D6.7: PoC results analysis & recommendation document

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Abstract	This deliverable provides the final performance results collected in the test campaigns conducted to demonstrate the functionalities implemented in the PoC, with respect to integrated 5G-NTN networks implementing gNB (monolithically or distributed) onboard NTN elements.
Keywords	PoC, NTN, 3GPP, TN, Physical architecture, test bench, scenario definition, performance evaluation

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DISCLAIMER

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Dissemination Level		
PU	*Public, fully open, e.g. web (Deliverables flagged as public will be automatically published in CORDIS project's page)*	✓
SEN	*Sensitive, limited under the conditions of the Grant Agreement*	
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* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

DATA: Data sets, microdata, etc.

DMP: Data management plan

ETHICS: Deliverables related to ethics issues.

SECURITY: Deliverables related to security issues

OTHER: Software, technical diagram, algorithms, models, etc.

EXECUTIVE SUMMARY

The present document represent the ultimate step of the technical programme of the 5G-STARDUST project, with respect to the execution of demonstration and testing campaigns and the related performance analysis, both providing inputs to the general recommendations and the roadmap towards the elevation of the 5G-STARDUST concept to a higher maturity (i.e. TRL 6+). In particular, the main objective of this deliverable is to validate the architecture concept presented in D3.1 and D3.2 and the main technical solutions developed in WP4 and WP5 and integrated in the designed Proof-of-Concept (PoC). As such, the main result of the conducted demonstration/testing campaigns has been the effectiveness of the design PoC and its potential for following-up demonstrations or further developments after the conclusion of the project.

From WP6 perspective, this document is the logical conclusion of the IV&V process documented in D6.3 and D6.5 on the basis of the architecture definition elaborated in D6.1.In more detail, this deliverable recaps the final definition of the system and the reference scenarios, taken as reference for conducting the demonstration campaign, whose actual execution and related performance analysis are the main output of this D6.7 deliverable.

In more detail, this document takes as a reference the architectural configuration (splits) consolidated in the previous phase of the PoC development and reviews the main components in terms of software (SW) and hardware (HW) elements constituting the terrestrial and non-terrestrial paths involved in the end-to-end connectivity concept developed in the project. In particular, it is worth reminding that the target Technology Readiness Level (TRL) for the project is 4-5, so that key elements for the realisation of a fully integrated 5G-NTN system are here considered. In this respect, a key role is being played by the User Equipment (UE) and the gNodeB (gNB) implementing the necessary Non-Terrestrial Network (NTN) adaptations.

In turn, the reference scenarios defined in D2.1 and further debated in D6.1, D6.2, and D6.5 are discussed with respect to residential broadband, in terms of general description and specific scenario implementation towards demonstration.

From previous D6.6 intermediate version, the details related to the actual demonstration campaign execution, the results collection as well as performances analysis are then provided in this D6.7 document in order to support the residential broadband scenario demonstration.

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ABBREVIATIONS

AI	Artificial Intelligence
CU	Centralised Unit
DU	Distributed Unit
GTP	Generic Tunnelling Protocol
HW	Hardware
IAB	Integrated Access and Backhaul
IP	Internet Protocol
IV&V	Integration, Verification, and Validation
KPI	Key Performance Indicator
MC	Multi Connectivity
MEC	Multi-Access Edge Computing
ML	Multi Link
MP	Multi Path
MPL	Multi-Path Layer
MPQUIC	Multi-Path QUIC
MPTCP	Multi-Path Transmission Control Protocol
NGAP	NG Application Protocol
NTN	Non-Terrestrial Network
PCI	Peripheral Component Interconnect
PoC	Proof of Concept
PSA	PDU Session Anchor
RF	Radio Frequency
RU	Radio Unit
SCTP	Stream Control Transmission Protocol
SDR	Software Defined Radio
SLE	Satellite Link Emulator
SMA	Sub-Miniature version A

SU	Switching Unit
SW	Software
TCP	Transmission Control Protocol
TGA	Traffic Generator and Analyse
TN	Terrestrial Network
UE	User Equipment

1 INTRODUCTION

1.1 POC CONCEPT AND DEVELOPMENT PHASES

The present document contains the demonstration outcomes results of the PoC bench in the context of WP6 'Integration, testing, and validation' overall aimed at the definition and integration of the PoC according to the system architecture defined in WP3 (Architecture Design) and on the basis of the activities carried out within WP4 (Radio Technologies) and WP5 (Networking Operations), whose main outputs in the form of SW/HW pieces are then the object of the PoC integration. In turn, once the PoC will be fully integrated and operational, the corresponding demonstration campaigns will be carried out, whose results analysis is performed immediately afterwards. A dedicated study-logic illustrating such a process is shown in Figure 1.

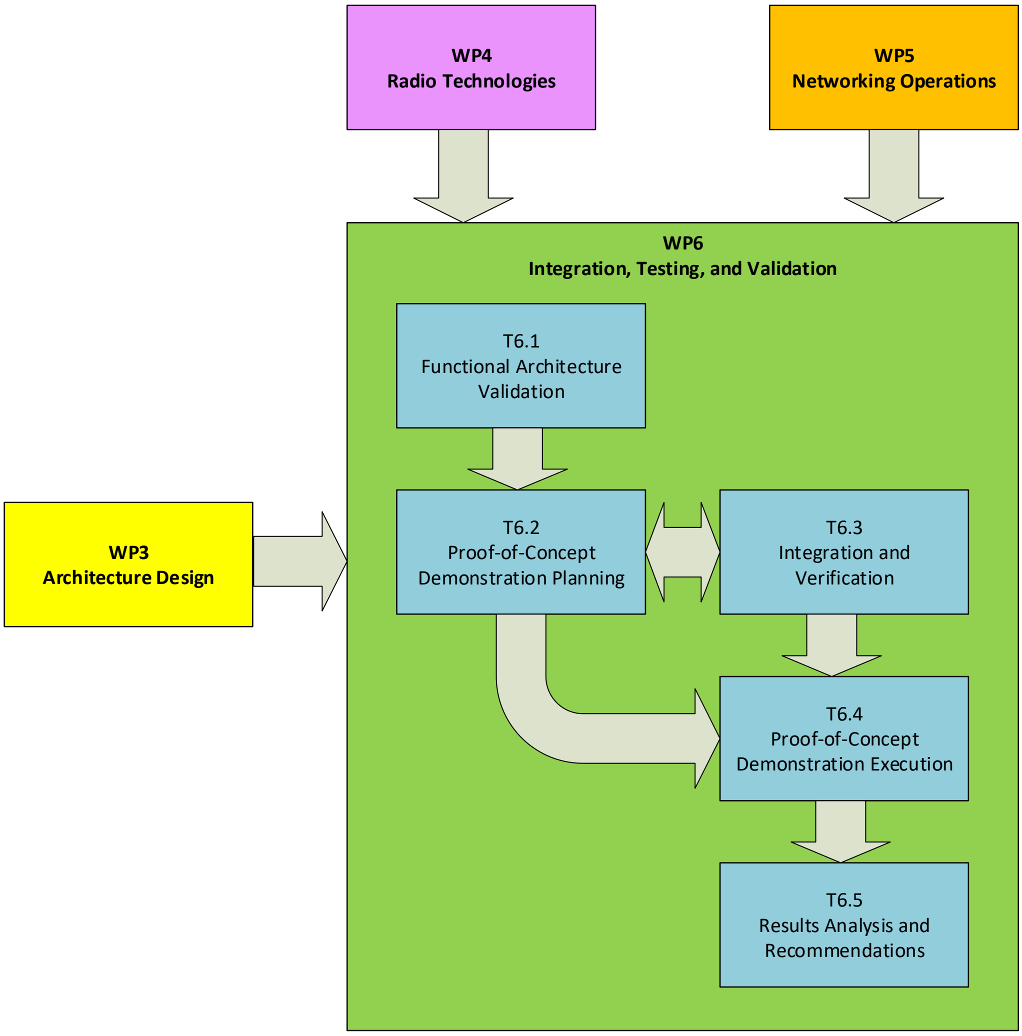

Figure 1 WP 6 interaction with development activities in 5G-STARDUST

From the above picture is therefore clear the role of this deliverable as output of Task 6.5 in providing the final documentation stage of WP6 as to report demonstration testing results conducted on the PoC. As such, the main indications provided in this document recap the demonstrated capabilities on the bench from the different building blocks previously defined, integrated and tested towards the full system verification. In this respect, obviously, a prerequisite for the definition of the functional architecture is the system design as developed in the course of WP3, so that in particular D3.2 [3] is the starting point for the definition of the PoC functional architecture.

In more detail, the discussions and findings summarised at the end of D3.2 [3] allowed to define the macro-architecture (see Figure 2) for the project PoCs so as to address both direct and indirect access, hence offering the possibility to address multiple scenarios.

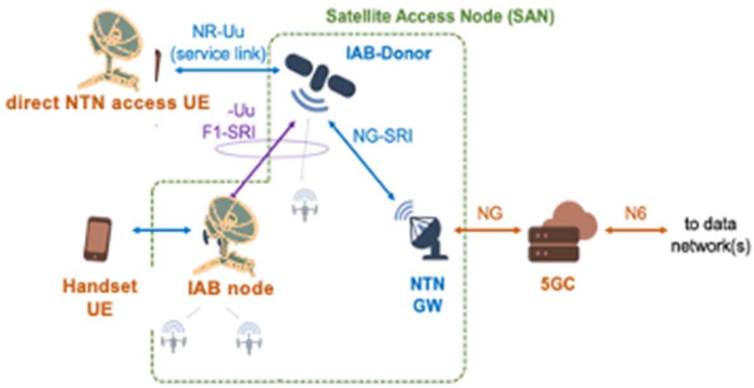

Figure 2 Macro-architecture of the NTN segment for the PoC (TN segment not shown here)

As a matter of fact, the access to the satellite in the indirect configuration will happen through a relay node, hence resembling that of an Integrated Access and Backhaul (IAB) node functionality, although this is not exactly the approach taken in the project. The adopted methodology does not rely on IAB implementation (for which no NTN adaptations have been addressed so far in 3GPP), but on the contrary the idea is to take advantage of an intermediate node responsible for interacting with a UE and extending its connectivity so as to reach the gNB, which is implemented (either fully or in a distributed manner) in the space segment. Further to this, it is expected to have different UE classes, able to achieve data connectivity in either Frequency Range 1 (FR1, *i.e.*, S-/L-band) or FR2 (*i.e.*, Ka-band) with different bandwidth availabilities. Last but not least, the satellite path is then complemented by a terrestrial counterpart in order to show the coexistence of different paths and demonstrate the added value of a unified network architecture, where both TN and NTN segments are available.

In general, the main objective of the PoCs were that of proving the added value coming from integrated TN and NTN networks implementing a regenerative Low Earth Orbit (LEO) satellite system. In that respect, first of all it is assumed to consider a transparent LEO setup as actual benchmark. Then in turn, some of the main functions to be considered for the demonstration to prove the value of integrating TN and NTN are about:

1) Support of FR1 frequency band and some characteristics of the FR2 frequency band (100 MHz bandwidth).

2) End-to-end connectivity through a unified radio interface

3) Multi-link/path achievement towards effective utilisation of the available TN/NTN resources

The demonstration of the FR2 capacities capabilities were in fact not performed on the PoC but with theoretical demonstration. This demonstration is in line with the objective 4 where the measurable results can be performed either by on laboratory test beds and or numerical simulation.

To this end, the overall PoC addresses network disaggregation by considering different functional splitting models aimed at showing performance fluctuations and the corresponding configuration adjustment.

Last but not the least, the final version of the demonstrator has been plugged to real user applications (refer to FUSECO forum demo in November 2025 discussed in D6.5 – Section 5.4.5 [7]), in order to have an impactful demonstration of the added value of the 5G-STARDUST concept by achieving a close-to-real setup (though still up to max. TRL 5).

1.2 TRL REVIEW

On the basis of the first iteration presented at the end of D3.2 [3], a successive refinement has been conducted to identify the macro-blocks necessary for the definition of the PoC, which are further summarised in Table 1, here below:

Table 1 PoC Macro-blocks and related TRL progression

Technology	Initial TRL	Estimated TRL	Support (full/partial)[1]	Notes
Regenerative payload	2	4	Full	Key demonstration objective of the project, also in relation to embark a gNB in space with all necessary functions from physical layer up to PDCP
Unified UE interface	2	4/5	Full	Key demonstration objective of the project, with respect to proving the benefits of integrating a UE into TN/NTN segments interchangeably.
ML supported TN/NTN MC on higher layers	2	4	Out of Scope (addressed only in WP5) [2]	Multi-connectivity supported in terms of multi-path protocols and related integration between core network, RAN, and UEs
AI data driven networking solutions for MC (management)	2	4	Out of scope (addressed only in WP5)[3]	Multi-connectivity management carried out in static manner, since AI would not bring much benefit in a PoC of limited size (i.e. few UEs)
AI data driven networking solutions for MC (slicing)	2	4	Partial	Network slicing supported in the sense of differentiating QoS classes, through static classes separation.

[1] In the case of partial support, not all functionalities as planned within 3GPP will be part of the PoC. Detailed description has been provided in the PoC technical specification, reported in D6.2 and D6.3.

[2] Multi-connectivity options were initially considered for integration in the WP6 PoC, but have been later not implemented in order to provide a more impactful analysis of their potential directly in WP5 through an extensive performance analysis.

[3] Data-driven optimisation though appealing was not included in the final PoC setup because of the limited added value, which could be only demonstrated with a larger setup (i.e. higher number of nodes and traffic flows), as analysed in more detail in D5.2 and D5.4.

Technology	Initial TRL	Estimated TRL	Support (full/partial)[1]	Notes
MEC platform for NTN nodes	2	4	Out of scope[4]	-
RAN softwarization	2	4	Full	Pretty much oriented to the achievement of gNB in space, either in the form of full gNB in space or in distribute manner (i.e. function CU/DU splitting)
Core Network Functionality	**4**	**5**	**Full**	The core network was tested already with gNBs placed at large distance, however not with gNBs at continuous variable delays. However, we do not expect to be a major issue

1.3 OBJECTIVE AND ORGANISATION OF THE DOCUMENT

The document is organised in five main parts:

- Section 2: it recaps the essentials of the PoC and the related components based on the consolidated configurations detailed in D6.4 [1];
- Section 3: it reviews the scenarios definitions and illustrates the necessary elements for the final implementation and demonstration;
- Section 4: it addresses the demonstration campaign execution in terms of planning, realisation and final collection of performance results.
- Section 5: it draws the main recommendations and elaborates on the main lessons learnt on the basis of the recorded performance.
- Section 6: it finally sums up the main conclusions and outlooks possible future evolution of the PoC.

[4] WP5 addressed the potentials of a MEC agent in space, but the actual integration in the WP6-developed PoC though considered a nice-to-have feature was eventually excluded from the final setup because of the increasing complexity of the whole implementation.

2 RECAP ON THE BENCH

2.1 ARCHITECTURE CONFIGURATIONS

The final PoC bench is able to demonstrate the Use Cases identified in the D2.1 [1] in line with the different splitting defined in the D6.1 [5] PoC functional architecture document.

The different splits [5]are reminded here after:

- Split #1 -Full gNB On Board: In this configuration the full gNB is implemented in space (both control- and user-planes), with the protocol stack implementing up to RRC, PDCP, and NAS layers and hence terminating the NR-Uu interface. The integration with the terrestrial infrastructure happens at both core and UE level, where dedicated aggregation and splitting points are defined to achieve the unification between the TN and NTN infrastructures.

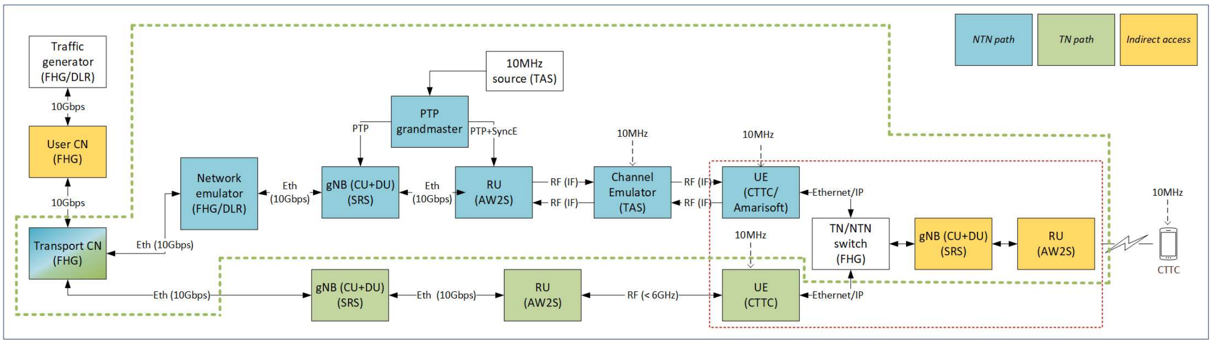

Figure 3 Architecture of the bench implementing full gNB onboard.

- Split #2 - CU/DU splitting: In this configuration, the traditional Split-2 from ORAN architecture is implemented, so that DU is accommodated in space while CU is implemented on ground, so that an F1 interface (for both user- and control-planes) is established over the space link established between satellites and ground stations (i.e. on the feeder link).

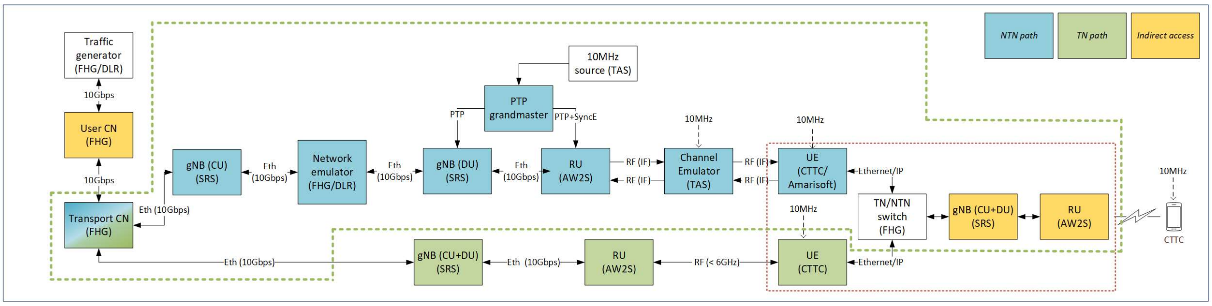

Figure 4 Architecture of the bench implementing DU/CU splitting, with DU onboard

[5] Please note that „splits" are to be intended as different architecture configurations rather than the corresponding 3GPP or ORAN functional splits

Similarly to the previous case, the integration with the terrestrial infrastructure happens at both core and UE level, where dedicated aggregation and splitting points are defined to achieve the unification between the TN and NTN infrastructures.

- Split #3 - Full gNB on board with 5GC functions: this configuration is fully aligned with the first one, with the only addition that here also UPF functions are implemented in space to provide more advanced networking functionalities such QoS management, routing, and possibly onboard applications (i.e. space edge computing). Also here, the integration with the terrestrial infrastructure happens at both core and UE level, where dedicated aggregation and splitting points are defined to achieve the unification between the TN and NTN infrastructures.

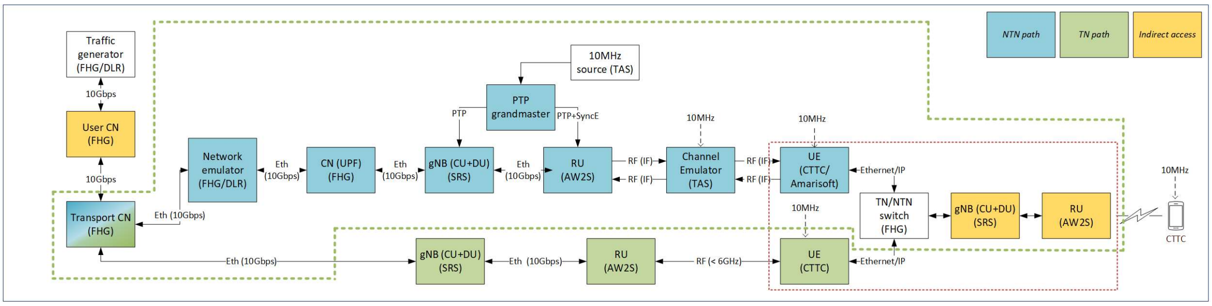

Figure 5 Architecture of the bench implementing full gNB onboard and UPF functionalities

The defined splits pose certain constraints on both the design and the logical architecture. In particular, the three splits imposed to separate the gNB in a minimum of two logical partitions, one for the CU, one for DU/RU, and to separate the Core Network as well in two logical partitions (one for the UPF function, one for the rest of the Core Network).

Considering the NTN feeder link, the typically implemented technology is well known and, as such, it presents no major points to be de-risked; based on this assumption, only the over-the-air latency is taken into account for the feeder link. The PoC bench uses an Ethernet link to simulate the feeder Radio Frequency (RF) link, limited currently to the traffic delay (propagation time) without other type of interferences (*e.g.*, weather, location discrepancies, etc.).

Considering the NTN “user” link, the complexity and specificity of the RF parts (OFDM waveform, Doppler effects, losses, among the others), the satellite to user link are emulated with a two-way RF satellite link emulator connected through RF wire (coaxial).

For the (TN) link, the connection are also performed with coaxial wires despite over the air link. The aim of the demonstrator is not to validate the already well-established capabilities of the TN but ensure that the commutation between the TN and the NTN is feasible.

The link between the final end user device and the IAB node functionality is performed by wire. This link is well known and only the access principle will be demonstrated.

2.2 MAIN COMPONENTS

As detailed in D6.5, the TN and NTN integrated network is based on the following equipment:

- One server for the “Core Networks”. It will host the following functionalities:
    - Traffic Generator

  - 5G Core Network system
  - 5G Core Network TN/NTN without NTN UPF functions
  - 5G Core Network NTN UPF functions
  - Feeder link channel Network Emulator (in case of split #3)
- One server for gNB TN/NTN. It will host the following functionalities:
  - DU NTN
  - CU NTN
  - DU TN
  - CU TN
  - Feeder link channel Network Emulator (in case of splits #1 & #2)
- Final UE server
- One IAB server. It will host the following functionalities:
  - gNB (CU+DU systems) final end user UE bridge
  - IAB switching function
- The RU modules to perform the conversion from the frames issued of the DU to generate the RF signal and its reverse link:
  - RU NTN
  - RU TN
  - RU IAB/NTN
  - RU IAB/TN
  - RU final end user UE bridge
  - RU final end user UE
- The Satellite Link Emulator.
- The Ethernet switch with the capacity of a 10 Gbit/s network and RJ-45/SFP+ cables to ensure the data transfers between each server.

3 SCENARIO DEFINITION

3.1 OVERVIEW

The selected scenarios deployment on following PoC architecture in Figure 6 aims to demonstrate by functional testing and related KPIs results collecting the 5G End-to-End connectivity carried out over a unified radio interface and across an effective coexistence of TN/NTN backhaul segment resources integration.

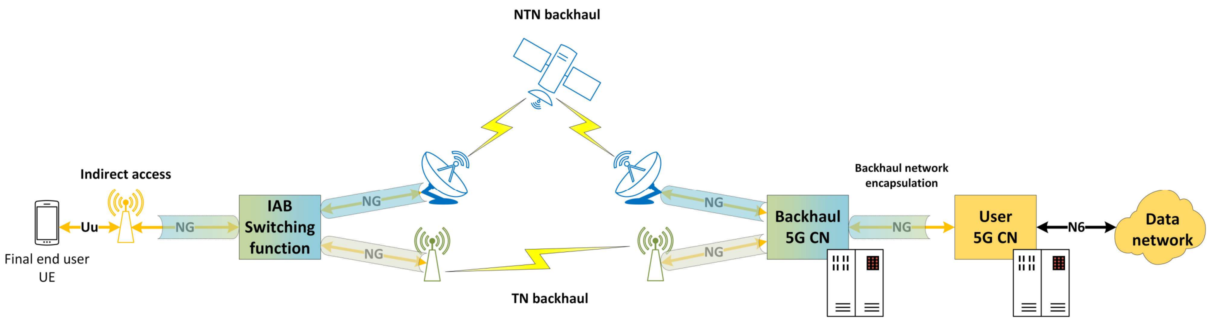

Figure 6: PoC macro architecture

Regenerative LEO payload NTN baseline is considered for all scenarios which induces performing all the tests as to characterize on-ground/board functional disaggregation from the split configurations (section 2.1) managed at bench software re-programmability.

The scenario implementation is also performed within the related overall context frame:

- Unique NTN LEO satellite quasi-earth fixed cell:
  - No NTN LEO satellite handover Feeder/User access link to manage.
  - Transmission signal characteristics related to the same trajectory profile ~300s loop – 20°/90°EL visibility.
- Unique TN cell:
  - The Final end user UE positioning is considered as a static parameter.
- Multiple generic user data packet traffic flows instantiation sized in consistency of link capacity to support KPIs measurement.
- End-user application services plugging are showcase purposes oriented:
  - Local implementation: video diffusion, file transfer.
  - External internet access from Final end user UE through user CN: Web browsing, video streaming, etc.

Main approach follows over the related bench set-up is to reflect how this infrastructure concept is experienced at Final end user level.

3.2 SCENARIO #1 RESIDENTIAL BROADBAND

3.2.1 General Description

The Residential Broadband scenario relied on the macro reference architecture from D3.2 where an IAB node is able to establish connectivity between an end user UE of a local TN segment (indirect access) and a 5G Core Network by a dual 5G TN/NTN backhaul transport segment in a consecutive way to convey steered traffic accordingly.

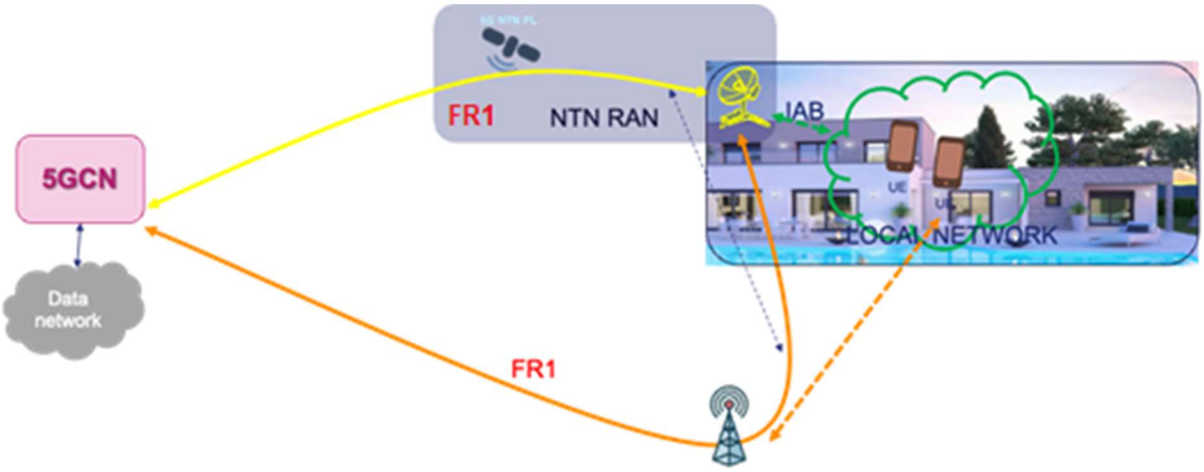

Figure 7: PoC#1 - Residential Broadband scenario reference architecture

It is then applied to the *PoC#1.1 - energy saving* and *PoC#1.2 – sparsely populated area* application uses cases:

- *PoC#1.1 – Energy saving*:

The NTN backhaul resource is exploited at night to reduce the energy consumption of the terrestrial counterpart.

Day connectivity is completely provided to UEs through the terrestrial infrastructure and at night the TN backhaul path is then switched off to support connectivity by NTN backhaul path.

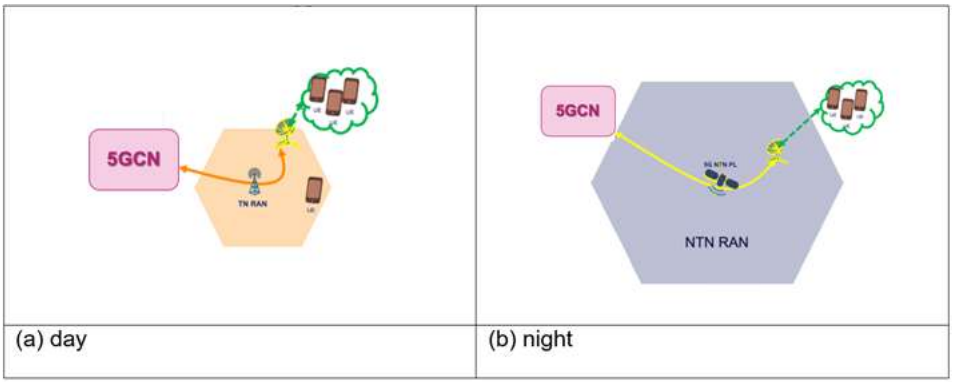

Figure 8: PoC#1.1 – Energy saving

Main outcome is to demonstrate a preset triggering exclusive 5G TN/NTN backhaul paths handover (full hard) through the global E2E network user connectivity and data traffic.

- *PoC#2.1 – Large sparsely populated area*

The NTN backhaul resource is exploited to provide connectivity over large areas with a limited population density where a terrestrial infrastructure might not be available.

Large and sparsely populated areas in which the NTN and TN backhaul resources can complement each other.

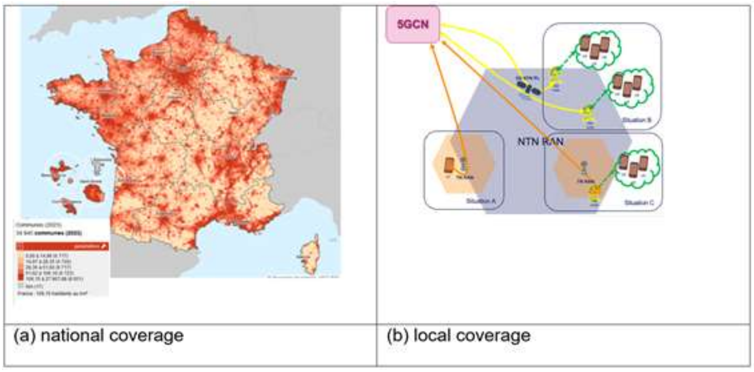

Figure 9: PoC#2.1 – Large sparsely populated area

Main outcome is to demonstrate an automatic triggering exclusive 5G TN/NTN backhaul paths handover (full hard) through the global E2E network user connectivity and data traffic.

3.2.2 Sequence of Actions

The residential broadband scenarios *PoC#1.1 – Energy saving* and *PoC#2.1 – Large sparsely populated area* are played on PoC bench according to the next flowchart structure presented in sections 5.2 and 5.4.1 of D6.5 [7], where switchover between TN and NTN networks is performed to achieve energy efficiency and effective data distribution without any service interruption.

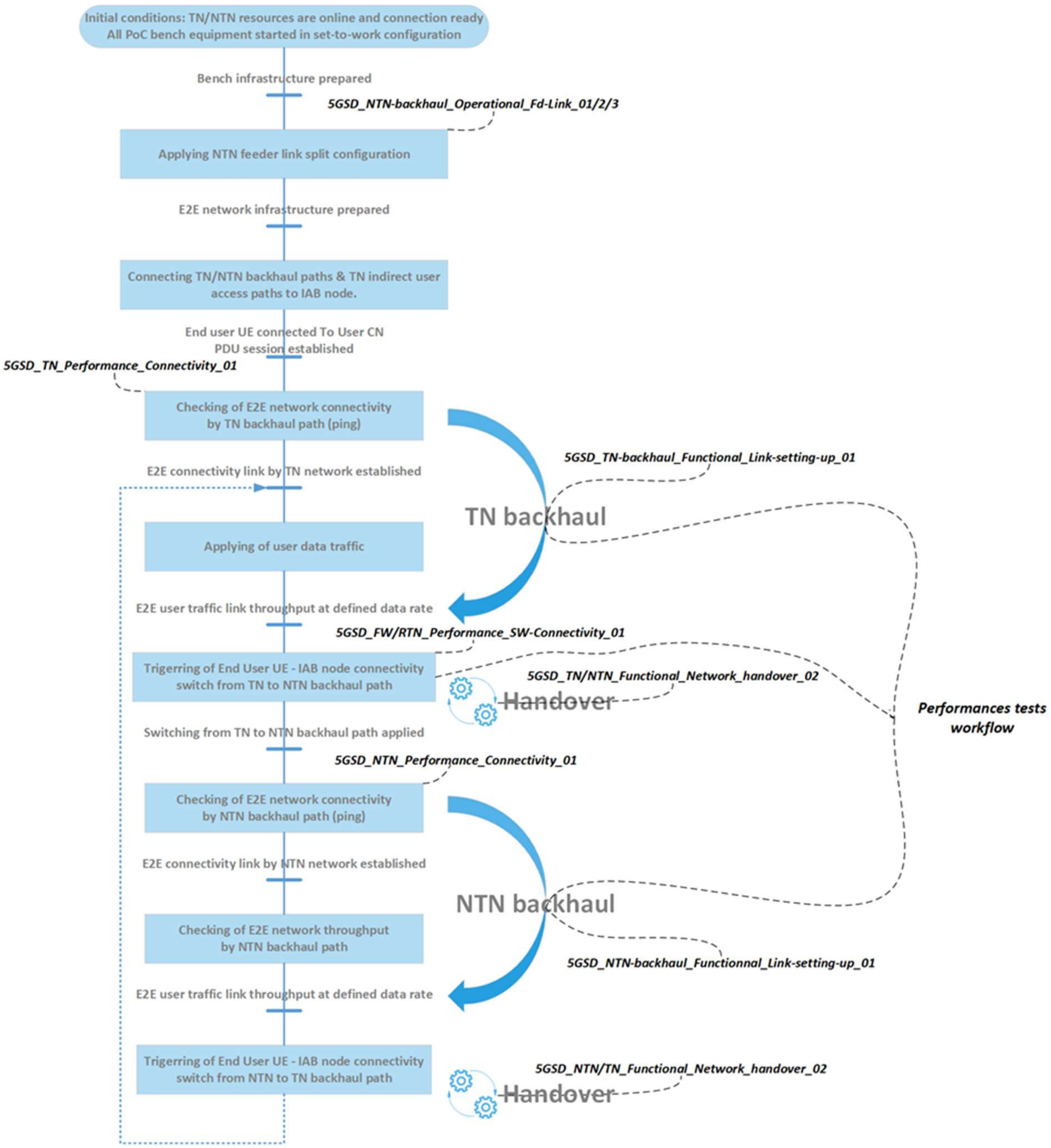

Figure 10: Residential broadband scenario flowchart.

For the sake of the performance comparison, the considered process (above flowchart) has been executed across the three on-board/ground functional split configurations, i.e. full gNB onboard, CU/DU split, and full gNB onboard +UPF functions. The detailed performance analysis is addressed in the next chapter 4, to better assess the impact of the considered configuration on the different protocols running at transport and application layer.

3.2.3 Scenario Implementation

The following diagram representation details how each PoC bench components are involved in the data flow at a functional-physical architecture level (split#1 – full gNB on-board) with also the related test interfaces to consider for both *PoC#1.1 – energy saving* and *PoC#2.1 – Large sparsely populated area* scenario application:

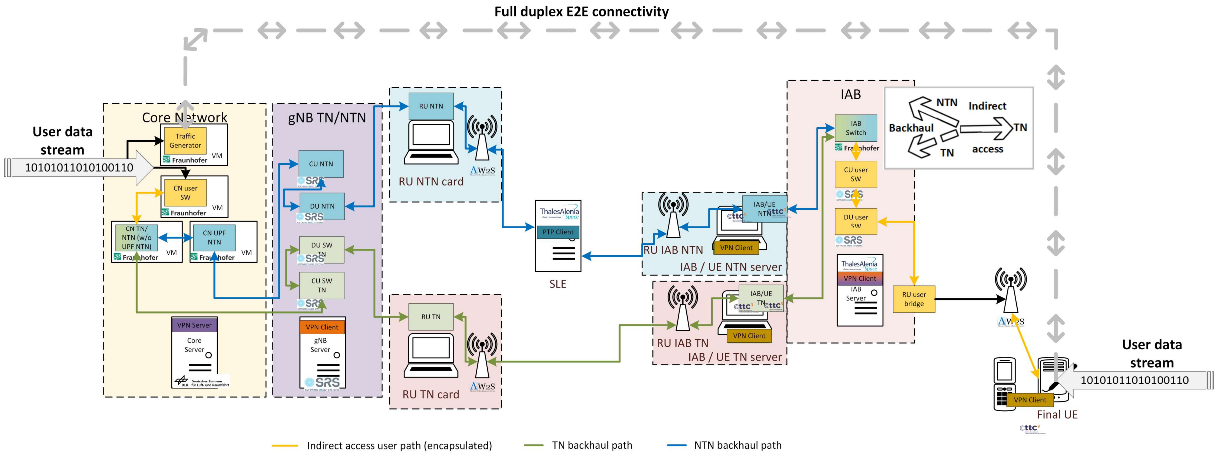

Figure 11: Overall testing data flow application, with application data exchanges between the UE (right-hand side) and the data network (absorbed in the core network within the traffic generator module) (left-hand side)

As to cover an E2E network scope the applicable testing is performed at edges components of user encapsulated link – indirect access path level with a full duplex connectivity checking between CN user and Final end user UE and some user data traffic injection over different kind of streams (TCP or UDP).

Then TN/NTN backhaul user data traffic flow steering is managed by a manual triggered script at IAB node level that sets a pre-defined commutation sequence:

- Nominal transport resource to transport user encapsulated data is on TN backhaul path which is connected by the IAB node with Indirect access user path of end user UE.
- Initial step is blocking the on-going traffic flow as to initiate a failover from established connectivity of Indirect access user path with TN backhaul to NTN counterpart.
- Proper set-up change is verified by latency magnitude as part of connectivity checking.

A very similar principle is considered for *PoC#2.1 – Large sparsely populated area* with the main difference consisting in an automatic triggered traffic flow steering from a TN path connectivity disabling from some path fading introduction.

Alternate testing can be run at other components level to support global PoC bench operating. The detailed tests procedures have been further transcribed in the D6.5 document [7], indeed focusing on the general system verification and the effective system components' integration.

4 DEMONSTRATION CAMPAIGNS

4.1 SCENARIO #1 RESIDENTIAL BROADBAND

4.1.1 Demonstration KPIs

The applicable KPIs selection associated to the PoC and categorized according to the User Applications and Service Continuity families has been done in D6.1 [5] document with items classification as required (R) or optional (O).

The related description according to the bench context deployment is provided in the following:

Related description according to bench context deployment is next provided:

- User Application Capabilities:
  - KPI_1.1 User experienced data rate (R):

    The PoC E2E network throughput (goodput) effectively received (DL) or transmitted (UL) at final end user UE level which corresponds to the amount of data (packets) correctly received (greater than or equal to the minimum targeted data rate) within a certain time window (lasting as long as a reasonable communication session in the context of the investigated scenario), with sufficient sampling granularity (instantaneous or average).
  - KPI_1.2 End-to-end Latency (R):

    As per 3GPP TS 22.261 definition: The E2E one way time that it takes to transfer a given piece of information over the Encapsulated User network, measured at the communication interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination (CN User – Final End User UE).
  - KPI_1.3 User service packet error rate (R):

    Refers to the amount of E2E network packets which have not been successfully delivered between CN User – Final End user UE (in consistency with communication session context) divided by the total number of sent packets.

- Service continuity

  This KPIs family refers to the capture of the related events at network layer switching various phases defined in time, as illustrated in the following Figure:

Figure 12: Illustration of KPIs network switching concept

- t0: Start of measurements (passive monitoring);
- t1: Event E, which implies to trigger a switch from one backhaul path to another.
- t2: Start of the network layer switching.
- t3: End of the network layer switching, IP connectivity and traffic established at the CN user – Final end user UE level.
- t4: End of measurements.

In this timeline there are three main phases to consider and assess through next KPIs:

PHASE 1 - Preparation of the network layer switching (Pre-switching):

- KPI_2.1 Phase 1 duration (O):

  Time between event (connectivity loss at IAB - End User gNB level) and the network layer switching decision at IAB level.

PHASE 2 - Network layer switching execution (In-switching):

- KPI_2.3 Phase 2 duration (O):

  Phase 2 duration (O): Time between switching decision and service available (connectivity and traffic established at Final end user UE).

PHASE 3 - Network Layer switching continuity (Post-switching):

- KPI_2.5 Switching success rate (O)

  Average user experienced throughput at Final end user UE (i.e. KPI_1.1) since service available post network layer switching divided by average experienced data rate prior event.

- KPI_2.6 Number of drop calls (R)

  User throughput failure ratio, defined as the percentage of user experienced data rate packet delivery error despite a successful switching from a network perspective.

The KPIs probing across PoC bench data-flow (split#1 – Full gNB on-board) is mapped in Figure 13 along with the related means identified to accordingly cover the scenario measurements:

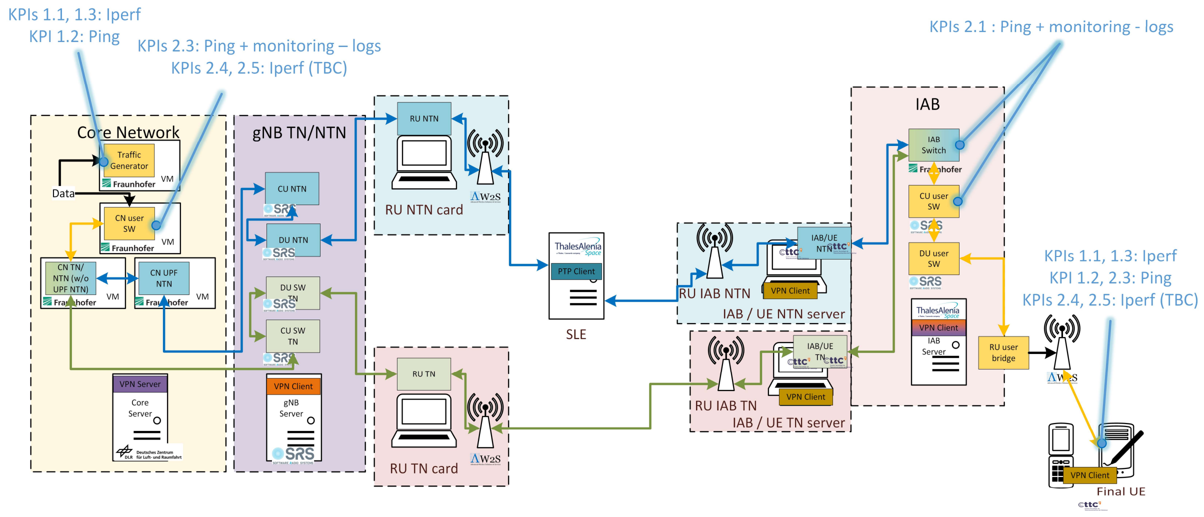

Figure 13 Maps of PoC bench KPIs probing (split#1 - Full gNB on-board).

Network *ping* utility is used for KPI_1.2, KPI_2.1 and KPI_2.3 related to latency and connectivity characteristics with the following settings:

- Continuous running from Final end user UE to User CN:
  - 5 ms interval
  - Timestamping
  - File logging

Network performance *Iperf* software tool is selected for KPI_1.1, KPI_1.3, KPI_2.4 and KPI_2.5 related to throughput characteristics with following settings:

- Forward link from CN user (client) to Final end user UE (server) and Return link from Final end user UE (client) to CN user (server):
  - UDP / TCP
    - Nominal link integrity data rate
    - 1s interval reporting
    - 300s maximum duration
    - Timestamping
    - File logging

More specifics tuning parameters like buffer length, socket length and Maximum Segment Size have been discussed in deliverable D6.5, where the results of the verification campaigns have been presented and discussed.

Last but not least, proper components logs could also complement KPIs collection with some resources usage monitoring while the several scenario validation tests based on *ps*/*top* commands.

4.1.2 Testing Campaign Definition and Planning

The test content activities of the scenario demonstration have been arranged aiming for an optimization of bench functional split configuration change occurrences and a proper characterization of data flow commutating by incremental traffic streams combination.

Related approach is more formally described from the Figure 14 following workflow presented in Section 5.4.1 of D6.5 [7] document, where UDP and TCP flows have been considered as 1) unidirectional and bidirectional streams over forward and return links. In the case of unidirectional streams, TCP or UDP are applied homogeneously on either forward or return links, in order to show the impact at protocol level on each specific link. In the case of bidirectional link, UDP or TCP have been first applied separately to both forward and return link, while the mixture of TCP and UDP traffic flows over both links was performed at last step to show the impact and the robustness of the considered setup against the more complete (and challenging) traffic configuration,

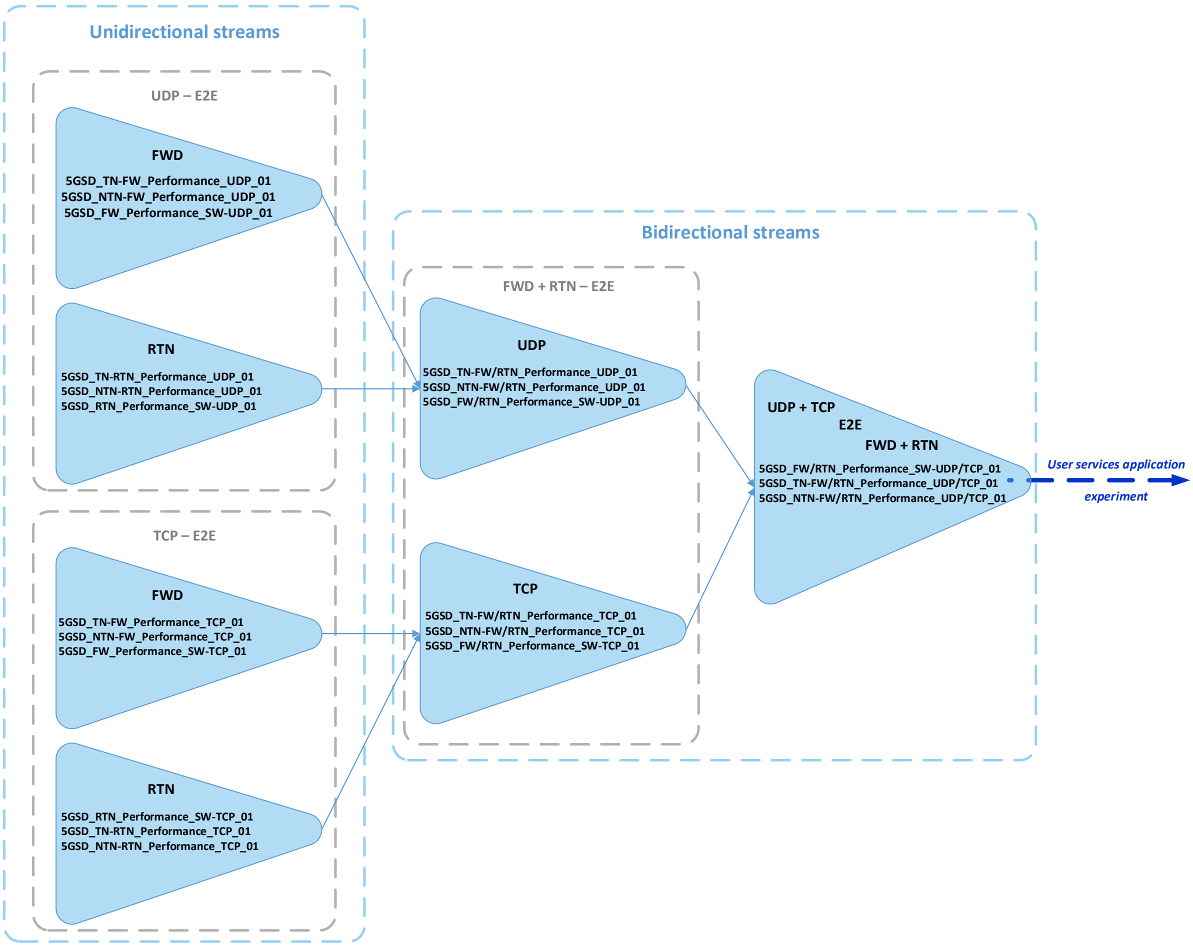

Figure 14: Demonstration scenario testing activities principle workflow

4.1.3 Demonstration execution

The performance testing run on PoC bench previously presented in section 5.2.2 of D6.5 [7] document have then been performed and are next reported accordingly in section 4.1.4 of the present document, by considering some Tests Case suite definition for KPIs coverage according to the following template:

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- KPIs <*x.y, a.b, …*>
  - Test Case suite – <*Test pattern*>_#<*Test series number*>:
    - <*Performance configuration test*>

  <Description of the procedure>

Accordingly, the following demonstration campaigns have been planned and accordingly executed:

- KPIs 1.2/2.1/2.3/2.4/2.5:
  - Test Case suite – Connectivity_#1:
    - 5GSD_TN_Performance_Connectivity_01
    - 5GSD_NTN_Performance_Connectivity_01
    - 5GSD_TN/NTN_Performance_SW-Connectivity_01

  Measurement of End-to-End user network latency either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Forward UDP_#1:
    - 5GSD_FW_Performance_SW-UDP_01
    - 5GSD_TN-FW_Performance_UDP_01
    - 5GSD_NTN-FW_Performance_UDP_01

  Measurement of UDP flow throughput integrity on End-to-End user network forward link channel either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Return UDP_#1:
    - 5GSD_RTN_Performance_SW-UDP_01
    - 5GSD_TN-RTN_Performance_UDP_01
    - 5GSD_NTN-RTN_Performance_UDP_01

  Measurement of UDP flow throughput integrity on End-to-End user network return link channel either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Bi-directional UDP#1:
    - 5GSD_FW/RTN_Performance_SW-UDP_01
    - 5GSD_TN-FW/RTN_Performance_UDP_01
    - 5GSD_NTN-FW/RTN_Performance_UDP_01

Measurement of UDP flow throughput integrity simultaneously on both End-to-End user network forward/return link channels either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Forward TCP_#1:
    - 5GSD_FW_Performance_SW-TCP_01
    - 5GSD_TN-FW_Performance_TCP_01
    - 5GSD_NTN-FW_Performance_TCP_01

Measurement of TCP flow throughput integrity on End-to-End user network forward link channel either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Return TCP_#1:
    - 5GSD_RTN_Performance_SW-TCP_01
    - 5GSD_TN-RTN_Performance_TCP_01
    - 5GSD_NTN-RTN_Performance_TCP_01

Measurement of TCP flow throughput integrity on End-to-End user network return link channel either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
  - Test Case suite – Performance Bi-directional TCP_#1:
    - 5GSD_FW/RTN_Performance_SW-TCP_01
    - 5GSD_TN-FW/RTN_Performance_TCP_01
    - 5GSD_NTN-FW/RTN_Performance_TCP_01

Measurement of TCP flow throughput integrity simultaneously on both End-to-End user network forward/return link channels either through TN or NTN backhaul path and over a transport switching sequence.

- KPIs 1.2/1.3/2.3/2.4/2.5:
    - Test Case suite Performance Bi-directional UDP+TCP_#1:
        - 5GSD_FW/RTN_Performance_SW-UDP/TCP_01
        - 5GSD_TN-FW/RTN_Performance_UDP/TCP_01
        - 5GSD_NTN-FW/RTN_Performance_UDP/TCP_01

    Measurement of mutual UDP with TCP flows throughput integrity simultaneously on both End-to-End user network forward/return link channels either through TN or NTN backhaul path and over a transport switching sequence.
    Each flow instantiation has been set at 1 Mbit/s data rate.

All this “Tests Case suites” have been run at least over a 60s period re-applied across the 3 on-board/on-ground splitting configurations (summarised earlier in section 2.1 of this document) and the collected results are reported in the next section 4.1.4 accordingly.

4.1.4 Performance results

The data collection is presented as to cover each Test Case suites previously presented in section 3.2.3 with measurements and related comments regroup as to compare a set of the three different configuration on-board/on-ground splits (e.g., denoted Conf-split#1, #2, and #3)

- Test Case suite – Connectivity_#1[6]:

  - Conf-split#1 - Averaged E2E network latency measurement:

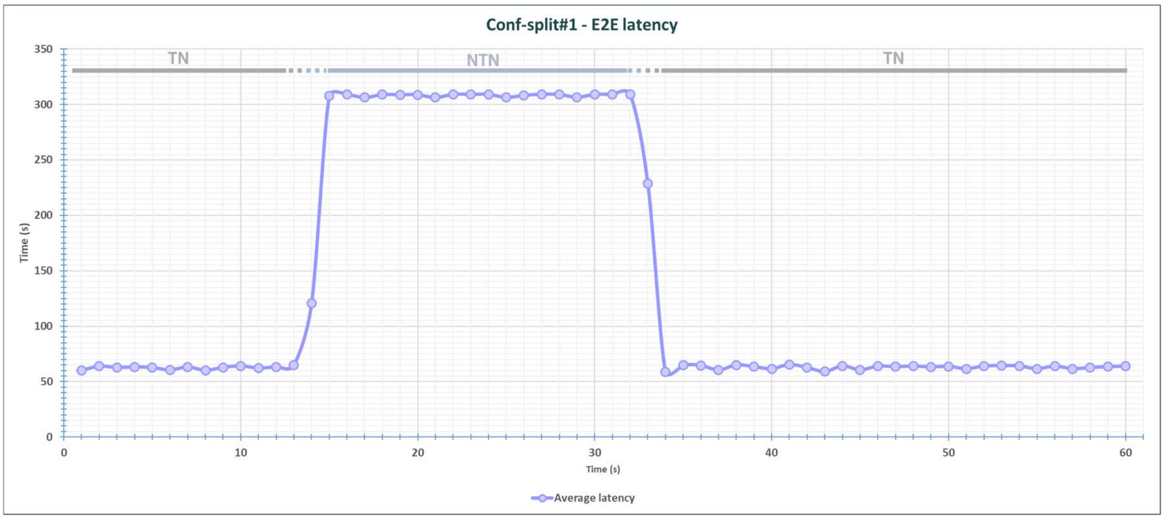


Figure 15: Conf-split#1 - Averaged E2E network latency measurement graph

  - Conf-split#2 - Averaged E2E network latency measurement:

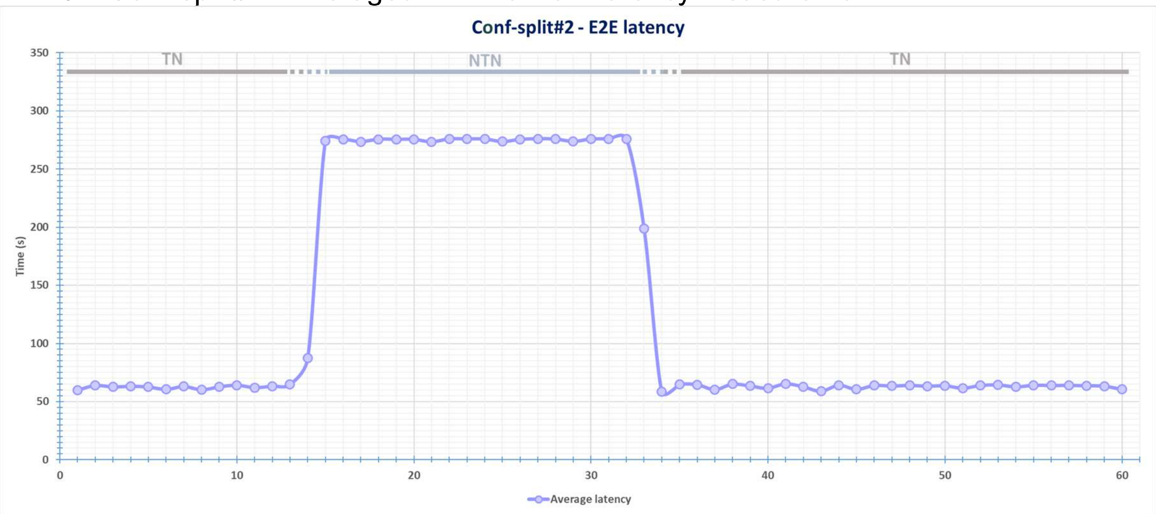


Figure 16: Conf-split#2 - Averaged E2E network latency measurement graph

[6] In these tests, the latency exhibited over the NTN latency has been artificially inflated to show better separation between TN and NTN curves, though not affecting the general validity of the obtained results.

- Conf-split#3 - Averaged E2E network latency measurement:

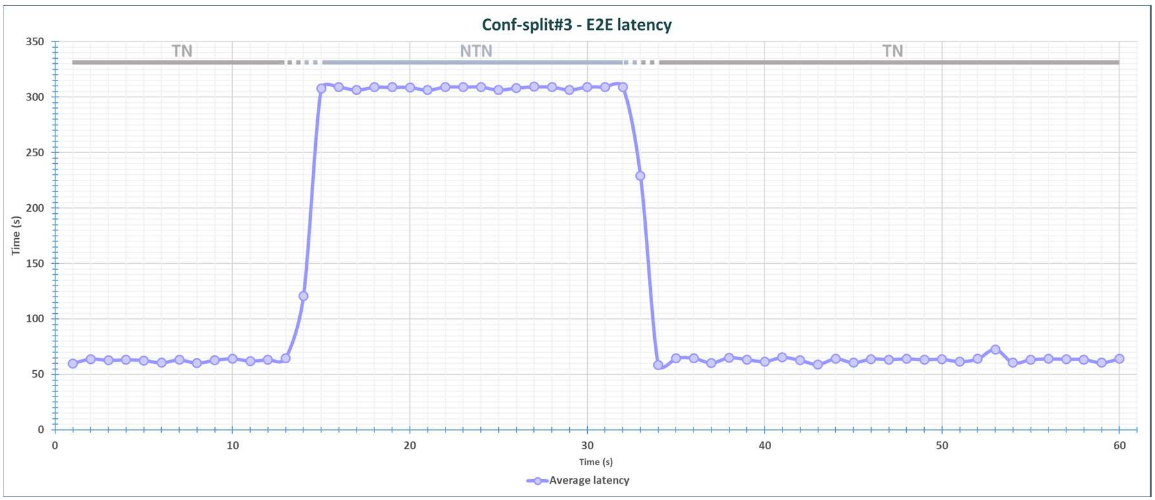


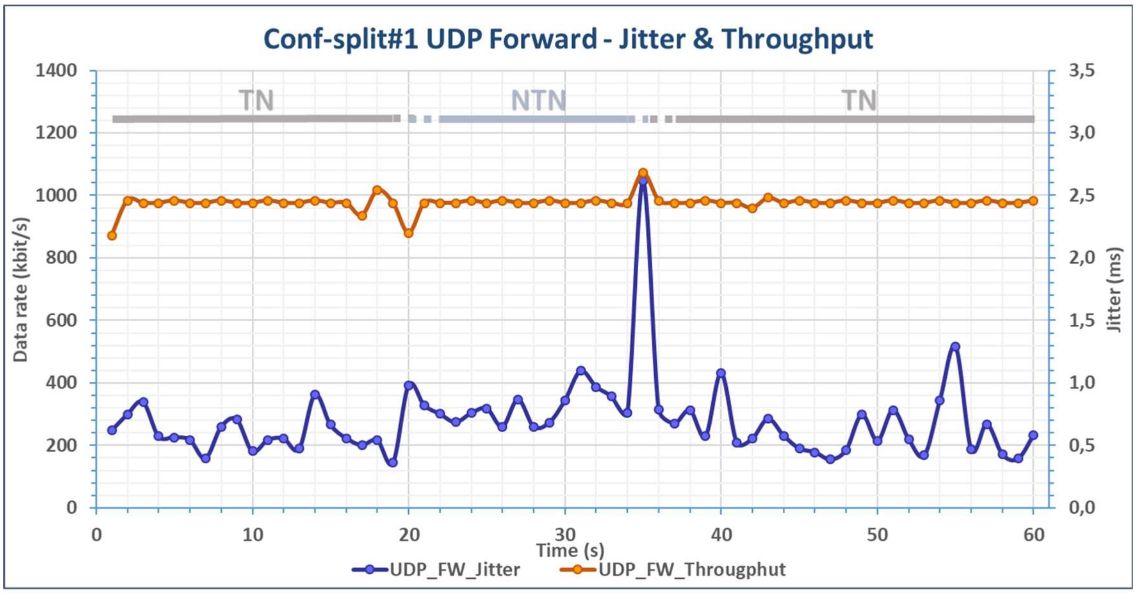
Figure 17: Conf-split#3 - Averaged E2E network latency measurement graph

All the three measurements graphs show some similar characteristics for the three configuration splits as to reflect a quite seamless TN-NTN-TN backhaul path switchover. The transition period occurs in less than a 1-2 seconds range, hence confirming the smooth transition from one network to another.

The latency magnitude is lower in case of split#2 as pre-configured offset was applied to reflect a the less on-board satellite payload processing complexity of this configuration.

- Test Case suite – Performance Forward UDP_#1:

    - Conf-split#1 – UDP FW link measurements:



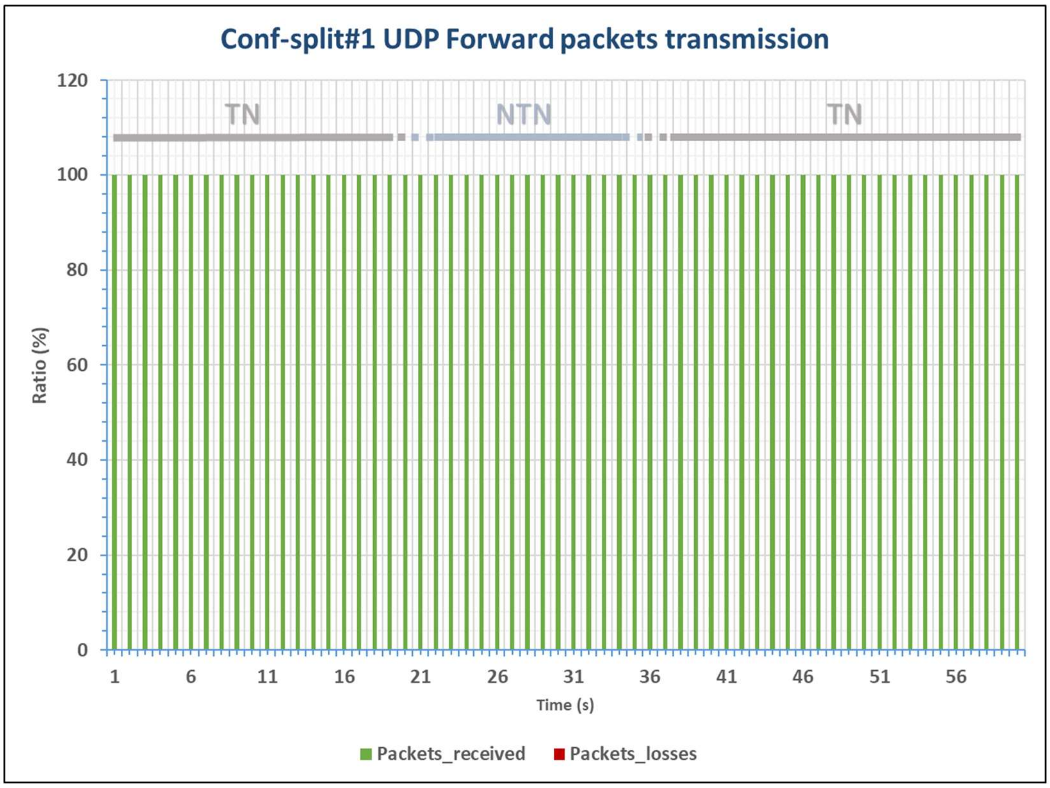
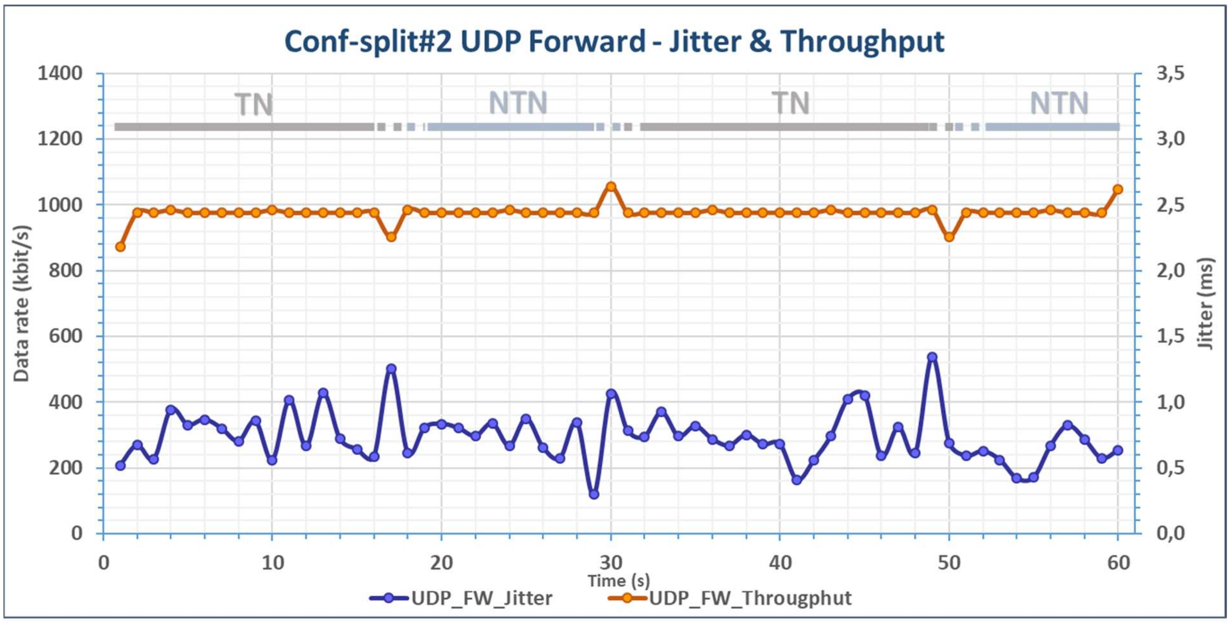


Figure 18: Conf-split#1 – UDP FW jitter & throughput data rate-packets transfer measurement graphs

- Conf-split#2 – UDP FW link measurements:



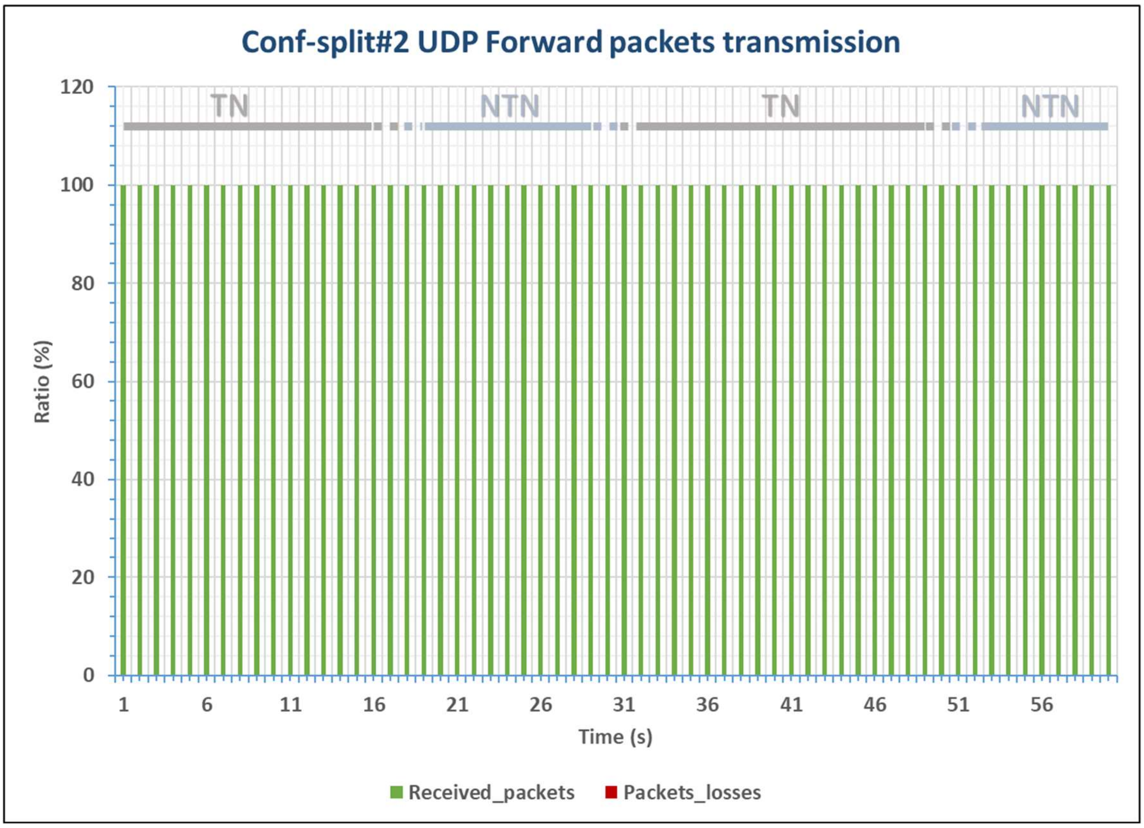
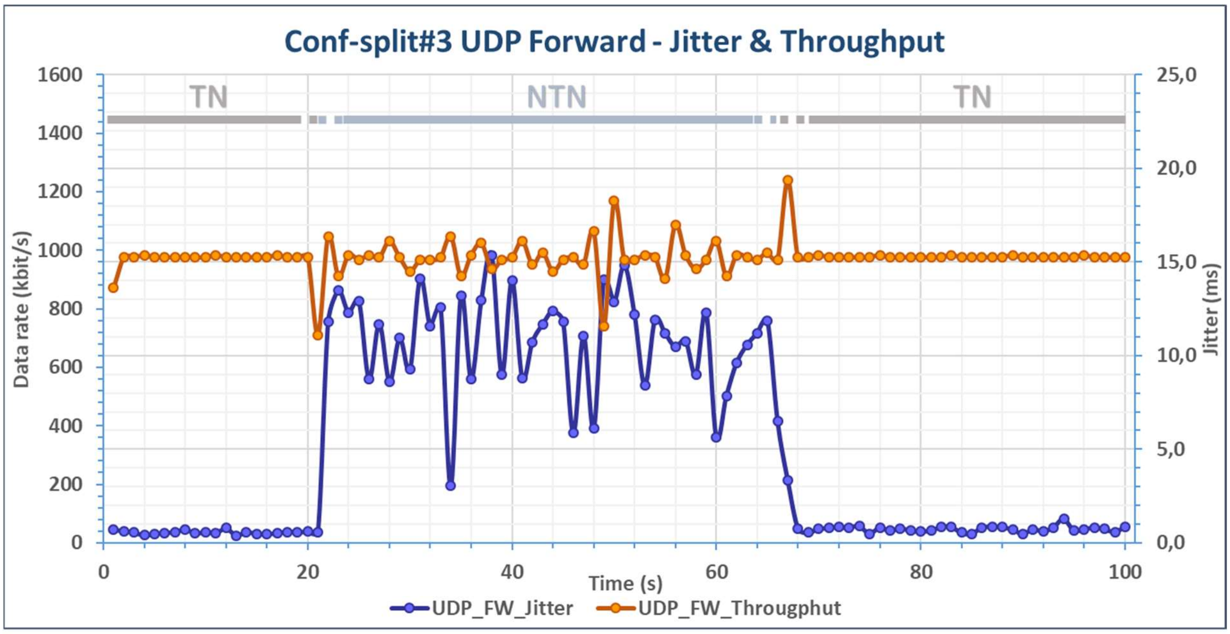


Figure 19: Conf-split#2 – UDP FW jitter & throughput data rate-packets transfer measurement graphs

- Conf-split#3 – UDP FW link measurements:



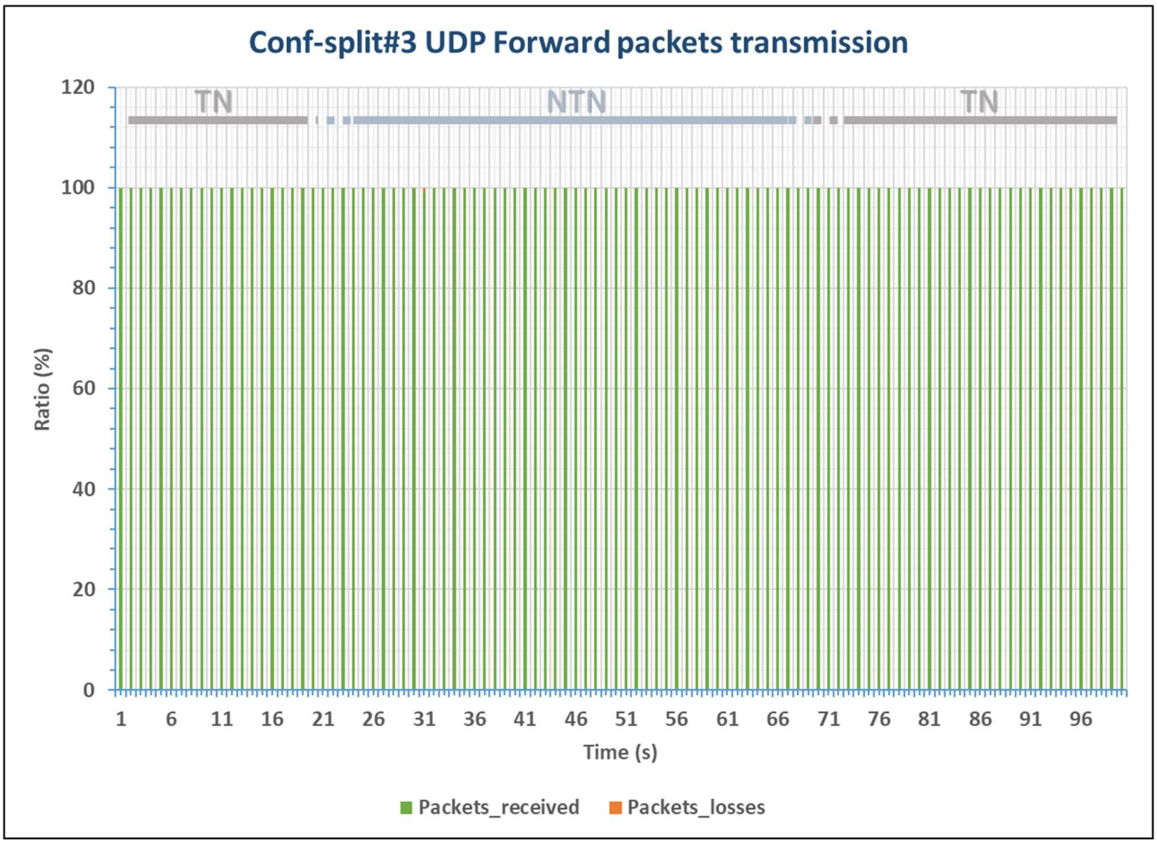
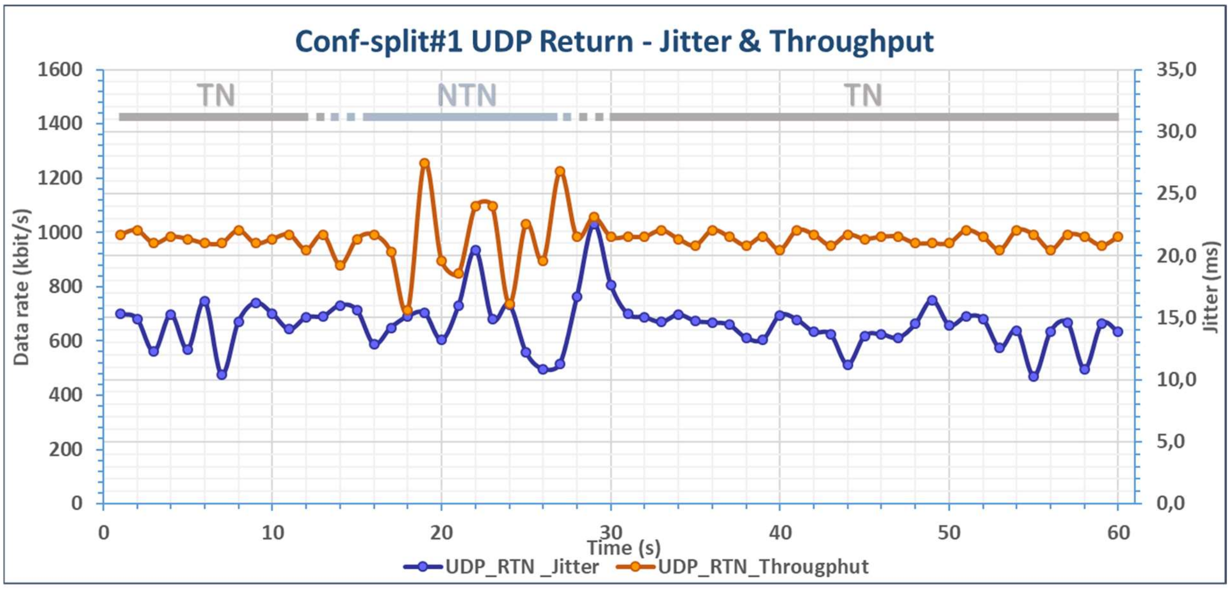


Figure 20: Conf-split#3 – UDP FW jitter & throughput data rate-packets transfer measurement graphs

These measurements graphs show a UDP forward link throughput integrity quite preserved over the test sequence which mainly induces variation on data rate and jitter only during the frame to perform backhaul path switchover although more significant ripples can be noticed for the split#3 configuration during the NTN period. In particular, the fluctuations observed for

Split#1 and Split#2 configurations are almost negligible from a numerical standpoint, whereas the ripples recorded in Split#3 as observed above are more relevant. Also from a numerical standpoint, these latter are more evident especially for the packet delay jitter (in the order of 10-15 ms). The data rate fluctuations are instead less prominent. Last but not least, the packet successful delivery rate is 100% for all configurations.

- Test Case suite – Performance Return UDP_#1:
  - Conf-split#1 – UDP RTN link measurements:



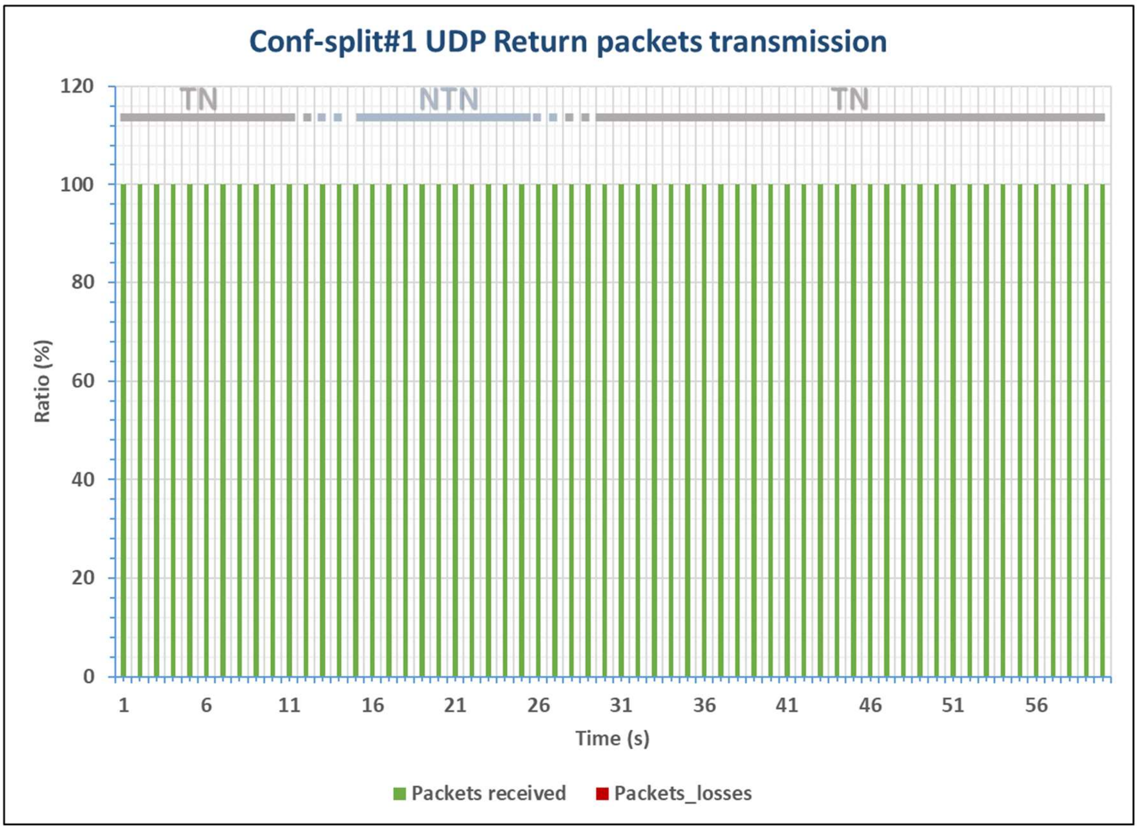
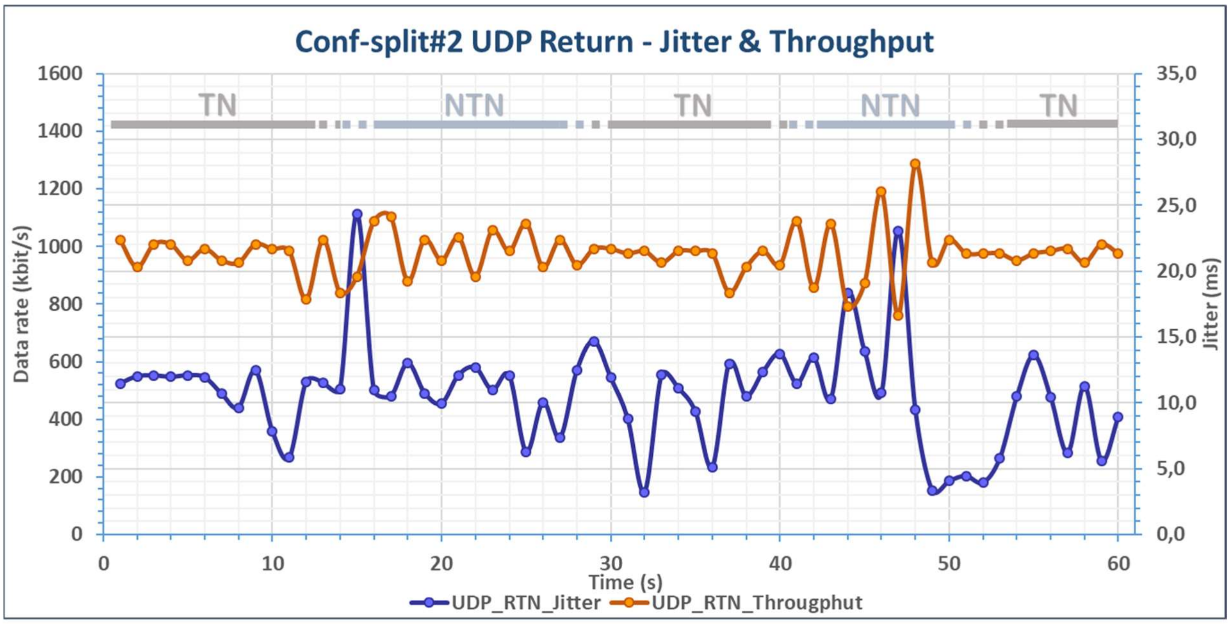


Figure 21: Conf-split#1 – UDP RTN jitter & throughput data rate-packets transfer measurement graphs

- Conf-split#2 – UDP RTN link measurements:



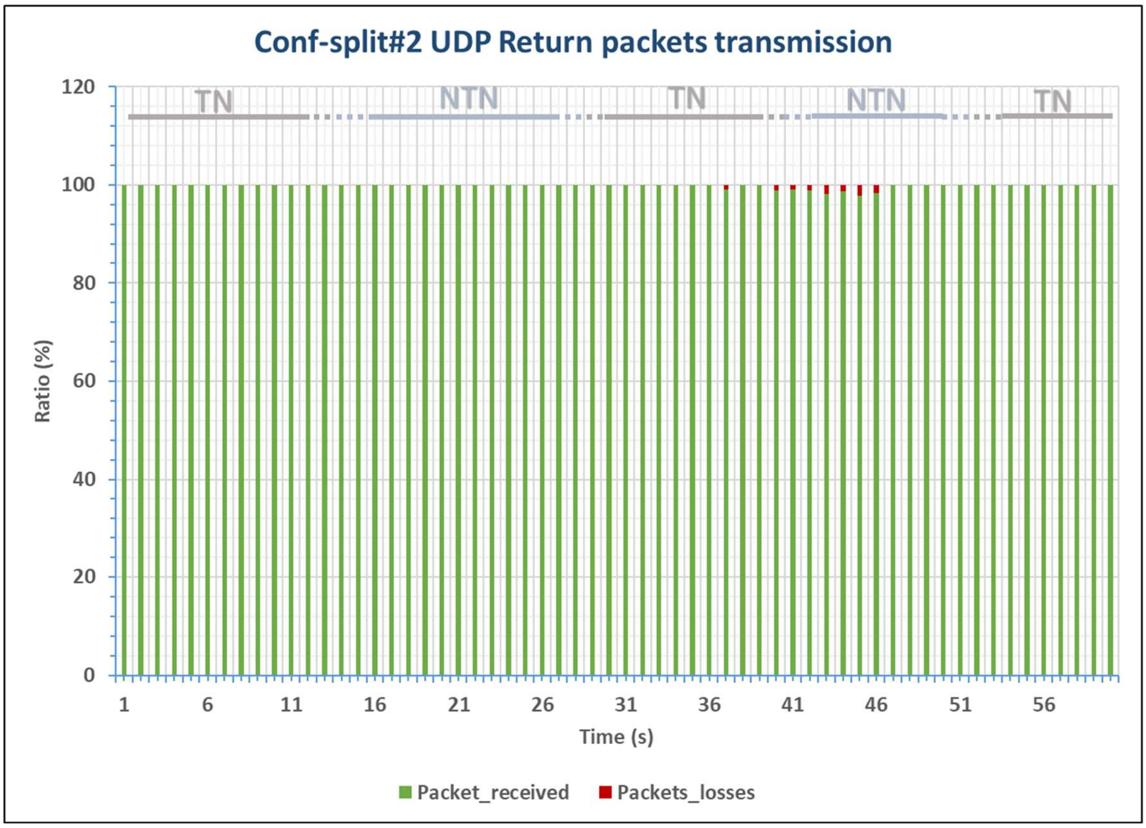
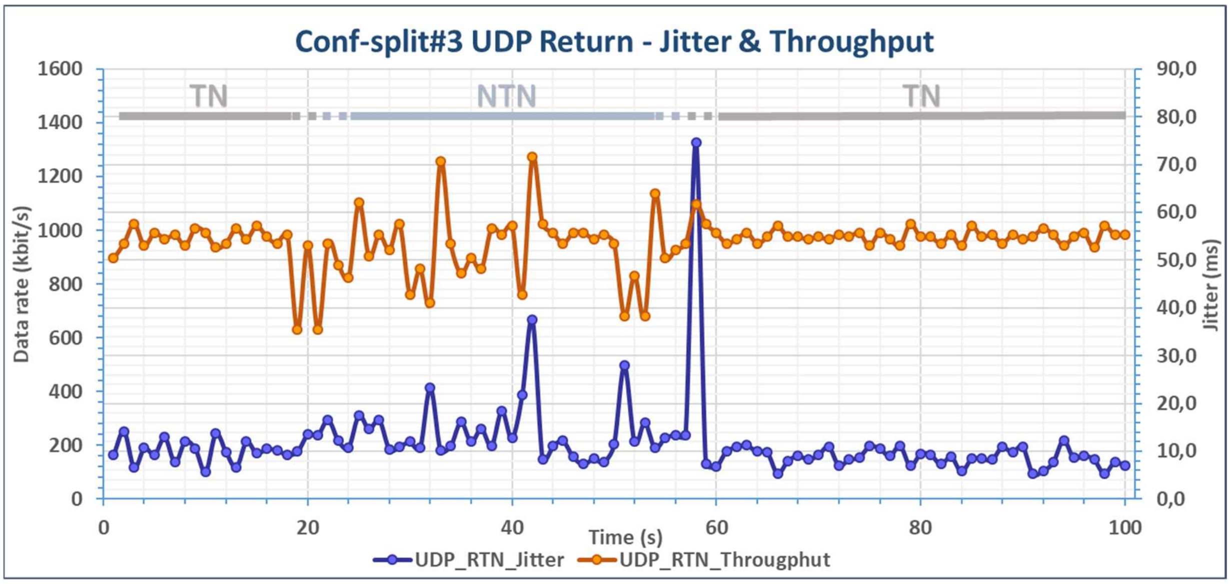


Figure 17: Conf-split#2 – UDP RTN jitter & throughput data rate-packets transfer measurement graphs

- Conf-split#3 – UDP RTN link measurements:



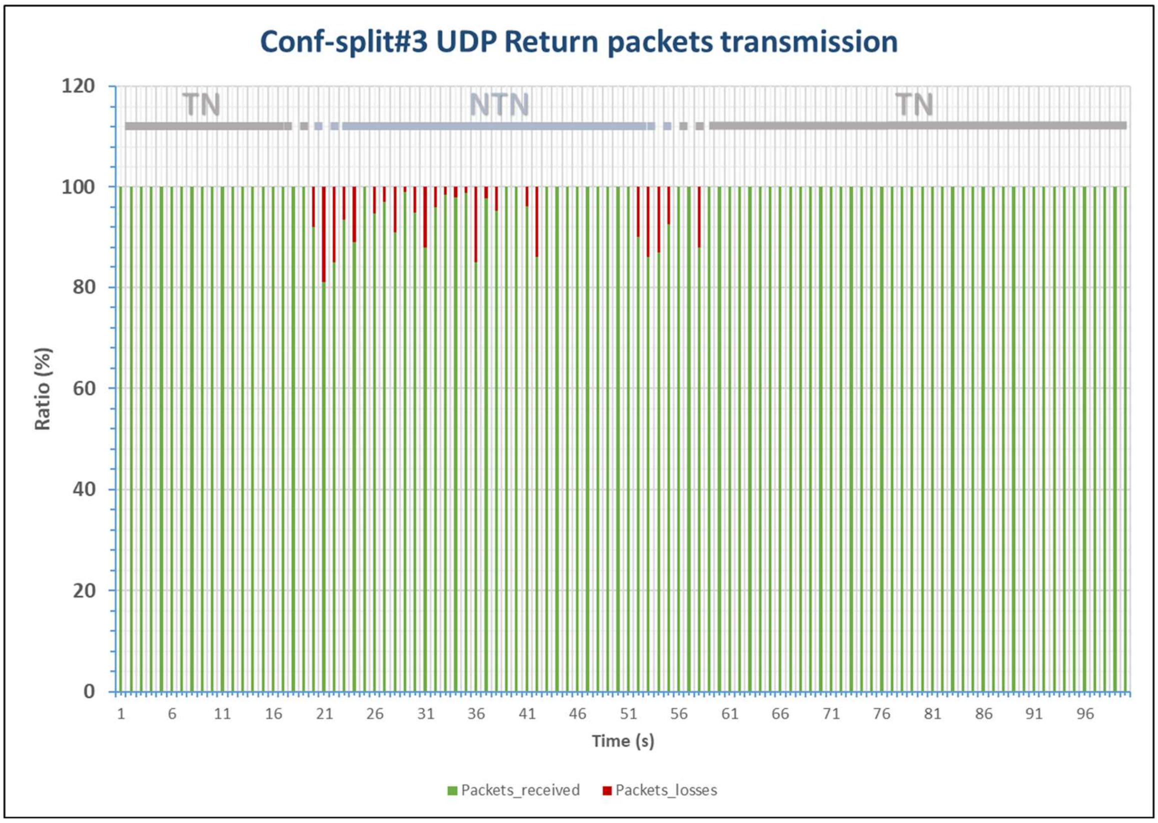


Figure 22: Conf-split#3 – UDP RTN jitter & throughput data rate-packets transfer measurement graphs

These measurements are still showing a UDP forward link throughput integrity quite preserved for the split#1 &#2 configuration over the test sequence despite more significant variation on data rate and jitter can be noticed as also pre-compensation mechanisms are more critical to apply on return channel.

Regarding the configuration split#3 there are a few more losses occurrences rather narrowed around a switchover of backhaul paths with almost double Jitter magnitude than other splits that could be caused by a delay emulation introduced on a different machine (UPF Core Network server instead of gNB). In general, it can be noticed how the performance results observed for the return link are less stable than those presented before for the forward link, with more important variations at packet delay jitter. Those at data rate level are also more evident than those for the forward link, but in terms of absolute numerical value the oscillation is not so critical.

- Test Case suite – Performance Bi-directional UDP#1:

  - Conf-split#1 – UDP FW + RTN link measurements:

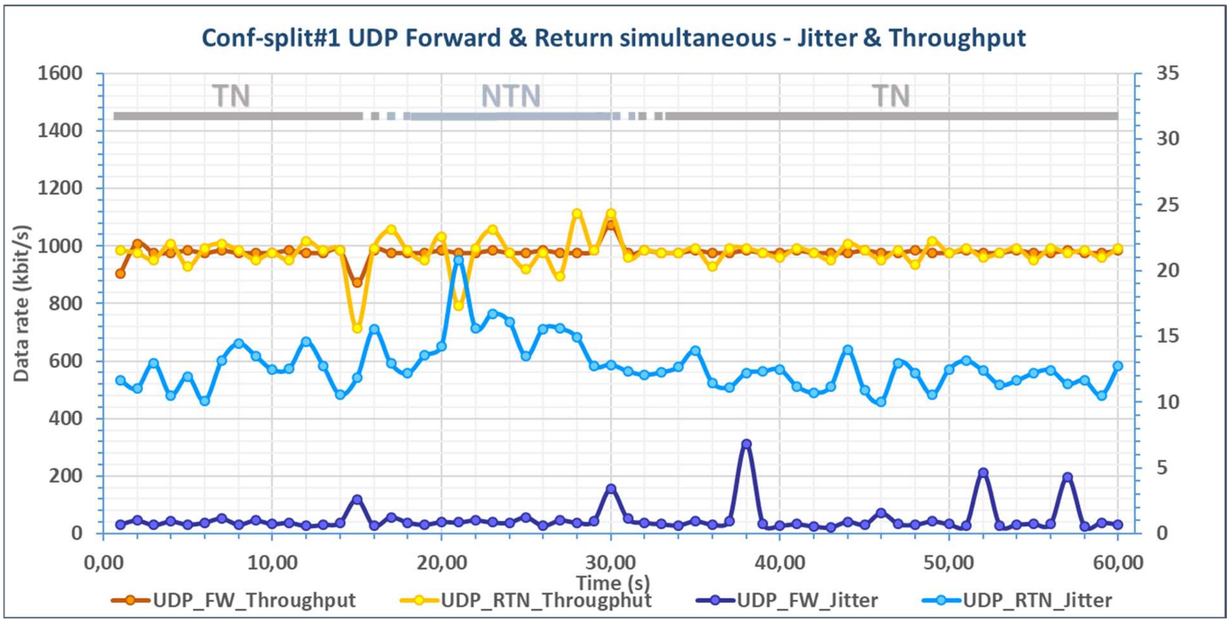
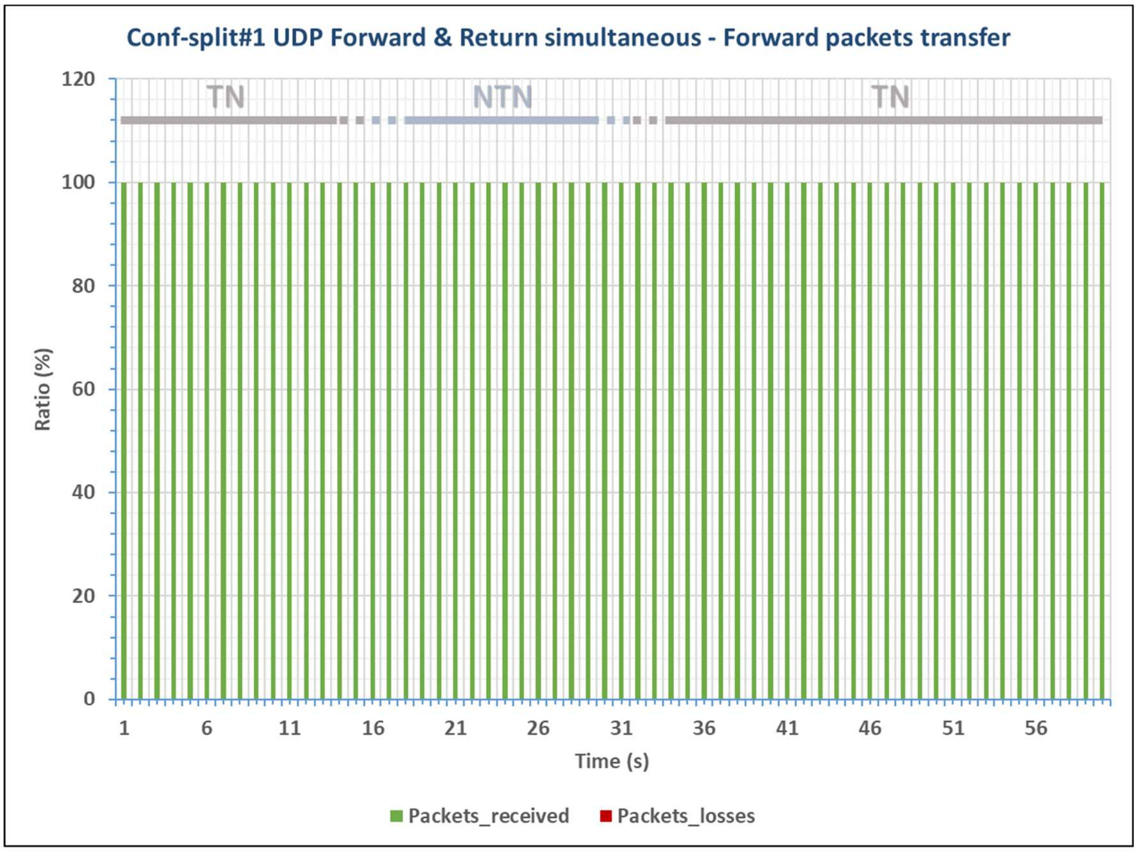


Figure 23: Conf-split#1 – UDP FW + RTN jitter & throughput data rate transfer measurement graphs



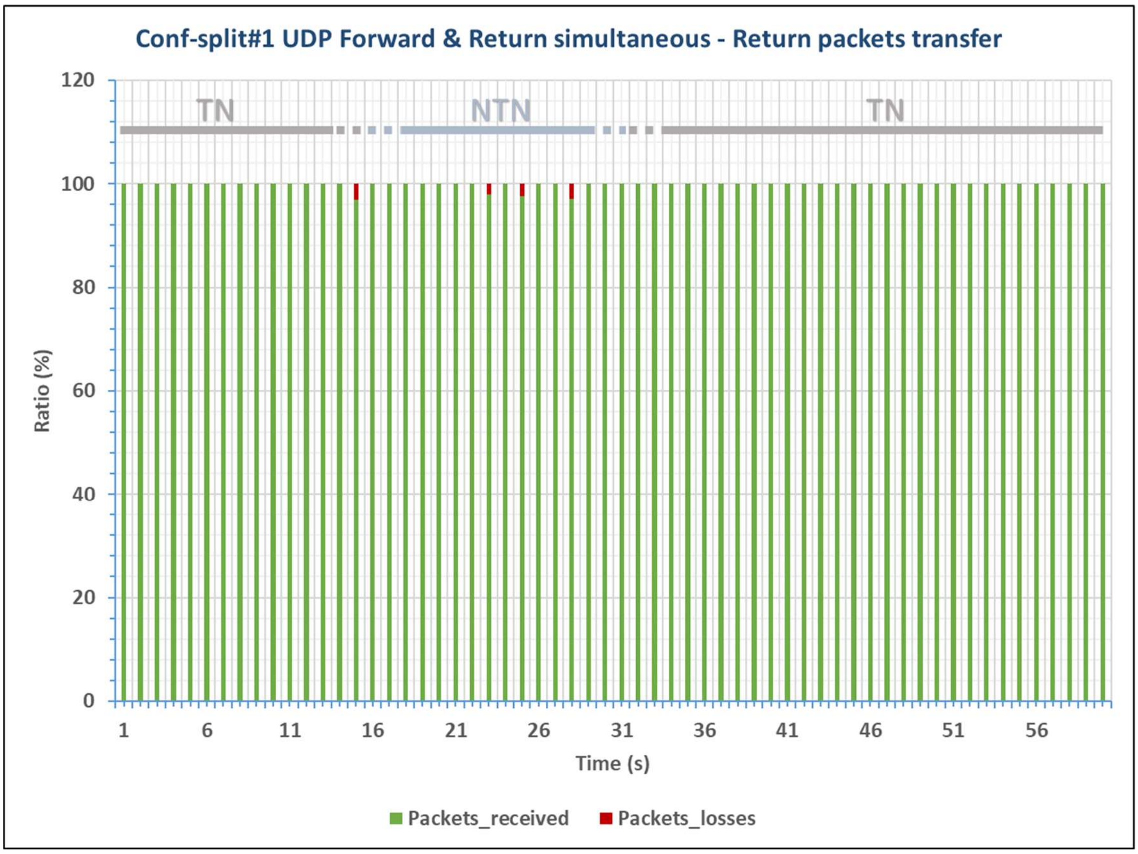


Figure 24: Conf-split#1 – UDP FW + RTN packets transfer measurement graphs

- Conf-split#2 – UDP FW + RTN link measurements:

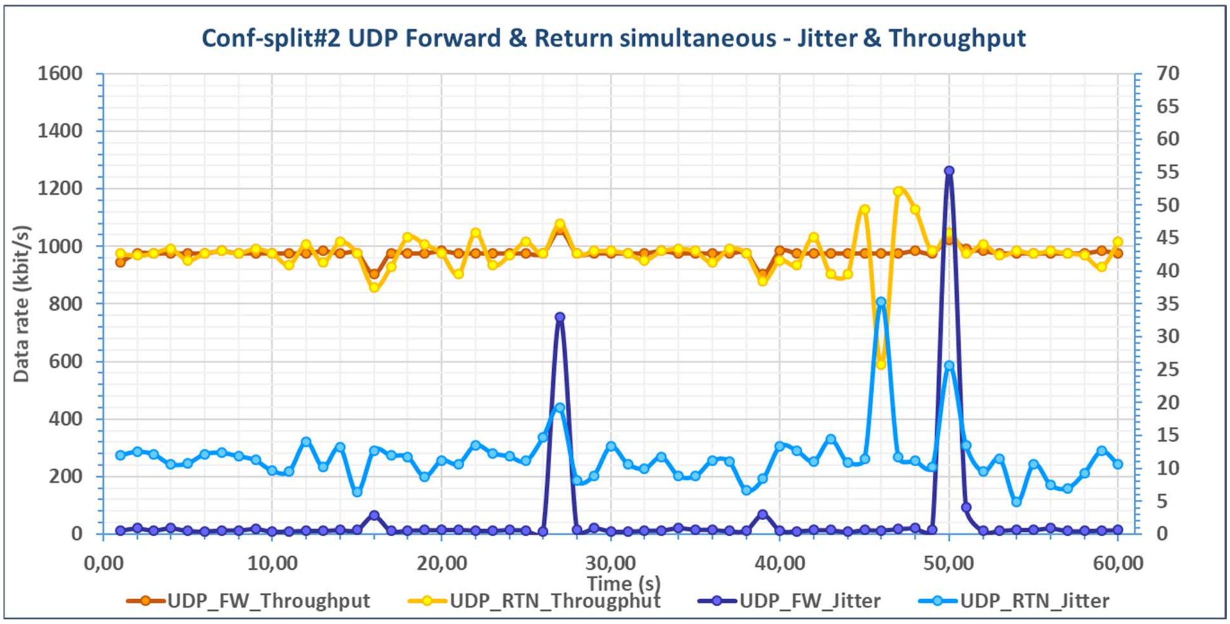


Figure 25: Conf-split#2 – UDP FW + RTN jitter & throughput data rate transfer measurement graphs

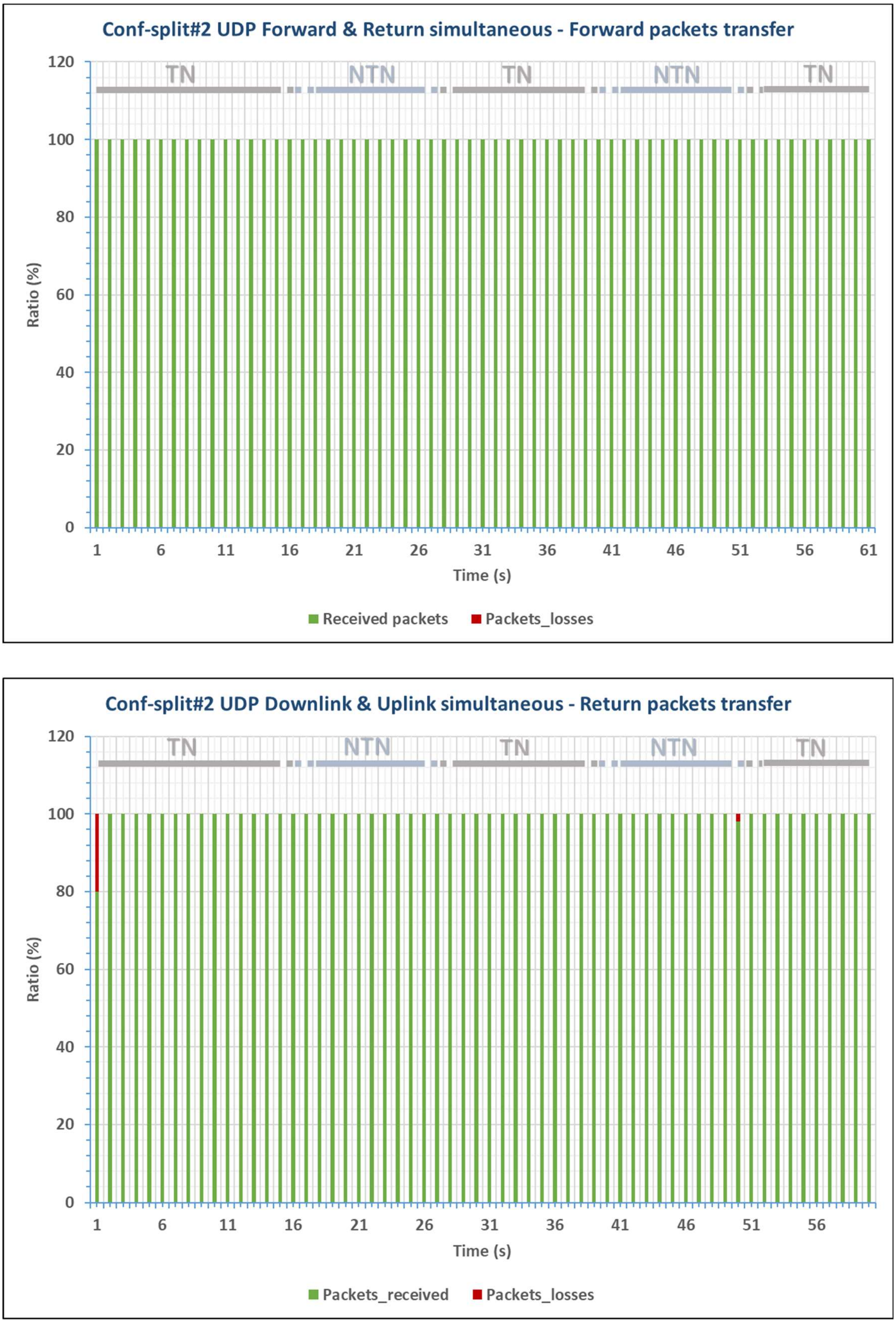


Figure 26: Conf-split#2 – UDP FW + RTN packets transfer measurement graphs

- Conf-split#3 – UDP FW + RTN link measurements:

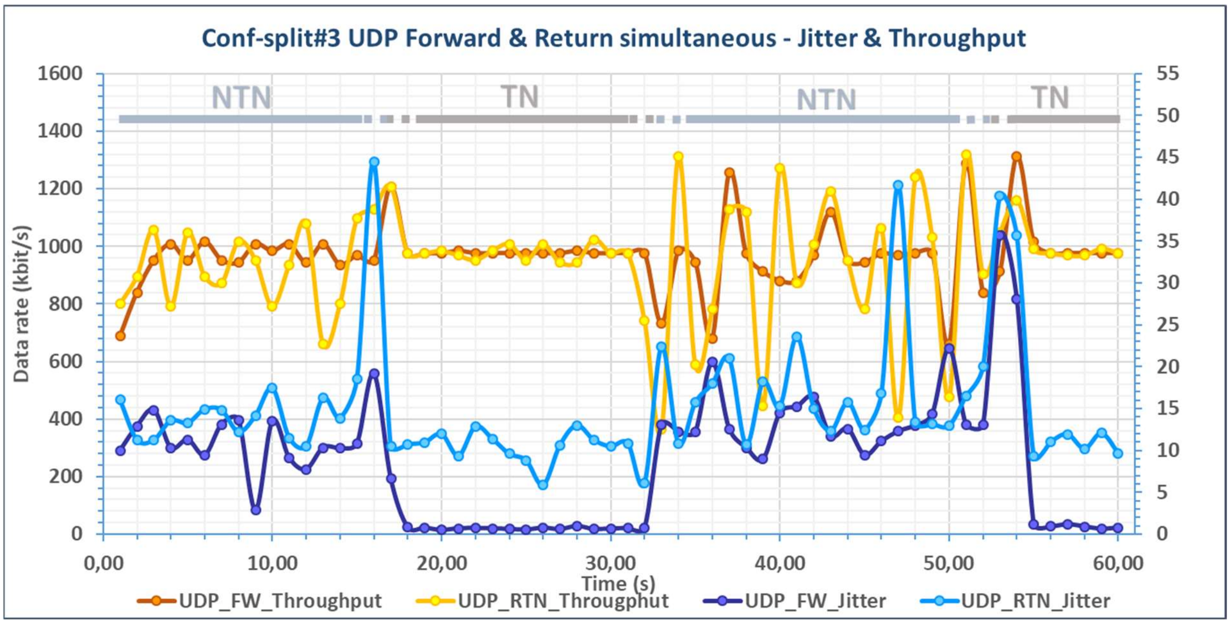
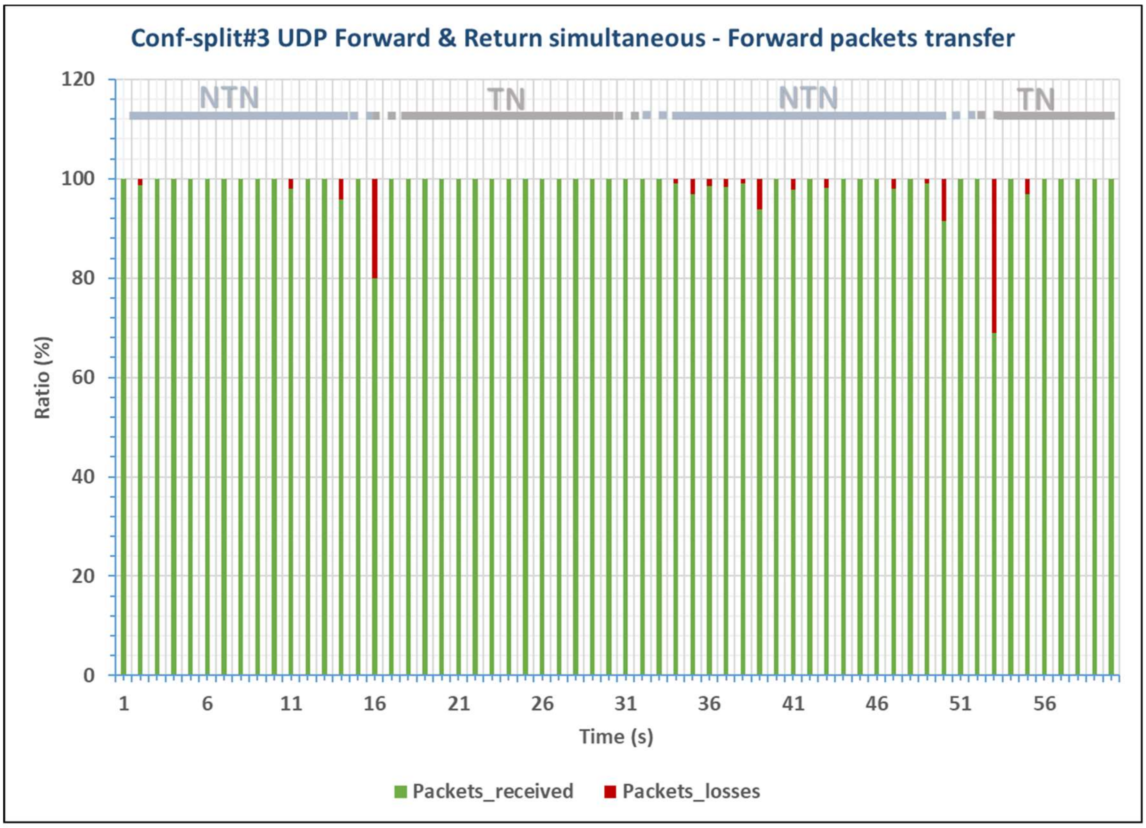


Figure 27: Conf-split#3 – UDP FW + RTN jitter & throughput data rate transfer measurement graphs



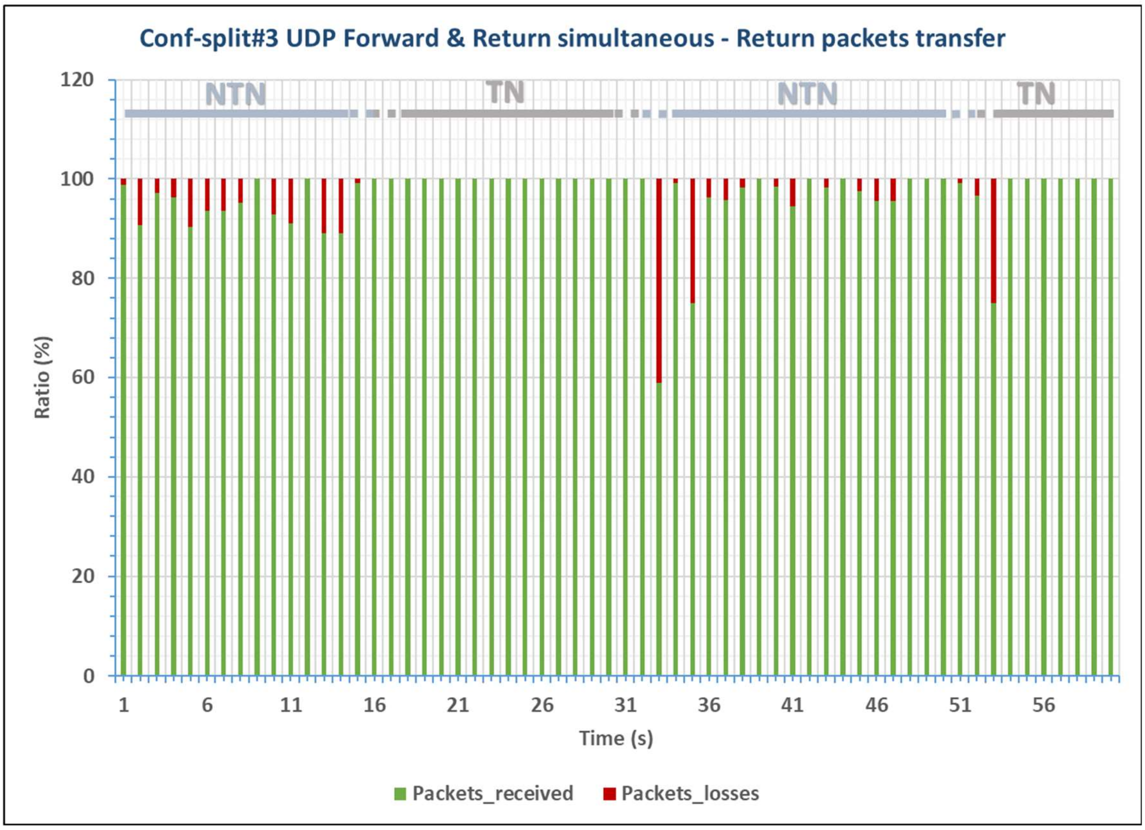
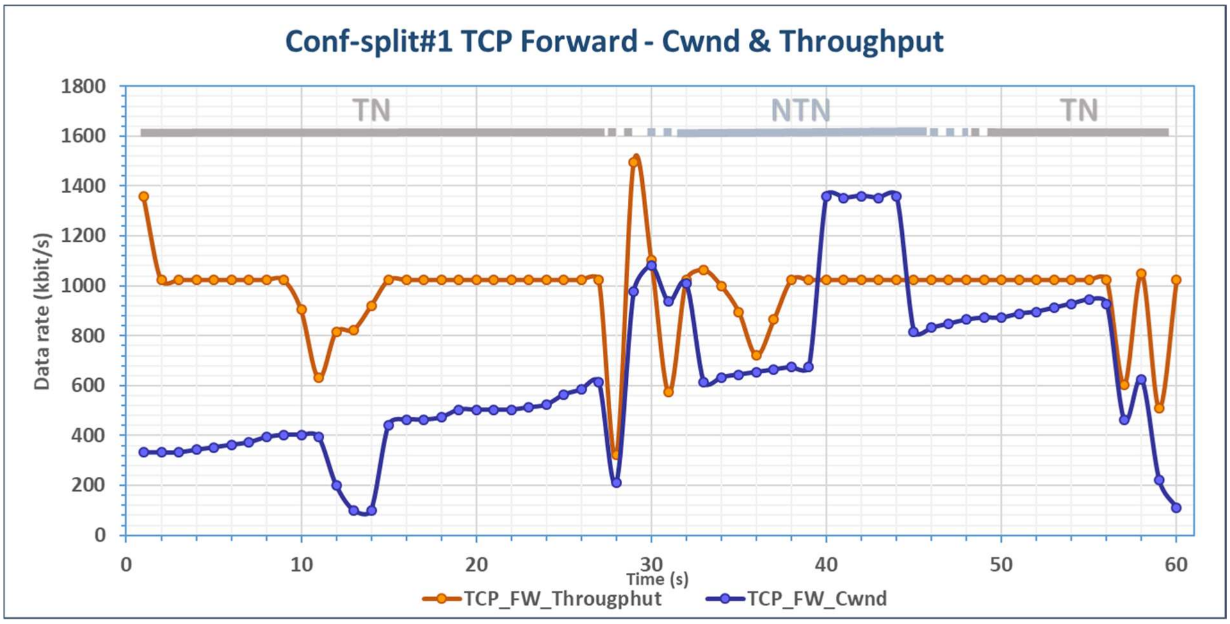


Figure 28: Conf-split#3 – UDP FW + RTN packets transfer measurement graphs

The results presented above with respect to the combination of simultaneous bidirectional forward + return UDP flow align pretty much to those just comment for the sake of unidirectional data flows, hence confirming the insights stated for the unidirectional case and that no impact across return and forward link traffic flows is exhibited.

- Test Case suite – Performance Forward TCP_#1:
    - Conf-split#1 – TCP FW link measurements:



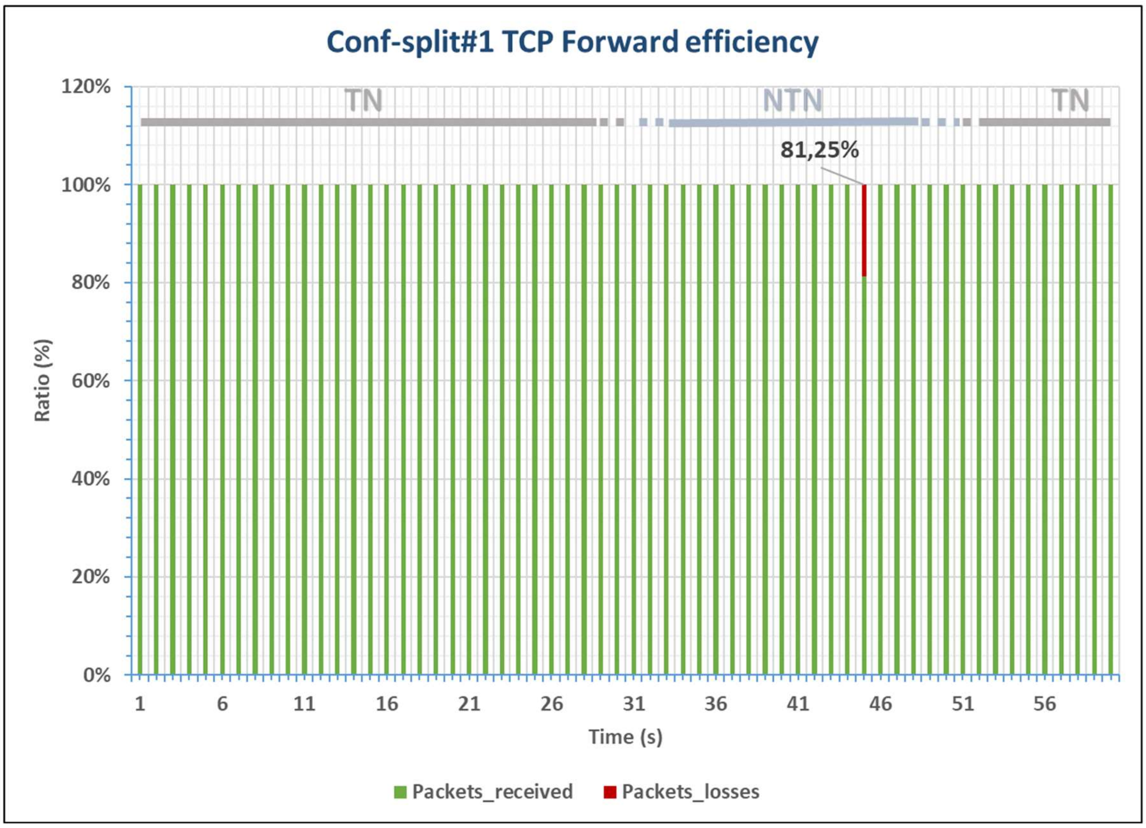
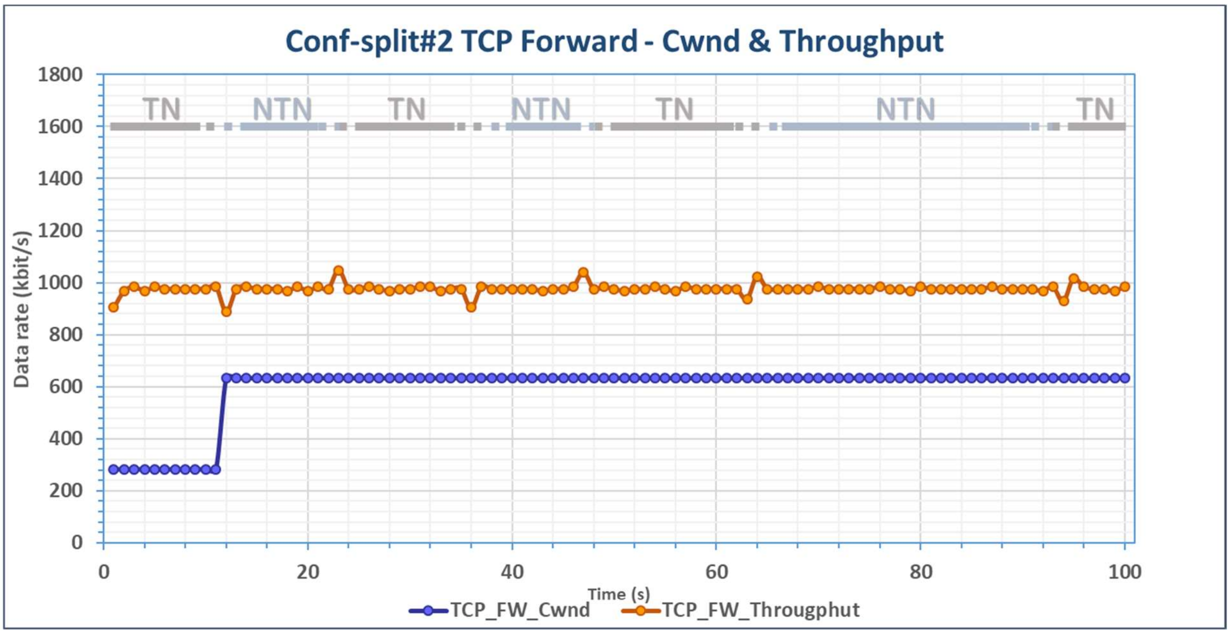


Figure 29: Conf-split#1 – TCP FW Cwnd & throughput data rate-packets transfer measurement graphs

- Conf-split#2 – TCP FW link measurements:



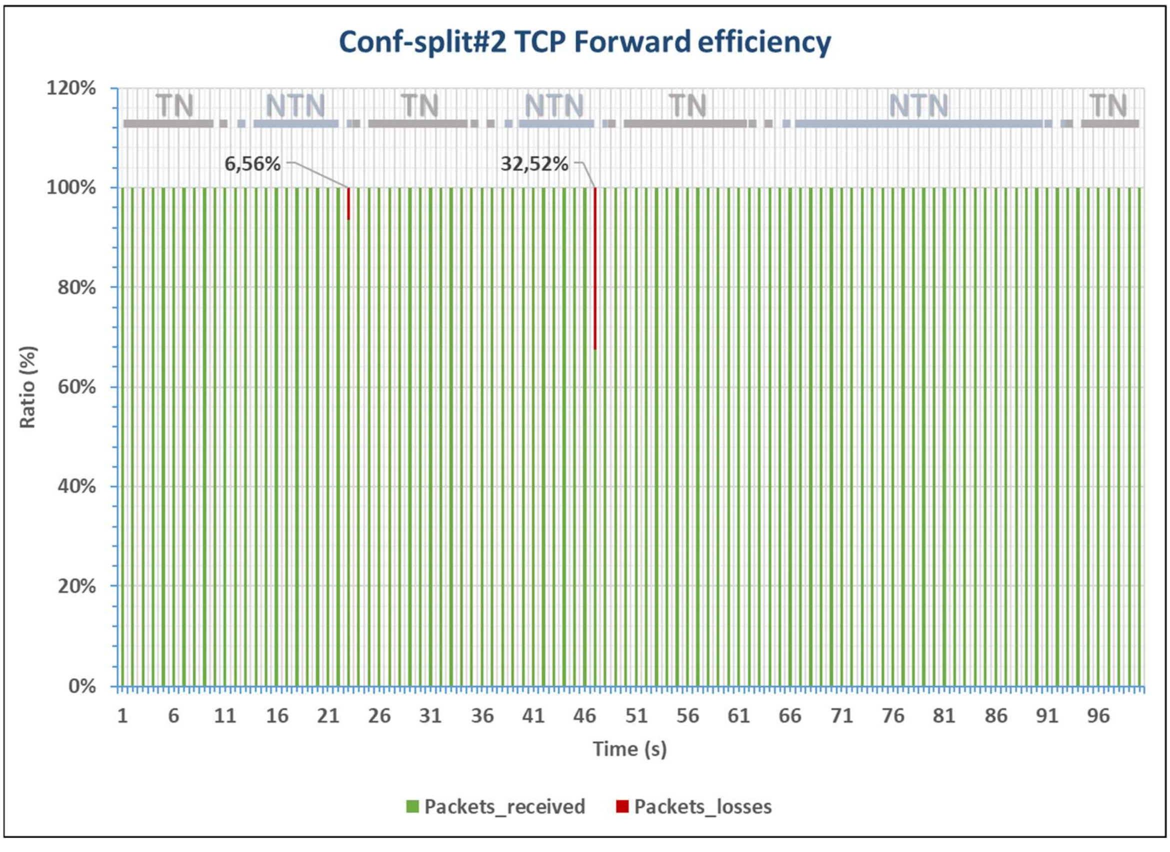
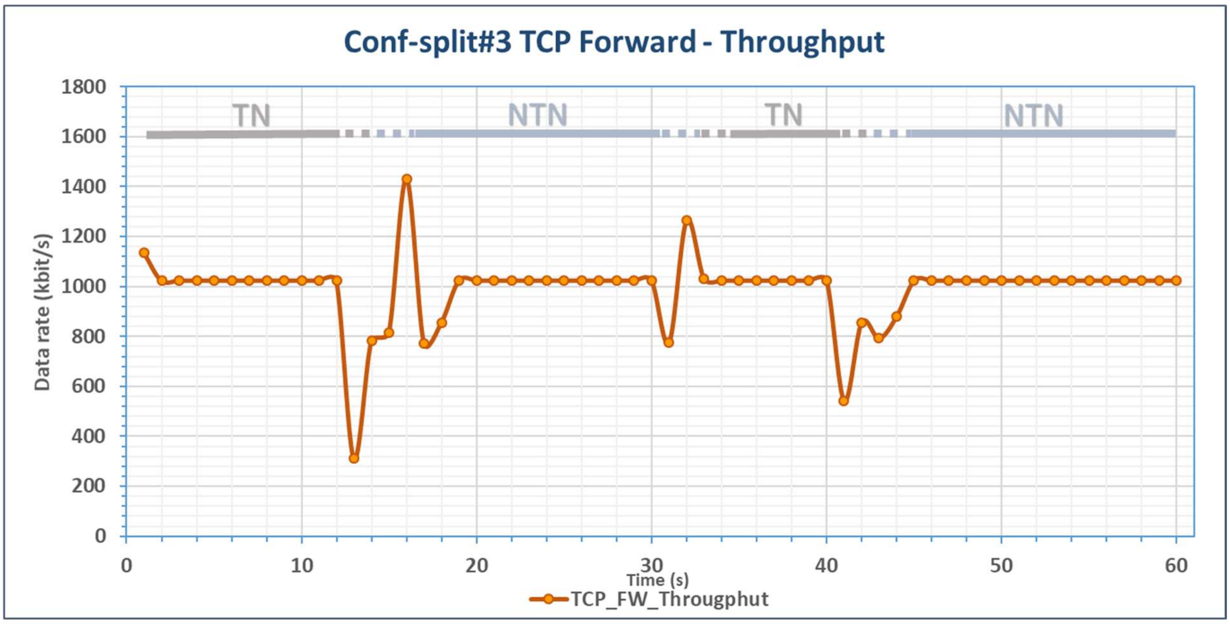


Figure 30: Conf-split#2 – TCP FW Cwnd & throughput data rate-packets transfer measurement graphs

- Conf-split#3 – TCP FW link measurements:



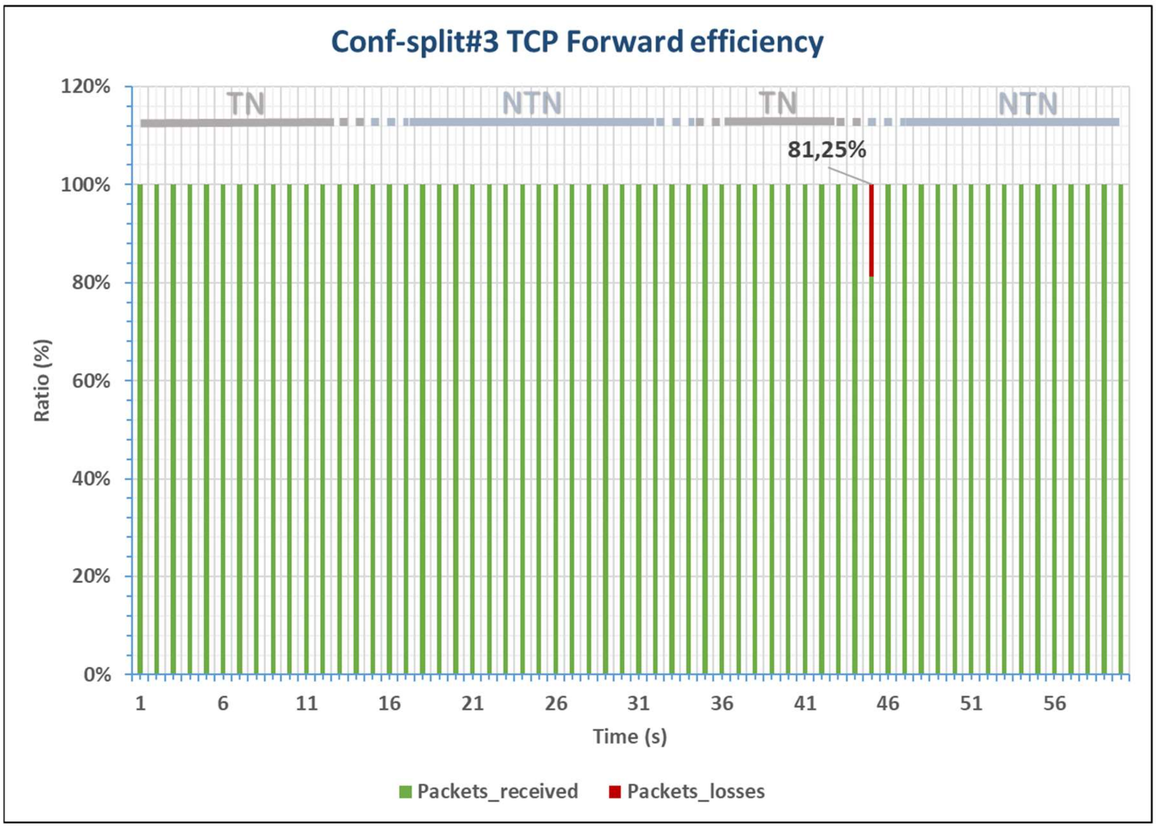
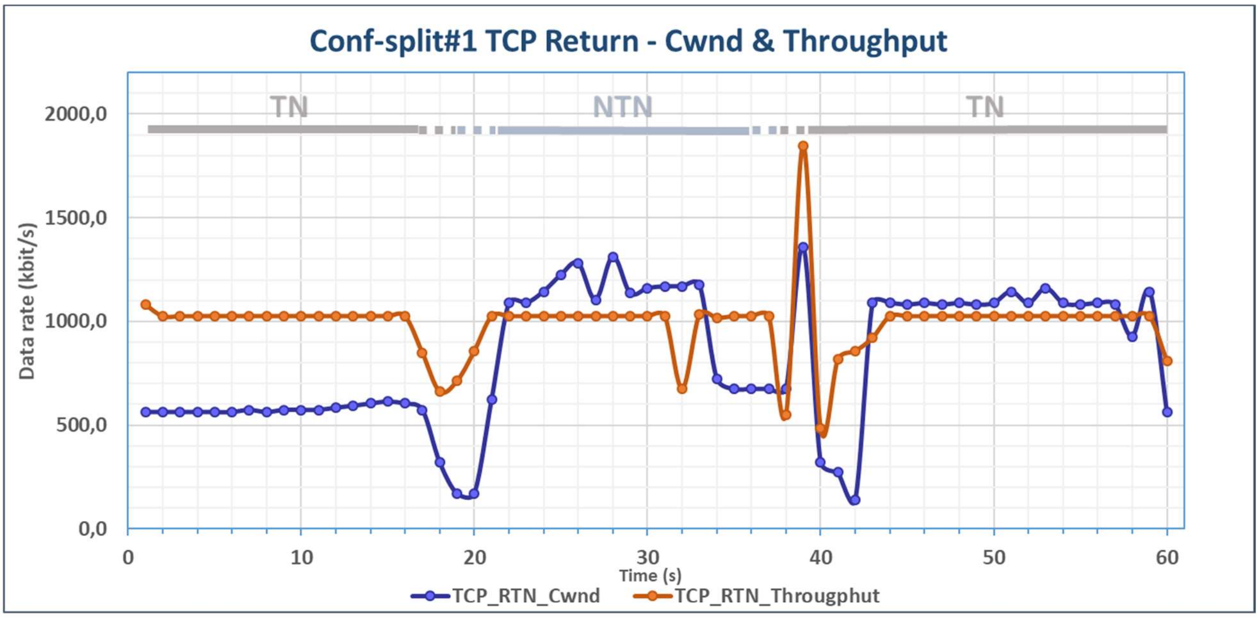


Figure 31: Conf-split#3 – TCP FW throughput data rate-packets transfer measurement graphs

These measurements are showing TCP forward link throughput integrity quite preserved by maintaining a nominal data-rate over a test sequence scale for all different configuration splits with most significant variation noticed during limited frame of backhaul path switchover without few related amount or occurrences packet loss. An observation of the Congestion window (Cwnd) provides complement to estimate instantaneous link stability characteristics where split#2 configuration flatness notably stands out. On the other hand, Split#1 and #3 provide more important fluctuations at data rate and consequently TCP cwnd, probably in relation to delay spike and some non-zero packet loss, resulting from the specific bench configuration in terms of modules implemented in different machines. This intuition is confirmed by the fact that Split #1 and Split#3 are both about gNB onboard hence implementing pretty much the same configuration, while Split#2 implements CU/DU splitting with the F1 interface established over the feeder link.

- Test Case suite – Performance Return TCP_#1:
    - Conf-split#1 – TCP RTN link measurements:



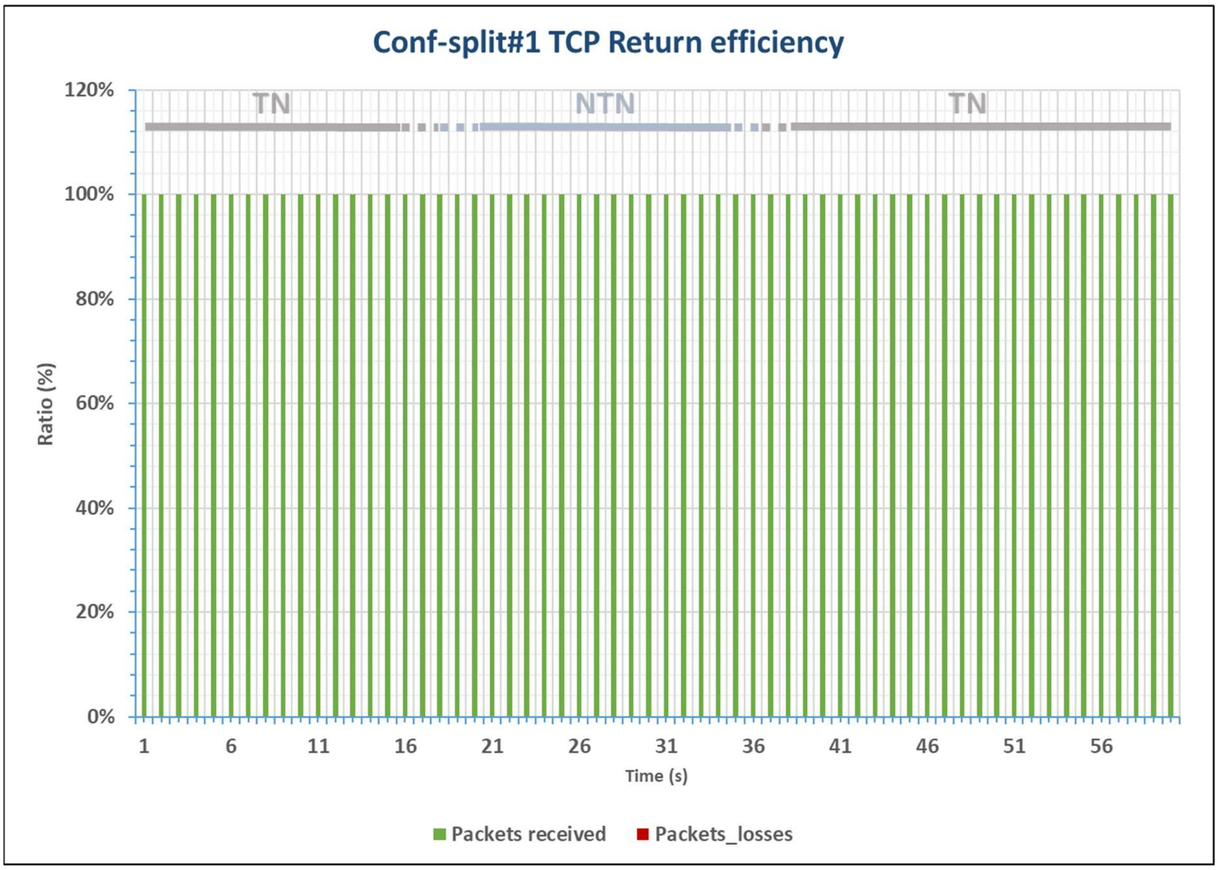
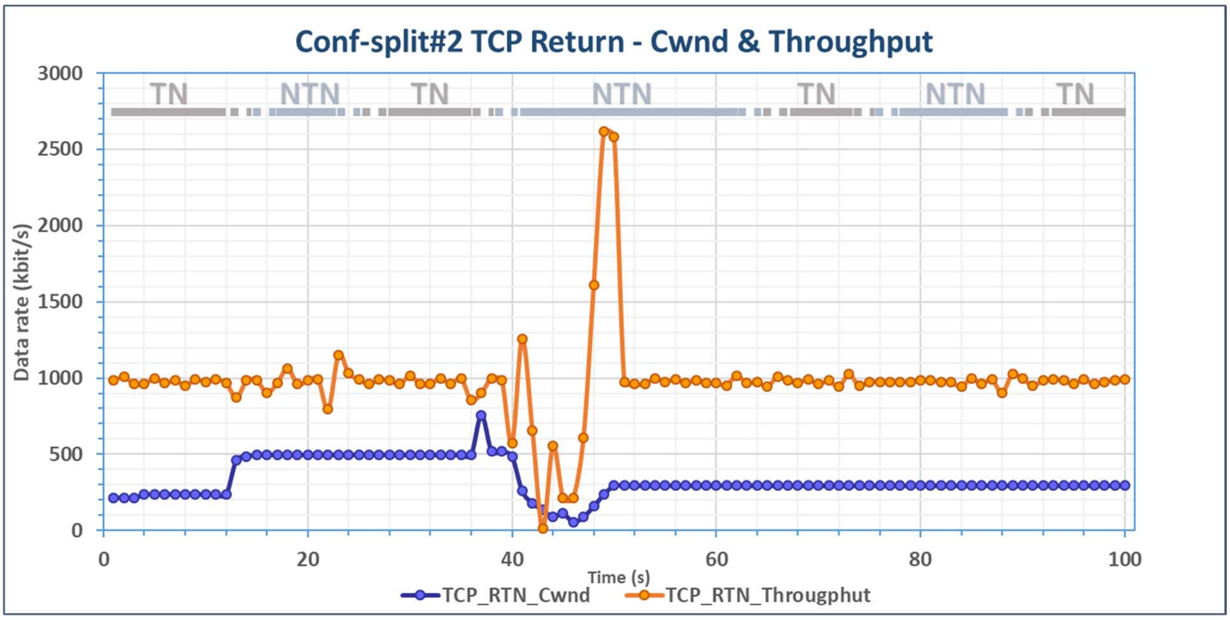


Figure 32: Conf-split#1–TCP RTN Cwnd & throughput data rate-packets transfer measurement graphs

- Conf-split#2 – TCP RTN link measurements:



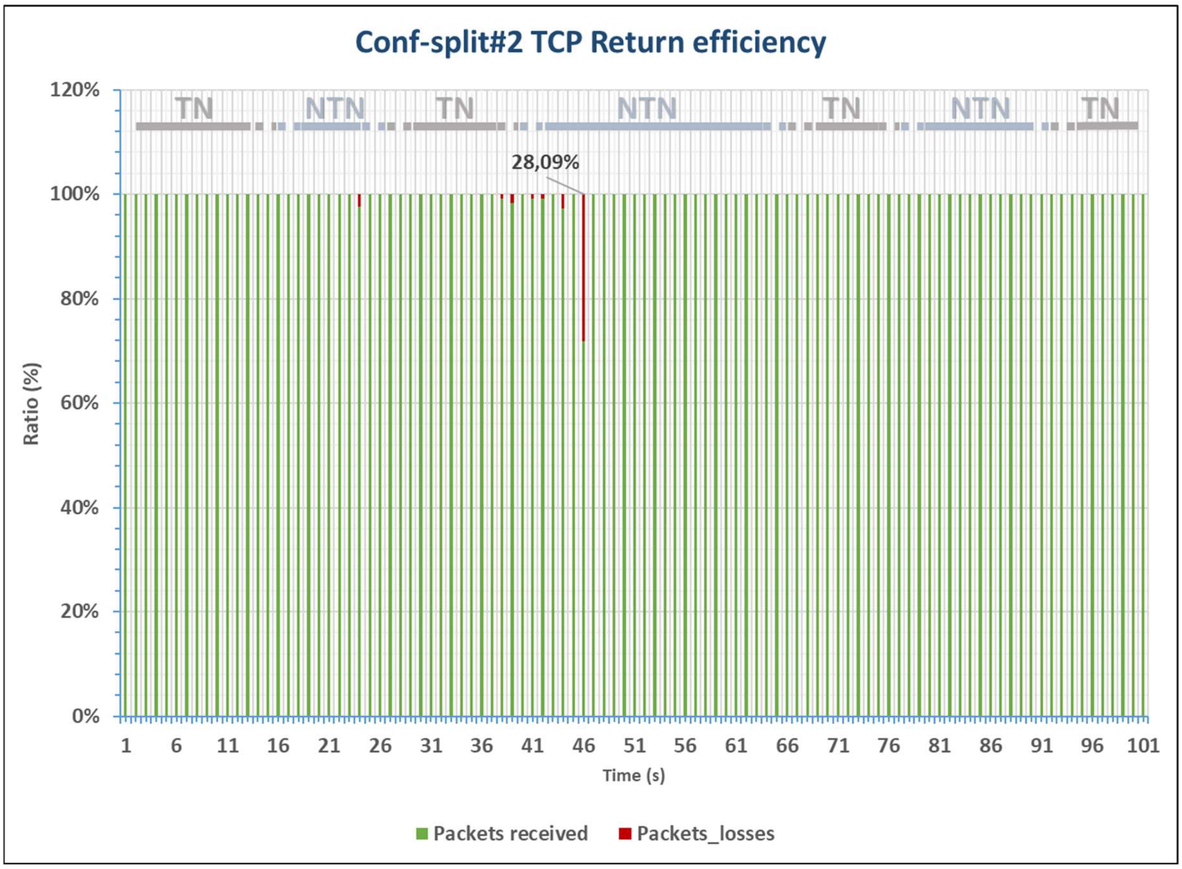
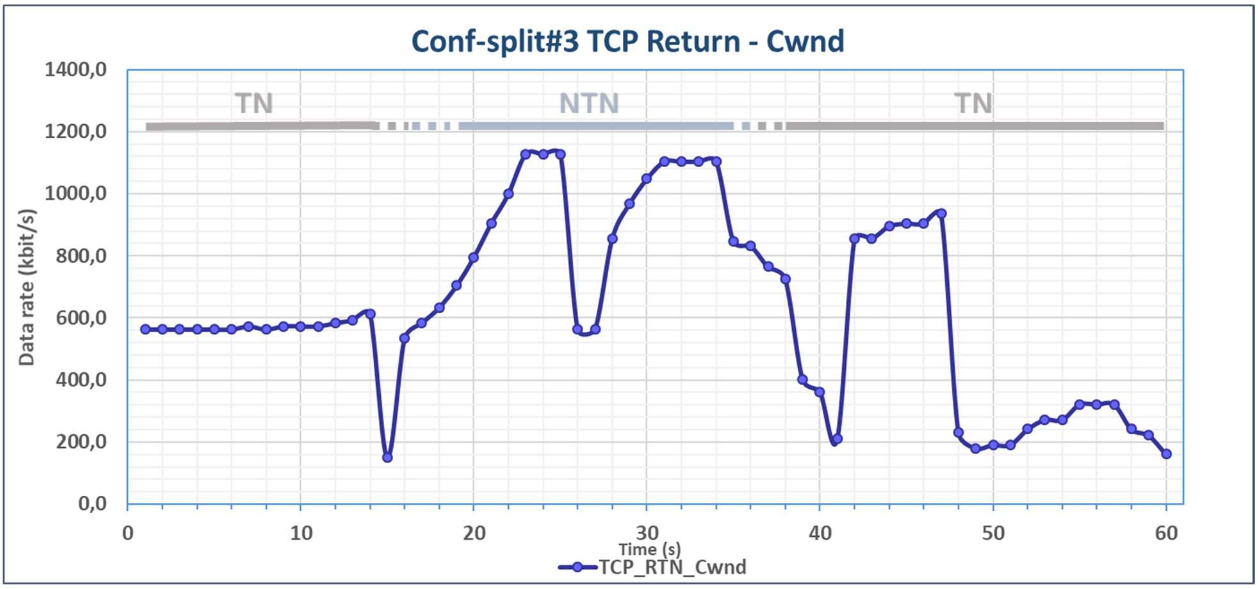


Figure 33: Conf-split#2 – TCP RTN Cwnd & throughput data rate-packets transfer measurement graphs

- Conf-split#3 – TCP RTN link measurements:



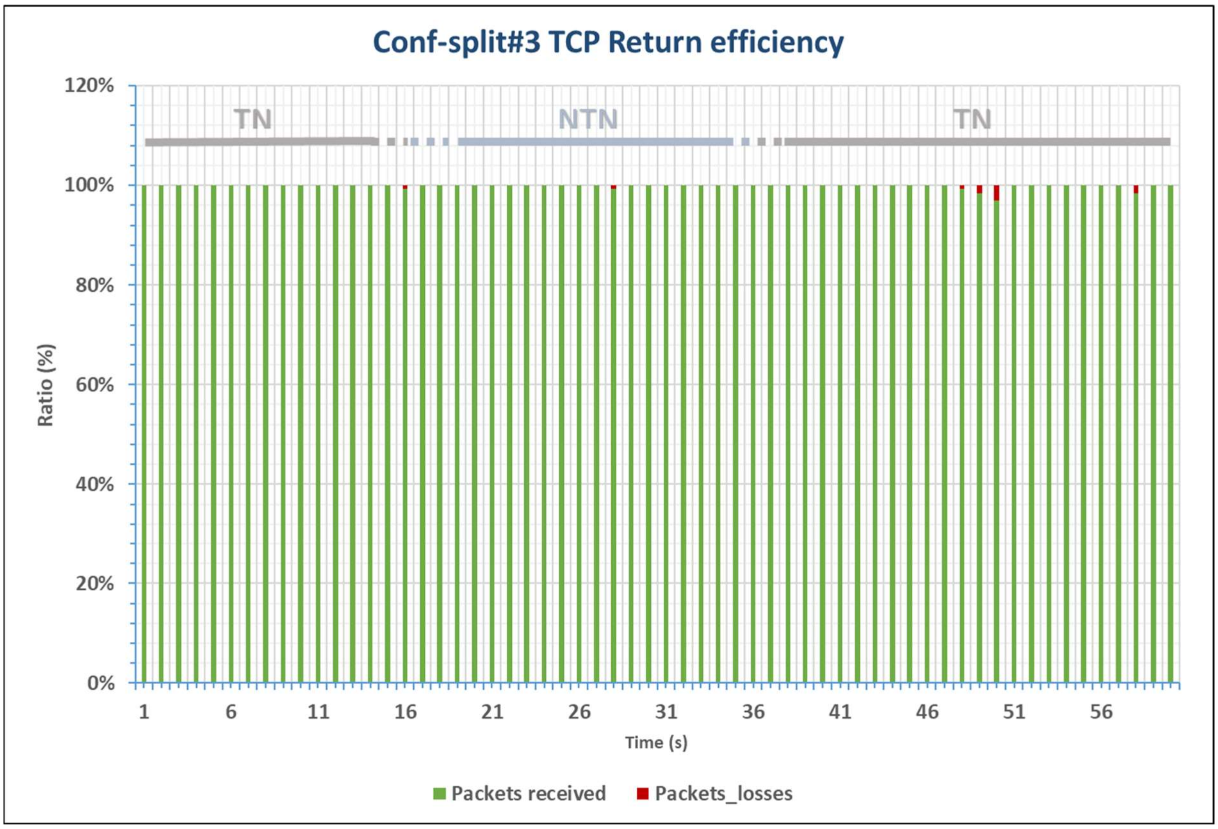


Figure 34: Conf-split#3 – TCP RTN Cwnd & throughput packets transfer measurement graphs

These measurements are also showing a high TCP link return integrity where besides a significant data-rate variation event from backhaul path switchover occurring on a limited period across the overall split#2 configuration stability there are similar performances than previous observations. As noted for the results collected from the UDP protocol configuration, the return link shows more important fluctuations with respect to the forward link, though not significantly affective the overall performance. Finally, it is also worth noticing that TCP tests are much more sensitive to network condition fluctuations than UDP, since this latter is besteffort while TCP adapts the congestion window and hence the throughput according to the estimated latency and any occurred packet loss.

- Test Case suite – Performance Bi-directional TCP_#1:

  - Conf-split#1 – TCP FW + RTN link measurements:

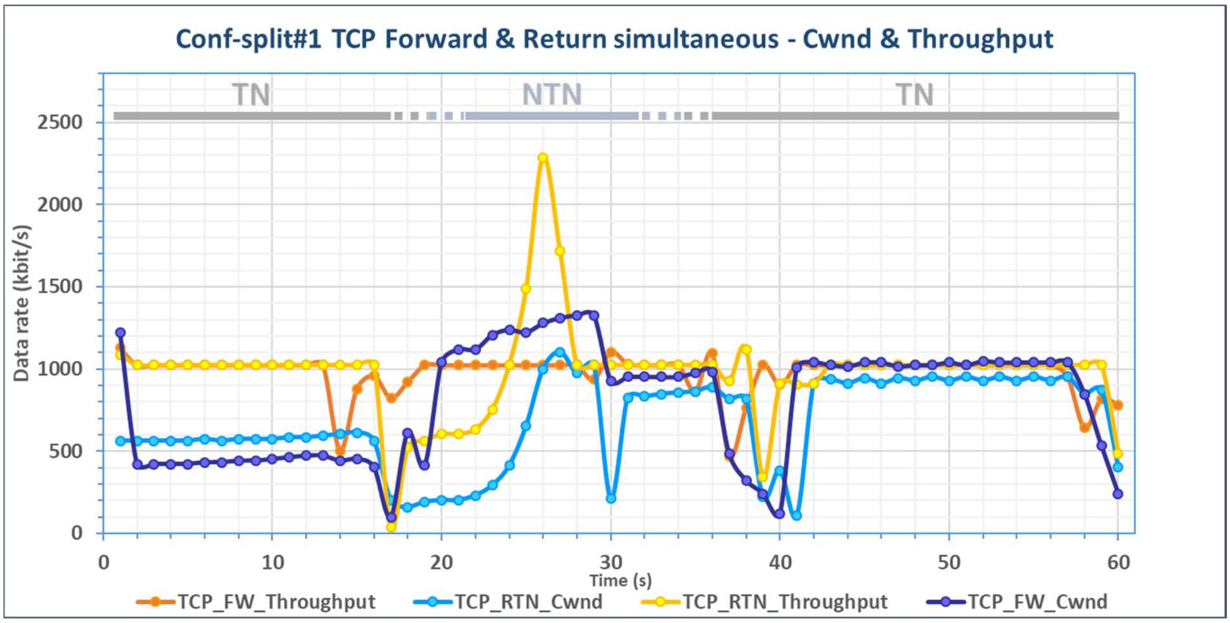
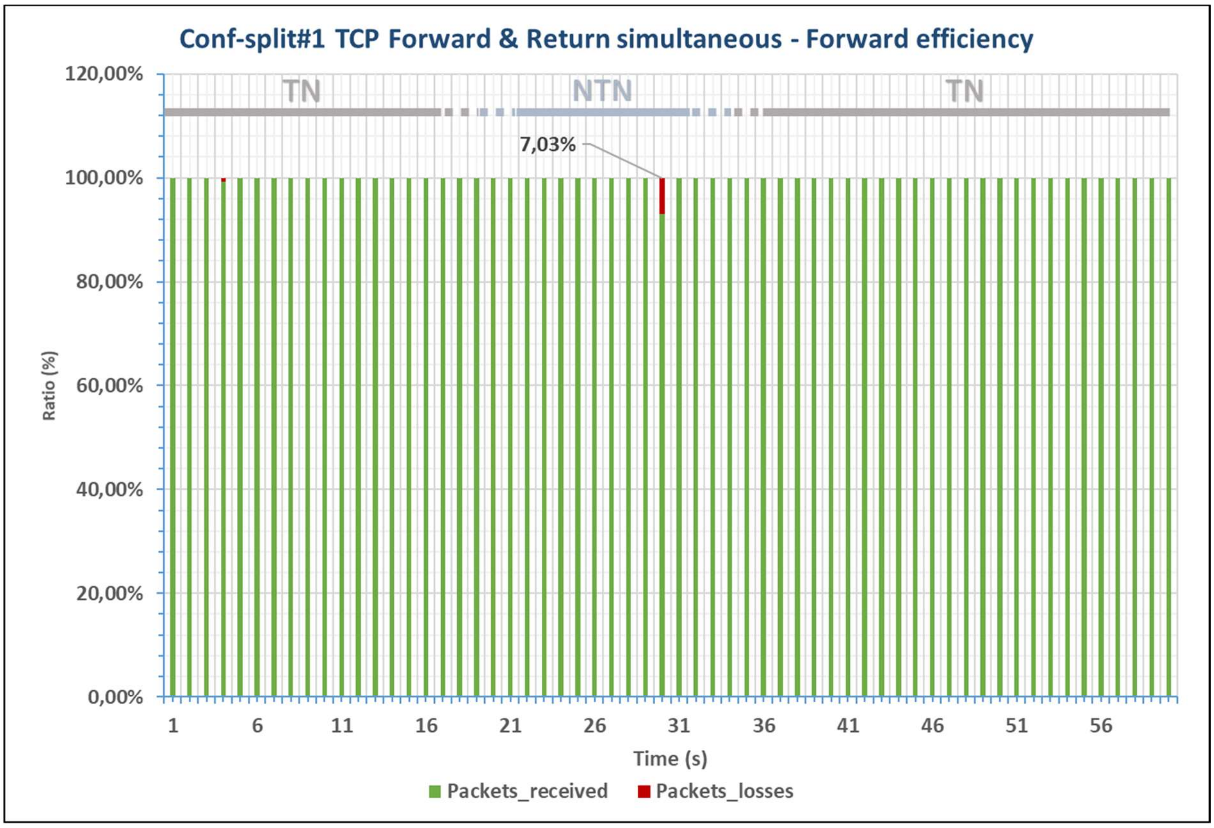


Figure 35: Conf-split#1 – TCP FW + RTN Cwnd & throughput data rate transfer measurement graphs



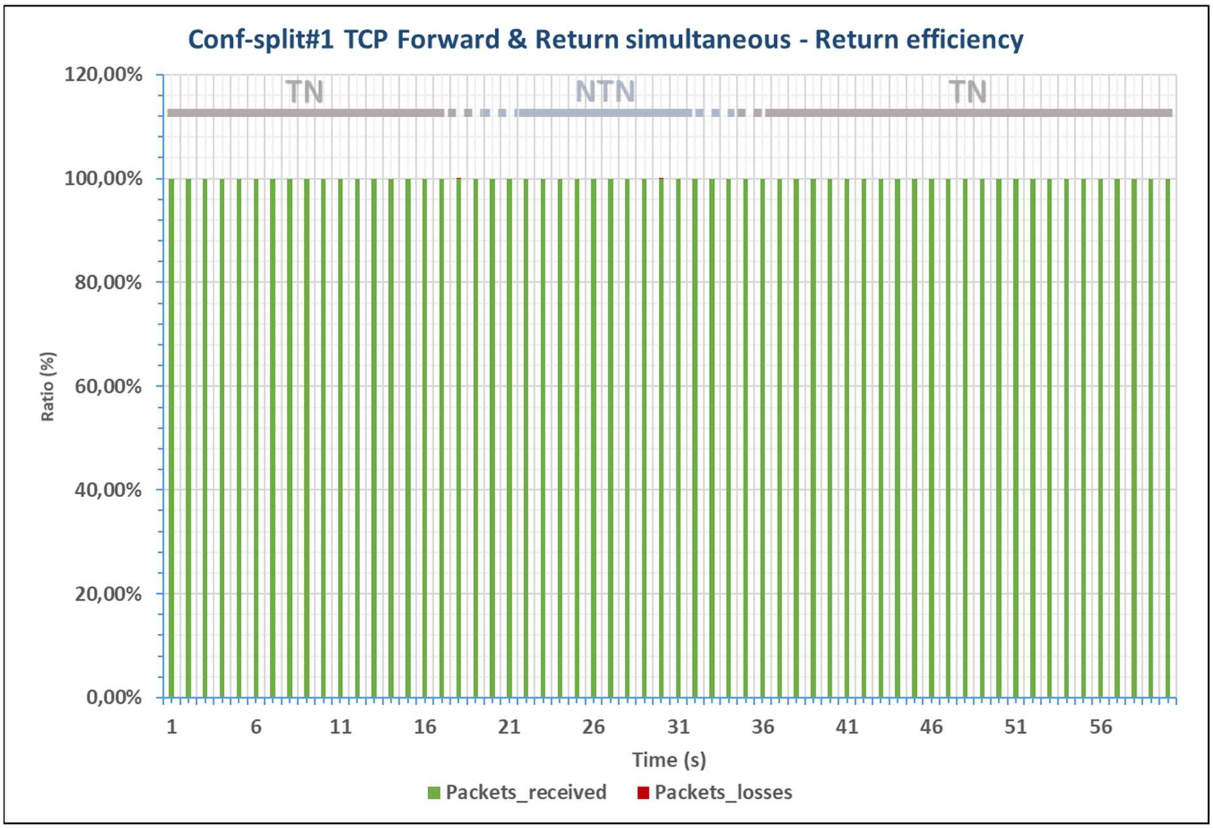


Figure 36: Conf-split#1 – TCP FW + RTN packets transfer measurement graphs

- Conf-split#2 – TCP FW + RTN link measurements:

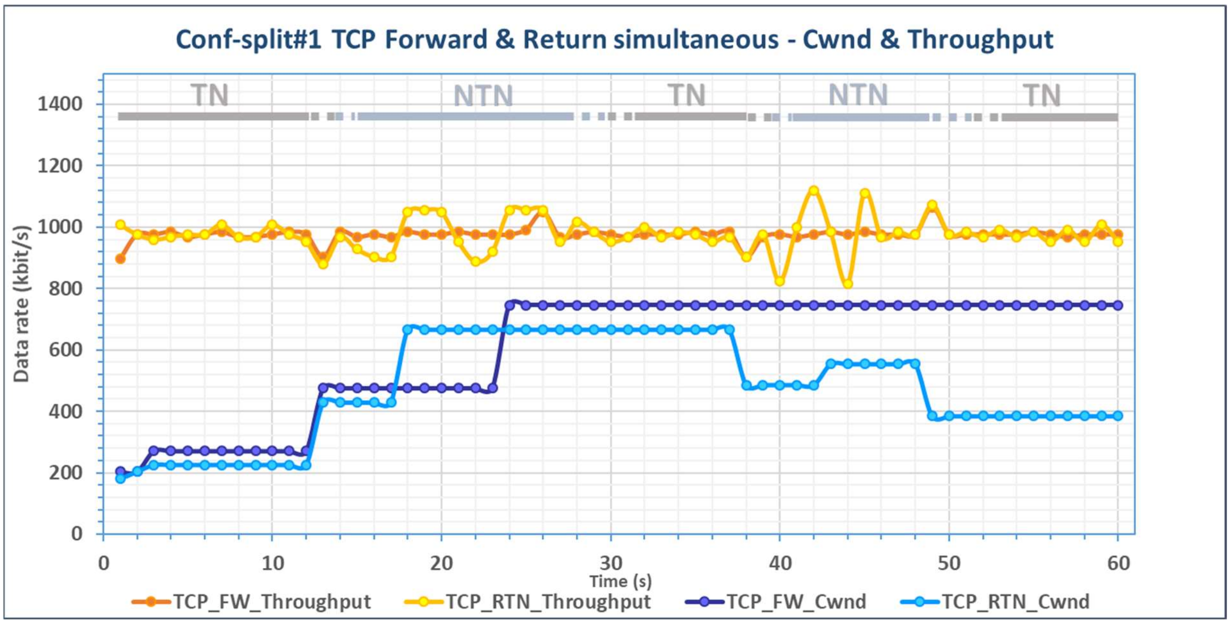
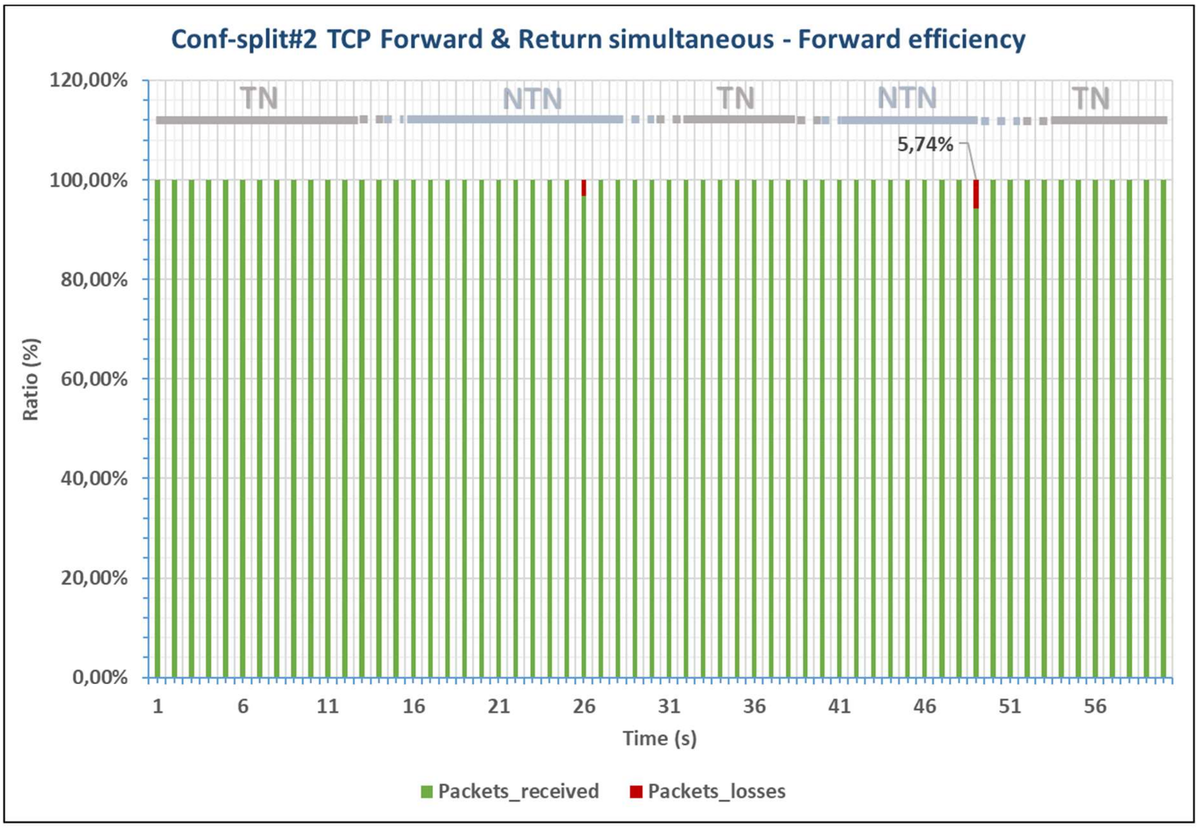


Figure 37: Conf-split#2 – TCP FW + RTN Cwnd & throughput data rate transfer measurement graphs



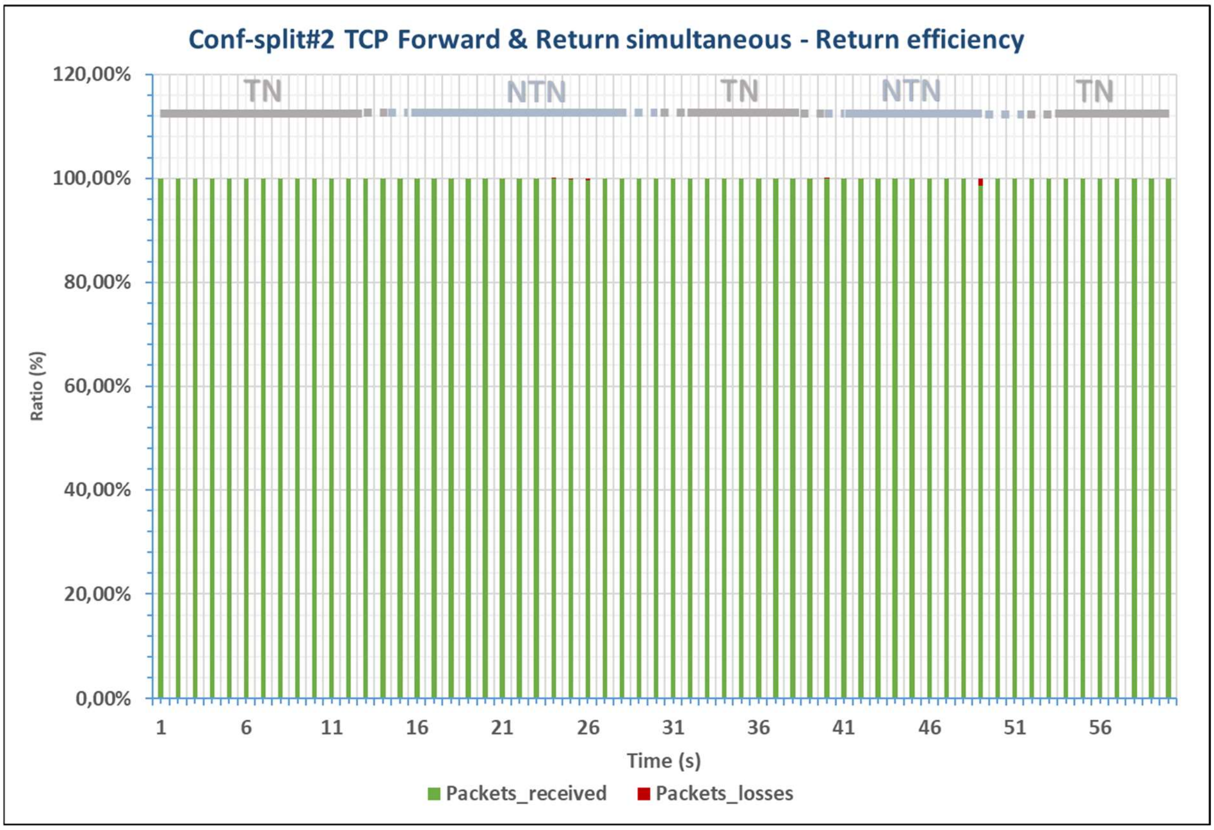


Figure 38: Conf-split#2 – TCP FW + RTN packets transfer measurement graphs

- Conf-split#3 – TCP FW + RTN link measurements:

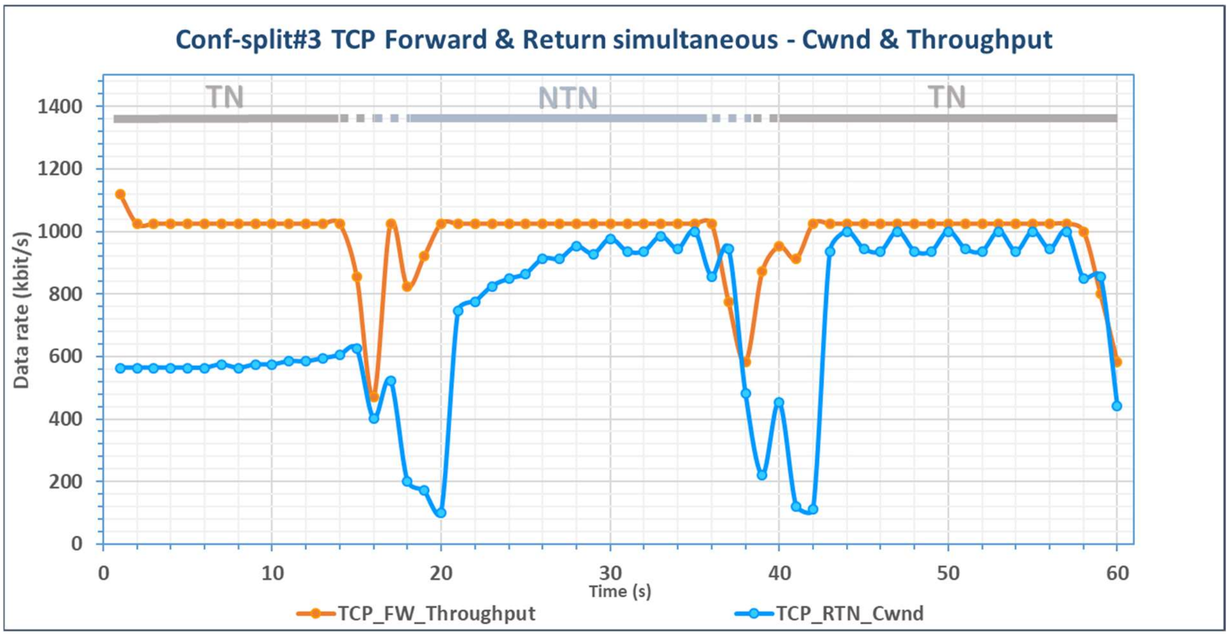


Figure 39: Conf-split#3 – TCP FW + RTN Cwnd & throughput data rate transfer measurement graphs

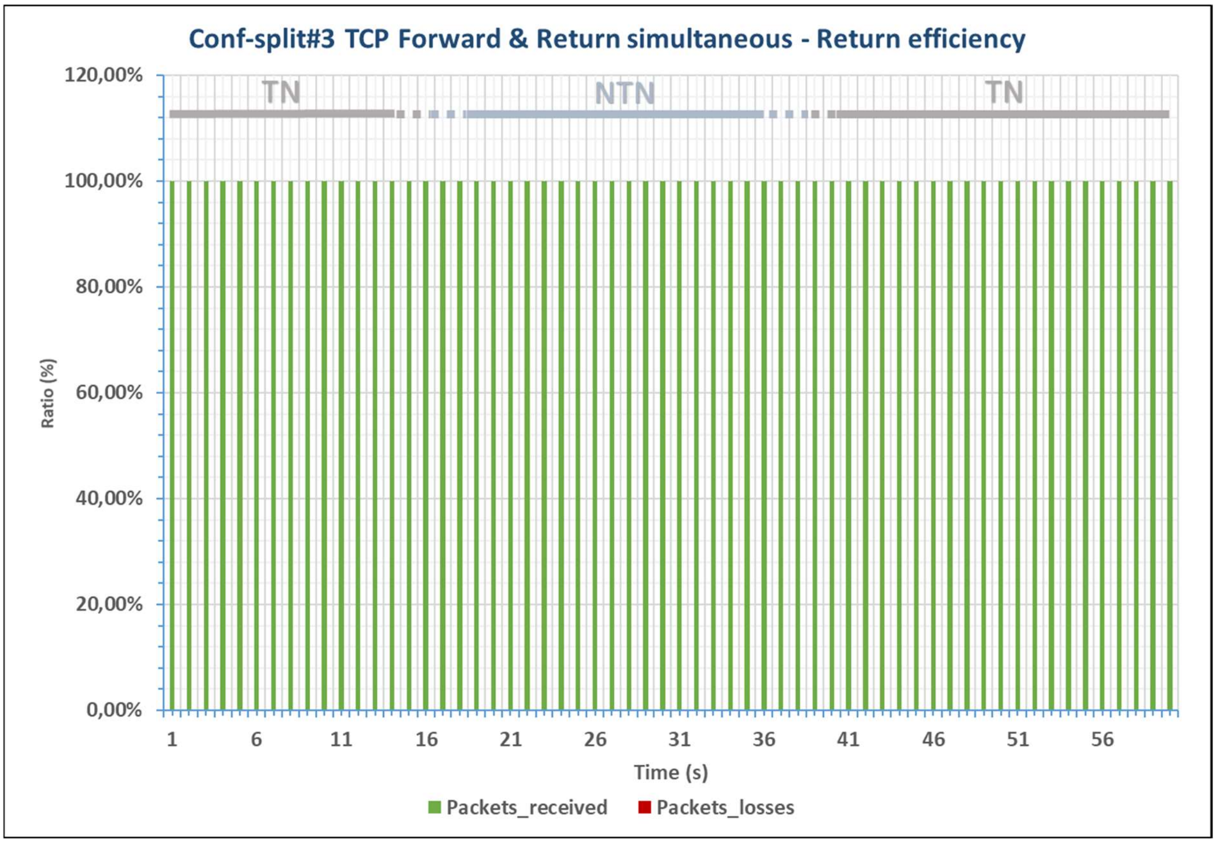


Figure 40: Conf-split#3 – TCP FW + RTN packets transfer measurement graph

A combination of simultaneous bidirectional TCP forward + return link flow provide some similar measurements to what was previously stated for unidirectional application cases, with still some relevant fluctuations observed for the return links, while the forward link (though still exhibiting important ripples) is more stable. This is once again in line with the results collected with the case of UDP.

- Test Case suite Performance Bi-directional UDP+TCP_#1:

    - Conf-split#1: UDP+TCP & FW+RTN link measurement:

Following graphs measurements are illustrating some data recorded of either UDP or TCP flow all running simultaneously on the PoC bench.

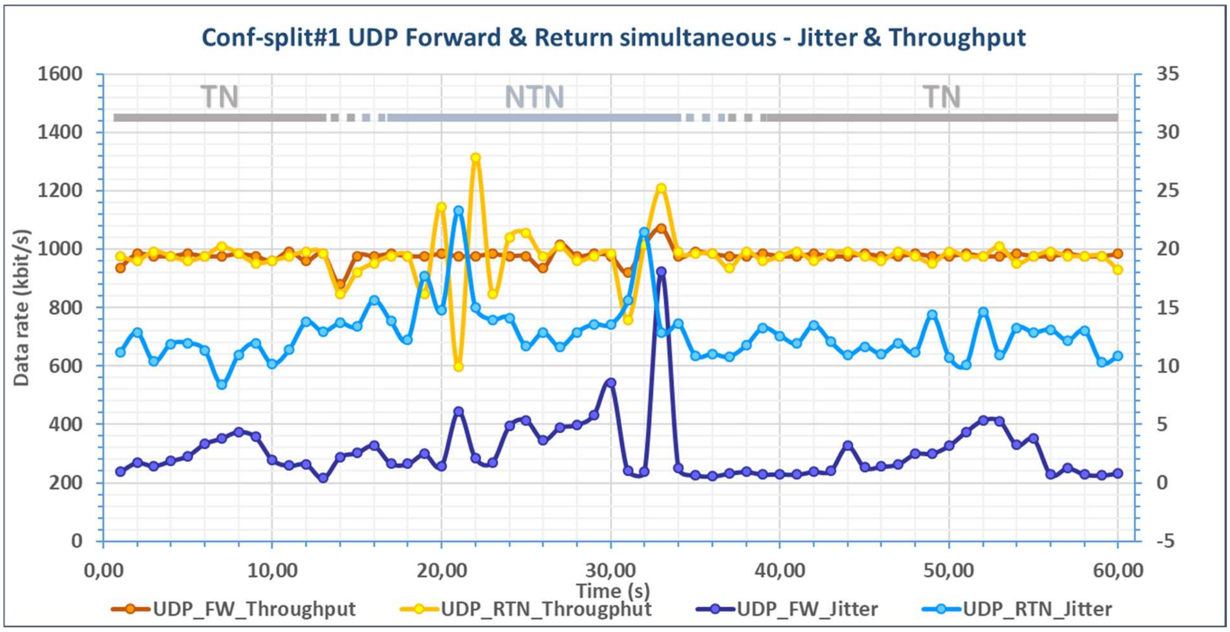
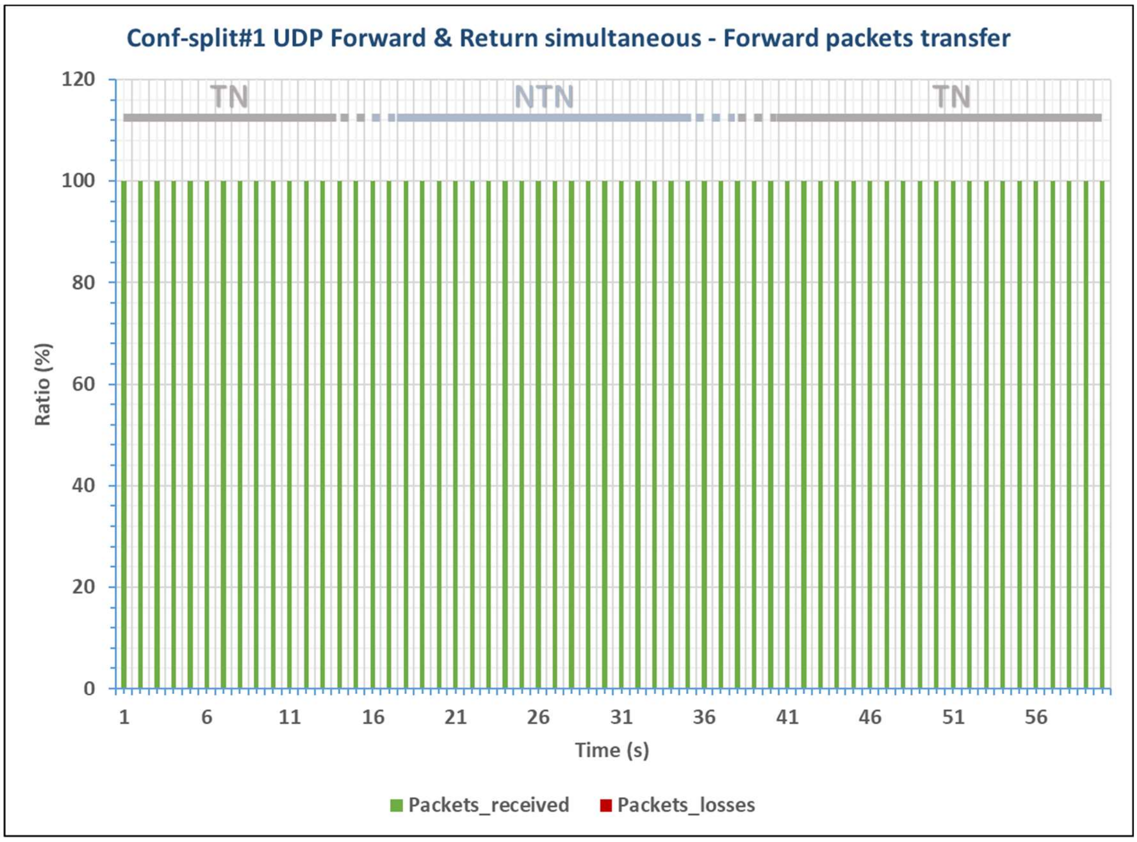


Figure 41: Conf-split#1 – UDP FW + RTN jitter & throughput data rate transfer measurement graphs (// TCP FW + RTN)



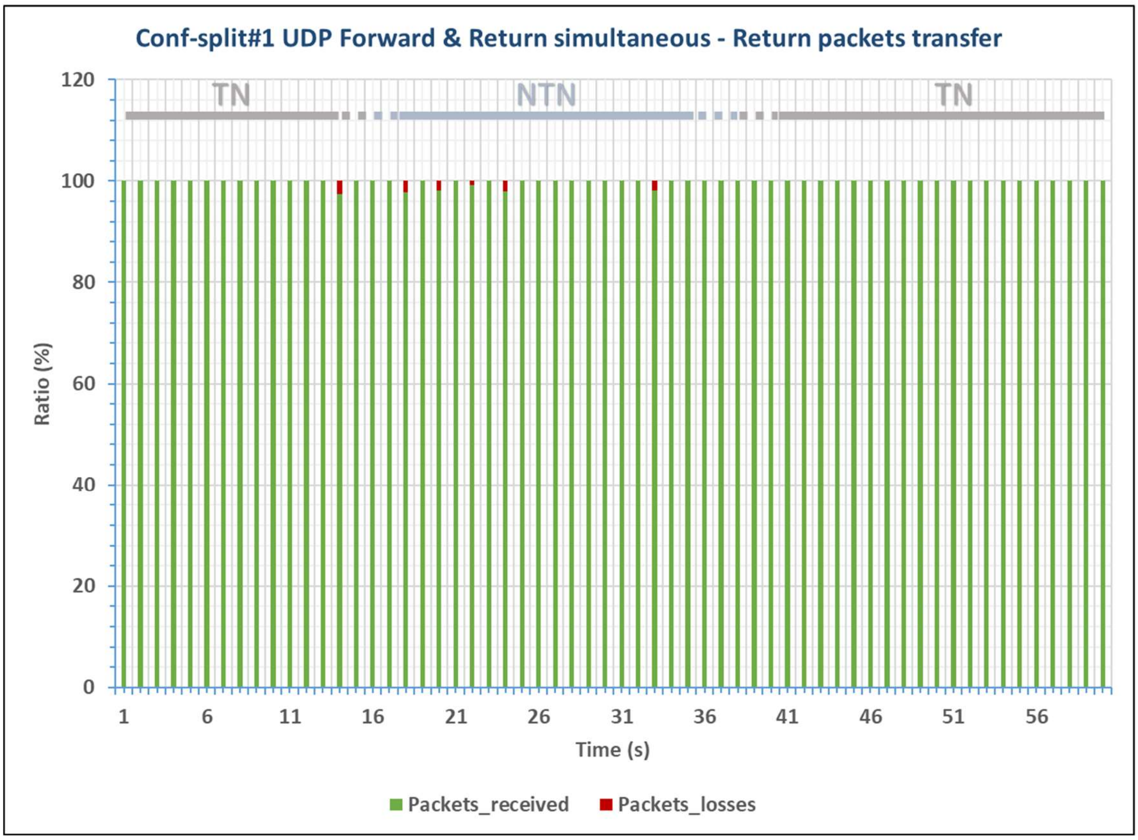


Figure 42: Conf-split#1 – UDP FW + RTN packets transfer measurement graphs (// TCP FW + RTN)

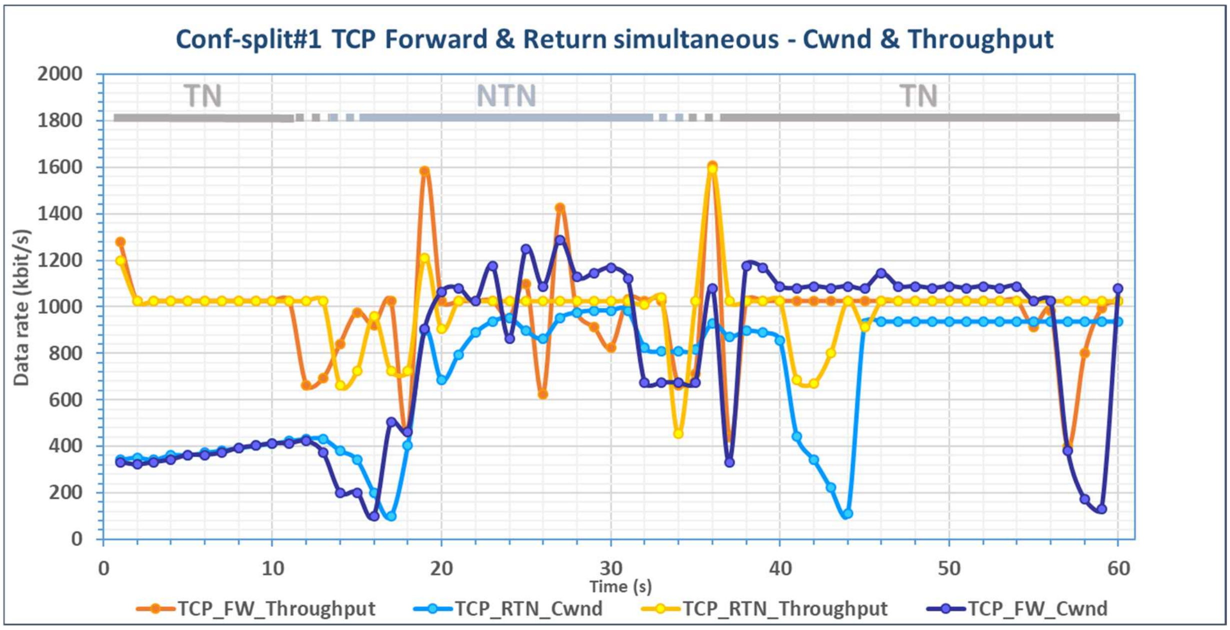
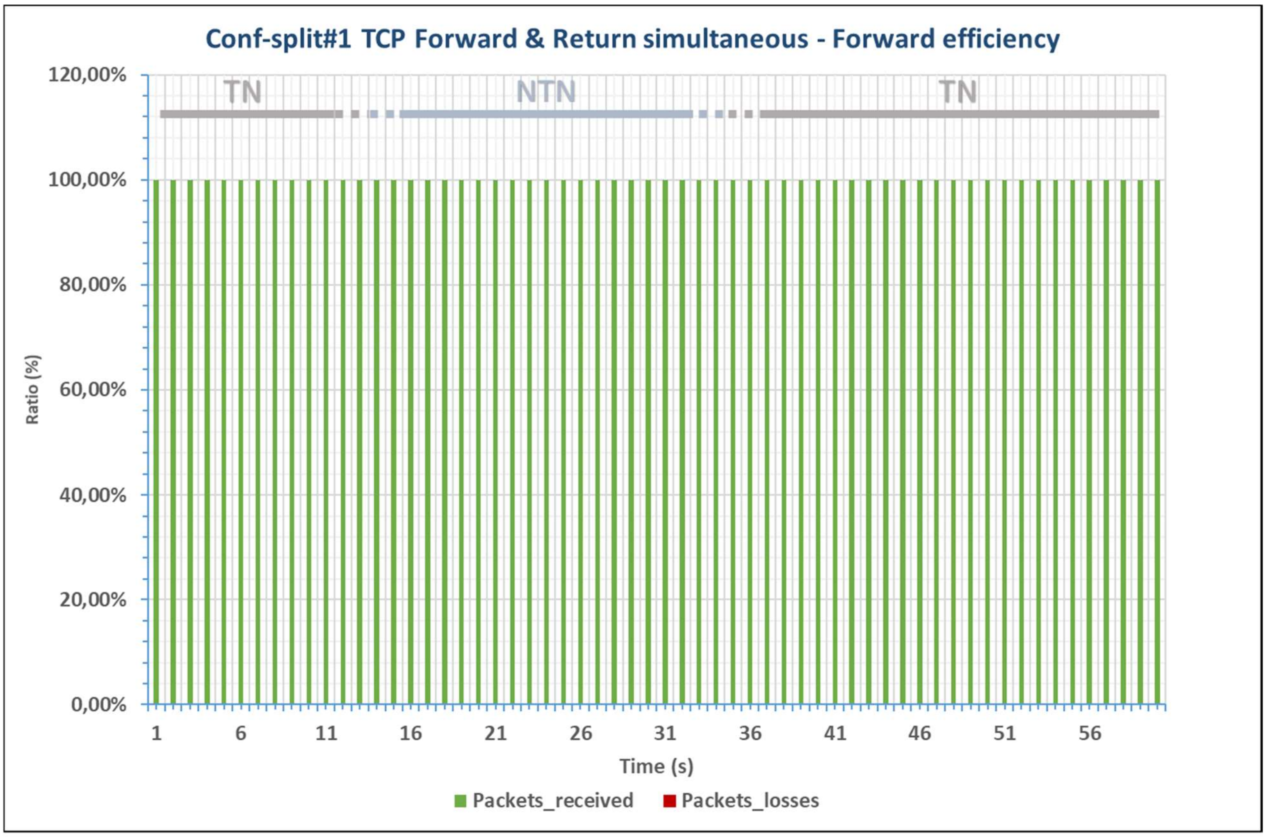


Figure 43: Conf-split#1 – TCP FW + RTN Cwnd & throughput data rate transfer measurement graphs ((// UDP FW + RTN)



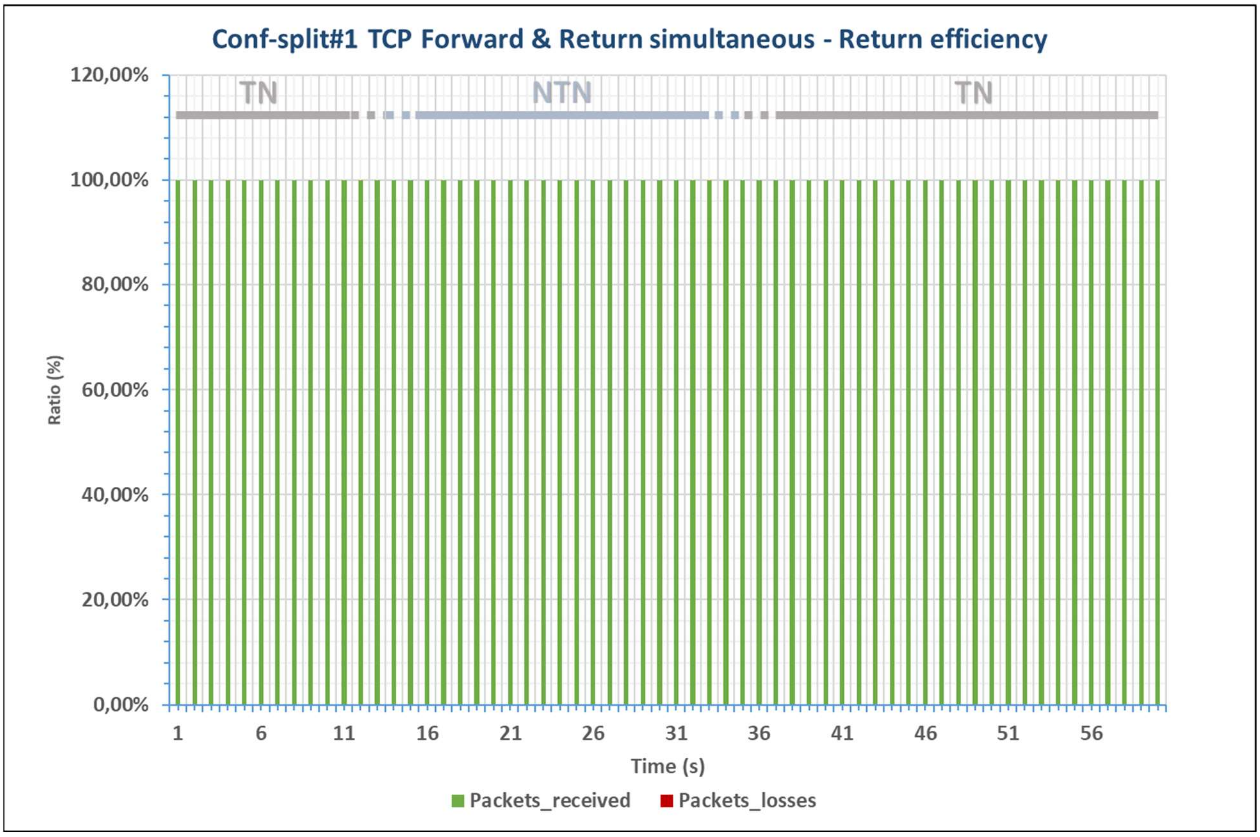


Figure 44: Conf-split#1 – TCP FW + RTN packets transfer measurement graphs (// UDP FW + RTN)

Conf-split#2: UDP+TCP & FW+RTN link measurement:

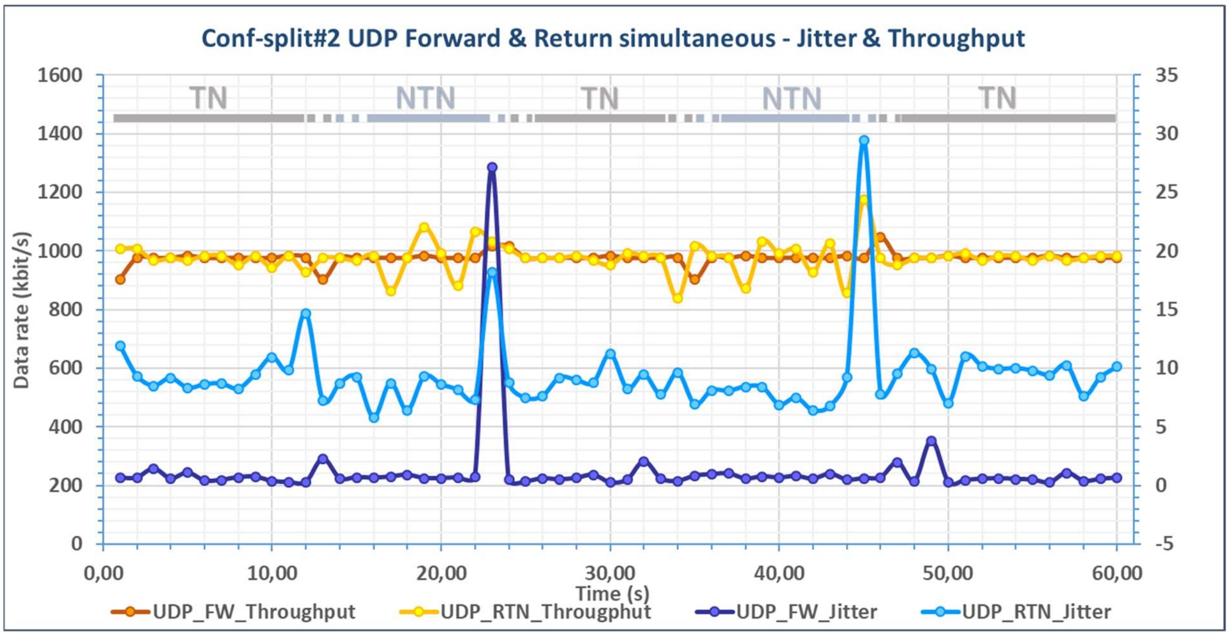
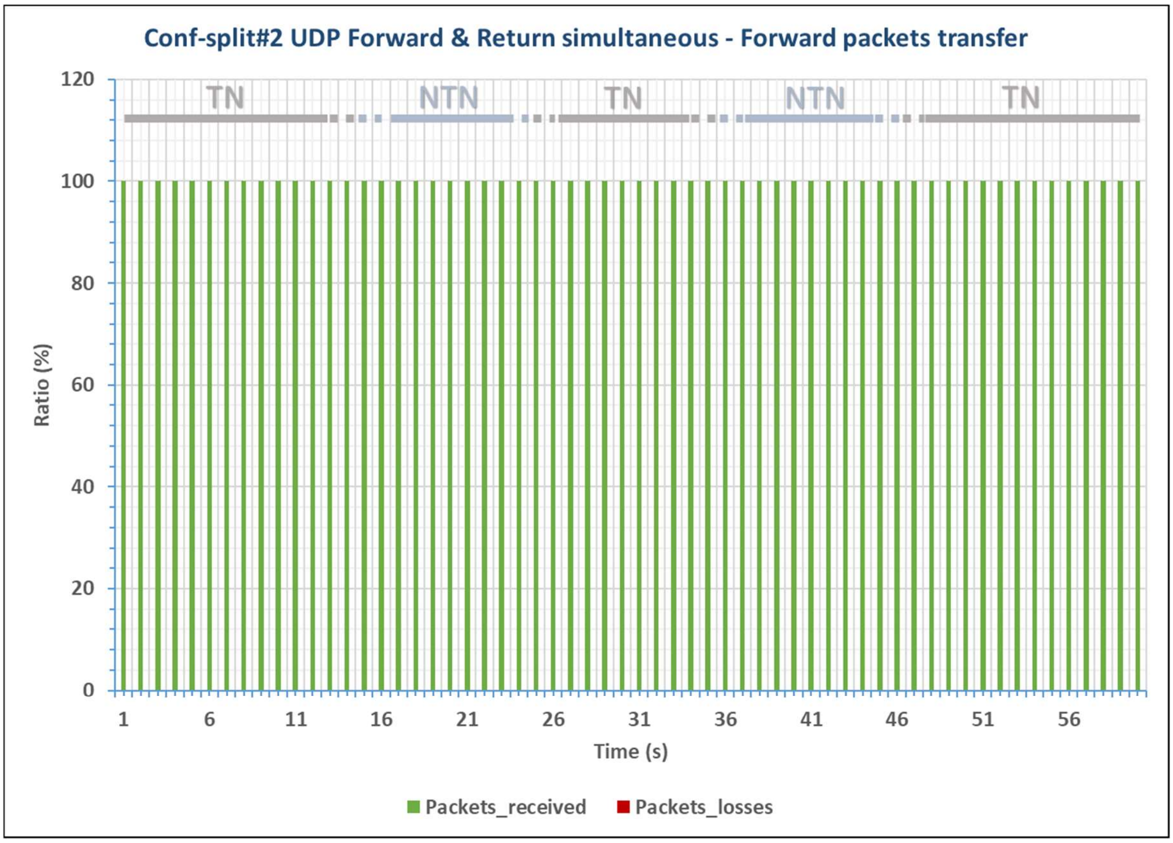


Figure 45: Conf-split#2 – UDP FW + RTN jitter & throughput data rate transfer measurement graphs (// TCP FW + RTN)



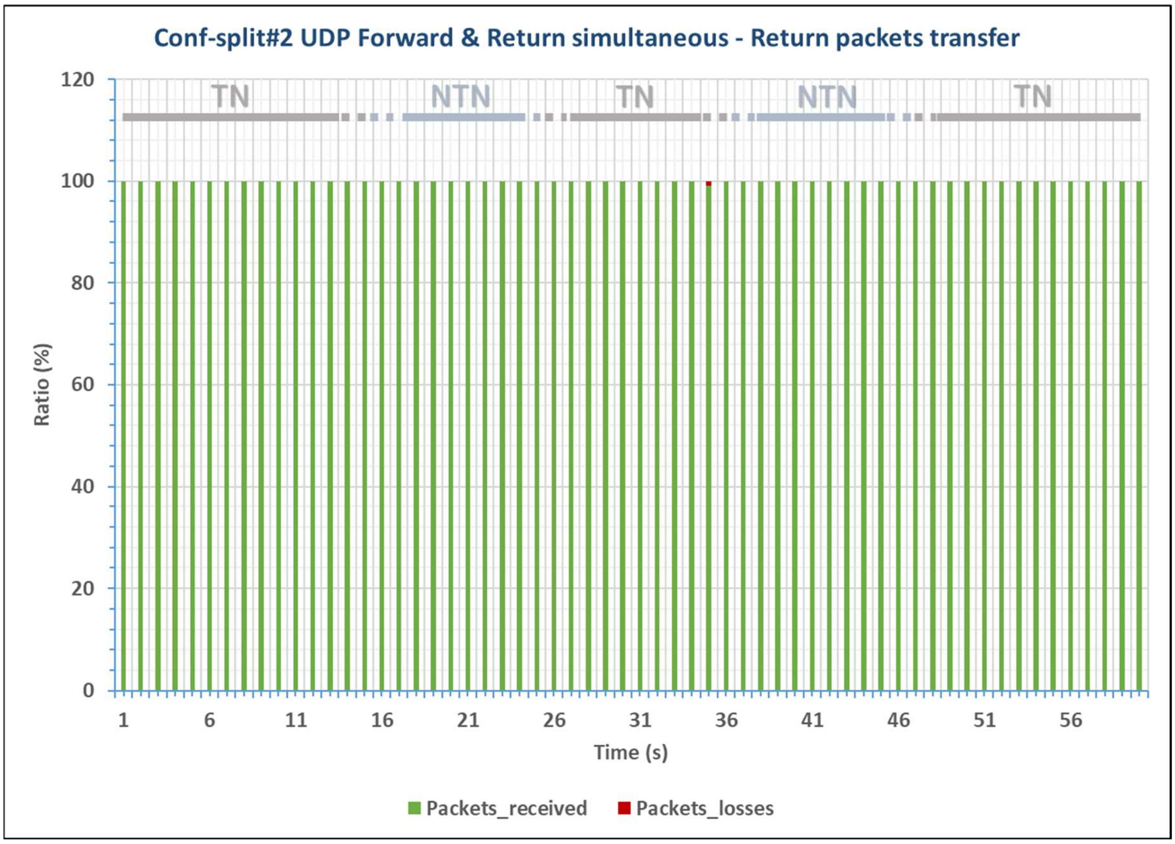


Figure 46: Conf-split#2 – UDP FW + RTN packets transfer measurement graphs (// TCP FW + RTN)

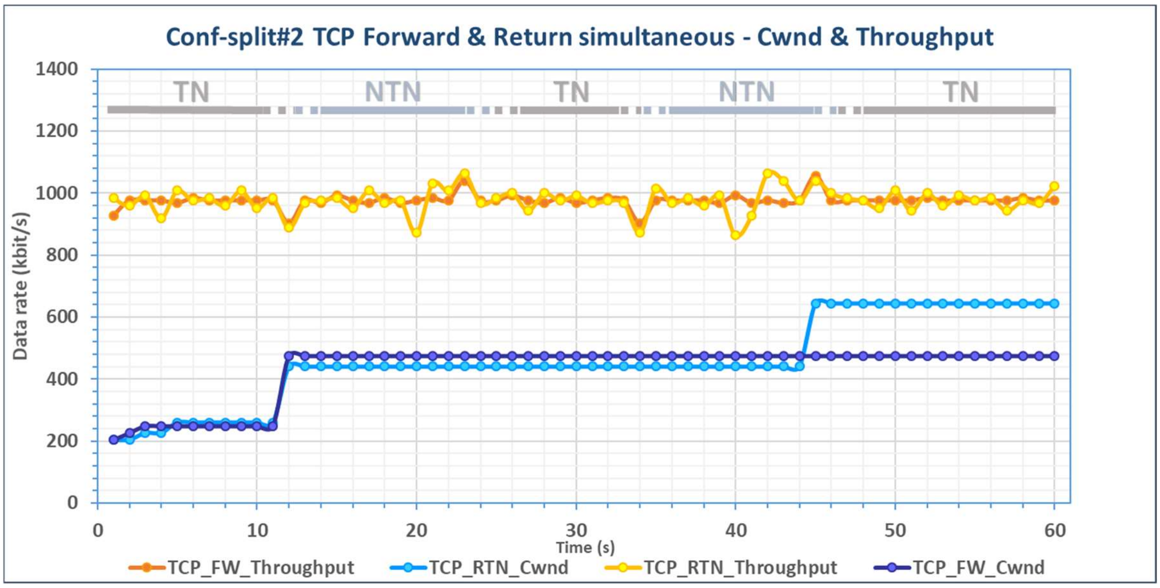
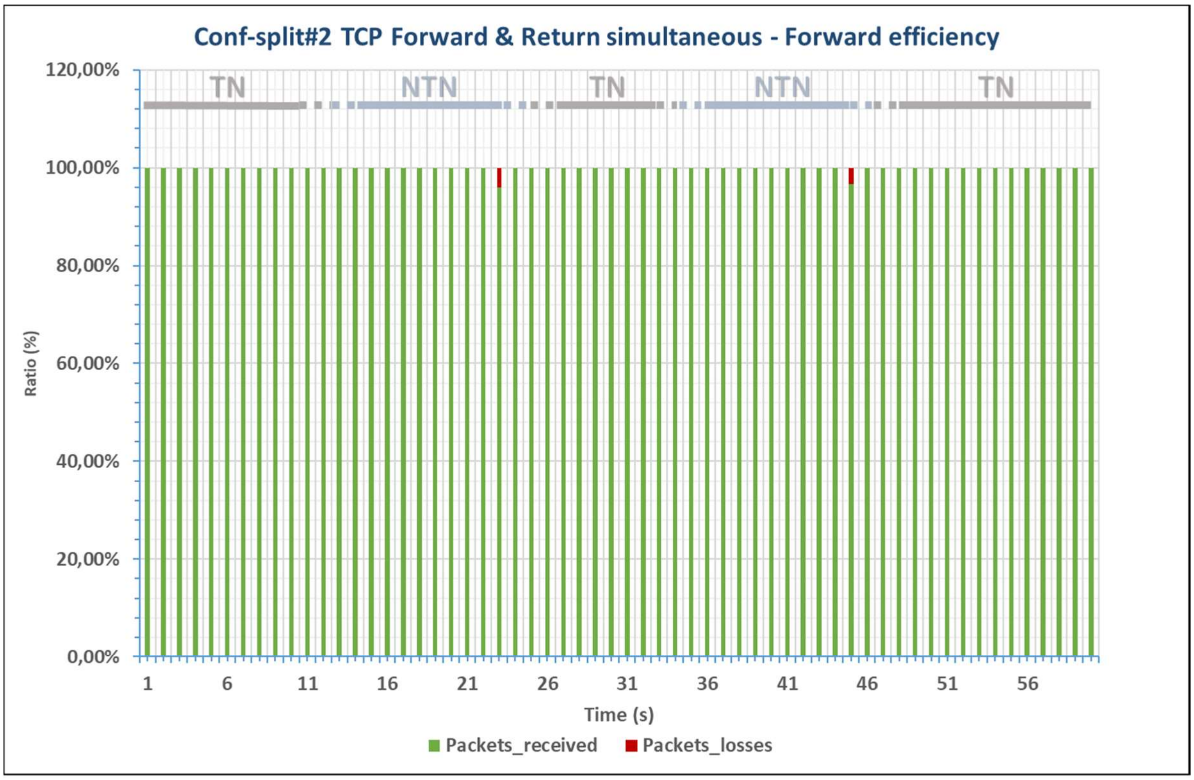


Figure 47: Conf-split#2 – TCP FW + RTN Cwnd & throughput data rate transfer measurement graphs ((// UDP FW + RTN)



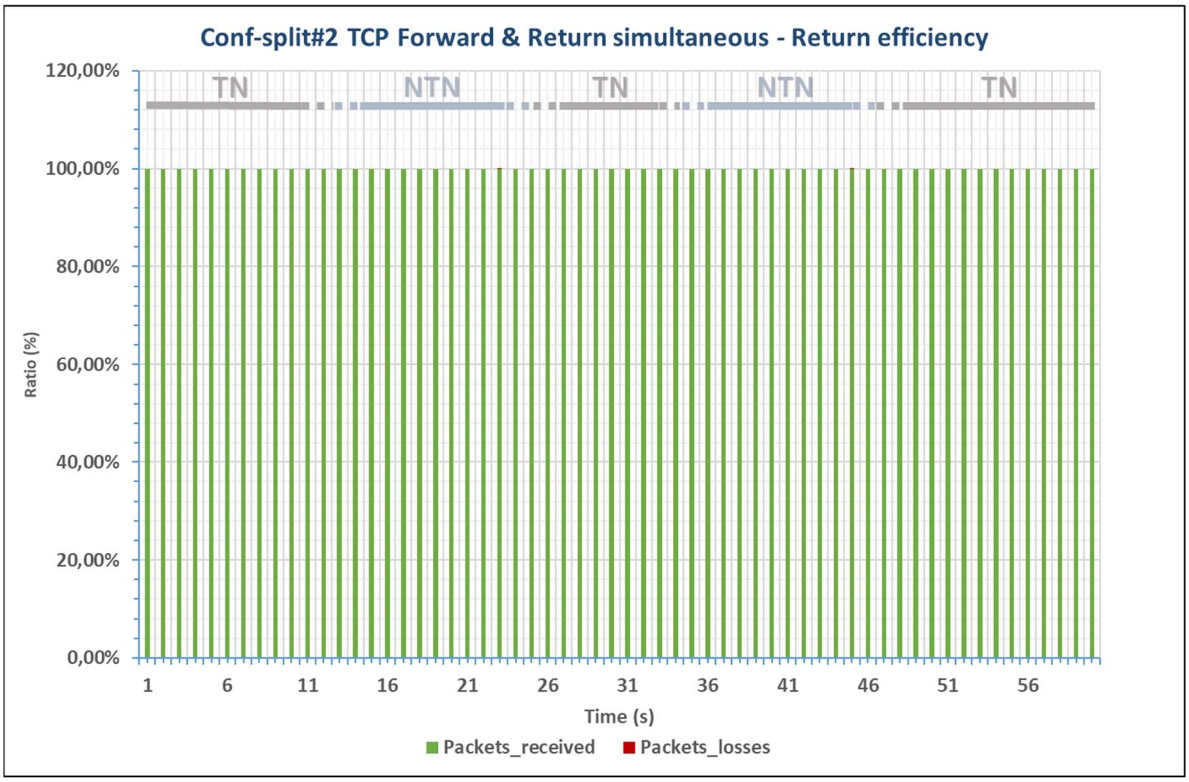


Figure 48: Conf-split#2 – TCP FW + RTN packets transfer measurement graphs (// UDP FW + RTN)

The full combination of simultaneous bidirectional UDP and TCP flow on forward + return link remain in consistency to what was already stated from previous tests cases, hence confirming the stability of the bench and more importantly the consistent behaviour of the considered system under different gNB configuration and traffic network conditions. This further confirmed the potential of such an analysed system and the appeal to extend further the scope of the demonstration beyond the 5G-STARDUST project lifetime.

5 MAIN LESSONS LEARNT AND FINAL RECOMMENDATIONS

5.1 SCENARIO #1 RESIDENTIAL BROADBAND

The global results from the test campaign has allowed to demonstrate quite good performances KPIs basis and especially about backhaul path switchover influence on traffic data link.

Although it can be considered that a throughput integrity is quite preserved during this phases there are differences to be noticed across the three different splits that could be also more precisely characterized by the complementary parameters measurements as respectively UDP - Jitter and TCP - Cwnd size.

Therefore less data rate and latency variation arise from split#1 and split#2 than for split#3 across the several testing performed. A potential explanation could come from a more important delay impairments sensitivity of UPF component when directly involved at on-board satellite payload. It would be however necessary to have further investigation as also at PoC bench level the related configuration simulation was implemented on two different dedicated Core Network and gNB machine servers.

Besides these remarks, a global PoC compliance can be then considered in the context of the residential broadband scenario and especially on an energy saving use case where some additional TN-NTN handover pre-defined mitigation at a global infrastructure level could also bring some performances optimization.

6 CONCLUSIONS

6.1 FINAL REMARKS

This test campaign outcomes conclude the PoC development with initial objectives coverage:

- 5G E2E connectivity by a unified radio interface with TN & NTN backhaul segment integration.
- Demonstration of an effective TN & NTN resources coexistence utilization.
- Characterisation of NTN network on-ground/board LEO payload functional disaggregation.

Despite missing high value feature such has multi-connectivity could not have been implemented mostly due to some timetable constraint it has provided some reliable functionalities bases that could be used for an assessment consolidation especially across by demonstrating some an end user experienced application (web browsing, VoIP, video streaming services, …).

The obtained results furthermore confirm the suitability of gNB-in-space implementation for achieving effective 5G connectivity across ground and space infrastructures. Last but not the least, the conducted analysis and the corresponding results presented in this document also confirm the high potential of the so-developed PoC towards future evaluations and extensions in the framework of 6G-NTN system developments, possibly part of follow-up projects.

6.2 POSSIBLE FUTURE POC EVOLUTION

Further PoC enhancement reflexion would be mainly driven by these following orientation:

- Operating: Dedicated interface aggregating all component management.
- Infrastructure: Implementation based on a material platform closer to real deployment.
- Features/capacities: Complete MP/MC integration, higher datarate/bandwidth capacities.
- Larger number of nodes, to show a more complete analysis as a function of data traffic and possibly mobility.
- Support of TN/NTN and NTN/NTN handover, towards a characterisation of a more complete system.
- Integration of network orchestration and slicing functions to optimally steer resource allocation and the consequent fulfilment of QoS/QoE demands at user level, in terms of the performance requirements at application level.
- Extension of the PoC, so as to feature multiple satellite and hence enable routing in space with the consequent performance analysis.

Co-funded by the European Union

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[1] D6.4: PoC design document

[2] D2.1: Scenarios, use cases and services.

[3] D3.2: End to end ground and space integrated architecture

[4] D4.6: Final report on AI-based radio resource management, RAN Softwarisation and onboard processing

[5] D6.1: PoC functional architecture document

[6] D6.2: PoC preliminary design document

[7] D6.5: PoC integration and validation test results

[8] D6.7: Results analysis & recommendation