Coexistence of Terrestrial and Non-Terrestrial Networks on Adjacent Frequency Bands

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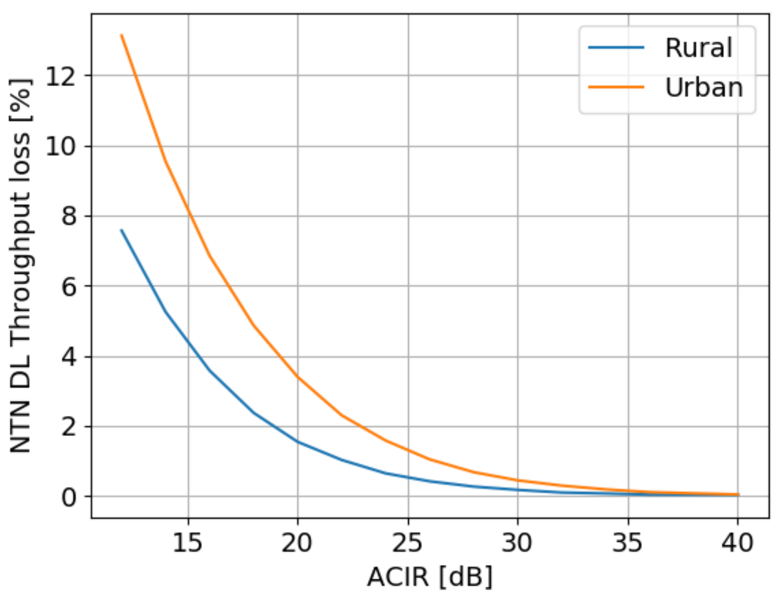
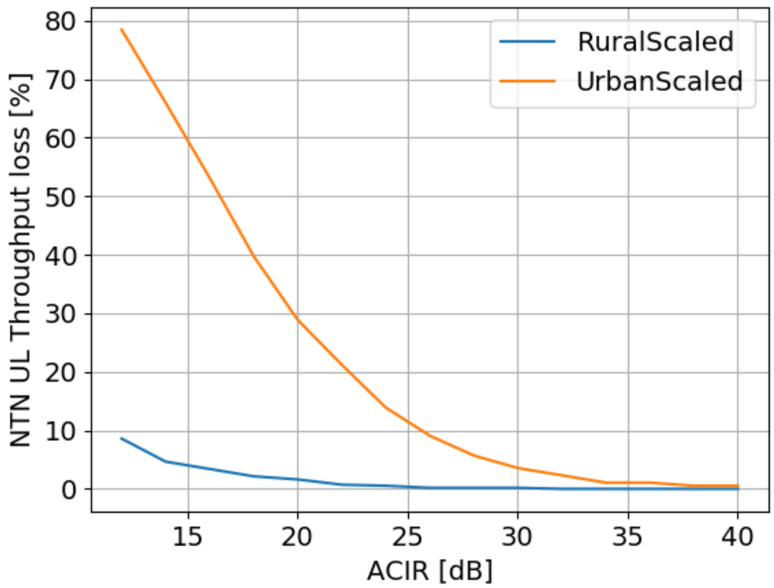
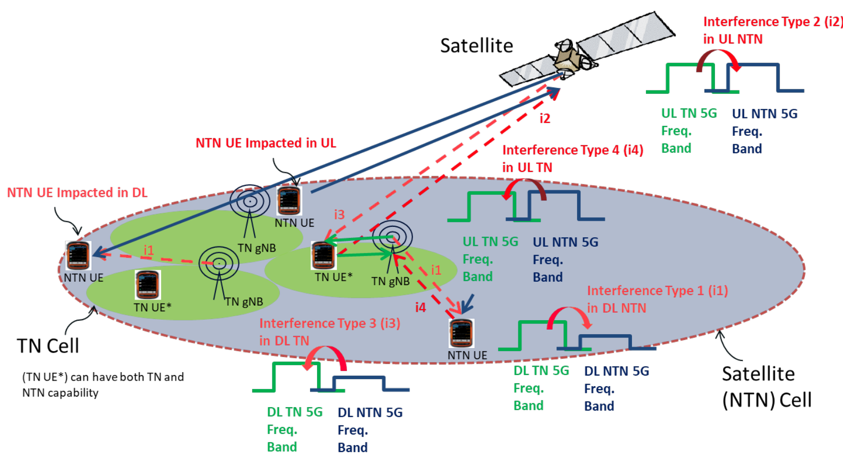
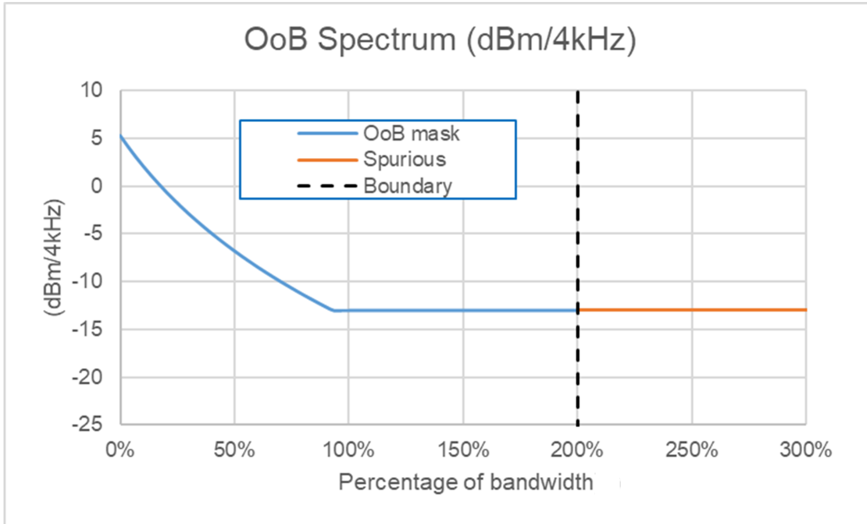
Abstract

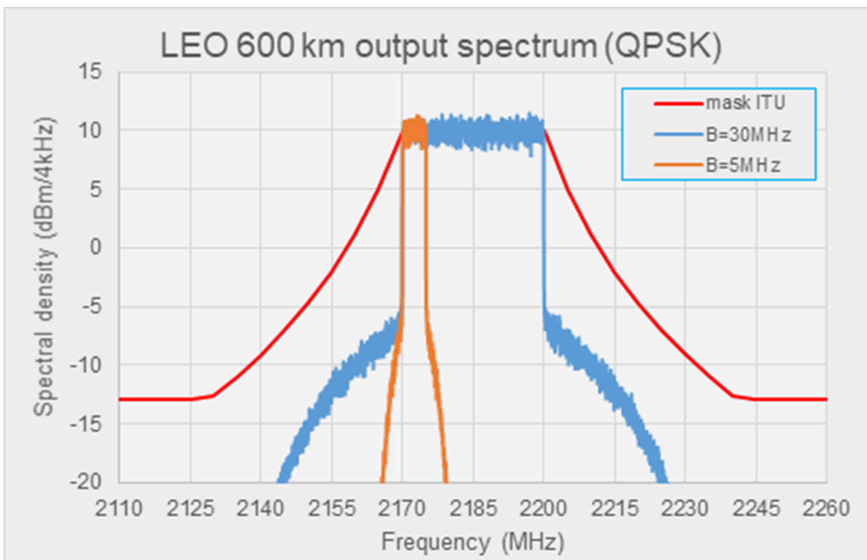
This paper presents the latest achievements concerning 3GPP Release-17 adjacent band coexistence simulation work on 5G New Radio Non-Terrestrial Networks (NTNs) for satellite communications. For the first time, 3GPP considered the introduction of Mobile Satellite Service (MSS) frequency bands for 3GPP User Equipment (UE) direct connectivity with satellites and had to consider the coexistence in adjacent bands with Terrestrial Networks (TNs). This paper will further explain the most challenging and the main surprising outcomes of this work, which opened new market opportunities for both terrestrial and non-terrestrial stakeholders. The main conclusions can be summarized as (1) NTN UE can reuse the current requirements of the TN UE, (2) the satellite connectivity does not require a dedicated satellite waveform, and (3) TN can co-exist with NTN on adjacent channels with relaxed ACIR requirements for the tested simulation scenario.

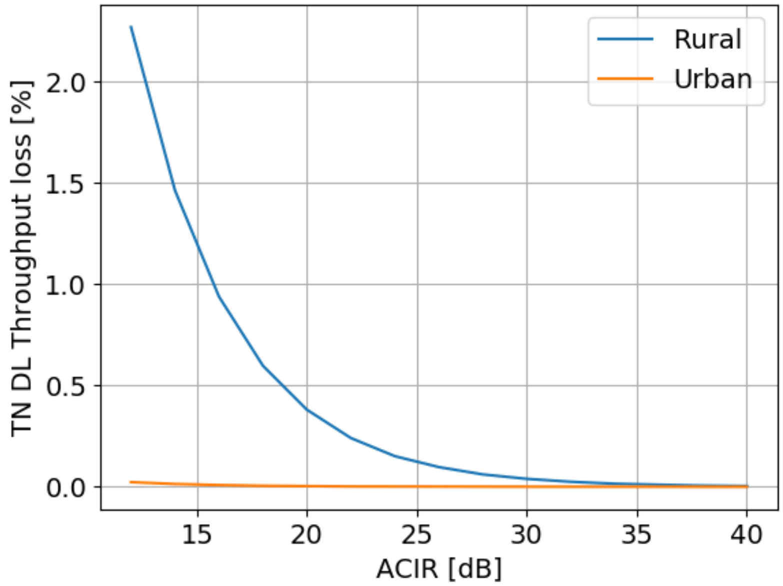


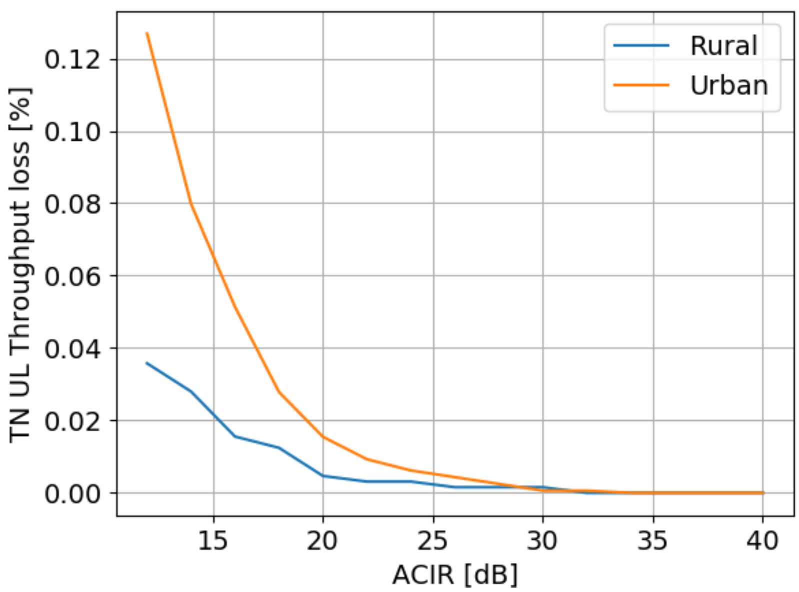

RuralScaled
UrbanScaled
NTN UL Throughput loss [%]
ACIR [dB]
0
10
20
30
40
50
60
70
80
15
20
25
30
35
40

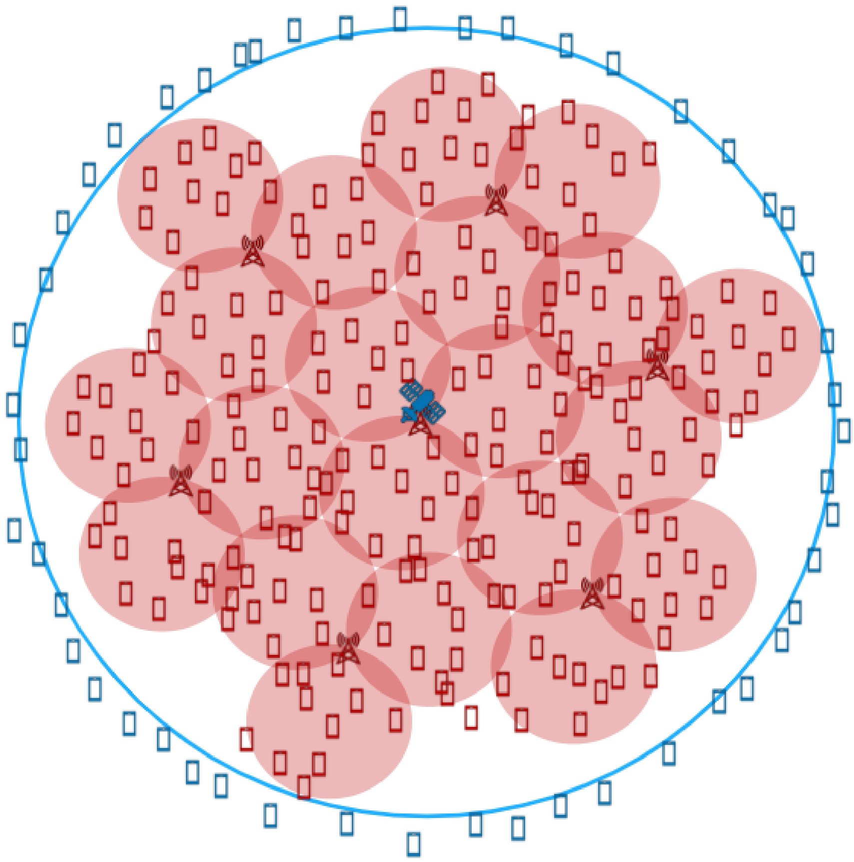

Satellite
Interference Type 2 (i2) in UL NTN
UL TN 5G Freq. Band
UL NTN 5G Freq. Band
i2
NTN UE Impacted in UL
Interference Type 4 (i4) in UL TN
NTN UE Impacted in DL
NTN UE
TN gNB
i3
i1
TN UE*
TN gNB
UL TN 5G Freq. Band
UL NTN 5G Freq. Band
i1
Interference Type 1 (i1) in DL NTN
i4
TN UE*
TN gNB
Interference Type 3 (i3) in DL TN
NTN UE
TN Cell
(TN UE*) can have both TN and NTN capability
DL TN 5G Freq. Band
DL NTN 5G Freq. Band
DL TN 5G Freq. Band
DL NTN 5G Freq. Band
Satellite (NTN) Cell

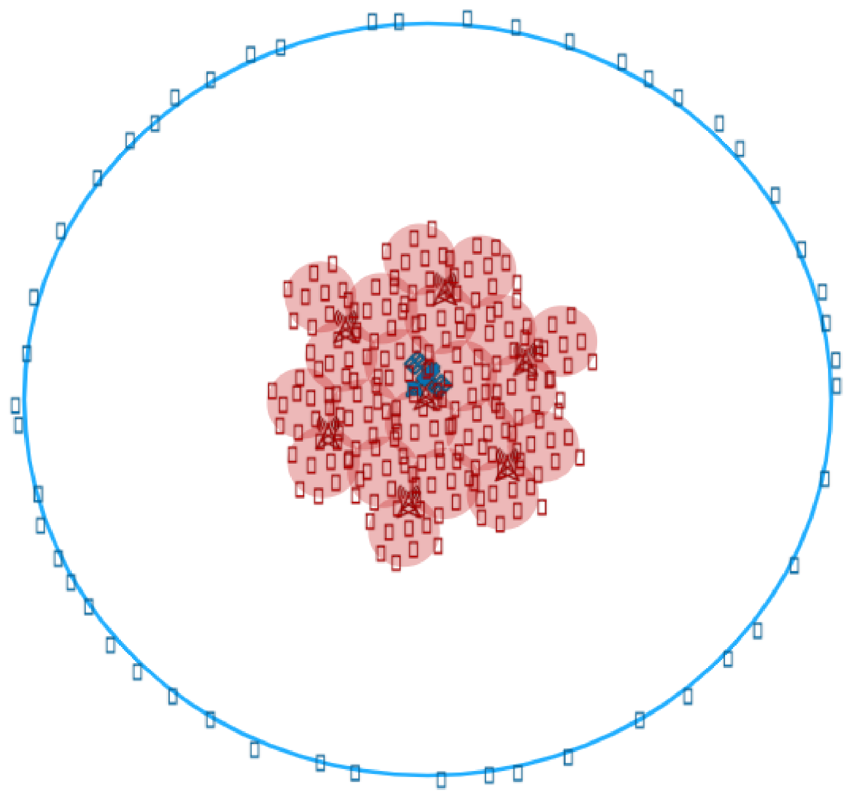

OoB Spectrum (dBm/4kHz)
OoB mask
Spurious
Boundary
(dBm/4kHz)
10
5
0
-5
-10
-15
-20
-25
0%
50%
100%
150%
200%
250%
300%
Percentage of bandwidth

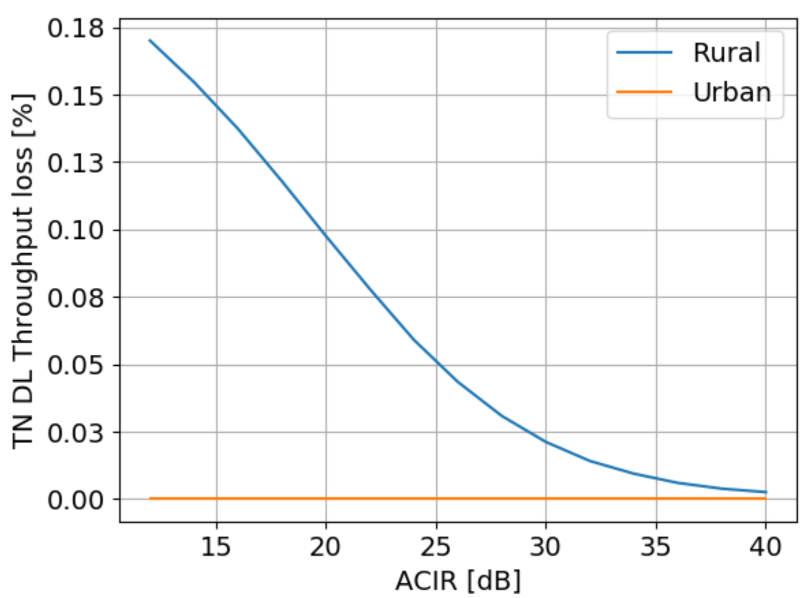

LEO 600 km output spectrum (QPSK)
mask ITU
B=30MHz
B=5MHz
Spectral density (dBm/4kHz)
15
10
5
0
-5
-10
-15
-20
2110
2125
2140
2155
2170
2185
2200
2215
2230
2245
2260
Frequency (MHz)


TN DL Throughput loss [%]
ACIR [dB]
Rural
Urban
0.0
0.5
1.0
1.5
2.0
15
20
25
30
35
40

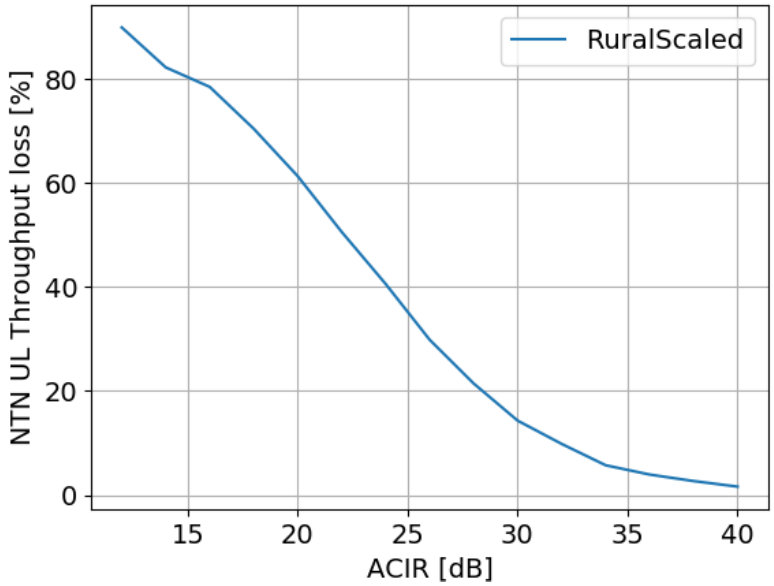

TN UL Throughput loss [%]
ACIR [dB]
Rural
Urban
0.00
0.02
0.04
0.06
0.08
0.10
0.12
15
20
25
30
35
40

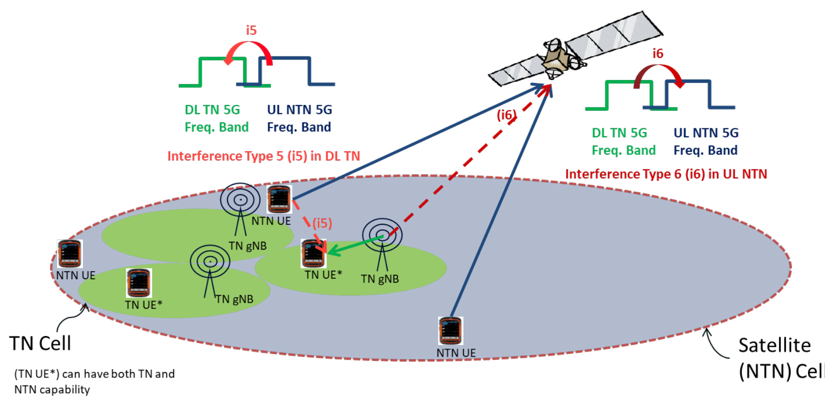


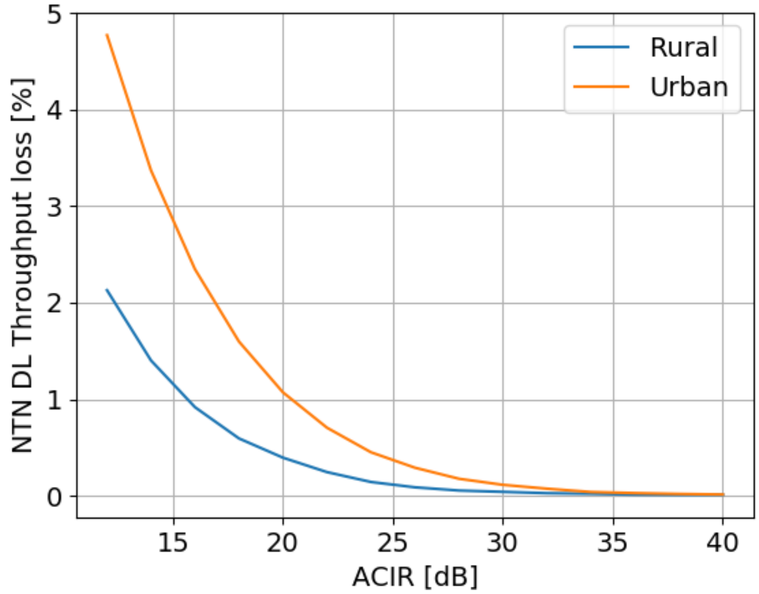




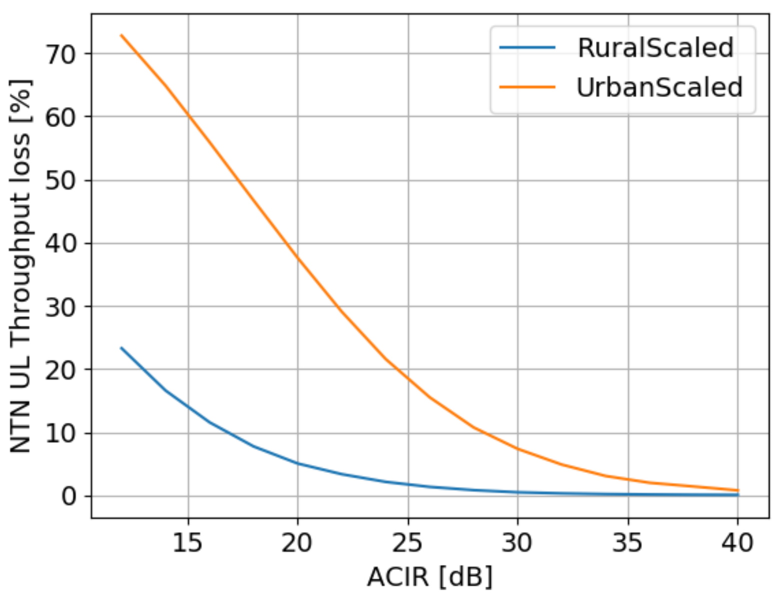
Rural
Urban
TN DL Throughput loss [%]
ACIR [dB]
0.18
0.15
0.13
0.10
0.08
0.05
0.03
0.00
15
20
25
30
35
40


RuralScaled
NTN UL Throughput loss [%]
0
20
40
60
80
15
20
25
30
35
40
ACIR [dB]

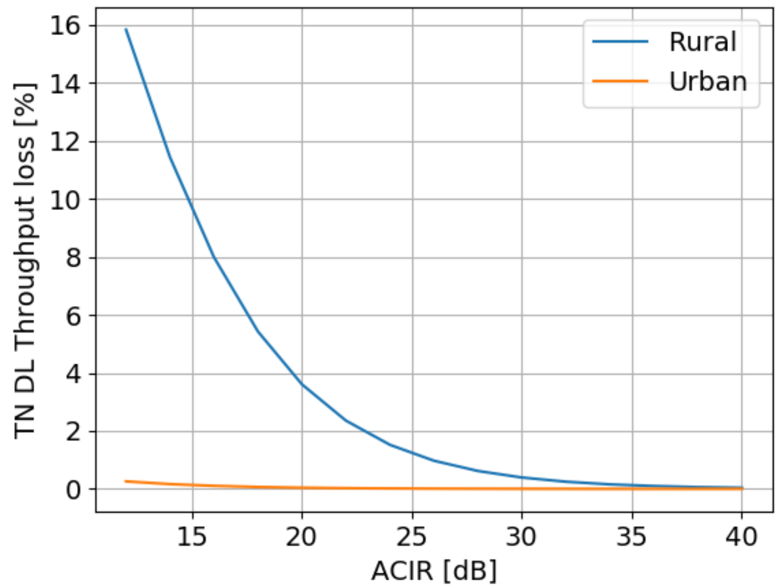

i5
DL TN 5G
Freq. Band
UL NTN 5G
Freq. Band
Interference Type 5 (i5) in DL TN
i6
DL TN 5G
Freq. Band
UL NTN 5G
Freq. Band
Interference Type 6 (i6) in UL NTN
(i6)
(i5)
NTN UE
TN gNB
TN UE*
TN gNB
NTN UE
TN UE*
TN gNB
NTN UE
TN Cell
(TN UE*) can have both TN and
NTN capability
Satellite
(NTN) Cell

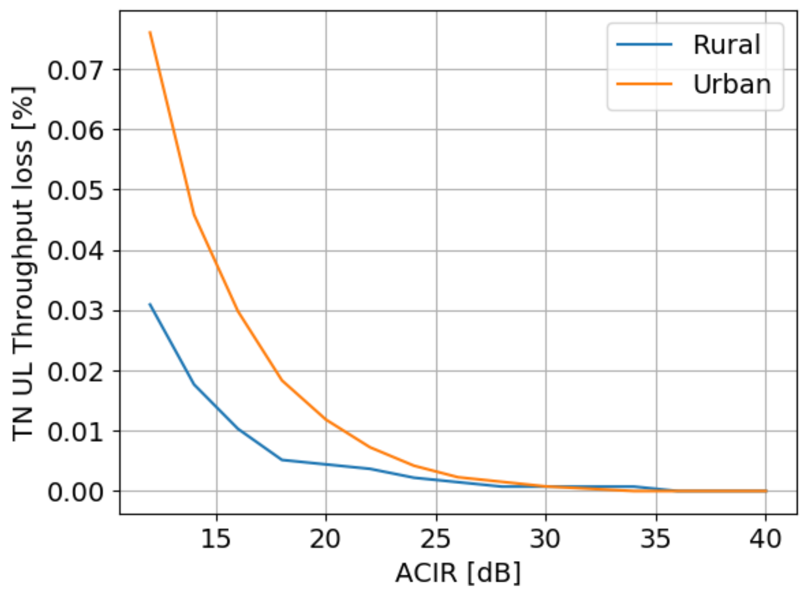


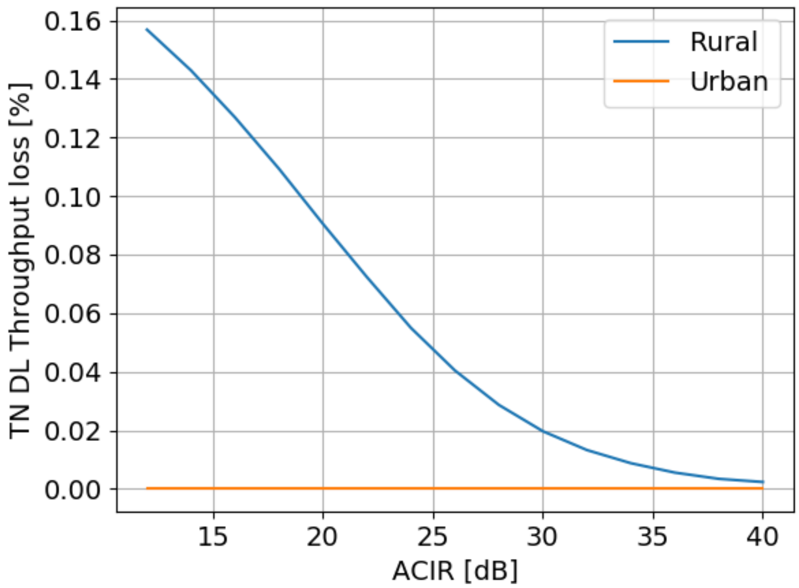
NTN DL Throughput loss [%]
ACIR [dB]
Rural
Urban
0
1
2
3
4
5
15
20
25
30
35
40

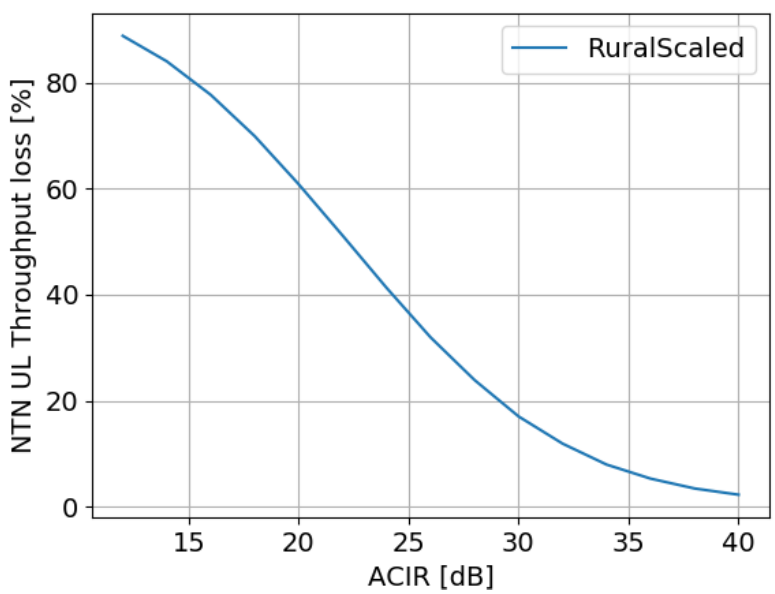


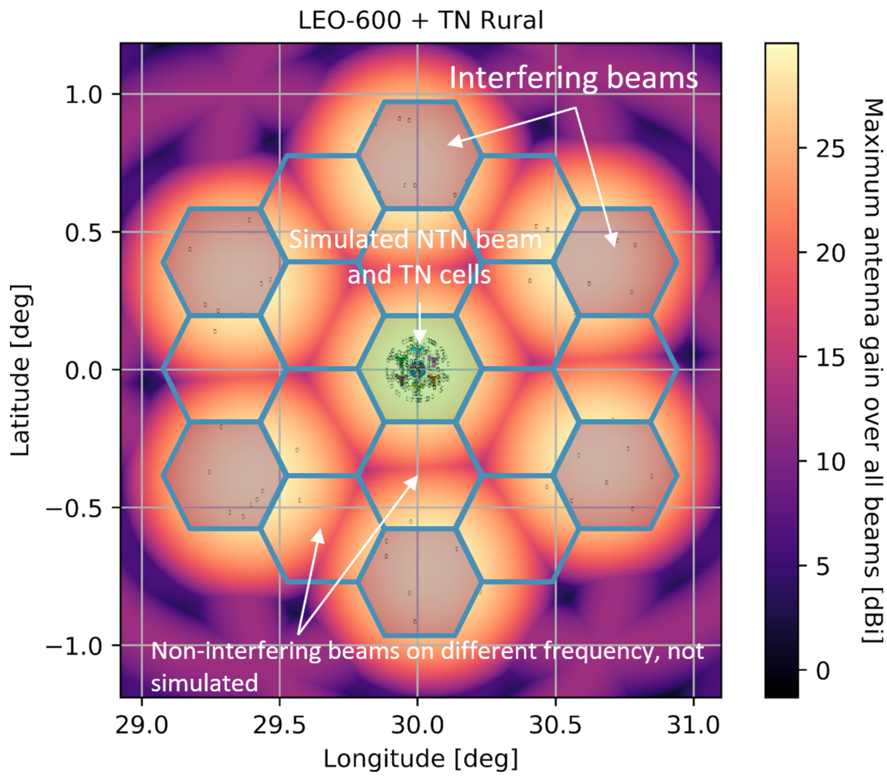
NTN UL Throughput loss [%]
ACIR [dB]
RuralScaled
UrbanScaled
0
10
20
30
40
50
60
70
15
20
25
30
35
40

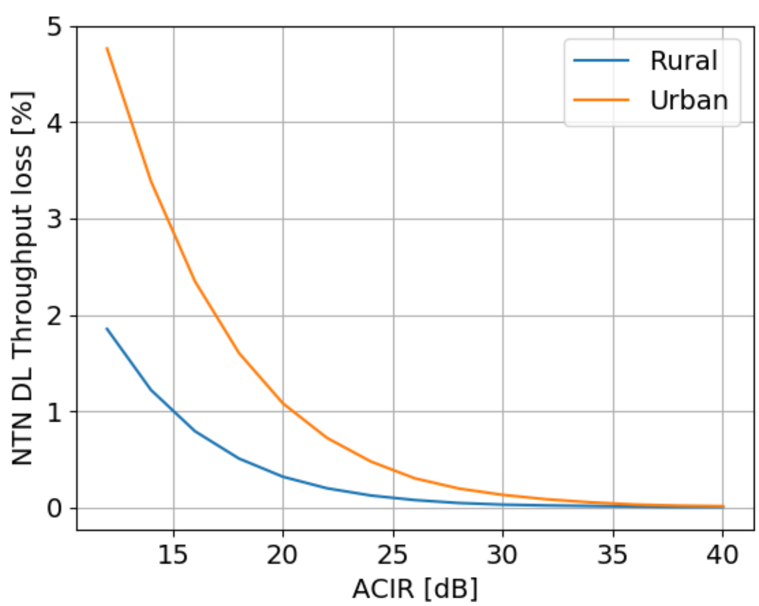

TN DL Throughput loss [%]
ACIR [dB]
Rural
Urban
0
2
4
6
8
10
12
14
16
15
20
25
30
35
40

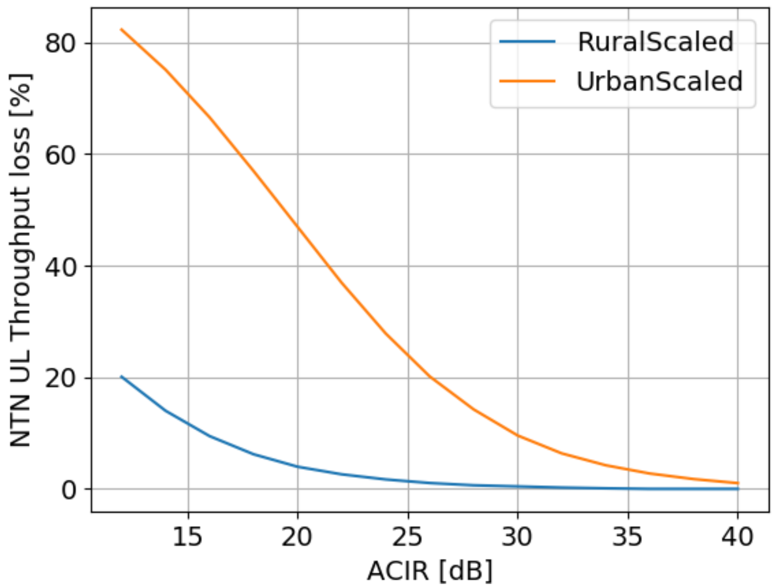

TN UL Throughput loss [%]
ACIR [dB]
Rural
Urban
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
15
20
25
30
35
40

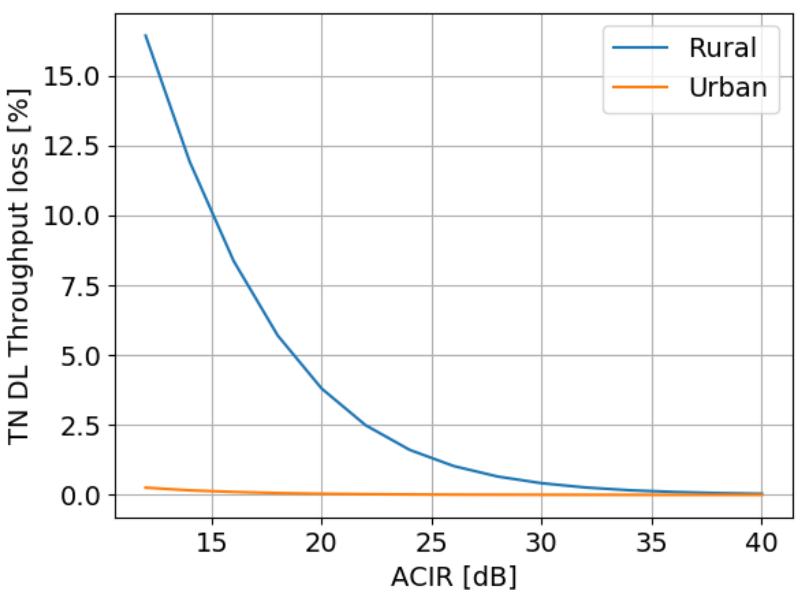

TN DL Throughput loss [%]
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
15
20
25
30
35
40
ACIR [dB]
Rural
Urban

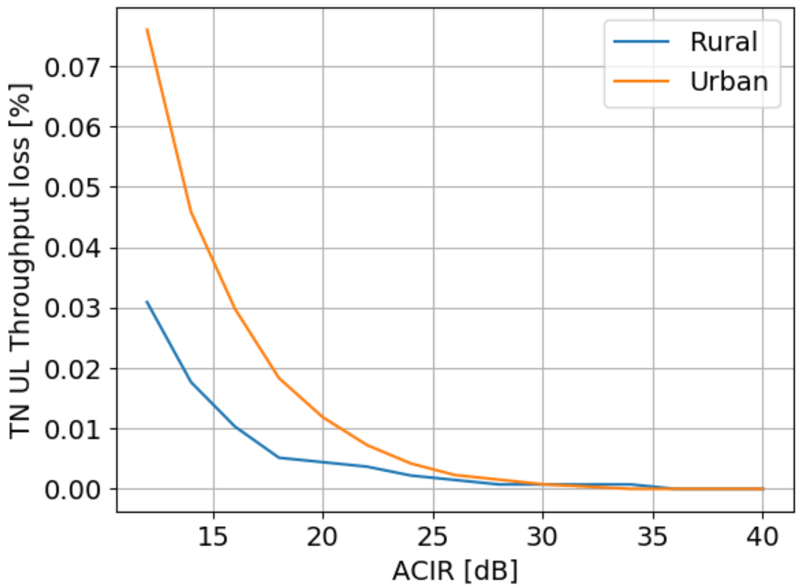

NTN UL Throughput loss [%]
80
60
40
20
0
15
20
25
30
35
40
ACIR [dB]
RuralScaled

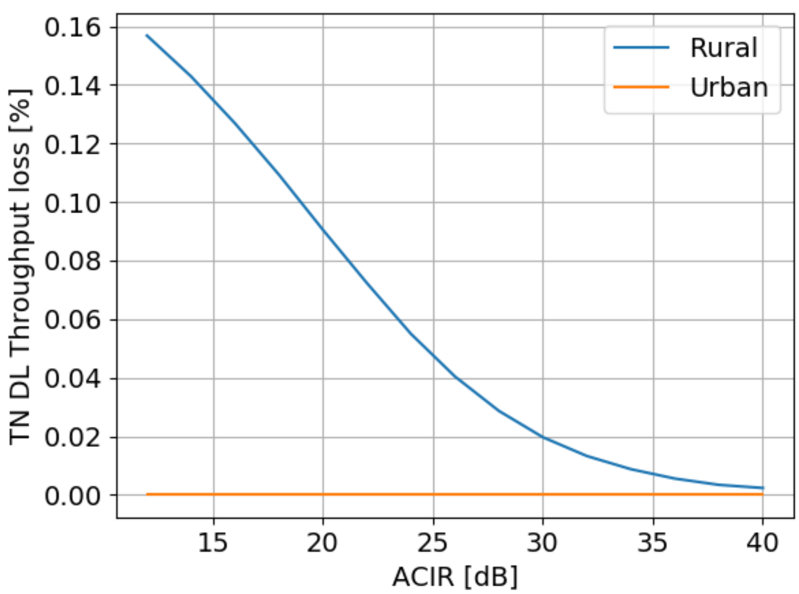

LEO-600 + TN Rural
Interfering beams
Simulated NTN beam and TN cells
Non-interfering beams on different frequency, not simulated
Latitude [deg]
Longitude [deg]
Maximum antenna gain over all beams [dBi]

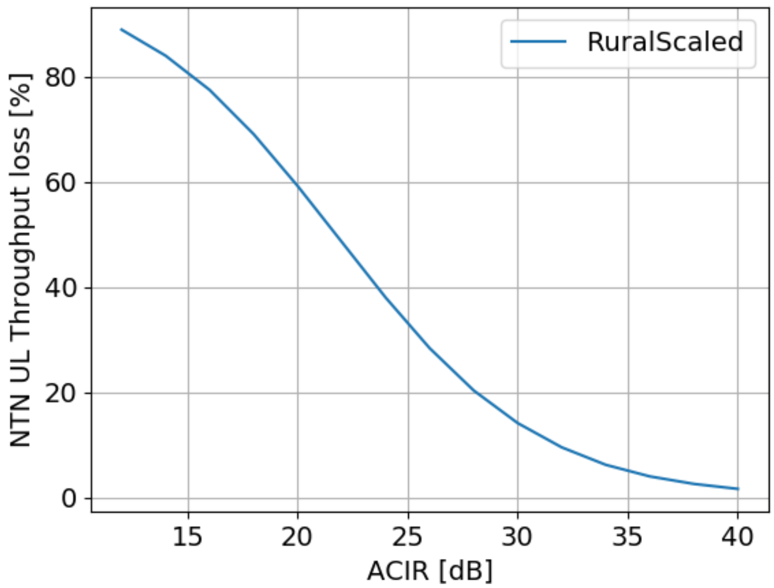

Rural
Urban
NTN DL Throughput loss [%]
ACIR [dB]

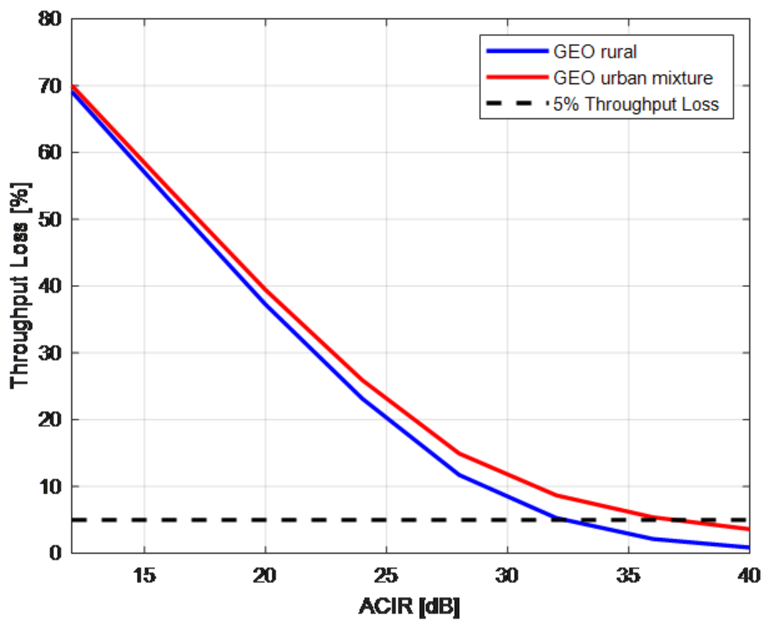

RuralScaled
UrbanScaled
NTN UL Throughput loss [%]
ACIR [dB]

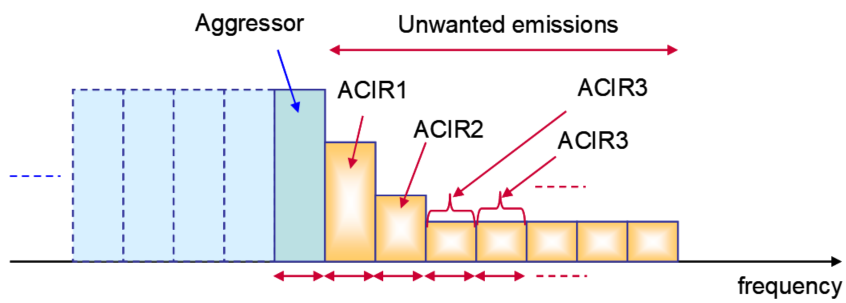

Rural
Urban
TN DL Throughput loss [%]
ACIR [dB]

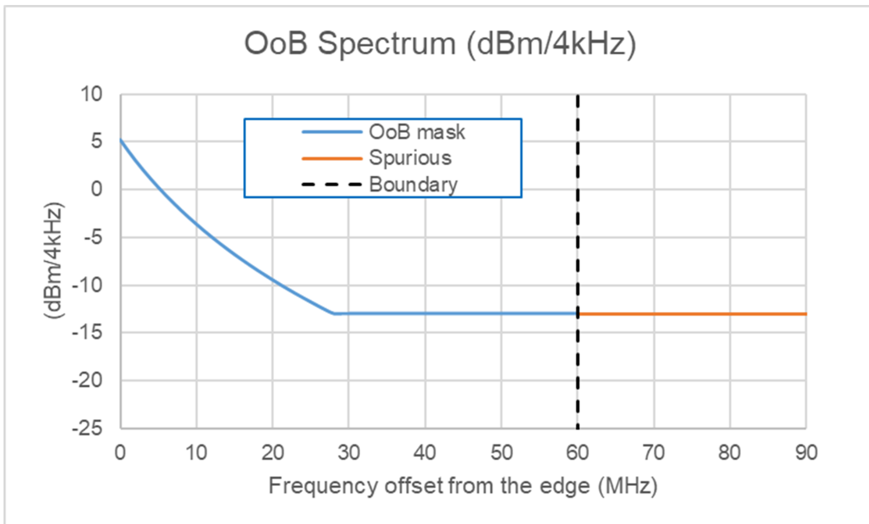

TN UL Throughput loss [%]
ACIR [dB]
Rural
Urban
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
15
20
25
30
35
40

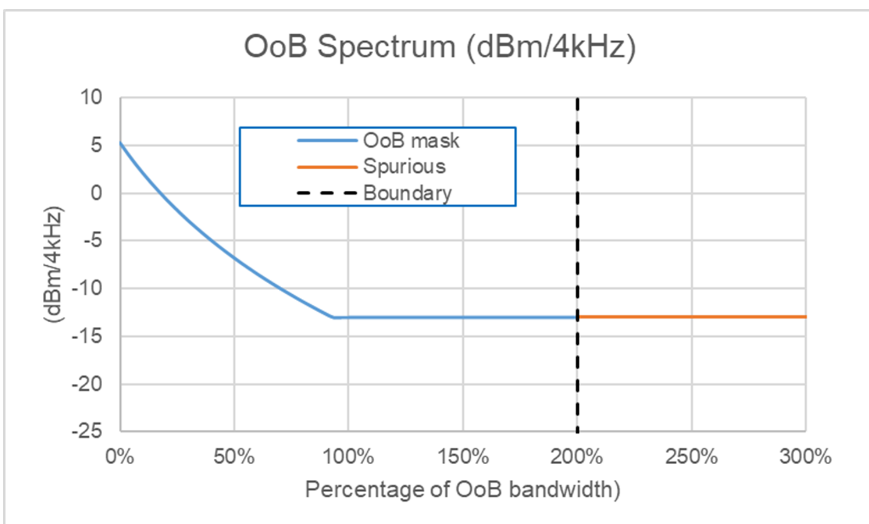

TN DL Throughput loss [%]
ACIR [dB]
Rural
Urban
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
15
20
25
30
35
40

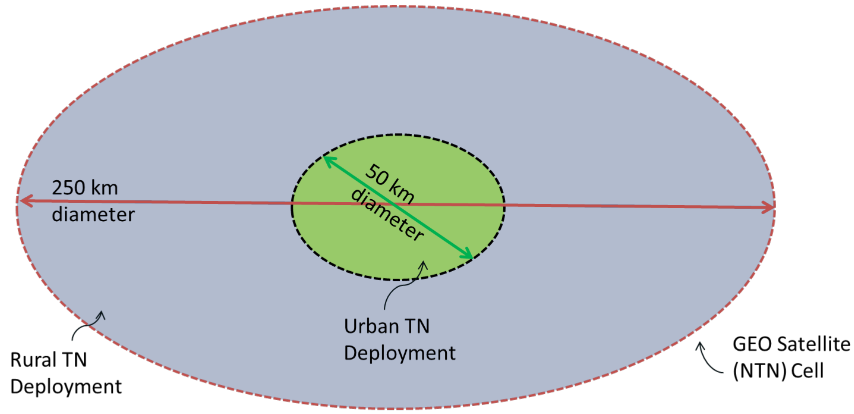

RuralScaled
NTN UL Throughput loss [%]
ACIR [dB]
0
20
40
60
80
15
20
25
30
35
40


GEO rural
GEO urban mixture
5% Throughput Loss
Throughput Loss [%]
ACIR [dB]
0
10
20
30
40
50
60
70
80
15
20
25
30
35
40


Aggressor
Unwanted emissions
ACIR1
ACIR2
ACIR3
ACIR3
frequency


OoB Spectrum (dBm/4kHz)
OoB mask
Spurious
Boundary
(dBm/4kHz)
10
5
0
-5
-10
-15
-20
-25
0
10
20
30
40
50
60
70
80
90
Frequency offset from the edge (MHz)


OoB Spectrum (dBm/4kHz)
OoB mask
Spurious
Boundary
(dBm/4kHz)
10
5
0
-5
-10
-15
-20
-25
0%
50%
100%
150%
200%
250%
300%
Percentage of OoB bandwidth)


250 km
diameter
50 km
diameter
Urban TN
Deployment
Rural TN
Deployment
GEO Satellite
(NTN) Cell

Coexistence of Terrestrial and Non-Terrestrial Networks on Adjacent Frequency Bands

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Abstract

This paper presents the latest achievements concerning 3GPP Release-17 adjacent band coexistence simulation work on 5G New Radio Non-Terrestrial Networks (NTNs) for satellite communications. For the first time, 3GPP considered the introduction of Mobile Satellite Service (MSS) frequency bands for 3GPP User Equipment (UE) direct connectivity with satellites and had to consider the coexistence in adjacent bands with Terrestrial Networks (TNs). This paper will further explain the most challenging and the main surprising outcomes of this work, which opened new market opportunities for both terrestrial and non-terrestrial stakeholders. The main conclusions can be summarized as (1) NTN UE can reuse the current requirements of the TN UE, (2) the satellite connectivity does not require a dedicated satellite waveform, and (3) TN can co-exist with NTN on adjacent channels with relaxed ACIR requirements for the tested simulation scenario.

I. Introduction

3rd Generation Partnership Project (3GPP) has been working on the 5G Non-Terrestrial Networks (NTN) from 2016 onwards [1] [2]. First with a study item, and then, with a "Solutions for NR to support non-terrestrial networks (NTN)" work item (WI) for 3GPP Release 17 [3]. The NTN WI developed technical specifications to mainly support transparent payload-based spaceborne systems, i.e., Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) scenarios.

One important part of the NTN specification work is the RF and coexistence developed in the 3GPP RAN4 working group. RAN4 identified and studied multiple adjacent channel coexistence scenarios, which vary based on terrestrial network and satellite assumptions, as well as aggressor-victim setups [4]. The related simulation work was divided into a simulation calibration phase (TN and NTN) and different coexistence configurations in priority order. The focus was on TN-NTN related coexistence, while NTN-NTN-scenarios were down-prioritized.

The simulator calibration work was initiated in the RAN4 #99-e meeting, i.e., multiple companies were encouraged to provide data from their simulator to collaboratively accomplish the calibration process. RAN4 decided to collect DL SINR, coupling loss, and Tx power for calibration purposes. The latest calibration results can be found in [5], and these were concluded to be close enough to be able to proceed to coexistence work.

The coexistence simulation work in adjacent channels serves normally to evaluate throughput loss (e.g., 5%, 10%, 15%, 20%) in terms of Adjacent Channel Interference Ratio (ACIR) for different combinations of e.g., TN deployments (e.g., rural, urban) and NTN deployments (e.g., LEO, GEO). Once this evaluation is done, Adjacent Channel Leakage Ratio (ACLR) and Adjacent Channel Selectivity (ACS) requirements can be derived from ACIR, as the relation between ACIR, ACLR, and ACS in linear format can be expressed in the form of Equation 1:

$$\frac{1}{ACIR} = \frac{1}{ACLR} + \frac{1}{ACS}. \tag{1}$$

For illustration, all parameters in Equation 1 are ratios between the main channel power and its emissions towards an adjacent channel. The ACLR is a transmitter side quantity, specifying the ratio of transmitted power on the main channel to its unwanted emission on the adjacent channel. The ACS, on the other hand, is a receiver-side property, implicating the ratio of the receiver filter attenuation on the assigned channel to the receiver filter attenuation on an adjacent channel. Finally, the total adjacent channel interference (ACI) is a linear sum of leaked power by the transmitter and adjacent channel signal power which cannot be filtered out by the receiver. Reducing the transmission power from Equation 1, one can derive ACIR for a transmitter and receiver pair, i.e., the ratio of the intended power of an adjacent channel transmission to the interference power experienced by the receiver due to the transmission.

The coexistence simulation approach follows a similar process as per TR 38.803 [6] and TR 36.942 [7]. The throughput loss of 5% is considered the basis for 3GPP standards requirements for adjacent channel coexistence. However, it is useful to evaluate if the loss is significantly higher when the ACIR is higher. The target SINR is considered usually 15 dB.

In this article, we study TN-NTN coexistence on adjacent frequency bands and present system-level simulation results aligned with the RAN4 simulation assumptions. The majority of the simulation results have also been contributed to 3GPP RAN4 working group meetings [8] [9]. The work influenced the related 3GPP technical report TR 38.863 [10].

II. 5G NTN Simulator

For evaluating the coexistence of terrestrial (TN) and non-terrestrial networks (NTN), a Network Simulator 3 (ns-3) [12] based 5G system-level simulator was utilized. Ns-3 is an open-source, discrete-event simulator targeted for research and educational use providing a common C++ framework for developing packet-level simulators of various technologies. To model 5G networks, ns-3 has been extended with 5G LENA [13], which models physical and Medium Access Control layers of NR and implements terrestrial propagation and channel models of 3GPP TR 38.901 [15]. To support NTN-specific features, 5G LENA and ns-3 were extended by adding support for 3GPP TR 38.811 [1] based channel and antenna modeling along with the global coordinate system [14]. Finally, to support hybrid TN and NTN scenarios, support for coordinate and direction translations was added to apply terrestrial channel modeling for terrestrial links (gNB-to-UE) and non-terrestrial channel models for non-terrestrial links (satellite-to-gNB, satellite-to-UE). In this study, we have focused on Frequency Range 1 (FR1), or more precisely, S-band, deployment of both terrestrial and non-terrestrial networks.

By default, the simulator only supported mapping of interference on physical resource block (PRB) resolution, i.e., 12 subcarriers, meaning that two transmissions could not interfere with each other unless their transmission frequencies overlapped. For modeling adjacent channel interference properly, the transmission needed to be extended so that the transmission on certain PRBs would be seen as interference on separate PRBs on entirely different frequency bands. In this research, the adjacent channel interference was modelled by making a copy transmission without payload on the adjacent channel, but with its power distributed equally on the interfered bandwidth and cut by the adjacent channel interference ratio (ACIR), which depended on the simulation scenario and additionally frequency range in case the source of ACI was a UE. The ACIR model is illustrated in Figure 1 representing the power emissions on the victim band caused by a transmission on the aggressor band [4]. The power emissions generally decrease as the distance between the aggressor and victim band in frequency increases, and for UE ACLR is assumed to increase as implied by Table I. For this simulation campaign and simplicity of analysis, a constant ACIR mask was assumed for the entire victim frequency band.

Fig. 1. 3GPP ACIR model from [4]

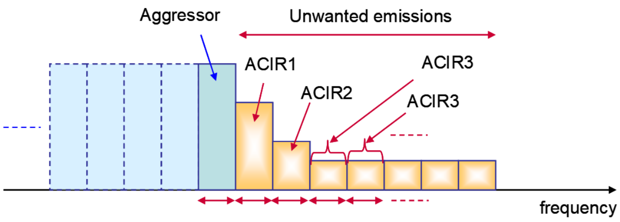


TABLE I
ACLR/ACS for TN (2 GHz) [10]

		NR	NB-IoT
BS	ACLR	45 dB	40 dB
	ACS	46 dB	46 dB
UE	ACLR	30 dB (ACLR1) 43 dB (ACLR2)	37 dB
	ACS	33 dB	28 dB

III. RAN4 coexistence scenarios and assumptions

3GPP RAN4 defined multiple hybrid TN and NTN scenarios, altering the aggressor and victim networks and link directions on FR1. The aggressor and victim networks are deployed on adjacent 20 MHz bands at 2 GHz center frequency, and all aggressor node transmissions cause interference to victim nodes of the simulation case.

As explained in Table II, NTN satellite bands' introduction started in descending order from n256, first with n256 (NTN MSS S-band) and then with n255 (NTN MSS L-band). Even if coexistence simulations considered 2 GHz (closer to n256) center frequency, 3GPP RAN4 decided to reuse the resulting requirements for both n256 and n255 NTN frequency bands. Therefore, for the rest of the work, coexistence analysis is related to FDD NTN n256 with FDD TN n1 and TDD TN n34; however, the resulting requirements are still valid for both FDD NTN n256 and FDD NTN n255.

The scenarios are presented in Table III. In each scenario, the statistics of the victim network are analyzed and compared to the baseline case where the aggressor interference is not present. Cases 1-4 can be considered to have FDD channel deployments with either adjacent DL bands or adjacent UL bands (e.g., coexistence in adjacent bands of MSS S-band FDD n256 with TN FDD n1 as represented in Figure 2), but cases 5 and 6 cover less common cases where there would be either DL or UL band

TABLE II
TN AND NTN FREQUENCY BANDS

Frequency Operating Band	Deployment Type	Uplink (UL) Operating Band	Downlink (DL) Operating Band	Duplex Mode
n1	TN	1920-1980 MHz	2110–2170 MHz	FDD
n34	TN	2010–2025 MHz	2010–2025 MHz	TDD
n256	NTN	1980–2010 MHz	2170–2200 MHz	FDD
n255	NTN	1626.5–1660.5 MHz	1525–1559 MHz	FDD

next to each other, or TDD band next to DL, UL, or another TDD band with opposite link directions interfering each other (e.g., coexistence in adjacent bands of MSS S-band FDD n256 with TN TDD n34 as represented in Figure 3).

Fig. 2. Satellite NTN Coexistence Scenarios 1-4 [10]

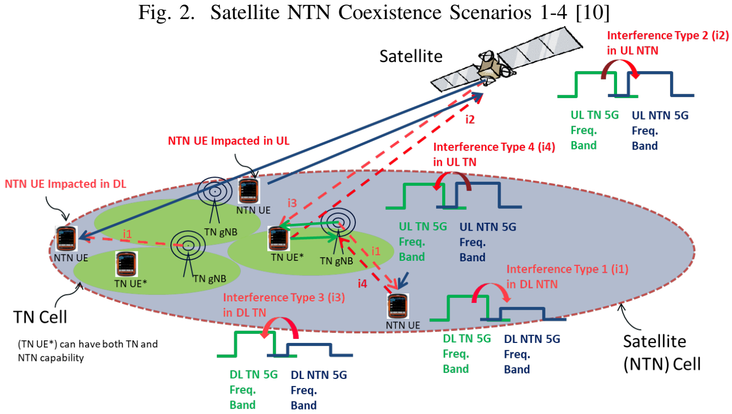


Fig. 3. Satellite NTN Coexistence Scenarios 5-6 [10]

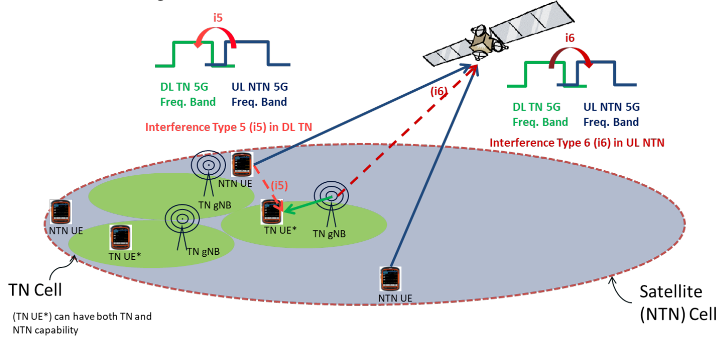


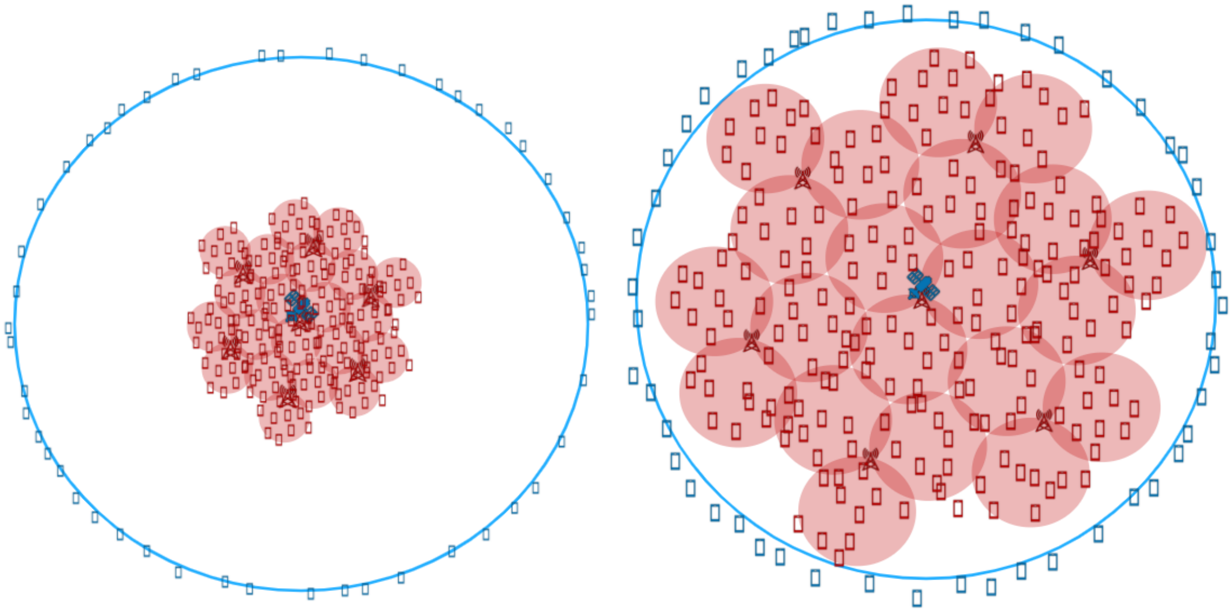
TABLE III
RAN4 COEXISTENCE CASES

Coexistence Case	Aggressor	Aggressor Nodes	Victim	Victim Nodes
1	TN DL	TN gNBs	NTN DL	NTN UEs
2	TN UL	TN UEs	NTN UL	Satellite Node
3	NTN DL	Satellite Node	TN DL	TN UEs
4	NTN UL	NTN UEs	TN UL	TN gNBs
5	NTN UL	NTN UEs	TN DL	TN UEs
6	TN DL	TN gNBs	NTN UL	Satellite Node

The satellite has multiple beams, each corresponding to one NTN Satellite Access Node (SAN) entity. Each beam uses a Bessel antenna model based on Set-1 parameters of [2] and the beams are arranged in a hexagonal grid. To speed up the simulations, only the center beam was used for the collection of statistics and had a fully simulated TN under its coverage; other beams were only present to provide background interference on the same frequency band as the center beam. The orbit of the satellite was varied between LEO-600 (LEO satellite at 600 km altitude), LEO-1200 (LEO satellite at 1200 km altitude), and GEO in the simulation. TN gNBs use a simple single-element non-AAS (Advanced antenna system) antenna model based on [15] and its gain, front-to-back ratio, beamwidth, and downtilt parameters are specified in Table 2.4.2-1 of [4] and [10]. The UEs are assumed to use omni-directional antennas with 0 dBi gain in all directions and are similar whether they are connected to TN or NTN.

Since the satellite beam coverage is potentially very large, varying between 50, 90, and 250 km diameter for LEO-600, LEO-1200, and GEO satellite beams, respectively, it would be computationally demanding to simulate the entire beam area filled with terrestrial gNBs and their users. Additionally, careful scenario planning is required to identify problematic cases and capture them in the simulation, but also to not create artificial issues which do not exist in real-world deployments. In this study, it was assumed that wherever TN coverage exists the UEs connect to TN gNBs, and outside the TN coverage area there would be UEs connected to the satellite. Two different deployments were tested: Urban and Rural with TN inter-site distances (ISD) of 750 m and 7500 m, respectively. Behind an isolation distance of 1500 m in the Urban case and 0 m in the Rural case from the TN edge, there would be UEs connected to NTN. The isolation distance in the Urban case is specified in [4] and set to compensate for the relatively small ISD of the Urban case and consequent small propagation losses from the TN area to the positions of the NTN UEs. Urban and Rural deployments are illustrated in Figures 4.

Fig. 4. Urban scenario and Rural scenarios with TN ISD = 750 m and 7500m, respectively

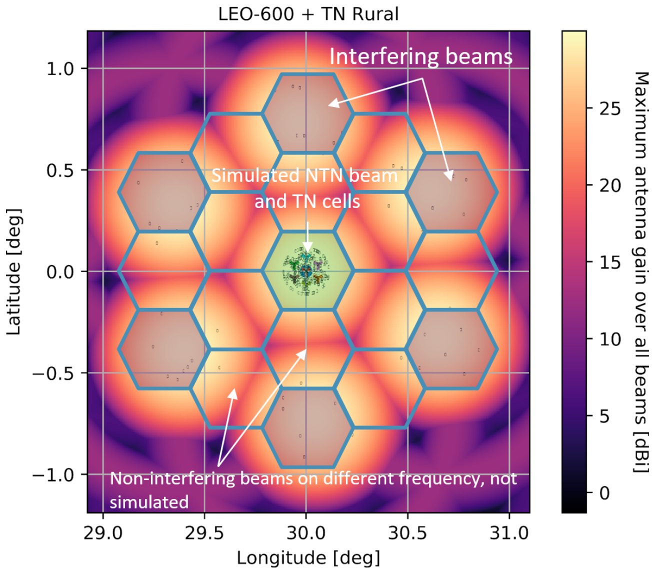


The simulated terrestrial network consists of a total of 7 sites, with each site hosting three 120-degree sector gNBs. Each gNB has 10 UEs randomly placed in the cell, and each UE may select the best cell among TN based on RSRP at the beginning of the simulation. The simulated 50 NTN UEs are placed outside TN with the isolation distance in place. All of the UEs have a so-called Full buffer traffic model enabled in both link directions, causing maximum interference effect whenever they are scheduled. Round-robin scheduling ensures all interference sources are evenly represented in the results.

While the networks are of sufficient size to be efficiently evaluated using a packet-level SLS, the scenario size does not necessarily capture the worst-case effect for a satellite beam in cases 2 and 6 due to its large coverage area, as can be seen from the example scenario view presented in Figure 5 where TN size is at its largest compared to the center beam diameter. Simply increasing scenario size would make the cases computationally too demanding to be simulated using a packet-level SLS. RAN4 proposed to adopt a scaling factor for the interference caused by TN UEs and TN gNBs to obtain realistic aggregate interference effects at the satellite. The idea of the scaling factor is simple: estimate the total number of similar TNs that could fit under the beam, consider 20% of them active simultaneously (i.e., activity factor = 20% as specified in [4]), and then scale up ACI caused by each aggressor transmission by the product of these numbers. As the TN was placed in the middle of the beam to get maximum interference effects in the scenarios when the satellite is the aggressor, the scaling factor was also decreased by the difference between peak and average gains of the beam in its coverage area. The scaled number of simultaneously active cells and the peak-to-average beam gain degradation factors per orbit and scenario are presented in Table IV.

The main target of the simulations was to obtain for each coexistence scenario an ACIR requirement between the aggressor and victim devices, which could be used to define ACLR and ACS limits for NTN-enabled devices. To limit the number

Fig. 5. Example scenario layout for LEO-600 satellite with 7 beams and Rural TN in the middle of the center beam and regular NTN users in surrounding interfering beams



of simulations, ACIR between the aggressor and victim band was swept between 12 and 40 dB by steps of 2 dB for each variation. Additionally, for the case 6 Urban scenario the tested ACIR range was extended up to 60 dB to get a sufficient ACIR requirement for that specific scenario.

TABLE IV
SCALED NUMBER OF SIMULTANEOUSLY ACTIVE TN CELLS UNDER NTN BEAM AREA IN COEXISTENCE CASES 2 AND 6

Deployment Scenario	LEO-600	LEO-1200	GEO
Urban	1680	5439	42000
Rural	21[1]	54	420
Beam gain peak-to-average degradation factor	-1.73 dBi[2]	-1.39 dBi	-1.48 dBi

[1] Assuming LEO-600 beam dimension and Rural TN diameter of 25 km (consisting of two times ISD plus two times cell range for seven simulated sites), the TN covers the necessary amount of area and scale-up is not needed.

[2] As the scale-up is not applied for LEO-600 and Rural scenario combination, the peak-to-average beam gain degradation is not applied in this case.

IV. RESULTS

Table V presents the ACIR requirements per NTN orbit, TN scenario, and coexistence case specified in Table III to obtain at most 5% average throughput loss for the victim nodes of the scenario. The ACIR requirements of the table have been rounded up to the first tested ACIR which does not cause unacceptable throughput degradation. As can be seen from the table, in many of the coexistence cases a low ACIR of 12 dB or potentially even less is enough to provide the necessary isolation of channels. Especially in cases 4 and 5, the interference was negligible, due to the isolation distance of the aggressor NTN UEs from the victim TN nodes. Additionally, in coexistence case 3 Urban layout where the TN UEs are close-by to their own network, the satellite cannot effectively cause ACI towards UEs due to a large difference in propagation losses. The only coexistence case where TN is the victim of NTN and ACIR requirement is slightly increased from the minimum tested value in case 3 with Rural TN, where the larger distance of TN UEs to their serving gNBs causes the propagation losses to the TN and satellite to be closer to each other, and ACIR requirement is slightly increased up to 20 dB for LEO-600 and LEO-1200.

Generally, either satellite or the UEs connected to it seem to suffer more from the presence of the terrestrial network than the opposite. With the chosen network layouts, NTN UEs not being inside the TN coverage area do not suffer from the TN DL transmissions, as is indicated by the ACIR requirements of case 1. However, the propagation loss to the GEO satellite is large enough to slightly increase the ACIR requirement from 12 dB of LEO satellites up to 18 dB as seen in Figure 6.

In a conclusion from cases 3, 4, and 5, seen in Figures 8, 9, and 10, where the NTN is the aggressor and TN the victim, it can be seen that the ACIR requirements are significantly lower than the current ACLR for both terrestrial gNB and UEs, which implies that NTN-enabled UEs can re-use current ACLR requirement of 30 dB and satellite ACLR can even be relaxed from the terrestrial requirement of 45 dB. In case 1, where TN gNBs are the aggressors and NTN UEs are victims, the TN UE ACS of 33 dB combined with TN gNB ACLR requirement of 45 dB is easily enough to guarantee sufficient ACIR and thus the isolation of frequency bands.

Coexistence cases 2 and 6, where NTN UL, i.e., receiving satellite is the victim, are the most difficult ones. The ACIR results for these cases are shown in Figure 7 and 11. In these scenarios, the scale-up factor described previously was applied to model the aggregate interference from the entire beam area. While the Rural layout does not cause difficulties in case 2 due to the relatively sparse UL under coverage area, the Urban one is much denser and consequently increases ACIR requirements by 10-16 dB. At most average ACIR of 34 dB is required between TN UEs and satellites of different orbits, but it should be noted that UE ACLR decreases towards channel edges as implied by ACLR1 and ACLR2 requirements for UE in Table I. For comparison, when a 13 dB increase in ACIR was applied on two-thirds of the victim band farther away from the aggressor band for comparison, which caused the ACIR requirement (for the third of the band closest to the aggressor) to decrease by 2-6 dB depending on orbit and TN scenario. The conclusion of scenario 2 is that the satellite and terrestrial network can co-exist on adjacent UL bands even with a relaxed satellite ACS requirement compared to 46 dB of TN in Table I.

Case 6 is the most challenging due to the high transmission power of the TN gNBs: even if the antennas are directed towards the horizon level and antenna gain from gNB towards the satellite is negative in dBi, each gNB causes interference equal to approximately 100 UEs due to 46 dBm transmission power of gNB and 23 dBm of UE. In a Rural layout, the ACIR requirement for acceptable performance losses was in the range of tested values, but in a densely populated Urban area NTN, UL, and TN DL bands cannot co-exist on adjacent channels either without proper guard-band or without performance losses, assuming ACLR requirement of 45 dB for TN gNB in Table I. As a conclusion for case 6, adjacent channel deployment of NTN UL and TN DL should be avoided in environments densely covered by TN. If we assumed increased gNB antenna directivity, i.e., less gain towards the satellite, by using e.g., AAS, the ACIR requirement might be relaxed; however, the satellite beam covers a large area which may host several types of antennas causing diverse levels of ACI towards the satellite.

The results of Table V have been contributed to 3GPP in [10], and they are well in line with results from other companies and organizations. The report contains detailed graphs of throughput loss per tested ACIR value.

TABLE V
ACIR REQUIREMENT FOR $< 5\%$ THROUGHPUT LOSS FOR THE VICTIM NETWORK BY NTN ORBIT, TN SCENARIO, AND COEXISTENCE CASE

Coexistence Case	Deployment Scenario	LEO-600	LEO-1200	GEO
1	**Rural**	12 dB	12 dB	16 dB
	Urban	12 dB	12 dB	18 dB
2	**Rural**	22 dB[1]	20 dB[2]	14 dB[3]
	Urban	32 dB[1]	34 dB[2]	30 dB[3]
3	**Rural**	20 dB	20 dB	12 dB
	Urban	12 dB[4]	12 dB[4]	12 dB[4]
4	**Rural**	12 dB[4]	12 dB[4]	12 dB[4]
	Urban	12 dB[4]	12 dB[4]	12 dB[4]
5	**Rural**	12 dB[4]	12 dB[4]	12 dB[4]
	Urban	12 dB[4]	12 dB[4]	12 dB[4]
6	**Rural**	36.70 dB	36.70 dB	34.47 dB
	Urban	36.70[6]dB	36.70[6]dB	36.89 dB[5]

[1] Assuming ACIR decreases by 13 dB towards the edges of the victim channel, ACIR requirements of 16 dB for Rural and 26 dB for Urban can be assumed for LEO-600.
[2] Assuming ACIR decreases by 13 dB towards the edges of the victim channel, ACIR requirements of 14 dB for Rural and 28 dB for Urban can be assumed for LEO-1200.
[3] Assuming ACIR decreases by 13 dB towards the edges of the victim channel, ACIR requirements of 12 dB for Rural and 24 dB for Urban can be assumed for GEO.
[4] 12 dB was the minimum tested value, but throughput loss $< 1\%$ indicates the victim network could manage with even lower ACIR.
[5] GEO scenarios with a 250 km diameter are not entirely composed of only urban TN scenarios and Urban case represents mixture of Urban and Rural.
[6] Urban ACIR requirements taken from Rural scenario

Moreover, one can notice that when the GEO satellite beam is covering an area, the GEO beam cannot cover only an urban deployment since this is not a realistic scenario. Currently, even in the densest metropolitan areas, there is no such urban deployment with a diameter of 250 km, and with the same urban density considered for the coexistence analysis simulations (see TR 38.863 [10]). Therefore, at least for the GEO satellite case, it is not realistic to consider a scenario entirely composed of urban deployment. It was decided by 3GPP in TR 38.863 to use LEO-600 Rural environment as representative case for ACIR value derivations as considering a full Urban deployment under a beam may result in an over-designed specification at least when considering the SAN ACS requirements.

Fig. 6. Scenario 1 NTN DL throughput loss for LEO-600, LEO-1200 and GEO

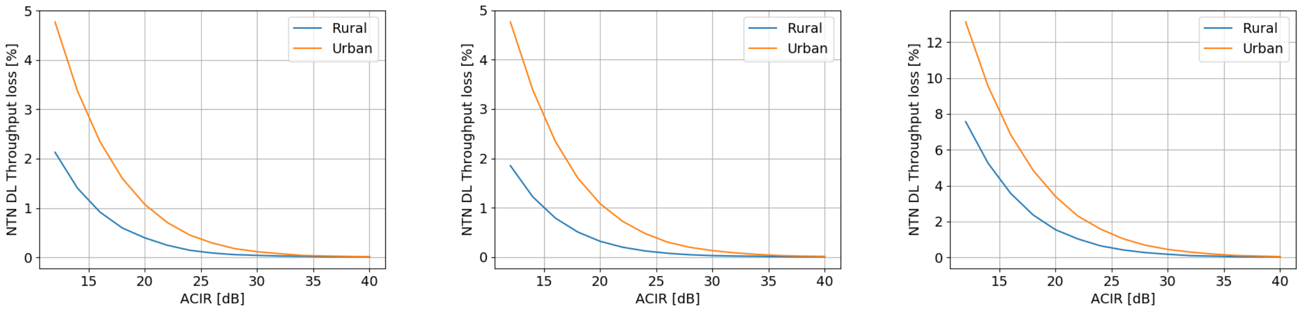
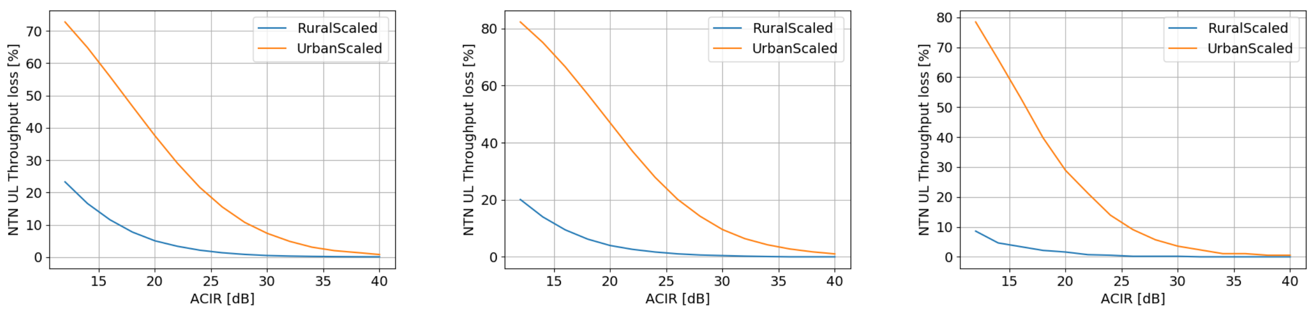


Fig. 7. Scenario 2 NTN UL throughput loss for LEO-600, LEO-1200 and GEO



For a GEO beam, the maximum ratio between the urban deployment area and rural deployment area is approximately 1:24, as shown in Figure 12 assuming a 50 km diameter for an urban deployment inside a 250 km diameter GEO satellite beam [16]. Resulting ACIR requirements are show in Figure 13 which represents the case for GEO urban mixture where the ACIR requirement at the 5% throughput loss is only 36.89 dB. This result indicates that a SAN ACS requirement for GEO urban mixture deployment is only 37.62 dB, which is lower than the 38 dB SAN ACS agreed as the baseline in RAN4#101-bis-e and further in TR 38.863 [10].

By placing the ACIR requirement per scenario from Table V with the opposite side NR ACLR or ACS value from Table I into Equation 1, one can derive the ACLR and ACS requirements for both SAN and NTN UE. The final 3GPP ACLR and ACS requirements for NTN SAN and UE are presented in Table VI and represented in TS 38.101-5 [17].

TABLE VI
ACLR/ACS FOR NR-NTN (2 GHZ) [10]

		GEO Class	**LEO Class**
NTN Satellite Access Node	ACLR	14 dB	24 dB
	ACS	38 dB	38 dB
NTN Satellite UE	ACLR	30 dB	30 dB
	ACS	33 dB	33 dB

V. OTHER SATELLITE REQUIREMENTS, CONFORMANCE TESTING, AND FUTURE PERSPECTIVES

Coexistence analysis served to identify ACLR and ACS values for different satellite classes, as part of the core requirements definition from TS 38.108 [18]. Two new frequency bands n256 (S-band) and n255 (L-band) have been introduced in Rel-17 for the Satellite Access Node for two SAN classes: GEO class and LEO class. Concerning the SAN classification, the current class classification is based on the requirements associated with SAN classes in a case-by-case manner including Interference over Thermal level (IoT level), In-channel Selectivity (ICS), Noise Figure (NF), ACLR, ACS, and emission requirements. The satellite altitude or orbit type were not identified as part of the class differentiation, and for this reason, LEO-600 and LEO-1200 were grouped in the same class. At least NF, ACLR, and ACS values are the same for LEO-600 and LEO-1200 and therefore are not requiring class differentiation. On the other hand, as a result of the coexistence studies, ACLR and ACS requirement values are different between GEO and LEO constellations, requiring a class differentiation. Moreover, the ACS

Fig. 8. Scenario 3 TN DL throughput loss for LEO-600, LEO-1200 and GEO

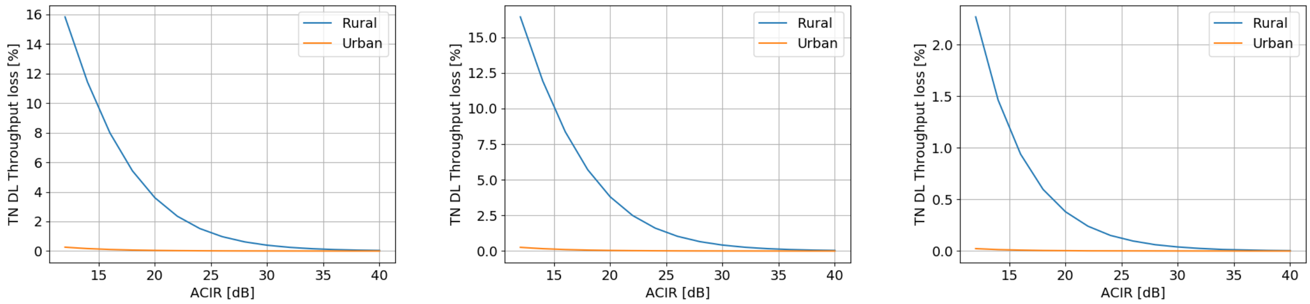
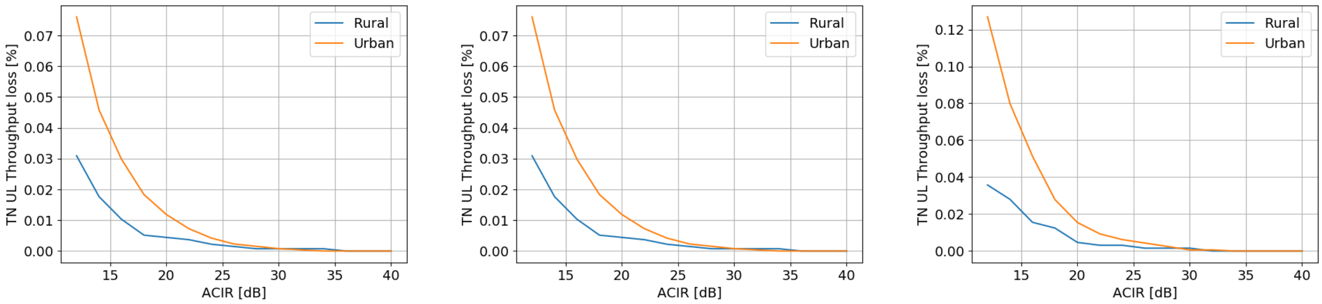


Fig. 9. Scenario 4 TN UL throughput loss for LEO-600, LEO-1200 and GEO



requirement value was further used to determine and specify the interfering signal mean power (dBm) used for SAN testing, resulting in a -57 dBm value for the GEO class and a -60 dBm value for the LEO class, according to Equation 2

$$I_{mean}\,[dBm] = SAN_{noisefloor} + ACS + 4.7dB = -174dBm/Hz + 10 \cdot \log_{10}(BW) + NF + ACS + 4.7dB, \quad (2)$$

where BW is the wanted signal bandwidth [Hz], e.g. 25 Physical Resource Blocks (PRBs) for a 5 MHz channel with a Sub-Carrier Spacing (SCS) of 15 kHz, NF is Noise Figure (7.4 dB for GEO, 4.3 dB for LEO-600 and LEO-1200), SAN ACS was obtained from coexistence simulations (see Scenario 6) as 38 dB, and 4.7 dB value is computed from $10 \cdot \log_{10}(10^{6/10} - 1)$ [19].

The waveform used for ACS tests also changed to CP-OFDM instead of DFT-s-OFDM concerning coexistence case 6 (TN TDD BS towards NTN SAN) considered as the worst case from the point of view of SAN ACS requirements. Differences exist as well in terms of emission requirements between GEO and LEO, e.g. Out-of-Band (unwanted) emissions and spurious emissions.

As previously mentioned, on top of ACLR and ACS SAN requirements, some other requirements were defined for instance Spurious and Out-of-Band (Unwanted) Emissions, Error Vector Magnitude (EVM), In-channel Selectivity (ICS), and others as found in [18]. Satellite payload has been tested against those requirements, as shown for instance in Figure 14 [20] where is represented the SAN LEO-600 output spectrum for different bandwidths using OFDM signal with satellite transponder optimised for QPSK modulation.

As general information, the principle was to follow ITU-R recommendation SM.1541-6 [21] at least for the frequency offset range within the first two break points, with the measurement bandwidth of 4 kHz. The Out-of-Band noise is mainly produced by inter-modulation noise generated by the power amplifiers and weakly filtered by the output filter in the region close to the bandwidth. The inter-modulation noise from Figure 14 was simulated considering the power amplifier non-linear responses (in amplitude and phase) and filling the bandwidth with a Gaussian signal to emulate OFDM multi-carrier operation. The ITU-R unwanted emissions limit was then compared against the satellite node spectrum of a 30 MHz signal, in blue, and the satellite node spectrum of a 5 MHz signal, in orange. Please note that the specified EIRP density, expressed in dBW/MHz, applies to all channel bandwidths. Therefore, the worst case will be the widest channel, since TR 38.863 [10] considers the same spectral density in dBW/MHz independently of the frequency bandwidth.

According to ITU-R SM.1541-6 recommendation [21], the Out-of-Band emissions are defined over an offset of 200% of the necessary bandwidth, that means, e.g. over 60 MHz from the edge of the 30 MHz SAN total bandwidth currently assigned for S-band. The reasoning does not change for S-band, L-band, or different type of satellite. Actually, the ITU-R SM.1541-6 recommendation [21] does not preclude the use of another band (e.g. S-band, L-band) or a different type of satellite (LEO,

Fig. 10. Scenario 5 TN DL throughput loss for LEO-600, LEO-1200 and GEO

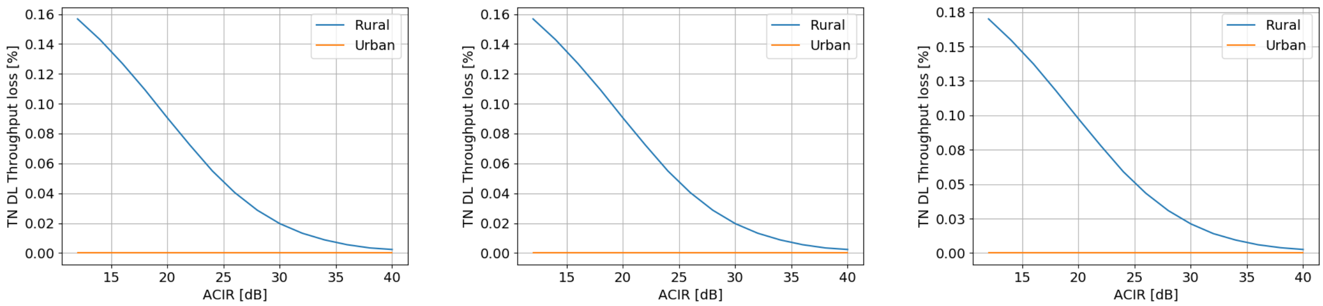
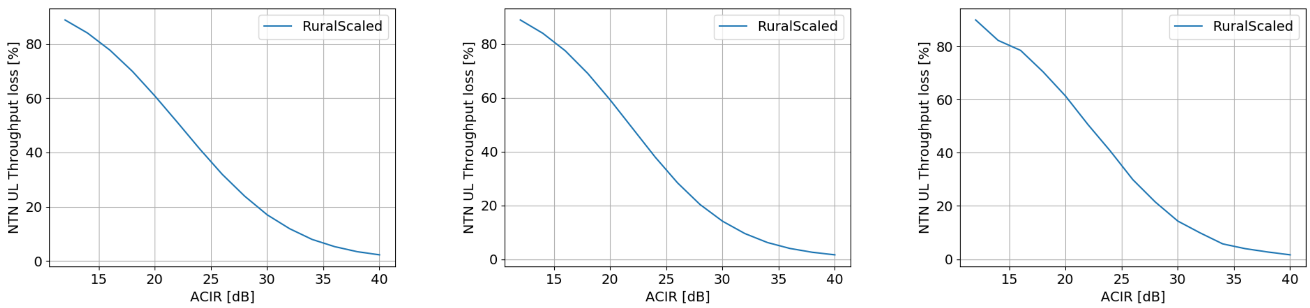


Fig. 11. Scenario 6 NTN UL throughput loss for LEO-600, LEO-1200 and GEO, for rural scenario



GEO). Please also note that the mask is defined at the input of the transmit antenna and therefore the antenna gain is not included. Moreover, according to ITU-R SM.1541-6 recommendation [21], another possible definition is to use an offset of 250% of the necessary bandwidth from the center of the frequency band, that means, e.g. over 75 MHz in the S-band from the center of the assigned band. In addition to Out-of-Band emissions, unwanted emissions in the spurious domain are specified at -13 dBm/4 kHz as per ITU-R SM.329-12 recommendation [22]. Figures 15 and 16 below show the Out-of-Band (OoB) and the spurious emission requirements, where the OoB emission is defined as [18]

$$\max\left(SE_{limit}, PSD_{channel} - \Delta_{Sat\_Class}[dB] - 40\cdot\log_{10}\left(\frac{f_{offset} - 0.002}{BW_{channel}}\cdot 2 + 1\right)\right)[dBm], \quad (3)$$

and therefore, SAN OoB emission is defined as the maximum between Spurious Emission (SE) limit and Power Spectral Density (PSD) attenuation, where

$$PSD_{channel}\left[\frac{dBm}{4kHz}\right] = P_{rated,c,sys} - 10\cdot\log_{10}\left(BW_{channel}\right) - 24. \quad (4)$$

The limits represented in Figures 15 and 16 are computed for a LEO-600 in S-band using the entire SAN S-band n256 bandwidth (i.e., 30 MHz), with a PSD of 8.25 dBm/4 kHz (corresponding to a SAN output power of 47 dBm and a SAN bandwidth of 30 MHz) and a $\Delta_{Sat\_Class}[dB]$ of 3 dB corresponding to a LEO SAN class [18]. For the example considered above (with a LEO satellite in S-band), the intersection between the two arguments occurs at approximately 27 MHz offset from the edge (at 90% of SAN bandwidth, from the edge of the band). Beyond 27 MHz offset (beyond 90% of SAN bandwidth value), the value for spurious emissions (-13 dBm/4 kHz) applies in the Out-of-Band domain as it is less stringent than the Out-of-Band emission value (see blue curve). After the OoB limit (i.e., the spurious boundary), the OoB limitation further continues with the spurious limitation.

As a result of the previously mentioned work, the following Satellite 5G NR (Non-Terrestrial Networks) technical documents have been approved at the 3GPP RAN-Plenary #96 (Budapest, 6th-9th of June 2022) for the Rel-17 NTN satellite connectivity using FR1 S-band (n256) and FR1 L-band (n255):

- Technical Specification TS 38.108 (NR; Satellite Node radio transmission and reception) [18];
- Technical Specification TS 38.101-5 (NR; User Equipment (UE) radio transmission and reception; Part 5: Satellite access Radio Frequency (RF) and performance requirements) [17];
- Technical Report TR 38.863 (Non-terrestrial networks (NTN) related RF and co-existence aspects) [10].

Fig. 12. GEO rural and urban mixture deployment

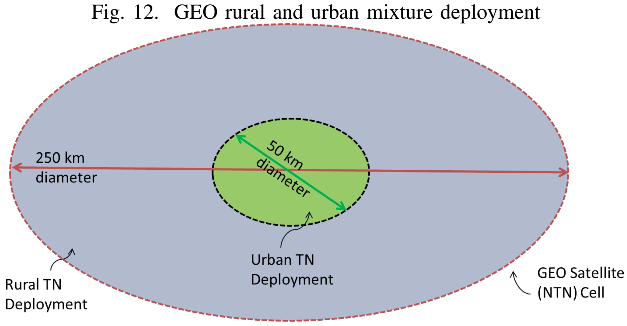
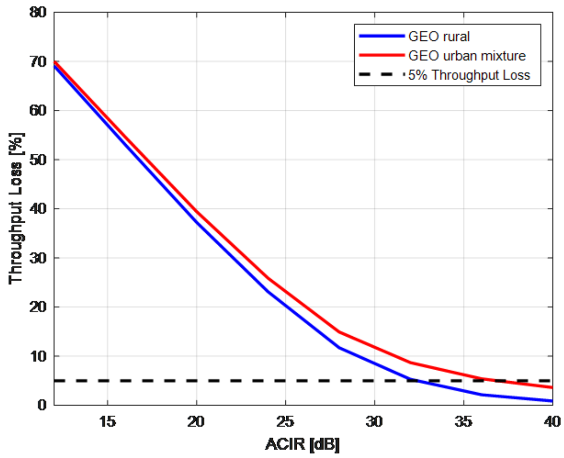


Fig. 13. Scenario 6 throughput Loss [%] as a function of ACIR [dB] for GEO rural and GEO urban mixture



NTN Rel-17 RAN4 work also defined satellite conformance testing in [25], together with demodulation performance in related TS 38.108 [18] and TS 38.101-5 [17] related clauses. NTN-related Radio Resource Management (RRM) requirements have been also updated in TS 38.133 [24], including e.g. measurement accuracy, GNSS accuracy, and timing compensation (NTN timing error) requirements for both idle and connected mode [26]. At the publication date of this article, the current NTN Rel-17 RAN4 releases are under the maintenance phase, and future work is currently considered in Rel-18 and Rel-19 NTN roadmaps, as shown in Table VII. Of course, many of these Study Items (SIs) or Work Items (WIs) will further have further implications for 3GPP RAN4 NTN future work, even if the lead work group (WG) is not explicitly mentioned to be 3GPP WG RAN4.

TABLE VII
NTN-RELATED STUDY ITEMS AND WORK ITEMS IN 3GPP FOR FUTURE RELEASES

Study Item (SI) or Work Item (WI) Title	SI or WI Acronym	Lead Work Group	Release #	Type
5G system with satellite backhaul	5GSATB	SA1	Rel-18	WI
Guidelines for Extra-territorial 5G Systems	FS_5GET	SA1	Rel-18	SI
Study on Security Aspects of Satellite Access	FS_5GSAT_Sec	SA3	Rel-18	SI
Study on requirements and use cases for network verified UE location for Non-Terrestrial-Networks (NTN) in NR	FS_NR_NTN_netw_verif_UE_loc	RP	Rel-18	SI
Study on Management Aspects of IoT NTN Enhancements	FS_IoT_NTN	SA5	Rel-18	SI
NR NTN (Non-Terrestrial Networks) enhancements	NR_NTN_enh	RAN2	Rel-18	WI
IoT (Internet of Things) NTN (non-terrestrial network) enhancements	IoT_NTN_enh	RAN2	Rel-18	WI
Study on 5GC enhancement for satellite access Phase 2	FS_5GSAT_Ph2	SA2	Rel-18	SI
Study on Support of Satellite Backhauling in 5GS	FS_5GSATB	SA2	Rel-18	SI
Study on satellite access - Phase 3	FS_5GSAT_Ph3	SA1	Rel-19	SI

For instance, the coexistence scenarios for above 10 GHz will most probably consider different NTN terminal characteristics (See for instance [27] for VSAT UE characteristics and initial simulation parameters) and different NTN-TN NR adjacent band coexistence scenarios parameters (See for instance [28] with discussions on Ka-band). Moreover, as agreed at 3GPP TSG-RAN WG4 Meeting #105 in November 2022, with respect to the Way Forward (WF) for above 10 GHz band definition and system

Fig. 14. SAN Spurious and Out-of-Band Unwanted Emissions [20]

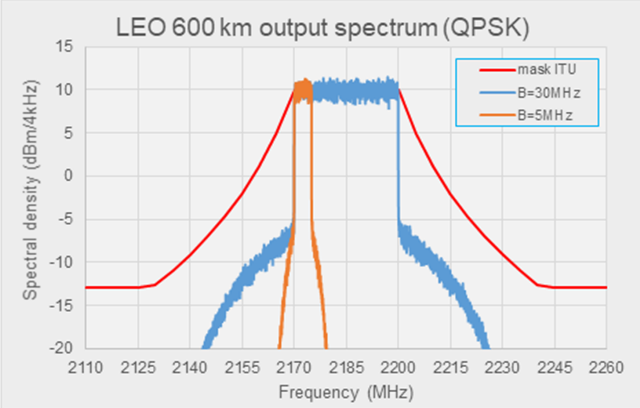
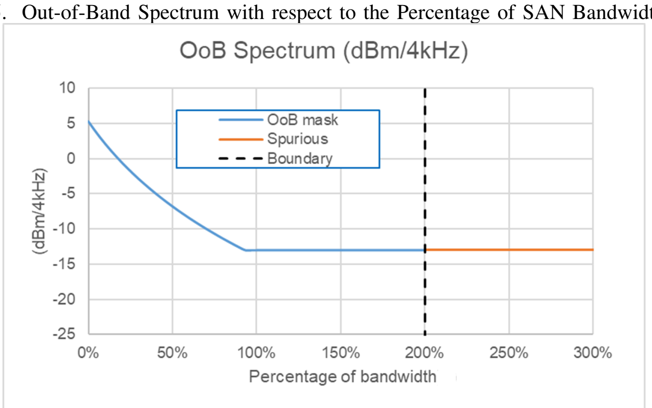


Fig. 15. Out-of-Band Spectrum with respect to the Percentage of SAN Bandwidth [23]



parameters (see R4-2220239 [29]), the following Ka-band configurations are considered as starting point:

- n511 with consideration of US/FCC regulations;
- n512 with consideration of CEPT regulations;
- n510 with consideration of US/FCC regulations.

with the following considerations:

- DownLink (DL): 17.7-20.2 GHz (n512, n511, n510);
- UpLink (UL): 27.5-30.0 GHz (n512), 28.35-30.0 GHz (n511), 27.5-28.35 GHz (n510).

Therefore, starting with Release-18, 3GPP RAN4 will also consider more directive terminal antennas with higher power classes adapted for Ka-band and potentially other frequency ranges [30] [31].

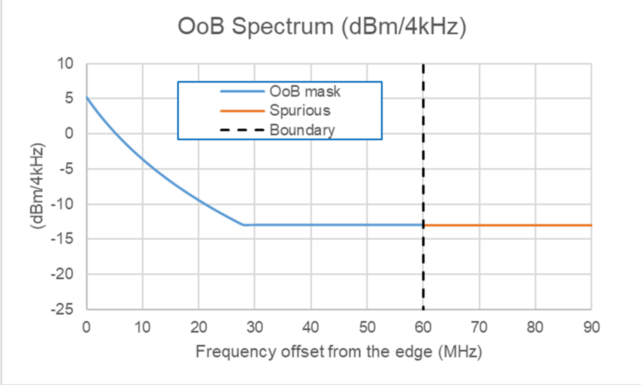
VI. Conclusions

One of the major conclusions of this work was that NTN UE can reuse the current requirements of the TN UE, as seen in Table VI and TS 38.101-5 [17]. Therefore, the same terminal can connect to both terrestrial networks and non-terrestrial satellite constellations. For this reason, the market will not be fragmented and therefore there will be a real opportunity for both terrestrial and satellite operators to increase the coverage and the quality of the service all over the world. This is one of the most important breakthroughs that 3GPP Release-17 work was able to justify because it clearly shows that satellite connectivity using 5G NR technology is not only for dedicated satellite 5G NR user equipment with a higher power class.

Another important finding is that TN can co-exist with NTN on adjacent channels with relaxed ACIR requirements for the tested simulation scenarios. As a matter of fact, the satellite requirements are lower compared to classic terrestrial Base Station (BS) requirements from previous 3GPP releases, as seen in Table VI and TS 38.108 [18]. It has been also noticed that NTN is generally the victim of TN. For instance, a satellite access node receiving transmissions easily suffers from a large beam area and a large number of interfering devices (e.g. TN User Equipments or ground TN Base Stations) under it, which was not obvious when the Release-17 work first started.

As future work, more directive terminal antennas with higher power classes adapted for above 10 GHz and operating in FDD mode will also be considered potentially for Release-18 and beyond Release-18, see for instance [30] and [31].

Fig. 16. Out-of-Band Spectrum with respect to Frequency offset from the SAN Bandwidth Edge [23]



VII. Data Availability Statement

The data sets analysed during the current study are available from the corresponding authors upon reasonable request.

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