWGN to the signal to provide the correct SNR for the link.



An example of a basic protocol test system for a Transparent Satellite in the lab

The test system can also be used to test transparent satellites where the System Under Test includes the Gateway and Terrestrial gNB.

Conclusion

The extension of cellular networks using satellites to provide greater coverage has its technical challenges which can be solved and tested to achieve reliable performance.

3GPP Release-17 has made changes to the protocol and baseband processing architecture to accommodate the high doppler shift and delay from an orbiting satellite. The increased path loss can be addressed through the system design and the appropriate choice of bandwidths and data rates for the Downlink and Uplink.

Very high confidence levels in the functioning and performance of the satellite system are required during development before launch as well as during the operational life of the system when software upgrades are required.

This is confidence is achieved through the use of UE simulator test systems to simulate actual traffic performance with test satellites in the ground-based laboratory.

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