SmartRAN Open Network Interoperability Centre (SONIC)

SONIC Phase #1 Final Project Report

17 December 2021

Index

1. Background

The government has published the Telecoms Diversification Strategy. Part of the strategy places an emphasis on OpenRAN technology and the potential for disaggregated RAN to be a game-changing technology in the diversification of the telecoms supply chain, driving inward investment and growth. The SONIC project complements this strategy: it supports delivery of its aims and demonstrates Government's commitment to diversification and innovation.

The SmartRAN Open Network Interoperability Centre (SONIC) was a joint programme between Digital Catapult and Ofcom for testing interoperability and integration of open networking solutions, starting with Open RAN.

SONIC demonstrated and fostered an open disaggregated network ecosystem in the UK, of large and small suppliers along with the telecoms industry, helping to develop a supply chain with multiple suppliers for each element in the technology stack. SONIC was live and operational from June 2021 and evolved over time to create a foundation for broader national testbed and laboratory initiatives.

The need to intervene and ensure that the ecosystem around OpenRAN develops in a way that is beneficial to the UK overall, addressing UK specific strategic issues and maximising the role of UK based organisations within it. The government and Regulator will gain a good and direct understanding of the technology readiness / maturity /challenges and roadmap and the interoperability/integration challenges, to inform their policies.

Following the Telecoms Supply Chain Review, and the NCSC advice on High Risk Vendors, there is now a startling concentration of supply of mobile telecommunications equipment in the UK, with only two acceptable vendors (Ericsson and Nokia) deployed in the nationwide mobile networks across the four operators. The new Telecoms Diversification Task Force, along with Ofcom and NCSC, have identified OpenRAN as a potential mitigation strategy, as it will lower the barrier to entry for new vendors, and has the potential to increase the number of suppliers.

There are OpenRAN commercial activities in the UK and commercial and public policy activities globally, but these will not focus on the UK public policy requirements for sustainable long term diversified set of suppliers, instead focusing on near term vendor swaps or promoting other nations public policies, and local suppliers.

In addition, this is an emerging technology and technological movement, and for it to achieve the aims promised, OpenRAN will require support from many organisations to encourage participation and lower the barriers to deployment, in the UK and globally.

1.1. Benefits

This programme was proposed to support the UK OpenRAN ecosystem critically to provide insight and understanding on the technology and maturity to Ofcom and the government. In addition, it also signalled to the market on the current direction of thinking and help to stimulate activity in the UK and globally, and encourage innovators, startups and investors to look at OpenRAN and telecoms in general.

SONIC-1, the initial deployment, was to enable a quick introduction and for Ofcom to learn by building along with Digital Catapult and their partners initial OpenRAN end to end systems. This is a critical moment as policies are being developed around the supply chain diversification, and knowledge at this stage will be very beneficial in supporting Ofcom's work in relation to supply chain diversity, resilience, and security. For example, having factual knowledge about the maturity and deployability of solutions, and numbers of options will help to evaluate realistic and achievable ambitions and targets.

1.2. Sonic-1 aim / objectives

SONIC-1 was the first deployment of the SONIC centre by the Digital Catapult in collaboration with Ofcom, in June 2021. It will be a commercially neutral and technology non-partisan OpenRAN 5G solution, to learn the issues and maturity of a multi-vendor disaggregated RAN solution, investigating the interdependencies of different vendors' OpenRAN technology building blocks.

The key objective of SONIC-1 is to build a real-world UK public multi-vendor OpenRAN open network facility on top of the existing Digital Catapult 5G testbed, followed by experimentation and sharing of results:

- Launch of the SONIC platform by May 2021
  - Three, separate disaggregated OpenRAN 5G mobile base stations
  - Including at least 2 different vendors for each building block
  - Enabling swapping of each building block
- Ofcom provided the opportunity to improve knowledge and insight into the technology
- The outputs are shared through events, talks and publications
- A target of [5] partners are identified for later phases in the SONIC programme

Post launch analysis and testing will identify the sufficiency of O-RAN Alliance interface implementations for open interoperability between vendors, the performance of the end to end system

1.3. Sonic-1 description of scope

The project was delivered through four work packages as below

1. Open RAN test bed build & commission
2. Experimental analysis validation & reporting
3. Engagement with external stakeholders & evolution of SONIC
4. Project Management, Communication & Dissemination

1.3.1.WP1 - Open RAN test bed build & commission

Building and commissioning a real-world indoor Open RAN test bed on top of Digital Catapult's 5G test bed. Including the requirements, architecture and design, procuring, integrating and installing disaggregated OpenRAN from multiple vendors. This work package was planned to be completed in May 2021.

Sub-tasks

- T1.1: Open RAN Test Bed System Requirements and Architectural Design.
- T1.2: Procurement of Open RAN Technology Building Blocks.
- T1.3: Open RAN Installation, Commissioning and Core Network Integration.

1.3.2.WP2 - Experimental analysis validation & reporting

Designing, conducting and documenting an experimentation campaign to verify and validate the sufficiency of Open RAN functions and interfaces to fulfil the mobile network operators' (MNOs) performance, operational, security and resilience requirements, benchmarking against monolithic RAN solutions. This work pack was planned to be carried out from May 2021 to October 2021.

Sub-tasks

- T2.1: Benchmark the Disaggregated Open RAN against monolithic RAN Offerings.,
- T2.2: Interoperability Testing and Validation.
- T2.3: Security and Resilience Testing of the Disaggregated RAN.

1.3.3.WP3 - Engagement with external stakeholders & evolution of SONIC

Engaging with external stakeholders to gain participation in SONIC-1 and build consensus, support, and participation in the overall SONIC programme. These include vendors, other governmental organisations, test beds, labs, standards development organisations, operators of public, private, and neutral host networks. Develop the business plan for the 5 year plus overall SONIC programme, including ecosystem landscape, investment, technology and use case areas, and overall business plan. This work pack was planned to be carried out throughout the project until October 2021

Sub-tasks

- T3.1: Engagement with External Stakeholders.
- T3.2: Evolution of SONIC, system requirements for permanent, reference and changing elements.

1.3.4.WP4 - Project Management, Communication & Dissemination.

Provide an administrative and technical management service to the project, and to communicate and disseminate the project results into international research and industry forums in order to pave the way for successful exploitation, and lead into the full SONIC programme. This includes preparing the Benefits Realisation template for the SONIC-1 project and updating the achievements as the project progresses.
This work pack will be carried out throughout the project until October 2021, with a launch event in May 2021.
Sub-tasks

- T4.1: Project Administrative, Financial, Legal and Technical Management.
- T4.2: Communication and Dissemination.
- T4.3: OpenRAN Benefits Realisation template for SONIC1.

1.4. Sonic-1 overall milestones & deliverables of the project

MS Ref	Milestone Due Date	Milestone Name	Deliverable Name, Description and Evidence
MS1.1	31/12/2020	Procurement of first Open RAN deployment (part 1 of 2)	Completed commercial agreements for first Open RAN deployment This will be evidenced by providing to DCMS the POs from the vendors for the first Open RAN deployment - "chain #1" of 3.
MS2.1	31/01/2021	Set-up of SONIC Project, including internal and external communication channels	**Deliverable D4.1** Set-up of Project, including Internal and External and communication channels. Setting up the Project, including Project Management structure; procedures; document storage; project plan and timeline; secure resources; reporting; project meeting schedules; project review meetings; completing Digital Catapult internal project gateways; monitoring project milestones and deliverables; monitoring of risks, including corrective measures. This will be evidenced by the content of the Project Initiation Document, including the project plan, risks, as well as the slides from the Project Kick Off.

MS2.2	28/02/2021	SONIC outline of overall Business Plan	**Deliverable D3.1** SONIC Outline of overall Business Plan Complete a draft business plan for the evolution of SONIC beyond SONIC-1. To be evidenced by a document shared to DCMS, including initial versions of the strategic case, commercial case and management case for the 5-year SONIC facility.
MS2.3	31/03/2021	Procurement of Open RAN MVP extensions (part 2)	Completed commercial agreements for all Open RAN deployments, and auxiliary equipment This will be evidenced by providing to DCMS the POs from all of the vendors for the Open RAN deployments - "chains #1, #2 and #3, as well as the auxiliary equipment from the framework suppliers.
MS2.4	31/03/2021	Prepare an OpenRAN Benefits Realisation template for SONIC1, with draft input	**Deliverable D4.4** Prepare the OpenRAN benefits realisation template for SONIC1, with draft input Creating the Benefits Realisation template for the SONIC1 project. The Benefits Realisation Template used as part of the 5G Programmes within the DCMS 5G Testbed and Trials work will be used as a starting point, updated to be specific to Open RAN, and the scope of SONIC1. This will be evidenced by providing to DCMS an agreed version of the Benefits Realisation template for SONIC-1.
MS3.1	30/05/2021	SONIC Phase #1 Commissioning & Launch	**Deliverable D1.1** Open RAN Installation, Commissioning and Core Network Integration Report. This will be evidenced by a report provided to DCMS covering: ● System requirements (both technical and non-technical) for the Open RAN test bed. ● Design of the Open RAN test bed system architecture including network functions and interfaces. ● Outline of vendors and products selected for the OpenRAN testbed, system integrators, and test and measurement ● Summary of the high-level design, low level design, and installed network including limitations and lessons learned.
			Deliverable D4.2 SONIC Phase #1 Launch Event. Carrying out a professionally run public event, with engaging content and speakers, online or at Digital Catapult Office depending on safety. It will introduce the

			Open RAN testbed, describe the technology and opportunities and lessons learned as well as the future plans for the SONIC facility. Evidenced by the completion of the event, to be attended by DCMS.
MS3.2	30/06/2021	Finalise the OpenRAN Benefits Realisation template for SONIC1	**Deliverable D4.5** Finalise the OpenRAN Benefits Realisation template for SONIC1 Creating a draft view of the achievements of the SONIC1 project within the agreed template. This will be evidenced by providing to DCMS a draft completed Benefits Realisation template for SONIC-1.
MS3.3	30/06/2021	SONIC Complete Business Plan and proposal for evolution	**Deliverable D3.2** SONIC Complete Business Plan and proposal for evolution Update of the outline in D3.1, to complete a final business plan for the evolution of SONIC beyond SONIC-1, in the format and to the level of detail required by DCMS. To be evidenced by a document shared to DCMS, including the strategic case, commercial case and management case for the 5-year SONIC facility, suitable for approval and investment.
MS4.1	30/8/2021	SONIC Phase #1 Experimentation & Exploitation	**Deliverable D2.1** Open RAN Benchmarking, Interoperability, Security and Resilience Interim update. This will be evidenced by a report provided to DCMS covering: ● The test plan covering the points in Deliverable D2.2 ● with interim or partial results ● outline of outstanding experiments and testing required ● (Note, this may fairly raw results with limited explanation)

MS4.2	30/10/2021	SONIC Phase #1 Experimentation & Exploitation	**Deliverable D2.2** Open RAN Benchmarking, Interoperability, Security and Resilience Testing Report. This will be evidenced by a report provided to DCMS covering: ● ease of integrating Open RAN components from different vendors ● interoperability of Open RAN components from different vendors, i.e. the ability to switch between (at least two), and functionality ● the interdependencies of Open RAN technology building blocks, and sufficiency of interface definitions ● benchmarking of Open RAN with monolithic RAN products ● Implications of potential resilience and security vulnerabilities associated with new interfaces introduced by the Open RAN architecture
			Deliverable D3.3 SONIC Phase #1 Engagement Report This will be evidenced by a report provided to DCMS covering: ● Summary of the dissemination and communication carried out by the SONIC-1 project, including events, articles and reports ● Engagement and alignment with non-commercial UK Open RAN activities such as the UK Telecoms Centre ● Summary of engagement with Open RAN vendors with potential interest ● Alignment with commercial activities in the UK, such as mobile operators and neutral host and private networking companies ● Engagement with and participate in industrial forums, e.g., the Open RAN initiative within the Telecom Infra Project (TIP) ● Engagement with other such as industrial businesses, or international Standards Development Organisations (SDOs) related to Open RAN

			Deliverable D4.3 SONIC Phase #1 Final Project Report. This will be evidenced by a report summarising the entire project provided to DCMS covering: ● Summary of the Project overall as outlines in the Project Initiation Document and the achievements against the milestones and deliverables, and lessons learned with the following reports included as annexes: ● Open RAN Installation, Commissioning and Core Network Integration Report (Deliverables D1.1) ● Open RAN Benchmarking, Interoperability, Security and Resilience Testing Report (Deliverable D2.1) ● SONIC Phase #1 Engagement Report (Deliverable D3.3) ● Update the OpenRAN Benefits Realisation template for SONIC1 (Deliverable D4.6)
			Deliverable D4.6 Update the OpenRAN Benefits Realisation template for SONIC1 A final version of the completed Open RAN SONIC1 Benefits Realisation template at the end of the project, including the results of the SONIC1. This will be evidenced by providing to DCMS a final agreed and approved Benefits Realisation template for SONIC-1.

Table 1: Sonic-1 overall milestones & deliverables

2. Summary of Progress against Objective

Sonic1 is an initial yearlong project started in November-20 and was delivered through 4 work packages listed below.

1. Open RAN test bed build & commission
2. Experimental analysis validation & reporting
3. Engagement with external stakeholders & evolution of SONIC
4. Project Management, Communication & Dissemination

2.1. WP1- Open RAN testbed build & commission

The project team carried out requirements gathering, designed, procured, integrated and installed disaggregated OpenRAN from multiple vendors. SONIC-1's initial installation and integration developed in the first seven-month period of the project and completed in June-2. This phase focused on the Open RAN element only, reusing the existing 5G and future network test bed, including reusing the common infrastructure, 5G core, management, and orchestration systems from the Digital Catapult 5G Testbed. This is a static deployment, with the vendors and architecture designed at the outset, implemented, and then used. The commissioning of the initial build was completed in June 2021, and the facility was launched with an event showcasing the use of ORAN facilities with end-to-end 5G applications.

The SONIC-1 deployment is made up of three baseline [Reference OpenRAN Chains] Open RAN multi-vendor distributed 5G base stations, with Radio Unit (RU), Distributed Unit (DU), Central Unit (CU), and RIC - RAN Intelligent Controller from different vendors; and two 5G standalone (5G-SA) core networks [*Figure 1*]. The 3 Baseline configuration chains (including the vendors) are depicted in Figure 1. Configurations 1 to 3 are hosted by Digital Catapult, whilst only Configurations 2 and 3 will be hosted by Ofcom with their cores hosted at the Digital Catapult, making a total of 5 deployed OpenRAN chains in this first phase of the SONIC Labs.

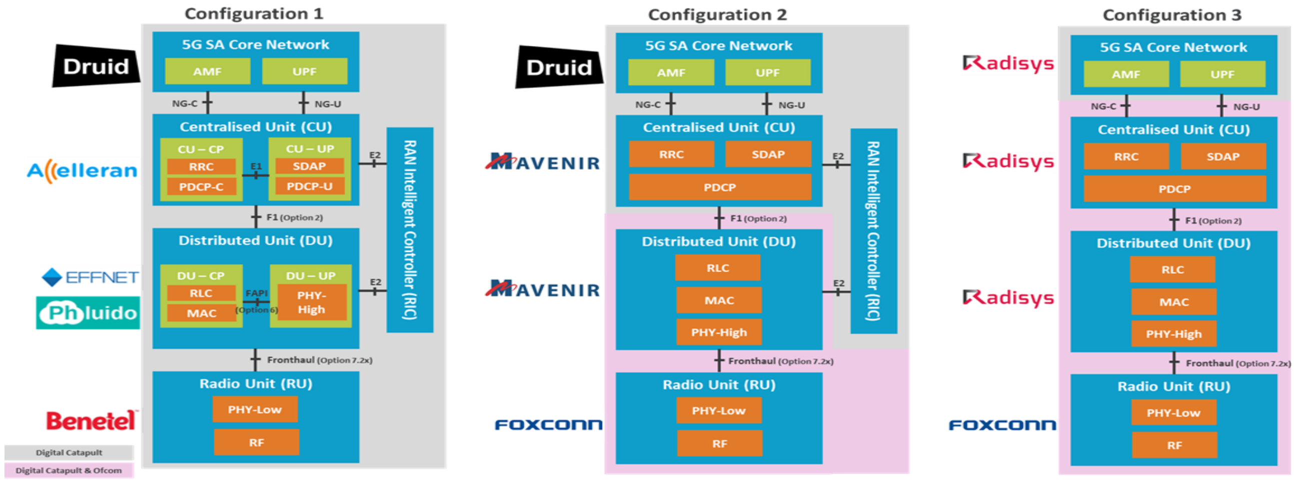

Figure 1 SONIC Labs configuration chains

The deployment is geographically distributed across three sites, namely: Digital Catapult (London), Digital Catapult (Brighton - Fusebox) and OFCOM Riverside House (London) [*Figure 2 (b)*]. The initial deployment was supported by eight different vendors [*Figure 1(a)*], namely: Mavenir, Radisys, Accelleran, Benetel, Foxconn, Phluido, Effnet and Druid. The findings from this work package serve as a foundation for further work in WP2 responsible for experimental analysis, validation, and reporting; as well as WP3 responsible for Engagement with external stakeholders and the evolution of SONIC Labs.

(a)

(b)

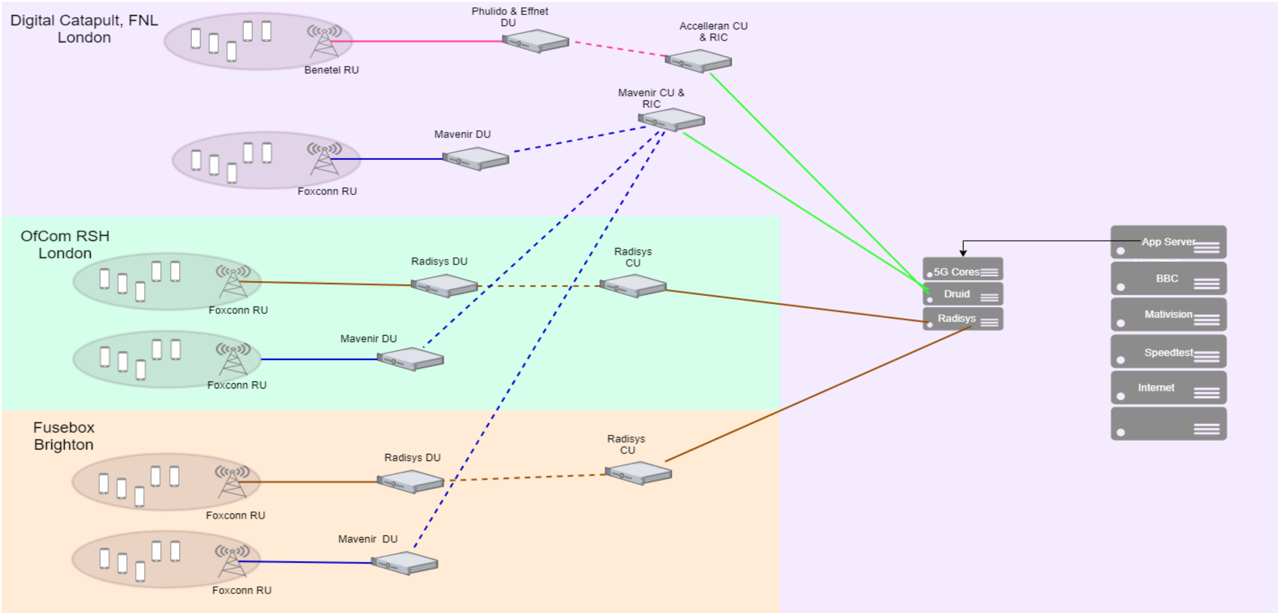

FIGURE 2 SONIC VENDORS AND OVERALL SONIC LABS HIGH LEVEL DEPLOYMENT & ARCHITECTURE: (A) LAUNCH VENDORS; (B) HIGH-LEVEL DEPLOYMENT ARCHITECTURE

Deliverable ***"D1.1 - Open RAN Installation, Commissioning and Core Network Integration Report"*** covers in detail about system requirements and overall architecture, description of the constituent components of the three baseline Open RAN chains [Accelleran, Mavenir and Radisys] and lesson learned

In addition to this it was identified the need of Test and Measurement (T&M) equipment's to comprehensive testing of the Interoperability/Integration testing, conformance testing, end to end performance/benchmark testing or wrap around testing keeping the Open RAN system as the system under test. However, in the initial stages of SONIC Labs, the focus of testing will be around interoperability and end to end benchmark testing of the Open RAN system(s). consequently, the Test & Measurement (T&M) equipment's requirement was highlighted. Procuring specialised Test & Measurement (T&M) Equipment for SONIC phase 1 was outside the scope originally. Having T&M equipment's can ensure better benefit realisation of the project and as significant savings made in procuring various Open RAN and core network components, a change request [CR3] was then raised with DCMS to allow the usage of leftover funds towards procuring T&M equipment's and eventually was agreed.

2.2. WP2 - Experimental analysis validation & reporting.

This work pack was led by OFCOM with the support of DC. Aim hear was to design, conduct and document an experimentation campaign to verify and validate the sufficiency of Open RAN functions and interfaces to fulfil the mobile network operators' (MNOs) performance, operational, security and resilience requirements. This work package had 2 deliverables *"**D2.1 - Open RAN Benchmarking, Interoperability, Security and Resilience Testing Interim Report**"* and *"**D2.2 - Open RAN Benchmarking, Interoperability, Security and Resilience Testing Final Report**"*. D2.2 being and extension of D2.1

D2.1 completed in August-2021 and D2.2 was completed in December-2021; this deliverable describes the work done in the period July-November 2021 to: (i) benchmark the 3 integrated Open RAN chains completed by 15th June 2021; (ii) investigate suitability and possibility of swapability of components; and (iii) validate the methodology for interoperability and swapability testing across the new chains.

The three reference Open RAN chains [Figure 1 SONIC Labs configuration chains] were integrated and demonstrated on time for the SONIC Labs launch event on 15th June 2021. Further work was done to test the stability of these chains and prepare them for cross-vendor swapability testing in the period July-September 2021. Multiple software (Open RAN components) and hardware (RU and compute infrastructure) swapability test cases of Open RAN vendor-diverse chains were identified to undergo integration, interoperability, End-to-End (E2E) performance and reliability tests. This is a comprehensive set of test cases for SONIC, some of which, based on our hands-on experience and the learned lessons in SONIC integration work so far (Section 3.9). Some of these tests were attempted in Phase 1; however, the listed swapability test cases are intended to provide the test framework for SONIC Labs as it continues beyond the current Phase 1.

The testing involved 3 stages:

1) Integration tests to ensure Open RAN components (e.g., 5G Core, CU, DU, RU etc) are operational and capable of establishing PDU sessions.
2) E2E peak performance testing under excellent radio conditions to ensure fairness and repeatability at this stage of the project.
3) E2E reliability tests run over 24 hours to assess the consistency of the Key Performance Indicators (KPIs) and service availability. Cutting edge test and measurement equipment were identified & procured.

This work package introduces SONIC Labs, discusses SONIC Labs build activities and combines key finding and the lessons learned from Ofcom and Digital Catapult sites, focuses on additional piece of work taken in evaluating the initial set of test and measurement tools required to carry out various tests within SONIC Labs and details the exhaustive list of various swapability, interoperability, E2E performance and reliability test which will also form basis for test that will be carried in SONIC Labs phase 2, reports the KPIs, test results and lessons learned from the swapability and performance test for the chains deployed and provides overall lessons learned in SONIC Labs phase 1.

2.3. Engagement with external stakeholders & evolution of SONIC

This work package was led by DC and the objective of this work package was to engage with external stakeholders to gain participation in SONIC-1 and build consensus, support, and participation in the overall SONIC programme. We carried out a series of engagement activities with vendors, governmental organisations, test beds, labs, standards development organisations, operators of public, private, and neutral host networks.

This work package has 3 deliverables "***D3.1 SONIC Outline Of Overall Business Plan***" Delivered on 26th Feb-21, "***D3.2 SONIC Outline Of Overall Business Plan***" Delivered on 30th Jun-21 and "***D3.3 Sonic Phase 1 Engagement report***" Delivered on 13th Dec-21.

D3.1 aimed at developing the business plan for the 5 year plus overall SONIC programme, including ecosystem landscape, investment, technology and use case areas, and overall business plan. **D3.2** is an extension of **D3.1** and built on the initial business plan. D3.2 as agreed with DCMS took a different approach to complete this deliverable due to the clash between the Sonic Labs launch and DCMS business case submission. We provide a series of documents as requested by DCMS for their business case to government, the main ones being a new cost model, an outline of the strategic objectives and milestones and some timelines. **D3.3** outlines the engagement activities carried out through the project SONIC-1, the stakeholders engaged with during the project, as well as the insights and learnings from those engagements.

2.4. Project Management, Communication & Dissemination

This work package provided project administrative, financial, legal, technical management, communication and dissemination. Also established OpenRAN Benefits Realisation template for SONIC1.

This work package had 6 deliverables listed below

- D4.1 Set-up of SONIC Project, including internal and external communication channels completed and delivered on 31st Jan-21
- D4.2 SONIC Phase #1 Launch Event completed and delivered on 24th Jun-21
- D4.3 SONIC Phase #1 Final Project Report, this Report
- D4.4 Prepare the OpenRAN benefits realisation template for SONIC1, with draft input, completed and delivered on 1st May-21
- D4.5 Finalise the OpenRAN Benefits Realisation template for SONIC1, completed and delivered on 30th Jun-21
- D4.6 Update the OpenRAN Benefits Realisation template for SONIC1, completed and delivered on 17th Dec-21

2.5. Sonic-1 milestones & deliverables actuals

MS Ref	Del Ref	Milestone Name	Milestone Due Date	Actual delivered	Comments
MS1.1	NA	Procurement of first Open RAN deployment (part 1 of 2)	31/12/2020	31/12/2020	On Time
MS2.1	D4.1	Set-up of SONIC Project, including internal and external communication channels	31/01/2021	31/01/2021	On Time
MS2.2	D3.1	SONIC outline of overall Business Plan	28/02/2021	28/02/2021	On Time
MS2.3	NA	Procurement of Open RAN MVP extensions (part 2)	31/03/2021	31/03/2021	On Time
MS2.4	D4.4	Prepare an OpenRAN Benefits Realisation template for SONIC1, with draft input	31/03/2021	01/05/2021	Mutually agreed the delay
MS3.1	D1.1	Open RAN Installation, Commissioning and Core Network Integration Report	30/05/2021	13/07/2021	CR2
	D4.2	SONIC Phase #1 Launch Event.	30/05/2021	24/6/2021	CR1
MS3.2	D4.5	Finalise the OpenRAN Benefits Realisation template for SONIC1	30/06/2021	30/06/2021	On Time

MS3.3	D3.2	SONIC Complete Business Plan and proposal for evolution	30/06/2021	30/06/2021	On Time
MS4.1	D2.1	Open RAN Benchmarking, Interoperability, Security and Resilience Interim update.	30/8/2021	30/8/2021	On Time
MS4.2	D2.2	Open RAN Benchmarking, Interoperability, Security and Resilience Testing Final Report.	30/10/2021	03/12/2021	CR4
	D3.3	SONIC Phase #1 Engagement Report	30/10/2021	10/12/2021	CR5
	D4.3	SONIC Phase #1 Final Project Report.	30/10/2021	17/12/2021	CR5
	D4.6	Update the OpenRAN Benefits Realisation template for SONIC1	30/10/2021	17/12/2021	CR5

Table 2: Sonic-1 overall milestones & deliverables against actuals delivery dates

3. Completion Report Sonic1 & Test Exit Report

SONIC Phase #1 Final Project Report. Completion report for this phase of SONIC. For use by the project and DCMS. To include: (i) full description of design, build, management, and operational elements of the project; (ii) details of technical architecture and security considerations; (iii) assessment of the success of the programme against its objectives and intended benefits. (Some relevant content may be copied from a previously completed deliverable D1.1: Open RAN installation, commissioning and core network integration report)

Test exit report(s). For use by the project and DCMS. To include: (i) high level description of each set up; (ii) the test and measurement equipment used; process of validation; (iii) key performance indicators (KPIs); (iv) Open RAN benchmarking, interoperability, security and resilience testing (relevant content from deliverable D2.2); and (v) technical lessons learnt.

3.1. SONIC Labs Open RAN deployment

Figure 3 presents the overall SONIC Labs design constituting three 5G standalone (5G-SA) Open RAN systems/chains geographically distributed across three sites, namely: Digital Catapult (London), Ofcom Riverside House, and Digital Catapult (Brighton - Fusebox). The Open RAN systems/chains were integrated with two 5G-SA core networks, the Druid (Raemis) and the Radisys (Trillium) core networks. The 5G-SA core networks were also integrated with various application servers, residing in an external data network, namely: the BBC/Aardman Magic Window into Roman baths application server; the Mativision Shared Immersive Experience application server; Digital Catapult's speed test application; and of course, with further public internet. Following the recommendations from the Open RAN vendors, SONIC Labs experimented with four 5G-capable end User Equipment (UEs), namely: OnePlus Nord, OPPO Find X2 Pro, Samsung A90 and Samsung S20 and OnePlus 8T. It is worth noting that of the four UEs considered only the OnePlus Nord and 8T successfully connected to all three 5G Standalone (5G-SA) O-RAN chains deployed in the SONIC Labs; this was mainly due to the manufacturers' regional locks on handset, in particular in 5G-SA handset operational mode.

Digital

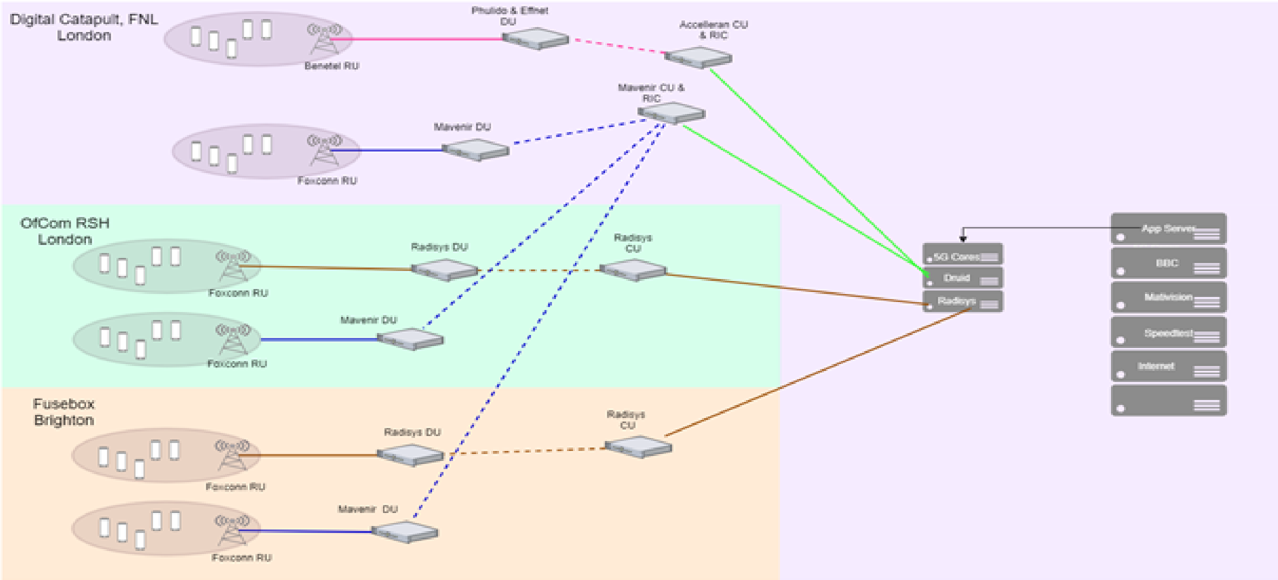

Figure 3: Overall SONIC LABS HIGH LEVEL Deployment ARCHITECTURE

3.1.1.Accelleran Open RAN Deployment

This Open RAN chain, in Figure 4, is a 5G standalone RAN system supporting an end-to-end cloud native and O-RAN aligned 7.2x split RAN network implementation by Accelleran, Effnet, Phluido and Benetel. The system was deployed in Digital Catapult's Network Operation Centre (NOC) in London and integrated with Druid's Raemis Private 5G Core Network as well as the OnePlus Nord and 8T User Equipment (UE).

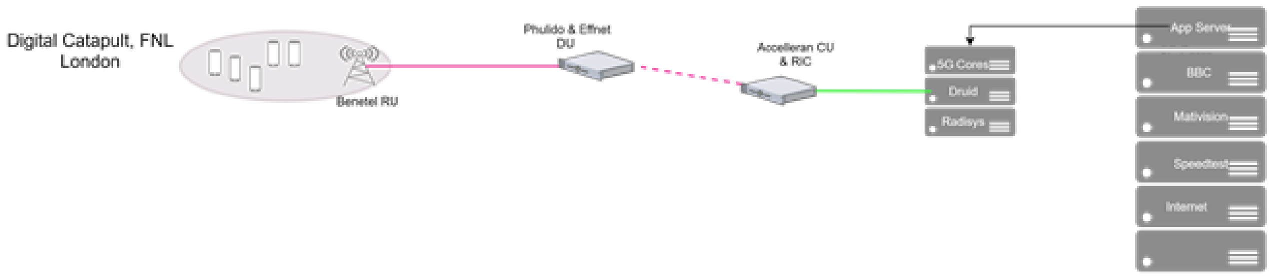

Figure 4: SONIC Labs O-RAN Chain #1: Accelleran Integration

3.1.1.1. Accelleran Integration within SONIC Labs

3.1.1.1.1. 5G Radio Access Network

This Open RAN chain is 5G standalone RAN system supporting an end-to-end cloud native and O-RAN aligned 7.2x split RAN network implementation by Accelleran, Effnet, Phluido and

Benetel. The system was deployed in Digital Catapult's Network Operation Centre (NOC) in London and integrated with Druid's Raemis Private 5G Core Network.

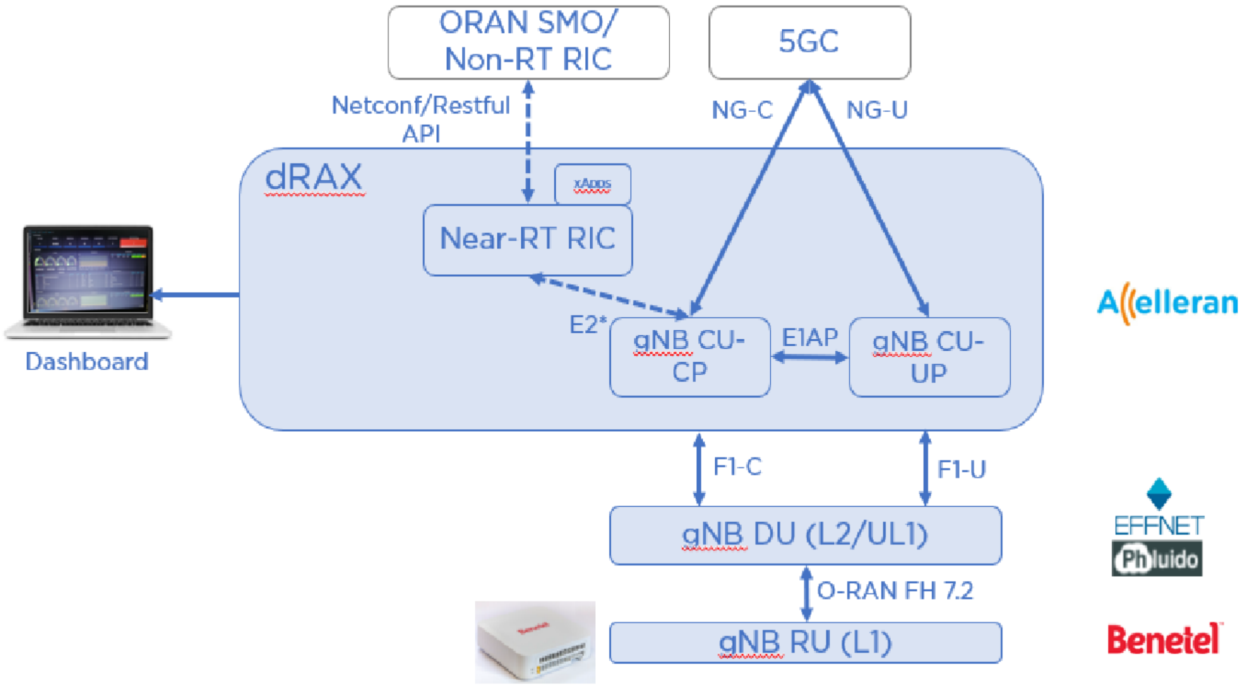

FIGURE 5 SONIC LABS CHAIN #1: SOLUTION ARCHITECTURE

Table 3 presents a description of the constituent components of this Open RAN chain.

Open RAN Network Function	Supported Features
dRAX – Accelleran	• Fully containerized. • Near-Real Time RAN Intelligent Controller (RIC). • Dashboard xApp. • xApp framework (xApp application lifecycle management). • Restful API/Netconf.
Centralised Unit (CU) - Accelleran	• Fully containerized SW • 3GPP Baseline • 5G-SA • eMBB • Network Slicing • Cell reselection – intrafreq 5g only • QoS and Bearer Management o Up to 2 PDU session per UE o 1 DRB per PDU session o 5QI 1-9 • Radio Resource Management

	o RRM Algorithm Framework o UE Admit Control – Basic o Bearer Admission Control – Basic o Mobility Management – Single event driven o Overload and Congestion Management - None • Security o Basic 3GPP Security o Control Plane Integrity Prot. (NIA1) o User Plane Ciphering (NEA1) • Interface support o NG, F1, E1 • Operational management o Static Netconf/YANG Config Management o Engineering Logging and Tracing • Mobility o Intra-gNB, Intra-Frequency Mobility only
Distributed Unit (DU) - Effnet L2 and Phluido Upper L1	• Fully containerized • L2 • Northbound: Option 2 of 3GPP TR 38.801 (F1-C and F1-U interface to CU) • Southbound: 5G FAPI • Upper L1 • Northbound: 5G FAPI • Southbound: 3GPP Split 7.2
Radio Unit (RU) - Benetel	• Transceiver Specification • 2 x 2 MIMO • Local Area Base Station Class • 20dBm/100mW RF power per antenna port (TDD) • 1 transceiver per unit (single cell) • BW support: 40MHz. • Band Support o TDD Bands n78. • Network Interfaces o ORAN v2.0 o 10 Gbe port, fibre o IPv4/IPv6 o Functional Split: 7.2x o Category B • Sync o GPS • Other Radio Specifications o 3GPP Release TS 38.104.V15 o Integrated GNSS (GPS, GLONASS, BDS)

	- 1Gbe Port for OAM/Remote update.
	• Power
	  - 12 V
	  - <40W (Max Tx power, full data traffic)
	• Physical/Environmental
	  - Dimensions: 240 x 240 x 60mm (3.5 litres)
	  - Weight: <1.7 Kgs
	  - Ingress Protection: IP22
	  - Temperature: 0 to +40ºC (operating)

Table 3 Components specification

Table 4 presents the nominal hardware requirements for the constituent components of this Open RAN chain.

Open RAN Network Function	Hardware Requirements
dRAX (dashboard, netconf, messaging framework, xApp framework, nRT-RIC and Centralised Unit (CU) – Control Plane (CP) on Kubernetes environment	• Persistent Storage: 256 GB • RAM: 32 GB • Cores: 4
Centralised Unit (CU) – User Plane (UP) for 1Gbps traffic	• Persistent Storage: 8 GB • RAM: 1 GB • Cores: 4
Distributed Unit (DU) for 1Gbps traffic	• Persistent Storage: 8 GB • RAM: 1 GB • Cores: 4 for L2 & 4 for Upper L1

Table 4 Nominal Hardware Requirements x86 Server Based

3.1.1.1.2. 5G Core Network: Druid

The Druid Raemis 5G Core Network (Figure 6) supports 5G standalone (5G-SA), 5G non-standalone (5G-NSA) as well as 4G. The SONIC Labs implementation only considered 5G standalone (5G-SA) leveraging the following Druid Raemis network functions: Access and Mobility Management Function (AMF), Session Management Function (SMF) and User Plane Function (UPF).

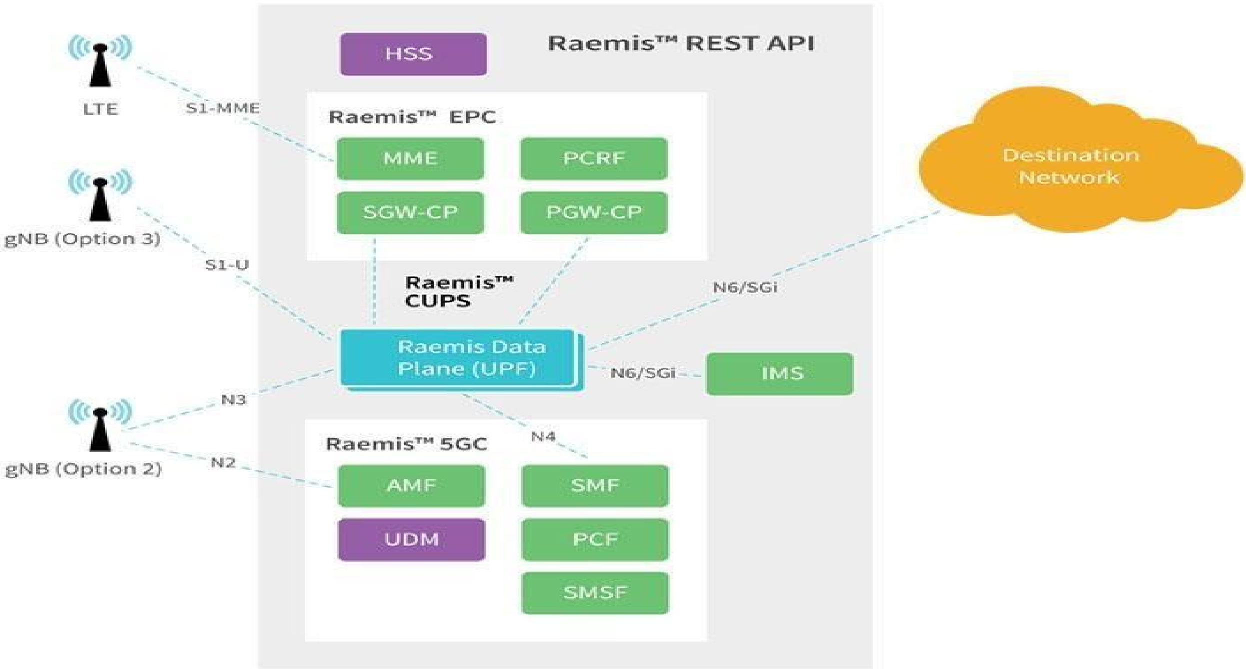

FIGURE 6 DRUID RAEMIS 5G CORE NETWORK

The installed Druid Raemis 5G Core network (Figure 7) required the following.

- Cent0S 7 Operating System (OS)
- 4 CPU Cores
- 4GB RAM
- 20 GB SSD disk storage
- At least two network interface ports, i.e. one for connecting to the Open RAN Centralised Unit (CU) and a second interface for the user plane break out to external data networks.

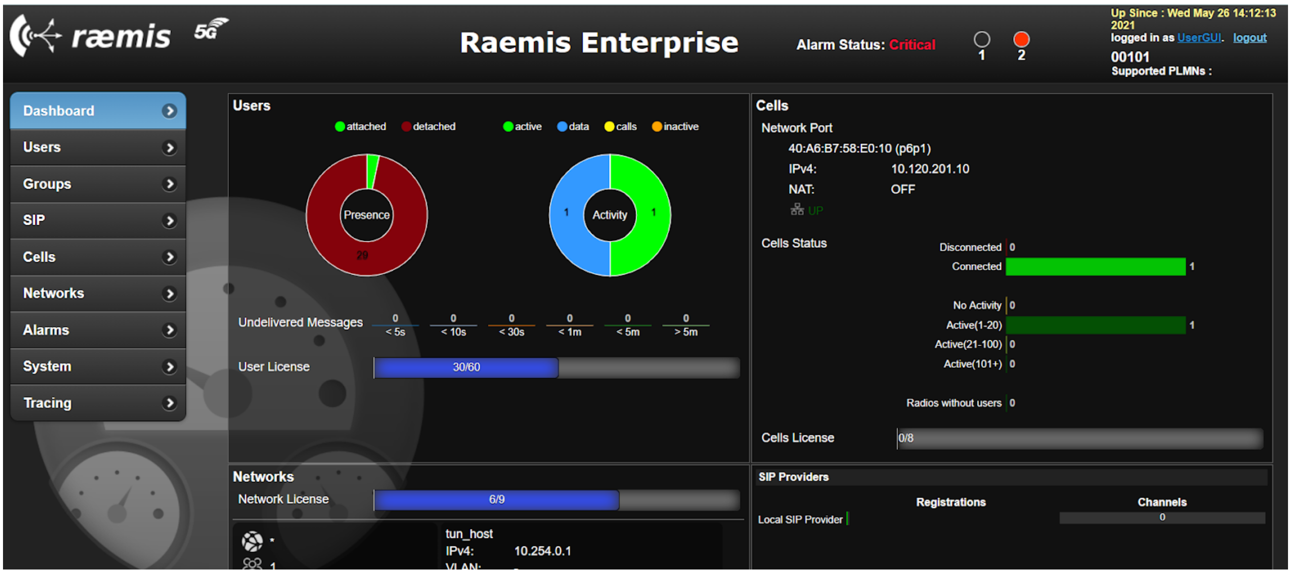

Figure 7 DRUID RAEMIS Dashboard

3.1.2.Mavenir Open RAN Deployment

This Open RAN chain, in Figure 8, is a 2-vendor Open RAN system integrated by Mavenir in a 5G Standalone network solution. The system is geographically distributed among three sites, namely: Digital Catapult London, Brighton, and Ofcom Riverside House. The solution utilised the Foxconn RPQN-7800 radio units and was integrated with Druid's Raemis Private 5G Core Network as well as the OnePlus Nord and 8T User Equipment (UE).

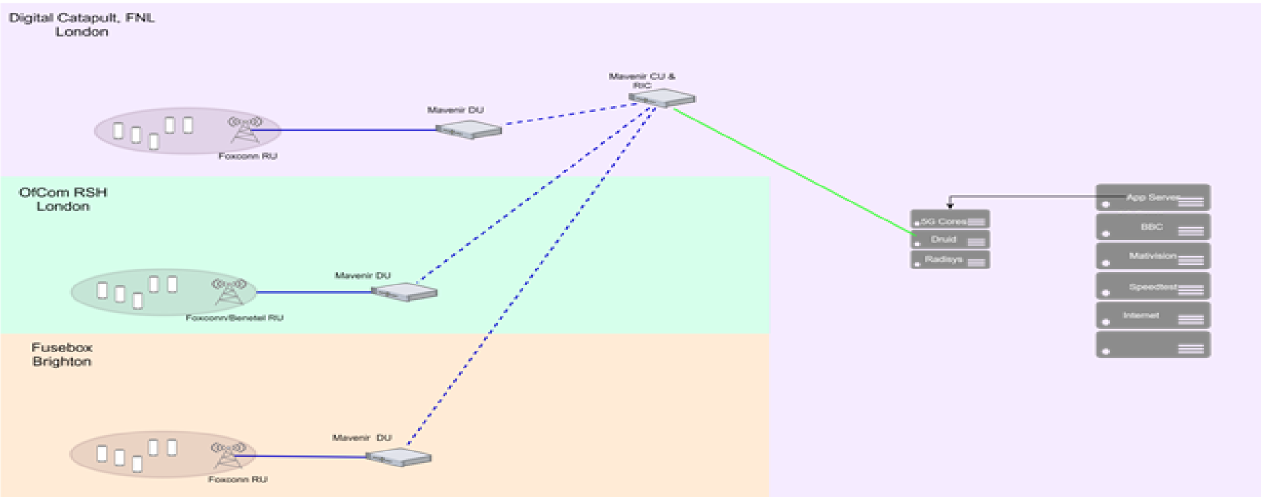

FIGURE 8: SONIC LABS O-RAN CHAIN #2: MAVENIR INTEGRATION

3.1.2.1. Mavenir Integration within SONIC Labs

3.1.2.1.1. 5G Radio Access Network

This Open RAN chain is a 2-vendor RAN system integrated by Mavenir in a 5G Standalone network solution. The system is geographically distributed among three sites, namely: Digital Catapult London, Brighton, and OFCOM riverside house. The solution utilises the Foxconn RPQN-7800 radio units (described in D1.1 under section 2.4.4) and integrated with Druid's Raemis Private 5G Core Network described in section 4.1.1.1.2.

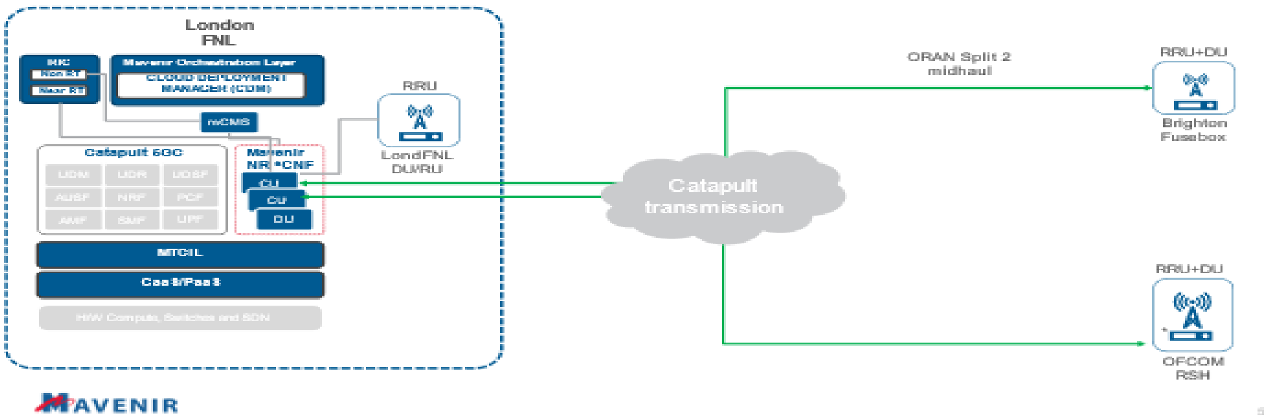

FIGURE 9 SONIC LABS CHAIN #2: SOLUTION ARCHITECTURE

Figure 9 presents Mavenir's fully containerized O-Cloud platform also known as Mavenir Webscale Platform (MWP). The infrastructure consists of master nodes managing the MWP clusters and related CaaS, PaaS, mCMS and MTCIL worker nodes deployed at Digital Catapult London. The architecture is flexible and supports SONIC Lab's requirements on the two functional split deployment options, namely.

- Option 1: The Centralised Unit (CU) and the Distributed Unit (DU) deployed at a single site, i.e., at Digital Catapult London.
- Option 2: The Centralised Unit (CU) and the Distributed Unit (DU) deployed at different SONIC Lab sites, i.e., the CU is deployed at Digital Catapult London while the DUs are deployed at Digital Catapult Brighton Fusebox and OFCOM Riverside house.

Figure 9 highlights Mavenir's software deployment architecture that primarily constitutes two major components, namely: the O-Cloud platform/Mavenir Webscale Platform (MWP) and the Mavenir vRAN software. The Mavenir vRAN software is made up of the Open RAN Centralised Unit (CU) and the Distributed Unit (DU) while the O-Cloud platform/Mavenir Webscale Platform (MWP) is made up CaaS, PaaS, mCMS and MTCIL software modules. The O-Cloud platform/Mavenir Webscale Platform (MWP) is are responsible for operation, configuration, and fault management. Mavenir's software modules were deployed on top of a CentOS Operating system within Docker based containers and relying on Kubernetes for container orchestration.

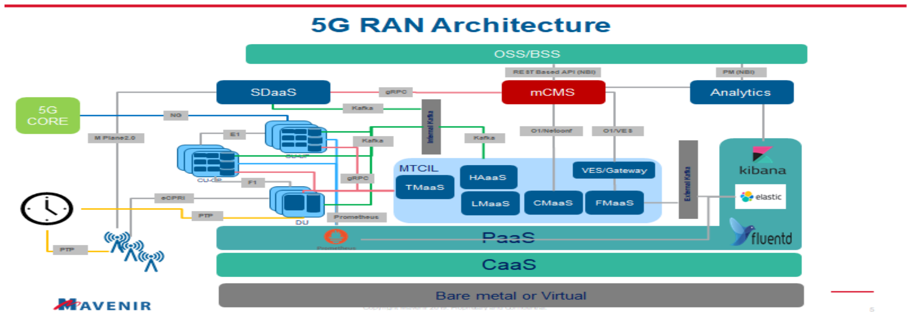

Table 5 presents the Fronthaul and Midhaul transport requirements required to support the Mavenir Open RAN chain.

Table 5 Transport Requirements

Transmission	Protocol	Physical req.	Max distance	Max RTT	Bandwidth
F1 (Midhaul)	Ethernet (L2/L3)	Fibre or metallic	<500km	20ms/80ms	Based on cell bandwidth. Minimum 1Gbps required
Fronthaul (7.2 Split)	Ethernet L2	Fibre	<10km	100µs	Minimum 10Gbps required

Figure 10 presents the detailed Bill of Materials (BoM) for this Open RAN chain.

5G BOM for SONIC DIGITAL CATAPULT Project		
Product	**Quantities**	**Responsibility**
RAN		
5G RRU 1 (Hardware)		
RRU Benetel (to be bought by DC); band n78 (40MHz) with integrated antenna, @ bandwidth TBA	1	Digital Catapult
5G RRU 2 (Hardware)		
RRU NEC; band n78 with integrated antenna, @ bandwidth TBA	1	Mavenir
5G RRU 3 (Hardware)		
RRU Foxconn; band n78, @ bandwidith TBA	1	Mavenir
Other Hardware		
CU/CEM/DU non-HA for RAN (Hardware)		
Servers for CU, CEM & DU		
CU / DU Dell PowerEdge R740 w6230R CPU - 2x26c 320GB (AC)-vCompute Node - 5G (containerised) - London	1	Digital Catapult
mCMS/TCIL/Analytics Dell PowerEdge R740 w6230R CPU - 2x26c 320GB (AC)-vCompute Node (containerised) - London	1	Digital Catapult
DU for 5G - Dell PowerEdge R740 w6230R CPU - 2x26c 320GB (AC)-vCompute Node (containerised) - Brighton	2	Digital Catapult
Mt Bryce accelerator card for DU - Optional (needed for 100MHz and above bandwidth)	3	Digital Catapult
K8 Master - Dell PowerEdge w6230R CPU - 2x26c 320GB - Control Node (containerised) - London	1	Digital Catapult
RIC - Dell PowerEdge R740 w6230R CPU - 2x26c 320GB (AC)-vCompute Node (containerised) - London	3	Digital Catapult
Interconnect Switches & Rack (non-HA)		
NFV/NON -NFV 42U Rack with 1P G2 Basic PDU - International -1 rack at 1 x Data Centres (London)	1	Digital Catapult
CISCO ToR - 1Gbe Nexus 3048 - 48port switch - AC (London & Brighton)	3	Digital Catapult
Cisco SFPs (500-295-100)	55	Digital Catapult
CISCO NEXUS 3172PQ 48 port 10+ (London)	1	Digital Catapult
ODF multimode, duplex LC for CPRI (Dark Fibre termination) - 3 x sites and 1 x Data Centre	4	Digital Catapult
Software		
CU/CEM/NFVi Licence fee for RAN (Software)		
CU - 5G SW Licence (one-off fee up to 50 sites only, subsequently per site / RRU fee)	1	Mavenir
DU - 5G SW Licence (one-off fee up to 50 sites only, subsequently per site / RRU fee)	1	Mavenir
mCMS SW Licence (one-off fee up to 50 sites only, subsequently per site / RRU fee)	1	Mavenir
Kubernetes Licence (per compute and utility node)	8	Mavenir
RIC capabilities	1	Mavenir
Antenna		
5G Antenna	3	Mavenir
RF Cable - Low Loss 1/2 Flexible Annular Corrugated Coax Cable (2 per site)	6	Digital Catapult
ACCESSORIES (Cables)		
GPS Antenna	3	Digital Catapult
GPS Antenna cable	3	Digital Catapult
Cat6 Ethernet Patch Cable - Standard Boot - RJ45 (10 ft length) | 24 AWG Pure Copper Conductor | 550 MHz | PoE | UL Listed | RoHS	8	Mavenir
10Gb 40Gb Multimode Duplex 50/125 OFNP Fiber Cable (OM3 Fiber Optic Cable/LC to LC Fiber Patch Cable) 20m - cable from RRU to Cell-site gateway	3	Mavenir
10Gb 40Gb Multimode Duplex 50/125 OFNP Fiber Cable (OM3 Fiber Optic Cable/LC to LC Fiber Patch Cable) 2m	55	Mavenir
Console cable (USB Console Cable USB to RJ45 Cable Essential Accessory of Cisco)	4	Mavenir
SFP FINISAR 10G - FTLX8571D3BC - for RRUs	3	Mavenir
SFP FINISAR 10G - FTLX8571D3BC - for Cell Site Gateway	3	Mavenir
Cable: 10M (33ft)MTP Female to Female 12 Fibers OM3 50/125 Multimode Trunk Cable, Type B, Elite, Plenum (OFNP), Aqua#68025	4	Mavenir
Power / POE++ adapters for RRU	3	Mavenir
Professional Services		
RAN Field deployment and testing	1	Mavenir
Support for 6 months	1	Mavenir

FIGURE 10 SONIC LABS CHAIN #2: BILL OF MATERIALS

3.1.3.Radisys Open RAN Deployment

3.1.3.1. Radisys system architecture

Radisys Open RAN chain, Figure 11, is a two-vendor Open RAN system integrated by Radisys in a 5G Standalone end to end network solution. The system is geographically distributed among three sites, namely: Digital Catapult London, Brighton, and Ofcom Riverside House. The solution utilised the Foxconn RPQN-7800e radio units and was integrated with Radisys' (Trillium) 5G Core Network as well as the OnePlus Nord and 8T User Equipment (UE).

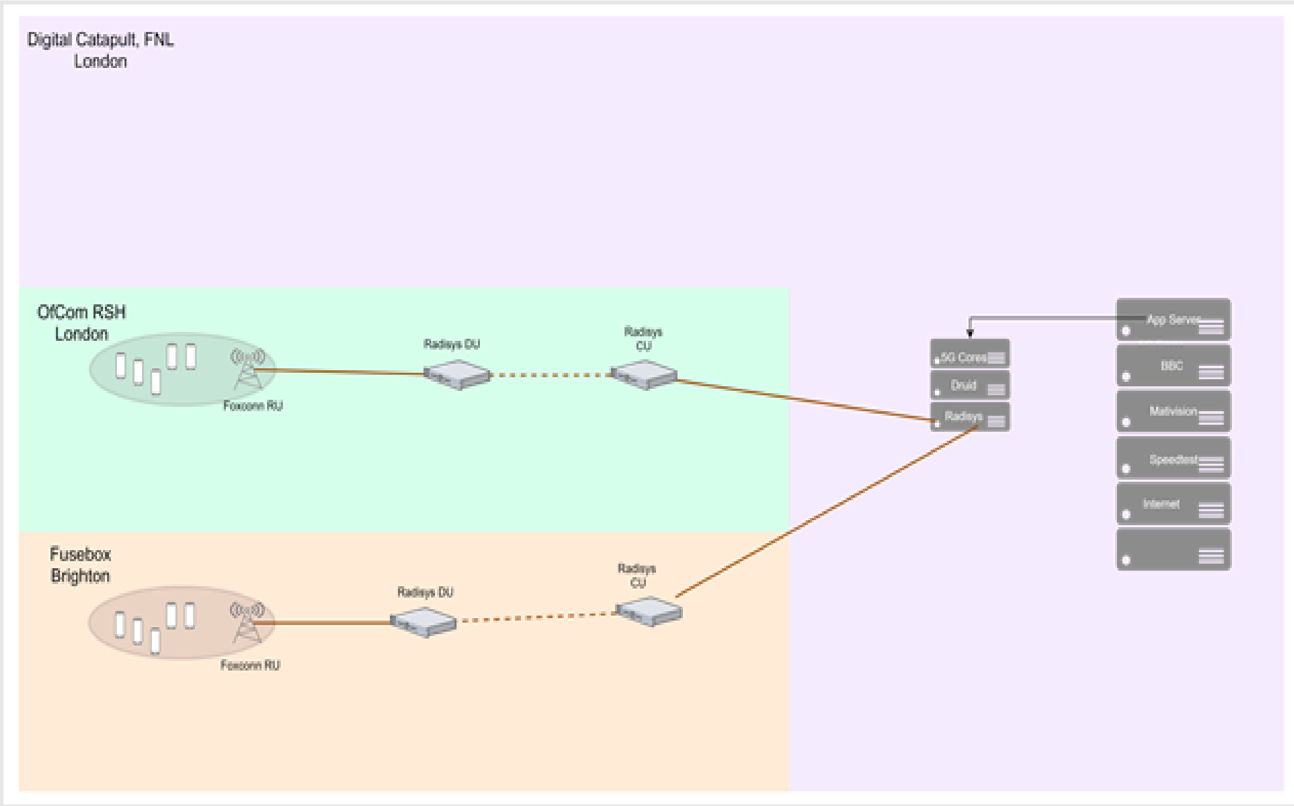

Figure 11: SONIC Labs O-RAN Chain #3: Radisys Integration

3.1.3.2. Radisys Integration within Digital Catapult SONIC Labs

3.1.3.2.1. 5G Radio Access Network

This Open RAN chain is a 2-vendor RAN system integrated by Radisys in a 5G Standalone end to end network solution. The system is geographically distributed among three sites, namely: Digital Catapult London, Brighton, and OFCOM riverside house. The solution utilises the Foxconn RPQN-7800 radio units (described in D1.1 under section 2.4.4) and was integrated with Radisys' 5G Core Network.

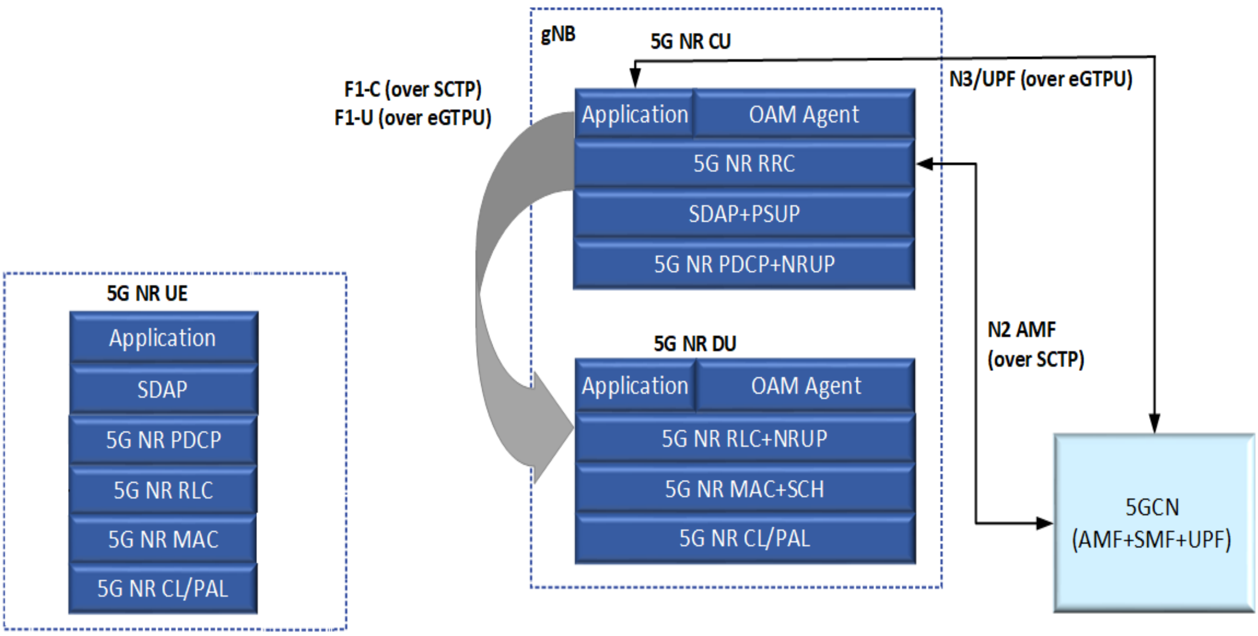

FIGURE 12 SONIC LABS CHAIN #3: SOLUTION ARCHITECTURE

Table 6 presents the functional and message compliance of the constituent components for this Open RAN chain.

Open RAN Network Function	Supported Feature set
Centralised Unit (CU) – Radisys	• Management and Orchestration; Performance Management Services (OAM FM) 3GPP TS 28.532 v16.3.0 • Management and Orchestration; 5G Network Resource Model (NRM) (OAM CM) 3GPP TS 28.541 v16.1.0 • Management and Orchestration; 5G Performance Measurements (OAM PM) 3GPP TS 28.552 v16.5.0 • Telecommunication management; Generic Network Resource Model (NRM); Integration Reference Point (IRP); Solution Set (SS) definitions 3GPP TS 28.623 v16.3.2 • General Packet Radio System (GPRS) Tunnelling Protocol User Plane (GTPv1-U) 3GPP TS 29.281 v15.7.0 • SDAP 3GPP TS 37.324 v15.1.0 • PDCP 3GPP TS 38.323 v15.3.0 • RRC 3GPP TS 38.331 v15.5.1 • NGAP 3GPP TS 38.413 v15.3.0 • PDU Session User Plane Protocol 3GPP TS 38.415 v15.2.0 • XnAP 3GPP TS 38.423 v15.3.0 • X2AP 3GPP TS 38.423 v15.5.0 • NRUP 3GPP TS 38.425 v15.3.0 • E1AP 3GPP TS 38.463 v15.4.0 • F1AP 3GPP TS 38.473 v15.5.0
Distributed Unit (DU) – Radisys	• Management and Orchestration; Generic Management Services (OAM FM) 3GPP TS 28.532 v16.3.0 • Management and Orchestration; 5G Network Resource Model (NRM) (OAM CM) 3GPP TS 28.541 v16.1.0 • Management and Orchestration; 5G Performance Measurements (OAM PM) 3GPP TS 28.552 v16.5.0 • Telecommunication management; Generic Network Resource Model (NRM); Integration Reference Point (IRP); Solution Set (SS) definitions 3GPP TS 28.623 v16.3.2 • General Packet Radio System (GPRS) Tunnelling Protocol User Plane (GTPv1-U) 3GPP TS 29.281 v15.7.0 • PHY 3GPP TS 38.211 v15.3.0 • 3GPP TS 38.212 v15.3.0 • 3GPP TS 38.213 v15.3.0 • 3GPP TS 38.214 v15.3.0 • MAC 3GPP TS 38.321 v15.3.0 • RLC 3GPP TS 38.322 v15.5.0 • NRUP 3GPP TS 38.425 v15.3.0

	• F1AP 3GPP TS 38.473 v15.5.0

Table 6 Functional and Message Compliance

Figure 13 presents the detailed Bill of Materials (BoM) for this Open RAN chain.

	5G FlexRAN (gNB - integrated DU/CU)		
No.	Item	Quantity	Description
1	Intel Server R2208WFQZSR - Intel Server Board S2600WFQR – QAT (Quick Assist Technology, 2 On-Board PCIE NVMEOcuLink Connectors, Featuring Intel C628) - Xeon Gold 6248 20 cores (2 sockets) - 16GB RDIMM 2 Rank 2933 x12 (192GB) - 480GB SSD	1	Server for gNB
2	Fortville PCIe Quad Fiber Ethernet X710-DA4FH NIC card should support SRIOV	1	NIC MH/BH+ FH
3	Intel SFP module FTLX8571D3BCV-IT (10Gbps SFP, Wavelength 850nm E10GSFPSR)	2	SFP Module (for ORU-DU)
4	Intel SFP module AFBR-709DMZ-IN3 (10Gbps SFP, Wavelength 850nm E10GSFPSR)	4	SFP Module (for CU-CN, CU-DU)
5	Intel i350 Quad Port 1GbE BASE-T	1	1Gb NIC
6	Vista Creek N3000 FPGA (BD-NVV-10AT1151AES - 2x2x25GB)	1	FEC FPGA (Sub6 100Mhz)
7	PCIE AUX Power cable AXXGPGPUCABLE (for VC in Intel Wolfpass Server)	1	Power Cable for Vista Creek (works with Intel Server)
8	1588 PTP Grandmaster Clock Qulsar QG2 with GPS Antenna	1	1588 Clock source
9	LC/LC Duplex 9/125 Multi Mode Fiber	4	Fiber cables
10	CAT 6A Cables	4	Ethernet cables (for DU-GM and RRH-GM)
11	Foxconn Sub 6 RRH Indoor RPQN-7801 (4T 4R)	1	5G RRH 4T$R
12	12V Power Supply	1	Power supply for RRH
13	Whip Antenna (n78 band)	4	Antenna for RRH
14	SMA-M to SMA-F adaptor	2	RRH Adaptors
15	SMA-F to SMA-F adaptor	2	RRH Adaptors
16	SMA Male to SMA Male Cable -2m	8	RF Cables
17	ZFRSC-42-S+ RF Splitters	2	Splitters
18	RF Terminator (50 ohm)	2	RF Terminator
19	Attenuators	12	10db/20db/30db (each 3)
20	Micro USB cable	1	RRH to Laptop (USB)
21	Table Fan	1	to cool down RRH
22	PDU Softswitch	1	to remotly Power OFF/ON ORU
23	Desktop (i7/Windows)	1	Required for ORU serial console and UE control
	TOTAL		

Figure 13 SONIC LABS CHAIN #3: BILL OF MATERIALS

Figure 14 presents the system requirements for the constituent components of this Open RAN chain.

Hardware Requirements	Software Requirements	Library Dependencies
• **Server** Intel® Server System R2208WF0ZS • **Processor** Intel(R) Xeon(R) Gold 6148 CPU @ 2.40GHz • **Memory** 64 GB RAM • **Networking Device** Intel 82599ES 10-Gigabit SFI/SFP+ Network Connection (10GbE NIC) • **QAT Accelerator Card** Intel® QuickAssist Adapter 8950-SCCP ***NOTE***: For SA mode, the QAT card is required to run in the OTA setup. For PAL setup, the QAT card is not required.	• **OS for gNB CU** CentOS version 7.4.1708 with GCC version 5.4.0 • **RT Linux Patch** 3.10.0-693.2.2.rt56.623.el7.x86_64	• **gNB CU** • DPDK version 19.11 for PAL integration • DPDK version 20.05 to enable security for NGP • DPDK version 18.08 for Intel L1 integration • libnuma-dev • libhugetlbfs-dev • libstdc++-static version libstdc++.so.6 • libpcap-dev • Wireless Sub System (WLS) module from Intel • lksctp version ksctp-tools-devel-1.0.17-2.el7.x86_64 • doxygen version 1.8.11 • GLIBC library compatible with the GCC version 5.4.0 • **NGP** • Openssl • Openssl-Dev • readline-devel • **OAM** • confD version 6.7 • python-pip • paramiko • libxml2-utils • epel-release • python-devel • libffi-devel • openssl-devel • libcrypto.so.1.0.2k • libcrypto.so.1.0.0

FIGURE 14 SONIC LABS CHAIN #3: SYSTEM REQUIREMENTS

3.1.3.2.2. 5G Core Network: Radisys

The Radisys 5G Core Network (Figure 15) solution supports Access and Mobility Management Function (AMF) and Session Management Function (SMF) for control plane management and User Plane Function (UPF) for data plane management. The AMF, SMF, and UPF Network Functions (NFs) are compliant with 3GPP Release 15 specification and support the following reference point interfaces.

- N1. Reference point between the UE and the AMF.
- N2. Reference point between the RAN and the AMF.
- N3. Reference point between the RAN and the UPF.

- N4. Reference point between the SMF and the UPF.
- N11. Reference point between the AMF and the SMF.

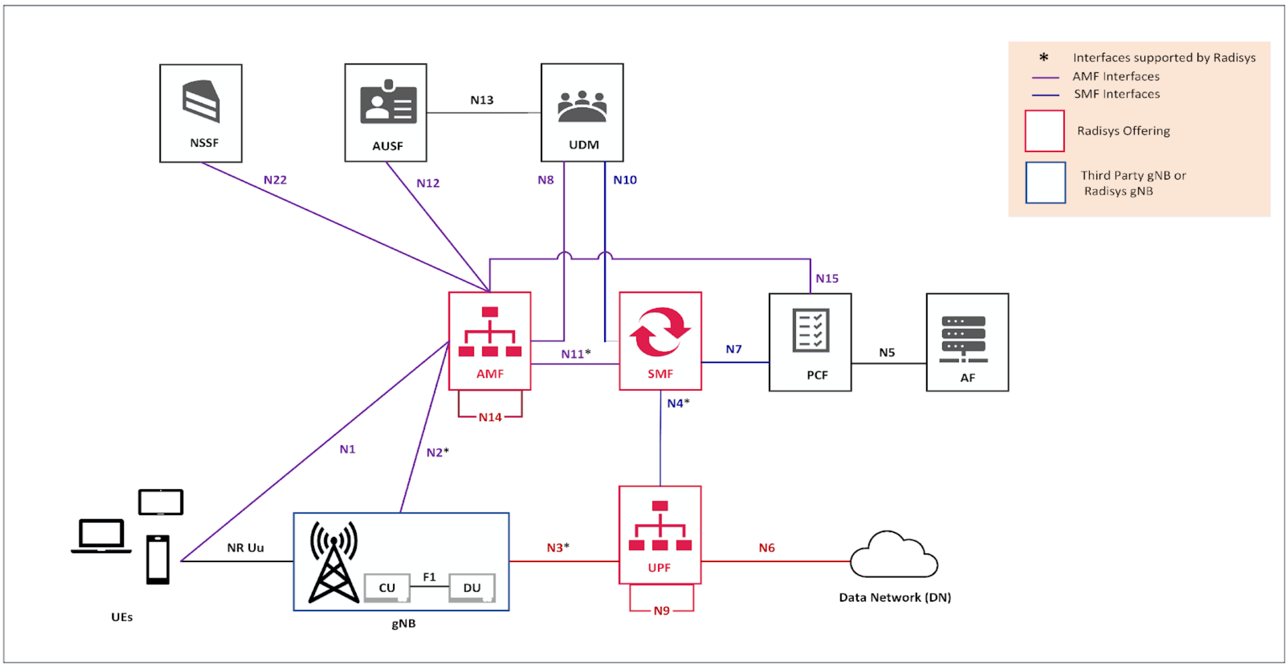

FIGURE 15 RADISYS 5G CORE NETWORK

Figure 16 presents the system requirements for the Radisys 5G Core Network.

Component	Hardware Requirements	Software Requirements
AMF/SMF/UPF	**Server** Supermicro SuperServer **Manufacturer** Supermicro **Product Name** SYS-6029P-TR **Processor** Intel® Xeon® Gold 6248 27.5M Cache 2.50 GHz 20 cores (two sockets) **Network** Intel 82599ES 10-Gigabit SFI/SFP and Network Connection (two 10GbE NIC-X710DA4FH) ***NOTE:*** NIC should support DPDK drivers. **DPDK Poll Mode Drivers (PMDs)** • All Intel network devices • vmxnet3 • virtio • Cisco VIC • Chelsio T4/T5 • Amazon Elastic Network Adapter • All Intel QAT devices VFs	**OS** Linux version 4.4.0-135-generic #161-Ubuntu SMP Mon Aug 27 10:45:01 UTC 2018 x86_64 x86_64 x86_64 GNU/Linux **GCC** GCC (Ubuntu 5.4.0-6ubuntu1 to 16.04.10) version 5.4.0 20160609

Figure 16 Radisys 5G Core Network system requirements

3.1.3.3. Radisys Integration within Ofcom SONIC Labs: Hardware swap

Ofcom Riverside house Radisys integration consists of RU, DU and CU components that are interconnected to Radisys core network hosted by the Digital Catapult as shown in Figure 17.

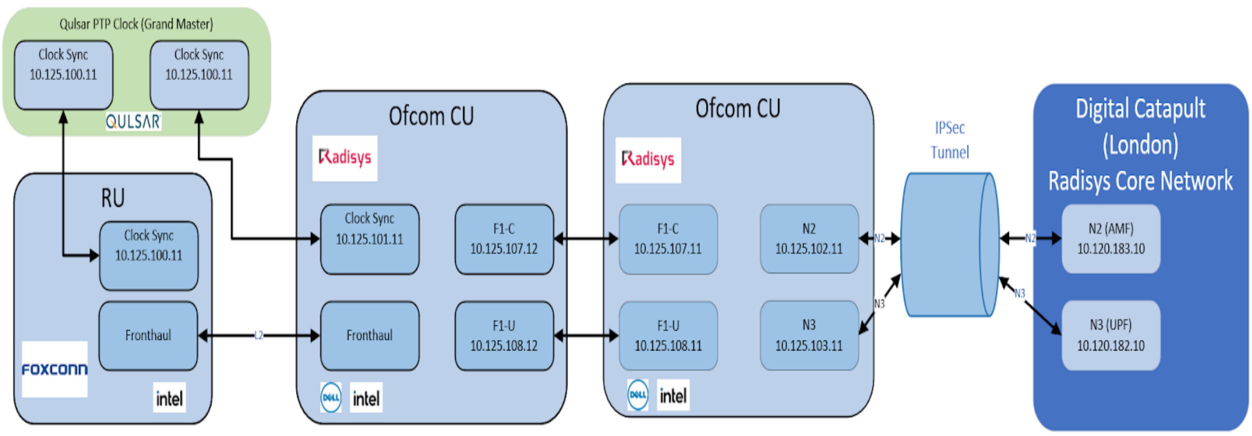

Figure 17: Ofcom - digital Catapult Radisys chain System architecture

The selected hardware platform is the Dell XE2420 commercial off-the-shelf (COTS) that supports Intel FPGA PAC N3000 (Intel Arria 10 GT FPGA) via Dell OAM integration. The Dell XE2420 platform is the shortest depth 2S server currently offered by Dell EMC (17.4" / 444mm). In addition, it is designed to operate outside the data centre (e.g. it can be deployed in street cabinets) with extended operating temperatures from 5°C to 40°C. These features are essential when considering deployment in telco cell sites.

The CU platform was modified to include Intel Quick Assist c62 series card to support over-the-air security acceleration. Both CU and DU platforms were modified to include Intel x710 Network Interface Cards that support DPDK features desired by Radisys. Software configuration and installation took one month after all the baseline requirements related to the hardware were fulfilled.

Highlights of this COTS hardware swap include:

- COTS Hardware swap: CU and DU are running on Dell XE2420 and Dell OAM N3000 servers, respectively. Dell XE2420 is a short form factor edge server designed for harsh environments outside of data centres.
- CU and DU are running on separate servers (Distributed RAN deployment)
- DU is accelerated with Intel N3000 v3 Accelerator card (L1 Acceleration)
- We are connecting to Radisys core network hosted by the Digital Catapult

When considering RAN deployments, it is essential to consider the environmental factors of the deployment. For instance, CU may be deployed in a temperature-controlled operator datacentre, while DU may be deployed on a cell site cabinet. Figure 18 and Figure 19 illustrate the difference between Dell R740 platform and Dell XE2420. It is worth noticing that the R740 is cabled from the back, like traditional datacentre servers, while XE2420 is cabled from the front of the servers.

Figure 18: Xe2420 Hardware platform front and back, image: dell

The depth difference can be observed in Figure 19, where the top server is R740, and the three bottom servers are XE2420s.

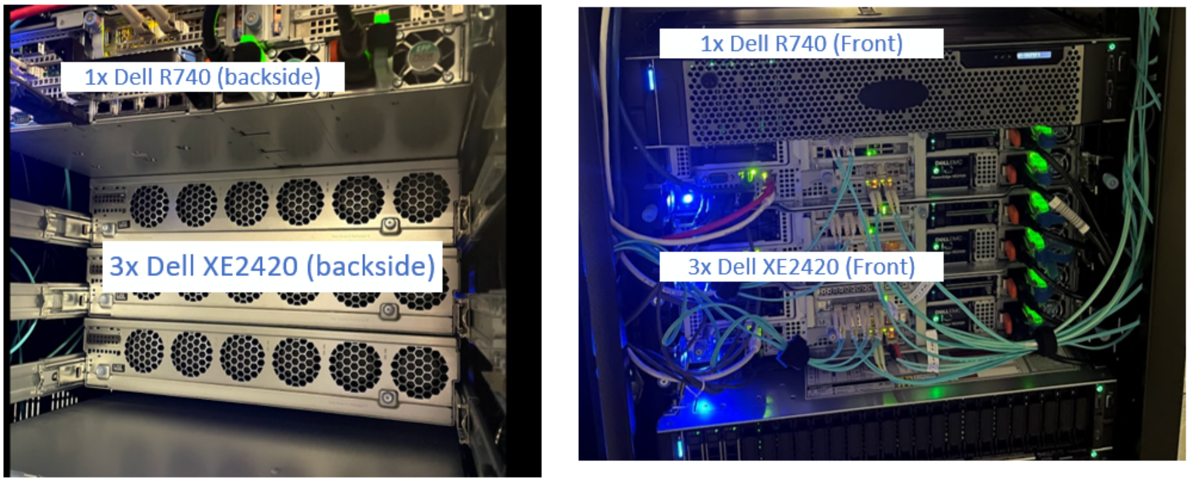

FIGURE 19 COMPARISON OF XE2420 HARDWARE PLATFORM WITH R740 PLATFORM

3.2. Security and Resilience

The UK Government published its 5G Supply Chain Diversification Strategy in November 2020. This strategy sets out an ambitious plan to grow the telecommunications supply chain while ensuring it is secure and resilient to future trends and threats. This long-term vision for the telecommunications supply chain is one where:

- network supply chains are disaggregated providing network operators more choice and flexibility to build their networks.
- open and interoperable interfaces promote a “best-of-breed” or “best cost” approach that bolsters quality, innovation, and resilience.
- the global supply chain for components is distributed across regions creating resilience and flexibility.
- standards are set transparently and independently promoting quality, innovation and security and interoperability.
- security and resilience is a priority and key consideration in network design and operation.
-

As part of this vision, the government also set out a plan to establish a UK wide R&D ecosystem to accelerate and pull forward the development of open interfaces and interoperable technologies. To support this, government announced the funding of the UK Telecommunications Lab (UKTL) in addition to SONIC Labs.

Post this announcement in the first half of 2021 we discussed with the then UKTL team within DCMS on how to align the two proposed activities.
The scope/intent of SONIC Labs is to create a platform for existing and emerging suppliers to come together to test and demonstrate the interoperability capabilities of their solutions, starting with 5G Open RAN.

The UKTL on the other hand, was then proposed to focus on independently testing network equipment security, resilience, and performance under various conditions – providing access to representative, operational examples of the UK’s critical next-generation telecommunications networks.

Given both SONIC Labs and UKTL were to be DCMS funded, we agreed we would not operate in isolation, but rather we are actively working together to understand areas of complementarity, exploit synergies where possible, whilst simultaneously delivering on the intended scope and objectives of each facility. Given the scope of these facilities, we scoped SONIC Labs to not directly perform or address specific security or resilience testing.

It is, however, important to understand (at least at a high-level) the potential security risk/challenges that may be introduced by Open RAN. Firstly, we should note that security risks/attack vectors that may compromise a monolithic RAN solution are (likely to be) equally applicable to Open RAN. However, as we move towards virtualisation of the RAN, the introduction of new functions and

interfaces, the decoupling of hardware and software, the use of open source, etc., all of which are introduced in an O-RAN solution (see
Figure 10), it is not unreasonable to assume this carries the risk of expanding the threat and attack surface of the network. This is being addressed by the O-RAN Alliance through its Security Focus Group (SFG) where the risk-based approach to security set out by 3GPP is used as the foundation.

On the other hand, current vendors with apparently monolithic products today take components from other organisations, and are also implementing virtualisation and container based microservices, with a similar increase in the attack vectors, however, without the transparency, and visibility of these new risks. At this stage it is unclear whether Open RAN is more or less secure than alternative architectures, but it is clear that there should be continuing focus on securing the interfaces and technologies introduced.

As part of the continuing the SONIC Labs, we will monitor the progress of the SFG and will work with other DCMS projects, to ensure there is a consistent and joined-up view on the learnings that come out of the SONIC Labs and the security/resilience testing undertaken by any other initiatives. SONIC Labs intends to take the advice and recommendations from DCMS' security focused activities when they are ready, and provide guidance to the vendors on the best practice.

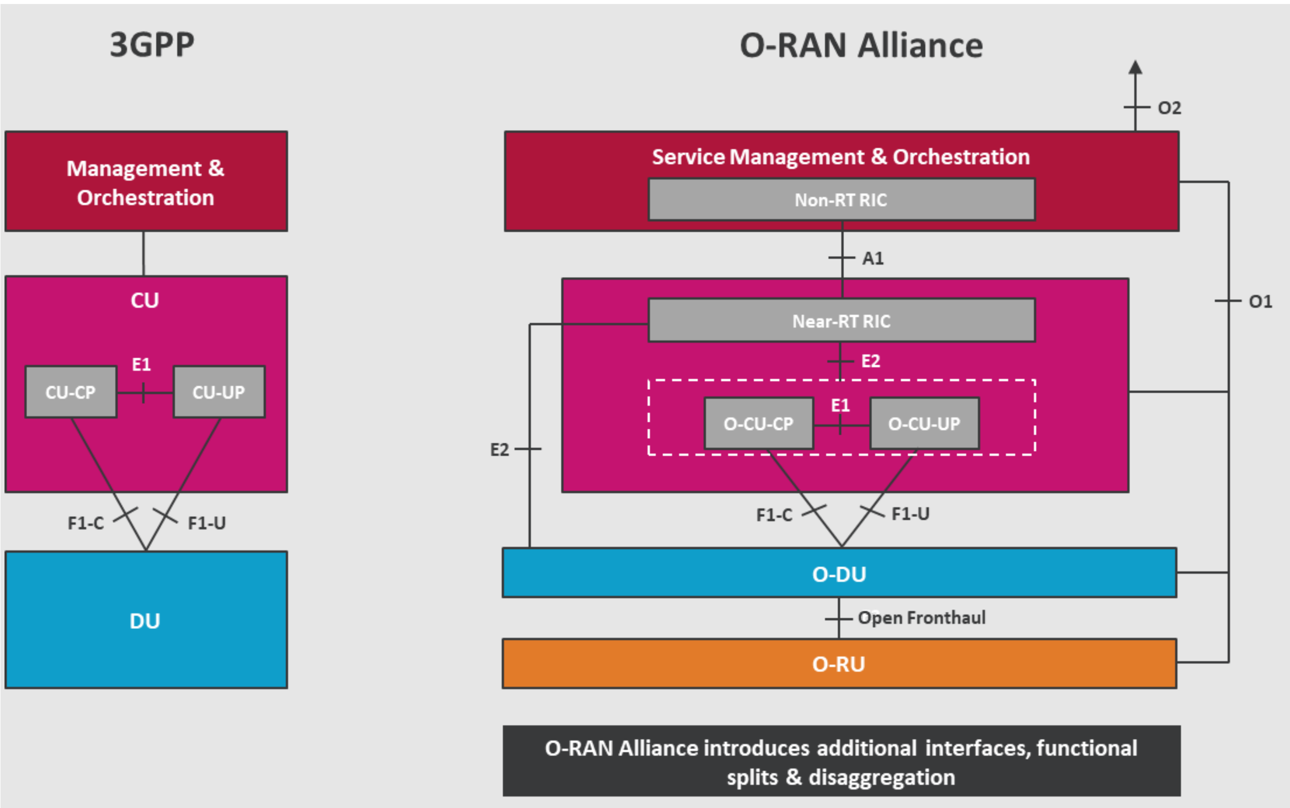

FIGURE 20 RAN ARCHITECTURES: 3GPP VERSUS O-RAN ALLIANCE

3.3. Test and Measurement equipment's.

Evaluation of various T&M vendors was not initially covered under Sonic-1 scope and later was included through change request [CR4]. There are numerous T&M vendors across the world specialising in various measurements that can be performed on Open RAN networks. These are quite specialised and expensive. So, it was vital to pin down a good selection process and evaluate the T&M vendor before procuring T&M equipment. The project team spent time doing a thorough evaluation of the T&M vendors and designed selection criteria. Various technologists and engineers from the Catapult and Ofcom then evaluated nine T&M vendors in multiple areas of measurements for over two months across SONIC and non-SONIC testbeds, multiple locations and projects. This additional scope will capture what was done and the evaluation results under D 2.2. The T&M vendors' names will be anonymised in the information on the Catapult's evaluation, as per the terms of our non-disclosure agreement (NDA) with the vendors. The deliverable will, however, declare the name of the selected vendors.

3.3.1.Essential T&M equipment needed are as follows:

We identified 3 different types of T&M equipment's for this phase and the purpose for this is listed below.

- E2E Logging Tool for Commercial UEs: This tool will enable testers to increase the efficiency of the end-to-end benchmark testing of the complete Open RAN system. This logging tool will not only enable testers to get in depth logging from commercial off the shelf mobile phones but will also facilitate automated and repeatable testing using commercial devices' android interface over command line. We down selected **Keysight Nemo & PBM** for this.

- xHaul Network Analyser: This tool will enable testers to enhance and build confidence around interoperability and integration testing of the various Open RAN systems at the interface level. These analysers can perform many tests ranging from checking the drift on PTP timing synchronisation on a 5G Open RAN network, checking health of the physical interfaces by measuring latency or capacity on the link or capturing the CUSM (Control, User, Synchronisation and Management) plane data and ensuring its compliance with the 3GPP or Open RAN specification. We down selected **Viavi MTS5800** for this.

- RF Scanner: This tool will enable testers to monitor and check the health of the air interface or RF spectrum mostly on the downlink direction. Both Ofcom and Digital Catapult have access to RF analysers and are to procure RF scanners. RF scanner is a portable version of RF analyser but provides very meaningful measurements by decoding the RAN's broadcast channels and interference from the neighbouring cells. This will help with benchmarking test of the Open RAN system as well. We down selected **Rohde & Schwarz ROMES & TSMA** for this

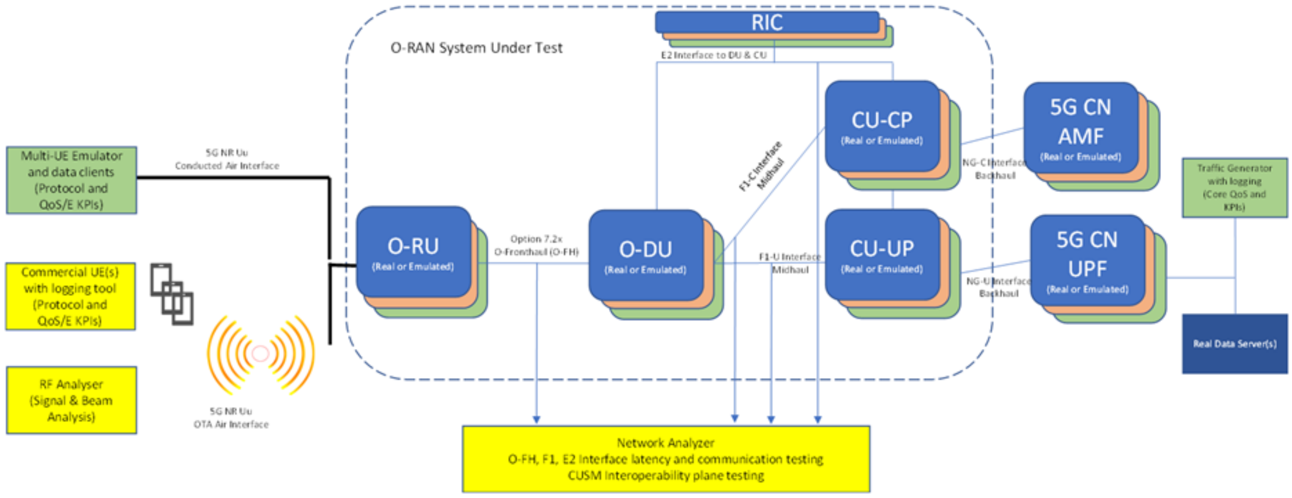

FIGURE 21 ESSENTIAL T&M (MARKED IN YELLOW) NEEDED ACROSS AN OPEN RAN CHAIN

3.3.2.Selection Criteria for T&M Tools

To select the best possible T&M vendor(s) for Phase 1 of SONIC labs; a technical evaluation framework was designed. The criteria defined in the evaluation framework should help specify and select the best possible T&M vendor for the SONIC Labs current and future requirement. The result of this evaluation will be anonymised and shared in the final report due later this year.

3.3.3.Selection criteria for E2E logging tool for commercial UE

The selection criteria for the E2E logging tool for commercial UE worked on 5 equally weighted criteria (20% each). These criteria were namely: O-RAN alignment of the vendor, list of devices supported, the measurements that the tool could produce, devices' usability and finally the commercials associated with the tool in order to procure within the budget. Each criterion divided into sub features as part of it which were scored out of 10 (10 is highest desired score and zero is the lowest).

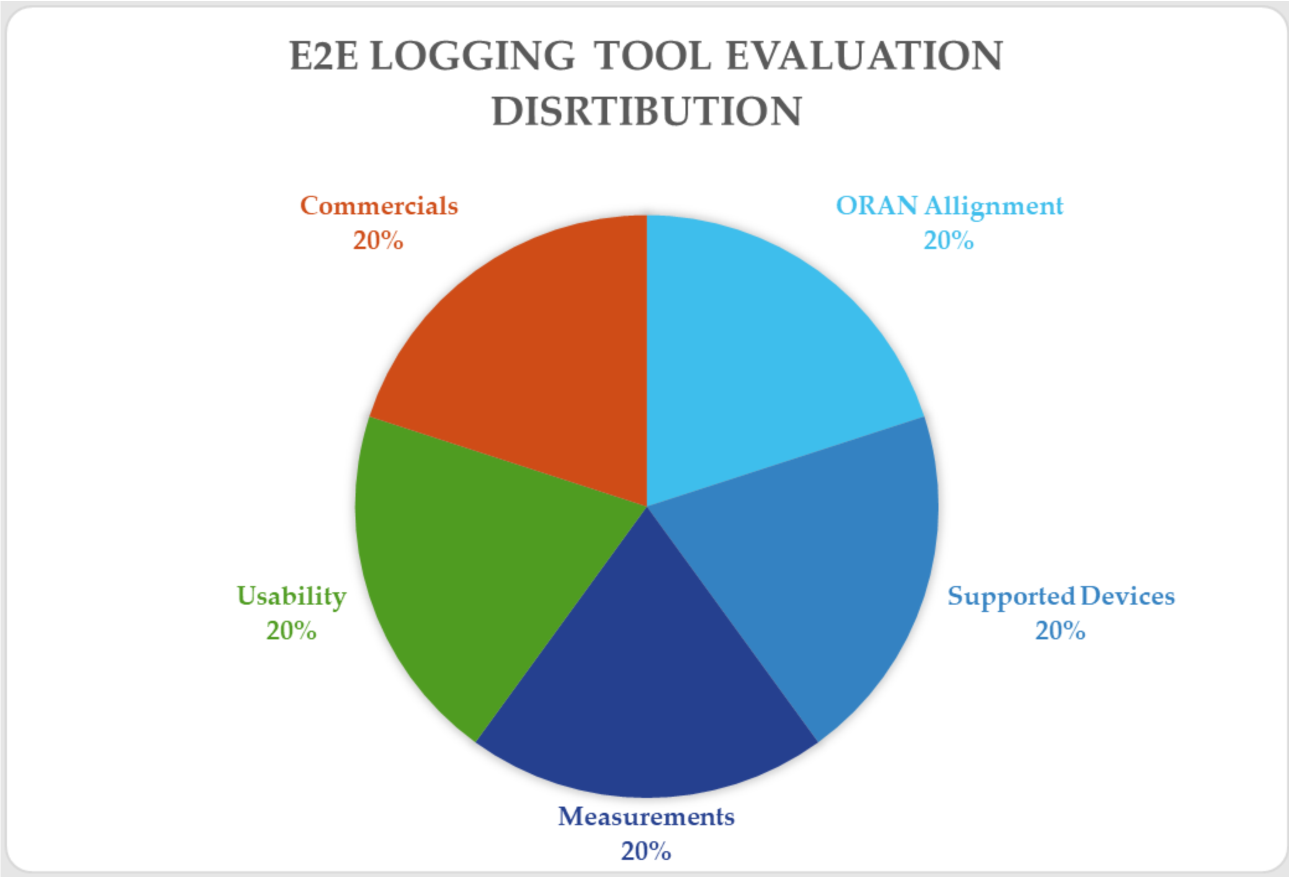

Figure 22 E2e T&M SELECTION criteria

Table 7 E2e T&M O-RAN ALIGNMENT

Category: ORAN Alignment (20% Weightage)	
Serial No	Feature
1	Strategic Alignment with other Open RAN related T&M tools
2	Support for O-RAN's TIFG Test Packages

Table 8 E2e T&M device support

Category: Supported Devices (20% Weightage)	
Serial No	Feature
1	Support for Qualcomm based smart phone devices
2	Support for Exynos based smart phone devices
3	Support for PCTEL or R&S RF Scanners
4	Support to control NB-IoT & CATM devices from at least Qualcomm (BG-96)
5	Support to control NB-IoT & CATM devices from other chip manufacturers

Table 9 E2e T&M measurements and features

Category: Measurements 20% Weightage	
Serial No	Feature
1	RF Measurements and its visualisation from devices or scanner (SINR, RSRP, RSRQ)
2	Physical Layer Stats (UL/DL BLER, PDSCH/PUSCH throughput/rank, Modulation index etc.)
3	MAC Layer Stats (RACH, MCS, DCI Decodes, DLSCH/ULSH rates)
4	RLC Layer Stats (radio bearer rates, radio bearer stats, AM/UM/TM mode stats)
5	PDCP Layer Stats (PDCP UL/DL rates)
6	Lower Layer Signalling (RACH, DCI, UCI)
7	Higher Layer Signalling (RRC/NAS)
8	Control Plane Signalling Latency Measurements
9	Control Plane KPIs (success/failures of attach, registration, pdu session est etc.)
10	Support for application layer logging (rates, latency etc.)
11	Support for application layer KPIs (FTP file downloads, success/failure pings etc.)

Table 10 E2e T&M usability and accessIbility

Category: Usability: Testing & Logging (20% Weightage)	
Serial No	Feature
1	Support for running automated E2E signalling and data test on a connected device
2	Support of various data applications (Ping, TWAMP, VoNR/LTE, Streaming, iperf, FTP, HTTP etc.)
3	Ability to record and replay logs from the device
4	Ability to use a post processing tool (if any) - Optional
5	Ability for the tool to generate report at the end of the test run
6	Support for Indoor (or Walk) testing - Optional
7	Support for Outdoor (or drive) testing - Optional

Table 11 E2e T&M SUPPLIERS' cost and technical support

Category: Commercials: Cost & Technical Support (20% Weightage)	
Serial No	Feature
1	Pre-Sales Technical Support from Vendor
2	Pre-Sales Commercial Support from Vendor
3	Cost (One off buy)
4	Cost (Yearly subscription model)

3.3.4.Selection criteria for xHaul Network Analyser

The selection criteria for the xHaul Network Analyser also focused on 5 criteria with 20% weightage each. These criteria were namely ORAN alignment of the vendor, list of test of physical interfaces, testing Open RAN specific interfaces, its usability and finally the commercials associated with the tool in order to procure within the budget. Each criterion had sub features as part of it which were similarly scored out of 10.

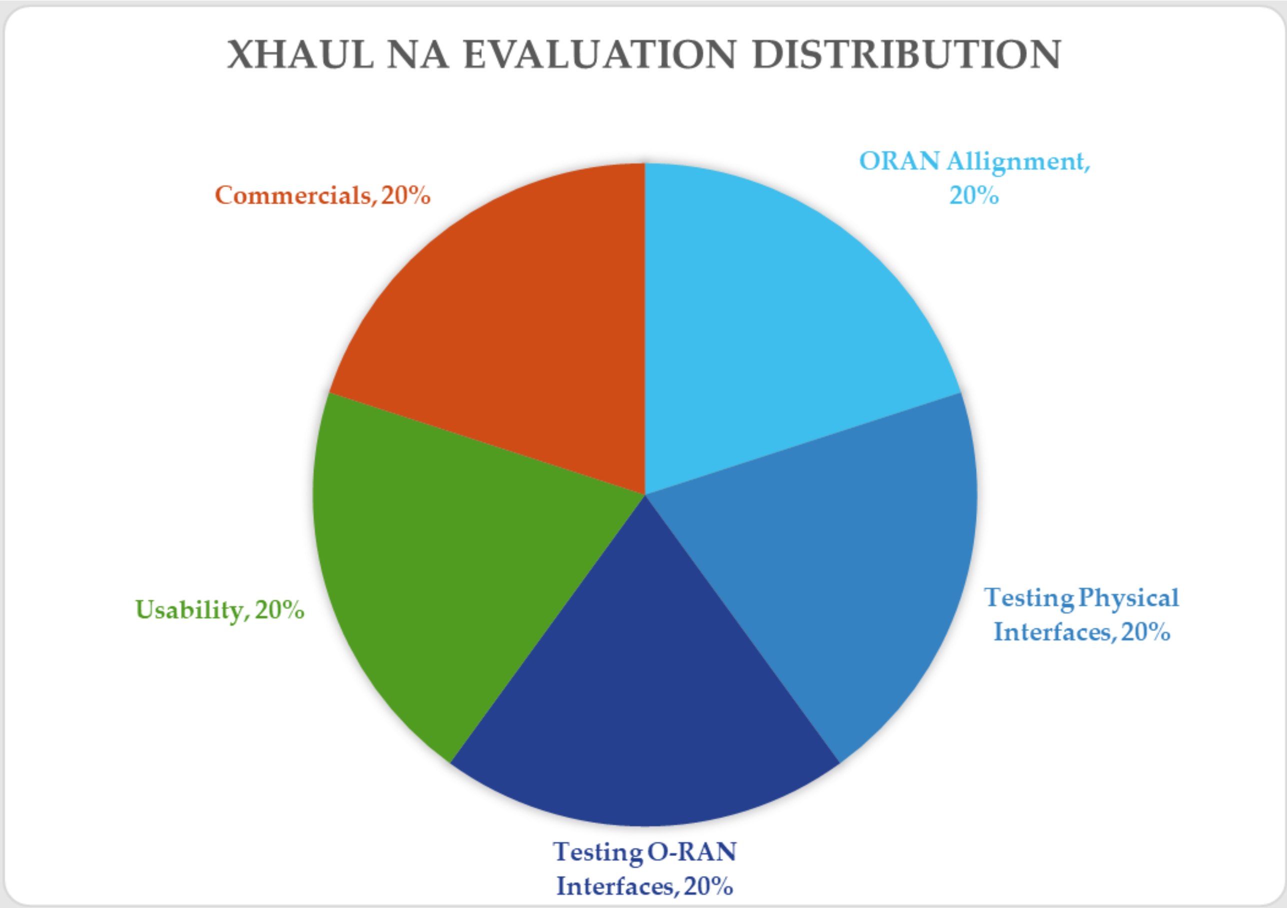

Figure 23 XHAUL PROTOCOL ANALYSER SELECTION CRiteria

Table 12 XHAUL PROTOCOL ANALYSER O-RAN ALIGNMENT

Category: ORAN Alignment (20% Weightage)	
Serial No	Feature
1	Strategic Alignment with other Open RAN related T&M tools
2	Support for O-RAN's WG4 IOT/Conformance Test Packages

Table 13 xhaul protocol analyser capabilities

Category: Testing Physical Interfaces (20% Weightage)	
Serial No	Feature
1	Testing the interface between different O-RAN subsystem for latency
2	Testing against the master PTP clock for timing synchronization across xHaul
3	Testing SFPs and Cables
4	Support of FO TAP interfaces

Table 14 xhaul protocol analyser o-ran testing capabilities

Category: Testing O-RAN Interfaces 20% Weightage)	
Serial No	Feature
1	Open Fronthaul eCPRI testing (CUSM plane test/ PTP test)
2	MidHaul or F1 Interface Testing
3	Xn Interface testing (for future use)
4	E1/E2/O1/O2 Interface testing
5	Backhaul Interface testing

Table 15 xhaul protocol analyser usability and accessability

Category: Usability (20% Weightage)	
Serial No	Feature
1	Remote Testing Capabilities
2	GUI rating: Measurements/Testing Overall
3	Test Report and its extraction (cover wireshark logging)

Table 16 xhaul protocol analyser cost and technical support

Category: Commercials: Cost & Technical Support (20% Weightage)	
Serial No	Feature
1	Pre-Sales Commercial Support
2	Pre-Sales Technical Support
3	Cost (one off buy)

3.3.5.Selection criteria for RF Scanner

The selection criteria for the RF Scanner focused on 3 criteria with varying weightage. These criteria were namely usability, feature support both accounting for 25% weightage and finally commercials taking 50% weightage as these RF scanners are quite matured tool and hence the focus was more on the price of this test tool. Each criterion had sub features as part of it which were scored out of 10. Please note, the RF scanners are usually resold by some of the E2E logging tool vendors.

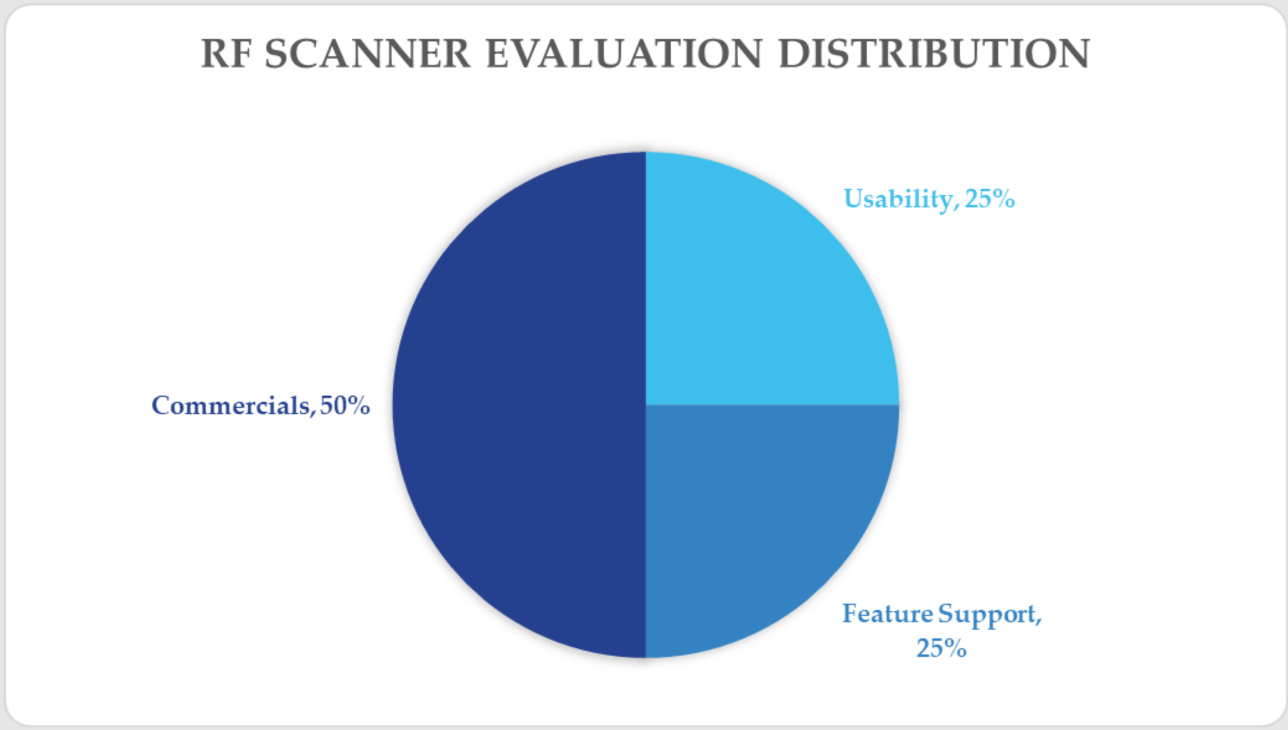

FIGURE 24 RF SCANNER SELECTION CRITERIA

TABLE 17 RF SCANNER USABILITY

Category: Usability (25% Weightage)	
Serial No	Feature
1	Should be able to be controlled by E2E benchmarking tool
2	Scanner should have its own GUI apart from E2E benchmarking tool
3	Should be able to work without GNSS feed.
4	Test Tool should come with Omnidirectional and Directional antennas recommended by supplier
5	Portability to carry out walk or drive test

TABLE 18 RF SCANNER FEATURES

Category: Feature Support (25% Weightage)	
Serial No	Feature
1	Real time spectrum scanner for LTE/NR/CATM/NB-IOT
2	Decoding Broadcast signals of the cells (MIBS/SIBS)
3	Sub 6 GHz FR1 band support

4	mmWave FR2 band Support
5	Beam identification & analysis (MIMO and multiple CC)
6	Power measurements (RSRP, RSRQ, SINR) for PS, SS
7	Real time ability to plot and show other cells around (interference)

Table 19 RF scanner cost and technical support

Category: Commercials (50% Weightage)	
Serial No	Feature
1	Existing Relationship (Other RF products)
2	Cost (InfoVista)
3	Cost (Keysight)
4	Cost (Accuver)
5	Cost (R&S)

3.4. Overview of interoperability, E2E performance and reliability tests

The default chains of the first phase of the SONIC Labs will provide baseline cases for benchmarking against additional nine targeted combinations of vendors provided in Table 20. Each chain will undergo integration and interoperability tests to ensure all the components, functions, and interfaces of each chain operational as shown in Figure 25 and Figure 26.

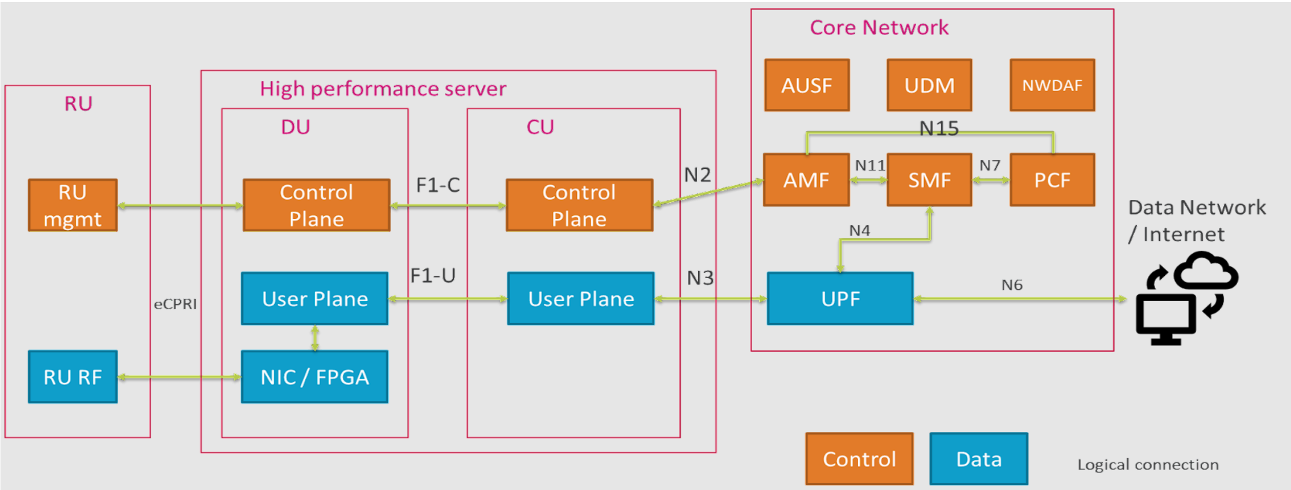

FIGURE 25 CHAIN COMPONENTS, FUNCTIONS, AND INTERFACES

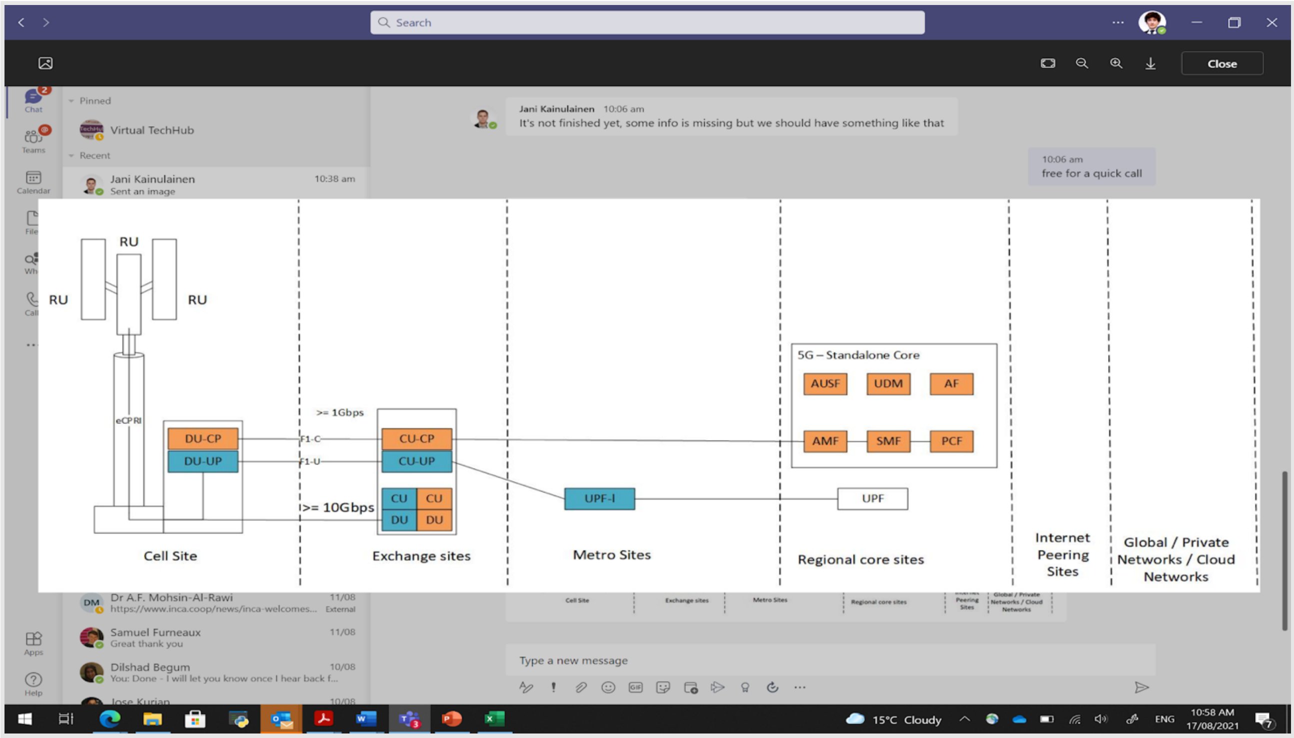

FIGURE 26 MAPPING OPEN RAN FUNCTION TO REALWORLD DEPLOYMENT EXAMPLE

Once a chain is completed and fully operational, it becomes the System Under Test (SUT) for the E2E system performance stage seen in Figure 27. The results of the E2E performance are then used to benchmark against the baseline cases.

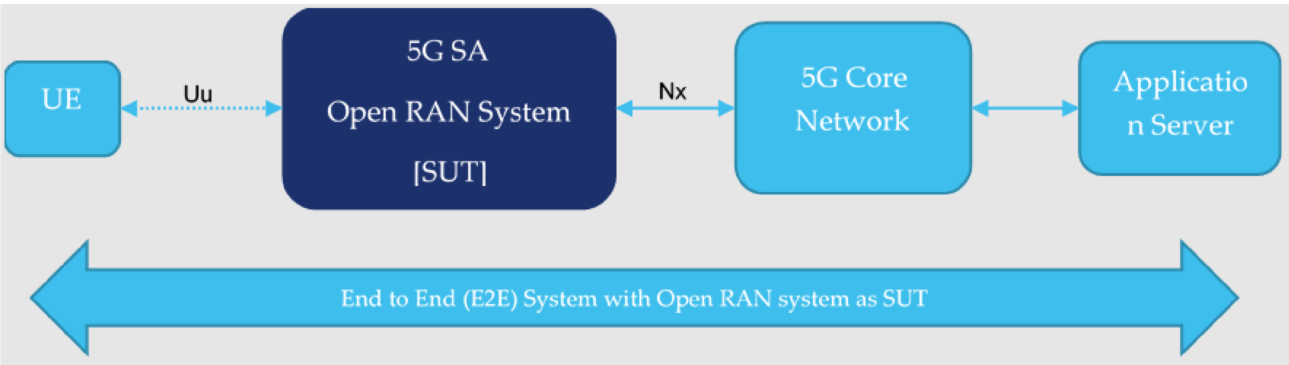

FIGURE 27 E2E SYSTEM PERFORMANCE

The first phase of SONIC Labs will focus on Interoperability Tests (IOTs) between different combinations of Open RAN vendors and peak downlink (DL) and uplink (UL) throughputs. The test procedures and methodologies are aligned with the relevant test specifications from the O-RAN Alliance. These are detailed in the following sections.

Table 20 Target deployment scenarios for testing

Category	Config	CN	CU	DU	RU
Baseline	1	Druid	Accelleran	Effnet/Phluido	Benetel
	2	Druid	Mavenir	Mavenir	Foxconn
	3	Radisys	Radisys	Radisys	Foxconn
CU, RU or CN Swap	4	Druid	Mavenir	Mavenir	Fujitsu
	5	Druid	Mavenir	Mavenir	Benetel
	6	Radisys	Accelleran	Radisys	Foxconn
	7	Druid	Mavenir	Mavenir	NEC
	8	Druid	Accelleran	Effnet/Phluido	Foxconn
	9	Druid	Radisys	Radisys	Foxconn
DU Swap	10	Druid	Mavenir	Radisys	Foxconn
	11	Radisys	Radisys	Effnet/Phluido	Benetel
	12	Radisys	Radisys	Mavenir	Foxconn

To complete the test cases listed above, it is preferred to use standard off-the-shelf test and measurements products (such as TEMS, QualiPoc, XCAL, Nemo, etc.). Indeed, when evaluating test equipment, automation features are prioritised to enable conducting 24-hour stability testing that includes the test UE performing downlink/uplink file transfers and ping tests. The data collected allowed us to characterise the distributions of these metrics (across all configurations tested) along with extracting the mean levels of performance. This is covered in more detail in D2.2 under Section 3.

Table 21 eCPRI message types

Message Type	Name
0	IQ Data
1	Bit Sequence
2	Real-Time Control Data
3	Generic Data Transfer
4	Remote Memory Access
5	One-Way Delay Measurement
6	Remote Reset
7	Event Indication
8	IWF Start-Up

9	IWF Operation
10	IWF Mapping
11	IWF Delay Control
12-63	Reserved
64-255	Vendor Specific

Where possible, tracing of the key interfaces (i.e. air interface, fronthaul, F1, E1 and E2) should also be undertaken. This will help in determining where an issue (when encountered) may reside within the chain, but also may provide an indication of how truly open these interfaces are. By means of an example, Table 21 lists the various eCPRI message types. We will probe and scrutinise the messages type over the fronthaul using a protocol analyser, the openness of the fronthaul will be assessed by quantifying how many messages of type 64 to 255 for vendor specific implementation.

3.5. Multi-vendor Integration and Interoperability tests

This section defines the integration and interoperability tests to build 5G SA operational Open RAN chains. The following sub-sections provide Tabulated test cases, procedures and expected results to determine a pass/fail outcome. On other hand, the purpose of the IOTs is to ensure that the Open RAN chains have open interfaces and support multi-vendor ecosystem. In Table 20, we highlighted a range of swapability cases involving different Open RAN components with particular focus on DU and RU combination to validate the openness of the O-FH interface. In the event of identifying a mismatch between DU and RU vendors, the E2E performance benchmarking under such scenario will be marked as failed and no KPIs will be reported. The cycle of testing is explained in Figure 28.

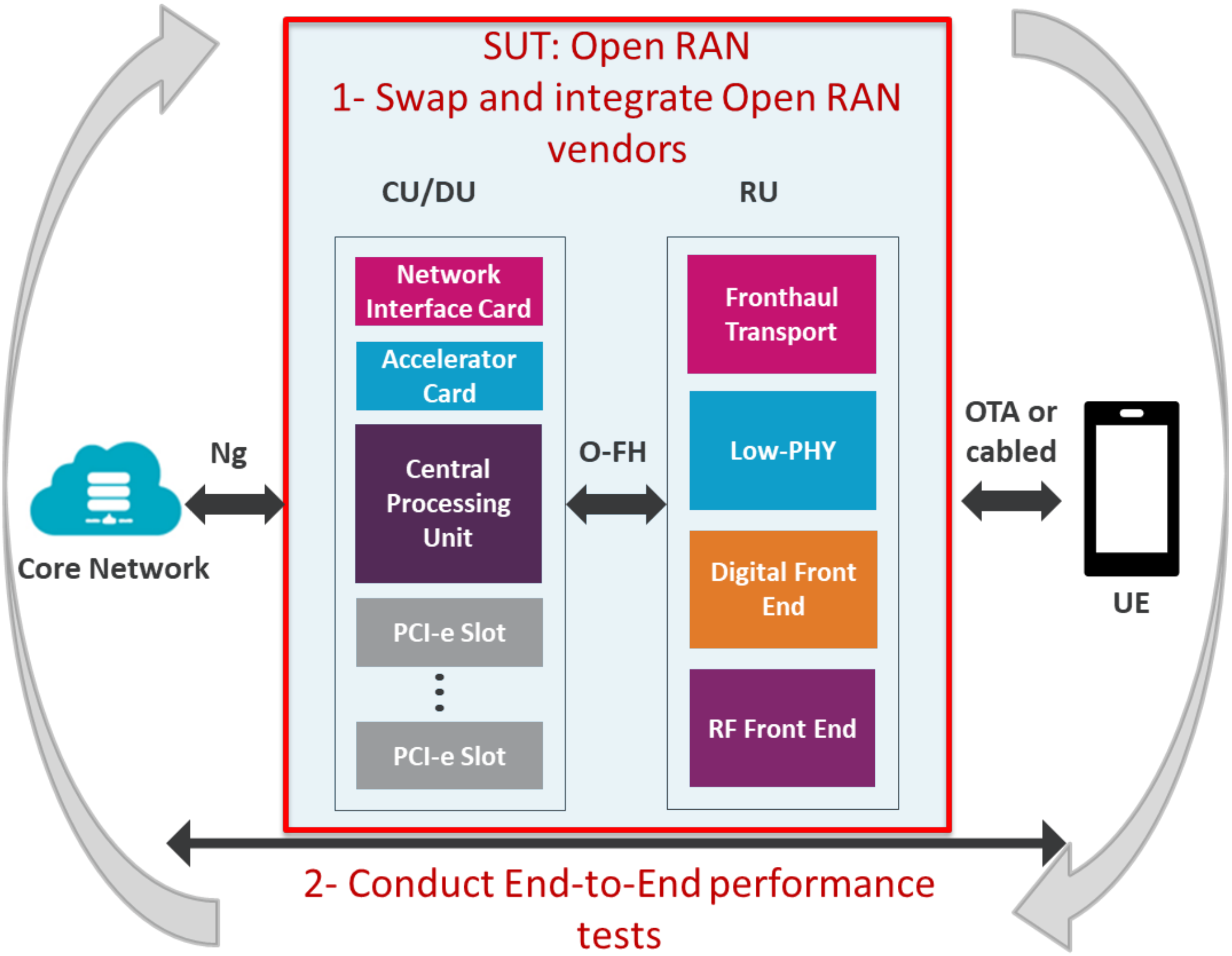

Figure 28 Testing cycle: swap, INTEGRATE, IOT, and capture SUT performance


CATAPULT
Digital

3.5.1.Deployment Test Cases, Procedures, and Expected Results

The deployment steps test cases including procedures, expected results and the possible outcomes are summarised in the Table 22.

TABLE 22 DEPLOYMENT TEST CASES, PROCEDURES, AND EXPECTED RESULTS

Test Case ID	Subsystem/ Interface Focus	Test Case Title	Test Procedure	Expected Result/Outcome
DEP_TC_1	CU-CP	CU CP NF Deployment	1.a Ensure Kubernetics platform is deployed if using container-based approach (Vendor Specific) 1.b Ensure Bare Metal platform is deployed if using baremetal based approach (Vendor Specific) 2. Depending upon vendor specific deployment run console commands. example commands to check pods "kubectl get pods"	1. Ensure CU CP services are instantiated and in service. 2. Alternatively check CU CP services are up and running on the CU/RIC/Management GUI as provided by the vendor.
DEP_TC_2	CU-UP	CU UP NF Deployment	See procedure of DEP_TC_1	1. Ensure CU UP services are instantiated and in service. 2. Alternatively check CU UP services are up and running on the CU/RIC/Management GUI as provided by the vendor.

DEP_TC_3	5G Core Network	5G Core Network NF Deployment	1. Ensure the platform on which the core network in running are instantiated and in service. 2. Ping the management IP address of the core network for the network connectivity check. 3. Login to 5G Core network terminal or GUI using its management IP and login credentials	1. Ensure that various 5G Core Network services (at least UPF, AMF & SMF) are instantiated and are in service. 2. Alternatively check 5G Core Network services are up and running using the management GUI of the core network.
DEP_TC_4	DU	DU NF Deployment	See procedure of DEP_TC_1	1. Ensure DU services are instantiated and in service. 2. Alternatively check DU services are up and running on the CU/DU/RIC/Management GUI as provided by the vendor.
DEP_TC_5	PTP	PTP Deployment	1. Ensure that the management port of the PTP server can be reached. 2. Login into the PTP server or grand master using its management GUI	1. Ensure ITU-T G.8275.1 profile (LLS-C1) is selected for PTP. 2. Ensure the PTP server and its services is correctly up and running 3. Ensure that the PTP Timing Port IP Address are reachable from both the DU and RU, respectively.
DEP_TC_6	RU	RU Deployment	1. Ensure that the management port of the RU can be reached from the DU as minimum to form the Fronthaul interface. 2. Ensure that the PTP feed has been provided to the RU	1. Ensure RU is ready and in the state to accept connection from the DU
DEP_TC_7	UE	USIM/APN Deployment	1. Ensure the UE being used for the testing support Stand Alone NR for band n77 and n78. Example device: One Plus 8T or One Plus NORD. 2. Ensure that the UE is populated with the USIM that has been configured on the core network. 3. Ensure the USIM has been correctly provisioned in the core network. Look for configuration such as PLMN, IMSI, Ki, OPC etc. are commissioned.	1. Once the cell is live, UE should automatically be able to register to the NR SA network.

			4. Ensure the UE configured with the correct APN settings as per the core network.	
DEP_TC_8	UE	UE Deployment	1. Ensure the UE being used for the testing support Stand Alone NR for band n77 and n78. Example device: One Plus 8T or One Plus NORD. 2. Ensure the UE diagnostic ports are exposed, and the device is in developer mode. 3. Ensure the UE can talk to the T&M laptop with E2E logging tool using a USB cable 4. Ensure that the E2E logging tool can also communicate with the UE and able to access its logging.	1. The UE and the T&M laptop can communicate with each other and retrieve UE logs and visualise it.
DEP_TC_9	Application Server(s)	Application Server(s) Deployment	1. IP connectivity between 5G Core UPF and Application server(s) is success. 2. Ensure that the firewall rules are correctly set to allow the UE to talk to Internet as well as locally hosted application server (s).	1. Once the cell is live, UE should be able to do both UL and DL data transmission with the 5G SA network.

3.5.2.Connectivity Test Cases, Procedures, and Expected Results

The connectivity test cases including procedures, expected results and the possible outcomes are summarised in the Table 23.

TABLE 23 CONNECTIVITY TEST CASES, PROCEDURES, AND EXPECTED RESULTS

Test Case ID	Subsystem /Interface Focus	Test Case Title	Test Procedure	Expected Result/Outcome

CON_TC_1	N2-Interface	CUCP - AMF Connectivity	1. IP Connectivity between CU CP and 5G CORE AMF is success. 2. Ensure AMF is listening for SCTP association with the CU CP. 3. Start tcpdump capture of the CU CP node and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine) 4. Restart (if needed) the CU-CP node and ensure CU CP pods are up and running 5. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.	1. Verify N2 Interface (SCTP connection between CUCP endpoint and AMF endpoint) is UP 2. Verify NGAP message "NGSetupRequest" is sent from CUCP to AMF 3. Verify NGAP message "NGSetupResponse" is received from CORE AMF to CUCP
CON_TC_2	N3-Interface	CUUP - UPF Connectivity	1. IP Connectivity between CU UP and 5G CORE UPF is success. 2. Start tcpdump capture of the CU CP or UP node and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine) 3. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.	1. Once UE start the registration process with the gNB then the N3 Interface can be verified. 2. Verify E1AP message "BearerContextSetupRequest" to contain the correct TLA N3 IP of CORE UPF. 3. Verify E1AP message "BearerContextSetupResponse" to contain the correct TLA N3 IP of CUUP.
CON_TC_3	E1-Interface	CUCP-CUUP Connectivity	1. IP Connectivity between CUCP and CUUP is success. 2. CUCP and CUUP is listening on port for SCTP association 3. Start tcpdump capture of the CU CP node and redirect the tcpdump packets to wireshark client for viewing it live.	1. Verify E1 Interface (SCTP connection between CUCP endpoint and CUUP endpoint) is UP 2. Verify E1AP message "E1SetupRequest" is

<table>
<tr><td></td><td></td><td></td><td>(example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine)
4. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.</td><td>sent from CUUP to CUCP.
3. Verify E1AP message "E1SetupResponse" is received from CUCP to CUUP - successful Outcome</td></tr>
<tr><td>CON_TC_4</td><td>F1C-Interface</td><td>CU CP - DU Connectivity</td><td>1. IP Connectivity between CUCP and DU is success.
2. CUCP and DU is listening on port for SCTP association
3. Start tcpdump capture of the CU CP node and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine)
4. Restart (if needed) the DU node and ensure CU CP pods are up and running
5. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.</td><td>1. Verify F1C interface (SCTP connection between CUCP endpoint and DU endpoint) is UP
2. Verify F1AP message "F1SetupRequest" is sent from DU to CUCP
3. Verify F1AP message "F1SetupResponse" is received from CUCP to DU – successful Outcome
4. Using the F1AP message "F1SetupRequest" retrieve the MIB and SIB1 information to see the common cell configurations for later use to compare and contrast various Open RAN deployments using E2E benchmarking test.</td></tr>
<tr><td>CON_TC_5</td><td>F1U-Interface</td><td>CU UP - DU Connectivity</td><td>1. IP Connectivity between CUUP and CORE UPF is success
2. Start tcpdump capture of the CU CP or UP node and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine)</td><td>1. Once UE start the registration process with the gNB then the F1U Interface can be verified.
2. Verify F1U interface (SCTP connection between CUUP endpoint and DU endpoint) is UP
3. Verify F1AP message "UEContextSetupResponse" from DU to CUCP to contain the correct CUUP-F1U IP.</td></tr>
</table>

			3. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.	
CON_TC_6	O-Fronthaul Interface	DU-RU connectivity	1. IP Connectivity between DU and RU is success for both management and data plane interfaces.	1. The RU and DU can communicate with each other over interfaces to each other.
CON_TC_7	PTP	PTP DU-GrandMaster Connectivity	1. IP Connectivity between PTP GM port and DU is success 2. Ensure that the timing synchronisation is being correctly received by DU using vendor specific commands or method. 3. If needed and available, use the T&M kit xHaul analyser to measure the timing in case of anomalies. (Procedure to test timing using the xHaul analyser might vary from T&M kit to T&M kit)	1. The DU should be able to receive PTP time synchronisation either directly or over a PTP aware switch.
CON_TC_8	PTP	PTP RU-GrandMaster Connectivity	0. IP Connectivity between PTP GM port and RU is success 2. Ensure that the timing synchronisation is being correctly received by RU using vendor specific commands or method. 3. If needed and available, use the T&M kit xHaul analyser to measure the timing in case of anomalies. (Procedure to test timing using the xHaul analyser might vary from T&M kit to T&M kit)	1. The RU should be able to receive PTP time synchronisation either directly or over a PTP aware switch.

3.5.3. O-FrontHaul (O-FH) Test Cases, Procedures, and Expected Results

The fronthaul test cases including procedures, expected results and the possible outcomes are summarised in the Table 24.

TABLE 24 OPEN-FRONTHAUL TEST CASES, PROCEDURES, AND EXPECTED RESULTS

Test Case ID	Subsystem/ Interface Focus	Test Case Title	Test Procedure	Expected Result/Outcome
OFH_TC_1	O-FrontHaul	S-Plane Test from WG4 Functional test of O-DU + O-RU using ITU-T G.8275.1 profile (LLS-C1)	These tests use the O-RAN M-Plane and O-DU NMS features. The O-DU must act as a PTP master compliant with the ITU-T G.8275.1 towards the FH interface under three conditions: • Startup • Nominal • degraded:	The O-RU is synchronising from the O-DU in accordance to the ITU-T G.8275.1 profile. This test case validates the correct synchronisation status of the O-RU.
OFH_TC_2	O-FrontHaul	M-Plane Test from WG4 Start-up in hierarchical mode	1) Transport layer initialisation 2) RU calls home to NETCONF client (TCP connection establishment) 3) Establish SSH Secure connection establishment 4) Validate NETCONF Capability discovery 5) Supervision of NETCONF connection 6) Retrieve of O-RU information and Additional configuration 7) Software management 8) Check C/U-Plane transport connectivity between O-DU and O-RU	Observe that both the O-DU and O-RU get in service successfully by monitoring correct transmission of 36 synchronisation signals and broadcast channel (i.e., PSS/SSS and SSB). Record values for downlink carrier frequency, cell, system information and SSB indices must match the radio setup configuration.

			9) Check U-Plane configuration between O-DU and O-RU 10) Fault and performance management activation 10) Retrieve of O-RU state, including synchronisation information, from O-RU 11) Configure the O-RU operational parameters: carrier activation	
OFH_TC_3	O-FrontHaul	Vendor Specific eCPRI packets	1. Using the xHaul analyser and nTAP, split the optic interface between DU and RU without affecting the performance of the O-FH interface. 2. Output of the split interface for both DU to RU and RU to DU should be then monitored by the xHaul network/protocol analyser. 3. Turn on th "capture" on the FH interface for both directions 4. Save the captured pcap file and export it to an external PC for easier visualisation. 5. Tester can also be configured to capture the packet count for vendor specific messages in the trace once the vendor specific message type (64-255) is known.	1. If on tracing the fronthaul we find a reasonable proportion of messages transferred are of type 64 to 255 then this may indicate an interface that is not truly open and will warrant further exploration 2. Refer to Table 15 eCPRI message typesin the document for the breakdown of different eCPRI message types.
OFH_TC_4	O-FrontHaul	Security on eCPRI packets	1. Using the xHaul analyser and nTAP, split the optic interface between DU and RU without affecting the performance of the O-FH interface. 2. Output of the split interface for both DU to RU and RU to DU should be then monitored by t 3. Turn on the "capture" on the FH interface for both directions 4. Save the captured pcap file and export it to an external PC for easier visualisation.	1. Look at captured eCPRI packets on the fronthaul interface ensure that the payload of the eCPRI are ciphered. 2. If not, understand from the vendor for the reasons for not "protecting" the eCPRI payload.

3.5.4. Acceptance criteria

The acceptance criteria test cases including procedures, expected results and the possible outcomes are summarised in the Table 25.

TABLE 25 ACCEPTANCE CRITERIA

Test Case ID	Subsystem/ Interface Focus	Test Case Title	Test Procedure	Expected Result/Outcome
ACC_TC_1	Open RAN as a whole	Cell Radiating	1. Ensure the cell is radiating at the frequencies and power that has been agreed with Ofcom licensing. 2. Using a RF Scanner or Spectrum analyser test and measure the RF health of the cell. 3. Ensure that the cell is transmitting its broadcast channels (MIBs and SIBs) and it can be verified using the UE or RF scanner logs in the E2E logging tool.	1. Phase 1 test focuses the test in excellent RF conditions. 2. Both UE and RF Scanner logs should record minimum performance of RSRP >-75 dBm and downlink SINR (dB) >25

ACC_TC_2	Open RAN as a whole	UE Registration	1. Ensure CUCP/CUUP/DU/RU are deployed and inservice and the cell is radiating 2. Ensure 5G CORE AMF is inservice 3. Power ON 5G UE (take it out of airplane mode) 4. Latch onto 5G SA Network 5. Start tcpdump capture of the CU CP node and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine) 6. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark. 7. UE starts registration procedure	Using the UE and the T&M laptop containing the E2E logging tool and captured pcap do the following. 1. Verify RACH Procedure 2. Verify RRC Setup Procedure is successful between UE and gNB 3. Verify UE sends RRCSetupComplete[dedicatedNAS-Message:Registration-Request] to gNB 4. Verify GnB-CU-CP sends NGAP Initial UE Message [NAS-PDU:Registration Request] to AMF over N2 interface 2. Verify NGAP message "NGSetupRequest" is sent from CUCP to AMF. 3. Verify NGAP message "NGSetupResponse" is received from CORE AMF to CUCP 3. Verify Authentication with AUSF is successful 4. Verify AMF obtains Subscription data from UDM successfully 5. Verify AMF sends Nsmf_PDUSession_UpdateSMContext Request to SMF to setup user plane function 6. Verify SMF sends PFCP Session Modification Request to UPF and gets back PFCP Session Modification Response from UPF 7. Verify SMF sends Nsmf_PDUSession_UpdateSMContext Response to AMF 8. Verify AMF sends Initial Context Setup Request [NAS-PDU: Registration Accept] to gNB

				9. Verify GnB sends RRCReconfiguration [Registration Accept] to UE successfully 10. Verify UE Registration is successfully complete

ACC_TC_3	Open RAN as a whole	PDU Session establishment	1. Ensure CUCP/CUUP/DU/RU are deployed and inservice and the UE has registered to the SA network successfully. 2. 5G CORE AMF and SMF are inservice 3. Ensure the "mobile data" is turned on the device so that UE triggers PDU establishment with the network. 4. Ensure tcpdump capture of the CU CP node (should have started before UE registration) and redirect the tcpdump packets to wireshark client for viewing it live. (example: C:\Program Files\PuTTY\plink.exe -ssh -batch -pw XXX2304 xxx@10.120.150.XX tcpdump -U -s0 'sctp or udp port 2152' -i any -w - | "C:\Program Files\Wireshark\wireshark.exe" -i - -k which re-directs tcpdump from a linux machine to controlling windows machine) 5. Analyse captured pcap with the filter "f1ap || rrc || ngap || e1ap" using wireshark.	Using the UE and the T&M laptop containing the E2E logging tool and captured pcap do the following. 1. Verify UE sends UL NAS TRANSPORT message for PDU Session Establishment Request over N2 interface 2. Verify AMF send Node Discovery message for SMF selection 2a. Verify AMF sends Nsmf_PDUSession_CreateSMContext Request to SMF over N4 interface. 3. Verify SMF sends Node Discovery message for UP selection 4. Verify AMF sends N2 PDU Session Resource Setup Request (NAS msg) to gNB CU-CP over N2 interface 5. Verify gNB sends AN specific resource setup for the UE to allocate gNB N3 Tunnel. 6. Verify that The gNB-CU-CP sends BEARER CONTEXT SETUP REQUEST to gNB-CU-UP over E1AP Interface 7. Verify that the gNB-CU-UP responds with a BEARER CONTEXT SETUP RESPONSE message containing the UL TNL address information for F1-U, and DL TNL address information for S1-U or NG-U. 8. Verify that gNB-CU-CP sends a BEARER CONTEXT MODIFICATION REQUEST message containing the DL TNL address information for F1-U and PDCP status. 9. Verify that gNB-CU-UP responds with a

				BEARER CONTEXT MODIFICATION RESPONSE message 10. Verify gNB sends the tunnel information to UPF via AMF and SMF in N2 PDU Session Request Ack response message over N2 interface
ACC_TC_4	Open RAN as a whole	External Data sessions	1. Ensure CUCP/CUUP/DU/RU are deployed and inservice and the UE has registered to the SA network successfully and established PDU session 2. Ensure UE is using the mobile data and not WiFi data. Also look at about UE in its settings to see if the UE has been allocated IPv4/IPv6 address from the SA network. 3. Initiate a ping to 8.8.8.8 (google server) and look at the ping responses using the E2E logging tool. 4. initiate a ping to internal application server(s) and look for the ping responses using the E2E logging tool	1. Ensure that UE can successfully ping external and internal application servers to form the E2E data connectivity.

3.6. E2E Performance Testing Methodologies and Benchmarking

In this section, we define the guiding principles and methods for fair and repeatable E2E testing for SONIC Labs Phase 1. We aligned our tests' procedures and methodologies to O-RAN Alliance. The system under test (SUT) is an Open RAN chain treated as a black box between a UE and an application server as shown in Figure 27. To ensure fairness and repeatability, test conditions, methodologies, procedures, and system under test configurations must be all recorded. Given the nature of SONIC Labs being indoors, the testing environment is laboratory-based. Although O-RAN Alliance suggests that laboratory tests should be conducted over cable or inside shielded box if OTA, careful spectrum characterisation and RU – UE alignment/positioning can offer a valid approach if testing over cable or in shielded box are not available. We will fully characterise and report the frequency bands and radio conditions for each chain and each location prior to testing.

Interoperability tests as well as all Open RAN components must be tested prior to E2E testing following the procedures and acceptance criteria from section 0. Open RAN chains (SUTs) will be differentiated based on their RF performance, radio interface adaptation, scheduling, and overhead management.

Reporting should provide the necessary information to allow replicating test conditions and results for fair comparison and benchmarking. The test procedures, conditions and reporting in this section have been extracted from O-RAN Alliance Test and Integration Focus Group End-to-end Test Specification and adapted to SONIC Labs Phase 1. Table 26 summarises minimum set of configuration parameters and information about the test environment and SUT.

Table 26 configurations of test environment and SUT at glance

Carrier frequency	
Total bandwidth	
Number of total RBs	
Number of sub-carriers	
Duplex mode	
Sub-carrier spacing	
Carrier prefix length	
Slot length	
Number of supported MIMO layers at both eNB/gNB and UE sides	
Antenna configuration at both gNB and UE sides	
Transmit power at antenna connectors at both gNB and UE sides	
Transmit power PSD (gNB/UE)	
Antenna gains at both gNB and UE sides	

DL/UL ratio (configuration) TDD duplex mode	
Test UE position with respect to O-RU antenna	Monitor RSTP vs RSRP across RUs to be within <3 dB
Deployment scenario	
List of T&Ms	
The Operating Systems at UE and application server	
SUT hardware	
SUT software	
SUT parameters and configuration	
Traffic conditions during test (full/finite buffer traffic model)	UDP & TCP
Mobility conditions	Stationary (Phase 1)
Interference conditions (load 0,30,…100%)	0%, i.e. single cell (Phase 1)
Radio conditions (thresholding provided in table 3)	LOS with integers of 2m without change of azimuth or integers of 49 dB using RF attenuator per antenna port (Phase 1)

3.6.1. Target Radio Conditions for SONIC Labs Phase 1

In Phase 1, SONIC Labs will consider excellent radio conditions where the UE is stationary served by a single RU with no interference (Single cell deployment). Radio conditions are assessed by measuring RSRP and SINR for given test & SUT configurations. RSRP values should be used for UL assessments, and the SINR values for DL assessment, thresholding of these parameters are provided in the following table.

TABLE 27 RADIO CONDITIONS THRESHOLDING

Radio conditions	RSRP (dBm) SS-RSRP (dBm)	DL SINR (dB) DL SS-SINR (dB)	MCS & MIMO Rank
Excellent (cell centre)	> -75	> 25	Highest MCS & MIMO rank (peak rates)
Good	-75 to -90 (typical -85)	15 to 20 (typical 17)	Out of scope
Fair	-90 to -105 (typical -95)	5 to 10 (typical 7)	Out of scope

Poor	< -105 (Typical -110)	< 5 (typical 3)	Lowest MCS & MIMO rank (lowest rates)

3.6.2. Functional Tests' Procedures and KPIs: Registration and Deregistration of single UE

The test setup is a single RU with a single stationary UE placed under excellent radio conditions using

SS-RSRP as the main KPI as shown in Table 27.

Test procedure for SONIC Labs Phase 1 goes as follows:

1. Test configurations must be fully recorded in Table 26.
2. RU of the SUT must be unloaded and ensure no interference.
3. Power on the UE, it shall send REGISTRATION REQUEST message and it shall successfully register.
4. Initiate full-buffer UDP bi-directional data transmission between the application server and UE.
5. The registration procedure messages shall be captured, and the latency of the registration procedure shall be measured and recorded in Table 12. The duration of the test should be at least 3 minutes when the throughput is stable. The PDU session establishment procedure messages shall also be captured and verified.
6. Power off the UE and UE shall send DEREGISTRATION REQUEST message. UE shall successfully de-register from the 5G SA network.
7. The de-registration procedure messages shall be captured, and the latency of de-registration procedure shall be measured and recorded in Table 28. The PDU session release procedure messages shall also be captured and verified.
8. Capture radio parameters such as RSRP, RSRQ, CQI, PDSCH SINR and Throughput (average sample per second)
9. Repeat steps 3 to 8, for a total of 10 times and record the KPIs mentioned in Table 28.

Table 28 SA registration/de-registration latency KPI record table of single UE

KPI	Repeat time										Calculation		
	1	2	3	4	5	6	7	8	9	10	Min	Max	Av.
Registration Time (millisecond)													
De-registration Time (millisecond)													

3.6.3.E2E U-Plane latency test

The test setup is a single RU with a single stationary UE placed under excellent radio conditions using

SS-RSRP as the main KPI as shown in Table 27.

Test procedure for SONIC Labs Phase 1 goes as follows:

1. Test configurations must be fully recorded in Table 26.
2. RU of the SUT must be unloaded and ensure no interference.
3. Power on the UE, it shall send REGISTRATION REQUEST message and it shall successfully register followed by PDU establishment so end to end data transmission can be performed.
4. Initiate ICMP ping bi-directional data transmission between the application server and UE.
5. Capture radio parameters such as RSRP, RSRQ, CQI, PDSCH SINR and Throughput (average sample per second).
6. Repeat for 10 times.

TABLE 29 LATENCY (RTT) TESTS' KPIS

KPI	Repeat time									Calculation		
	1	2	3	4	5	6	7	8	9	10	Min	Max	Average
DL Pings													
UL Pings													

3.6.4.Peak Performance Tests: DL Throughput Tests' Procedures and KPIs

The E2E performance testing will assess the peaks of KPIs for a single stationary UE in under excellent radio conditions in a single cell according to Table 27.

The purpose of the test is to measure the maximum achievable user data throughput in the downlink direction.

The test procedure for SONIC Labs Phase 1 goes as follows:

1. The test configuration should be recorded in the format of Table 26
2. RU of the SUT must be unloaded and ensure no interference.
3. The UE must be placed under excellent radio conditions according to the SINR thresholds in Table 11.

4. The UE is powered on and registered to the network.
5. Initiate and verify downlink full-buffer UDP data transmission from the application server.
6. The UE should achieve peak and stable throughput over the highest possible downlink MCS, downlink transport block size and downlink MIMO rank (number of layers).
7. Capture KPIs in the format of Table 30. The duration of the test should be at least 3 minutes when the throughput is stable. The location and position of the UE should remain unchanged during the entire measurement duration.
8. The UE should be turned off or set to airplane mode, if possible, to empty the buffers.

The capture of log data is stopped. The downlink full-buffer UDP data transmission from the application server is stopped.

0. The UE should be turned off then on again using, e.g. airplane mode, to empty the buffers.
0. Start the downlink full buffer TCP data transmission from the application server to the UE
0. Repeat 6 to 9

TABLE 30 DL TEST RESULTS (MEDIAN AND STANDARD DEVIATION FROM THE CAPTURED SAMPLES)

	UDP	TCP
Transmitted DL throughput		
Received L1 DL throughput [Mbps]		
L1 DL Spectral efficiency [bps/Hz]		
Received Application DL throughput [Mbps]		
RU RSTP & PDSCH [dBm]		
UE RSRP [dBm]		
UE RSRQ [dB]		
UE SINR [dB]		
MIMO rank		
PDSCH MSC		
DL PRB number		
PDSCH BLER [%]		

3.6.5.Peak Performance Tests: UL Throughput Tests' Procedures and KPIs

Repeat the DL peak throughput procedure with the exception of UDP and TCP data transmission flow from the UE to the application server and capture KPIs in Table 31.

TABLE 31 UL TEST RESULTS (MEDIAN AND STANDARD DEVIATION FROM THE CAPTURED SAMPLES)

	UDP	TCP

Transmitted UL throughput		
Received L1 UL throughput [Mbps]		
L1 UL Spectral efficiency [bps/Hz]		
Received Application UL throughput [Mbps]		
PUSCH transmit power [dBm]		
UE RSRP [dBm]		
UE PDSCH SINR [dB]		
UE SINR [dB]		
MIMO rank		
PUSCH MSC		
UL PRB number		
PUSCH BLER [%]		

3.6.6.E2E Reliability Tests

This is a set of the functional, latency and peak DL/UL throughput tests run in a periodic fashion, e.g. once every hour, for 24 hours. The tests must be run for a single RU and a single stationary UE under excellent conditions. The test procedures for the individual tests are defined in sub-sections 4.62.,4.6.3,4.6.4 and 4.6.5. The latency measures must be recorded in Table 32.

TABLE 32 RELIABILITY TESTS

Duration (hrs)	PDU/call drops	DL average throughput	UL average throughput	Average RTT
1				
2				
3				
4				
…				
24				

3.7. Reference Chains Experimental Setup

3.7.1.Accelleran Reference Chain Setup

Accelleran chain is deployed in the Future Networks Lab (FNL) in the Digital Catapult in London. The chain assembled out of 4 vendors with a Druid Core, Accelleran (CU), Effnet (DU High Phy & RLC), Phluido (DU Low Phy) and Benetel (RU) as shown in Figure 29. Phluido and Effnet interface with each other's over the FAPI interface which is not an Open RAN interface.

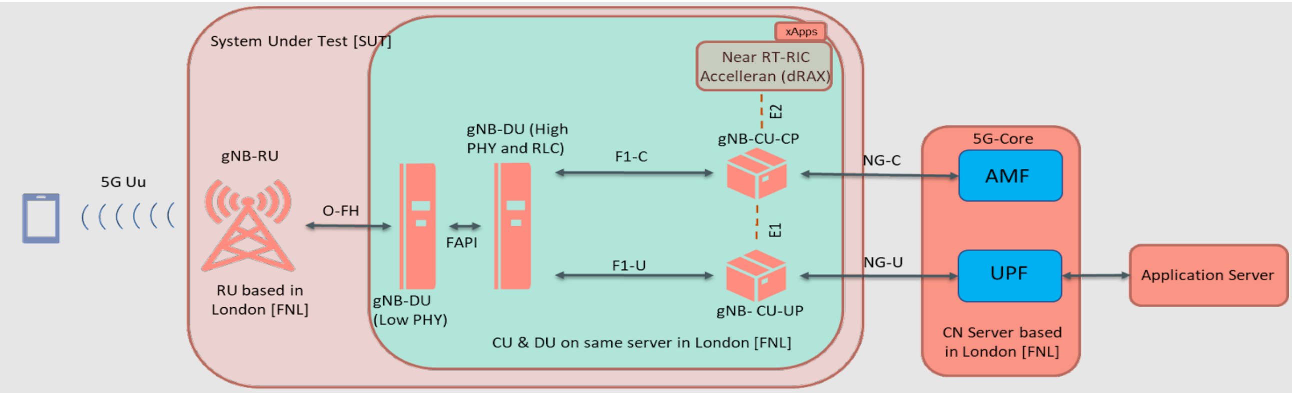

FIGURE 29 ACCELLERAN CHAIN

The testing for Accelleran has been conducted in an indoor lab environment for a single RU and stationary UE both placed inside a shielded box (with no interference) with excellent radio conditions as described in section 4.6.1. In Figure 30, we provide a snapshot to the radio conditions from the time of our test campaign for Accelleran.

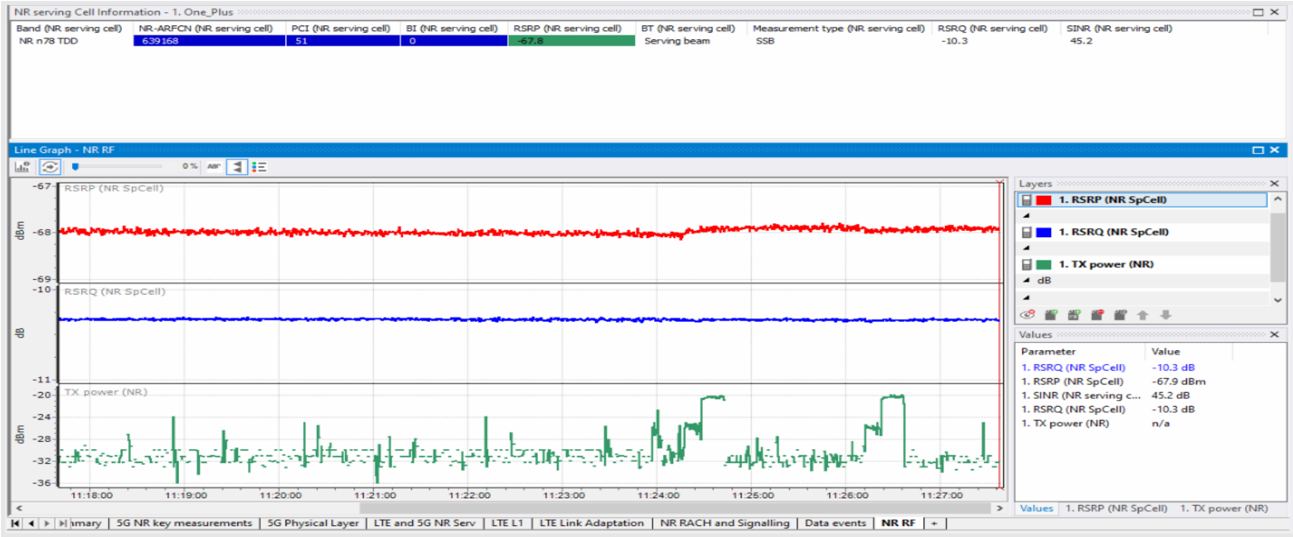

FIGURE 30 ACCELLERAN RADIO CONDITIONS

Table 33 lists the key RAN configurations of the Accelleran chain. The set of T&M equipment used in the following test campaign are:

1. Keysight NEMO outdoor: collecting UE measurements, e.g. RSRP, NR protocol messaging stack, latency.
2. Keysight NEMO PBM: data analytics and visualisation of the UE measurements collected from the tests.
3. Faraday cage/ shield box: this to isolate the RU and UE from external radio conditions and ensure excellent signal levels.
4. R&S FSW26.5 Signal Analyser: characterise the radio conditions and the air-interface of 5G NR.
5. Directional antenna horn: used to probe the air-interface of 5G NR. With ~ 12 dBi at 3.5GHz.
6. Cabling: coax cables used for the FSW and USB cables used to connect the UE NEMO indoor and exchange data and commands with the NEMO outdoor.
7. Wireshark: used alongside tcpdump to capture traffic across various interfaces in the RAN chain.
8. Application server: this is used to terminate the RAN chain with data source and sink. From the core side CentOS Linux 7 was used whilst the UE is run with Android 11.

The selected T&M list was established via an intensive evaluation exercise described in Section 3.3.

TABLE 33 ACCELLERAN CONFIGURATION AT GLANCE

Configurations of test environment and SUT at glance	
Carrier frequency	n78 - SSB carrier: 639168 ARFCN (7907 GSCN, 3587.52 MHz)

Total bandwidth	40 MHz
Number of total RBs	106
Number of sub-carriers	1272
Sub-carrier spacing	30 KHz
Cyclic prefix length	0.26 us
Slot length	500us (14xOFDM symbol)
Number of supported MIMO layers at both eNB/gNB and UE sides	2 DL and 1 UL
Antenna configuration at both gNB and UE sides	RU: 2x2 MIMO omni antennas- UE: OnePlus 8T
Transmit power at antenna connectors at both gNB and UE sides	RU: UE:23dBm
Transmit power PSD (gNB/UE) (dBm/Hz)	~ -82 dBm/Hz (cabled - hence no antenna/MIMO gain)
Antenna gains at both gNB and UE sides	Combined gain estimated to 10-15 dBi
DL/UL ratio (configuration) TDD duplex mode	DL: 0.75 - UL: 0.25
The Operating Systems at UE and application server	UE: Android - Application server: CentOS Linux 7
SUT hardware	CN-CU-DU: Dell740 / RU: Benetel
SUT software	CN: Druid Raemis Enterprise v4.6.0.1-1; RIC: Drax: ric-3.0.0-rc5; CU: Accelleran release-2.2-chimay-966d907; DU: Effnet 0630 (release of 30th of June); DU: Phluido L1/Phluido: 0.8.1-r3852; RU: Benetel verxxx
SUT parameters and configuration	Single BWP, best effort QoS
Traffic conditions during test (full/finite buffer traffic model)	UDP & TCP
Mobility conditions	Stationary
Interference conditions	0%, i.e. single cell
Radio conditions (thresholding provided in table 3)	Excellent radio conditions (SINR >25 dB, SS-RSRP > -75 dBm)

3.7.2.Radisys Reference Chain Setup

There are two Radisys chains. One is deployed and distributed between two of the Digital Catapult sites, core network (CN) being deployed in the FNL (Digital Catapult offices in Euston Road, London) whilst the CU, DU and RU are all deployed in Digital Catapult's 5G Testbed in Fusebox in Brighton. This chain is assembled out of Radisys Core, CU, DU and a Foxconn RU. The second chain is deployed and distributed in a similar fashion to the first chain but distributed between the FNL (Core Network software) and Ofcom's Riverside House (RSH) in London.

Figure 31 illustrates the Radisys deployment scenario consisting of O-RAN complaint functions & interfaces and the CU in this deployment is also located at the edge cite along with DU and RU in Fusebox, Brighton. The CU is connected to 5G Core Network from Radisys in Digital Catapult network operation centre remotely. The RIC function is not present in this chain. The CU & DU is hosted on stand-alone server which is then connected to RU on an Open-fronthaul interface.

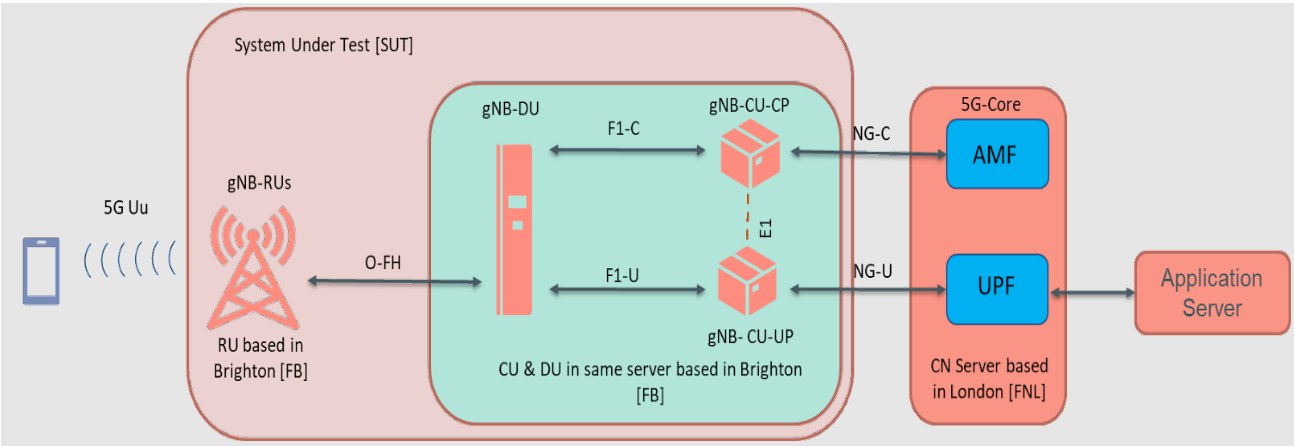

Figure 31 Radisys chain

Table 34 Radisys configuration at glance

Configurations of test environment and SUT at glance	
Carrier frequency	n78, PointA: 3.4716 GHz, SSB: 3.47952 GHz, Offset to Carrier: 0
Total bandwidth	100 MHz
Number of total RBs	273
Number of sub-carriers	3276
Sub-carrier spacing	30 KHz
Cyclic prefix length	Normal
Slot length	500us (14xOFDM symbol)
Number of supported MIMO layers at both eNB/gNB and UE sides	2 DL and 1 UL
Antenna configuration at both gNB and UE sides	RU: 4 omni antenna elements; UE: OnePlus 8T
Transmit power at antenna connectors at both gNB and UE sides	RU: UE:23dBm
Transmit power PSD (gNB/UE) (dBm/Hz)	TBC
Antenna gains at both gNB and UE sides	TBC
DL/UL ratio (configuration) TDD duplex mode	DL: 0.75 - UL: 0.25
The Operating Systems at UE and application server	UE: Android 11 - Application server: CentOS Linux 7
SUT hardware	CN-CU-DU: Dell740 / RU: Foxconn
SUT software	CN: Radisys-TRILLIUM_5GCN_SMF/AMF/UPF_BIN_REL_2.3.2; CU/DU: Radisys Version 2.3.0_28Jan2021; RU: Foxconn verxxx
SUT parameters and configuration	Single BWP, best effort QoS
Traffic conditions during test (full/finite buffer traffic model)	UDP & TCP
Mobility conditions	Stationary
Interference conditions	0%, i.e. single cell
Radio conditions (thresholding provided in table 3)	Excellent radio conditions (SINR >25 dB, SS-RSRP > -75 dBm)

Table 34 lists the key RAN configurations for the Radisys chain. Some of the configurations have not be measured due to ongoing debugging and integration on both chains (Ofcom and Digital Catapult).

The set of T&Ms used in the following test campaign are given as follows:

1. Keysight NEMO outdoor: collecting UE measurements, e.g. RSRP, NR protocol messaging stack, latency, … etc.
2. Keysight NEMO PBM: data analytics and visualisation of the UE measurements collected from the tests.
3. R&S Handheld spectrum analyser: used to measure the power spectrum of the RU.
4. Directional antenna horn: used to probe the air-interface of 5G NR. With ~ 12 dBi at 3.5GHz.
5. Cabling: coax cables used for the FSW and USB cables used to connect the UE NEMO indoor and exchange data and commands with the NEMO outdoor.
6. Wireshark: used alongside tcpdump to capture traffic across various interfaces in the RAN chain.
7. Application server: this is used to terminate the RAN chain with data source and sink. From the core side CentOS Linux 7 was used whilst the UE is run with Android 11.

The selected T&M list was established via an intensive evaluation exercise described in Section 3.3.

3.7.3.Mavenir Reference Chain Testing

There are two identical Mavenir chains. One is deployed in the FNL at the Digital Catapult and a second being integrated in Ofcom's RSH. Mavenir chain is assembled out of Druid Core Network (CN) and Mavenir RIC/CU/DU and a Foxconn RU.

Figure 32 illustrates the Mavenir deployment scenario consisting of O-RAN complaint functions & interfaces and the RIC & CU in this deployment is also located at the edge cite along with DU and RU in Digital Catapult, London. The CU is connected to 5G Core Network from Druid in Digital Catapult network operation centre. The RIC, CU & DU are hosted on stand-alone server(s) individually which is then connected to RU on an Open-fronthaul interface.

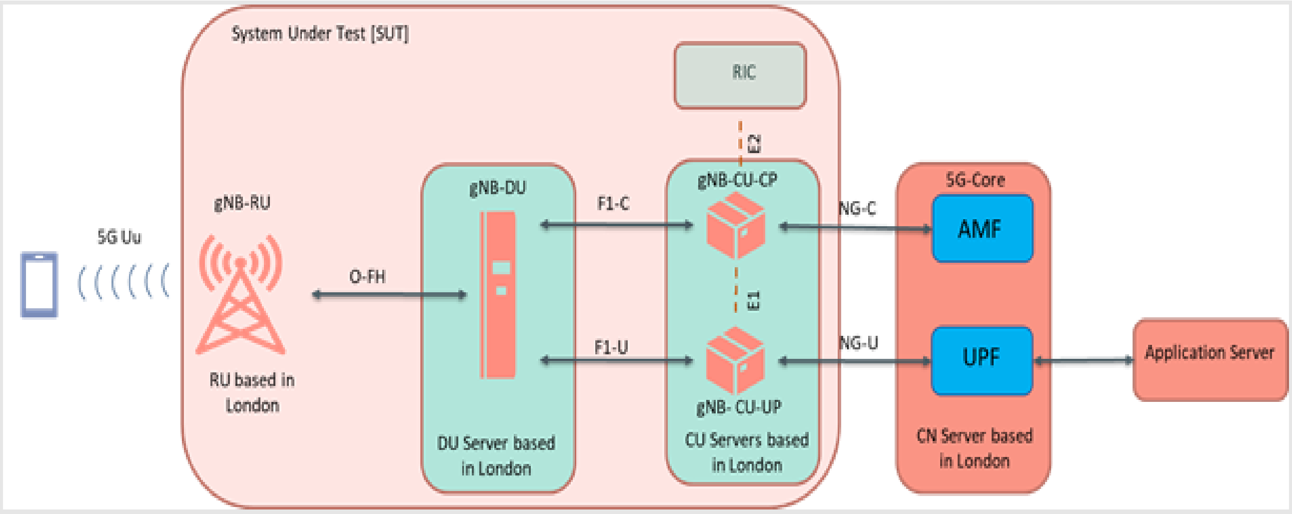

Figure 32 MAVENIR CHAIN

The testing for Mavenir has been conducted in an indoor lab environment for a single RU and stationary UE with excellent radio conditions as described in section 4.6.1. In Figure 33, we provide a snapshot to the radio conditions from the time of our test campaign for Mavenir.

Figure 33 MAVENIR RADIO CONDITIONS

Table 35 lists the key RAN configurations. The set to T&Ms used in the following test campaign are given as follows:

1. Keysight NEMO outdoor: collecting UE measurements, e.g. RSRP, NR protocol messaging stack, latency.
2. Keysight NEMO PBM: data analytics and visualisation of the UE measurements collected from the tests.
3. R&S FSW26.5 Signal Analyser: characterise the radio conditions and the air-interface of 5G NR.
4. Directional antenna horn: used to probe the air-interface of 5G NR. With ~ 12 dBi at 3.5GHz.
5. Cabling: coax cables used for the FSW and USB cables used to connect the UE NEMO indoor and exchange data and commands with the NEMO outdoor.
6. Wireshark: used alongside tcpdump to capture traffic across various interfaces in the RAN chain.

7. Application server: this is used to terminate the RAN chain with data source and sink. From the core side CentOS Linux 7 was used whilst the UE is run with Android 11.

The selected T&M list was established via an intensive evaluation exercise described in Section 3.3

Table 35 MAVENIR CONFIGURATION AT GLANCE

Configurations of test environment and SUT at glance	
Carrier frequency	n78 - SSB carrier: 630624 ARFCN (3459.36 MHz)
Total bandwidth	100 MHz
Number of total RBs	273
Number of sub-carriers	3276
Sub-carrier spacing	30 KHz
Cyclic prefix length	Normal
Slot length	500us (14xOFDM symbol)
Number of supported MIMO layers at both eNB/gNB and UE sides	2 DL and 1 UL
Antenna configuration at both gNB and UE sides	RU: 2x2 MIMO omni antennas- UE: OnePlus 8T
Transmit power at antenna connectors at both gNB and UE sides	RU:30-42dBm (estimated) UE:23dBm
Transmit power PSD (gNB/UE) (dBm/Hz)	~ -82 dBm/Hz (cabled - hence no antenna/MIMO gain)
Antenna gains at both gNB and UE sides	Combined gain estimated to 10-15 dBi
DL/UL ratio (configuration) TDD duplex mode	DL: 0.70 - UL: 0.20
The Operating Systems at UE and application server	UE: Android - Application server: CentOS Linux 7
SUT hardware	CN-CU-DU: Dell740 / RU: Foxconn
SUT software	CN: Druid Raemis Enterprise v4.6.0.1-1; RIC: R0.9-00.04.B01; CUCP: Mavenir 5.0.326.25 CUUP: Mavenir 2.0.14.0; DU: Mavenir 5.0.326.25 RU: Foxconn v1_5_15q_524
SUT parameters and configuration	Single BWP, best effort QoS
Traffic conditions during test (full/finite buffer traffic model)	UDP & TCP
Mobility conditions	Stationary
Interference conditions	0%, i.e. single cell

Radio conditions (thresholding provided in table 3)	Excellent radio conditions (SINR >25 dB, SS-RSRP > -78 dBm)


CATAPULT
Digital

3.8. Key KPI

3.8.1. Accelleran-effnet-phluido-Benetel O-RAN deployment [Original]

Testbed property type	Specific Property Metric Title	Unit of measurement	Early Integration	Current	Target	Description/Notes
Accelleran-effnet-phluido-Benetel O-RAN deployment [Original]	Icmp ping to device - round trip time to core	Milliseconds	28.1	28.1	10 to 20	Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	Icmp ping to core - round trip time to device	Milliseconds	27.9	27.9	10 to 20	Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	UDP to device [DL] - through put (Mbps)	Mbps	1	129.29	320	Early integration values --> observed as 1 Mbps at the vendors lab on 25th March Throughput is limited as TDD pattern are limited in the DU. Only 1 UL/DL slot in the frame used and not all. Max MCS achieved is 16QAM in test system. With UE, the CSI is not being sent and lowest MCS being scheduled.
	TCP to device [DL] - through put (Mbps)	Mbps	1	58.03	320	Early integration values --> observed as 1 Mbps at the vendors lab on 25th March Throughput is limited as TDD pattern are limited in the DU. Only 1 UL/DL slot in the frame used and not all. Max MCS achieved is 16QAM in test system. With UE, the CSI is not being sent and lowest MCS being scheduled.
	UDP from device [UL] - through put (Mbps)	Mbps	1	14.2	40	Early integration values --> observed as 1 Mbps at the vendors lab on 25th March

						Throughput is limited as TDD pattern are limited in the DU. Only 1 UL/DL slot in the frame used and not all. Max MCS achieved is 16QAM in test system. With UE, the CSI is not being sent and lowest MCS being scheduled.
	TCP from device [UL] - through put (Mbps)	Mbps	1	13.82	40	Early integration values --> observed as 1 Mbps at the vendors lab on 25th March Throughput is limited as TDD pattern are limited in the DU. Only 1 UL/DL slot in the frame used and not all. Max MCS achieved is 16QAM in test system. With UE, the CSI is not being sent and lowest MCS being scheduled.
	Control plane - successful registrations	10 attempted	10	10	10	10 attempted and all are successful
	Control plane - registrations time	Milliseconds	N/A	1534.1	N/A	Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency
	Control plane - deregistration’s time	Milliseconds	N/A	416.9	N/A	Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency

	Reliability/stability - mean time between failures (loss of connectivity)	Hours	0.4	36	24	Current Values: Test was stopped at 36 hours, however this could have been more if the test was not stopped. Auto recovery Open RAN systems were not in place once system crashes.

3.8.2.Radisys-Radisys-Foxconn O-RAN deployment [Original]

Testbed property type	Specific Property Metric Title	Unit of measurement	Early Integeration	Current	Target	Description/Notes
Radisys-Radisys-Foxconn O-RAN deployment [Original]	Icmp ping to device - round trip time to core	Milliseconds	30	32.25	10 to 20	Early integration values are reported from the vendors lab. Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	Icmp ping to core - round trip time to device	Milliseconds	30	32.8	10 to 20	Early integration values are reported from the vendors lab. Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	UDP to device [DL] - through put (Mbps)	Mbps	650	239.27	820	Early integration values are reported from the vendors lab.
	TCP to device [DL] - through put (Mbps)	Mbps	Not tested	fail	820	Early integration values are reported from the vendors lab.
	UDP from device [UL] - through put (Mbps)	Mbps	Not recorded	15.63	320	Early integration values are reported from the vendors lab.
	TCP from device [UL] - through put (Mbps)	Mbps	Not recorded	1.87	320	Early integration values are reported from the vendors lab.

	Control plane - successful registrations	10 attempted	2	2	10	Early integration values are reported from the vendors lab.
	Control plane - registrations time	Milliseconds	N/A	3249.5	N/A	Early integration values are reported from the vendors lab & Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency
	Control plane – deregistration time	Milliseconds	N/A	1003	N/A	Early integration values are reported from the vendors lab & Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency
	Reliability/stability - mean time between failures (loss of connectivity)	Hours	0.4	2	24	Early Integration values system was quite unstable till the new Software was implemented which improved by a small margin. Reliability tests campaign could not be executed with the SUT from Radisys due to the current stability of the RAN software. Auto recovery Open RAN systems were not in place once system crashes.

3.8.3.Mavenir-Mavenir-Foxconn O-RAN deployment [Original]

Testbed property type	Specific Property Metric Title	Unit of measurement	Early Integeration	Current	Target	Description/Notes
Mavenir-Mavenir-Foxconn O-RAN deployment [Original]	Icmp ping to device - round trip time to core	Milliseconds	20.06	20.06	10 to 20	Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	Icmp ping to core - round trip time to device	Milliseconds	24.1	24.1	10 to 20	Ping value will not change much between early integration to current as the underlaying config of gNB has not changed during phase1
	UDP to device [DL] - through put (Mbps)	Mbps	Not Tested	568.14	820	Early integration values were not tested at DC due the availability of the complete chain in time. Vendor has not supplied these values either in the survey done by DC.
	TCP to device [DL] - through put (Mbps)	Mbps	Not Tested	207.82	820	Early integration values were not tested at DC due the availability of the complete chain in time. Vendor has not supplied these values either in the survey done by DC.
	UDP from device [UL] - through put (Mbps)	Mbps	Not Tested	35.41	190	Early integration values were not tested at DC due the availability of the complete chain in time. Vendor has not supplied these values either in the survey done by DC.
	TCP from device [UL] - through put (Mbps)	Mbps	Not Tested	35.2	190	Early integration values were not tested at DC due the availability of the complete chain in time. Vendor has not supplied these values either in the survey done by DC.
	Control plane - successful registrations	10 attempted	10	10	10	

	Control plane - registrations time	Milliseconds	N/A	438.7	N/A	Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. «As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency
	Control plane - deregistration time	Milliseconds	N/A	416.2	N/A	Early Integration values were not possible as no relevant test and measurement tools were available in Sonic lab. As per O-RAN.TIFG.E2E-Test.0-v01.00 The purpose of the test is to verify the full registration and de-registration procedure with a single UE. The test also verifies the PDU session establishment and release procedures. The test validates the 3GPP standard registration/deregistration procedure and the latency of the procedure. but not necessarily theoretical best latency
	Reliability/stability - mean time between failures (loss of connectivity)	Hours	24	24	24	Before the use of T&M tools it was noticed that the RAN had good stability and managed to run for days before the Open RAN components would crash. However, once crashed, the RAN needs to be started manually whereas RAN should self-recover after software crashes.

3.9. Technical Lesson Learned

3.9.1. Accelleran Integration Lessons Learned

- Integration with Druid 5G Core network over the NG interface was straightforward both in the control plane and the user plane.
- The L1 implementation, from Phluido, didn't require any dedicated hardware accelerator cards to offload some of the L1 functionality, e.g. FEC.
- This Open RAN chain was executed on top of a common Linux distribution, namely Ubuntu 18.04; and required low latency Linux kernel patches to optimise performance.
- This Open RAN chain didn't require an external PTP server for timing synchronisation between the RU and the DU.
- This Open RAN chain deployment required specific BIOS configuration for the DU/CU server such as CPU real time performance, C and P flag settings.
- The fronthaul interface of this O-RAN chain was only able to function with a specific network interface (NIC) card, namely intel x520; other NIC cards e.g. intel x710 caused a buffer underrun on the RU side.
- The RU of this O-RAN chain required a firmware upgrade to support the TimingAdvanceOffset feature (TS 38.331) as provided by the UE. Initially the TA was set to 0.
- The fronthaul packets from the DU were being transmitted out-of-order, thereby requiring re-ordering by the RU. Each packet had a symbol index number that increments then wraps every 10.24 secs. This index is the input into the algorithm. This was not expected in a point-to-point link but was observed in the lab and the firmware upgrade was made and tested.

- It was observed that the configuration of transmission frequencies is hard coded into the firmware of this Benetel RU unit (RAN500), consequently any modifications to the configured transmission frequencies required a firmware upgrade of the RU.
- This Open RAN chain required a software upgrade of both the CU and DU in order to support the following: 2x2 MIMO, multiple UEs and improved system stability from a few minutes to multiple hours/days.

3.9.2.Mavenir Integration Lessons Learned

- Integration with the Druid 5G Core Network over the NG interface was straightforward both in the control plane and the user plane.
- This Open RAN chain's DU L1 implementation is based on the Intel FlexRAN reference design and required dedicated hardware accelerator cards (Intel Vista Creek N3000) to offload some of the L1 functionality, e.g. FEC.
- This Open RAN chain leverages the Data Plane Development Kit (DPDK) opensource libraries to accelerate packet processing in the user plane.
- This Open RAN chain was executed on top of a common Linux distribution, namely CentOS 7.6; and required low latency Linux kernel patches to optimise performance.
- This Open RAN chain required an external PTP server (SONIC Labs used Qulsar QG 2, but other options would be suitable too) for timing synchronisation between the RU and the DU.
- This Open RAN chain deployment required specific BIOS configuration for the DU/CU server such as CPU real time performance, C and P flag settings.
- This Open RAN chain required specification on server workload partitioning, with specific network and server hardware configurations down to which card in which slot, which CPU, some firmware version settings.
- It was observed that the RF configurations for the RU (Foxconn RPQN-7800) such as transmission frequencies and antenna attenuation, etc, can be easily modified using configuration files without requiring a firmware upgrade of the RU.
- This Open RAN system required an overall software upgrade to support cutting-edge functionality such as: the RAN Intelligent Controller (RIC), xApps, Mavenir Centralised Management System (mCMS) and Mavenir Telco Cloud Integration Layer (mTCIL). It is worth noting that the software upgrade process was considerably lengthier (4 months) than previously anticipated.

On Ofcom Riverside House site, Mavenir was not able to utilise the Dell XE2420 hardware platform as it is not part of their tested product portfolio. Instead, Mavenir decided to ship a new hardware platform (server) to Ofcom for the CU-DU component. Integration of the Dell R740 platform has started recently, and it continues in Phase 2 of the SONIC project. Results of this inter-site integration will be published as part of Phase 2.

Mavenir chose to avoid integration with the Dell XE2420 server platform with the given timelines, as it was not tested in their labs. To date, this suggests that the vendor faces challenges when OpenRAN solutions are built on COTS hardware not tested by them. Generally, to guarantee deterministic RAN performance, an Open RAN supplier will need to validate their products on a wide range of platforms, which will require a vast number of resources. As a result, we expect suppliers to incrementally grow the COTS-based general purpose HW on which their products are validated and supported. Moreover, with maturity, it is expected that differences in supplier support now will converge to a broader, common set of COTS platforms from which network providers will be able to choose. All the current COTS platforms tested in the SONIC Labs are based on Intel FlexRAN.

3.9.3.Radisys Integration Lessons Learned

- Integration with Radisys' (Trillium) 5G Core Network over the NG interface was straightforward both in the control plane and the user plane, as expected.
- Deployment and execution of this Open RAN system required multiple manual configurations that could be automated to improve the end user experience - the deployment was not as user-friendly as expected.
- This Open RAN chain's DU L1 implementation of was based on the Intel FlexRAN reference design and required dedicated hardware accelerator cards (Intel Vista Creek N3000) to offload some of the L1 functionality, e.g. FEC.
- This Open RAN chain required specific a cryptographic card (Intel Quick Assist Technology - Intel QAT8970) installed into the CU/DU server in order to support over the air authentication of UEs.
- This Open RAN chain leverages the Data Plane Development Kit (DPDK) opensource libraries to accelerate packet processing in the user plane.
- This Open RAN chain was executed on top of a common Linux distribution, namely CentOS 7.8; and required low latency Linux kernel patches to optimise performance.
- This Open RAN chain required an external PTP server (SONIC Labs used Qulsar QG 2, other options could be suitable too) for timing synchronisation between the RU and the DU.
- This Open RAN chain deployment required specific BIOS configuration for the DU/CU server such as CPU real time performance, C and P flag settings.
- It was observed that the RF configurations for the RU (Foxconn RPQN-7800e) such as transmission frequencies and antenna attenuation, etc, can be easily modified using configuration files without requiring a firmware upgrade of the RU. For instance, the transmission frequency was easily modified to operate within the 3.4 to 3.6 GHz band to conform with the SONIC's spectrum licence. Likewise, the transmit power was easily improved by decreasing the individual port attenuation from 30dB to 20dB.
- It was observed that most of the CU, DU and L1 configurations were hardcoded e.g. UL and DL MCS values, 5QI values, etc.
- It was observed that the Radisys' (Trillium) 5G Core Network version 2.3.2 was very unstable (in the order of minutes) and did not release the UE context cleanly upon UE de-registration. The Radisys' (Trillium) 5G Core Network was updates from version 2.3.2 to version 2.5.3 that improved the stability (in the order of hours) and also performed a clean UE context release.

- It was observed that Radisys' L1, CU, DU version 2.3.2 was very unstable (in the order of minutes) and continuously crashed with "Segmentation Fault" failure. The Radisys' L1, CU, DU version 2.3.2 was updated to version 2.5.3 that improved the stability (in the order of hours).
- The Radisys' L1, CU, DU modules (version 2.5.3) were successfully installed, built and configured on two different COTS hardware platforms namely Dell XE2420 (at OFCOM Riverside House) and Dell R740 (at Digital Catapult London and Brighton).

In Ofcom site, Radisys Open RAN chain successfully implemented a Distributed RAN deployment with the CU and DU running on separate Dell XE2420 servers at OFCOM Riverside House and connected to Radisys Core Network hosted at the Digital Catapult.

The level of deployment automation could be improved. During the deployment, significant amount of time was spent on platform configurations and installing dependencies manually. Automation in this would speed up the process, making the product more testable and reduce amount of support hours needed. The documentation is generally well written, but it has many manual steps related to base platform configuration that could be automated. Manual steps could be removed by utilising modern automation tools.

3.9.4. Accelleran Reference Chain Testing Lessons Learned

- RF Spectrum: The RU as configured by the integrators was above the spectrum originally specified to them by Digital Catapult which was between 3.4 GHz to 3.6 GHz. This violated the spectrum license by 20 MHz. It was only noticed once the testing starting with a spectrum analyser at SONIC labs, see Figure 34. In future, the integrators and SONIC labs should be very careful and deploy processes in place to detect the spectrum usage earlier in the cycle. Also, SONIC labs will apply for higher bandwidth for test spectrum licenses with Ofcom to increase the frequency selection flexibility.

Figure 34 RSRP of Accelleran (Cabled)

- RU Configuration: The RU was reconfigured to match the licensed spectrum. However, UE registration failed despite excellent radio conditions - debugging from the RAN vendors was inconclusive but suggested misalignment in the 5G NR framing structure which caused excessive time error. Due to time pressure, the RU was reversed to the previous firmware which meant running the RU outside the dedicated spectrum in a shielded box. The final tests of this chain were carried out in a RF shielded box.

- E2E Data Performance: During the initial deployment in June 2021 of this Open RAN chain: firstly, the RAN was configured to SISO and it was seen that the throughput performance using internet speed test was around 15Mbps DL and 1Mbps UL. The reason behind this limited performance is due to partial use of the total number of slots both in the DL and UL (1 slot out of 7 DL - 1 slot out of 2 in the UL). The Accelleran Open RAN consortium then released further releases which improved the DL and UL performance significantly but not to the theoretical maximum yet. Details of latest performance KPIs have been provided already in D2.2 under sections 6.2.5.

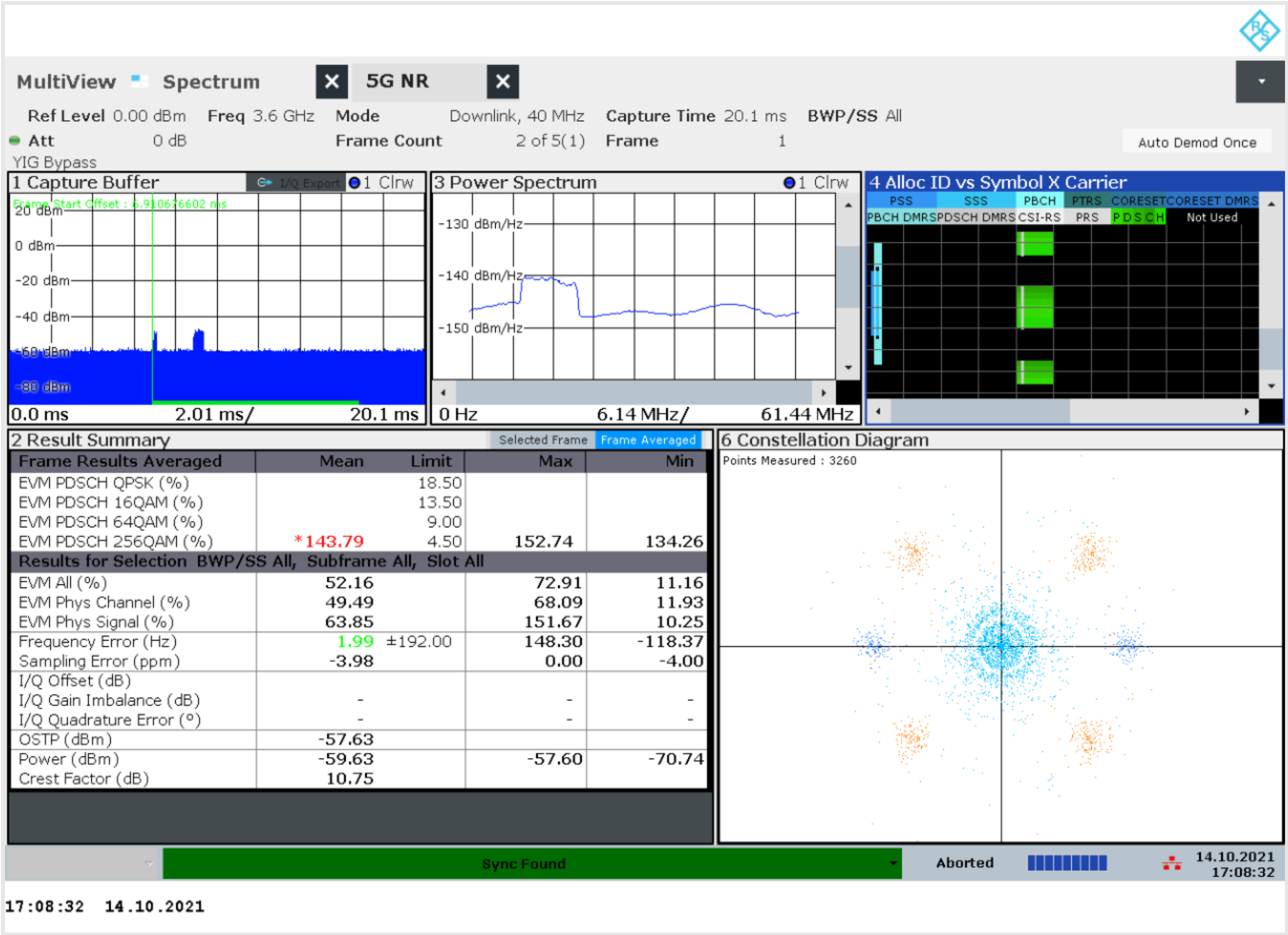

FIGURE 35 RF AND AIR-INTERFACE CHARACTERISTICS OF ACCELLERAN (IN SHIELDED BOX)

- E2E Data Performance: The Open RAN chain still has to mature on the MAC scheduler side as far as the raw uplink and downlink throughput of the chain is concerned. The MAC scheduler should correctly configure the UE to report the channel estimation parameters, so that the MAC can optimize the performance for throughput both on uplink and downlink direction. Technical details of this lesson are provided in D2.2 under sections 6.2.5. The vendors in the consortium are also seeing similar performance and doing further test and optimisation to improve the MAC scheduling of the Open RAN chain.

- E2E Data Performance: Throughput on the uplink seemed capped by the scheduling resources given to the UE to transmit data. Detailed technical measurements can be found in D2.2 under sections 6.2.6. Again, this observation was also noticed by the vendors and they are still working on improving the UL performance and future release will ensure better scheduling on the uplink and thus improving the overall throughput performance.

- Observation around the maturity of the Open RAN (F1) interface implantation: As mentioned, the UE was placed in a RF shielded box but it was noticed that the DL throughput performance was not constant. Interference and Block error rate (BLER) are usually the cause for such observations but since the UE was placed in shielded box and also the BLER was around 3%, those aspects can be ruled out. However, upon discussions with the RAN vendors, one possible reason could point at the flow control between DU and CU. This needs further investigations on the RAN side and highlights the early-stage maturity of the Open RAN components.

- Overall RAN Stability: The stability of this Open RAN chain has come a long way since the first deployment of the chains in the SONIC Labs. Roughly, the RAN would crash every 15 to 30 mins depending upon the activities running on it. However, with the later releases: the stability had increased to couple of hours. It was also noticed that it was mostly the DU which was crashing. These behaviours were reported to the vendors, DU vendor provided further stability builds which improved the stability of the RAN chain in which most recent test was stopped at 36 hours without failure.

- RAN Operation: RAN systems are designed to autonomously operate and during the instances of software or hardware crashes, the RAN management should be able to recover itself and start operating. Due to the earlier maturity (TRL) of the individual components, as well as the overall integration (set together for the first time in SONIC Labs), this functionality is not seen in the software releases shared by the Open RAN vendors in this chain. However, upon discussions with the vendors, such features for auto recovery of the RAN are being tested and will be made available in future releases, with the clear intention to test them in the SONIC Labs Phase 2 engagement.

3.9.5.Radisys Reference Chain Testing Lessons Learned

- RF Spectrum: the vendor was instructed to configure the RAN to operate within a dedicated licensed spectrum. However, during testing that the Foxconn RU was found to operate across the 3.6 GHz boundary. In future, the integrators and SONIC labs should be very careful and deploy processes in place to detect the spectrum usage earlier in the cycle as well as the rest of the RAN functions and configurations being stable and in-line with the agreed specification prior to testing.

- RF Spectrum: another observation, the RU was found to cause excessive noise spillage spanning a substantial range (1 GHz bandwidth from 3 to 4 GHz). The out of band noise was more than 25 dB above the noise floor of our spectrum analyser. However, the target band SNR was more than 30dB above the RU noise level, see Figure 36 power spectrum of the foxconn Ru. The reason is unknown, but it could be originated from analogue circuitries due to limited dynamic range and power saturation. It is recommended that the RF characterisations is done in a radio chamber and beyond the target bandwidth to ensure no harmful interference being caused to adjacent bands.

Figure 36 power spectrum of the foxconn Ru

- RF Normalisation: it was found that the power attenuation was set to 30 dB to all antenna ports, reducing to 20 dB allowed the UE to register with ping latency in the range of 20 to 50 msec. This could be a result of automatic gain control (AGC) manual configuration rather than being dynamic. In excellent radio conditions, as shown for testing conditions in Figure 37, this may be hard to observe, however in mobile use cases where the UE is experiencing variable channel conditions such configuration may limit the power adaptability of the RU and hence impact overall performance. In the next phase of SONIC Labs vendors must be requested to record/report, and potentially (in more mature products) to avoid any hardcoding in the AGC. It is also advised the vendors/integrators to run basic stability tests following the completion of integration of the RAN chains prior to handover to E2E performance testing.

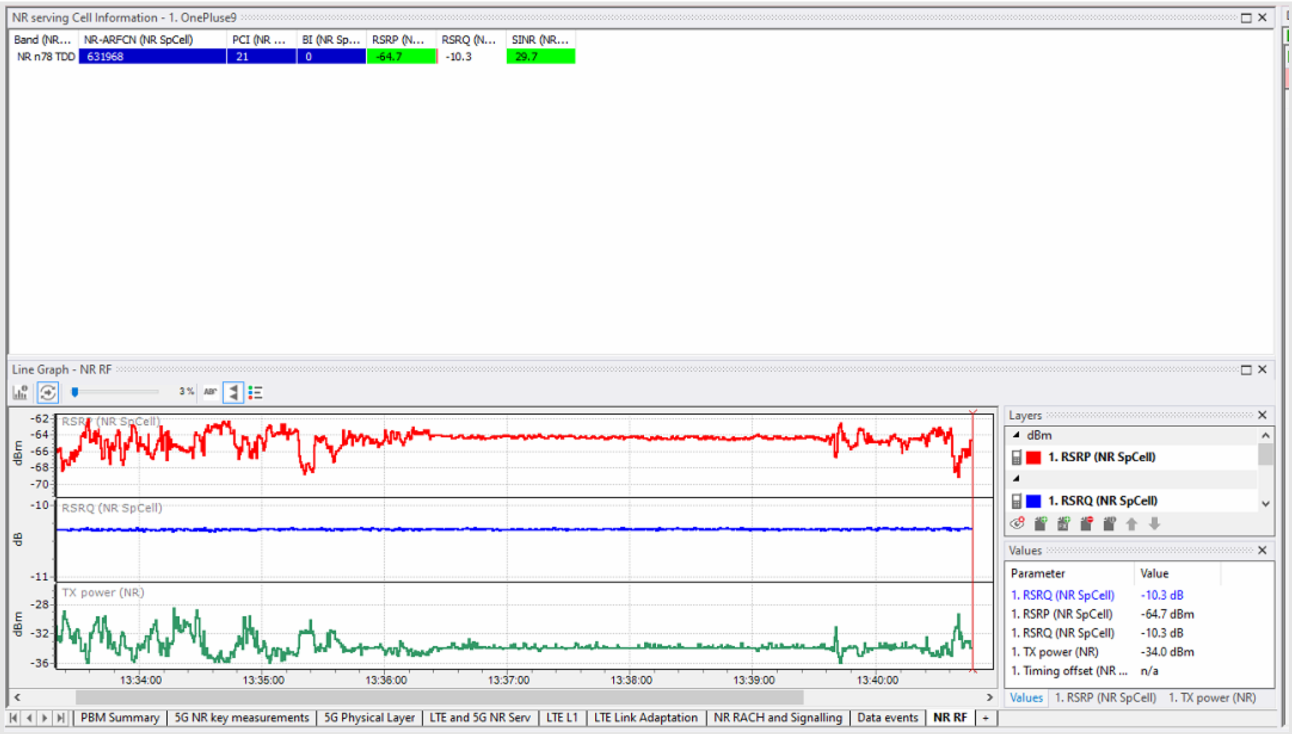

FIGURE 37 EXCELLENT RADIO CONDITIONS DURING TESTING OF RADISYS

- Control plane stability: functional tests of registration and de-registration were performed after configuring the spectrum within the licensed range (3.4716 - 3.5716 GHz). However, lowering the RF normalisation by 10 dB allowed multiple registration attempts followed by persistent failures in the core network citing segmentation failures. . Stability tests were reported back to the vendor.

- Hardcoding of RAN Configuration: in the version of the DU/CU provided by the vendor the UL/DL throughput tests revealed that the MCS had been hardcoded to a fixed MCS index rather than adaptive to channel conditions. Figure 38 shows that despite excellent radio conditions, the MCS (9) is fixed to 64 QAM in the DL and QPSK in the UL. Following reconfiguring of the RAN manually to allow higher MCS order, persistent failures prevented re-evaluating the DL/UL throughputs. Ideally, the RAN configuration should allow adaptive MCS and the vendors should have flagged that the RAN has elements being hardcoded.

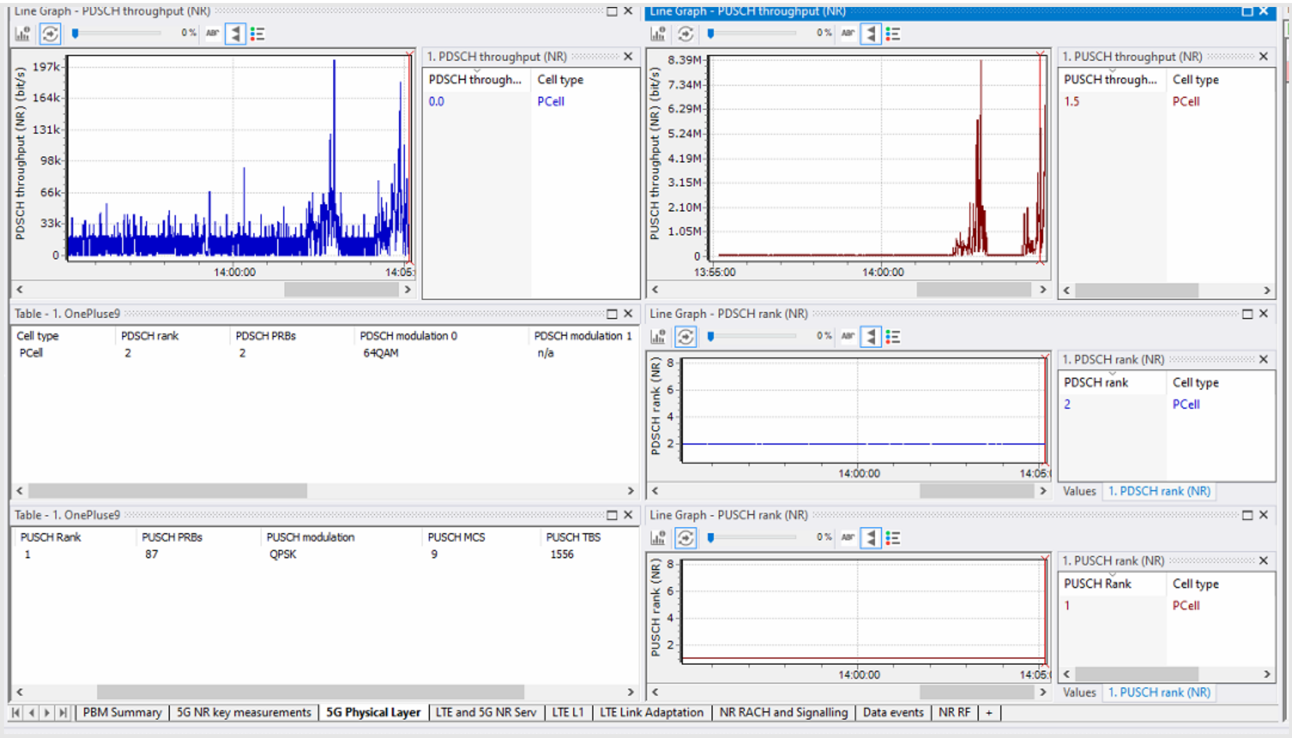

FIGURE 38 HARDCODING OF THE PDSCH/PUSCH

- Core Network Stability: the chain encountered persistent failures in CN which prevented the completion of SONIC Labs Phase 1 test plan as defined in Section 5. Following this, new upgrades to the CN was requested to allow the completion of the E2E performance tests as mentioned earlier. Upon completion of core network upgrade; there were improvements seen with regards to the stability of the core network; however, it is still far from being commercial grade core network. Detailed explanation can be found in D2.2 under Section 6.3.2.1.

3.9.6.Mavenir Reference Chain Testing Lessons Learned

- Operational: Features must be integrated and tested in the vendors lab environment before attempting integration on existing operational SONIC chains. Compatibility of hardware and O-RAN software components should be verified to de-risk the integration process. Going forward, the vendors and SONIC team must agree a framework to control version releases and allow performance testing and swapability before introducing new features to Open RAN chains. This should allow fair and efficient maturity tracking for the Open RAN systems.

- RF Spectrum: Foxconn RU is causing about 10 dB noise spillage outside the target bandwidth and extending the range of tests, i.e. 500 MHz, see the Black and Green traces of

Figure 39. This could be a filtering problem occurring either due to lack of analogue/digital filtering or excessive Tx Power. Similar observation was captured in the Radisys chain of the Fusebox lab in Brighton. Use of shielded chambers is essential to avoid harmful interference into adjacent spectra and services. It is also advised that the vendors establish reference chains in their labs to characterise to rule out local configuration problems and calibrate performance.

- RF Interference: The target bandwidth for this chain (3.45 – 3.55 GHz) overlaps significantly with other local operators. Given that the FNL is in a busy part of London, 5G spectrum is expected to be ever more crowded with time. Use of shielded chambers help with stationary co-located user terminals, however mobility and multi RU testing would require UE emulators to conduct tests in a completely cabled environment.

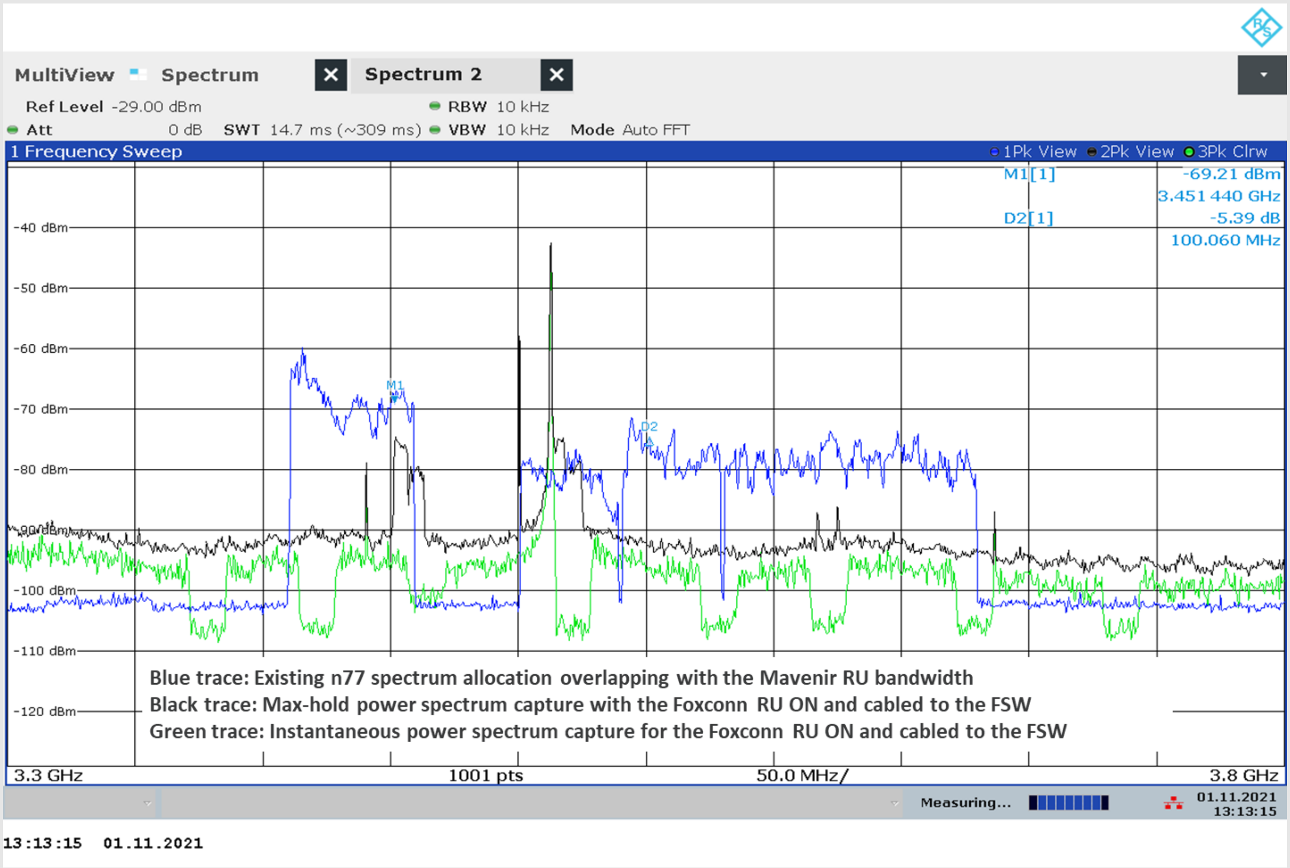

Figure 39 FNL Mavenir RF characteristics

- Air-interface characteristics: The SSS and PSS are very noisy. This test was done in a cabled environment and hence the noise in the PSS and SSS could have only been generated from the analogue front end of the Foxconn RU, during the digital to analogue conversion. If the RU is instructed to transmit beyond its dynamic range then quantisation and clipping noise are to be generated, added to the SSS/PSS, and transmitted through the channel, 5m coaxial cable in this case. Hence, the received SNR is being poor due to poor transmitted SNR.

Ideally, the automatic gain control (AGC) should be configured correctly to make sure that the waveforms are not clipped, and quantisation noise kept to minimum or adjust the power allocation digitally. Capturing the PSS and SSS were only possible after applying excessive attenuation on the FSW Signal Analyser as its front end was overloaded. It can be seen below in Figure 40 that the Tx power is in excess of 0 dBm with 20 dB attenuation, the capture buffer in fact has a clear clipping effect. The SSS and PSS constellations are foggy due to the high noise levels being mixed with the QPSK and BPSK constellations. Vendors are advised to do due diligence testing, attempting to register the UE resulted in persistent failures in the DU.

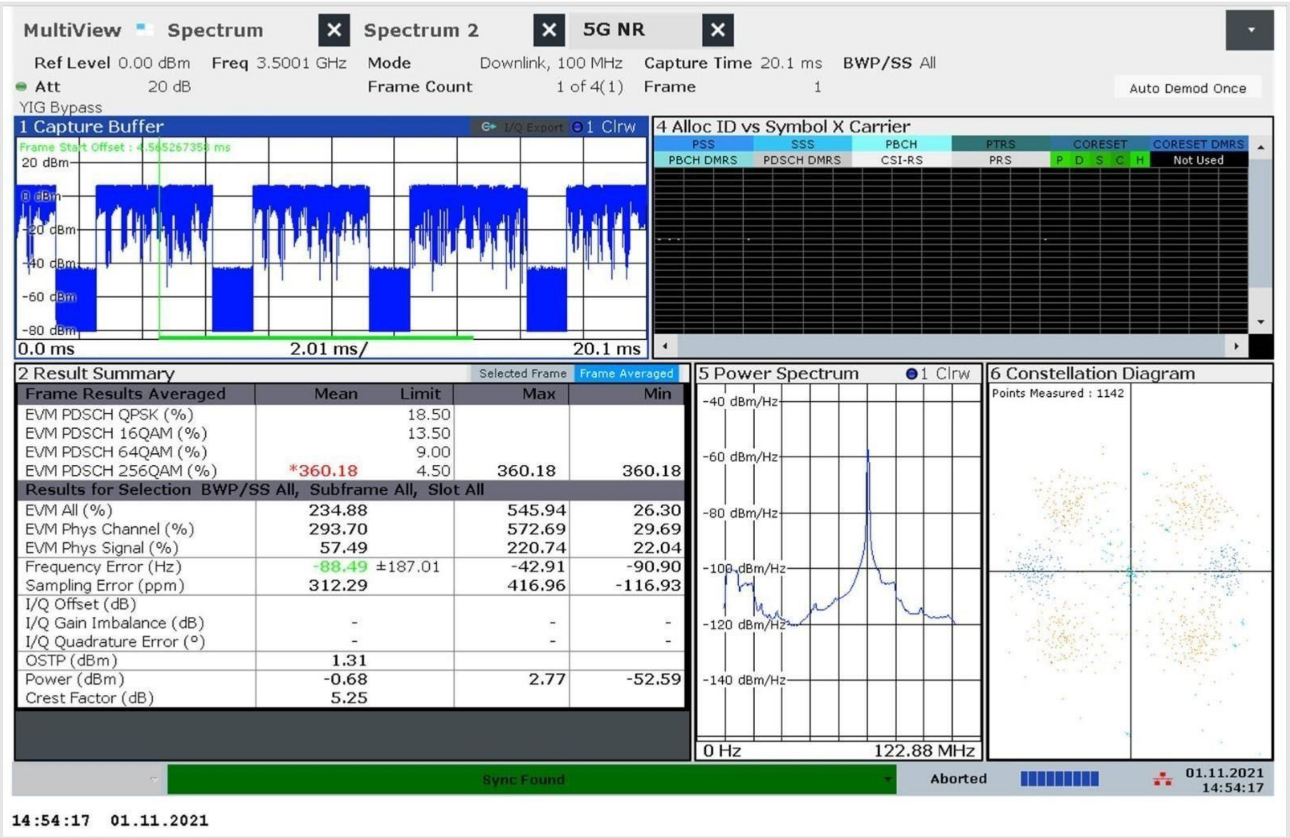

FIGURE 40 FNL MAVENIR AIR INTERFACE CHARACTERISTICS

- E2E Data Performance: : As expected for the most mature chain in the SONIC Labs Phase 1, the Open RAN chain seems to have a matured implementation of the MAC scheduler side as far as the raw uplink and downlink throughput of the chain is concerned. The MAC scheduler seems to configure the downlink scheduling resources for the UE dynamically based on the reported channel estimation parameters by the UE. The throughput performance reported in this report; could have been improved further with the use of shield box and optimisation sessions with the RAN vendors; we intend to follow these in the next phase of SONIC Labs.

- E2E Data Performance: Throughput on the uplink seemed capped by the scheduling resources given to the UE to transmit data. This needs to be investigated further with the RAN vendors but similar behaviour was also noticed on other Open RAN chains in the SONIC labs

- RAN Operation & Stability: RAN systems are designed to autonomously operate and during the instances of software or hardware crashes, the RAN management should be able to recover itself and start operating. In the software releases shared by the RAN vendors: this functionality is not seen. However, the overall stability of the RAN once it is up and running has been completely satisfactory.

4. Summary of lessons learned

An earlier detailed list of learned lessons from the first integration phase (January-June 2021) has been reported in Section 6.1 of D1.1 and also detailed list of lesson lerned has been captured under D2.2 under section 6

4.1. The key lessons learned from SONIC Labs Phase 1:

1. The methodology of doing co-deployment of solutions was proven to be highly valued by the SONIC Labs participants. Whilst this is valuable and necessary for SONIC Labs operation, in order to get first hand experience of the realities of the products, it was also highly valued by the SONIC Labs vendors engaged in Phase 1, who really appreciated having expert technical support in a new deployed environment.

2. Integration and deployment of a 5G SA Open RAN system at both the hardware- and software-level proved to be more challenging than anticipated. Contributors to this include deficiencies in the customer documentation and the scale of manual configuration required. Given the TRL's of the suppliers currently participating in the SONIC Labs, it is fully expected these areas will improve as their product offerings mature.

3. At this point in time there are dependencies between the software and hardware, and a network provider will have to work very closely with a candidate Open RAN supplier(s) to ensure full compatibility with the COTS hardware (including NIC and Accelerator cards) and the Open RAN products they procure for deployment. The disadvantage of moving to a COTS-based architecture is that the task for an Open RAN supplier to validate their products on such a wide range of platform combinations will require a vast amount of resource. As a result, we expect suppliers to incrementally grow the COTS supply base on which their products are validated and supported on - evidence of that was clear during SONIC Labs testing from vendors with more mature products. Moreover, with maturity it is expected that the differences in supplier support seen today will converge to a broader, common set of COTS platforms from which network providers will be able to choose.

4. Given the integration challenges observed to date in the SONIC Labs there is the open question of whether (or not) the CAPEX/OPEX savings that are frequently associated with Open RAN will be realised in practise. At the moment there appear to be a possible shift from CAPEX savings to increased OPEX due to a growing cost for the network provider to provide a larger in-house capability and/or draw on the expertise of a third-party System Integrator to build-out an Open RAN deployment. It is expected that this should change with time, with the maturation of products and in particular maturation of management

interfaces and capabilities in an open way - which should be an area of increased focus in SONIC Labs Phase 2.

5. There are some differences in the variant of Option 7.2x fronthaul interface implemented by the suppliers currently participating in the SONIC Labs. The majority of SONIC Labs supplier's support Option 7.2a, however, one supplier supports Option 7.2b. Indeed, the integration process required close collaboration between the DU and RU suppliers and software changes. Whilst there are pros and cons for supporting Option 7.2a versus Option 7.2b, respectively, it is important to profile and understand the nature of eCPRI messages that pass over the fronthaul and determine how truly open this interface is, and understanding also the wider vendor ecosystem support for the different options. In particular, Option 7.2b uses "modulation compression" and could pave the way for a proprietary mapping between the binary symbols (passed from the DU) to QAM I/Q samples (generated in the RU). This is an area of further work where tracing the fronthaul interface will examine whether (or not) eCPRI messages exchanged between DU and RU exploit vendor-specific message IDs, thus lowering interoperability and interchangeability of vendors in the network.

6. The RF conformance of early-stage RU products is an area that should be monitored closely. In particular, validating the correct operation of carrier frequency and bandwidth configurations along with monitoring/measuring the out-of-band emissions is strongly recommended. Moreover, it is recommended to work closely with the RU supplier to understand the level of configurability of transmission power, carrier frequency and bandwidth (since these were hard-coded in one of the products in the SONIC Labs), along with confirming support of (what are typically default and important) capabilities like automatic gain control.

7. At this stage of development, some Open RAN suppliers are not comfortable in swapping out elements in a known, tried-and-tested configuration, and replacing them with product(s) from a supplier(s) they have not already partnered/collaborated with. Whilst we see the SONIC Labs as a key enabler for encouraging/fostering collaboration and growing a larger/more diverse ecosystem, it may require further developments in product maturity for the suppliers who participate in the SONIC Labs to feel more comfortable in exposing their products to the swapability tests that were planned - even in a commercially neutral and "safe" environment (compared to an Operator lab). At this stage, it is fair to maintain a healthy level of scepticism on whether (or not) the "Lego" nature that Open RAN offers will fully materialise, especially in light of 1) to 4) above.

8. Intel has made significant progress in providing 5G base station silicon through its Atom P5900 processor and currently enjoys an estimated 40% market share. With the prevalence of Intel's x86-based architecture and their FlexRAN baseband PHY reference design in Open RAN - there is a significant risk of shifting the dependency from two RAN equipment suppliers to a single chipmaker in the 5G supply-chain.

9. Operationally, SONIC Labs Phase 1 served well in learning where to streamline operational activities, from the baseline knowledge sharing when engaging with vendors to the planning of the integration and testing activities with realistic support. The drive to get to a working chain is not always necessary, or even possible, and we need to be clearer in what is being tested, at what level, and what is the next phase of the product in their roadmap. In particular, clarity of options supported, minimal conformance testing, clarification of software adaptability, etc. - effectively leading to a better clarification of TRL definitions for SONIC Labs. This is something that we will take forward in SONIC Labs Phase 2, both to support us in engaging with the vendors, but also making any benefit realisation analysis easier.

10. Vendors engaged in SONIC Labs value very highly the end-to-end nature of the testing provided in the labs, and the test-house Test & Measurement equipment introduced in SONIC Labs Phase 1. Even in cases when the tests failed (expectedly due to the product TRL or unexpectedly), all vendors benefited in product TRL maturation through engaging with the SONIC Labs testing regime.

11. It is particularly interesting to see the approach to openness of solutions for different vendors depending on what TRL their product is, but also where they see themselves in the mobile network supply chain. One group might see themselves as a OpenRAN component supplier, and another group more as an Open RAN solution provider. The first group is particularly open to new opportunities and engaging with wider ecosystem. The second group seems to be more open towards new RU vendors, but less interested (though still open) around CU and DU swapability.

12. Whilst we managed to install and operate RIC solutions, there was not sufficient time to test the manageability of the interfaces due to some of the chains' integration stabilising late in the process. It remains one of the starting points for SONIC Labs into Phase 2, primarily to understand the maturity of the management interfaces in higher TRL (TRL7+) and also understanding where in the product development roadmap [are those features started to be introduced into the products.

13. Throughout the engagement the importance of representative deployment environments was highlighted from all vendors. Whilst vendors will undertake continuous device-under-test testing during development, they will leave for later, and with limited cases, testing with

actual products from other vendors. Therefore, the approach to combine bench-testing (device/subsystem testing) with full end-to-end integration testing both in the lab and in representative environment is considered validated in SONIC Labs Phase 1. SONIC Labs Phase 2 will use realistic deployment environments (public indoor and outdoor) for this.

14. Based on our interactions with the suppliers currently participating is the SONIC Labs. It has been observed that their resources are stretched. The process of growing the RAN equipment ecosystem should not be limited to increasing the supply base of products and solutions. Professional services and operational models need to be in place to support the deployment and management of any new solution. As a result, a key question that has to be considered is - do new entrants have the scale to provide and/or support the needs of network providers both locally and on a global scale?

4.2. Next steps, based on the learnings and activities in SONIC1:

- SONIC Labs will continue with a further two-year programme. Some of the vendors and products involved in SONIC1 will continue into the next phase of SONIC Labs, either for integration or as part of a reference network. The Cohorts will be selected based on what makes sense with new products and integrations in order to increase the innovation and options in the UK ecosystem, and we expect some of the vendors to be part of it with their newer products, or new integrations to other products.
- SONIC1 has had some influence on the telecom's ecosystem in the UK, this is covered in the engagement report D3.3. They have learned many things to improve processes, documentation, ways of integrating and testing, how to be migrated from their own labs to third party. In addition, there are discussions on integration activities that were not happening when we started, and some developing strategies for partnerships for reaching the widest possible potential customer base.
- The structure of the next phase of SONIC Labs has been developed in order to take account of lessons learned, such as the approach to cohorts, having multiple procurement activities to underlying hardware differences. There are deliverables within the next phase of SONIC labs to provide a further report on lessons learned and how it will be applied.