System-level simulations for Non-Geosynchronous Satellite Orbit (NGSO) constellations

DVB White Paper

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Background

Recent initiatives of Non-Geosynchronous Satellite Orbit (NGSO) constellations, such as SpaceX's Starlink, Eutelsat OneWeb, SES-O3b, Amazon's Kuiper, Telesat's Lightspeed and others are aiming to provide global low delay, high-capacity communications. Those initiatives demonstrate the need to satisfy the ever-increasing demand for broadband communication to anyone, anywhere, anytime.

Unlike the well-established Geosynchronous Satellites (GSO), which orbit the Earth at altitude of 36,000 km around the equator, NGSO satellites orbit the Earth at much lower altitudes and in orbits that are not necessarily parallel to the equator. The orbit times of NSGO satellites are much shorter than the 24 hours of a GSO satellite and therefore a constellation of satellites is needed to cover a given point on earth. On the other hand the advantage is that different satellites in the constellation, each covering a different area on Earth, can use the same transmission and reception frequencies without causing interference to each other, thus, given the same range of frequencies, the overall capacity that can be carried by such a constellation is much higher than the capacity that can be served by a GSO satellite.

So, despite the added complexity of building, launching and operating a constellation of satellites, NGSO provides enhanced capacity, improved link budget, reduced latency, and the ability to cover any point on Earth.

Figure 1 shows a simplified architecture of an NGSO network. It is composed of the terminals (RCS2T) served by different satellites. The satellites are connected to each other by Inter-Satellite Links (ISL) and, through gateway stations to a terrestrial network.

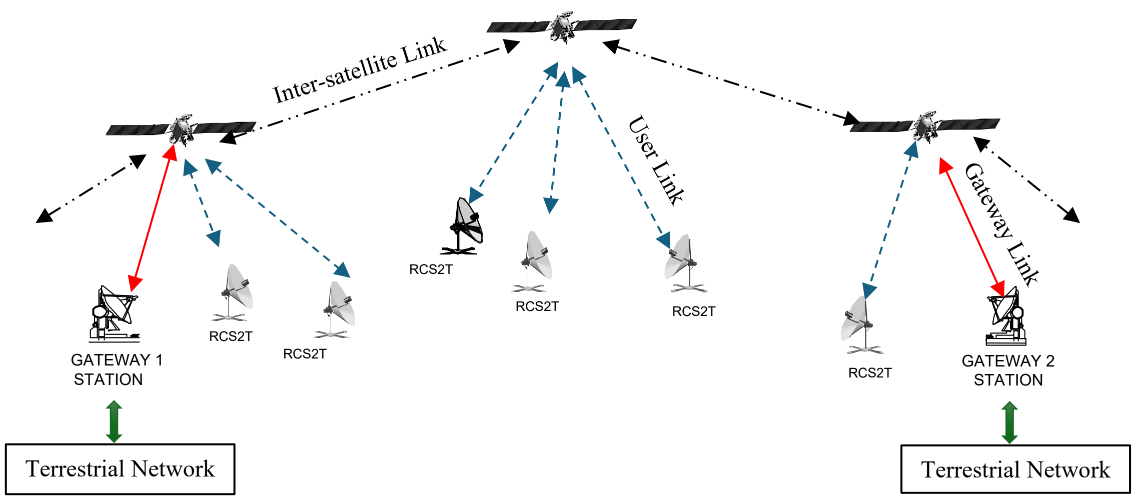


Figure 1: NGSO Satellite Constellation Architecture

The DVB Return Channel Satellite communications specification, DVB-RCS2 [1] has recently been enhanced to support NGSO, thus offering, together with the forward channel specification DVB-S2X [2] a standardized air interface for those systems. A standards-based solution is a key to an open and competitive market, which would ensure its growth and resilience.

As part of DVB's Verification and Validation (V&V) activities, system-level simulations were performed for a Low Earth Orbit (LEO) satellite, at 600 km height. The simulations compare the return-link performance of an NGSO system at 30 GHz, for three return channel air interface waveforms: DVB-RCS2 Linear Modulation (LM) bursts,[1] DVB-S2X, and 3GPP NR-PUSCH. The simulations are a continuation of the work done in ETSI [3] for GSO. The frequency of 30 GHz belongs to the frequency range designated as FR2

[1] DVB-RCS2 specification defines, in addition to the Linear Modulation waveform, Continuous Phase Modulation (CPM) and a Spread Spectrum Version.

(17.3 to 20.2 GHz for downlink and 27.5 to 30 GHz for uplink) in 3GPP TS 38.101-2: NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone [4], and it is selected as it provides wideband channels that can serve broadband data demand as expected in such systems.

Simulation Description

Consider a satellite system consisting of a satellite serving terminals arranged in cells in the satellite coverage area, as depicted in Figure 2. The purpose of system-level simulations is to estimate the statistics of the system throughput, user throughput and other operational performance metrics experienced by the users and operators of such a system, or rather, compare the statistics of those metrics for different air interface protocols in a given common scenario.

Figure 2: Cellular deployment of the simulated cells

The simulations use Monte Carlo methods, collecting the required statistics over a set of “drops” (the statistical case). In each drop the simulation:

1. Randomly selects the terminals in each of the observed cells.
2. Randomly selects the traffic to be carried by each terminal according to a chosen traffic model.
3. Evaluates the received signal strength of each terminal at the receiver (the satellite, in our case).
4. Based on those calculations, the simulation evaluates, for each of the terminals in the centre cell, the interference coming from all the other cells, and the signal-to-interference-plus-noise ratio (SINR) seen by the receiver.
5. Using Link Level Simulations [3], the SINR value can be mapped, for each of the evaluated air interfaces, to the effective bitrate carried by each link.

The results of each drop are collected, and their statistics are processed. The basic statistics are represented in the histogram (or the resulting distribution function) of variables, such as the SINR of the users, the throughput assigned for the users, and the total throughput of all the users in the system.

In this case, the simulations were performed with a terminal using a directional 60 cm Electronically Steerable Antenna (ESA). The traffic model used was a full buffer model, implying continuous transmission. Statistics were accumulated for the central cell in Figure 1, while terminals in the other cells in that figure are the ones that produce interference to the central cell terminals. The simulations gather the statistics for the medium access layer above the physical layer (RLC/LLC). They take into account the scheduling of the traffic packets, the overhead of each air interface and the link adaptation mechanism, which enables adapting the link to the reception conditions. Full details for the simulations can be found in TM-S0587r2: TN2: Simulation Report on Comparison of DVB-RCS2 and 3GPP NR NTN Technologies in LEO Systems. Magister Solutions, April 2025 [5].

The main distinguishing factor of the simulations reported here, compared to those in [3], is the fact that they were performed for a LEO satellite of which the location is not stationary, as is the case for GSO, but rather moving across the sky and causing a substantial Doppler shift, which is an order of magnitude higher than that experienced by mobile terminals in a GSO system or in terrestrial systems. Since satellite trajectories are predictable, most of that shift can be compensated. The extent of the compensation depends on the accuracy of the information on the satellite trajectory, the terminal location, and the timing. To assess this effect, the simulations were performed at three levels of compensation: 97.5% which is a moderate accuracy that can be achieved by a terminal not connected to a Global Navigation Satellite System (GNSS); 99.3% for a terminal connected to GNSS; and ideal compensation of 100%.

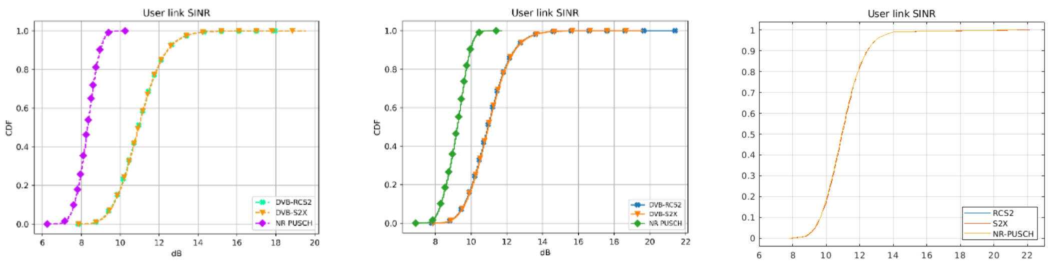
The frequency deviation between the terminal transmitter and the receiver at the satellite causes a degradation in performance that is caused by several effects:

- Reduced signal to noise, as the received signal is not captured in its entirety by the receiver filter. This effect is proportional to the percentage of the deviation to the signal bandwidth, and it affects the 5G OFDM much more strongly than the DVB wideband signals.
- Inter-carrier interference, which is present if there is no guard band between carriers and is present only in 5G OFDM.
- Phase errors, which cause errors in the signal demodulation process and higher symbol error rates.

Frequency deviations are inherent in all wireless systems, and they are caused, in addition to the Doppler shift, by oscillator misalignment and phase noise. Auxiliary signals, pilots in the DVB waveforms, and various reference signals like De-Modulation Reference Signals (DMRS) and Phase and Timing Reference Signals (PTRS) in the 5G-NR waveforms, are built in to correct for those errors. Those signals, however, correct for phase errors while in order to correct for Doppler shift, it is necessary to establish a feedback loop between the receiver and the transmitter, to correct for the transmission frequency. Such frequency correction loops were specified for DVB-RCS2 but closed loop frequency correction does not yet exist in the 5G-NR standard [6] and the 5G-NR waveform is much more sensitive to Doppler and required higher level of compensation.

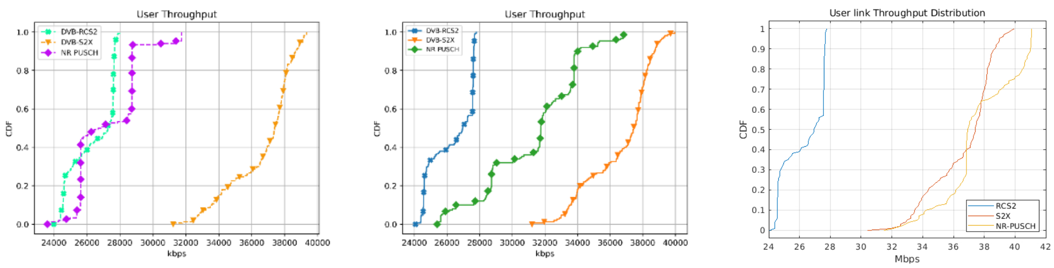
Simulation Results

The results are presented in Cumulative Distribution Function (CDF) graphs. Figure 3 below shows the distribution of the user link SINR for the three physical layers with three different levels of Doppler compensation, namely 97.5% (approximately 6.6–9.54 kHz residual Doppler), 99.3% (approximately 1.84–2.65 kHz residual Doppler), and 100% ideal compensation (0 Hz residual Doppler). Figure 4 shows the distribution of the user link throughput and Figure 5 the overall system throughput distribution. All presented results include the effects of Doppler shift and scanning loss from ESA. The throughput parameters (user link and system link), are the main key performance indicators that a system operator would require as they are directly related to the user experience and to the commercial viability of the system. The SINR statistics for 5G-NR are concentrated around lower values than those of the DVB waveforms for both cases of non-ideal Doppler compensation. The lower SINR value is the root cause of the difference in throughput between the NR-PUSCH and the DVB-S2X waveforms.



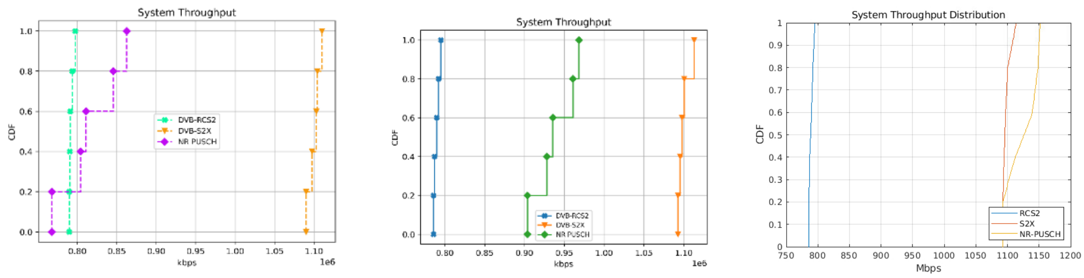
(a) 97.5% Doppler Compensation (b) 99.3% Doppler Compensation (c) 100% Doppler Compensation

Figure 3: User Link SINR Distribution



(a) 97.5% Doppler Compensation (b) 99.3% Doppler Compensation (c) 100% Doppler Compensation

Figure 4: User Link Throughput Distribution



(a) 97.5% Doppler Compensation (b) 99.3% Doppler Compensation (c) 100% Doppler Compensation

Figure 5: System Throughput Distribution

Discussion

As demonstrated by the graphs in the previous section, the DVB waveforms (both RCS2 and S2X), enjoy an advantage of 2-3 dB in SINR (at the 80th percentile, depending on the level of compensation), thanks mainly to their better resilience to Doppler effects. This better resilience is mainly explained by the single carrier format of DVB and the use of roll-off factors and carrier spacing, effectively preventing inter-carrier interference.

For comparison, the OFDM waveform used by 5G-NR suffers from a loss of orthogonality between the subcarriers, induced by the frequency shift. However, the NR PUSCH waveform shows an advantage in throughput (both user link and system throughput) over the legacy LM DVB-RCS2 waveforms, as can be observed in Figures 4 and 5.

This advantage can be explained by the fact that the NR-PUSCH waveform supports higher modulation orders than the legacy RCS2, as one can observe in [3]. The DVB-S2X waveforms, on the other hand, which are more efficient, show similar throughput to NR-PUSCH in the case of an ideal (100%) Doppler compensation, however, with a moderate level of Doppler compensation, DVB-RCS2 and NR-PUSCH show similar performance, while DVB-S2X shows a clear advantage over both legacy DVB-RCS2 and NR PUSCH. This is mainly facilitated by highly spectrally efficient MODCODs, with a fine granularity, and the high-capacity frames, providing a very small overhead.

The latest version of DVB-RCS2, enhanced to support NGSO satellites, enables, among other additions, the use of DVB-S2X waveforms on the return link, thus making it possible to make use of DVB-S2X to improve the throughput and capacity of an NGSO satellite system.

References

[1] DVB BlueBook A155-2r5 (Draft EN 301 545-2 V1.5.1) (2024-09): Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System (DVB-RCS2); Part 2: Lower Layers for Satellite standard.

[2] DVB BlueBook A083-2r4 (Draft EN 302 307-2 V1.4.1) (2024-02): Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 2: DVB-S2 Extensions (DVB-S2X).

[3] ETSI TR 103 886 v.1.1.1 (2025-03) : Satellite Earth Stations & Systems (SES); DVB-S2x/RCS2 versus 3GPP New Radio protocol technical comparison for broadband satellite systems

[4] 3GPP TS 38.101-2: NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone.

[5] TM-S0587r2: TN2: Simulation Report on Comparison of DVB-RCS2 and 3GPP NR NTN Technologies in LEO Systems. Magister Solutions, April 2025.

[6] P. Delbeke, D. Duyck: 5G-NR GNSS independent time and frequency synchronization in NTN scenarios, Ka Conference 2023, Bradford, UK, October 2023.