Project Management

COMP-O-RAN - Project Report Summary for Dissemination

PRJ025 version 1.0

This CoMP-O-RAN dissemination project report summarises the project aims, security considerations, results and lessons learned, referencing deliverables where appropriate.

Revision History

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Reference Documentation

#	Document Title	Reference
1	Acronym and Abbreviation Register	RGT004

Acronyms/Abbreviations

This document contains the following acronyms:

5G	Fifth-generation technology standard for broadband cellular networks
All-in-one	gNB acts as RU, DU & CU and connects to the 5G Core via the NG interface
Backhaul	Interface between CU and 5G core
BWT	Blu Wireless
CJT	Coherent Joint Transmission
CoMP	Coordinated Multi-point
Comporan	Short for CoMP-O-RAN Project
Comporan Small Cell	The integrated 5G cell & mmW prototype deployed at Millbrook
CSC	Abbreviation of CoMP-O-RAN Small Cell prototype
CSI	Channel State Information
CQI	Channel Quality Indicator
CU	Centralised Unit
DCMS	Department For Culture, Media & Sport
DL	Downlink, from gNB basestation to UE
DPB	Dynamic Point Blanking
DPS	Dynamic Point Selection
DU	Distributed Unit
Fronthaul	Interface between DU and RRU
gNB	5G basestation node
HARQ	Hybrid Automatic Repeat reQuest
HLA	High Level Architecture
ICNIRP	The International Commission on Non-Ionizing Radiation Protection
ISD	Inter-Site Distance
Midhaul	Interface between DU and CU
mmW	Millimetre Wave
Mu1	Physical layer is running in Numerology 1 mode, meaning 2 slots/subframe (i.e., 0.5 msec slots)
MTU	Maximum Transmission Unit. The maximum packet size specified to be handled between two ends of the packet interface.

NCJT	Non-Coherent Joint Transmission
NCSC	National Cyber Security Centre
nFAPI	network Functional Application Platform Interface. The protocol between the DU and RU entities
NG	NG interface connects a gNB to the 5G Core
ORAN	Open RAN
PCAP	Packet Capture file. A file format used by various packet capture software applications
PCP	PBSS Control Point. A type of WIFI AP (Access Point)
PTMP	Point-to-Multipoint
PTP	Point-to-Point
RAN	Radio Access Network
RF	Radio Frequency
RRU	Remote Radio Unit
RTD	Round Trip Delay. The average time taken for information to travel in one direction, be operated on and return back to the origin.
RU	Radio Unit. In ORAN Split6, the RU contains the radio plus some portion of the Physical Layer processing and connects to the DU over a Fronthaul Interface.
Split2	ORAN-defined split where the RU & DU are combined into a single unit and connects to the CU via the F1 interface
Split6	ORAN-defined architecture where the RU and CU/DU are separate entities and connected via an nFAPI interface
STA	Station. WIFI terminology for an end-point that connects to an Access Point
TARA	Threat Assessment and Remediation Analysis. Used to identify cyber vulnerabilities and identify mitigation.
TRP	Transmission Reception Points
TSCoP	Technology Code of Practice, a cross-government agreed standard
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink, from UE to gNB basestation
UoG	University of Glasgow

1 Dissemination Executive Summary

This dissemination document highlights the closure of the CoMP-O-RAN Project outlining what was achieved and why. It summarises the experiences and findings gained during the project life cycle from development and prototyping phases through to testing in real environments. The document concludes with Benefit Realisation of the CoMP-O-RAN Small Cell concept and its goal of a reduced 'cost per bit' deployment model.

The CoMP-O-RAN consortium includes:

- Airspan Communications Limited
- Blu Wireless UK Limited
- Radisys UK Limited
- University of Glasgow
- Dense Air Limited (lead partner)

The project goal was to develop a prototype 5G small cell network that extends the bounds of what is currently commercially available, modifying and integrating existing commercial components to enable new deployment models that enhance coverage, performance, and cost. The deployment model is targeted at both private networks and neutral host for public Mobile Network Operators (MNOs), leveraging the UK 5G vendor supply chain.

There are several key technical aspects that were achieved during the execution of this project:

- Implemented an Open RAN Split 6 end-to-end system with a novel fronthaul solution:
    - Successfully integrated sub-systems from Airspan, Radisys and Blu Wireless with Dense Air as lead system integrator.
    - Consortium-led implementation of Coordinated Multi-point (CoMP) using O-RAN Split 6 fronthaul.
    - Implemented Dynamic Point Selection for 5G SA using a method supported by current 5G UEs/handsets (3GPP Release 15).
    - Validated the concept of mmWave Mesh as a Fronthaul technology to lower deployment OpEx and CapEx.
- Validated the benefits of CoMP for small cell deployments:
    - Delivered Spatial Diversity and Spatial Multiplexing gains.
    - Proved capacity improvements of small clusters compared to macrocells.
    - Demonstrated energy/bit savings of CoMP small cells.
- Developed lab and testbeds:
    - Marlow lab created and used for Consortium integration and manufacturing test.
    - Initial TV5G CoMP-O-RAN Component testbed at Teesside International Airport.
    - Permanent Millbrook CoMP-O-RAN 5G testbed.
- Solid foundations to further develop:
    - Power optimisation strategies.

  - Optimisation of CapEx and OpEx.
  - Commercial hardware and system solutions including Supply Chain.

The CoMP-O-RAN Consortium achieved all the targets set out in the original Grant Offer document with evidence presented in quarterly deliverables:

- Explore the full product development lifecycle (from concept design through to hardware prototyping and proof-of-concept deployment and validation), how alternative radio backhaul, enhanced radio performance with a novel 5G New Radio CoMP algorithm and software implementation can complement existing mobile networks, with the expectation of a reduced cost-per-bit and delivery of an enhanced 5G network performance.
- Enable the integration of a radio backhaul into a cell and create the ability to mesh cells for ease of deployment, resulting in the significantly reduced need for expensive fibre installations linking every cell.
- Through research and development of a novel 5G New Radio CoMP algorithm developed by The University of Glasgow and a new software implementation, develop a product that will be O-RAN based and able to form part of a multi-vendor RAN deployment.
- Test the novel product within the Dense Air Radio lab, individual component test field trials at the CoMP-O-RAN and Tees Valley Combined Authority supported Teesside International Airport, test lab, and the full CoMP-O-RAN test and trials at the Dense Air Operated UTAC Millbrook Proving Ground, providing real world conditions to test whilst still within a controlled environment for the multivendor try out.
- Provide multiple use case try-out opportunities particularly in the SMART City and transport applications, as well as a secure environment to evaluate and document the solutions' impact in real-world scenarios ahead of scaled commercial deployments.

A summary of the successful deployment and performance testing of the CoMP-O-RAN Small Cells in our test sites.

2 Introduction

With increasing high network upgrade costs and declining capital budgets, CoMP-O-RAN is intended to offer Mobile Network Operators the ability to continue supporting ever increasing user demands across diversified, high performance use cases. CoMP-O-RAN project focused on the development activities for a novel solution to deploy small cells in a 5G network. The conclusion of the project is intended to be a stepping stone into the production of a standard product that can be used in multiple environments.

CoMP-O-RAN lead Dense Air together with consortium members and the grant funding support from the UK Government Department for Culture Media and Sport now under the umbrella of the Department for Science Innovation and Technology, to "explore across the full product development lifecycle (from concept design through to hardware prototyping and proof-of-concept deployment and validation), how alternative radio backhaul, enhanced radio performance with a novel 5G New Radio CoMP algorithm and software implementation can complement existing mobile networks, with the expectation of a reduced cost-per-bit and delivery of an enhanced 5G network performance"

Successful operational use cases of a 5G network using 5G prototype small cells at UTAC Millbrook Proving Ground where all the development activities are proven. With the successful deployment and validation of the prototypes, the discussion regarding the pathway to production for commercial deployment can be initiated.

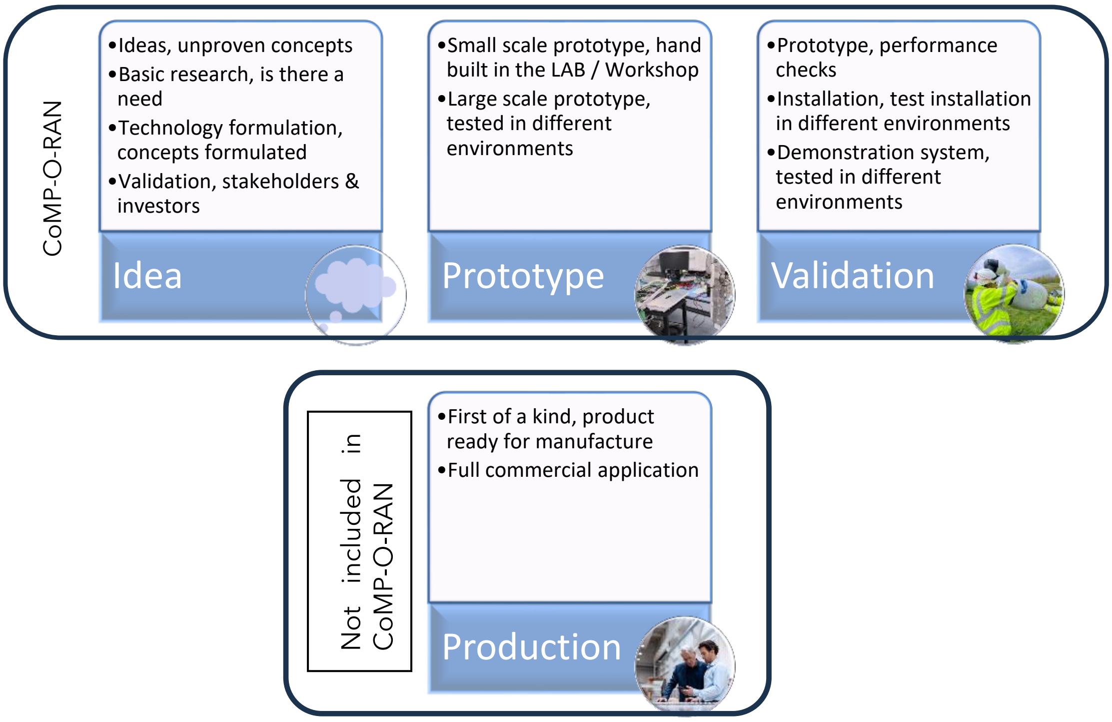

Figure 1 – CoMP-O-RAN Development Process

The Key Objectives were:

a. Modular system by integrating all sub modules into one frame.
b. Single power supply to the small cell.
c. Flexibility in option of fibre or fibreless small cell connectivity.
d. Efficient switching using CoMP algorithm.

3 Project structure

Critical to this function is to agree a common method for collaboration, issue tracking and financial control. Communication between Consortium members was regular, professional and honest, with additional meetings as required to work through any issues that prevented progress. There is always an opportunity for lessons learned to improve engagement and each member were encouraged for any feedback that would assist their development or reporting efforts.

3.1 Management and Organisation

The CoMP-O-RAN management structure included project management, engineering, finance, deployment, and operations teams. CoMP-O-RAN lead partner responsibility, co-ordinating with consortium members to drive the project to a successful conclusion.

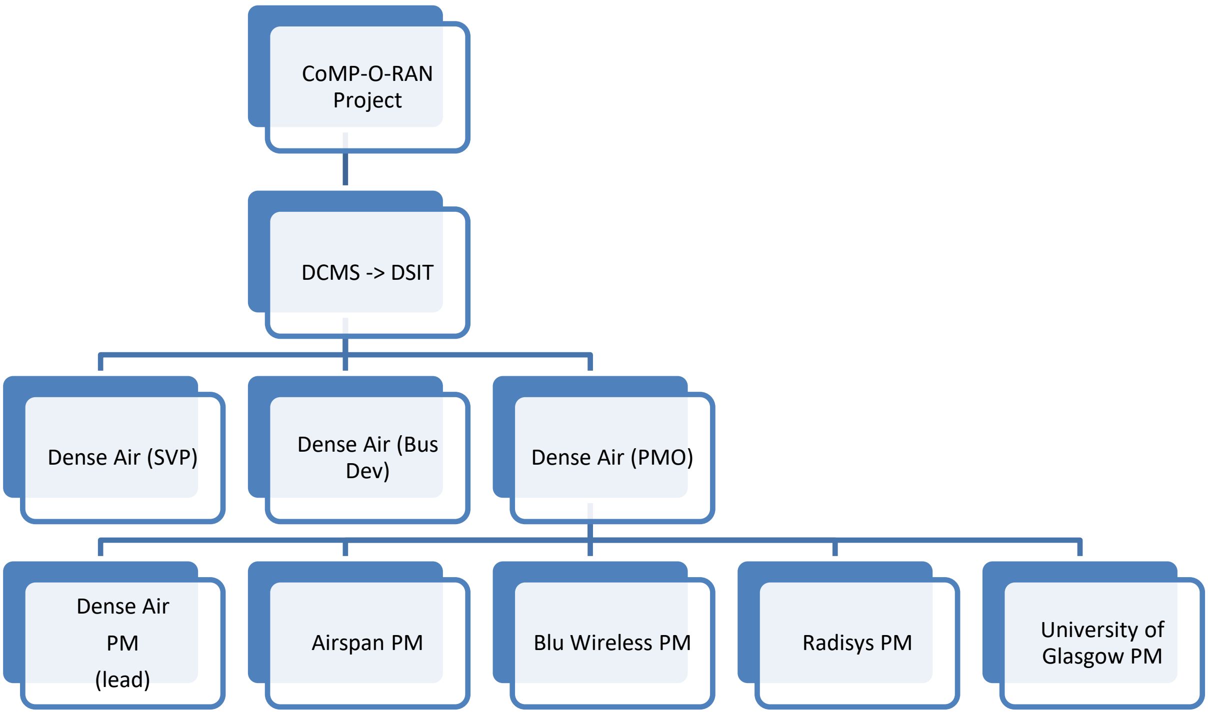

Figure 2 – CoMP-O-RAN Project Management Overview

3.2 Consortium Participants

The Consortium partners were chosen based on their expertise to bring the project to a success conclusion. Each partner was asked to put in their own words their expertise and contribution to the project.

3.2.1 Dense Air

Dense Air is part of Sidewalk Infrastructure Partners' CoFi platform, advancing shared broadband solutions to help close the digital divide and make connectivity more open, shared, and inclusive. Office in Marlow, UK.

dense air

- Responsible for operating the lab setup and providing access to consortium partners as required
- Producing baseline system throughput figures at documented stages of integration
- Work with partners to assist achieving their delivery contributions
- Being the system integrator for the consortium
- Responsible for collating results and documenting a Test Report

3.2.2 Airspan

Airspan is the supplier of the 5G radios with UK office in Slough, UK

- Provide required gNBs units for the lab
- Assist, as required, with initial system integration of the AS1900 into the Druid
- Raemis 5G Core and Radisys CU
- Develop and assist with integration of the nFAPI/split 6 against Radisys CU/DU

3.2.3 Blu Wireless

Blu Wireless is the supplier of the ultra-fast, low latency mmWave systems based in Bristol, UK

- Wireless technology based on Blu Wireless Hydra modem for IEEE 802.11-2016 DMG delivering a wireless fronthaul link
- Delivered off the shelf solutions for lab testing
- Configured units and assisted with initial system integration of the mmWave nodes into the test stations
- Worked with Dense Air to define and refine the configurations of mmWave nodes for point to point and point to multipoint links

3.2.4 Radisys

Radisys is a global leader in open telecom solutions, based in Godalming, UK

- CU/DU integration with Druid 5G Core and Airspan Split6
- Implement CoMP DPS algorithm based on UoG input. Where possible, design with compatibility to a future NCJT implementation
- Assist with CoMP testing on PTMP station

3.2.5 University of Glasgow

The team in University of Glasgow providing simulation and coordination algorithms, based in Glasgow UK.

- Work with Radisys on CoMP API requirements.

- Develop Release15-compatible CoMP algorithm and provide algorithm
- pseudocode to Radisys
- Work with Radisys on integration to the CU/DU stack
- Assist with CoMP testing on PTMP station

3.3 Technical Architecture

The CoMP-O-RAN project aimed to develop a small cell prototype that integrated a 5G radio for access with additional mmW networking elements that allows small cells to be connected together to form clusters. This cluster is connected to a server running a 5G stack. The 5G stack co-ordinates the 5G radios into a managed cluster, creating a higher performing cell than would traditionally be possible using a macro 5G cell or multiple separate small cells.

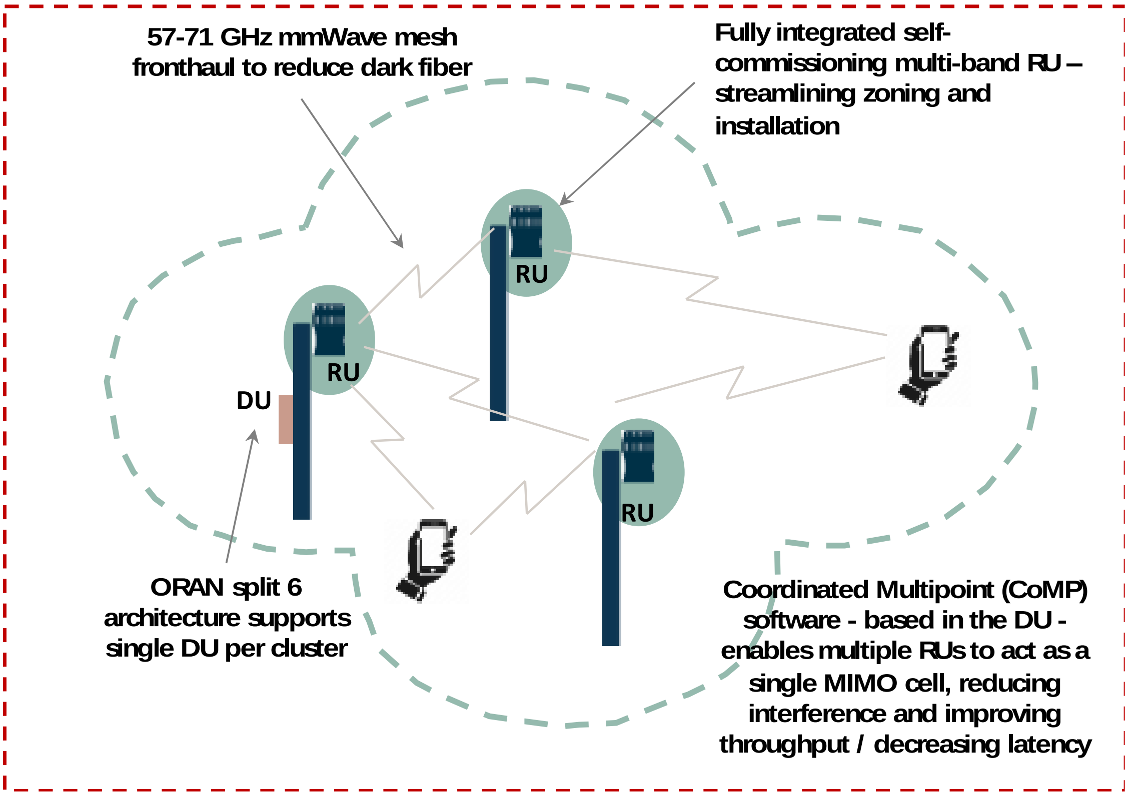

Figure 3 – CoMP-O-RAN Basic Architecture

As shown in Figure 3, these CoMP-O-RAN small cells are inter-connected via an integrated millimetre wave (mmW) radio, reducing the reliance on costly fibre connections to street furniture. These small cells are aggregated to a single point where a local cell-edge server will provide the 5G stack and centralised scheduler.

3.4 Major Events

Key milestones demonstration dates

Major events	Date
Project start	1st Feb. 2022
DCMS visits the CoMP-O-RAN LAB in Marlow	21st July 2022
Cenex 2022, CoMP-O-RAN Introduction to project targets	7th / 8th Sept. 2022
DSIT visits CoMP-O-RAN setup in Millbrook	13th July 2023
Cenex 2023, CoMP-O-RAN use case demo	6th/ 7th Sept. 2023
Project end	30th Sept. 2023

Table 1 – CoMP-O-RAN Key Milestones

3.5 Security

A prime consideration the project. The CoMP-O-RAN system developed from conception through to TRL6/7. It is a requirement to acknowledge the effort and processes required to take the demonstrator to higher levels of TRL, as good practises should be built into the development process, not applied to near the end.

3.6 Marlow Lab Equipment

A new CoMP-O-RAN Lab was constructed in the Dense Air UK head office. The Marlow lab proved itself a solid foundation for the development and testing of solutions from component testing through to the testing of a total system. The Lab comprised five servers, seven RUs with static UEs, and a programmable attenuator simulating UE mobility through a network.

3.7 Site deployment in Teesside

Objective to try out the concepts developed in the Marlow Lab in a real environment, a deployment in Teesside International airport proved to be a valuable testing ground where deployment of commercially available components were tested for interfacing and performance comparisons to Marlow lab results.

3.8 Site deployment in Millbrook

Dense Air have a long history of using Millbrook (UTAC) as a testbed for trialling new networks. The close partnership with Dense Air and the existing 4G and 5G networks meant that the site offered an ideal location for the integration testing of CoMP-O-RAN.

3.9 Deployment Labour

There was significant effort to deploy the prototypes on the two main sites (Teesside Airport and Millbrook Proving Ground). The lessons learned during the deployment phase, including the configuration of the small cells on the poles, were hugely beneficial in preparation for future deployment in a commercial environment.

The deployment at Millbrook proved to be easier due to the ability of the pole to be lowered so installation could be made at ground level.

4 CoMP-O-RAN Prototypes

The prototype CoMP-O-RAN units were designed by Dense Air Engineering, consortium members and manufacturing partners.

The prototype design is a pole-mounted unit providing 180° coverage of 5G and mmW links. This allows the trial of both single and double deployments (to cover 360°) to investigate fibred and mmW Fronthaul connections.

A small batch of prototypes were manufactured by a UK Contract Manufacturer (CM) for demonstration and test in Millbrook. The assembled units were then tested in the Dense Air Marlow lab before being deployed to site.

4.1 CoMP-O-RAN small cell Development Process

The prototype development process involved the following departments and external parties:

- Hardware Engineering
- Product Engineering
- System Engineering
- Purchasing
- Test Engineering
- Deployment
- Operations
- Contract Design Consultants
- Contract Manufacturing

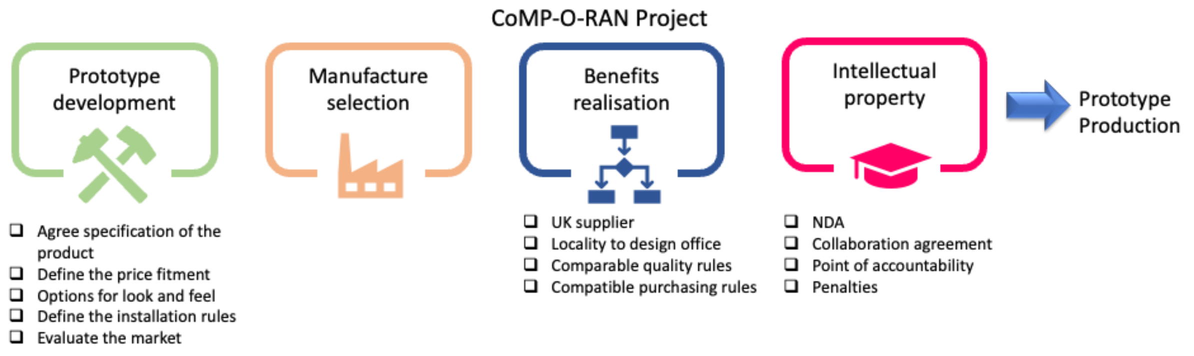

Figure 4 – CoMP-O-RAN Small Cell Prototype Development Process

Once the decision to manufacture has been made, the development enters the next phase which follows manufacturing through to deployment testing, as show in Figure 5.

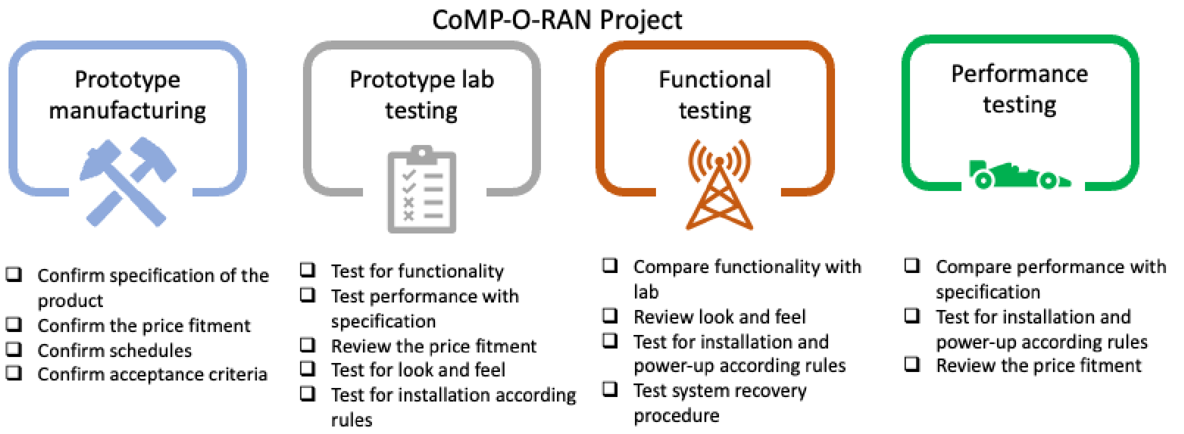

Figure 5 - Development Process from Manufacturing to Deployment

4.2 CoMP-O-RAN small cell design

Figure 6 shows the internal architecture of the CoMP-O-RAN small cell and the other constituent components of the CoMP network, highlighting the contributions from all members of the consortium.

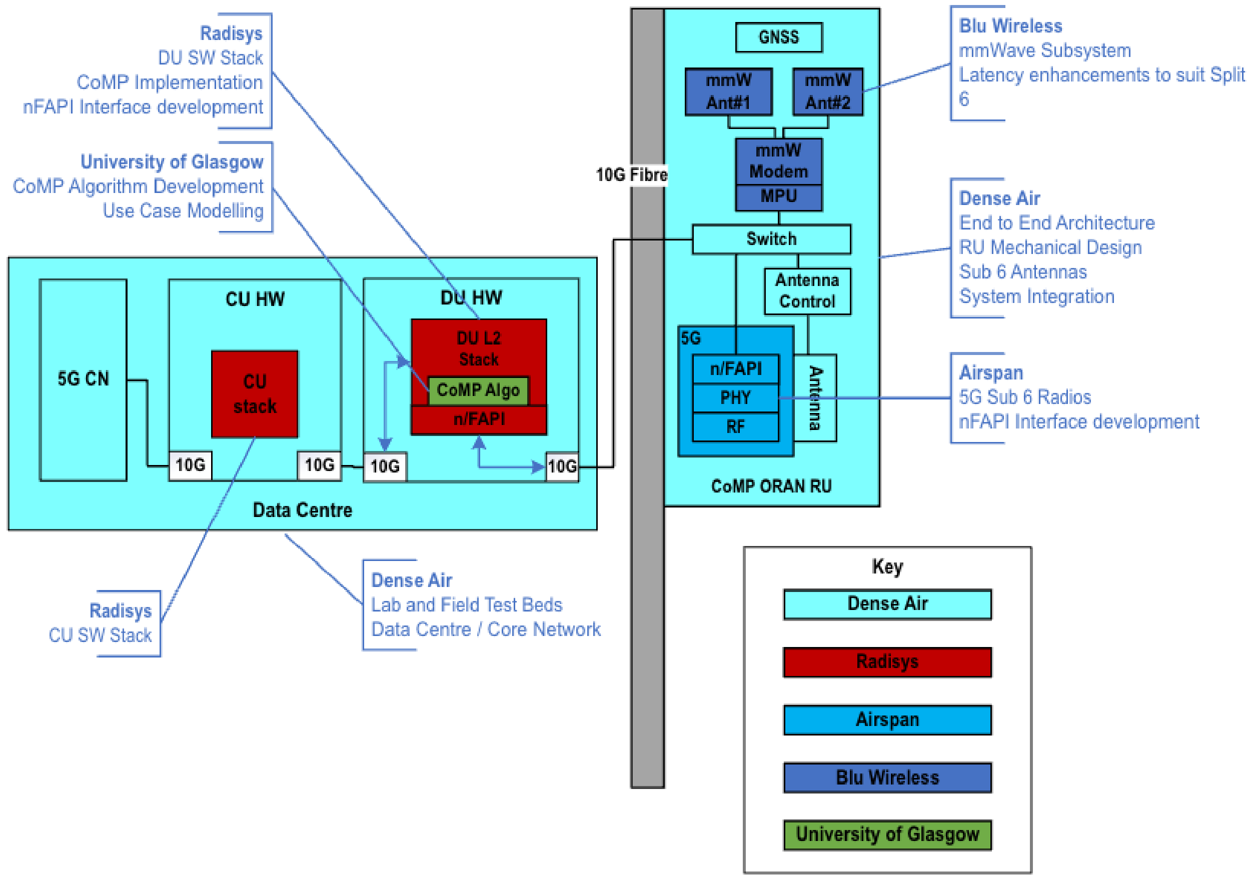

Figure 6 – CoMP System Overview with Consortium Contributions

The 5G Core, CU and DU all runs on standard commercial computer servers. The CoMP-O-RAN small cell, termed the Comp ORAN RU in *Figure 6* is the main hardware development in the CoMP-O-RAN project. This required development effort from Airspan, Blu Wireless and Dense Air to convert the design into the integrated prototype.

University of Glasgow contributed the initial study into CoMP schedulers and also provided system simulation of expected performance. The implementation of the CoMP scheduler, control of the multi-RU system and the air interface configuration under Radisys' responsibility. Dense Air lead the integration of the component parts in the Marlow Comp lab.

The key features of the CoMP-O-RAN design are in Table 2.

Feature	Description
UK SKU	n77 (3.7GHz to 4.0GHz)
2 x 2.5Gbps Fibre Connection	Daisy Chains two CoMP-O-RAN Small Cells to provide 360° coverage
1 x 10Gbps Fibre Connection	Fibre backhaul connection to DU mounted on pole, pole cabinet or local data centre.
1x 5G Airspan Radio	Single 5G n77 band of up to 100MHz bandwidth
Electronically controlled Antenna	Software Configurable Antenna via an embedded processing board.
mmWave Backhaul	Integrated 60GHz mmWave fronthaul
Fibrolan Switch	Connects external fibre and mmW interfaces to internal components.
2 x External LED Indicators	LEDs indicating: power on/off, connected state on/off, alarm for components. Externally visible for Operational purpose. Ability to turn off LEDs to avoid attracting attention.

Table 2 - Key Features of CoMP-O-RAN Small Cell

The internal components are housed inside a purpose-built housing that provides thermal and environmental protection.

4.3 Manufacture and Test

Figure 7 below shows the production of the CoMP-O-RAN small cell. Note that the design has two parts that are joined together during final assembly to produce a single, bonded unit.

Figure 7 – CoMP-O-RAN Small Cells in manufacture and assembly

The CoMP-O-RAN small cells were tested in the Comp lab in Marlow. The test plan provides coverage for all the external interfaces and exercises the internal components independently, as shown in Figure 8.

Final tests connect the RU into a cabled 5G network and checks a UE connects as expected. This is shown in Figure 9. mmWave tests that the integrated modems connect to test mmWave modems and link performance is as expected.

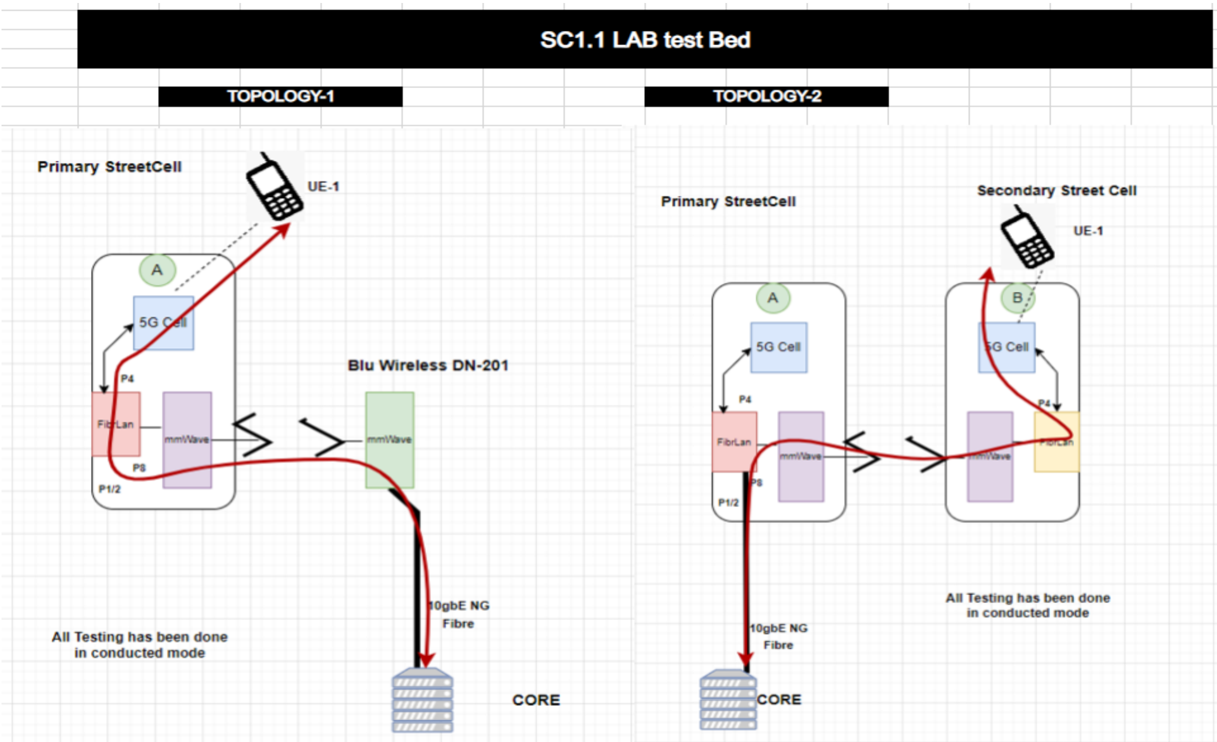

Figure 8 - Marlow CSC Testbed

Figure 9 – Integration testing of prototype CSCs with CoMP-O-RAN rack

An example of the final protype on a test stand can be seen in Figure 10.

Figure 10 – Final CoMP-O-RAN small cell prototype on a test stand at Cenex 2023

4.4 Prototype Deployment

The poles at Millbrook can be winched up and down, making installation a ground-level activity as shown in Figure 11.

Figure 11 – Single CoMP-O-RAN unit installation on a winched pole

Only 3 cables are required to be connected during installation. Fibre backhaul, power and ground, as shown in Figure 12.

Figure 12 – Power and fibre cabling covered by the shroud

After the bracket has been mounted and external cables applied, the CoMP-O-RAN prototype is tested using a laptop to prove it has powered correctly and all the components are in operational mode. Note that the CoMP-O-RAN small cell can co-exist with other mounted equipment. At Millbrook, most masts have CCTV and a 4G cell, as shown in Figure 13.

Figure 13 – Operational checks before repositioning the pole

4.5 Technical achievements

- Executed concept to deployed prototypes in approximately a year.
- Integrated 4 commercially available components into a single housing.
- Field tests of the prototypes to understand capabilities and limitations.

4.6 Lessons Learned

Several valuable lessons are highlighted:

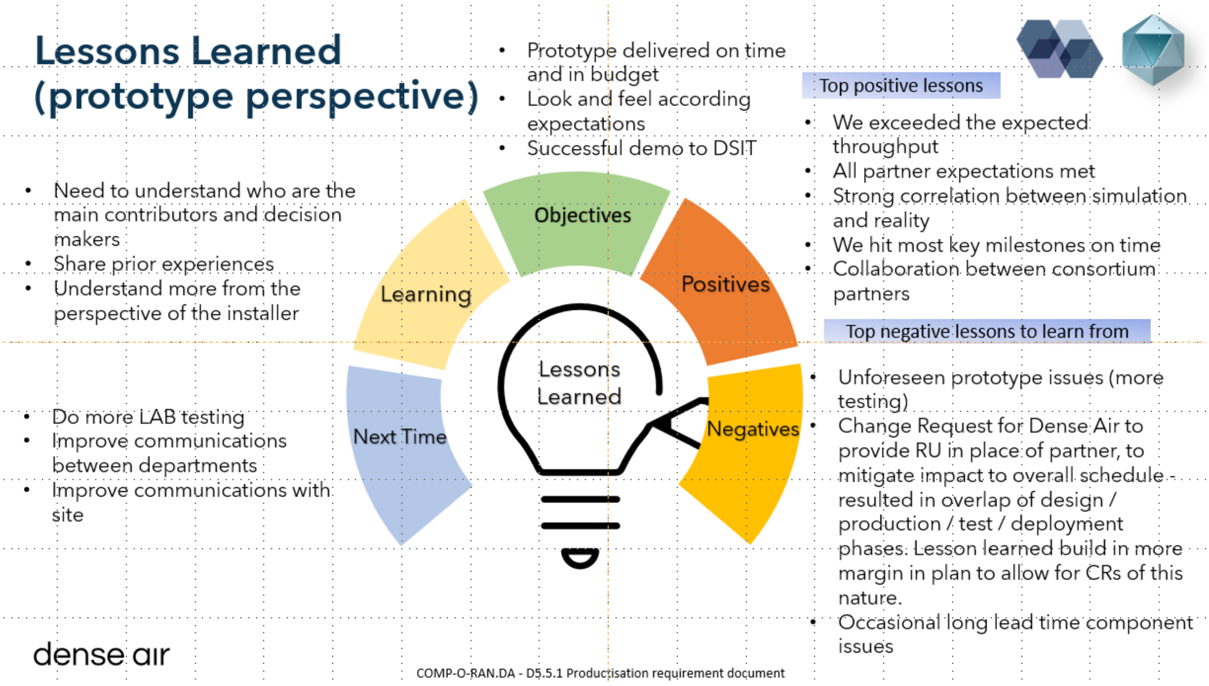

Figure 14 – Lessons Learned

5 Lab Design and Deployments

The CoMP-O-RAN lab design and build was the initial and most valuable deliverable for the CoMP-O-RAN project. This was an early requirement as the Marlow lab was the sole site for integrating the 5G core, Radisys CU/DU stack and Airspan RUs and was required for Continuous Integration activities. It was also used to benchmark and integrate mmW and early insights into the small cell system performance.

The TV5G CoMP-O-RAN Component testbed at Teesside International Airport was the first external deployment, and designed to provide feedback on 5G and mmW components using commercially available products, configured as a facsimile of the later integrated CoMP-O-RAN Small Cells (CSC). Lessons learned looped back to accelerate deployment at the Millbrook site.

The final deployment at Millbrook Proving Ground, used insights from lab and TV5G to inform the design and configuration of a dedicated CoMP-O-RAN network. The output from this stage will directly influence further small cell designs and deployments.

The following subsections detail the above testbeds.

5.1 Marlow CoMP-O-RAN Lab Development

The CoMP-O-RAN lab is situated in Dense Air's primary office in Marlow, Buckinghamshire and was developed to aid design and test of prototype Small Cells and Split6/CoMP software development and integration. The lab design enabled both on-site and remote consortium development. The lab test plan is documented with baseline results of Core integration with CU, DU and RU completion hand over.

Lab activities were a combination of:

- R&D testing to develop baseline knowledge of how the components work and perform.
- Creating a common integration environment where all partners could work together, remotely (via VPN) and on-site.
- Creating a common platform that could be replicated to enable parallel development, debug & testing.
- Executing the lab test plan to understand system performance.

Both DSIT (nee DCMS) and partners attended a lab visit and demonstration in July 2022. The CoMP-O-RAN lab build specification show in Figure 15, consisting of a server room, storeroom, and main lab area. The main lab area contained the CoMP-O-RAN small cell prototyping and manufacturing test along with the CoMP-O-RAN integration setups.

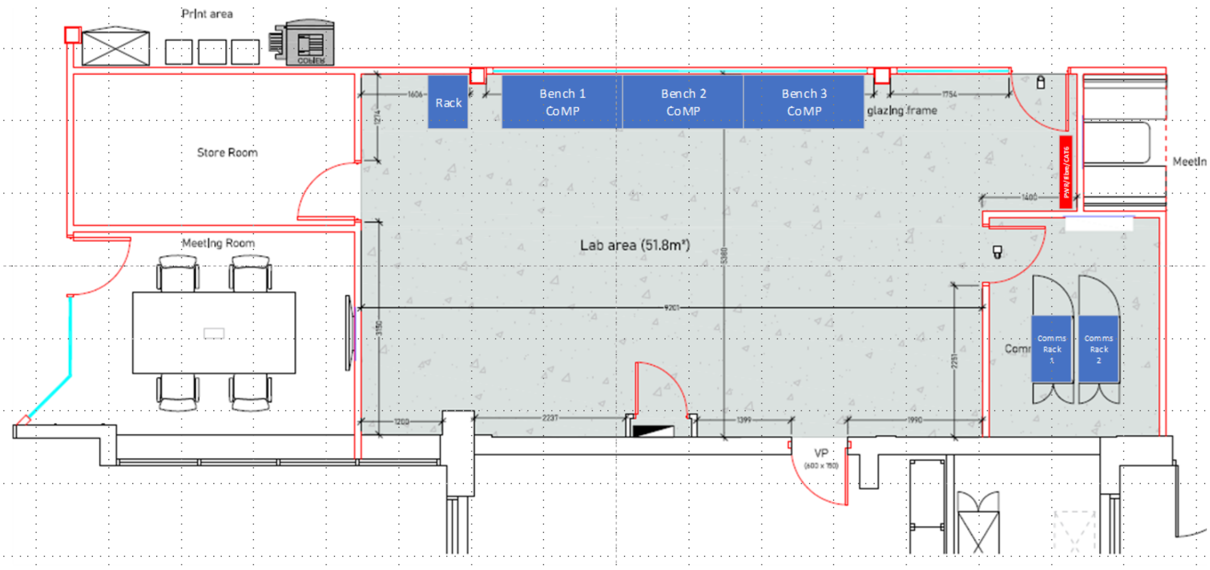

Figure 15 – Plan layout of Marlow CoMP-O-RAN Lab

Figure 16 shows the evolution of the lab integration setups. Initial integration was with Radisys CU/DU with Druid 5G Core, and this verified the base platform that was replicated to create 3 lab setups that could be used in parallel. The Blu Wireless mmW and 5G units were independently tested to understand performance. They were integrated together initially as a backhaul between Airspan 5G and 5G Core, and later as a fronthaul interface once Split6 was implemented on the DU and RU.

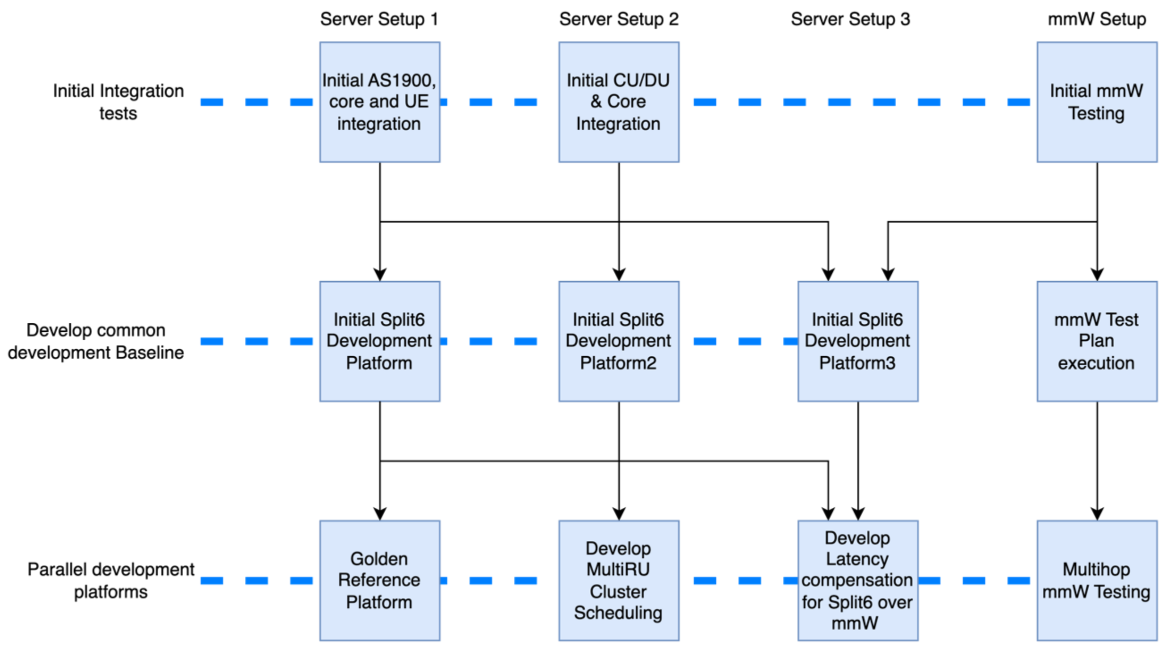

Figure 16 – Lab test setup utilisation

The culmination of lab testing was the multi-RU setup, which replicated the Millbrook deployment and was the main multi-RU integration platform, used extensively to develop and validate the CoMP-O-RAN features required for later deployment tests. It includes a Multi-Channel attenuator that simulated a UE moving from one radio to another, exercising the CoMP-O-RAN scheduler in the DU.

The Golden Reference platform is a system that is always left in a working state, useful for rapidly comparing changes and for creating baseline system performance figures. Setup3 was used as a second single-RU system which includes a mmW fronthaul link between DU and RU. This platform identifies measurements and system effects of fronthaul latency.

Figure shows photos of the CoMP-O-RAN lab. The left-hand photo shows the main lab with a CoMP-O-RAN rack evolved to contain all the radio side of Setup2, containing five AS1900 RUs. The right-hand photo shows the rack in the server room. Of the five servers, three were the CU/DU processing servers for setups 1, 2 & 3. The other two servers were virtual machine host servers, running network management and 5G core functions required in the system.

Figure 18 – Marlow CoMP lab photos

5.2 TV5G CoMP-O-RAN Component Deployment Site (Teesside)

Teesside International Airport provided a testbed location to understand how to deploy the radio units that were being integrated in the CSC and to loop back learnings to the later Millbrook deployment. This testbed was termed TV5G and was specifically used to provide:

- A work-through of first outdoor radio and networking configuration.
- Test throughput, latency, reliability, and multi-hop in the first mmW deployment.
- Survey gNB 5G radiation characteristics and compare to simulation.
- Survey real-world mobile phone throughput on the site.
- Document findings so they can be applied at Millbrook.

Figure 19shows the six pole sites at the airport. The first two poles used existing light furniture, the remaining four were greenfield poles. All six poles were fibred and networked together in a control room which housed the required network switches and servers.

A total of nine Airspan AS1900 5G cells were distributed on the 6 poles to create a mixture of single sector (180° coverage) and dual sector (360° coverage) cells. A total of eight Blu Wireless DN201 mmW units were deployed on four poles to create a small mesh.

Figure 19 – TV5G Component testbed at Teesside International Airport

The AS1900 5G radios were covered by an early prototype shroud that demonstrated the CoMP-O-RAN small cell's appearance when deployed.

Figure 17 – Early CoMP-O-RAN small cell prototype at TV5G with external mmW

5.3 Millbrook Deployment Site (Bedfordshire)

Situated an hour's drive from Dense Air's Marlow office, Millbrook Proving Ground has a long history of vehicle testing in the UK and hosts a diverse set of testing facilities. This facility has been used for previous DCMS 5G programmes by Dense Air, Blu Wireless and Airspan, and provides infrastructure hosting 4G, 5G and mmW equipment. By building on this existing infrastructure, this project leverages investments from previous DCMS projects.

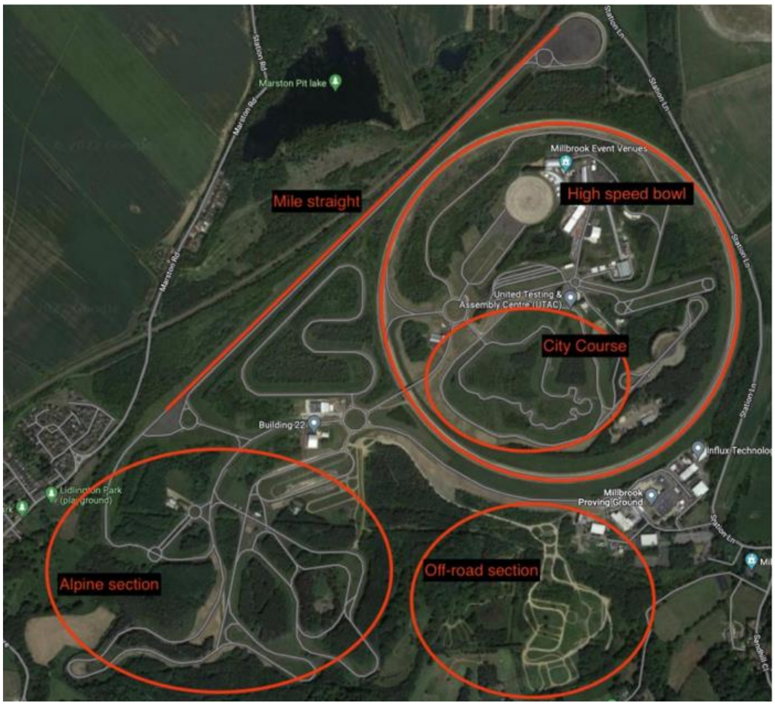

Figure 18 – Major sections of Millbrook Vehicle Proving Ground

First over air test and prototype CoMP-O-RAN configuration deployed at Millbrook. It combined the system development work achieved in the lab with the deployment learnings from the TV5G test deployment.

The Millbrook three deliverables:

1. COMP-O-RAN Test plan document (Millbrook)

   Outlines the hardware to be deployed including compute resources, specific test plan for the Millbrook site and outlines the main goals of the deployment.
2. COMP-O-RAN 5G CoMP ORAN prototype small cell baseline hardware complete and installed at Millbrook available and documents the hardware manufacture and test process, and summarise the deployment findings.
3. COMP-O-RAN Test & Trial completion at Millbrook summarising the output from the test campaign.

Figure 19 - Pole locations used for the CoMP-O-RAN Cell

The Millbrook CoMP-O-RAN tests used five poles that encompassed the City Course route, as shown in Figure 19. The locations were chosen to provide a suitable trade-off between overlapping 5G cells and line-of-sight, which is a hard requirement for mmW links. Dense

Air also have an office area located beside the server room. The masts at Millbrook are lowered by winch, which was an advantage in early deployment when the small cells were debugged in the field, avoiding booking cherry-pickers.

Figure 20 - CoMP-O-RAN Small Cell pole installation

The poles, fibre hub container and server room provide all the networking infrastructure for CoMP project testing. The design preference was to isolate traffic testing from Millbrook infrastructure so that it could be operated without constraints.

The network interconnections between the CoMP-O-RAN cells installed on the poles, the Fibre Hub Container (FHC) fibre interconnection point, and the switches and servers housed in the CAV 5G CoMP-O-RAN computer rack in the server room.

Management of the CoMP-O-RAN network:

- Isolate CoMP-O-RAN traffic from the Millbrook corporate network
- Dynamically configure networking connections between RUs and the CU/DU servers (mmW or fibred)

The NMS is in the cloud, the CSCs uses internet access to enable full remote monitoring and configuration.

5.4 Data Acquisition and DenseWare

Dense Air's DenseWare analytics platform is designed to aggregate statistics extracted from an operating radio system, providing unique insights into how the systems is operating and interacting.

5.4.1 Real-time Telemetry for Split6/CoMP

Near real-time logs from the network side (DU entity) provide an in-depth understanding of the UEs environment and how the DU uses that information to drive the CoMP algorithm. DU logs were parsing at the rate of approximately 10,000 reports per minute to extract information on what each UE reported and how the DU combined those reports to schedule the whole cell. These reports were parsed and pushed to a cloud service that combined them with the handsets reported location to provide a coherent picture of the network and mobile ends of the system.

A cloud-based presentation platform visualised that data using flexible graphic tools. figure 24 shows an example window showing the location of the mobile handset (car) on the City course, correlated in real-time with UE measurement reports showing signal level, throughput and the radio is was connected to.

Figure 24 - Cloud-based telemetry tracking UE location with TRP measurements.

The telemetry this system provided was invaluable to understanding the state of each radio and its contribution to the mobile phone download and interference. It also provided the basic 5G demo platform for the Cenex 2023 show, where Dense Air demonstrated the system performance to government and council officials, and UK MNO providers.

5.4.2 NQT Mobile Phone App

The NQT (Network Quality Test) app is a Dense Air R&D project with the aim to combine network statistics, air interface indicators and quality of user experience reports into a Quality of Experience tool built into a mobile handset application.

The top two objectives of this application, can be summarised as:

1. Collect air interface indicator data from UEs and feed into DenseWare databases for long term assessment, statistical analysis, and predictions.
2. Run unintrusive real-time tests to assess current network conditions and inform and educate users of the predicted Quality of Experience at a given time at their location.

Common use-cases for NQT include:

- Identifying locations that have poor mobile user experience.
- Highlighting improvements following the deployment of small cells.
- Obtaining network indicators such as RSSNR, RSRP and SINR.
- Collected comparative 4G and 5G networks statistics.

NQT is integrated with DenseWare, where the data platform provides visualisation and analysis of the collected data.

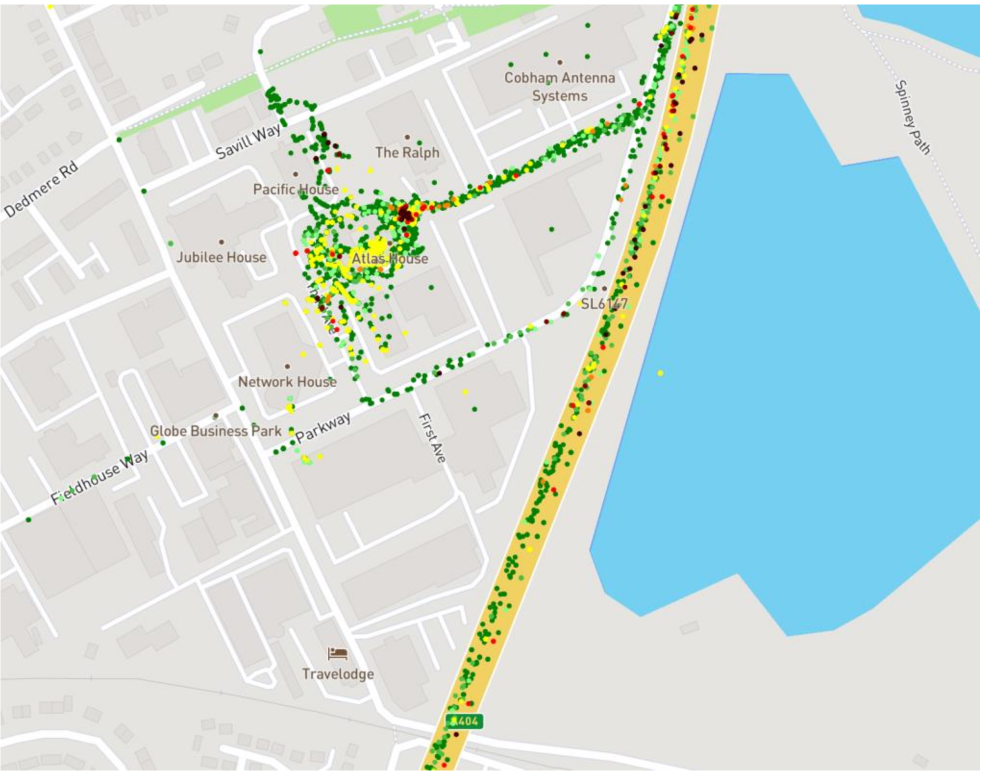

Figure 21 – Example of Dense Air's RSSNR network measurements around Marlow office

5.4.3 Long-term Network Statistics

The network side statistics are taken from a longer-term statistics log on the DU. These statistics are generated every 30 seconds and contain both 30-second summaries and rolling counters. Radisys and Dense Air collaborated to generate a set of statistics suitable for deeper analysis.

These statistics are used to generate utilisation figures for each radio (TRP), allowing DenseWare to be aware of split6 statistics and provide insights into how well CoMP is operating in the field. These can be used to determine how well the cluster is scaled, for example, and to inform future refinements like power or DU server optimisations.

The elements of the process in collecting and processing DU log data, through to producing insights. In this phase of development, statistics are extracted using pulled data sources into a python parser. A future refinement will integrate these statistics with the Network Element Manager, to provide a more automated interface into DenseWare.

The large datasets are aggregated in Google Cloud which provides native tools for querying large databases.

A key concept behind DenseWare is the use of Google serverless technology. Big Query is Googles serverless data warehousing service. It interfaces with Google AI capabilities, as well as Googles serverless container-based compute platform Cloud Run. The serverless paradigm enables DenseWare to scale resources to process the huge volumes of data associated with MNO network performance and other use-cases.

As the CoMP-O-RAN clustering technology is deployed as public and private networks, it will be essential to have the capability to collect crowdsourced network data and evaluate CoMP-O-RAN cluster performance, continuously, at scale over short- and longer-term time frames. The data collected will enable Dense Air to continue to optimise the algorithm based on how user equipment (UE) interacts with the CoMP-O-RAN clusters.

6 Tests, Results Findings

Each stage of the development produced their own set of findings which are detailed in the sections below.

6.1 Key Lab Findings

The lab was the preferred location for testing general system capabilities that did not require radiated tests.

6.1.1 Throughput versus mmW Link

Lab mmW experiments showed that the Blu Wireless mmW unit operating in the MCS mode expected in the field could handle approximately double the total bits/second and many times the packets/second requirements of a fully-loaded RU. This was a significant finding, as it validated that mmW links could aggregate multiple RUs, and had the potential to exercise the trade-off between performance and fibre costs.

The critical interfaces are between the RU Layer1 and the DU, as there are many interfaces and packet handling is time-critical. PCAP nFAPI captures between DU & RU interface on the AS1900 all-in-one gNB showed packets profiles was dominated by large packets, particularly when only a single UE was attached.

The initial decision was to limit the MTU to 7K packets between these interfaces as this would minimise the packets/second handling and not breach the 7920 bytes limitation imposed by the Blu Wireless mmW units. The Blu Wireless limitation was a hard requirement as it implements a Layer2 Ethernet bridge which cannot support packet segmentation/re-assembly.

The maximum throughput to a single UE was measured at this point as it provided the lowest number of packets/second for a fully utilised system. This provided a baseline to compare other MTU strategies. It is ultimately desirable to use as low an MTU size as possible, as it minimises system dependencies where each interface would need to support that MTU.

In the lab, the MTU was reduced and the maximum transfer to a UE re-tested. Results, after debug and adjustments to the interfaces on the DU and RU side, showed an MTU of 1500 bytes could achieve the same single-UE throughput of the previous 7K packet. This was a significant result as it completely removed the requirement for Jumbo packet support in the system.

6.1.2 Split6 Latencies

Latency is an important Split6 measurement as it affects various parts of the system but is especially critical to the 5G Downlink Hybrid ARQ (HARQ) process.

The Small Cell Forum nFAPI protocol provides for a maximum latency of 2msecs across the nFAPI interface. OAI also lists their stacks latency limit as around 2msecs in either direction. For the Round-Trip Delay (RTD), a mmW latency of 4msec latency was initially targeted. Blu Wireless optimisations more than met this target, ultimately providing a RTD of approximately 2.5 msecs at desired bitrate. Latencies are in units of slots (0.5 msecs) which provide the granularity of the simulator for predicting downlink throughput. These latencies are configured into the DU at startup to trigger the DU to start scheduling the downlink the correct number of slots in advance.

The latency estimates were used in the downlink HARQ simulator to predict the maximum downlink achievable to a single UE when using various number of mmW hops. The pool of HARQ IDs is limited to 16, therefore latencies mean that at HARQ ID starvation limits downlink throughput to a single UE as latency increases.

In the lab, the available downlink to a UE was tested over a single mmW hop, with the result being slightly higher at 87.5%. The 4% deviation from the 83.5% is considered to be due to under-utilisation of the mmW interface for a single RU.

6.2 Key TV5G Component Findings

The TV5G Component testbed provided useful deployment recommendations and baseline performance figures. It provided a valuable learning environment for deployment, commissioning, and testing of 5G & mmW components. These findings were applied to the Millbrook deployment and design of next generation equipment.

The findings are split into system, mmW and 5G sections below.

6.2.1 TV5G Component System Findings

Remote power control equipment is very useful for initial trial tests and for remote re-configuration. It is recommended to install this while installing the main equipment to speed up commissioning.

Fibre to pole installations were delayed beyond the start of deployment. To complete the major installations on the pole and pole cabinets, the networks were combined in novel ways to help complete installation and commissioning tests. The 5G radios were backhauled using mmW to a single pole with fibre, while waiting for pole fibre installation to complete.

Fibre trunking between the TV5G server room and a cabling room were delayed. To aid networking between the poles, smaller networking switches were installed in the cabling room to provide required network switching options.

These flexible networking options informed simpler installation guidelines that require less installed infrastructure during the initial installation stages.

6.2.2 TV5G Component mmW Findings

After initial deployment in the winter, a tree with foliage developed that affected line-of-sight between two poles. This provided an opportunity to adjust deployment guidelines to avoid this occurring in future deployments. It also provided an option to learn how to cope with links that become unreliable over time. A continuous "link-up" logging was useful to show statistics of the link. Tracking the link MCS in addition would allow the "link-down" state to be predicted before it occurred.

Two mmW links at TV5G were in-line of each other. During channel testing it was evident that distant in-line idling links can cause enough interference to throttle downlink speeds. This highlights the need for frequency planning but also provided the statistics that can identify when this is happening in the field.

The TV5G poles site provided baseline performance of mmW links at various distances and validation of link budget predictions. It also provided a site for continuous link testing, generating links statistics over normal and atypical weather conditions.

6.2.3 TV5G Component 5G Findings

The TV5G site provided the environment to learn how to configure and deploy the Airspan AS1900 5G radios. Specifically, how to optimise cell configuration in a small cluster site for reliable handovers.

The greenfield 5G site also provided a mechanism to learn how to use site surveys and radio test equipment to observe system behaviour. These were used during drive tests to log and visualise how adjustments to cell configuration parameters impacted cell features like handovers.

6.3 Key Millbrook Findings

CoMP-O-RAN testing has successfully concluded and validated that Split6 and scheduling can work in the field and can produce additional cell gains compared to using a single Macro cell. The Millbrook site provided the means to understand the system under test and provided a baseline for further experimentation, tuning exercises, and algorithmic investigations.

The RSRP captures of a UE lap of the Millbrook City Course were passed by University of Glasgow to validate against their simulated results. In general, the measurements aligned well with their simulation and general TRP switching points were at expected locations.

Millbrook testing produced many findings which are summarised in the sub-sections below.

6.3.1.1 Concept Validation

The performance of the CoMP-O-RAN 5G and mmWave radios closely matched the individual components installed at TV5G, validating the integrated design and manufacture. The Split6/CoMP Millbrook City Course provided a mobile scenario, where the circuit proved the systems Distributed Point Scheduler worked, using the RU to serve the UE without requiring handovers. This validates the concept of the CoMP-O-RAN small cell.

6.3.1.2 RU out-of-sync

After the 5G components were converted to Split6, occasionally an RU in the cluster would report late packets after a reboot. Late packets mean there is no transmission during that slot as data has arrived too late to be transferred to the radio. During a test run this could be observed by some sites having occasional or consistently low power. The solution was to reboot the RU and analyse its output log to determine if the RU was operating normally.

Updates from Airspan to mitigate this issue and improve reliability were applied. However, in the field this continued less frequently, further monitoring continued to determine if this is due to:

- Degradation of synchronisation timing over time
- RU rebooted and entered a poor timing state from the start.

A further fix has been applied by Airspan that showed further reliability improvements in the lab. This is continues to be monitored at Millbrook.

Various manual checks are performed before a test run to determine the system state. Monitoring scripts have been deployed in the system which summarise the state of all RUs continuously, reducing the time required to check the system before test runs.

6.3.1.3 Low throughput for Pole Cabinet UEs

Static UEs were installed in the Pole cabinets to provide an easy method of loading each TRP. The intention was that the static UEs would load the network and a mobile UE being driven around the track would switch serving TRPs, sharing its capacity with the static UEs as it navigated its way around the track.

Airspan Airspots were used in the lab for Split6/Comp testing and its capabilities were well understood with respect to the 5G configuration used for the lab and Millbrook. However, in the field they proved to have low throughput under test. The units were retested in the lab and verified that they performed as expected.

The impact was low as the CoMP tests were modified to compensate. The Pole Cabinet UEs would be useful for future repeatable tests so the intention is to resolve the issue this quarter.

6.3.1.4 DU challenges during Cenex 2023 Demo

During the Cenex 2023 event and CoMP demonstration, Day1 demonstrations were hampered by unexplained DU crashes. A UE_ID overflow condition was later found in the DU software, uncovered by an aggressive 5G UE trying to attach to the CoMP network. This was fixed overnight by Radisys and rolled out to Millbrook for testing the next day. This rectified the issue, with no unusual DU effects observed during Day 2 of the event. This was a good example of the close working relationship in the consortium.

6.3.1.5 Low TCP Throughput

Throughput acceptance tests in the lab were based on UDP tests, as these provide an accurate indicator of upper capacity limits of the system. For user experience, TCP is usually used as it is the predominant Internet transport protocol.

Initial TCP tests at Millbrook resulted in very low, variable TCP throughput, as low as 10% of the UDP capacities. This was conformed with lab tests and low-level debug showed that the UE was sending a very low rate of service requests to the uplink scheduler. This resulted in slow packets acknowledgements back to the sender, collapsing the TCP window and suppressing throughputs.

As a mitigation to speed up the test activity, Radisys modified the DU uplink scheduler to give speculative UL grants to all connected UEs. This improved TCP throughput greatly, increasing TCP throughput to within 10% of UDP throughput when using more than 10 threads/streams.

6.4 Consortium Results summary

Test results from the UTAC Millbrook deployment were logged according to the Millbrook Test Plan which completed successfully, with its main goals being:

I. Design a novel Small Cell with integrated 5G access radios and mmW fronthaul radios.
II. Deploy Small Cell prototypes in an outdoor testbed.

III. Test the equipment across required operational scenarios and gauge its effectiveness.
IV. Design, integrate and test a DU Split6 CoMP cluster scheduler to manage connections over multiple radios with overlapping coverage footprint.
V. Use project findings to inform the features a commercial design would require that could be commercially deployed.

Test results from Millbrook were shared with the consortium partners. Their opinions and comments are contained in individual Test & Trial completion reports which are summarised in the following sub-sections.

6.4.1 Airspan

Airspan's Test & Trial completion support document comments on the Millbrook results, including details of on-site support. In summary, Airspan determined CoMP was operational and provided expected capacity improvements compared to a single RU.

Airspan has provided on-site support during deployment and testing the small cell 5G component. Although the antenna interface to the radio deviates significantly from the Airspan AS1900 reference design, in their interpretation the radiated performance meets their expectations.

6.4.2 Radisys UK

Radisys Test & Trial opinions on Millbrook test results. In summary, the CU and DU performance aligned well with their lab testing results, where Radisys proved Split6 performance before delivery sign-off by Dense Air. Radisys supplied further recommendations to aid future developments:

- Early availability of test platforms would have help reduce the integration and testing cycle.
- Having a local integration platform would have streamlined the integration process.
- A platform dedicated to stress capacity testing in the lab early detection of issues seen in the field.

6.4.3 University of Glasgow

University of Glasgow's Test & Trial comments on the lab and Millbrook tests. In summary, UoG found that the field RSRP measurements aligned well with simulated values. Also, UE TRP switching matched simulated predictions, used to predict CoMP algorithm performance.

6.4.4 Blu Wireless

Blu Wireless's Test & Trial commented on the mmW tests results from TV5G and Millbrook tests. In summary, link performance of the CoMP-O-RAN Small Cell aligned with their expectations, proving links >200m can achieve the data rates required for carrying small cell split6 fronthaul.

6.5 Gap analysis

The test plan written near the start of the project had evolved during CoMP-O-RAN project execution. Some of the tests were modified or deferred due to time constraints or understanding of component behaviour. Other changes were due to refinement of test goals over time. In general, the broader CoMP-O-RAN tests were all covered in some form with tuning operations and long-term tests deferred to post project.

These gaps are listed below:

- Investigate performance gains from tuning 5G Tx power.
  This may be better implemented in the lab, where interference can be controlled.
  Tune lab setup3 to provide an interference lab reference.
- Complete mmW Tx power calibration to gain further understanding on mmW link budget.
- Complete implementation of long-term mmW statistics gathering at Millbrook, including integration with an on-site weather station.
- Repeat CoMP tests using mmW as the fronthaul.

There are also other tests and investigations we plan on performing post project. These are:

- Handovers between clusters.
  Additional 5G CoMP clusters are under planning at Millbrook which would provide an opportunity to test handovers between clusters.
  Handovers would also provide a means to compare no-CoMP to CoMP at Millbrook, by splitting the City Course into smaller clusters and compare performance against the single cluster.
- Resolve low throughput for static UEs situated in pole cabinets compared to lab performance.

7 Project assessment

During the execution of the project various documents were generated within our normal process or specially in accordance with Annex 5. The level of comments received from DCMS / DSIT experts were both valuable and constructive meeting our expectations for the project.

7.1 Successes and challenges

The project brought together teams from both industry and academia to work on both hardware and software components of the overall Comp-Cluster design. This collaboration was hugely successful as the project created an environment for open discussion, test iteration and solution design.

Throughout the testing, Dense Air collaborated with UoG to optimise their simulation accuracy and compare against field results. This validated both the simulation as an accurate facsimile of the testbed and the deployment performed as expected. This important step also validates the CoMP algorithm simulation results, as the simulation is based on an accurate model.

The Split6 development between Radisys and Airspan required the Dense Air lab as this allowed both parties to continuously integrate their software, steadily improving reliability and capacity during the project. This provided the foundation to test the CoMP algorithm designed by UoG and implemented by Radisys.

Radisys expanded on this solution, adding multi-RU capability, verifying in both the CoMP-O-RAN lab and on-site at Millbrook. This allowed more aspects of the system limits to be exercised, e.g., TRP-switching behaviour, TRP capacity limits, DU capacity limits.

Teesside provided an initial opportunity to test the Blu Wireless mmW solution prior to Millbrook deployment of CoMP-O-RAN Small Cells. Performance matched and exceeded expectations. This was an encouraging validation on the concept of integrating mmW into the CSC. In addition, fibre installations at TV5G were delayed meaning the 5G deployment commissioning tests were completed using mmW as the backhaul, showing very promising out-of-the-box link reliability and avoiding further delay.

Using Millbrook Proving Ground as the test ground for CoMP-O-RAN proved advantageous as the location is near Marlow, there is an existing close working relationship Millbrook, and there was an ideal location ready with fibred masts. Another Millbrook attribute was that the masts were winchable, allowing the initial CSC prototypes to be worked on without requiring cherry-pickers.

The CoMP-O-RAN Small Cells were a complex integration of components and was taken from a concept to a deployed working prototype in approximately 18 months. This prototype successfully integrated modified hardware, software and firmware from Consortium parties, the productive collaboration is considered a success.

The fronthaul mmW connection has been validated in the CoMP-O-RAN lab as a reliable interface between a split6 DU and CU. This is novel feature and has the expectation of reducing deployment costs for small cells, moving the architecture to a commercial advantage through reduced capital and operational expense.

The system implementation of CoMP on the DU validated that coordinated operation could be realised using features present in 3GPP Release 15. This allows CoMP to be field tested in real-world environments using the current generation of commercial handsets. The expected capacity improvements of Split6 small clusters compared to macrocells could also be field-tested.

Finally, the Millbrook deployment provides a solid foundation to continue refinement of:

- Power optimisation strategies for reducing joules/bit
- Optimisation of CapEx and OpEx
- Commercial hardware and system solutions including Supply Chain
- Spatial Diversity and Spatial Multiplexing gains

7.2 Impact of the results

This section presents some key findings from tests and impact on a future design of CoMP-O-RAN Small Cell.

The Split6 latency simulation and verification with the CoMP-O-RAN implementation has highlighted the cost trade-off of latency. The Scheduler/MAC/nFAPI latency in the DU and nFAPI/Phy latency in the RU were largely fixed during the life of this project. Improvements can be made but requires an optimisation stage that was beyond the aims of this project. The latency of the mmW component is fixed per-hop, therefore the cost of mmW hops on potential UE throughput can be simulated and verified using the Comp network. Currently, 3 hops of the mmW interface will reduce a UE throughput to 50% of the radio interface, which is a useful figure for dimensioning the CoMP system and predicting performance.

Deployment testing has shown that guaranteeing line-of-sight needs to be an important consideration during planning, paying particular attention to foliage. Low-level Link monitoring is required, to detect possible issues before they cause link failure.

The 5G and mmW antenna have a fixed relationship which also requires consideration during planning. Positioning may require trade-off analysis between mmW link performance and 5G performance.

The Split6/CoMP system optimises downlink throughput and makes no attempt to optimise uplink. In the current scheme, uplink capacity is shared between the TRPs / RUs. Typical deployments heavily favour downlink capacity, so this is not considered to be a limitation at this point. It remains a consideration for deployments that require an uplink bias like CCTV transport, for example.

Development of the CoMP system has resulted in the restriction of 8 TRPs/DU. This restriction is an important consideration when planning a deployment. A more flexible cluster size would allow more optimisations for optimising DU/RU ratios.

8 Project security

A workstream for security was created to manage the security aspects of the project.

The first part of the security workstream was to develop a security framework for all consortium members to operate within. This involved nominating a security lead per partner and overall security lead to manage the workstream.

The following framework was developed by the team to capture product security, development security and a day-to-day security for the project.

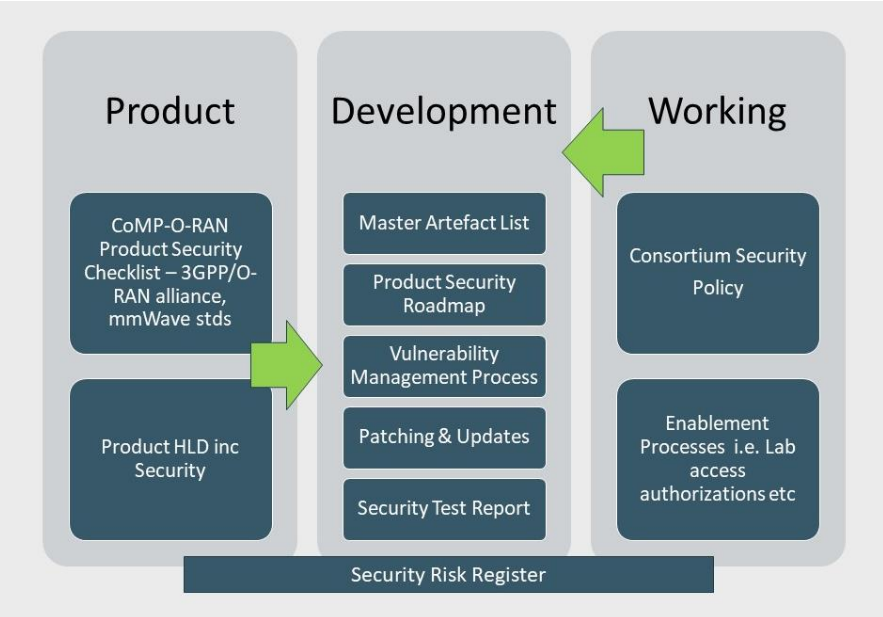

Figure 22 - Proposed Security Framework

In essence there were three broad areas of security the project was trying to manage.

Firstly product security was an area where the individual components that were being supplied were assessed from a threat risk analysis perspective.

The second aspect was a security framework where development activities could be captured and assessed for risk and finally the day to day working security between all parties involved in the project.

At the outset one the critical deliverables for security was a working security policy between the partners for access to the secure lab environment. A lab security policy was developed and policed by the project management team. Each member of the consortium who required access to the secure Marlow Lab environment was authorised and onboarded as part of the policy.

Following the onboarding to the lab environment each partner was asked to complete a Threat and Risk Analysis study, based on the NCSC vendor assessment template. The NCSC template was used as it related back to TSCoP requirements and the TSA. The purpose of this exercise was to give a view on the potential risk each vendor was carrying from a development point of view. The completed exercise highlighted several findings.

- Those with a mature R&D lifecycle showed less risk as one would expect.

- Those with less mature security compliance procedures were active in making improvements.

As the project advanced, an R&D security lifecycle was proposed for future projects. This lifecycle was created with the aim to ensure that early capture of vulnerabilities is detected in the SW build prior to it being released, and matches the internal gate process.

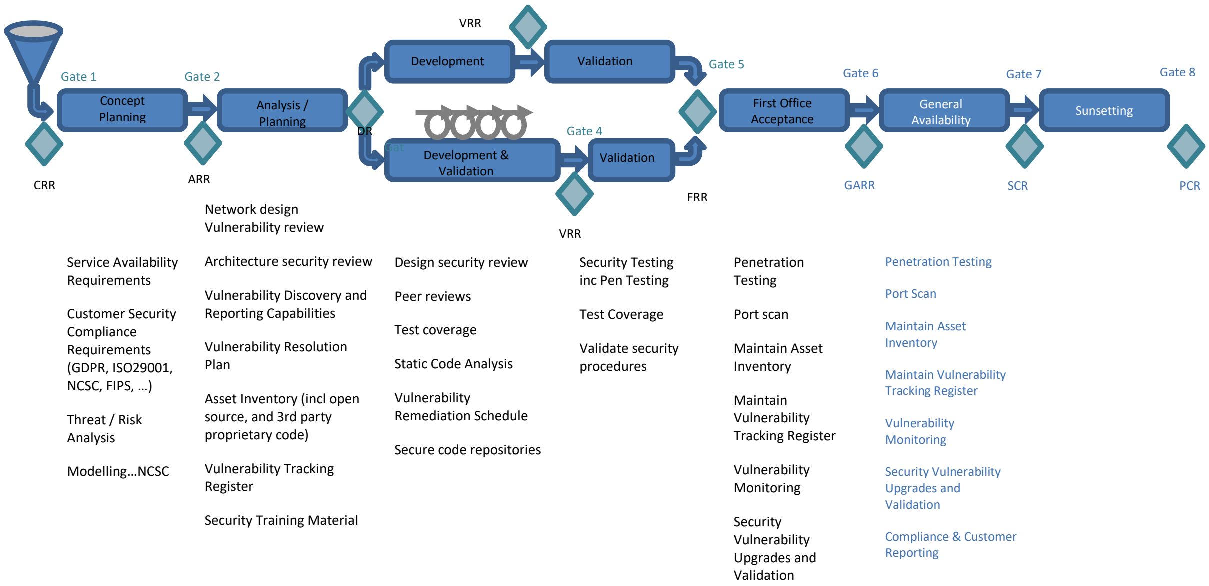

Figure 23 - Security Development Lifecycle

The CoMP-O-RAN project short timeline was insufficient to cover the full lifecycle. For CoMP-O-RAN a decision was made to focus on the TARA and use that to demonstrate the potential risks the project may encounter.

Security fatigue was a factor in the project, functionality was prioritised to ensure that for the Millbrook test we had a working product. The consortium acknowledged that this was less than expected. Future consortium projects plan to ensure more resources are allocated at the front end to the security delivery from both a governance point of view and an analyse of the threats and risks.

The principles related to security to be considered in product design and functionality.

1. Usability of the product with security in place
2. Restrict certain access to authorised users
3. Protect sensitive data when in transit
4. Protect against unauthorised access and modification
5. Protect against compromise from connected technology
6. Security events should be logged and monitored

8.1 Approach to security

The approach to security was to ensure that each partner could work securely with each other, that they had their own development environment in the Marlow lab and that the product could be securely integrated for trial. An access policy was created that each partner followed up on, several Juniper Secure Connect (JSC) licences were acquired to allow for multiple con-current users to have access to the CoMP Firewall. The access control was managed by the project manager for CoMP-O-RAN.

8.2 Outcome from Security related deliverables

The initial deliverable, a framework that focuses the consortium security efforts, the TARA that each component partner delivered, the working information security policy (lab access) and evidence for SW components. The deliverables included reports on the internal R&D processes each organisation took towards security.

8.3 Lessons learned

The main lessons learned around security, is the focus ensuring security is given the priority it needs within a project. Often in the midst of a project the priority of technically getting something to work outweighs the security demands. Likewise, projects where we are delivering a trial quality level often suffer from security fatigue where time pressures force people to choose between functionality and robustness.

From a security perspective, the project delivered a solid collaboration framework that was enforced and policed by project management in terms of the day-to-day lab work that led to a successful trial. The initial TARA exercise highlighted the maturity of vendors security management processes. It is recommended this is repeated several times during future projects to track the trajectory of security posture improvements in terms of development.

The project also delivered a viable strategy and framework for product security, development security and day to day access security. From a product and development security perspective we were able to understand the contents of each vendors contributions, Radisys and Airspan submitted additional security tooling reports which aim to identify potential vulnerabilities and issues.

This project highlighted vendors at a different level of maturity in their R&D processes, which presents a challenge to finding consistency across the piece, from what controls have and have not been implemented. Consortium members like Airspan and Radisys use well known tools to detects security issues in their products and to mitigate them, and are a good benchmark.

As the project progressed, with time compression, there was an increasing sense in priority to ensure that the trail system was working and was able to be deployed at Millbrook. Ideally the integrated system would include penetration testing of the system. The prototype system development reached to TRL6/7, and deployment is limited to a known pre-production test environment at Millbrook. Therefore, security testing and integration was given a lower order of priority. While this was acceptable for our CoMP-O-RAN project, as the threats to the systems and risk were considered low, future projects will require a higher degree of security rigour as we head towards commercial grade systems.

8.3.1 Successes

- Cohesive Security Framework – a solid strategy that divided the areas of risk up and followed established practices.
- Collaboration – Good collaboration to deliver the TARA and other evidence for security testing.
- TARA – Helped deliver a view on each of the consortium's security posture and maturity from a product development perspective.

- Well Controlled Lab – Lab was secure and resources within it were well managed to prevent potential for conflicts.

8.3.2 Challenges

- Completed full end to end security testing – acceptable for trial level quality, but not for commercialising the product.
- Security Fatigue – Great ambition at the start of the project which needed additional support as we progressed.

8.4 Remote Access

Remote access was a common means of accessing the systems in the lab or deployed on TV5G and Millbrook testbed sites. Each consortium member had personalised username and password for VPN access to the CoMP lab. VPN access to TV5G and Millbrook was restricted to Dense Air employees only due to restricted access controls imposed by the owners of the testbeds, who have their own security policies.

8.5 Conclusions

The security framework developed during this project can be used for future 'beyond trial' projects. The framework provides a solid foundation of assessing the threats and risks, and then stages in development to mitigate and remediate. Finally, the framework should develop a common policy and agreement to work together securely.

9 Dissemination and media

The goal of this project was focused primarily on the technical build and test of the CoMP-O-RAN hardware and software solution; however, it was important that progress made in achieving these goals are disseminated to create awareness within the telecoms industry – specifically the solutions USP, target use cases and its application in a real world setting.

Cenex 2023 was targeted as an event at the end point of the project where we could show how CoMP-O-RAN advances O-RAN network typologies and enables the use and application of this technology to support existing and future use cases across different market verticals and to influence the 5G ecosystem as it matures.

9.1 Website and Video

To provide the consortium with a single online presence a website was commissioned alongside a short explainer video. This provided the team with a single point of presence to send people for information on the project, who is involved and what 'CoMP-O-RAN' was all about.

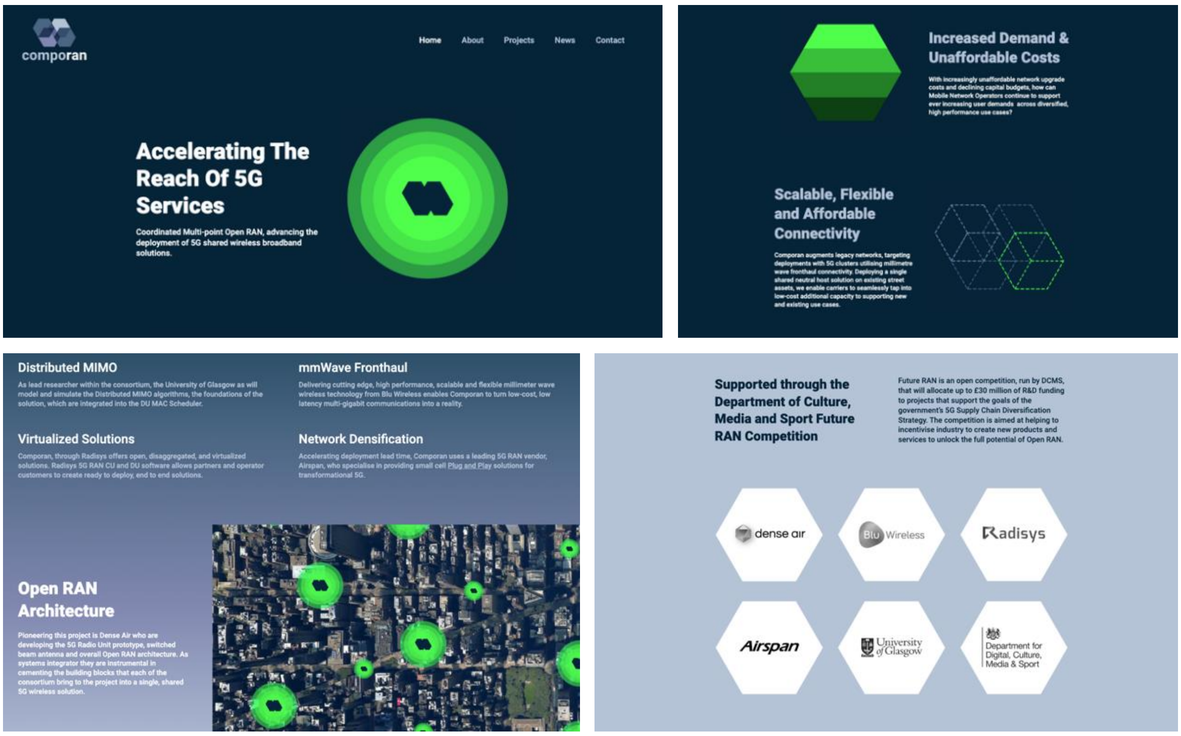

Figure 24 – Images from CoMP-O-RAN Website: www.comporan.co.uk

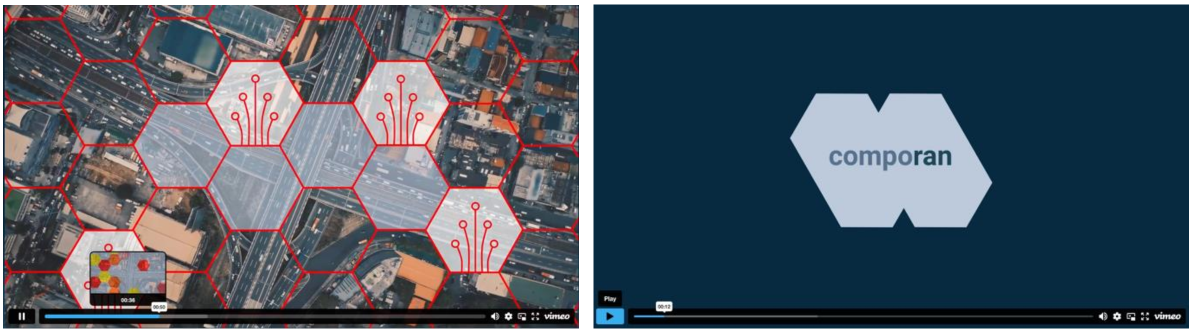

Figure 25 – CoMP-O-RAN Promotional Video

The CoMP-O-RAN Promotional Video is publicly hosted on Vimeo at this link: https://vimeo.com/750416053

9.2 Speaking Opportunities – Industry Dissemination

9.2.1 Small Cells World Summit 2023

Paul Senior, Chairman and Founder of Dense Air, spoke on "Why Split 6" at the Small Cells World Summit in 2023 providing the opportunity to discuss the progress made in the development of the CoMP-O-RAN solution; specifically, the use of Multi TRP 'Comp' and Small Cells. Dense Air was joined by CoMP-O-RAN partners Radisys in this panel discussion and proved to be one of the most widely discussed topics at the event.

Figure 26 - LinkedIn Dense Air Post at Small Cells World Summit 2023

Figure 27 - Paul Senior during panel discussion at Small Cell World Summit 2023

9.2.2 ConnectX 2023

Paul Trubridge, SVP Global Solutions Strategy Dense Air, joined the Dense Airs US team to speak at ConnectX 2023 on "Making Open RAN Work": This event provided a great opportunity for the dissemination of CoMP-O-RAN outside of the UK to industry in the US. As we have proved, CoMP-O-RAN cluster solutions is a critical component in 'Making Open RAN Work'.

Figure 28 - LinkedIn post of Dense Air's

Figure 28 shows a Dense Air LinkedIn blogpost on the learnings from ConnectX panel discussion 'Making Open RAN Work'.

9.2.3 MWC 2023

Dense Air Team: Dense Air's attendance at Mobile World Conference in 2023 provided management with time to sit down with UK Government Minister Julia Lopez, Minister of State (Minister for Data and Digital Infrastructure) and Minister of State for Media, Tourism and Creative Industries. This opportunity provided the team with a chance to debrief the Minister on the progress being made on the CoMP-O-RAN project, the tests and trials being carried out and feedback how welcome the support from UK Government.

Figure 29 – UK DCMS Minister Julia Lopez with Dense Air team at MWC 2023

9.2.4 UK 5G Innovation Network

"5G in Urban Places": Early in the CoMP-O-RAN project Paul Senior was invited to join a panel discussion at the UK5G Innovation Network event in Birmingham. Joined by members of industry Paul spoke about how CoMP-O-RAN targeted this specific use case for high demand areas such as urban centres.

Figure 30 – Paul Senior at UK5GIN event in Birmingham

9.3 Cenex

Cenex 2022 provided the consortium with the first opportunity to showcase to industry and member from the Department for Culture, Media and Sport the progress that had been made in the previous 12 months.

Members from each of the consortium partners attended the event and supported a demonstration of an existing Dense Air network across the Millbrook test tracks. This demonstration highlighted the need for multi TRP switching to provide consistent connectivity to vehicles – a key attribute which CoMP-O-RAN solved.

Figure 31 – CoMP-O-RAN Demonstration vehicles supplied by Jaguar Land Rover

Figure 32 - Dense Air stand hosted the CoMP-O-RAN team and collateral

The Dense Air stand hosted the CoMP-O-RAN team and communications collateral to diseminate the focus and goals of the project.

Figure 33 – Dense Air Sponsored Cenex 2023 Promotional Material

As sponsors of the Cenex 2023 event we were included in promotional material and the event catelogue.

Figure 34 - Paul Senior interviewed on CoMP-O-RAN

Al Clarke, working for Cenex, Interviewed Paul Senior about the project, the partners and the innovation in Open RAN network infrastructure.

Figure 35 - DCMS attending the Dense Air stand to discuss CoMP-O-RAN

Members of the project management team from DCMS attending the Dense Air stand to discuss CoMP-O-RAN project milestones and success to data.

10 Cenex 2023

10.1 Design of test equipment

To perform the 5G demonstrations for Cenex2023 a prototype simulator was built into the roof box of the test vehicle. The test equipment exercised the main features of the 5G system, connectivity, TRP switching and Bandwidth. This equipment performed very well throughout the day and with the collected information was also transmitted over the air into the Dense Air Cenex booth.

Figure 36 – 5G Roof box Telemetry System

Figure 37 – Optimised 5G Custom Box Telemetry System

The prototype test gear itself then went through a development cycle to a next generation of prototype providing a handheld solution that can also be attached to the roof of a test vehicle, shown in Figure 37.

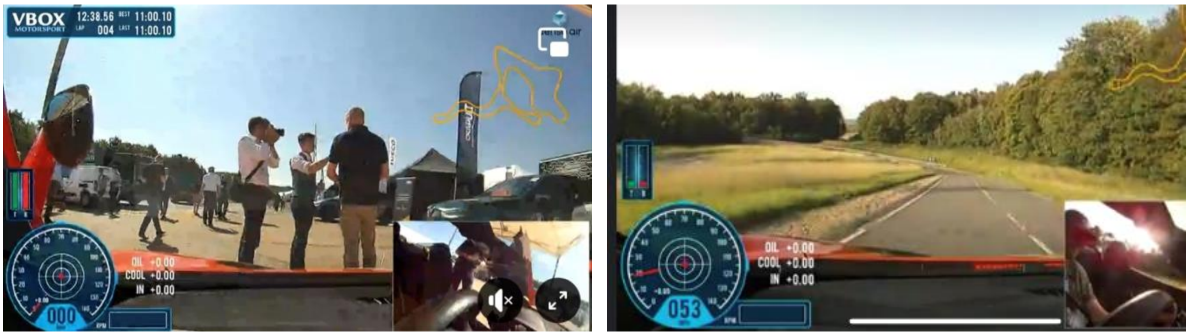

Figure 38 – Real-time Camera Relayed Back to Dense Air Cenex Stand

Cameras mounted in the car streamed back to the Dense Air stand to show the viewpoint of the driver. This setup was used to demonstrate the networks' ability to carry high volumes of data over the network from a moving vehicle.

Tablets were mounted in the car to show guests, during a drive test of the city course (CoMP-O-RAN network route) how the network performed:

- Cell TRP switching (not handing over)
- Simultaneous connections to multiple cells
- Performance (Upload and Download)
- RF Characteristic's

Figure 39 – City Course Masts with CoMP-O-RAN Small Cells

The City Course was the focal point for the onsite development of the CoMP-O-RAN project and for the demonstration.

10.2 Benefit realization

Cenex LCV 2023, hosted in UTAC Millbrook, enabled Dense Air and CoMP-O-RAN consortium partners to demonstrate the features and functionality of the CoMP-O-RAN system in a real-world environment to both Mobile Network Operators and industry guests.

As Millbrook had been used for ongoing testing a trial deployment of both 4G small cell technologies and CoMP-O-RAN 5G small cell system we were able to demonstrate to guests a comparison of:

- 4G small cell network on the hilltop route which provided typical 4G network performance, including weak spots and cell handover.
- 5G CoMP-O-RAN network on the city course which showcased no handover from cell to cell and enhance performance this cluster design provided.

To demonstrate the functionality of the CoMP-O-RAN cluster design Dense Air created a cell simulation demonstration that visualised the functionality of the network as user drove around the course.

Figure 40 - City Course Demonstration of CoMP-O-RAN

During the event Jo Shanmugalingam, Second Permanent Secretary at the Department for Transport visited the team to discuss how CoMP-O-RAN cluster technology provides a crucial step forward for the telecoms industry in supporting CAV and transport use cases. Seen here with Jim Estes, CEO Dense Air, Paul Senior, Founder and Chairman of Dense Air and Jonathan Eaton, Consultant at Dense Air.

Figure 41 - Jo Shanmugalingam Permanent Secretary DfT with Dense Air Executives

Louise Lancaster, Digital Infrastructure Department for Science, Innovation and Technology talked with the Dense Air and Consortium partners about the development of streetCell V1.1 – the hardware component developed through CoMP-O-RAN, of specific interest.

Figure 42 - Industry and public engagement at the Dense Air stand

Figure 43 – Dense Air Stand, Cenex 2023

Paul Senior spoke at Cenex 2023 during the CAM Tech Talk sessions. These sessions provided Paul with the opportunity to talk through the development of streetCell through to testing at Millbrook.

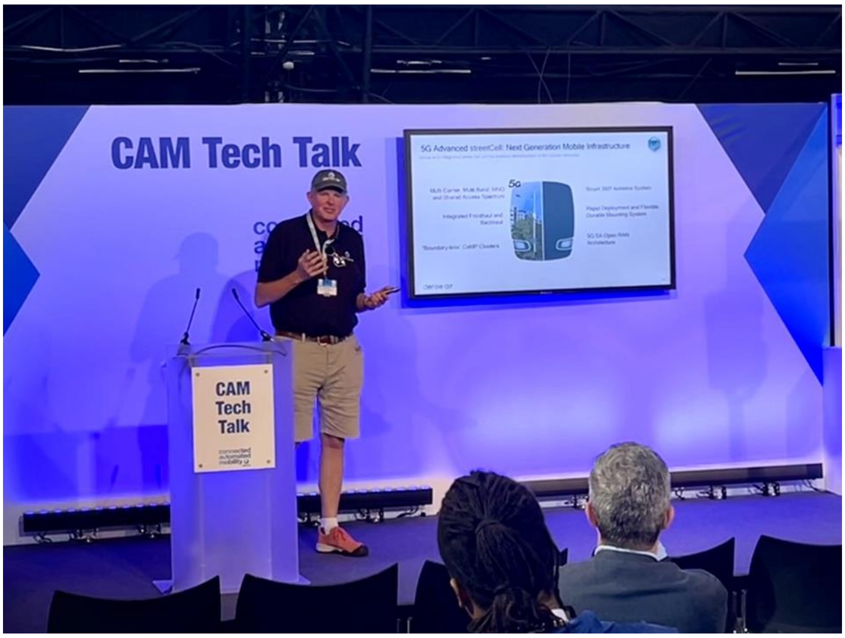

Figure 44 - Paul Senior presentation at Cenex 2023

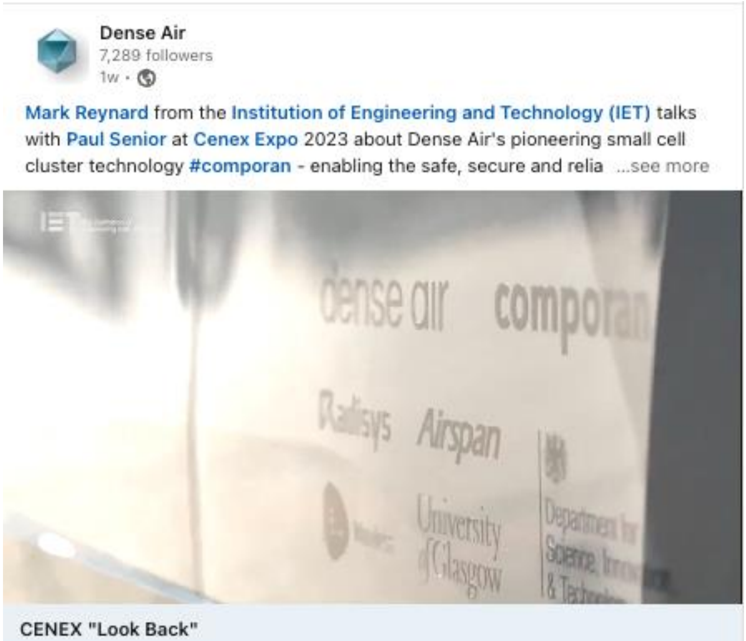

Figure 45 – Dense Air Social Media Posting on CoMP-O-RAN / Cenex2023

https://www.linkedin.com/feed/update/urn:li:activity:7118677372412850176

11 Sustainability

CoMP-O-RAN Project product development includes a Sustainability Road Map/Strategy and key elements of sustainability. This explains the activities originally planned for the long-term sustainability of the CoMP-O-RAN technology, the relationship to the Dense Air product portfolio development plan and CoMP-O-RAN Product development leading to commercialisation.

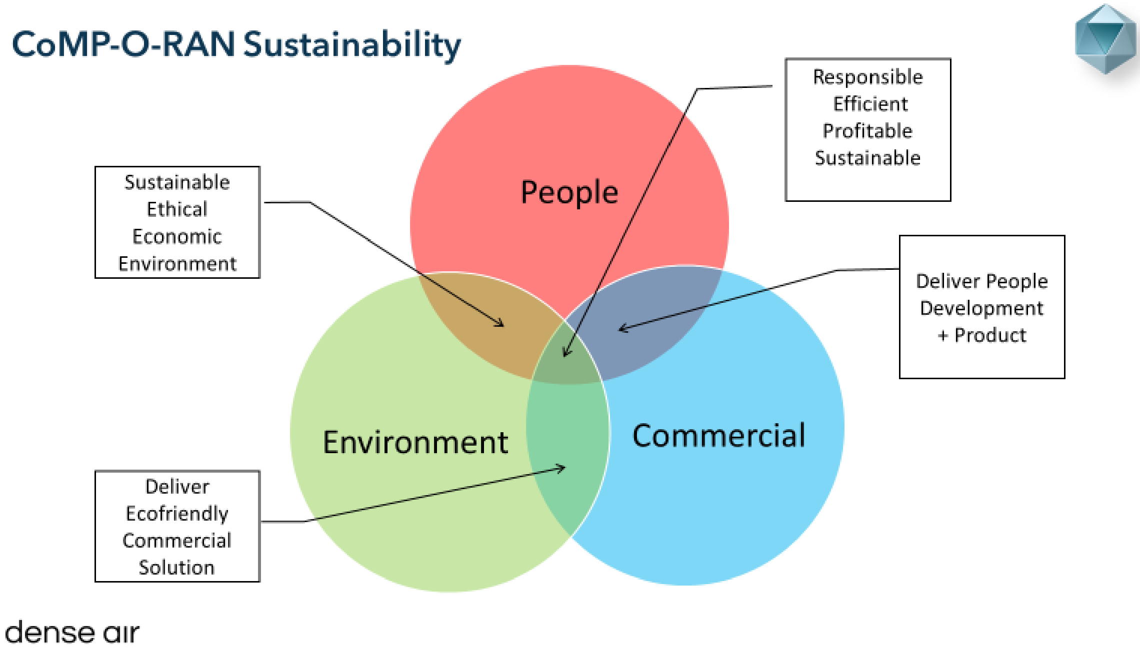

Figure 46 – CoMP-O-RAN Sustainability Chart

The CoMP-O-RAN project sustainability goal is a proven TRL level6/7 technology proven in a controlled field environment, that is defined on a product roadmap that ultimately will deliver a product to commercial readiness level.

The outcomes of the project from a sustainability standpoint meets the three elements of Environmental, commercial and personnel growth.

These can be articulated in the three pillars of:

- Environmental – the solution is developed to provide an environmental benefit over existing technology. In the case of CoMP-O-RAN a reduced requirement for deployed fibre and civil engineering cost with a single unit to provide multiple MNO hosting.
- Commercial – the solution creates a commercial and profitable business opportunity that fills a gap or creates a new business model, with a robust supply-chain model, a unique integrated small cell.
- People – creates a foundation and opportunity for personal development for telecom engineering, securing jobs and opportunities in the UK. Resulting in a sustainable UK R&D centre and laboratory based in Marlow.

Dense Air is not a component manufacturer, its development process looks to utilise existing fully developed hardware and software, systems integrate and customise to meet our portfolio of products, that in turn satisfy market and customer needs.

- Assembly of protype/NPI units takes place in the United Kingdom
- Intellectual Property (IP) developed in customized works is captured with IP Agreements and registered where appropriate.
- Co-ordinated freight movements (based on Incoterms 2020), inventory deployments and returns.
- Vendor forecasts based on demand generation, lead times and MOQs.

Maintaining a secure supply-chain approach is an important commercial pillar of sustainability.

12 Benefits realisation and lessons

The CoMP-O-RAN concept evolved from a market requirement to provide a small cell network capability to areas where fibre had limitations and power enabled through various solutions. To prove out the development of the Comp split6 algorithm in a integrated radio unit containing both a 5G gNodeB and mmWave to be used for back haul where fibre is not available or not cost effective.

For a normal cluster to work, fibres are required to be connected to each pole small cell as well as electrical power. For CoMP-O-RAN small cells the system relies on only 1 fibre to be connected to only 1 small cell in any cluster, the remaining small cells (up to 8) are connected via a mmWave link between the poles forming a CoMP-O-RAN cluster.

Therefore, the 'cost per bit' can be calculated based on the disruption in the installation environment where there are no fibres to the poles where small cells are needed to be installed.

Consequently the 'Cost per bit' benefit realisation of the project is the main element of the CoMP-O-RAN Benefit Realisation strategy and road map.

12.1 Cost per bit

To calculate the success and realise the benefit of CoMP-O-RAN we look specifically at the use cases where both fibre and power are either limited or in some cases not available or difficult to install.

Consequently, the decision to install both fibre and power in extreme cases can be cost prohibitive. Linking through a CoMP-O-RAN Mesh can provide a suitable alternative to traditional method.

12.1.1 Power

Power to small cells can be provide by several method both connected and independent:

- Utilising the spare pole capacity where the lighting is changed from halogen to LED
- National Grid power supply
- Solar panel

- Solar panel and battery storage
- ICE Generator and battery storage
- Fuel Cell
- Wind turbine

Basically, the provision of power is not a major contributing block to a network deployment. It is a requirement to support the operation of a small cell.

In most cases of small cell deployment, the assets used have a minimum provision of power, such as a building, lamp post etc.

12.1.2 Assets

With regards to the use of third-party assets, such as lamp posts, street furniture, bridges, towers, and buildings. The use or provision of an asset is a fundamental requirement to attach a small cell to. Therefore, in a cost calculation a suitable asset in general is not a limiting factor, and as stated above the majority have a readily available power supply, or a suitable low-cost option is available.

12.1.3 Fibre

An essential mode of connectivity in simplistic terms supporting the connectivity of base station to a Network Core.

The concept of CoMP-O-RAN produced a path to potential cost saving of reduced fibre connections in multiple scenarios.

It should be noted that there are many contributing factors to take into consideration for any network deployment and attention to access to local authority assets, natural and built up topography and geographical barriers.

Therefore, the following cost per bit calculation should be considered along with other contributing factors.

12.1.4 Cost Calculation

Cost 5G asset = a

Cost of Power =b

Cost of mmWave unit =w

Cost of Fibre per/250m = f

Cost of fibre link per year= l

Amortisation is excluded from the calculation.

12.1.4.1 Typical Fibred Deployment

Scenario of 6 off small cells connected via fibre 250m apart with a 5year fibre link.

standard calculation for a multi fibred deployment

$$6(a + 5b) + (5f) + 6(5l) = y£$$

12.1.4.2 CoMP-O-RAN deployment example

Scenario of 6 off small cells connected via 1 fronthaul fibre with a 5year fibre link.

Calculation with a single cell fibred with mmWave back haul mesh to 5 units

$$\underline{\mathbf{6(\mathit{a}+\mathit{w}+5b(\mathit{y}+1.2)) + \mathit{f} + 5\mathit{l} = \mathit{x}£}}$$

The justification to use CoMP-O-RAN over a standard small cell deployment should be based upon:

Decision based upon Cost per bit **=** **<u>x£ < y£</u>**

12.1.4.3 Topography

The local environment has a major impact in the decision-making process, specifically in the case of natural barriers such as rivers and geological obstructions. Challenging topography will add a significant cost to any deployment. A technical solution such as CoMP-O-RAN that negates intensive civil costs and time delays to a project, is therefore a technical decision which outweighs any commercial cost decision.

The sustainability of CoMP-O-RAN going forward will include cell share, the hosting of multiple MNOs on a streetCell™ unit also incorporating energy savings management system. This will be realised in the Open Networks Ecosystem Beach project which will be deployed in Worthing, West Sussex.

12.2 Use case as an example

Urban areas where roads and sidewalks would need to be excavated to install fibre, fibre would only be needed to one pole in the cluster, other poles would be connected over the air by mmWave resulting in less disruption during installation.

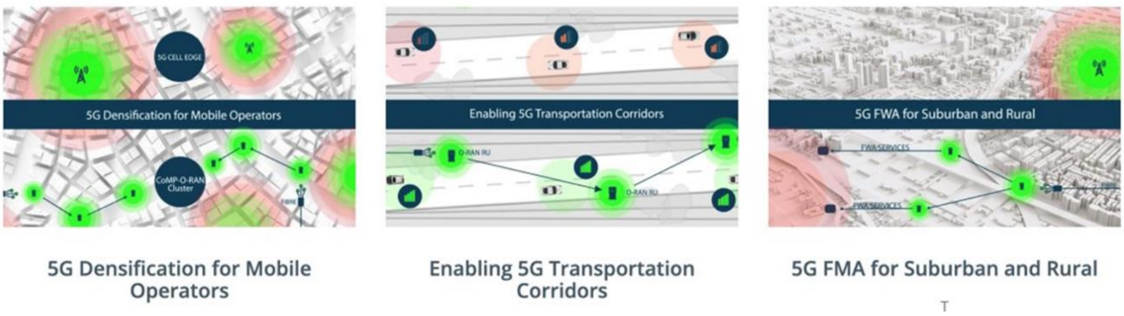

Figure 47 – Deployment Scenarios

Bridging natural barriers such as rivers where fibre is to one part of a village or town and there is a need for connectivity across a natural divide.

12.3 Learning from the project

a) Working at close quarters with consortium members.
b) Turning a novel idea into reality.
c) How security was handled and how it can be improved.
d) How to create and manage of a new engineering capability in the UK.
e) How to align management thoughts in the novel product.

f) Documenting all aspects of a project.
g) Development of a culture to foster co-operation with Consortium partners.
h) Instilling a culture of 'lessons learnt'.
i) Instilling a culture of 'secure by design'.
j) Knowledge transfer into the creation of new technical solutions and products.
k) Collective knowledge gain by all partners in the development
l) Collective, accelerated development, leading to rapid scale up of resources and results.
m) Test and Trial, 'Test and Trial', 'Test and Trial'!

12.3.1 Why do the project

a) Opportunity to work with consortium partners to create a totally new technology solution.
b) Government funding that supports a concept and de-risks the financial exposure of partners
c) Working in partnership with DSIT on a project which has wide exposure and shared learnings.
d) Dense Air conceived the CoMP-O-RAN idea, however, the challenge to bring partners together to accelerate concept to reality would not have taken place without intervention by DCMS (DSIT) FRANC Funding.
e) Innovation of next generation of technology
f) Establish a UK technology base.
g) Create a product that will form the foundation of a product portfolio and export business opportunity.
h) Secure a robust supply-chain.
i) Develop and enhance our collective security capability.

The project scope together with vital government funding attracted like-minded partners to come together as a consortium to execute a project that develops a novel idea into a tangible reality.

CoMP-O-RAN has achieved all the key milestones with performance and reliability exceeding expectations, the project is seen internally with all partner organisations as a great success.

13 Conclusion

The project has successfully implemented a CoMP-O-RAN small cell unit and network cluster from concept to TRL6/7 in approximately 18 months. This project has strengthened cooperative links between four leading UK telecommunications companies and a prestigious UK University, implementing a novel telecommunications system that can be adapted to a commercial reality.

The implementation and testing regimes covered all the major aims and has provided great insight into further UK-based developments and IP to protect the art. The end of the CoMP-O-RAN project is certainly not the end of the Split6/CoMP concept but an opportunity which will be refined over the coming period.

13.1 Post-CoMP-O-RAN

The project aim was to develop and test a network of prototypes and to prove the concept according to the requirement of the GFA. The project has advanced to the performance testing stage with a report showing the validation against simulation and real use case scenario achieves the Consortium expectation.

The success of the CoMP-O-RAN Small Cell network highlighted that the Split6/CoMP concept works. The next steps require an optimised design that can be manufactured to a desired cost point. This optimisation requires a deeper level of integration than was appropriate for the timescales of CoMP-O-RAN, however, the concept will be carried forward into the Beach Project to address future security aspects, software and interfaces and supply chain.

13.2 Summary from Consortium members

As this is a Dense Air document, contributions have been made by the consortium members and they were asked for their final statement after the completion of the project.

Rajadurai Vijithan, PM, Airspan Communications Limited

"Airspan is pleased to be a member of this prestigious consortium, led by DenseAir, that aims to accelerate innovation in 5G and Open RAN. In addition to developing new features and supplying the Airspeed 1900 radio unit, Airspan also helped to integrate the nFAPI/split-6 with Radisys CU/DU and enable the split-6 ORAN multi-TRP cluster implementation for a 5G NR standalone network. We believe this technology will play a key role in future 5G solutions"

Mark Barrett, Chief Commercial Officer, Blu Wireless Technology Ltd.

The successful delivery of the CoMP-O-RAN project enables a whole rethink of the next generation of 5G Networks. The integration of Blu Wireless' mmWave module, ZephyrBlu into a 5GNR solution, has been a real step change as industries no longer have that same dependence on per site fibre connectivity. Instead, they now have a complementary solution *that can work in tandem with legacy networks, and deliver consistently high bandwidth, low latency and resilient network performance essential for today's advanced applications.*

Now, multiple 5G small cells can be deployed on existing street assets in clusters around a single fibre connection, significantly driving down the capital investment needed for future 5G network densification. One of the key notable features that we've delivered through CoMP-O-RAN and are proud of is our low latency. We have engineered the mmWave platform to enable wireless links to be used across a number of ORAN domains, including fronthaul, midhaul or backhaul.

Brett Ditum, PM, Radisys UK

Radisys UK were a key partner in the CoMP-O-RAN Project awarded under the Future RAN (FRANC) competition. The project was focused on improving the TCO around 5G NR densification via optimisation and deployment of small cell clusters that relied on mmWave transport to offset need for excessive fibre transport infrastructure.

Radisys developed and implemented a partner modelled algorithm on key Network Functions that has been tested in the field and will be commercialised and manufactured in future. Our investment in this project supports Radisys wider market position and directly impacted the UK 5G skills base and ecosystem driving a key objective; i.e. supplier diversity among the vendor landscape.

The formal lessons learned and benefit realisation deliverables, that are part of the overall project, capture the detailed learnings from this project and are available to the wider community for the benefit of the UK 5G ecosystem. Especially with regard to Security related aspects of network delivery under the TSA/TSR landscape.

Shuja Ansari, PM, University of Glasgow

"The CoMP-O-RAN Project, in which the University of Glasgow played a pivotal role, has revolutionized the performance and cost of densified 5G New Radio (NR) outdoor small cell clusters. This collaborative effort, working alongside Dense Air Limited, Airspan Communications Limited, Blu Wireless UK Limited, and Radisys UK Limited, has successfully realized several benefits and made a substantial impact, largely driven by our innovative and novel algorithms for Coordinated Multi-point (CoMP) in non-ideal fronthaul settings within the ORAN Split 6 architecture. The CoMP-O-RAN project aimed to push the boundaries of 5G technology, and our contributions were instrumental in achieving this goal. Algorithms developed by the University of Glasgow was implemented and integrated with subsystems from various partners to demonstrate the viability of mmWave transport system. The project has validated the advantages of CoMP for small cell deployments, delivering spatial diversity, multiplexing gains, and energy/bit savings. Furthermore, the development of labs and testbeds, such as the Marlow lab and the Millbrook 5G testbed, lays a solid foundation for future research and commercialization, demonstrating the power of innovation and collaboration in advancing the 5G technology landscape. The lessons learned here provide invaluable insights for the industry's continued growth and development, showcasing the significance of cutting-edge algorithms and collaborative efforts in shaping the future of 5G networks."

Paul Senior, Founder and Chairman, Dense Air Limited

"CoMP-O-RAN set-out to revolutionize the performance and cost of densified 5G New Radio (NR) using outdoor small cell clusters and I believe we have surpassed our original targets",

said Paul Senior, Founder and Chairman of Dense Air Networks. "The project succeeded despite huge technical challenges and we completed an end to end integration of standard Open RAN technologies from multiple partners to create a seamless solution which will has become a platform for multiple Open RAN products from the consortium". The "streetCell", that Dense Air created has a tightly integrated a mmWave transport systems that enables a novel 5G NR CoMP algorithm to operate over a Split 6 O-RAN interface. This is a world first and enables the deployment of 5G small cell networks at a fraction of the cost of traditional fibre based deployments".

